Chapter 1

Introduction

1.1. The mean annual rainfall in Boston is approximately [1050 mm], and the mean annual evapotranspiration is in the range of [380–630 mm] (USGS). On the basis of rainfall, this indicates a [subhumid] climate. The mean annual rainfall in Santa Fe is approximately [360 mm] and the mean annual evapotranspiration is [< 380 mm]. On the basis of rainfall, this indicates an [arid] climate.

Chapter 2

Fundamentals of Flow in Closed Conduits

2.1. $D_1 = 0.1$ m, $D_2 = 0.15$ m, $V_1 = 2$ m/s, and

$$A_1 = \frac{\pi}{4}D_1^2 = \frac{\pi}{4}(0.1)^2 = 0.007854 \text{ m}^2$$
$$A_2 = \frac{\pi}{4}D_2^2 = \frac{\pi}{4}(0.15)^2 = 0.01767 \text{ m}^2$$

Volumetric flow rate, Q, is given by

$$Q = A_1V_1 = (0.007854)(2) = \boxed{0.0157 \text{ m}^3/\text{s}}$$

According to continuity,

$$A_1V_1 = A_2V_2 = Q$$

Therefore

$$V_2 = \frac{Q}{A_2} = \frac{0.0157}{0.01767} = \boxed{0.889 \text{ m/s}}$$

At 20°C, the density of water, ρ, is 998 kg/m^3, and the mass flow rate, $\dot{m}$, is given by

$$\dot{m} = \rho Q = (998)(0.0157) = \boxed{15.7 \text{ kg/s}}$$

2.2. From the given data: $D_1 = 200$ mm, $D_2 = 100$ mm, $V_1 = 1$ m/s, and

$$A_1 = \frac{\pi}{4}D_1^2 = \frac{\pi}{4}(0.2)^2 = 0.0314 \text{ m}^2$$
$$A_2 = \frac{\pi}{4}D_2^2 = \frac{\pi}{4}(0.1)^2 = 0.00785 \text{ m}^2$$

The flow rate, Q_1, in the 200-mm pipe is given by

$$Q_1 = A_1V_1 = (0.0314)(1) = 0.0314 \text{ m}^3/\text{s}$$

and hence the flow rate, Q_2, in the 100-mm pipe is

$$Q_2 = \frac{Q_1}{2} = \frac{0.0314}{2} = \boxed{0.0157 \text{ m}^3/\text{s}}$$

The average velocity, V_2, in the 100-mm pipe is

$$V_2 = \frac{Q_2}{A_2} = \frac{0.0157}{0.00785} = \boxed{2 \text{ m/s}}$$

2.3. The velocity distribution in the pipe is

$$v(r) = V_0 \left[1 - \left(\frac{r}{R}\right)^2\right] \qquad (1)$$

and the average velocity, $\bar{V}$, is defined as

$$\bar{V} = \frac{1}{A}\int_A V \, dA \qquad (2)$$

where

$$A = \pi R^2 \qquad \text{and} \qquad dA = 2\pi r dr \qquad (3)$$

Combining Equations 1 to 3 yields

$$\bar{V} = \frac{1}{\pi R^2}\int_0^R V_0 \left[1 - \left(\frac{r}{R}\right)^2\right] 2\pi r dr = \frac{2V_0}{R^2}\left[\int_0^R r dr - \int_0^R \frac{r^3}{R^2} dr\right] = \frac{2V_0}{R^2}\left[\frac{R^2}{2} - \frac{R^4}{4R^2}\right]$$
$$= \frac{2V_0}{R^2}\frac{R^2}{4} = \boxed{\frac{V_0}{2}}$$

The flow rate, Q, is therefore given by

$$Q = A\bar{V} = \boxed{\frac{\pi R^2 V_0}{2}}$$

2.4.

$$\beta = \frac{1}{A\bar{V}^2}\int_A v^2 \, dA = \frac{4}{\pi R^2 V_0^2}\int_0^R V_0^2 \left[1 - \frac{2r^2}{R^2} + \frac{r^4}{R^4}\right] 2\pi r dr$$
$$= \frac{8}{R^2}\left[\int_0^R r dr - \int_0^R \frac{2r^3}{R^2} dr + \int_0^R \frac{r^5}{R^4} dr\right] = \frac{8}{R^2}\left[\frac{R^2}{2} - \frac{R^4}{2R^2} + \frac{R^6}{6R^4}\right]$$
$$= \boxed{\frac{4}{3}}$$

2.5. $D = 0.2$ m, $Q = 0.06$ m^3/s, $L = 100$ m, $p_1 = 500$ kPa, $p_2 = 400$ kPa, $\gamma = 9.79$ kN/m^3.

$$R = \frac{D}{4} = \frac{0.2}{4} = 0.05 \text{ m}$$
$$\Delta h = \frac{p_1}{\gamma} - \frac{p_2}{\gamma} = \frac{500 - 400}{9.79} = 10.2 \text{ m}$$
$$\tau_0 = \frac{\gamma R \Delta h}{L} = \frac{(9.79 \times 10^3)(0.05)(10.2)}{100} = \boxed{49.9 \text{ N/m}^2}$$
$$A = \frac{\pi D^2}{4} = \frac{\pi (0.2)^2}{4} = 0.0314 \text{ m}^2$$
$$V = \frac{Q}{A} = \frac{0.06}{0.0314} = 1.91 \text{ m/s}$$
$$f = \frac{8\tau_0}{\rho V^2} = \frac{8(49.9)}{(998)(1.91)^2} = \boxed{0.11}$$

2.6. $T = 20°\text{C}$, $V = 2$ m/s, $D = 0.25$ m, horizontal pipe, ductile iron. For ductile iron pipe, $k_s = 0.26$ mm, and

$$\frac{k_s}{D} = \frac{0.26}{250} = 0.00104$$
$$\text{Re} = \frac{\rho V D}{\mu} = \frac{(998.2)(2)(0.25)}{(1.002 \times 10^{-3})} = 4.981 \times 10^5$$

From the Moody diagram:

$$\boxed{f = 0.0202 \text{ (pipe is smooth)}}$$

Using the Colebrook equation,

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{k_s/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right)$$

Substituting for k_s/D and Re gives

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{0.00104}{3.7} + \frac{2.51}{4.981 \times 10^5\sqrt{f}}\right)$$

By trial and error leads to

$$\boxed{f = 0.0204}$$

Using the Swamee-Jain equation,

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right]$$
$$= -2\log\left[\frac{0.00104}{3.7} + \frac{5.74}{(4.981 \times 10^5)^{0.9}}\right]$$

which leads to

$$\boxed{f = 0.0205}$$

The head loss, h_f, over 100 m of pipeline is given by

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = 0.0204\frac{100}{0.25}\frac{(2)^2}{2(9.81)} = 1.66 \text{ m}$$

Therefore the pressure drop, Δp, is given by

$$\Delta p = \gamma h_f = (9.79)(1.66) = \boxed{16.3 \text{ kPa}}$$

If the pipe is 1 m lower at the downstream end, f would not change, but the pressure drop, Δp, would then be given by

$$\Delta p = \gamma(h_f - 1.0) = 9.79(1.66 - 1) = \boxed{6.46 \text{ kPa}}$$

2.7. From the given data: $D = 25$ mm, $k_s = 0.1$ mm, $\theta = 10°$, $p_1 = 550$ kPa, and $L = 100$ m. At 20°C, $\nu = 1.00 \times 10^{-6}$ m^2/s, $\gamma = 9.79$ kN/m^3, and

$$\frac{k_s}{D} = \frac{0.1}{25} = 0.004$$
$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.025)^2 = 4.909 \times 10^{-4} \text{ m}^2$$
$$h_f = f\frac{L}{D}\frac{Q^2}{2gA^2} = f\frac{100}{0.025}\frac{Q^2}{2(9.81)(4.909 \times 10^{-4})^2} = 8.46 \times 10^8 fQ^2$$

The energy equation applied over 100 m of pipe is

$$\frac{p_1}{\gamma} + \frac{V^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V^2}{2g} + z_2 + h_f$$

which simplifies to

$$p_2 = p_1 - \gamma(z_2 - z_1) - \gamma h_f$$
$$p_2 = 550 - 9.79(100 \sin 10°) - 9.79(8.46 \times 10^8 fQ^2)$$
$$p_2 = 380.0 - 8.28 \times 10^9 fQ^2$$

(a) For $Q = 2$ L/min $= 3.333 \times 10^{-5}$ m^3/s,

$$V = \frac{Q}{A} = \frac{3.333 \times 10^{-5}}{4.909 \times 10^{-4}} = 0.06790 \text{ m/s}$$
$$\text{Re} = \frac{VD}{\nu} = \frac{(0.06790)(0.025)}{1 \times 10^{-6}} = 1698$$

Since Re < 2000, the flow is laminar when $Q = 2$ L/min. Hence,

$$f = \frac{64}{\text{Re}} = \frac{64}{1698} = 0.03770$$
$$p_2 = 380.0 - 8.28 \times 10^9(0.03770)(3.333 \times 10^{-5})^2 = 380 \text{ kPa}$$

Therefore, when the flow is 2 L/min, the pressure at the downstream section is $\boxed{380 \text{ kPa}}$.
For $Q = 20$ L/min $= 3.333 \times 10^{-4}$ m^3/s,

$$V = \frac{Q}{A} = \frac{3.333 \times 10^{-4}}{4.909 \times 10^{-4}} = 0.6790 \text{ m/s}$$
$$\text{Re} = \frac{VD}{\nu} = \frac{(0.6790)(0.025)}{1 \times 10^{-6}} = 16980$$

Since Re > 5000, the flow is turbulent when $Q = 20$ L/min. Hence,

$$f = \frac{0.25}{\left[\log\left(\frac{k_s/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right)\right]^2} = \frac{0.25}{\left[\log\left(\frac{0.004}{3.7} + \frac{5.74}{16980^{0.9}}\right)\right]^2} = 0.0342$$
$$p_2 = 380.0 - 8.28 \times 10^9(0.0342)(3.333 \times 10^{-4})^2 = 349 \text{ kPa}$$

Therefore, when the flow is 2 L/min, the pressure at the downstream section is $\boxed{349 \text{ kPa}}$.

(b) Using the Colebrook equation with $Q = 20$ L/min,

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right] = -2\log\left[\frac{0.004}{3.7} + \frac{2.51}{16980\sqrt{f}}\right]$$

which yields $\boxed{f = 0.0337}$. Comparing this with the Swamee-Jain result of $\boxed{f = 0.0342}$ indicates a difference of $\boxed{1.5\%}$, which is more than the 1% claimed by Swamee-Jain.

2.8. The Colebrook equation is given by

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{k_s/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right)$$

Inverting and squaring this equation gives

$$\boxed{f = \frac{0.25}{\{\log[(k_s/D)/3.7 + 2.51/(\text{Re}\sqrt{f})]\}^2}}$$

This equation is "slightly more convenient" than the Colebrook formula since it is quasi-explicit in f, whereas the Colebrook formula gives $1/\sqrt{f}$.

2.9. The Colebrook equation is preferable since it provides greater accuracy than interpolating from the Moody diagram.

2.10. $D = 0.5$ m, $p_1 = 600$ kPa, $Q = 0.50$ m^3/s, $z_1 = 120$ m, $z_2 = 100$ m, $\gamma = 9.79$ kN/m^3, $L = 1000$ m, k_s (ductile iron) = 0.26 mm,

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.5)^2 = 0.1963 \text{ m}^2$$
$$V = \frac{Q}{A} = \frac{0.50}{0.1963} = 2.55 \text{ m/s}$$

Using the Colebrook equation,

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{k_s/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right)$$

where $k_s/D = 0.26/500 = 0.00052$, and at 20°C

$$\text{Re} = \frac{\rho V D}{\mu} = \frac{(998)(2.55)(0.5)}{1.00 \times 10^{-3}} = 1.27 \times 10^6$$

Substituting k_s/D and Re into the Colebrook equation gives

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{0.00052}{3.7} + \frac{2.51}{1.27 \times 10^6\sqrt{f}}\right)$$

which leads to

$$f = 0.0172$$

Applying the energy equation

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_f$$

Since $V_1 = V_2$, and h_f is given by the Darcy-Weisbach equation, then the energy equation can be written as

$$\frac{p_1}{\gamma} + z_1 = \frac{p_2}{\gamma} + z_2 + f\frac{L}{D}\frac{V^2}{2g}$$

Substituting known values leads to

$$\frac{600}{9.79} + 120 = \frac{p_2}{9.79} + 100 + 0.0172\frac{1000}{0.5}\frac{(2.55)^2}{2(9.81)}$$

which gives

$$\boxed{p_2 = 684 \text{ kPa}}$$

If p is the (static) pressure at the top of a 30 m high building, then

$$p = p_2 - 30\gamma = 684 - 30(9.79) = 390 \text{ kPa}$$

This (static) water pressure is adequate for service.

2.11. The head loss, h_f, in the pipe is estimated by

$$h_f = \left(\frac{p_\text{main}}{\gamma} + z_\text{main}\right) - \left(\frac{p_\text{outlet}}{\gamma} + z_\text{outlet}\right)$$

where $p_\text{main} = 400$ kPa, $z_\text{main} = 0$ m, $p_\text{outlet} = 0$ kPa, and $z_\text{outlet} = 2.0$ m. Therefore,

$$h_f = \left(\frac{400}{9.79} + 0\right) - (0 + 2.0) = 38.9 \text{ m}$$

Also, since $D = 25$ mm, $L = 20$ m, $k_s = 0.15$ mm (from Table 2.1), $\nu = 1.00 \times 10^{-6}$ m^2/s (at 20°C), the combined Darcy-Weisbach and Colebrook equation (Equation 2.43) yields,

$$\begin{aligned} Q &= -0.965D^2\sqrt{\frac{gDh_f}{L}}\ln\left(\frac{k_s/D}{3.7} + \frac{1.774\nu}{D\sqrt{gDh_f/L}}\right) \\ &= -0.965(0.025)^2\sqrt{\frac{(9.81)(0.025)(38.9)}{20}}\ln\left[\frac{0.15/25}{3.7} + \frac{1.774(1.00\times10^{-6})}{(0.025)\sqrt{(9.81)(0.025)(38.9)/20}}\right] \\ &= 0.00265 \text{ m}^3/\text{s} = 2.65 \text{ L/s} \end{aligned}$$

The faucet can therefore be expected to deliver $\boxed{2.65 \text{ L/s}}$ when fully open.

2.12. From the given data: $Q = 300$ L/s $= 0.300$ m^3/s, $L = 40$ m, and $h_f = 45$ m. Assume that $\nu = 10^{-6}$ m^2/s (at 20°C) and take $k_s = 0.15$ mm (from Table 2.1). Substituting these data into Equation 2.43 gives

$$Q = -0.965D^2\sqrt{\frac{gDh_f}{L}}\ln\left(\frac{k_s/D}{3.7} + \frac{1.784\nu}{D\sqrt{gDh_f/L}}\right)$$

$$0.2 = -0.965D^2\sqrt{\frac{(9.81)D(45)}{(40)}}\ln\left(\frac{0.00015}{3.7D} + \frac{1.784(10^{-6})}{D\sqrt{(9.81)D(45)/(40)}}\right)$$

This is an implicit equation in D that can be solved numerically to yield $\boxed{D = 166 \text{ mm}}$.

2.13. Since $k_s = 0.15$ mm, $L = 40$ m, $Q = 0.3$ m^3/s, $h_f = 45$ m, $\nu = 1.00 \times 10^{-6}$ m^2/s, the Swamee-Jain approximation (Equation 2.44 gives

$$\begin{aligned} D &= 0.66\left[k_s^{1.25}\left(\frac{LQ^2}{gh_f}\right)^{4.75} + \nu Q^{9.4}\left(\frac{L}{gh_f}\right)^{5.2}\right]^{0.04} \\ &= 0.66\left\{(0.00015)^{1.25}\left[\frac{(40)(0.3)^2}{(9.81)(45)}\right]^{4.75} + (1.00\times10^{-6})(0.3)^{9.4}\left[\frac{40}{(9.81)(45)}\right]^{5.2}\right\}^{0.04} \\ &= 0.171 \text{ m} = \boxed{171 \text{ mm}} \end{aligned}$$

The calculated pipe diameter (171 mm) is about 3% higher than calculated by the Colebrook equation (166 mm).

2.14. The kinetic energy correction factor, α, is defined by

$$\int_A \rho\frac{v^3}{2}dA = \alpha\rho\frac{V^3}{2}A$$

or

$$\alpha = \frac{\int_A v^3 dA}{V^3 A} \tag{1}$$

Using the velocity distribution in Problem 2.3 gives

$$\begin{aligned} \int_A v^3 dA &= \int_0^R V_0^3\left[1 - \left(\frac{r}{R}\right)^2\right]^2 2\pi r\; dr \\ &= 2\pi V_0^3\int_0^R\left[1 - 3\left(\frac{r}{R}\right)^2 + 3\left(\frac{r}{R}\right)^4 - \left(\frac{r}{R}\right)^6\right] r\; dr \\ &= 2\pi V_0^3\int_0^R\left[r - \frac{3r^3}{R^2} + \frac{3r^5}{R^4} - \frac{r^7}{R^6}\right]dr \\ &= 2\pi V_0^3\left[\frac{r^2}{2} - \frac{3r^4}{4R^2} + \frac{r^6}{2R^4} - \frac{r^8}{8R^6}\right]_0^R \\ &= 2\pi R^2V_0^3\left[\frac{1}{2} - \frac{3}{4} + \frac{1}{2} - \frac{1}{8}\right] \\ &= \frac{\pi R^2 V_0^3}{4} \end{aligned} \tag{2}$$

The average velocity, V, was calculated in Problem 2.3 as

$$V = \frac{V_0}{2}$$

hence

$$V^3 A = \left(\frac{V_0}{2}\right)^3 \pi R^2 = \frac{\pi R^2 V_0^3}{8} \tag{3}$$

Combining Equations 1 to 3 gives

$$\alpha = \frac{\pi R^2 V_0^3/4}{\pi R^2 V_0^3/8} = \boxed{2}$$

2.15. The kinetic energy correction factor, α, is defined by

$$\alpha = \frac{\int_A v^3 dA}{V^3 A} \tag{1}$$

Using the given velocity distribution gives

$$\begin{aligned}\int_A v^3 dA &= \int_0^R V_0^3 \left(1 - \frac{r}{R}\right)^{\frac{3}{7}} 2\pi r\ dr \\ &= 2\pi V_0^3 \int_0^R \left(1 - \frac{r}{R}\right)^{\frac{3}{7}} r\ dr \end{aligned} \tag{2}$$

To facilitate integration, let

$$x = 1 - \frac{r}{R} \tag{3}$$

which gives

$$r = R(1-x) \tag{4}$$

$$dr = -R\ dx \tag{5}$$

Combining Equations 2 to 5 gives

$$\begin{aligned}\int_A v^3 dA &= 2\pi V_0^3 \int_0^1 x^{\frac{3}{7}} R(1-x)(-R)dx \\ &= 2\pi R^2 V_0^3 \int_0^1 x^{\frac{3}{7}}(1-x)dx = 2\pi R^2 V_0^3 \int_0^1 (x^{\frac{3}{7}} - x^{\frac{10}{7}})dx \\ &= 2\pi R^2 V_0^3 \left[\frac{7}{10}x^{\frac{10}{7}} - \frac{7}{17}x^{\frac{17}{7}}\right]_0^1 \\ &= 0.576\pi R^2 V_0^3 \end{aligned} \tag{6}$$

The average velocity, V, is given by (using the same substitution as above)

$$\begin{aligned} V &= \frac{1}{A}\int_A v\ dA \\ &= \frac{1}{\pi R^2}\int_0^R V_0 \left(1 - \frac{r}{R}\right)^{\frac{1}{7}} 2\pi r\ dr = \frac{2V_0}{R^2}\int_1^0 x^{\frac{1}{7}} R(1-x)(-R)dx \\ &= 2V_0 \int_0^1 (x^{\frac{1}{7}} - x^{\frac{8}{7}})dx = 2V_0 \left[\frac{7}{8}x^{\frac{8}{7}} - \frac{7}{15}x^{\frac{15}{7}}\right]_0^1 \\ &= 0.817 V_0 \end{aligned} \tag{7}$$

Using this result,

$$V^3A = (0.817V_0)^3\pi R^2 = 0.545\pi R^2 V_0^3 \tag{8}$$

Combining Equations 1, 6, and 8 gives

$$\alpha = \frac{0.576\pi R^2 V_0^3}{0.545\pi R^2 V_0^3} = \boxed{1.06}$$

The momentum correction factor, β, is defined by

$$\beta = \frac{\int_A v^2 dA}{AV^2} \tag{9}$$

In this case,

$$AV^2 = \pi R^2(0.817V_0)^2 = 0.667\pi R^2 V_0^2 \tag{10}$$

and

$$\begin{aligned}\int_A v^2 dA &= \int_0^R V_0^2 \left(1 - \frac{r}{R}\right)^{\frac{2}{7}} 2\pi r\ dr \\ &= 2\pi V_0^2 \int_1^0 x^{\frac{2}{7}} R(1-x)(-R)dx = 2\pi R^2 V_0^2 \int_0^1 (x^{\frac{2}{7}} - x^{\frac{9}{7}})dx \\ &= 2\pi R^2 V_0^2 \left[\frac{7}{9}x^{\frac{9}{7}} - \frac{7}{16}x^{\frac{16}{7}}\right]_0^1 = 0.681\pi R^2 V_0^2 \end{aligned} \tag{11}$$

Combining Equations 9 to 11 gives

$$\beta = \frac{0.681\pi R^2 V_0^2}{0.667\pi R^2 V_0^2} = \boxed{1.02}$$

2.16. The kinetic energy correction factor, α, is defined by

$$\alpha = \frac{\int_A v^3 dA}{V^3 A} \tag{1}$$

Using the velocity distribution given by Equation 2.73 gives

$$\begin{aligned}\int_A v^3 dA &= \int_0^R V_0^3 \left(1 - \frac{r}{R}\right)^{\frac{3}{n}} 2\pi r\ dr \\ &= 2\pi V_0^3 \int_0^R \left(1 - \frac{r}{R}\right)^{\frac{3}{n}} r\ dr \end{aligned} \tag{2}$$

Let

$$x = 1 - \frac{r}{R} \tag{3}$$

which gives

$$r = R(1-x) \tag{4}$$

$$dr = -R\ dx \tag{5}$$

Combining Equations 2 to 5 gives

$$\begin{aligned}\int_A v^3 dA &= 2\pi V_0^3 \int_0^1 x^{\frac{3}{n}} R(1-x)(-R)dx \\ &= 2\pi R^2 V_0^3 \int_0^1 x^{\frac{3}{n}}(1-x)dx = 2\pi R^2 V_0^3 \int_0^1 (x^{\frac{3}{n}} - x^{\frac{3+n}{n}})dx \\ &= 2\pi R^2 V_0^3 \left[\frac{n}{3+n}x^{\frac{3+n}{n}} - \frac{n}{3+2n}x^{\frac{3+2n}{n}}\right]_0^1 \\ &= \frac{2n^2}{(3+n)(3+2n)}\pi R^2 V_0^3 \qquad (6)\end{aligned}$$

The average velocity, V, is given by

$$\begin{aligned}V &= \frac{1}{A}\int_A v\ dA \\ &= \frac{1}{\pi R^2}\int_0^R V_0\left(1-\frac{r}{R}\right)^{\frac{1}{n}} 2\pi r\ dr = \frac{2V_0}{R^2}\int_1^0 x^{\frac{1}{n}} R(1-x)(-R)dx \\ &= 2V_0 \int_0^1 (x^{\frac{1}{n}} - x^{\frac{1+n}{n}})dx = 2V_0\left[\frac{n}{1+n}x^{\frac{1+n}{n}} - \frac{n}{1+2n}x^{\frac{1+2n}{n}}\right]_0^1 \\ &= \left[\frac{2n^2}{(1+n)(1+2n)}\right] V_0 \qquad (7)\end{aligned}$$

Using this result,

$$V^3 A = \left[\frac{2n^2}{(1+n)(1+2n)}\right]^3 V_0^3 \pi R^2 = \frac{8n^6}{(1+n)^3(1+2n)^3}\pi R^2 V_0^3 \qquad (8)$$

Combining Equations 1, 6, and 8 gives

$$\begin{aligned}\alpha &= \frac{\frac{2n^2}{(3+n)(3+2n)}\pi R^2 V_0^3}{\frac{8n^6}{(1+n)^3(1+2n)^3}\pi R^2 V_0^3} \\ &= \boxed{\frac{(1+n)^3(1+2n)^3}{4n^4(3+n)(3+2n)}}\end{aligned}$$

Putting $n = 7$ gives $\boxed{\alpha = 1.06}$, the same result obtained in Problem 2.15.

2.17. $p_1 = 30$ kPa, $p_2 = 500$ kPa, therefore head, h_p, added by pump is given by

$$h_p = \frac{p_2 - p_1}{\gamma} = \frac{500-30}{9.79} = \boxed{48.0 \text{ m}}$$

Power, P, added by pump is given by

$$P = \gamma Q h_p = (9.79)(Q)(48.0) = \boxed{470 \text{ kW per m}^3\text{/s}}$$

2.18. $Q = 0.06$ m^3/s, $D = 0.2$ m, $k_s = 0.9$ mm (riveted steel), $k_s/D = 0.9/200 = 0.00450$, for 90° bend $K = 0.3$, for the entrance $K = 1.0$, at 20°C $\rho = 998$ kg/m^3, and $\mu = 1.00 \times 10^{-3}$ Pa·s, therefore

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.2)^2 = 0.0314 \text{ m}^2$$
$$V = \frac{Q}{A} = \frac{0.06}{0.0314} = 1.91 \text{ m/s}$$
$$\text{Re} = \frac{\rho V D}{\mu} = \frac{(998)(1.91)(0.2)}{1.00 \times 10^{-3}} = 3.81 \times 10^5$$

Substituting k_s/D and Re into the Colebrook equation gives

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{0.00450}{3.7} + \frac{2.51}{3.81 \times 10^5\sqrt{f}}\right)$$

which leads to

$$f = 0.0297$$

Minor head loss, h_m, is given by

$$h_m = \sum K\frac{V^2}{2g} = (1.0 + 0.3)\frac{(1.91)^2}{2(9.81)} = 0.242 \text{ m}$$

If friction losses, h_f, account for 90% of the total losses, then

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = 9h_m$$

which means that

$$0.0297\frac{L}{0.2}\frac{(1.91)^2}{2(9.81)} = 9(0.242)$$

Solving for L gives

$$\boxed{L = 78.9 \text{ m}}$$

For pipe lengths shorter than the length calculated in this problem, the word "minor" should not be used.

2.19. From the given data: $p_0 = 480$ kPa, $v_0 = 5$ m/s, $z_0 = 2.44$ m, $D = 19$ mm $= 0.019$ m, $L =$ 40 m, $z_1 = 7.62$ m, and $\sum K_m = 3.5$. For copper tubing it can be assumed that $k_s = 0.0023$ mm. Applying the energy and Darcy-Weisbach equations between the water main and the faucet gives

$$\frac{p_0}{\gamma} + z_0 - h_f - h_m = \frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1$$
$$\frac{480}{9.79} + 2.44 - \frac{f(40)}{0.019}\frac{v^2}{2(9.81)} - 3.5\frac{v^2}{2(9.81)} = \frac{0}{\gamma} + \frac{v^2}{2(9.81)} + 7.62$$

which simplifies to

$$v = \frac{6.622}{\sqrt{107.3f - 0.2141}} \tag{1}$$

The Colebrook equation, with $\nu = 1 \times 10^{-6}$ m^2/s gives

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s}{3.7D} + \frac{2.51}{\text{Re}\sqrt{f}}\right]$$

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{0.0025}{3.7(19)} + \frac{2.51}{\frac{v(0.019)}{1\times10^{-6}}\sqrt{f}}\right]$$

$$\frac{1}{\sqrt{f}} = -2\log\left[3.556\times10^{-5} + \frac{1.321\times10^{-4}}{v\sqrt{f}}\right] \quad (2)$$

Combining Equations 1 and 2 gives

$$\frac{1}{\sqrt{f}} = -2\log\left[3.556\times10^{-5} + \frac{1.995\times10^{-5}\sqrt{107.3f - 0.2141}}{\sqrt{f}}\right]$$

which yields

$$f = 0.0189$$

Substituting into Equation 1 yields

$$v = \frac{6.622}{\sqrt{107.3(0.0189) - 0.2141}} = 4.92 \text{ m/s}$$

$$Q = Av = \left(\frac{\pi}{4}0.019^2\right)(4.92) = 0.00139 \text{ m}^3\text{/s} = \boxed{1.39 \text{ L/s } (= 22 \text{ gpm})}$$

This flow is [very high] for a faucet. The flow would be [reduced] if other faucets are open, this is due to increased pipe flow and frictional resistance between the water main and the faucet.

2.20. From the given data: $z_1 = -1.5$ m, $z_2 = 40$ m, $p_1 = 450$ kPa, $\sum k = 10.0$, $Q = 20$ L/s $= 0.02$ m^3/s, $D = 150$ mm (PVC), $L = 60$ m, $T = 20$°C, and $p_2 = 150$ kPa. The combined energy and Darcy-Weisbach equations give

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_p = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + \left[\frac{fL}{D} + \sum k\right]\frac{V^2}{2g} \quad (1)$$

where

$$V_1 = V_2 = V = \frac{Q}{A} = \frac{0.02}{\frac{\pi(0.15)^2}{4}} = 1.13 \text{ m/s} \quad (2)$$

At 20°C, $\nu = 1.00 \times 10^{-6}$ m^2/s, and

$$\text{Re} = \frac{VD}{\nu} = \frac{(1.13)(0.15)}{1.00\times10^{-6}} = 169500$$

Since PVC pipe is smooth ($k_s = 0$), the friction factor, f, is given by

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{2.51}{\text{Re}\sqrt{f}}\right) = -2\log\left(\frac{2.51}{169500\sqrt{f}}\right)$$

which yields

$$f = 0.0162 \tag{3}$$

Taking $\gamma = 9.79$ kN/m^3 and combining Equations 1 to 3 yields

$$\frac{450}{9.79} + \frac{1.13^2}{2(9.81)} + (-1.5) + h_p = \frac{150}{9.79} + \frac{1.13^2}{2(9.81)} + 40 + \left[\frac{(0.0162)(60)}{0.15} + 10\right]\frac{1.13^2}{2(9.81)}$$

which gives

$$h_p = 11.9 \text{ m}$$

Since $h_p > 0$, a booster pump is required. The power, P, to be supplied by the pump is given by

$$P = \gamma Q h_p = (9.79)(0.02)(11.9) = \boxed{2.3 \text{ kW}}$$

2.21. (a) Diameter of pipe, $D = 0.75$ m, area, A given by

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.75)^2 = 0.442 \text{ m}^2$$

and velocity, V, in pipe

$$V = \frac{Q}{A} = \frac{1}{0.442} = 2.26 \text{ m/s}$$

Energy equation between reservoir and A:

$$7 + h_p - h_f = \frac{p_A}{\gamma} + \frac{V_A^2}{2g} + z_A \tag{1}$$

where $p_A = 350$ kPa, $\gamma = 9.79$ kN/m^3, $V_A = 2.26$ m/s, $z_A = 10$ m, and

$$h_f = \frac{fL}{D}\frac{V^2}{2g}$$

where f depends on Re and k_s/D. At 20°C, $\nu = 1.00 \times 10^{-6}$ m^2/s and

$$\text{Re} = \frac{VD}{\nu} = \frac{(2.26)(0.75)}{1.00 \times 10^{-6}} = 1.70 \times 10^6$$

$$\frac{k_s}{D} = \frac{0.26}{750} = 3.47 \times 10^{-4}$$

Using the Swamee-Jain equation,

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right] = -2\log\left[\frac{3.47 \times 10^{-4}}{3.7} + \frac{5.74}{(1.70 \times 10^6)^{0.9}}\right] = 7.93$$

which leads to

$$f = 0.0159$$

The head loss, h_f, between the reservoir and A is therefore given by

$$h_f = \frac{fL}{D}\frac{V^2}{2g} = \frac{(0.0159)(1000)}{0.75}\frac{(2.26)^2}{2(9.81)} = 5.52 \text{ m}$$

Substituting into Equation 1 yields

$$7 + h_p - 5.52 = \frac{350}{9.81} + \frac{2.26^2}{2(9.81)} + 10$$

which leads to

$$\boxed{h_p = 44.5 \text{ m}}$$

(b) Power, P, supplied by the pump is given by

$$P = \gamma Q h_p = (9.79)(1)(44.5) = \boxed{436 \text{ kW}}$$

(c) Energy equation between A and B is given by

$$\frac{p_A}{\gamma} + \frac{V_A^2}{2g} + z_A - h_f = \frac{p_B}{\gamma} + \frac{V_B^2}{2g} + z_B$$

and since $V_A = V_B$,

$$\begin{aligned} p_B &= p_A + \gamma(z_A - z_B - h_f) = 350 + 9.79(10 - 4 - 5.52) \\ &= \boxed{355 \text{ kPa}} \end{aligned}$$

2.22. From the given data: L = 3 km = 3000 m, Q_ave = 0.0175 m^3/s, and Q_peak = 0.578 m^3/s. If the velocity, V_peak, during peak flow conditions is 2.5 m/s, then

$$2.5 = \frac{Q_\text{peak}}{\pi D^2/4} = \frac{0.578}{\pi D^2/4}$$

which gives

$$D = \sqrt{\frac{0.578}{\pi(2.5)/4}} = 0.543 \text{ m}$$

Rounding to the nearest 25 mm gives

$$\boxed{D = 550 \text{ mm}}$$

with a cross-sectional area, A, given by

$$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.550)^2 = 0.238 \text{ m}^2$$

During average demand conditions, the head, h_ave, at the suburban development is given by

$$h_\text{ave} = \frac{p_\text{ave}}{\gamma} + \frac{V_\text{ave}^2}{2g} + z_0 \qquad (1)$$

where p_ave = 340 kPa, γ = 9.79 kN/m^3, $V_\text{ave} = Q_\text{ave}/A = 0.0175/0.238 = 0.0735$ m/s, and z_0 = 8.80 m. Substituting into Equation 1 gives

$$h_\text{ave} = \frac{340}{9.79} + \frac{0.0735^2}{2(9.81)} + 8.80 = 43.5 \text{ m}$$

For ductile-iron pipe, $k_s = 0.26$ mm, $k_s/D = 0.26/550 = 4.73 \times 10^{-4}$, at 20°C $\nu = 1.00 \times 10^{-6}$ m^2/s, and therefore

$$\text{Re} = \frac{V_\text{ave} D}{\nu} = \frac{(0.0735)(0.550)}{1.00 \times 10^{-6}} = 4.04 \times 10^4$$

and the Swamee-Jain equation gives

$$\frac{1}{\sqrt{f_\text{ave}}} = -2 \log \left[\frac{k_s/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}} \right] = -2 \log \left[\frac{4.73 \times 10^{-4}}{3.7} + \frac{5.74}{(4.04 \times 10^4)^{0.9}} \right]$$

and yields

$$f_\text{ave} = 0.0234$$

The head loss between the water treatment plant and the suburban development is therefore given by

$$h_f = f \frac{L}{D} \frac{V^2}{2g} = (0.0234) \frac{3000}{0.550} \frac{0.0735^2}{2(9.81)} = 0.035 \text{ m}$$

Since the head at the water treatment plant is 10.00 m, the pump head, h_p, that must be added is

$$h_p = (43.5 + 0.035) - 10.00 = 33.5 \text{ m}$$

and the power requirement, P, is given by

$$P = \gamma Q h_p = (9.79)(0.0175)(33.5) = \boxed{5.74 \text{ kW}}$$

During peak demand conditions, the head, h_peak, at the suburban development is given by

$$h_\text{peak} = \frac{p_\text{peak}}{\gamma} + \frac{V_\text{peak}^2}{2g} + z_0 \tag{2}$$

where p_peak = 140 kPa, γ = 9.79 kN/m^3, $V_\text{peak} = Q_\text{peak}/A = 0.578/0.238 = 2.43$ m/s, and z_0 = 8.80 m. Substituting into Equation 2 gives

$$h_\text{peak} = \frac{140}{9.79} + \frac{2.43^2}{2(9.81)} + 8.80 = 23.4 \text{ m}$$

For pipe, $k_s/D = 4.73 \times 10^{-4}$, and

$$\text{Re} = \frac{V_\text{peak} D}{\nu} = \frac{(2.43)(0.550)}{1.00 \times 10^{-6}} = 1.34 \times 10^6$$

and the Swamee-Jain equation gives

$$\frac{1}{\sqrt{f_\text{peak}}} = -2 \log \left[\frac{k_s/D}{3.7} + \frac{5.74}{\text{Re}^{0.9}} \right] = -2 \log \left[\frac{4.73 \times 10^{-4}}{3.7} + \frac{5.74}{(1.34 \times 10^6)^{0.9}} \right]$$

and yields

$$f_\text{peak} = 0.0170$$

The head loss between the water treatment plant and the suburban development is therefore given by

$$h_f = f\frac{L}{D}\frac{V^2}{2g} = (0.0170)\frac{3000}{0.550}\frac{2.43^2}{2(9.81)} = 27.9 \text{ m}$$

Since the head at the water treatment plant is 10.00 m, the pump head, h_p, that must be added is

$$h_p = (23.4 + 27.9) - 10.00 = 41.3 \text{ m}$$

and the power requirement, P, is given by

$$P = \gamma Q h_p = (9.79)(0.578)(41.3) = \boxed{234 \text{ kW}}$$

2.23. The energy equation applied between the reservoir and the outlet is given by

$$40 - \left[K_e + \frac{fl}{D} + K_v\right]\frac{V^2}{2g} - h_t = \frac{V^2}{2g}$$

which can be put in the form

$$h_t = 40 - \left[K_e + \frac{fL}{D} + K_v + 1\right]\frac{V^2}{2g} \qquad (1)$$

For a sharp-edged entrance, $K_e = 0.5$, for an open globe valve, $K_v = 10.0$, and from the given data: $D = 0.05$ m, $A = \pi D^2/4 = 0.001963$ m^2, $Q = 4$ L/s $= 0.004$ m^3/s, $V = Q/A = 2.038$ m/s, $L = 125$ m, $\nu = 1.00 \times 10^{-6}$ m^2/s, $k_s = 0.23$ mm, $\text{Re} = VD/\nu = 1.02 \times 10^5$, and using the Swamee-Jain equation,

$$f = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D} + \frac{5.74}{\text{Re}^{0.9}}\right)\right]^2} = \frac{0.25}{\left[\log\left(\frac{0.23}{3.7(50)} + \frac{5.74}{(1.02\times10^5)^{0.9}}\right)\right]^2} = 0.0308$$

Substituting into Equation 1 gives

$$h_t = 40 - \left[0.5 + \frac{(0.0308)(125)}{0.05} + 10.0 + 1\right]\frac{(2.038)^2}{2(9.81)} = 21.27 \text{ m}$$

Therefore, taking $\gamma = 9.79$ kN/m^3, the power extracted by the turbine is given by

$$P = \gamma Q h_t = (9.79)(0.004)(21.27) = \boxed{0.833 \text{ kW}}$$

A similar problem would be encountered in calculating the power output at a $\boxed{\text{hydroelectric facility}}$.

2.24. The head loss is calculated using Equation 2.78. The hydraulic radius, R, is given by

$$R = \frac{A}{P} = \frac{(2)(1)}{2(2+1)} = 0.333 \text{ m}$$

and the mean velocity, V, is given by

$$V = \frac{Q}{A} = \frac{5}{(2)(1)} = 2.5 \text{ m/s}$$

At 20°C, $\rho = 998.2$ kg/m^3, $\mu = 1.002 \times 10^{-3}$ N·s/m^2, and therefore the Reynolds number, Re, is given by

$$\text{Re} = \frac{\rho V(4R)}{\nu} = \frac{(998.2)(2.5)(4 \times 0.333)}{1.002 \times 10^{-3}} = 3.32 \times 10^6$$

A median equivalent sand roughness for concrete can be taken as $k_s = 1.6$ mm (Table 2.1), and therefore the relative roughness, $k_s/4R$, is given by

$$\frac{k_s}{4R} = \frac{1.6 \times 10^{-3}}{4(0.333)} = 0.00120$$

Substituting Re and $k_s/4R$ into the Swamee-Jain equation (Equation 2.38) for the friction factor yields

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s/4R}{3.7} + \frac{5.74}{\text{Re}^{0.9}}\right] = -2\log\left[\frac{0.00120}{3.7} + \frac{5.74}{(3.32 \times 10^6)^{0.9}}\right] = 6.96$$

which yields

$$f = 0.0206$$

The frictional head loss in the culvert, h_f, is therefore given by the Darcy-Weisbach equation as

$$h_f = \frac{fL}{4R}\frac{V^2}{2g} = \frac{(0.0206)(100)}{(4 \times 0.333)}\frac{2.5^2}{2(9.81)} = \boxed{0.493 \text{ m}}$$

2.25. The frictional head loss is calculated using Equation 2.78. The hydraulic radius, R, is given by

$$R = \frac{A}{P} = \frac{(2)(2)}{2(2+2)} = 0.500 \text{ m}$$

and the mean velocity, V, is given by

$$V = \frac{Q}{A} = \frac{10}{(2)(2)} = 2.5 \text{ m/s}$$

At 20°C, $\rho = 998$ kg/m^3, $\mu = 1.00 \times 10^{-3}$ N·s/m^2, and therefore the Reynolds number, Re, is given by

$$\text{Re} = \frac{\rho V(4R)}{\mu} = \frac{(998)(2.5)(4 \times 0.500)}{1.00 \times 10^{-3}} = 4.99 \times 10^6$$

A median equivalent sand roughness for concrete can be taken as $k_s = 1.6$ mm (Table 2.1), and therefore the relative roughness, $k_s/4R$, is given by

$$\frac{k_s}{4R} = \frac{1.6 \times 10^{-3}}{4(0.500)} = 0.0008$$

Substituting Re and $k_s/4R$ into the Swamee-Jain equation (Equation 2.39) for the friction factor yields

$$\frac{1}{\sqrt{f}} = -2\log\left[\frac{k_s/4R}{3.7} + \frac{5.74}{\mathrm{Re}^{0.9}}\right] = -2\log\left[\frac{0.0008}{3.7} + \frac{5.74}{(4.99\times10^6)^{0.9}}\right] = 7.31$$

which yields

$$f = 0.0187$$

The frictional head loss in the culvert, h_f, is therefore given by the Darcy-Weisbach equation as

$$h_f = \frac{fL}{4R}\frac{V^2}{2g} = \frac{(0.0187)(500)}{(4\times0.500)}\frac{2.5^2}{2(9.81)} = 1.49 \text{ m}$$

Applying the energy equation between the upstream and downstream sections (Sections 1 and 2 respectively),

$$\frac{p_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_f$$

which gives

$$\frac{p_1}{9.79} + \frac{2.5^2}{2(9.81)} + (0.002)(500) = \frac{p_2}{9.79} + \frac{2.5^2}{2(9.81)} + 0 + 1.49$$

Re-arranging this equation gives

$$\boxed{p_1 - p_2 = 4.80 \text{ kPa}}$$

2.26. The Hazen-Williams formula is given by

$$V = 0.849 C_H R^{0.63} S_f^{0.54} \qquad (1)$$

where

$$S_f = \frac{h_f}{L} \qquad (2)$$

Combining Equations 1 and 2, and taking $R = D/4$ gives

$$V = 0.849 C_H \left(\frac{D}{4}\right)^{0.63}\left(\frac{h_f}{L}\right)^{0.54}$$

which simplifies to

$$\boxed{h_f = 6.82\frac{L}{D^{1.17}}\left(\frac{V}{C_H}\right)^{1.85}}$$

2.27. Comparing the Hazen-Williams and Darcy-Weisbach equations for head loss gives

$$h_f = 6.82\frac{L}{D^{1.17}}\left(\frac{V}{C_H}\right)^{1.85} = f\frac{L}{D}\frac{V^2}{2g}$$

which leads to

$$\boxed{f = \frac{134}{C_H^{1.85}D^{0.17}}\frac{1}{V^{0.15}}}$$

For laminar flow, Equation 2.36 gives $f \sim 1/\mathrm{Re} \sim 1/V$, and for fully-turbulent flow Equation 2.35 gives $f \sim 1/V^0$. Since the Hazen-Williams formula requires that $f \sim 1/V^{0.15}$, this indicates that the flow must be in the $\boxed{\text{transition regime}}$.

2.28. The Manning equation is given by

$$V = \frac{1}{n} R^{\frac{2}{3}} S_f^{\frac{1}{2}} = \frac{1}{n} \left(\frac{D}{4}\right)^{\frac{2}{3}} \left(\frac{h_f}{L}\right)^{\frac{1}{2}}$$

which re-arranges to give

$$\boxed{h_f = 6.35 \frac{n^2 L V^2}{D^{\frac{4}{3}}}}$$

2.29. Comparing the Manning and Darcy-Weisbach equations gives

$$h_f = 6.35 \frac{n^2 L V^2}{D^{\frac{4}{3}}} = f \frac{L}{D} \frac{V^2}{2g}$$

which leads to

$$\boxed{f = 125 \frac{n^2}{D^{\frac{1}{3}}}}$$

For laminar flow, Equation 2.36 gives $f \sim 1/\text{Re} \sim 1/V$, and for fully-turbulent flow Equation 2.35 gives $f \sim 1/V^0$. Since the Manning equation requires that $f \sim 1/V^0$, this indicates that the flow must be fully turbulent or $\boxed{\text{rough}}$.

2.30. Equating the Hazen-Williams and Manning head loss expressions

$$6.82 \frac{L}{D^{1.17}} \left(\frac{V}{C_H}\right)^{1.85} = 6.35 \frac{n^2 L V^2}{D^{\frac{4}{3}}}$$

which re-arranges to give

$$\boxed{n = \left(1.04 \frac{D^{0.082}}{V^{0.075}}\right) \frac{1}{C_H^{0.93}}}$$

2.31. Choose the $\boxed{\text{Darcy-Weisbach equation}}$ since this equation is applicable in all flow regimes. The Hazen-Williams and Manning equations are limited to particular flow conditions (transition and fully turbulent respectively).

2.32. (a) The Hazen-Williams roughness coefficient, C_H, can be taken as 110 (Table 2.2), L = 500 m, D = 0.300 m, V = 2 m/s, and therefore the head loss, h_f, is given by Equation 2.82 as

$$h_f = 6.82 \frac{L}{D^{1.17}} \left(\frac{V}{C_H}\right)^{1.85} = 6.82 \frac{500}{(0.30)^{1.17}} \left(\frac{2}{110}\right)^{1.85} = \boxed{8.41 \text{ m}}$$

(b) The Manning roughness coefficient, n, can be taken as 0.013 (approximation from Table 2.2), and therefore the head loss, h_f, is given by Equation 2.85 as

$$h_f = 6.35 \frac{n^2 L V^2}{D^{\frac{4}{3}}} = 6.35 \frac{(0.013)^2 (500)(2)^2}{(0.30)^{\frac{4}{3}}} = \boxed{10.7 \text{ m}}$$