REFERENCES AND FURTHER READING

Further reading on Urban Health

Feachem, R.G., Bradley, D., Garelick, H. and Mara, D.D. (1983). ***Sanitation and Disease: Health Aspects of Excreta and Wastewater Management***. Chichester: John Wiley & Sons.

Hardoy, J.E., Cairncross, S. and Satterthwaite, D. (1990). ***The Poor Die Young: Health and Housing in Third World Cities***. London: Earthscan Publications Ltd.

Hardoy, J.E. and Satterthwaite, D. (1989). ***Squatter Citizen: Life in the Urban Third World***. London: Earthscan Publications Ltd.

Harpham, T., Lusty, T. and Vaughan, P. (1988). ***In the Shadow of the City: Community Health and the Urban Poor*****.** Oxford: Oxford University Press.

Harpham, T. and Tanner, M. (1995). ***Urban Health in Developing Countries: Progress and Prospects*****.** London: Earthscan Publications Ltd.

Tabibzadeh, I., Rossi-Espagnet, A. and Maxwell, R. (1989). ***Spotlight on the Cities: Improving Urban Health in Developing Countries*****.** Geneva: World Health Organization.

Further reading on Simplified Sewerage

Recommended reading is denoted in the list of references by references given wholly in **bold**. Postal addresses and ISBNs (international standard book numbers) are also given for ease of obtaining these items. In addition the following are also recommended:

de Azevedo Neto, J.M. (1992). ***Innovative and Low Cost Technologies Utilized in Sewerage*****.** Environmental Health Program Technical Series No. 29. Washington, DC: Pan American Health Organization. Postal address: PAHO, 525 23rd Street NW, Washington DC 20037, USA.

Mara, D. (1996). ***Low-cost Sewerage*****.** Chichester: John Wiley & Sons. ISBN: 0 471 966916. Postal address: John Wiley & Sons, Baffins Lane, Chichester PO19 1UD, England.

Reed, R.A. (1995). ***Sustainable Sewerage: Guidelines for Community Schemes*****.** London: IT Publications. ISBN 1 85339 305 3. Postal address: IT Publications, 103-105 Southampton Row, London WC1B 4HH, England.

References

Note: some key references listed below are available on the Internet – see the end of this Section for further details.

ABNT (1986). *Projeto de Redes Coletoras de Esgoto Sanitário*. Brazilian Standard No. 9649. Rio de Janeiro: Associação Brasileira de Normas Técnicas.

Ackers, J.C., Butler, D. and May, R.W.P. (1996). ***Design of Sewers to Control Sediment Problems*****. Report No. 141. London: Construction Industry Research and Information Association.** ISBN: 086017 443 3. Postal address: CIRIA, 6 Storey's Gate, London SW1P 3AU, England.

Alfaro, R. (1997). *Linkages between Municipalities and Utilities: An Experience n Overcoming Urban Poverty*. Urban Environmental Sanitation Working Paper. Washington, DC: UNDP – World Bank Water and Sanitation Program.

Bakalian, A., Wright, A., Otis, R. and de Azevedo Neto, J. (1994). *Simplified Sewerage: Design Guidelines*. Water and Sanitation Report No. 7. Washington, DC: The World Bank.

Barnes, D., Bliss, P.J., Gould, B.W. and Valentine, H.R. (1981). *Water and Wastewater Engineering Systems*. London: Pitman Books Ltd.

Black, M. (1994). ***Mega-Slums: The Coming Sanitary Crisis*****. London: WaterAid.** ISBN: 0 951 3466 1 X. Postal address: WaterAid, Prince Consort House, 27-29 Albert Embankment, London SE1 7UB, England.

Butler, D. and Pinkerton, B.R.C. (1987). *Gravity Flow Pipe Design Charts*. London: Thomas Telford Ltd.

Carlier, M. (1986). *Hydraulique Générale et Appliquée*. Paris: Editions Eyrolles.

Chanson, H. (1999). *The Hydraulics of Open Channel Flow*. London: Arnold.

Chaplin, S.E. (1999). Cities, sewers and poverty: India's politics of sanitation. *Environment and Urbanization* **11** (1), 145-158.

Chezy, A. (1776). Formule pour trouver la vitesse de l'eau conduit dan une rigole donnée. Dossier 847 (MS 1915) of the manuscript collection of the École National des Ponts et Chaussées, Paris. Reproduced in: Mouret, G. (1921). Antoine Chézy: histoire d'une formule d'hydraulique. *Annales des Ponts et Chaussées* **61**, 165-269.

Chow, V.T. (1959). *Open Channel Hydraulics*. New York, NY: McGraw-Hill Book Co.

Colebrook, C.F. (1939). Turbulent flow in pipes, with particular reference to the transition between the smooth and rough pipe laws. *Journal of the Institution of Civil Engineers* **11**, 133-156.

Cotton, A.P. and Saywell, D.L. (1998). *On-plot Sanitaiton for Low-income Urban Communities: Guidelines for Selection*. Loughborough University: University of Technology, WEDC.

Cunningham, A. (1883). Recent hydraulic experiments. *Minutes of the Proceedings of the Institution of Civil Engineers* **71**, 1-94.

de Andrade Neto, C.O. (1985). Uma solução eficaz e de baixo custo para o esgotamento sanitário urbano. *Engenharia Sanitária,* Rio de Janeiro **24** (2), 239-241.

de Melo, J.C. (1994). *Sistema Condominial de Esgotos: Razões, Teoria e Prática.* Brasília: Caixa Econômica Federal.

de Melo, J.C.R. (1985). Sistemas condominiais de esgotos. *Engenharia Sanitária,* Rio de Janeiro **24** (2), 237-238.

Diacon, D. (1997). *Slum Networking: An Innovative Approach to Urban Development*. Coalville, England: Building and Social Housing Foundation.

Dooge, J.C.I. (1992). The Manning formula in context. In *Channel Flow Resistance: Centennial of Manning's Formula* (ed. B.C. Yen), pp. 136-185. Littleton, CO: Water Resources Publications.

Escritt, L.B. (1984). *Sewerage and Sewage Treatment: International Practice* (ed. W.D. Haworth). Chichester: John Wiley & Sons.

Foley, S., Soedjarwo, A. and Pollard, R. (2000). *Case Study – Of the People, by the People, for the People: Community-based Sewer Systems in Melang, Indonesia*. Jakarta: World Bank/UNDP Water and Sanitation Program for East Asia and the Pacific.

Franceys, R., Pickford, J. and Reed, R. (1992). *A Guide to the Development of On-site Sanitation*. Geneva: World Health Organization.

Ganepola, P. (2000). Personal communication (National Housing Development Authority, Ministry of Housing and Urban Development, Colombo, Sri Lanka).

Ganguillet, E. and Kutter, W.R. (1869). Versuch zur Augstellung einer neuen allgeneinen Furmel für die gleichformige Bewegung des Wassers in Canalen und Flussen. *Zeitschrift des Osterrichischen Ingenieur – und Architecten-Vereines* **21**, (1), 6-25 and (2), 46-59. Translated into English by: Hering, R. and Trautwine, J.C. (1888 and 1891). *A General Formula for the Uniform Flow of Water in Rivers and Other Channels*. New York, NY: John Wiley & Sons.

Gauckler, P. (1867). Études théoriques et pratiques sur l'écoulement et le mouvement des eaux. *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences* **64**, 818-822.

Gauckler, P. (1868). Du mouvement de l'eau dans les conduites. *Annales des Ponts et Chaussées* **15**, 229-281.

General Board of Health (1852). *Minutes of Information Collected with Reference to Works for the Removal of Soil Water or Drainage of Dwelling Houses and Public Edifices and for the Sewerage and Cleansing of the Sites of Towns*. London: Her Majesty's Stationery Office.

GHK Research and Training (2000). *Strategic Planning for Municipal Sanitation: A Guide* (Part C3: Tools for Sanitation Choice). London: GHK Research and Training.

Gidley, J.S. (1987). *Ericson, Nebraska Flat Grade Sewers*. Report No. WWBLCS11. Morgantown, WV: National Small Flows Clearinghouse, University of West Virginia.

Guimarães, A.S.P. (1986). *Redes de Esgotos Simplificadas.* Brasília: Programa das Nações Unidas/Ministério do Desenvolvimento Urbano e Meio Ambiente.

Guimarães, A.S.P. (2000). Personal communication (GAIA Engenharia, Rio de Janeiro, Brazil).

Hagen, G.W. (1881). Neuere Beobachtung über die gleichförmige Bewegung des Wassers. *Zeitschrift für Bauwesen* **31**, 221-223.

HR Wallingford and Barr, D.I.H. (1994). *Tables for the Hydraulic Design of Pipes, Sewers and Channels*, 6th edition, volume 1. London: Thomas Telford Services Ltd.

Kolsky, P. (1998). *Storm Drainage: An Engineering Guide to the Low-cost Evaluation of System Performance*. London: IT Publications.

Lillywhite, M.S.T. and Webster, C.J.D. (1979). Investigations of drain blockages and their implications on design. *The Public Health Engineer* **7** (2), 53-60.

Luduvice, M. (2000). Personal communication (CAESB, Brasília DF, Brazil).

Luduvice, M., Neder, K.D. and Teixeira Pinto, M. (1999). *Produtividade e Eficiência na Implantação e Operação de Sistemas de Esgotamento Sanitário: A Experiência da CAESB*. Brasília: Companhia de Saneamento do Distrito Federal.

Machado Neto, J.C.O. and Tsutiya, M.T. (1985). Tensão trativa: um critério econômico de esgoto. *Revista DAE*, São Paulo, **45** (140), 73-87.

Manning, R. (1890). On the flow of water in open channels and pipes. *Transactions of the Institution of Civil Engineers of Ireland* **20**, 161-207.

Mara, D. (1996). *Low-cost Urban Sanitation*. Chichester: John Wiley & Sons. ISBN: 0 471 96163 9. Postal address: John Wiley & Sons, Baffins Lane, Chichester PO19 1UD, England.

Mara, D. (1999). Condominial sewerage in Victorian England. *Water and Environmental Manager* **4** (5), 4-6.

Metcalf & Eddy Inc. (1981). *Wastewater Engineering: Collection and Pumping of Wastewater*. New York, NY: McGraw-Hill Publishing Co.

Ministry of Urban Development (1995). *Manual on Sewerage and Sewage Treatment*, 2nd ed. New Delhi: Government of India Press.

Nigreiros, S. (1998). CAESB: A um passo da universalização dos serviços. *Saneamento Ambiental*, São Paulo (52), 20-29.

Nikuradse, J. (1933). *Strömungsgesetze in Rauchen Röohren*. Forschungsheft No. 361. Berlin: Verein Deutscher Ingenieure.

Otis, R.J. and Mara, D.D. (1985). *The Design of Small-bore Sewers*. TAG Technical Note No. 14. Washington, DC: The World Bank.

Pegram, G. and Palmer, I. (1999). *The Applicability of Shallow Sewer Systems in South Africa*. Report No. TT113/99. Pretoria: Water Research Commission.

Pomeroy, R.D. (1990). *The Problem of Hydrogen Sulphide in Sewers*. London: Clay Pipe Development Association.

Reed, R. and Vines, M. (1992*a*). *Reduced Cost Sewerage in Orangi, Karachi, Pakistan*. Loughborough, England: University of Technology (Water, Engineering and Development Centre).

Reed, R. and Vines, M. (1992*b*). *Reduced Cost Sewerage in the Community Development Project of Orangi, Karachi, Pakistan*. Loughborough, England: University of Technology (Water, Engineering and Development Centre).

Sarmento, V. de B. A. (2000). Personal communication based on field surveys in Vila Planalto, Brasília DF and Rocas and Santos Reis, Natal RN (doctoral student, School of Civil Engineering, University of Leeds).

Sinnatamby, G.S. (1983). *Low-cost Sanitation Systems for Urban Peripheral Areas in Northeast Brazil*. PhD Thesis. Leeds: University of Leeds, Department of Civil Engineering.

Sinnatamby, G.S. (1986). *The Design of Shallow Sewer Systems*. Nairobi: United Nations Centre for Human Settlements. Postal address: UNCHS, PO Box 30030, Nairobi, Kenya.

Sinnatamby, G., McGarry, M. and Mara, D. (1986). Sewerage: shallow systems offer hope to slums. *World Water* **9**, 39-41.

Strickler, A. (1923). *Beiträge zur Frage der Geschwindigkeits formel und der Rauhigkeitszahlen für Ströme, Kanale und geschlossene Leitungen.* Mitteilungen des Eidgenössischen Amtes für Wasserwirtschaft No. 16, Bern, Switzerland. Translated into English by: Roesgan, T. and Brownie, W.R. (1981). *Contributions to the Question of a Velocity Formula and Roughness data for Streams, Channels and Closed Pipelines*. Translation No. T-10. Pasadena, CA: California Institute of Technology, W.M. Keck Laboratory of Hydraulics and Water Resources.

Tayler, K. (1996). Low-cost sewerage systems in South Asia. In *Low-cost Sewerage* (ed. D. Mara), pp. 33-71. Chichester: John Wiley & Sons.

Watson, G. (1995). ***Good Sewers Cheap? Agency-Customer Interactions in Low-Cost Urban Sanitation in Brazil.*** **Water and Sanitation Currents. Washington, DC: The World Bank.** Postal address: Water and Sanitation Program, The World Bank, 1818 H Street NW, Washington DC 20433, USA.

Weisbach, J. (1855). *Die Experimental Hydraulik*. Freiburg: Engelhardt-Verlag.

Williams, G.P. (1970) Manning formula – a misnomer? *Journal of the Hydraulics Division, American Society of Civil Engineers* **96** (HY1), 193-199.

Williamson, J. (1951). The laws of flow in rough pipes: Strickler, Manning, Nikuradse and drag-velocity. *La Houille Blanche* **6** (5), 738-757.

World Bank (1993). *World Development Report 1993: Investing in Health*. New York, NY: Oxford University Press.

World Health Orgnization (1996). *Water Supply and Sanitation Sector Monitoring Report 1996: Sector Status as of 31 December 1994*. Geneva: WHO. [WHO is due to publish in late 2000/early 2001 the sector status as of 31 December 1999.]

Yao, K.M. (1974). Sewer line design based on critical shear stress. *Journal of the Environmental Engineering Division, American Society of Civil Engineers* **100** (EE2), 507-521.

Yen, B.C. (1992). Hydraulic resistance in open channels. In *Channel Flow Resistance: Centennial of Manning's Formula*. (ed. B.C. Yen), pp.1-135. Littleton, CO: Water Resources Publications.

Zaidi, S.A. (2000). *From the Lane to the City: the Impact of the Orangi Pilot Project's Low Cost Sanitation Model*. London: WaterAid.

Publications available on the Internet

Go to the following website:

http://www.sanigate.net/topics.php3

and click on "Low-cost sewerage" to access on-line the following references listed above:

Bakalian *et al.* (1994),
Foley *et al.* (2000),
Sinnatamby (1986),
Sinnatamby *et al.* (1986) and
Watson (1995).

Appendix 1

Velocity of Flow Equations

In the 18th and 19th centuries three principal equations for the velocity of flow in open channels and pipes were developed. These are:

(1) The **Chézy** equation,

(2) The **Gauckler-Manning** equation, and

(3) The **Darcy-Weisbach** equation.

The Chézy and Gauckler-Manning equations are related as the Ganguillet-Kutter equation for the Chézy coefficient of flow resistance includes the Kutter roughness coefficient, *n* which is identical to that used in the Gauckler-Manning equation.

The Darcy-Weisbach equation introduces the Darcy-Weisbach friction factor, *f*, which for turbulent flow in both rough and smooth pipes is given by the **Colebrook-White** equation used in modern sewer design (see, for example, Butler and Pinkerton, 1987).

To these three equations, we can add a fourth:

(4) the **Escritt** equation,

also used in modern sewer design (Escritt, 1984).

The discussion that follows is based principally on Chow (1959), Yen (1992) and Chanson (1999).

A1.1 THE CHÉZY EQUATION

Antoine Chézy developed his equation for the velocity of flow in 1775 (Chézy, 1776):

$$v = C_{Ch}\, r^{1/2}\, i^{1/2} \qquad \text{(A1.1)}$$

where C_{Ch} is the Chézy coefficient of flow resistance, defined by the later Ganguillet-Kutter equation (Ganguillet and Kutter, 1869) as:

$$C_{Ch} = \{23 + (0.0155/i) + (1/n)\} / \{1 + [23 + (0.0155/i)\,(n/r^{1/2})]\} \qquad \text{(A1.2)}$$

where n = Ganguillet-Kutter roughness coefficient (dimensionless, but see Section A1.2.1).

A1.2 THE GAUCKLER-MANNING EQUATION

As noted in Section 2.3, the Gauckler-Manning equation was developed by Gauckler (1867, 1868) and Manning (1890) (and also by Hagen, 1881; see Cunningham, 1883). The original form of the equation was:

$$v = C_{GM}\, r^{2/3}\, i^{1/2} \qquad \text{(A1.3)}$$

where C_{GM} is the Gauckler-Manning coefficient of flow resistance, now taken as the reciprocal of n in the Ganguillet-Kutter equation (n is now known as Manning's n, rather than as Kutter's n).

Strickler[1] (1923) gave the following equation for n:

$$n = d_{50}^{1/6} / 21.2 \qquad \text{(A1.4)}$$

where d_{50} = median sediment diameter, m.

Strickler's equation for n is important as it was the first to attempt to relate the coefficient of roughness to sediment size, a concept later developed by Nikuradse (1933) in his use of an equivalent sand grain size as a measure of the effective roughness height (k_s). Williamson (1951) used Nikuradse's adjusted data to give the following relationship between n and k_s:

$$n = k_s^{1/6} / 26.4 \qquad \text{(A1.5)}$$

where k_s is in m (the value of k_s is commonly given in mm, but its unit in equations A1.5, A1.6, A1.7 and A1.10 is m).

A1.2.1 Dimensions of *n*

The original metric version of the Gauckler-Manning equation (i.e. for v in m/s and r in m) is equation 2.13:

$$v = (1/n)\, r^{2/3}\, i^{1/2} \qquad \text{(2.13)}$$

The corresponding "English" version (for v in ft/s and r in ft) is:

$$v = (1.486/n)\, r^{2/3}\, i^{1/2} \qquad \text{(2.13a)}$$

The numerical values of n used in equations 2.13 and 2.13a are the same (for example, 0.013 for slimed sewers). Thus, assuming that the two numerators (1 and 1.486) are pure numbers (i.e. dimensionless), the dimensions of n would be $T\, L^{-1/3}$; Chanson (1999), for example, gives the units of n as $s/m^{1/3}$. However, as pointed out by Chow (1959), it is not reasonable for n to contain a dimension of time since it is a measure of surface roughness, and therefore should contain only some dimension of length.

If the numerators (1 and 1.486) are not considered pure numbers, but rather to contain $\sqrt{g}$ (which has units of $m^{1/2}/s$), then there are two possibilities (Chow, 1959):

> *either* the numerators have the dimensions of $L^{1/3}\, T^{-1}$ and n is dimensionless,
>
> *or* the numerators contain only $\sqrt{g}$, so leaving the dimension of $L^{1/6}$ for n (i.e. n has units of $m^{1/6}$ or $ft^{1/6}$).

In fact Chow (1959) shows that:

$$n = [\phi(r/k_s)]\, k_s^{1/6} \qquad \text{(A1.6)}$$

---

[1] In France and francophone countries the Gauckler-Manning equation is generally known as the Manning-Strickler equation with C_{GM} written as k (see Carlier, 1985).

where k_s is the Nikauradse equivalent sand grain size which has the dimension of L. Assuming that $\phi(r/k_s)$ is dimensionless, equation A1.6 confirms that n has the dimension $L^{1/6}$ (as indeed shown by equations A1.4 and A1.5, assuming their denominators are pure numbers).

Chow (1959) further points out that:

(1) if n is considered dimensionless, then the conversion of the metric form of the equation to its English form involves conversion of the length dimension of the numerator ($L^{1/3}$), that is the conversion of $m^{1/3}$ to $ft^{1/3}$. Thus, since 1 m = 3.2808 ft, the numerator in the English equation is $3.2808^{1/3}$, i.e. 1.486, and so equation 2.13a is obtained.

(2) if n has the dimension of $L^{1/6}$, then its values in equation 2.13 and 2.13a cannot be the same as the factor $3.2808^{1/6}$ (= 1.219) must be involved. That is to say, if n is the value in metric units and n' that in English units, then

$$n' = 1.219\, n \qquad (2.13b)$$

and since n and n' have dimensions of $L^{1/6}$, the numerators now have the length dimension of $L^{1/3 + 1/6}$, i.e. $L^{1/2}$. The English numerator is thus $3.2808^{1/2}$, i.e. 1.811, and the English form of the equation is:

$$v = (1.811 / n')\, r^{2/3}\, i^{1/2} \qquad (2.13c)$$

Substituting equation 2.13b:

$$v = (1.811 / 1.219\, n)\, r^{2/3}\, i^{1/2}$$

$$= (1.486 / n)\, r^{2/3}\, i^{1/2} \qquad (2.13a)$$

Thus equation 2.13a can be obtained both on the assumption that n is dimensionless, and if it has the dimensions of $L^{1/6}$. As noted by Chow (1959), it was simpler for those working in the late 19th and early 20th centuries to take n as dimensionless and use the same value for it in both the metric and English forms of the equation (and so avoid the incongruity of using $n = 0.013\ m^{1/6}$, for example, in equation 2.13a which otherwise contains only English units). However, from the point of view of modern fluid mechanics, it is clearly preferable to consider that n is related to the Nikuradse equivalent sand grain size and thus, from equation A1.5, has dimensions of $L^{1/6}$.

A1.2.2 A modern form for the Gauckler-Manning equation

Dooge (1992) completes his erudite review of Manning's equation with the following paragraph (which we might amend only to refer to both Gauckler and Manning):

"If Manning were with us today he would be pleased to learn that his formula was still being widely used. However, he would probably argue trenchantly that the formula should be written in the form:

$$v = M\, (r / k_s)^{1/6}\, (g\, r\, i)^{1/2} \qquad [(A1.7)]$$

so that M would be a dimensionless constant varying slightly with the shape of the channel. Manning would also probably recommend strongly a carefully planned series of experiments to determine M for the range of shapes of cross section important in engineering practice. He would be right to so argue in both cases."

From equations 2.13 and A1.5 the value of M in equation A1.7 can be shown to be 8.4.

A1.3 THE COLEBROOK-WHITE EQUATION

The Darcy-Weisbach equation, developed by Weisbach (1855) and the basis of the modern Colebrook-White equation, is given by:

$$v = \sqrt{(8g / f)}\ r^{1/2}\ i^{1/2} \qquad \text{(A1.8)}$$

where f is the dimensionless Darcy friction coefficient. Inspection of equation A1.8 shows that the term $\sqrt{(8g / f)}$ is the Chézy coefficient, C_{Ch} (see equation A1.1).

The definition of f has occupied many hydraulic engineers over the past 150 years, and equations for laminar, transient and turbulent flow were developed to relate f to the Reynold's number ($\mathbf{R_e}$), defined as:

$$\mathbf{R_e} = vr / \upsilon \qquad \text{(A1.9)}$$

where υ = kinematic viscosity, m^2/s.

For turbulent flow ($\mathbf{R_e} > 25\ 000$) in both smooth and rough pipes f is given by the Colebrook-White equation (Colebrook, 1938; see also Butler and Pinkerton, 1987 and H R Wallingford and Barr, 1994):[2]

$$1/f^{1/2} = -2 \log [(k_s/14.8r) + (0.63/\mathbf{R_e} f^{1/2})] \qquad \text{(A1.10)}$$

A1.4 THE ESCRITT EQUATION

Escritt (1984) gives his equation for wastewater flow in circular sewers in the form :

$$v = 26.738\ D^{0.62}\ i^{1/2} \qquad \text{(A1.11)}$$

where v = velocity of flow, metres per *minute*
D = diameter, *millimetres*

Changing the units of v to m/s and D to m and writing D as $4r$ gives:

$$v = (1 / 0.013)\ r^{0.62}\ i^{1/2} \qquad \text{(A1.12)}$$

The hydraulic radius, r in this equation is "not the cross-sectional area divided by the wetted perimeter, but averaged, with remarkable accuracy, the cross-sectional area divided by the sum of the wetted perimeter and one-half the width of the water-to-air surface" (Escritt, 1984), that is:[3]

$$r = a / [p + (b/2)] \qquad \text{(A1.13)}$$

Equation A1.12 shows the Escritt equation to be a variant of the Gauckler-Manning equation, with n taken as 0.013 for slimed sewers, and with r defined by equation A1.13 and having the exponent 0.62 rather than 2/3.

---

[2] Different values of the constants 14.8 and 0.63 in equation A1.10 are used in the Colebrook-White equation given by both Butler and Pinkerton and HR Wallingford and Barr, as these authors give the equation in terms of D rather than r ($D = 4r$), and they define $\mathbf{R_e}$ as vD/υ rather than as vr/υ.

[3] Based on their measurements on the Mississippi River, Humphreys and Abbot (1861; cited in Dooge, 1992) give an equation for the velocity of flow in large streams which contains the term $a / (p + b)$.

Appendix 2

Comparative Simplified Sewer Design Trials

The simplified sewer design examples given by UNCHS (Sinnatamby, 1986) and the World Bank – UNDP (Bakalian *et al.*, 1994) were used to compare the results obtained using (a) the Gauckler-Manning equation, (b) the Colebrook-White equation, and (c) the Escritt equation, which are described in Appendix 1.

A2.1 UNCHS DESIGN EXAMPLE

The design example for the in-block sewer shown in Figure A2.1 (Sinnatamby, 1986) was used to compare the results obtained with the three velocity of flow equations. The original design (Table A2.1) was based on achieving at peak flow a self-cleansing velocity of 0.5 m/s, rather than a minimum tractive tension of 1 Pa. The results of the comparative design trial are given in the Table A2.2 and A2.3 for the three equations both for a minimum self-cleansing velocity of 0.5 m/s (using the design equations given in Mara, 1996) (Table A2.2) and for a minimum tractive tension of 1 Pa (using the design equations given in Section 2) (Table A2.3).

Minimum self-cleansing velocity (Table A2.2)

The calculated values of the sewer diameters are all < 100 mm, which is therefore the diameter which would be selected for the whole of the in-block sewer. The values calculated from the Gauckler-Manning and Escritt equations are within 1-4 mm, with the former giving the smaller values. The diameters calculated from the Colebrook-White equation are the largest, and larger than the Gauckler-Manning diameters by up to 12 mm.

Minimum tractive tension (Table A2.3)

The calculated diameters are larger than those calculated for the minimum self-cleansing velocity (Table A2.1) by up to 9 mm (but I_{min} is a third lower). The comments made above for minimum self-cleansing velocity are equally applicable here. An additional point is that for three sewer sections (B1-1, B1-2 and B1-3) the Colebrook-White equation gives a diameter just above 100 mm, whereas those given by the other two equations are below it – thus the output of the PC-based design must include calculated diameters as well as selected (i.e. commercially available) diameters, so that the output can be manually checked and adjusted (here, in the case of the Colebrook-White calculated diameter of 102 mm, the diameter chosen by manual checking would be 100 mm, rather than the next available size of 150 mm).

Examination of Tables A2.2 and A2.3 indicates that the preferred velocity of flow equation is the Gauckler-Manning equation.

A2.2 WORLD BANK – UNDP DESIGN EXAMPLE

The design example, given in Bakalian *et al.* (1994) and detailed below, was also used to compare the three equations for a minimum tractive tension of 1 Pa.

Design example

Design an interceptor sewer for a town with a current population of 10,800 which is expected to grow to 14,400 in 10 years time. *Data*: water consumption, 250 litres per person per day; return factor, 0.80; peak flow factor, 1.8.

The results of the comparative design trial are as follows:

(a) **Gauckler-Manning equation** (n = 0.013)

Sewer gradient: 0.001 m/m

Sewer diameter: 392 mm

(b) **Colebrook-White equation** (k_s = 1.5 mm)

Sewer gradient: 0.001 m/m

Sewer diameter: **403** mm

(c) **Escritt equation**

Sewer gradient: 0.0009 m/m

Sewer diameter: **403** mm

As with the UNCHS design example, the Colebrook-White and Escritt equations give a diameter just above a standard pipe size (400 mm), and the Gauckler-Manning equation one just below it – confirming (a) that the PC-based design output requires manual checking to avoid the selection of the next largest diameter (in this case 450 mm); and (b) that the Gauckler-Manning equation is the preferred design equation.

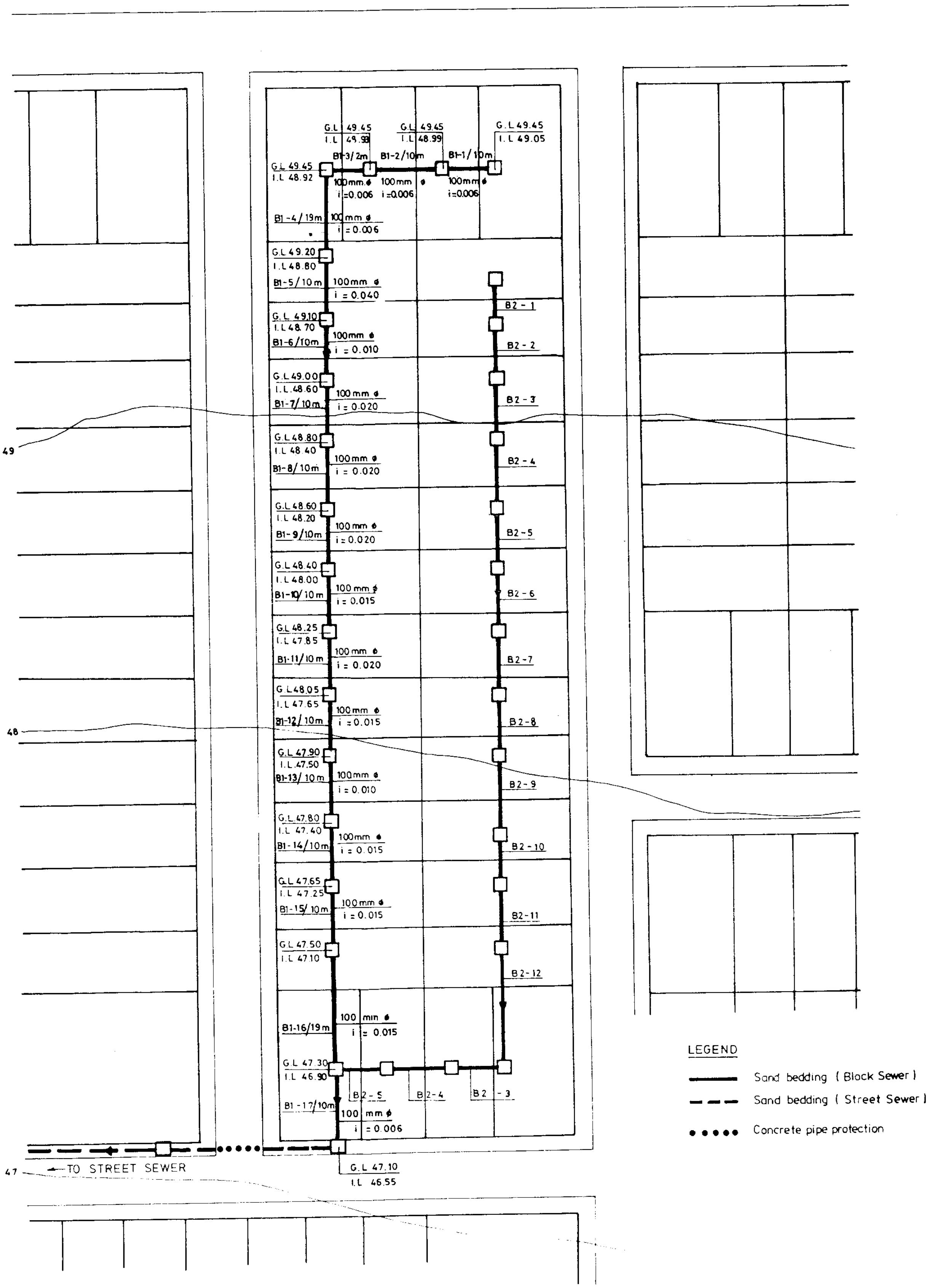

Figure A2.1 In-block sewer layout for UNCHS design example. *Source*: Sinnatamby (1986).

Table A2.1 Hydraulic calculations for UNCHS in-block simplified sewer design example shown in Figure A2.1 using the Gauckler-Manning equation with *n* = 0.013, for a minimum self-cleansing velocity of 0.5 m/s and a minimum flow of 2.2 l/s

						Ground level		Invert level							Depth of sewer		
Sewer reference (1)	Length (2)	Number of houses served (3)	Flow upstream (4)	Flow along the stretch (5)	Flow down stream (6)	Up-stream (7)	Down-stream (8)	Up-stream (9)	Down-stream (10)	Difference in invert level (11)	Gradient (12)	Diameter (13)	Flow at full section (14)	Velocity of flow (15)	Up-stream (16)	Down-stream (17)	Depth of down-stream chamber (18)
B1-1	10	1	2.2	-	2.2	49.45	49.45	49.05	48.99	0.06	0.06	100	4.03	0.50	0.40	0.46	0.46
B1-2	10	2	2.2	-	2.2	49.45	49.45	48.99	48.93	0.06	0.06	100	4.03	0.50	0.46	0.52	0.52
B1-3	2	3	2.2	-	2.2	49.45	49.45	48.93	48.92	0.01	0.06	100	4.03	0.50	0.52	0.53	0.53
B1-4	19	4	2.2	-	2.2	49.45	49.20	48.92	48.80	0.12	0.06	100	4.03	0.50	0.53	0.40	0.40
B1-5	10	5	2.2	-	2.2	49.20	49.10	48.80	48.70	0.10	0.010	100	5.22	0.55	0.40	0.40	0.40
B1-6	10	6	2.2	-	2.2	49.10	49.00	48.70	48.60	0.10	0.010	100	5.22	0.55	0.40	0.40	0.40
B1-7	10	7	2.2	-	2.2	49.00	48.80	48.60	48.40	0.20	0.020	100	7.40	0.80	0.40	0.40	0.40
B1-8	10	8	2.2	-	2.2	48.80	48.60	48.40	48.20	0.20	0.020	100	7.40	0.80	0.40	0.40	0.40
B1-9	10	9	2.2	-	2.2	48.60	48.40	48.20	48.00	0.20	0.020	100	7.40	0.80	0.40	0.40	0.40
B1-10	10	10	2.2	-	2.2	48.40	48.25	48.00	47.85	0.15	0.015	100	6.40	0.73	0.40	0.40	0.40
B1-11	10	11	2.2	-	2.2	48.25	48.05	47.85	47.65	0.20	0.020	100	7.40	0.80	0.40	0.40	0.40
B1-12	10	12	2.2	-	2.2	48.05	47.90	47.65	47.50	0.15	0.015	100	6.40	0.73	0.40	0.40	0.40
B1-13	10	13	2.2	-	2.2	47.90	47.80	47.50	47.40	0.10	0.010	100	5.22	0.55	0.40	0.40	0.40
B1-14	10	14	2.2	-	2.2	47.80	47.65	47.40	47.25	0.15	0.015	100	6.40	0.73	0.40	0.40	0.40
B1-15	10	15	2.2	-	2.2	47.65	47.50	47.25	47.10	0.15	0.015	100	6.40	0.73	0.40	0.40	0.40
B1-16	19	16	2.2	-	2.2	47.50	47.30	47.10	46.90	0.20	0.011	100	5.47	0.70	0.40	0.40	0.54
B1-17	10	32	2.2	-	2.2	47.30	47.10	46.76	46.70	0.06	0.006	100	4.03	0.50	0.54	0.40	0.55

Notes: (a) Minimum gradient = 0.006
(b) Original design example used $q_{\min}$ = 2.2 l/s, rather than the currently recommended value of 1.5 l/s.
(c) Sewer diameters given are those rounded up to next available diameter, see Table A2.2 for calculated values.

Source: Sinnatamby (1986).

Table A2.2 Hydraulic calculations for UNCHS in-block simplified sewer design example using the Gauckler-Manning, Colebrook-White and Escritt equations for a minimum self-cleansing velocity of 0.5 m/s and a minimum flow of 2.2 l/s

		Sewer diameter (mm)[b] calculated from		
Sewer section (Figure A2.1)	Sewer gradient[a] (m/m)	G-Manning equation[c]	C-White Equation[d]	Escritt equation[e]
B1-1	0.006	81	93	82
B1-2	0.006	81	93	82
B1-3	0.006	81	93	82
B1-4	0.013	75	80	71
B1-5	0.010	73	85	75
B1-6	0.010	73	85	75
B1-7	0.020	64	74	65
B1-8	0.020	64	74	65
B1-9	0.020	64	74	65
B1-10	0.015	68	78	69
B1-11	0.020	64	74	65
B1-12	0.015	68	78	69
B1-13	0.010	73	85	75
B1-14	0.015	68	78	69
B1-15	0.015	68	78	69
B1-16	0.011	73	84	74
B1-17	0.020	64	74	65

[a] Minimum gradient = 0.006.
[b] Sewer diameters given are those calculated rather than rounded up to next available diameter.
[c] Equation 2.13 with $n = 0.013$.
[d] Equations A1.8 and A1.10 with $k_s = 1.5$ mm.
[e] Equations A1.12 and A1.13.

Table A2.3 Hydraulic calculations for UNCHS in-block simplified sewer design example using the Gauckler-Manning, Colebrook-White and Escritt equations for a minimum tractive tension of 1 Pa and a minimum flow of 2.2 l/s

		Sewer diameter (mm)[b] calculated from		
Sewer section (Figure A2.1)	Sewer gradient[a] (m/m)	G-Manning equation[c]	C-White equation[d]	Escritt Equation[e]
B1-1	0.004	87	**102**	90
B1-2	0.004	87	**102**	90
B1-3	0.004	87	**102**	90
B1-4	0.013	70	80	71
B1-5	0.010	73	85	75
B1-6	0.010	73	85	75
B1-7	0.020	64	74	65
B1-8	0.020	64	74	65
B1-9	0.020	64	74	65
B1-10	0.015	68	78	69
B1-11	0.020	64	74	65
B1-12	0.015	68	78	69
B1-13	0.010	73	85	75
B1-14	0.015	68	78	69
B1-15	0.015	68	78	69
B1-16	0.011	73	84	74
B1-17	0.020	64	74	65

[a] Minimum gradient = 0.004
[b] Sewer diameters given are those calculated rather than rounded up to next available diameter.
[c] Equation 2.13 with $n = 0.013$.
[d] Equations A1.8 and A1.10 with $k_s = 1.5$ mm.
[e] Equations A1.12 and A1.13.

Appendix 3

Hydrogen Sulphide Generation

Hydrogen sulphide generation in sewers leads to microbial corrosion of the crown of concrete and asbestos – cement sewers (Figure A3.1). The likelihood of H_2S generation is given by Pomeroy's (1990) **Z** factor:

$$\mathbf{Z} = 3\,(\mathrm{BOD}_5)\,(1.07)^{T-20}\,i^{-1/2}\,q^{-1/3}\,(p/b) \qquad \text{(A3.1)}$$

where BOD_5 = 5-day, 20°C biochemical oxygen demand of the wastewater, mg/l
T = temperature, °C
i = sewer gradient, m/m
q = wastewater flow, l/s
p = wetted perimeter, m
b = breadth of flow (see Figure 2.1), m

and 3 is the conversion factor resulting from changing the units of q from ft^3/s in Pomeroy's original equation to l/s.

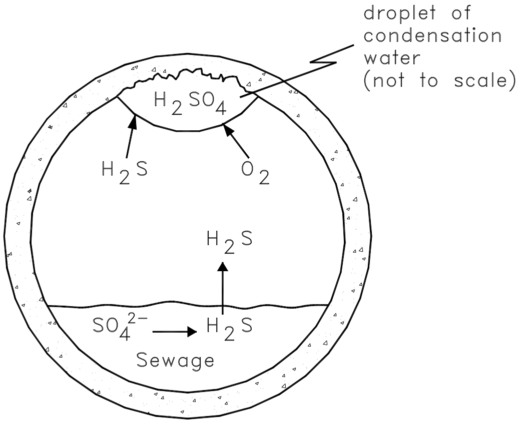

Figure A3.1 Microbially induced corrosion of the crown of concrete or asbestos cement sewers: sulphates in the wastewater are reduced anaerobically by sulphate-reducing bacteria to hydrogen sulphide, some of which leaves the wastewater to raise its partial pressure in the atmosphere above the flow (Henry's law), and then some of this H_2S goes into solution (Henry's law again) in droplets of condensation water clinging to the sewer crown – this H_2S is oxidized by the aerobic bacterium *Thiobacillus thioparus* to sulphuric acid (H_2SO_4), which corrodes the concrete. Sewer crown collapse within 10-20 years is not uncommon.

The value of **Z** calculated from equation A3.1 is used diagnostically as follows:

$\mathbf{Z} < 5000$: H_2S generation unlikely

$5000 < \mathbf{Z} < 10\,000$: H_2S generation possible

Z > 10 000: H_2S generation very likely

With simplified sewerage, hydrogen sulphide generation can be expected to be a common problem. For example, for a flow of 1.5 l/s of wastewater with a BOD_5 of 250 mg/l at 25°C in a sewer laid at 1 in 214 and flowing at a proportional depth of flow of 0.2, **Z** can be calculated as follows, using equations 2.4, 2.6 and 2.8 to calculate p/b for $d/D = 0.2$:

$$\theta/2 = \cos^{-1}[1 - 2(d/D)]$$

$$= 0.927 \text{ radian}$$

$$p/b = (\theta/2)/\sin(\theta/2)$$

$$= 1.159$$

$$\boldsymbol{Z} = 3 \times 250\,(1.07)^5\,(1/214)^{-1/2}\,(1.5)^{-1/3}\,(1.159)$$

$$= 16\,000$$

Thus H_2S generation is very likely, and this is why the small diameter pipes used in simplified sewerage schemes should normally be of either vitrified clay or PVC.