Bacterial Activity in Harvested Rain Water

Richard Hill BSc CEng FIChemE

1 INTRODUCTION

1.1 Preamble

Water is a natural solvent and rain water will dissolve or entrain a wide variety of contaminants as it becomes exposed to them. This can be of concern in the harvesting of rain water for some uses, but there is a good deal of confusion as to the nature of potential contaminants in rain water and their implications for rain water use. The purpose of this short paper is to provide some background and clarification to the subject.

1.2 Contaminants in Rain Water

When raindrops first condense in the upper atmosphere they are essentially pure water but quickly become contaminated with a range of materials. These are categorised by their chemical properties and summarised in Fig 1 as:

- Dissolved gases
- Dissolved minerals – inorganic salts such as chalk and salt
- Dissolved organic matter – compounds which contain carbon
- Suspended solids – particulate or colloidal matter which does not truly dissolve
- Microbiological contaminants

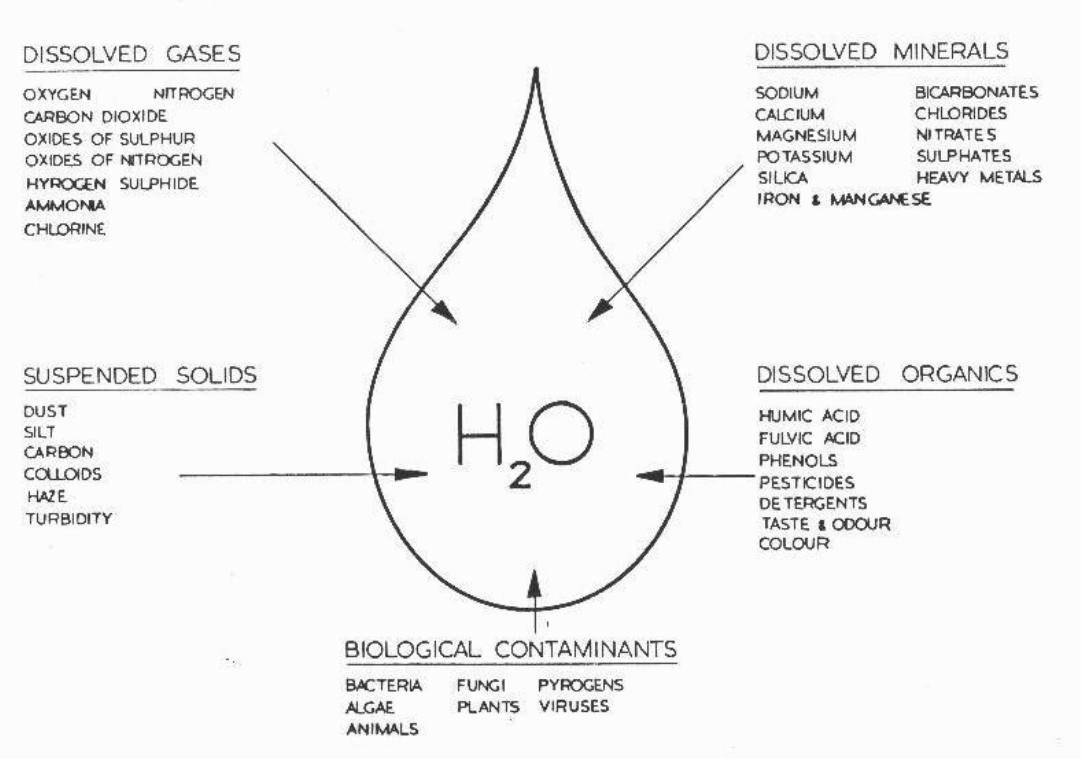

Fig 1.1 – CONTAMINANTS IN WATER

Initially as rain falls through the atmosphere it will dissolve gases – mainly oxygen and carbon dioxide from air but also, in areas where there is atmospheric pollution, oxides of sulphur and nitrogen from industrial emissions. In coastal areas rain will also mix with spray from the sea giving rise to dissolved salts in the harvested rain water. It will also wash particulate solids such as fine dust from the air, and these will remain in suspension. The atmosphere also contains a wide range of airborne bacteria, fungal spores and similar microbiological life forms and these will also be present in harvested rain water.

When the rain falls onto grassland it will dissolve more carbon dioxide because the concentration of carbon dioxide in the air at ground level is higher than in the surrounding air as a result of photosynthesis of the grass. If the rain falls onto non permeable surfaces such as roofs, roadways or hardsatndings, then further contamination will occur. Roofs are often covered with lichens and faecal matter from bird and animal droppings and these will give rise to dissolved organic matter.

It is, therefore, evident that harvested rain water is not a pure substance nor is it consistent since its characteristics will vary in both type and concentration depending on where the rain has fallen and how it has been collected and how it is stored.

2 ORGANIC MATTER

2.1 Natural Organic Matter

Rain water that falls on moorland areas typically dissolves humic and fulvic acids from decaying vegetable matter. These materials, known generically as “natural organic matter” (NOM) give rise to characteristic colours (green, yellow, brown), taste (phenolic, medicinal) in the water and odour (peaty, musty). This is particularly noticeable in Scottish streams fed from moorland sources. In the case of harvested rainwater, NOM can originate from sources such as rotting leaves on impervious ground and lichen on roofs. Whilst dissolved organic matter produces some effects which are similar to those produced by biological activity – colour, taste and odour – it should not be confused with biological activity. Colour, taste and odour caused by NOM do not change significantly over time because the organic molecules are chemically stable. However, they are readily decomposed by biological activity which will result in changes in the organoleptic properties of the water in storage.

Organic content of water is most commonly measured using total organic carbon (TOC) as a surrogate. Typical TOC concentrations in rain water often fall into the range 1 – 10mg/l but can be significantly higher. In the highly coloured waters found in swamps TOC can be as high as 200mg/l (Crittenden et al[1]).

Note that chlorination of water containing organic matter can result in the formation of trihalomethanes (THMs) as a by-product. These are carcinogenic if ingested and their concentration in drinking water is currently limited to a maximum of 100µg/l.

3 MICROBIOLOGICAL CONTAMINATION

3.1 Algae

Algae are simple green plants ranging from single to multicellular. The single celled blue-green algae are now considered to be bacteria (the cyanobacteria) but, like all algae, they photosynthesise so require sunlight. Algal growth tends to be seasonal with spring and autumn normally being the most active periods. Photosynthesis absorbs carbon dioxide and generates oxygen so assists in oxygenating water. However, the resulting growth in algae can cause physical blocking of pipes and pumps.

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[1] MWH, Water Treatment Principles and Design, Wiley 2005

Some species of algae and, in particular, the cyanobacteria, produce toxins (cyanotoxins) which are poisonous to animals and humans.

Algae are ubiquitous in slow moving or stagnant water which is exposed to sunlight[2] and grow rapidly at temperatures above about 5°C with the rate of growth increasing as the temperature increases to about 20-25°C[3]. Algal growth causes the green/brown discoloration and surface scum which is commonly observed in rain water stored in tanks open to the atmosphere and sunlight. Storing harvested rainwater at low temperature and in the absence of sunlight minimises the growth of algae. When algal cells die, they are broken down by bacteria, and so the presence of algae promotes bacterial growth by providing a nutrient substrate.

3.2 Bacteria

Bacteria are present in most waters and are naturally washed from the atmosphere by rain. Bacteria are instrumental in the decay of biological matter such as leaves, lichens and so on, so will be present in rain water that has been in contact with such material. This will typically occur in roof or hardstanding run-off. Not all bacteria are pathogenic but rain water which comes into contact with faecal matter such as bird or animal droppings will become contaminated with enteric coliform bacteria. Provided that the water is not being ingested this will not normally be a problem, although there is always a risk of inadvertent ingestion from wet hands and so on. Of more concern is the possibility of inhalation of pathogenic bacteria like *Legionella spp* which are commonly found in rain water[4]. Aerosols formed during spray irrigation[5] or WC flushing[6] may be a source of infection from rain water so contaminated. Consequently a risk assessment should always be undertaken for any rain water system.

Whilst the presence of organic matter in water provides a ready source of nutrient for bacterial growth it is by no means necessary. As Holden[7] states “Organic matter, admittedly, is a food supply for bacteria and favours their multiplication, but large numbers of bacteria may be found in water of the highest organic purity.” The higher the NOM, therefore, the greater is the likelihood of bacterial growth but the presence of NOM is not necessarily a precursor to bacterial activity, nor is the absence of NOM a barrier to bacterial activity.

There are many ways of categorising bacteria, one of which is by the way in which they use oxygen. There are three groups here: obligate aerobes which can survive only in the presence of oxygen, obligate anaerobes which can survive only in the absence of oxygen and facultative bacteria which can live under either condition.

3.3 Bacterial Growth

Bacterial populations in water are measured by growing bacteria under controlled laboratory conditions and counting the number of colonies that are formed, each from a single cell. The result is expressed as a number of “colony forming units” per millilitre of water (cfu/ml). The laboratory may count a single species (for example E Coli), a group of bacteria (for example total coliforms), or all bacteria (total viable count, TVC).

Bacterial growth occurs in a well established pattern of four phases. The first is the “Lag Phase” which is what happens when water first becomes contaminated with bacteria. Initially the population remains unchanged whilst the cells become acclimated to their environment and establish metabolic activity. This is followed by the “Exponential Phase” in which cells divide regularly by binary fission, and grow by geometric progression. The cells divide at a constant rate depending upon the

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[2] Bellinger E G, A Key to Common British Algae, CIWEM 1992

[3] Konopkat A and Brock T, Effect of Temperature on Blue-Green Algae, App Env Microbio, Oct. 1978, p. 572-576

[4] Sakamoto R, Legionella pneumophila in Rainwater on Roads, Emerging Infectious Diseases, 15 8 2009

[5] Donnison A et al, Bacterial survival and dispersal in spray irrigation aerosols, NZ J Agric Res 47 4 575-585, 2004

[6] Barker J and Jones M V, The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet J Appl Microbiol 99 2 339-347, 2005

[7] Holden W S, Water Treatment and Examination, Churchill 1970

composition of the substrate on which they feed and the environmental conditions. The growth rate is often expressed as the doubling time of the bacterial population. Exponential growth cannot be continued forever and stabilises in the "Stationary Phase" where growth is limited by one of three factors: lack of available nutrients (including oxygen in the case of aerobes), accumulation of inhibitory metabolites or lack of space. Finally there is the "Death Phase" in which the viable cell population declines[8]. The phases are shown graphically in Fig 3.1.

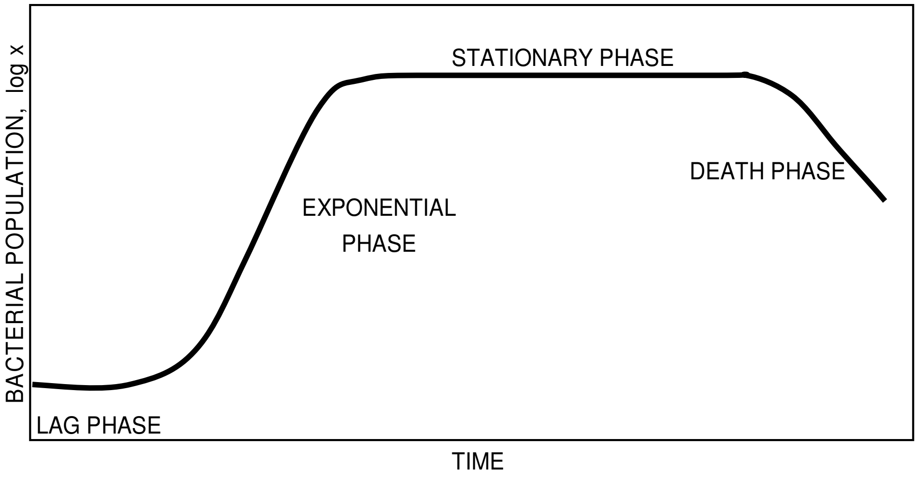

Fig 3.1 – BACTERIAL GROWTH CURVE

In the context of rainwater contamination it is the lag phase, or at least the time taken for the bacteria to become established which is most critical. Rain water will not usually remain stagnant for sufficient time for this to happen. However, if it is harvested and held in storage, then bacterial growth will move into the exponential phase. The length of the lag phase will depend on a wide variety of factors including the initial number of cells, the availability of nutrient, the time necessary for the cells to recover from physical damage or shock, the chemical composition of the water and the temperature.

In order for exponential growth to proceed there must be sufficient nutrient substrate available for the bacteria to feed on. The presence of organic matter (TOC) in the water will clearly provide such a food source, but other elements such as nitrogen, phosphorus, potassium and several trace elements are necessary for growth: the depletion of any one of them can cause a movement into the stationary phase. Monod[9] found that, where nutrient availability is limited, the rate of bacterial population growth is directly proportional to the nutrient concentration. However, if there is no limit on nutrient availability, as is likely to be the case in rainwater storage, the growth rate reaches a maximum as Fig 3.2 shows.

This maximum specific growth rate for most bacteria is about $2.0h^{-1}$, which is equivalent to a doubling time of about 20 minutes. Under these conditions a bacteria count of 1cfu/ml will increase to 1,000,000 in about six hours.

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[8] Todar K, On Line Textbook of Bacteriology, www.textbookofbacteriology.net 2005

[9] Monod, J et al, On The nature of allosteric transitions:A plausible model. *J. Mol. Biol* . 12 88-118.

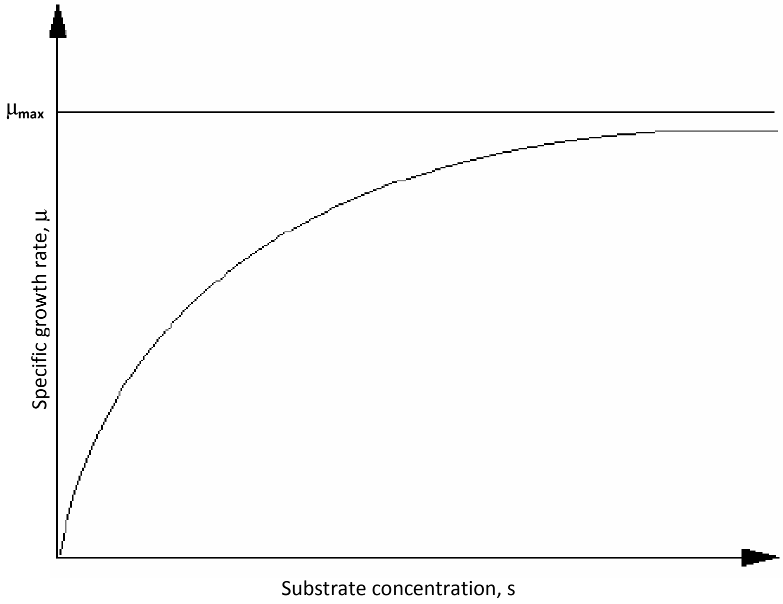

Fig 3.2 – EFFECT OF SUBSTRATE CONCENTRATION ON BACTERIAL GROWTH

Bacteria can survive at surprisingly low levels of nutrient. Indeed bacterial problems are routinely encountered in high purity water systems where TOC levels are at µg/l levels[10]. However, once exponential growth is established, it will continue until the substrate is exhausted when cells will begin to die. In the case of harvested rain water, which is not normally aerated during storage, the limiting factor is frequently oxygen. Once the oxygen levels become depleted by aerobic bacteria they will begin to die and anaerobic bacteria then begin to feed on the dead cells. When such anaerobic conditions occur there is almost always an associated unpleasant odour.

Another way of categorising bacteria is by their response to temperature. Once again there are three groups[11]. Psychrophilic bacteria such as *Pseudomonas spp* grow between 5-30°C, mesophilic types, which includes most common pathogens and enteric bacteria*, E Coli* and *Salmonella spp*, between 25-45°C and thermophilic types between 45-70°C. Researchers[12,13] have found that for each group there is an optimum growth temperature. At lower temperatures the growth rate is reduced. As the temperature increases so does bacterial growth until a maximum is reached. At higher temperatures the cells begin to die and the growth rate declines rapidly. The optimum temperature for psychrophilic bacteria is around 20-25°C, for mesophiles 35-40°C (around mammalian body temperature) and for thermophiles around 50-55°C. The growth rate at temperatures below 5°C is very low, as is the case in refrigerated storage of food. At the other extreme, Pasteurisation temperature of 80°C will kill most common bacteria. The relationship between temperature and growth rate for mesophilic bacteria is typically as shown in Fig 3.3.

The parameter which has been plotted here is the specific growth rate, µ, which is the quantity of bacterial cells formed per original cell per unit time. That is:

$$X_t = x_0 e^{\mu t}$$

where x_0 is the original bacterial population measured as cells per ml
x_t is bacterial population in cells per ml after a time t hours

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[10] Metzler T, Pharmaceutical Water Systems, Tall Oaks Pub, 2001
[11] Stephenson T et al, Process Science and Engineering for Water and Wastewater Treatment, IWA 2000
[12] Ratkowsky D A et al Relationship Between Temperature and Growth Rate of Bacterial Cultures, Jour Bact 149 1 1-5, 1982
[13] M. H. Zwietering M H et al Modeling of Bacterial Growth as a Function of Temperature, App Env Microbiol, 57 4 1094-1101 1991

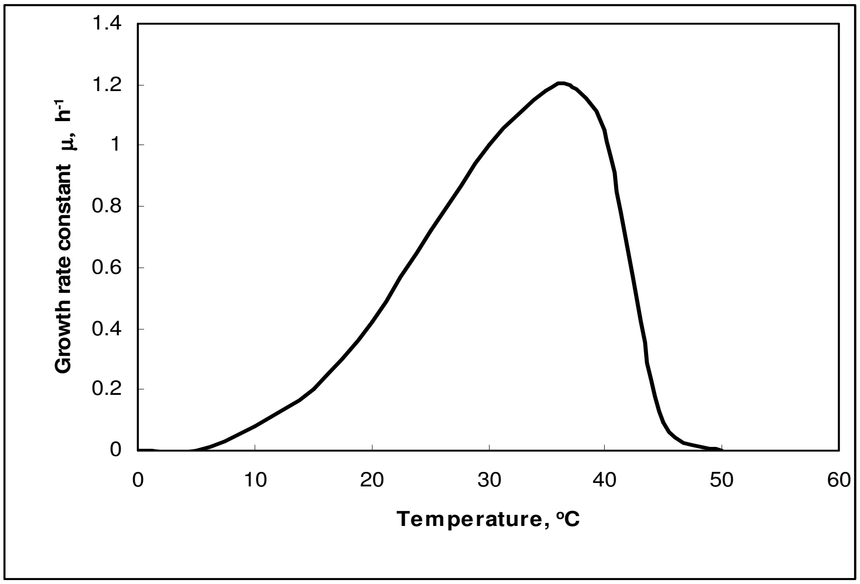

Fig 3.3 – GROWTH RATE CONSTANT vs TEMPERATURE FOR MESOPHILIC BACTERIA

The doubling time for the population referred to in Section 3.3 can be calculated by setting the ratio of $x_t/x_0 = 2$ as shown in Fig 3.4.

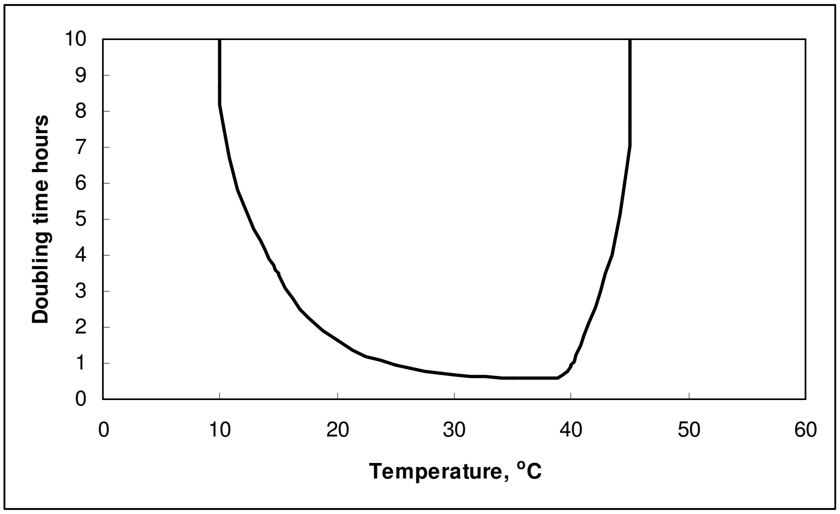

Fig 3.4 – DOUBLING TIME vs TEMPERATURE FOR MESOPHILIC BACTERIA

3.4 Discussion

From the foregoing review of microbiological growth it is clear that the process of rainwater quality deterioration is complex one in which bacteria, algae and organic matter have important and inter-related roles. Initial contamination with both natural organic matter and bacteria is inevitable but it is in storage that problems of discoloration and odour occur. In stagnant water bacterial populations secrete extra-cellular polysaccharides which are sticky and incorporate the bacterial cells into an adherent biofilm on surfaces of pipes and tanks.

There are four principle factors that can be controlled during storage of rain water: storage time, sunlight, oxygen and temperature.

4 MAINTAINING WATER QUALITY IN STORAGE

4.1 Quality Standards

There are currently no legislative standards for harvested rainwater although British Standard BS8515:2009 provides some guidelines for water quality, and these are summarised in Table 4.1.

TABLE 4.1 – WATER QUALITY GUIDELINES FROM BS8515:2009

Parameter	Units	Sprinklers	Watering & WCs
E Coli	cfu/100ml	1	250
Enterococci	cfu/100ml	1	200
Legionella sp	cfu/l	100	
Total coliforms	cfu/100ml	10	1000
Dissolved oxygen	mg/l	>1	>1
Turbidity	NTU	<10	<10
Turbidity if UV used	NTU	<1	<1
pH		5 – 9	5 – 9
Chlorine residual (if used)*	mg/l Cl_2	<2	<2
Bromine residual (if used)	mg/l Br_2	<2	<2

*<0.5mg/l Cl_2 for irrigation

BS8515:2009 (Appendix 2) provides guidance on filtration for rainwater systems but notes that *"readers might wish to note that some situations, e.g. where greater human exposure to the water is anticipated or where the water is to be used in public premises, could require higher water quality. In such cases, the system may incorporate treatment processes such as ultraviolet (UV) or chemical disinfection."* Once again a risk assessment is appropriate.

4.1 Storage Conditions

Storage time is of major importance: the longer the rain water is held in storage the greater will be the microbiological growth. Minimising storage time will minimise bacterial growth. Storage time means the actual time that the rain water remains in the storage system which may not be the same as the apparent time based on system volume. Short circuiting of tanks caused by, for example, the tank outlet being directly below the inlet connection, can have the effect of holding some of the water for a much longer period. Storage systems should be designed to ensure that there is no short circuiting of tanks and to prevent pipework dead legs.

Sunlight is a pre-requisite for algal growth, and excluding sunlight as far as is practicable will minimise algal growth and, hence, reduce the available nutrient substrate for bacterial growth.

Oxygen is necessary for the growth of aerobic bacteria but in its absence anaerobic bacteria will thrive living on the decaying aerobic bacteria cells. Providing some aeration for stored water will prevent anaerobic conditions from developing and thus help to reduce pathogen growth.

Temperature has a marked effect on bacterial growth rates, and minimising the storage temperature by careful location of storage tanks, preferably underground, will greatly reduce bacterial growth.

4.1 Treatment

BS8515:2009 recommends that filtration to <1.25mm (this would normally be referred to as "screening" rather than "filtration") before the collected rainwater enters storage. This may not remove light materials such as vegetable matter, insects and bird droppings and either a depth cartridge filter or deep bed granular media filter of the type used in swimming pools would be more appropriate if high quality is to be maintained.

Bacterial growth can be controlled by circulating stored water continuously through an ultraviolet irradiation unit. Provided that the water has good UV transmissivity, UV irradiation can achieve a 4-log reduction in bacteria counts. The recirculation itself creates turbulent flow conditions in pipework and this helps to minimise the formation of biofilms which are scoured from the surface by the flow.

4.2 Conclusion

A well engineered storage system should be capable of maintaining good microbiological quality in a rainwater harvesting system but the microbiological population will vary depending on where the rain water fell and how it was collected. Expert advice should be sought if there is any doubt as to the suitability of a system for a particular application.

Richard Hill BSc CEng FIChemE
Whitewater Ltd
Consulting Engineers& Scientists
86a Hazlemere Road
Penn
Bucks HP10 8AG, UK

Tel : +44 (0)1494 817373
Fax : +44 (0)1494 817373
Website: www.whitewaterlimited.com

AUTHOR

Richard Hill is a Chartered Chemical Engineer with forty years' experience in water treatment. After graduating from the University of Leeds in 1970 he joined the Water Research Centre and subsequently worked with a number of water and wastewater treatment plant contractors in R&D, commissioning, design, sales and training before setting up his own independent consultancy in 1988.

His involvement in water and wastewater management has covered a variety of industries including municipal water supply, power generation, pharmaceuticals, metal finishing, biotechnology, semiconductor manufacture, oil refining and food and drink.

He has acted as a Visiting Expert for the United Nations Industrial Development Organisation, is a Visiting Fellow at the Centre for Water Sciences at Cranfield University, and a Visiting Lecturer at UCL, at Brunel University and at UNESCO-IHE, Delft. He is a founder member of the Institution of Chemical Engineers' Water Subject Group and Past Chairman of the Institution of Chemical Engineers' Membership Committee.