Water Supply and Distribution Systems

Second edition

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Second edition

Dragan A. Savić and John K. Banyard

Published by Emerald Publishing Limited, Floor 5,
Northspring, 21-23 Wellington Street, Leeds LS1 4DL.

ICE Publishing is an imprint of Emerald Publishing Limited

Other ICE Publishing titles:
ICE Handbook of Urban Drainage
Richard Ashley, Brian Smith, Paul Shaffer and Issy Caffoor.
ISBN 9780727741783
Sustainable Water
Charles Ainger and Richard Fenner. ISBN 9780727757739
Land Drainage and Flood Defence Responsibilities, Fifth edition
Institution of Civil Engineers. ISBN 9780727760630

A catalogue record for this book is available from the British Library

ISBN 978-1-83549-847-7

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Cover photo: Caroline Ericson / Alamy Stock Photo

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Content Development Editor: Cathy Sellars
Books Production Lead: Emma Sudderick

Typeset by KnowledgeWorks Global Ltd.
Index created by David Gaskell

Contents

Preface to the second edition

The first edition of this book was published in 2011; since then, the field has undergone significant developments, driven by advancements in technology, changing environmental concerns and evolving regulatory frameworks. Much of what was viewed in 2011 as leading edge is now in many cases normal practice.

At a time when there is much criticism of the UK Water Industry it worth remarking that current compliance with UK standards (incorporating EU standards) stands at 99.97% overall. The quality of UK tap water is among the best in the world. As Editors, we have meticulously curated this updated edition to reflect the dynamic nature of water management in the belief that by doing so, we can help the UK and Europe to maintain their world leading position and provide the tools for others to meet similar standards.

All chapters have been thoroughly reviewed, and where appropriate the latest research findings, case studies and practical insights have been incorporated. Our expert contributors have delved deeper into critical topics, ensuring accuracy and relevance.

This second edition introduces fresh perspectives through revised chapters, addressing various design, operational, financial and sustainability considerations for water supply and distribution system management. Entirely new chapters, dealing with smart water systems and digitalisation, explore the integration of smart water technologies and predictive analytics in water infrastructure management, and, while previously in one chapter, water resource management and water treatment are now separated, giving these two topics their own identities.

This book would not be possible without the generosity of contributors, reviewers and practitioners who have shaped this edition and to them we extend our heartfelt gratitude. Their expertise and dedication have elevated the quality of this work.

As they embark on this journey through the ever-expanding intricacies of water supply and distribution, we invite our readers to engage with the evolving landscape. It is our hope that like the first edition this book will serve as a valuable resource for researchers, engineers, policymakers and students committed to ensuring a sustainable water future.

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KWR Water Research Institute, The Netherlands and
University of Exeter, UK

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Preface to the first edition

There are already a large number of textbooks covering hydraulics and water engineering, so why do we need yet another one to fill our bookshelves?

While the above is certainly a valid question, we, the editors, with long experience in both academia and with Water Service Providers were aware that there was a gap. With privatisation of the UK Water Industry in the late eighties, which brought changes to the organisation of the industry including a high level of regulation, a reduction in in-house expertise and a decline in research investment, there is a need to provide a useful reference book for practising engineers, particularly to provide information on up to date practice in today's increasingly complex Water Industry. This is important as practitioners in the developed (and the less developed) parts of the world face not only classical design and management problems, but also ever increasing environmental and sustainability requirements and concerns and at the same time few engineers can hope to keep pace with the vast amount of material presented at conferences and seminars. We also felt that there needed to be a book, which would provide a suitable guide for final year undergraduates and MSc students of water and environmental engineering courses, but which at the same time could be a useful reference after graduation when they enter employment with the Water Industry, environmental protection agencies or consultancies.

We have not tried to cover the whole of the Water Industry, but rather have focused on Water Distribution, where there have been major advances in the engineer's ability to optimise solutions, and obtain levels of understanding that have been denied to previous generations of practitioners.

To achieve this aim, we have assembled authors from academia, consultancy and the Water Service Providers to ensure that each chapter provides a balanced view of not only what is theoretically possible, but also what is practical both in the design office and in the world of water distribution system operation.

We hope that our readers will find this book helpful in their working lives, and that it will not become yet another tome that gathers dust on the bookshelves.

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About the editors

Dragan A. Savić FREng, CEng, FICE, FCIWEM

Dragan Savić is a Global Advisor on Digital Sciences and former Chief Executive Officer at KWR Water Research Institute based in The Netherlands and Professor of Hydroinformatics at the University of Exeter in the UK.

Dragan is an internationally recognised leading water engineering and pioneering hydroinformatics expert with over 40 years of experience working in engineering technology, academia and consultancy. He has influenced the water sector through academic research, mentoring of future water leaders, undertaking leading roles in international organisations, visiting/distinguished professor roles at various universities worldwide (e.g. China, Malaysia, Italy, Saudi Arabia, Serbia), and serving on advisory boards of water technology companies and government bodies. In addition to innovation and leadership skills, he is known for believing in bringing science into practice in the broader water sector and utilities in general.

Dragan is a founder and former director of the Centre for Water Systems at the University of Exeter, an internationally recognised group for excellence in water and environmental science research. He is a Chartered Civil and Water Engineer and an elected Fellow of the Royal Academy of Engineering, Member of the European Academy of Sciences (EURASC), Fellow of the Institution of Civil Engineers (ICE), Fellow of the Chartered Institution of Water and Environmental Management (CIWEM) and Fellow of the International Water Association (IWA).

John K. Banyard OBE, FREng, FCGI, BSc(Eng), CEng, FICE, FCIWEM

John joined Severn Trent Water on its foundation in 1974. In January 1990 he became Director of Engineering and in 1997 Asset Management for Severn Trent Water Ltd and was appointed to the main Board of Severn Trent Plc in January 1998. He was also a non-executive director of several subsidiary and joint venture companies from 1990 onwards including an appointment to the Board of the US subsidiary in April 2000.

On retirement from Severn Trent he became a board member of the Water Industry Commission for Scotland July 2005–June 2011. He was Chairman of the West Midlands Innovation and Technology Council 2006–2011. He was also Chairman of the Standing Joint Committee for the Infrastructure Conditions of Contract and Chairman of the Civil Engineering Standard Method of Management Panel for many years. Additionally, he works as an independent consultant.

He is a Chartered Civil Engineer and was elected a Fellow of the Royal Academy of Engineering in 1997. He became a Fellow of the City & Guilds of London Institute in 2000 and was awarded an OBE for services to Engineering and The Water Industry in December 2004.

John is the author of over 20 published papers on topics ranging from Project Appraisal and Computer Aided Drafting to the Collapse of Carsington Dam and Water Privatisation. In 1999, he was awarded the Frederick Palmer Prize by the Institution of Civil Engineers for his work on asset management. In 2004, he was invited to deliver the 5th International Brunel lecture for the Institution of Civil Engineers, involving over 30 presentations in 17 countries around the world.

He was a Royal Academy of Engineering Visiting Professor at the University of Loughborough 2001–2012. In 2014, he became Chairman of the Water Informatics Science and Engineering Doctoral Training Centre Advisory Board, a joint venture between water engineering departments at Bath, Bristol, Cardiff and Exeter Universities; retiring in 2023. He has been a mentor for recipients of the R A Eng leadership and Entrepreneurs Awards for many years.

John is a past President of the Pipeline Industries Guild, a past Master of the Worshipful Company of Engineers, and is also a member of the Water Conservators Livery Company; both being City of London Livery Companies.

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Abbreviations

ABC activity-based costing

ACO ant colony optimisation

AEX anion exchange

AI artificial intelligence

AM area meter

AMI advanced metering infrastructure

AMP asset management plan

AMR automatic meter reading

AoS appraisal of sustainability

ASR aquifer storage and recovery

AZNP average zone night pressure

BABE bursts and background estimates

BAC biological activated carbon

BCI Blue City Index

BMV burst main valve

BPSO best practicable sustainable option

CAPEX capital expenditure

CAMS catchment management strategy

CARE-W Computer Aided Rehabilitation of Water Networks

CBA cost–benefit analysis

CBA City Blueprint Approach

CBF City Blueprint Framework

CEA cost-effectiveness analysis

CFD computational fluid dynamics

CRI compliance risk index

DA decision analysis

DAF dissolved air flotation

DAFF dissolved air flotation over filters

DBP disinfection by-products

DCF discounted cashflow

DCM domestic consumption monitor

DDA demand-driven analysis

Defra Department for Environment, Food and Rural Affairs

DEM digital elevation model

DG Director General

DLF deflection lag factor

DMA distribution management areas

DMA district metered area

DOMS distribution operation and maintenance strategies

DPC direct procurement for customers

DPM discolouration propensity model

DRIP data rich, information poor

DRM discolouration risk model

DWDS drinking water distribution systems

DWI Drinking Water Inspectorate

DWQR Drinking Water Quality Regulations for Scotland

DWSP drinking water safety plan

EA Environment Agency

ECF electro-coagulation–flotation

EGL energy grade line

EIA economic impact assessment

EIA environmental impact assessment

ELL economic level of leakage

EPA Environmental Protection Agency

EPR evolutionary polynomial regression

EPS extended period simulation

ESG environmental, social, and governance

ESP extended period simulation

ET evapotranspiration

FBC flat-bottomed clarifier

FDO flexible design option

FEX fluidized ion exchange

FOSM first order second moment model

FSD fixed speed drive

GA genetic algorithm

GAC granular activated carbon

GCF Governance Capacity Framework

GDP gross domestic product

GGA global gradient algorithm

GHG greenhouse gas

GIS geographic information system

GPS global positioning system

GUI graphical user interface

GSS Guaranteed Standards Scheme

HDA head-driven analysis

HDN heuristic derived from nature

HDPE high-density polyethylene

HGL hydraulic grade line

HPPE high-performance polyethylene

IMF International Monetary Fund

IPCC Intergovernmental Panel on Climate Change

IRR internal rate of return

ISO International Organization for Standardization

IWA International Water Association

IWRM integrated water resources management

IWS intermittent water supplies

lcd litres per capita per day

MAIDE monitor, analysis, intervention, decision and evaluation

MCA multi-criteria analysis

MCS Monte Carlo simulation

MDPE medium-density polyethylene

MF microfiltration

MIEX magnetic ion exchange

MOGA multi-objective genetic algorithm

NF nanofiltration

NFW National Framework for Water

NHPP non-homogeneous Poisson process

NIC National Infrastructure Commission

NOM natural organic matter

NPSH net positive suction head

NPV net present value

NRV non-return valve

NRW Natural Resources Wales

NSO National Statistics Office

NTU nephelometric turbidity units

OECD Organization for Economic Co-operation and Development

OEP Office of Environmental Protection

Ofwat Office of Water Services

Ofwat Water Services Regulation Authority

OPA overall performance assessment

OPEX operational expenditure

OPI operational performance index

OPI operational performance indicator

OSEC on-site electrolytic chlorination

PAH polycyclic aromatic hydrocarbons

PALMM prevention, awareness, location, mitigation and mend

PCC per capita consumption

PDF probability density function

PE polyethylene

PFAS polyfluoroalkyl substances

PFI public finance initiative

PI performance indicator

PIC Public Interest Commitment

PLC programmable logic controller

PMA pressure managed area

PODDS Prediction of Discolouration in Distribution Systems

PPRA pre- and post-rehabilitation assessment

PRV pressure-reducing valve

PSBR public sector borrowing requirement

PSV pressure-sustaining valve

PU polyurethane

PVC polyvinyl chloride

RCP rapid crack propagation

RGF rapid gravity filter

RO reverse osmosis

ROA real options analysis

RTC real-time control

SA simulated annealing

SaaS software as a service

SBTI Science-based Targets Initiative

SCADA supervisory control and data acquisition

SEA strategic environmental assessment

SELL sustainable level of leakage

SIC Standard Industrial Classification

SIX suspended ion exchange

SoSI security of supply index

SOSM second order second moment model

SPEA Strength Pareto Evolutionary Algorithm

SROL social return on investment

SSF slow sand filtration

STPR social time preference rate

SWAN Smart Water Network Forum

TCFD Taskforce on Climate-related Financial Disclosure

TPF trends and pressures framework

TPI trends and pressures index

UF ultrafiltration

UKAS UK Accreditation Service

UKWIR UK Water Industry Research

UNCED UN Conference on Environment and Development

uPVC unplasticised polyvinyl chloride

VOC volatile organic compounds

VSD variable speed drive

WCED World Commission on Environment and Development

WDS water distribution system

WFD Water Framework Directive

WHO World Health Organization

WINEP Water Industry National Environmental Programme

WIS Water Industry Standard

WIS water into supply

WLC whole-life costing

WRAS The Water Regulations Advisory Scheme

WRc Water Research Centre

WRMP water resources management plan

WSP water safety plan

WSP water service provider

WTW water treatment works

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ISBN 978-1-83549-847-7
https://doi.org/10.1108/978-1-83549-846-020242001

Chapter 1
Historical development of water distribution practice

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1.1. Introduction

One of the problems facing the water distribution engineer is the longevity of the assets that they are responsible for. Today those fortunate enough to live in the developed nations of the world have come to take the supply of potable water for granted. Yet it is certainly within living memory of some of the population that there was a time when many houses had a single cold-water tap, with no bathroom, and certainly no washing machine or dishwasher. The very significant increase in volume of water consumed, not to mention far higher quality standards, are often overlooked and the technology is viewed as ‘the water flows through pipes as it did in my grandfather’s day’ with the result that many believe that the industry has ossified. Even more sadly, it is possible to find practitioners who also share the same beliefs, with a view that what was satisfactory for their predecessors must be satisfactory today. For that reason alone it is worth taking a short space within this book to review the historical development of water treatment and distribution. However, it is also important to provide at least a basic foundation of what has gone before to help better understand today’s technology and good practice. In doing so we shall hopefully prepare the way for future developments to be introduced to enhance today’s practices.

In reality the history of water supply and distribution is one of over 200 years of constant innovation and development. Where there have been lulls, it has not been through lack of effort, but rather waiting for science and technology to develop and, sometimes, waiting for those concepts to be capable of being deployed. The advent of the digital age has facilitated huge strides forward, with a result that the technical sophistication is now beyond the wildest imaginings of those who worked in the industry only 60 years ago.

1.2. History of water treatment and supply

It is impossible to say precisely when the first installations of artificial water supply were introduced. We know that man must always have needed access to clean water for survival. For nomadic peoples this was simply a matter of finding a clean river or spring.

Early conurbations were sited near to water sources, and there is evidence of early civilisations going back to at least the fourth millennium BC. The earliest form of water engineering appears to have been the construction of irrigation canals, but at some stage wells must have been constructed. Rather than get involved in lengthy discussions as to where or when the first water supply system was constructed, it will meet our needs in understanding the historical developments of water supply if we rely on Roman sources, and, in particular, the work of Frontinus (35–103 AD). Frontinus was certainly not the first Roman to write about water supply; approximately 100 years earlier, the architect Vitruvius (c.75–15 BC) had produced a large work on architecture, which included among many other topics the construction of aqueducts. However, Frontinus is a more helpful source because he was appointed manager of Rome's water supply in 97 AD. Furthermore, he left a report on his work, which has survived as a text book, which, well beyond his intentions, has been used to instruct (willingly or otherwise) generations of Latin students.

Frontinus was not an engineer; he was an extremely successful professional soldier who, in 76 AD, was appointed governor of Britain. At the end of his term as governor he returned to Rome having already written a book outlining military stratagems. He was faced by a new challenge, one for which he was not wholly prepared, and having tackled it, he produced 'De aquis urbis Romae'. In this he sets out his understanding of the history of Rome's water supply, saying that for the first 441 years of Rome's existence it was supplied by wells, springs and, of course, the River Tiber. However, around 312 BC the first aqueduct was brought into use, known as the Appian Aqueduct, after Appius Claudius Crassus, who was also responsible for the Appian Way. The aqueduct was around five miles long and much of it was constructed underground. He goes on to detail a further ten aqueducts, all constructed before he took office. Today's engineers might care to ponder the engineering feat of building such a structure, which Frontinus would describe as still being in use some 400 years after its initial construction.

It is interesting that Frontinus condemns the construction of the Alsietian (or Augusta) aqueduct by the emperor Augustus since the water is described as unwholesome and not used for consumption by the people. We have clear evidence, therefore, that there was at this time clear understanding of the link between water and illness, indeed it would be surprising if this were not the case.

The book goes on to reveal that, in modern parlance, Frontinus inherited a mess. He explains how he had all of the aqueducts surveyed and drawings produced, so that he did not have to waste his time going out to view problems personally, his subordinates could explain the issue to him with the help of the appropriate drawing. He had the aqueducts relined with lead to prevent leakage and vigorously pursued the owners of villas along the route of the aqueducts who had tapped into them to provide a free water supply to their properties. There was no water treatment as we would recognise it, but water discharged at the end of the aqueducts into tanks where impurities could settle out. Water was generally distributed around Rome by water sellers, and Frontinus has some harsh words for them. Overall, Frontinus applied his military background for standards and discipline very successfully to the management of the Roman aqueducts and, in doing so, gave a good indication of the tasks required of the asset manager, which would be recognised some 1900 years later.

Although Frontinus was only concerned with Rome's aqueducts, the provision of water supplies was extremely important to all of Rome's cities. Perhaps the most famous is the spectacular Pont du Gard near the French city of Nimes but it is by no means unique, and the ruins of the aqueduct that brought water into the city of Barcelona are still visible near to the Gothic cathedral.

Unfortunately, with the decline and, eventually, the fall of the Roman Empire, the aqueducts fell into disrepair and the population returned to the methods that had served Rome for the first 440 years of its existence (if Frontinus is indeed correct). It appears that in medieval times, monasteries started to pipe water as an addition to the supplies from wells on which they were frequently founded, and it is possible that some of this water found its way to the local population.

In 1589 Sir Francis Drake was instrumental in providing the city of Plymouth with a new water supply known as Drake's Leat, dug by hand (although not in the single day ascribed by legend), and in 1613 the New River was constructed to bring fresh water to the ever expanding city of London from the River Lea some 20 miles away. However, none of these schemes can really be compared with the technical achievements of the Romans. Equally, some 1400–1500 years after Frontinus, civilisation was indeed catching up with the Romans of his era.

The lack of water treatment and clean water supplies began to manifest themselves as the Industrial Revolution took place. Farm workers flocked to the new industrial cities to better their existence, but this placed huge strains on both water supplies and sanitation, both of which were extremely basic, and outbreaks of both typhoid and cholera became common place, albeit by no means continuous. The state of the working classes was exposed in a report by Edwin Chadwick, published in 1842, and quotations from these reports adequately demonstrate the misery of those days.

> *The various forms of epidemic, endemic and other disease caused, or aggravated or propagated chiefly among the labouring classes by atmospheric impurities produced by decomposing animal and vegetable substances, by damp and filth and close and overcrowded dwellings prevail among the population in every part of the kingdom…*
>
> *That such disease wherever its attacks are frequent is always founding connection with the above circumstances…*
>
> *The formation of all habits of cleanliness is obstructed by defective supplies of water.*

The poet Shelley went further in one of his works, stating that '*Hell is a city rather like London*'.

Although Chadwick's reports did start the movement to provide better living conditions, particularly in terms of sanitation, the lack of scientific understanding about the cause of disease was a major hurdle.

It is difficult now to fully understand why the link between impure water and disease was not appreciated, particularly as there is ample evidence that there was a desire for clean wholesome water. In 1852, the Metropolis Water Act required all water derived from the Thames and supplied in London within 5 miles of St Paul's Cathedral to be at first filtered, but, even so, the accepted medical theory for much of the nineteenth century was that typhoid and cholera were airborne diseases, spread by the breathing in of miasmas (foul air) and had nothing to do with water, which was considered 'clean' as long as it was clear and not turbid.

The germ theory of disease did, indeed, exist, but it was not accepted by the majority of the population nor scientific opinion. It had its proponents, one of whom was Dr William Budd of Bristol who recognised that clean sources of water were required to avoid the spread of cholera. In the early 1840s he had used a microscope to examine rice water, the term used for the stools produced by cholera patients; he found organisms that he had also found in drinking water and concluded (incorrectly) that the organism was a fungus, and was responsible for cholera. Dr Budd became one of the people responsible for establishing the Bristol Waterworks Company in 1846, which brought clean water to the city from the Mendip Hills through an aqueduct.

Budd wrote up his work in 1849, and was in correspondence with a Dr John Snow in London (who in 1849 had produced a paper suggesting that cholera was not spread by miasmas), but the paper produced little interest. Interestingly, a careful reading of Chadwick's report shows that he fully subscribed to the miasmic theory.

In 1854, there was an outbreak of cholera in Soho, a district of London loosely defined by what in modern London are Oxford Street, Regent Street, Leicester Square and Charing Cross Road. There was nothing exceptional about this, as London in those days suffered regular outbreaks of both cholera and typhoid, as indeed did most cities and large towns within the UK and, indeed, Europe and the USA. Dr Snow came to realise that all of his patients obtained water from the same pump in Broad Street. He plotted the progress of the outbreak on a map and demonstrated to the public authorities that the outbreak in Soho was indeed linked to the Broad Street pump, and persuaded them to remove the handle of the pump, after which the outbreak rapidly subsided. It is ironic that in the paper that he subsequently wrote in 1855 concerning the outbreak and his work in stopping it, he identified a number of patients who had used the Broad Street pump in preference to alternative sources closer to their homes. Subsequent investigation showed that the well which supplied the Broad Street pump was located very close to a cess pit. Despite the success in stopping this particular outbreak of cholera, the pump handle was in fact reinstated by the authorities once the epidemic had passed.

Snow's work was not accepted by the medical establishment. His case was not helped by the fact that he had subjected the water to chemical and microscopic examination and failed to identify any agent that he could categorically state was the cause of the cholera outbreak. Today this seems to us almost incredible, particularly as it was well known from microscopic examination that there were organisms in the water. However, it was to be another 30 years before the 'germ theory of disease' was to be established by the French scientist Louis Pasteur. It is impossible to put a precise date on Pasteur's work, as he published a number of papers from 1865 on, but by 1880 the case for germ theory was established as correct. Pasteur did not invent the germ theory, it had existed as a hypothesis for many years; what he did was to demonstrate convincingly that the germ theory was correct and the more widely accepted miasmic theory was invalid.

Looking back at historical actions is always difficult, and today it seems unbelievable that the perceived wisdom of the medical establishment supported the miasmic theory. It was certainly well known that drinking dirty water led to illness and that had been the case for centuries, it was one of the reasons given for medieval monasteries brewing beer, although there may also have been other incentives. Nonetheless, it was undoubtedly the case that until Pasteur's work, the majority opinion was that serious illnesses such as typhoid, cholera and even the plague were transmitted by miasmas. Although it easy to be critical of such failure to accept what is now obvious, history has many such examples: the failure of the Church to accept the work of Copernicus is one example, a far more recent one is the opposing views about the nature of the universe. Einstein's theory of relativity leads to the conclusion that the universe is constantly expanding as proposed by Hubble (the Big Bang theory) but there are others like Hoyle and Bondi who proposed a 'steady state' model; Hubble's ideas are now generally accepted, but there still persist a number of other models with their proponents which may eventually be proved to have some validity. Scientific progress tends to be incremental and it is against that background that we now need to view the development of the principal water treatment processes.

The first recorded instance of use of a filtration system for water treatment was Paisley, Scotland, in 1808. However, this did not reflect some farsighted public health concerns by the city fathers, rather it was installed by John Gibb to improve his cloth bleaching business. The town is sited on the side of the River Cart, which was notorious for becoming turbid in times of storm. This variability in water quality affected the colouring of the cloth being bleached. It is reported that he was so successful he was able to sell surplus water to those who wished to pay for it.

The first municipal installation of water filters (slow filters) was at Chelsea by James Simpson in 1829, some 23 years before the Metropolis Water Act referred to above.

The first installation of filters in the USA was in Richmond, Virginia in 1833, and there was a large installation of 'English' filters installed at Poughkeepsie in New York by James P Kirkwood in 1872. Thereafter the efficacy of water filtration as a means of avoiding outbreaks of disease became more readily demonstrable, however, although a well-designed filter made a tremendous improvement to the quality of water, it could not guarantee purity. By 1880 Pasteur's demonstration of the germ theory was becoming accepted and water professionals could start to concentrate on removing the offending organisms.

In 1895, George W Fuller, working at Louisville in the USA, was attempting to find the most appropriate way of treating the waters of the Ohio River and successfully combined the addition of chemical coagulants and water filtration to produce the now classical two stage process that is at the heart of many water treatment plants around the world. He formed his own consultancy practice subsequently, and was responsible for a much larger installation at Little Falls, New Jersey, in 1902.

Fuller also worked on the development of so called rapid gravity filters, which are commonplace today, being cleaned mechanically as part of the operational cycle, rather than depending on manual excavation of sand associated with the original slow sand filters. Although the basic concept of chemical coagulation followed by filtration has remained for over 120 years, that does not mean that there has been no progress. Doubtless if Fuller were to visit a modern treatment works he would recognise his basic process sheet, but he would also be amazed at the sophistication now deployed. The coagulation process is now carefully controlled by computers, and the separation process is undertaken in a variety of clarifier designs that improve performance beyond anything that he was able to achieve. Even his dependence on gravity for separation has been replaced, at times, by use of dissolved air flotation. More recently, the advent of membrane filtration has started to challenge the traditional flow sheet, but these devices, employing as they do filtration at a truly molecular level, still require protection in the form of roughing filters or the use of chemical coagulants to break the molecular bonds before separation takes place across the membrane with use of a partial vacuum.

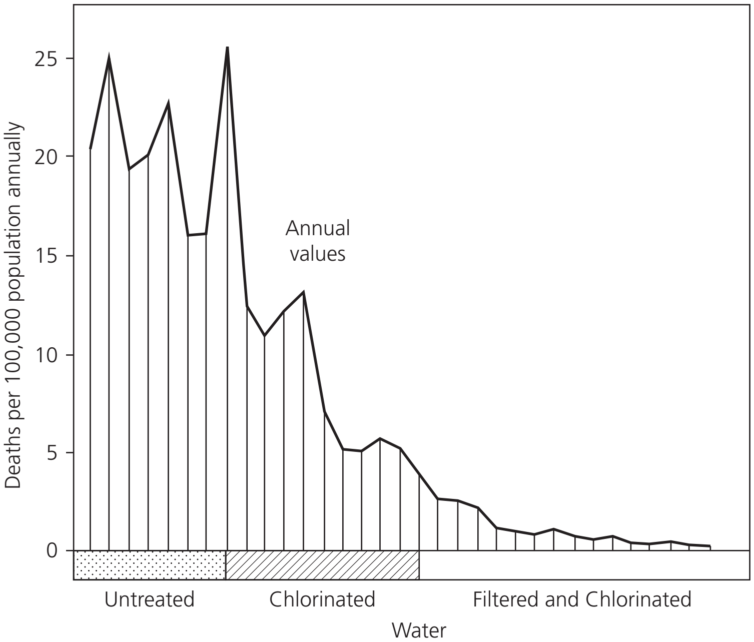
Despite the huge advances in coagulation and filtration, there remains one further element in the process of modern water treatment that has a major impact on the work of all water distribution engineers. This is the question of disinfection. While Fuller and his contemporaries were pursuing the removal of dangerous bacteria from the water supplies, an alternative approach was also being developed, that of simply killing the bacteria. Of course, the chemicals used had to be harmless to man and, hence, strong oxidising agents were used.

There are several claims made for the first use of chlorine in treating drinking water around the start of the twentieth century, particularly in Middlekerk and Antwerp. It is probable that its first use was not in the United Kingdom, although there are some references to Maidstone in 1897. What is well established is that, in 1903, there was an outbreak of typhoid at Fulborne Asylum in Cambridgeshire. The authorities sought permission from the House of Lords to introduce chlorine into the drinking water, but the request was refused on the grounds that it would be too dangerous. Twelve months later there was an outbreak of cholera in Lincoln and, one assumes learning from the experience at Fulborne, the city fathers did not seek any approval but went ahead with the use of chlorine and the outbreak rapidly abated. At this point they made a fatal mistake and stopped using chlorine, which in turn resulted in a further outbreak several years later. However, Lincoln is generally credited with the first use of chlorine in water treatment in the UK. From that time on, the use of chlorine became increasingly commonplace in the control of both typhoid and cholera. In 1909, the city of New Jersey became the first municipality in the USA to use chlorine as permanent element of its water purification process. Gradually, disinfection with chlorine (or compounds of chlorine such as hypochlorite) became part of the established water treatment process flow sheet.

In 1935 there was an outbreak of typhoid in Croydon, UK, and again chlorine had not been used in the treatment process. Following that outbreak, the UK legislation was changed and it became a requirement for potable water to contain a residual disinfectant when distributed through the public water supply network. Since that date there has not been a single reported case of waterborne cholera or typhoid within the UK.

The requirement for a residual disinfectant provides a major challenge to the distribution engineer. Initially, it was sufficient for the water to leave the treatment works with a high chlorine residual and for it to simply decay as it passed through the distribution system. However, public opinion turned against the taste of highly chlorinated water and, while the inaugural address of one president of the American Waterworks Association contained the suggestion that 'If you can't taste the chlorine, don't drink the water', this can only have brought comfort to the manufacturers of

Figure 1.1 Effect of water purification on the death rate from typhoid fever in a city drawing water from a clear lake



bottled water. Today's distribution engineer has to be able to manage the levels of chlorine within the distribution system to achieve a balance between the competing demands of public acceptability and public health. To do that, it is necessary to be able to predict the flow regimes within pipe networks, which is the subject of the next part of this review of the historical development of water distribution practice.

But before we move on, there is one final piece of this particular 'treatment jigsaw' that needs to be understood. Three processes are required for effective water treatment and each stage is essential, it is not a 'pick and mix' situation. Figure 1.1 shows the efficacy of the standard three stage approach.

Typical improvement in death rate following introduction of Water Treatment Technology (Fair, Geyer and Okun, 1966).

1.3. Evolution of pipeline materials

As we have seen with water treatment technology, we shall also find continuous evolution of pipeline materials over the last 150 years.

We can again start with Rome, where Frontinus makes it clear that lead was used for pipes and also to make discharge devices to control flows from aqueducts and cisterns. It is also interesting to note in passing that 100 years earlier, Vitruvius appears to report (his writings are not always clear because he presumes detailed knowledge of then current practice) problems with what appears to be an inverted siphon, where material technology could not withstand the bursting forces. It may therefore be the case that Roman preference for aqueducts rather than pipes across valleys related to limitations in pipe materials rather than ignorance of the hydraulic phenomena which allow inverted siphons to function.

It is also clear that clay pipes were available to Roman engineers and, indeed, earlier civilisations but they also would have limitations in terms of bursting resistance and were probably used for sewers (where such existed). We should, perhaps, stress that there is no suggestion of Roman houses all having running water. A few very rich individuals had water piped to their houses to a single point of discharge but, as Frontinus makes clear, the vast majority depended on collection themselves from cisterns at the end of aqueducts or the services of water sellers who (supposedly) collected water from cisterns and distributed it around Rome in carts.

Again, with the fall of the Roman empire much of this was lost and we have to wait until the Middle Ages to find any return to public water supply provision.

Early water mains were made from hollowed out tree trunks, joined with a socket and spigot joint which itself was sealed by wrapping in lead or some other material. There are numerous examples of this technology in museums.

1.3.1 Iron pipe

It is not clear when the first cast iron water pipes were introduced, but it is known that cast iron pipe was used to distribute water to the various fountains of the Palace of Versailles in 1672. It is of passing interest that there was, and still is, insufficient water to feed all of the fountains at the same time, and so they had to be switched on or off as the King approached or passed them.

In all probability, there were earlier uses of cast iron pipes but they are less celebrated and, sadly, not recorded; although the American Ductile Iron Pipe Research Association reports their first use as 1455 in Siegerland, Germany. However, it is clear that cast iron pipe began to be used for water supply in the eighteenth and nineteenth centuries. The first recorded use of cast iron pipe for water supplies in the USA appears to be in the early 1800s in the New Jersey and Philadelphia areas, where they replaced traditional wooden pipes. Initially, these pipes were cast horizontally and were of uneven quality, but around 1850 vertical casting was developed, which produced a far more reliable product. There was no standardisation of sizes for these early pipes, and engineers would specify not only the internal diameter of the pipe they required but also its wall thickness.

The next major advance was the invention of the centrifugal spinning process in 1918. In this, instead of a mould which defined the internal and external diameters, there was only a hollow circular mould that fixed the external diameter. This was rotated at speed about its longitudinal axis and molten metal was poured into it. The centrifugal force took the molten metal to the internal surface of the mould and the quantity of liquid iron applied defined the internal diameter. This process provided a far more uniform pipe material with less possibility of air bubbles or casting flaws. This process gradually replaced vertical and horizontal casting, but of course could not be used for pipe fittings such as Tee junctions and bends.

In 1955, a further advance was made with the development of ductile iron pipes. Traditionally, pipes had been made of gray iron, which was strong and durable, but brittle. By modifying the metallurgical composition, a material was developed that was far less brittle and could accept a small amount of deformation. Although being developed in the United States in the mid 1950s, it did not reach the UK until the 1970s. Initially it appeared to be a far superior material, and was manufactured in part from scrap steel (although still technically an iron), however, experience showed that it was more prone to corrosion than the gray iron that it had replaced. There then followed a series of developments aimed at corrosion prevention, starting with on-site wrapping in polythene sheets, through to today’s standard of factory applied multicoated protection systems.

A number of other materials were developed and challenged the traditional approach of iron water mains, and we shall look at those shortly, however, before doing so we should also look at jointing of pipes.

The early cast iron pipes were sealed with what was known as a run lead joint. Molten lead was poured into the annulus between the spigot of one pipe and the socket of the other pipe. As the lead cooled, it solidified and shrank, it then had to be compressed by use of a series of chisel like tools and a hammer to form a water tight joint. It was of course necessary to insert caulking before the lead to prevent it running down the length of the spigot. Some pipes also had a small channel cut into the inner circumference of the spigot to assist in making the joint and providing a path and holding channel for the lead. This highly skilled and somewhat dangerous technique was replaced by the invention of the sealing ring. There are several different styles of ring, generally protected by patents, but for the purpose of this introduction they can be viewed as an ‘O’ ring that is compressed between the spigot and the socket at each joint. Flanged joints and various mechanically restrained joints are also available, but push fit joints are most commonly used for external infrastructure (buried pipes).

1.3.2 Asbestos cement pipe

One of the early rivals to cast iron was the development of asbestos cement pipe. Essentially, this is a cement pipe that gets its tensile strength from the incorporation of 11% asbestos fibres. The pipes were used from the 1920s to the 1980s, and many kilometres are still in use around the world,