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Design implications of the distribution of pollutants in collection and storage systems used in small rural water supplies

A.S. Petrie, A.G. Cram
Faculty of Health and the Environment, Leeds Metropolitan University, Calverley Street, Leeds, LS1 3HE, U.K.
stewart.petrie@virgin.net g.cram@lmu.ac.uk

Abstract

The quality of water entering, leaving and resident in collection and storage systems of rural springs used as potable supplies was monitored during different atmospheric conditions. Microbiological, chemical, physio-chemical and radiological analyses were carried out for a range of contaminants. The changes in the distribution of these contaminants over time was monitored and related to meteorological conditions and to physiochemical conditions within the collection and storage system. The distribution of contaminants in different collection systems was compared, and related to the differences in the physical dimensions and configurations of the collection systems, and to the quality and the spring flow of the influent water. Water quality improves markedly during dry or very cold periods when spring flow rate is reduced. An increase in the difference in temperature between the influent waters and the water in the system produces an increased stratification in contaminants and a decrease in the time taken to reach this state. Where water is influent to the top of the collection vessel, stratification is more pronounced than when it is influent to the base or centre of the vessel. Contamination by radon is reduced where the influent water is introduced to the top of the vessel and subject to aeration. The results are discussed in relation to the design of collection systems for potable water in remote rural areas where treatment is not routinely carried out, and to make more efficient the treatment systems where it is.

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1 Introduction

1.1 Background

The spread of disease has been connected with water quality since the mid-nineteenth century. The famous incident of the Broad Street Pump in 1854 was one of the first instances where epidemiological studies convincingly linked water with illness (Dadswell[1]). By removing the handle of the pump, Dr John Snow elegantly brought to an end a cholera outbreak which had caused over 500 deaths. Proof that treatment can affect the ability of water to spread disease was first shown in 1892. The contaminated River Elbe in Germany supplied two towns. Altonia escaped the cholera because its supply was filtered whereas the supply to the adjacent Hamburg was not (Dadswell[1]).

Throughout this century, water has continued to be associated with disease. In the United Kingdom cholera and typhoid have diminished as water treatment has improved and an ever increasing number of people have been connected to water supplies, with filtration and chlorination. A study of the major outbreaks of waterborne disease will show that the majority have been associated with unchlorinated or defectively chlorinated supplies. Only two outbreaks of cryptosporidiosis and one incident of chemical gastroenteritis did not fit into this category during the fifty years between 1937 and 1986 (Galbraith *et al*[2]).

Of the thirty-four outbreaks of waterborne disease recorded during that period, thirteen of the supplies were small rural supplies, i.e. not mains supplies. The toll of disease involved over 1,900 cases. If these figures are looked at in isolation and the number of people who have become ill are related to the numbers drinking water from small rural supplies and mains water an interesting picture develops. The danger of contracting a disease by drinking water from small rural supplies rather than public supplies, can be calculated, using United Kingdom Department of the Environment (DoE) figures, to lie in the area of twenty-two times more probable. If the figures from the last decade alone are compared the additional risk from small rural supplies goes up to over fifty times (Galbraith *et al*[2]). Furtado *et al*[3] reported that of 26 outbreaks of communicable disease in which there was evidence of waterborne transmission 19 outbreaks were attributable to drinking water. Of these 10 were chlorinated mains supplies and 9 were small rural supplies. It is interesting to note that, whereas *Cryptosporidium* was the causative agent in the chlorinated supplies, a range of pathogens was associated with the other incidents, including *Giardia*, *Campylobacter*, *Astrovirus* and small round structured virus (SRSV) as well as *Cryptosporidium*. Small rural water supplies are therefore intrinsically more dangerous than mains supplies. This may not be surprising considering the lack of treatment involved. Studies have shown that over 50% of all small rural water supplies are contaminated with faecal material. This figure rises to over 70% if spring supplies are looked at separately and even this number may be an under-estimation.

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Epidemiological studies in Canada have also shown that there is a non-trivial endemic level of unreported disease due to the consumption of tap water (Payment *et al.*[4]). This level of severity of disease results in few demands on the medical profession and thus does not figure in disease statistics. Payment's work involved studying the gastro-intestinal effects of drinking water and shows that levels of illness from water are much higher than is generally appreciated. He concluded that 35% of the gastro-intestinal illness found in his study were water related and preventable (Payment *et al*[4]). It is suggested that the endemic level of disease must be even higher amongst people using small rural supplies.

1.2 The Legislation in the European Union and the United Kingdom

The 1980 European Community "Directive on the Quality of Water Intended For Human Consumption" (80/778/EEC[5]) laid down a standard of drinking water quality applicable to all member states.

The World Health Organisation (WHO) sets down guidelines for water quality[6].

1.3 Collection systems

Collection systems within small rural water supplies are no more sophisticated today than they were last century. The literature is full of designs for large scale collection and treatment systems, typically for large urban or "mains" supplies, but the area of rural water collection remains largely undeveloped. References can be found for new materials out of which to construct these systems, but the design of a pipe entering one end of a collection vessel, and another leaving the other end remains essentially unchanged. Indeed it can be demonstrated that many of the techniques developed by the Victorian engineers for large country houses, such as the "Robert's rainwater separator", are largely lost to the modern consumer of rural water.

Modern methods of water purification (Don and Chisholm[7]) published in 1911 discusses at some length the benefits of different methods of water storage available, in addition to the various treatment methods in use at that time. The systems in use in the latter parts of the 19th century made provision for settlement, standing, and filtration, even in relatively small supplies. Such provision is rarely, if ever, made today.

More modern texts on the problems associated with small rural supplies are intended for use in developing countries and disaster relief situations. Perhaps the most comprehensive of these is Engineering in Emergencies (Davies and Lambert[8]), but even this concentrates more on treatment than the collection and storage as methods to make drinking water safer.

The fundamental principles for providing microbiologically safe drinking water are the exclusion of excremental contamination and the prevention of subsequent contamination of the treated water (Dadswell[1]). Source protection of small rural water supplies is generally poor. Treatment is often absent or inadequately maintained and storage can vary between the good and the atrocious. It can be demonstrated therefore that small rural supplies will often fail to meet these fundamental principles.

Risk assessment by individuals is weighted against hazards that they have direct control over. The public will consider a risk to be 1,000 times greater than it really is, if it is involuntary, such as the drinking of mains water (Morgan[9]). There may be an additional mental risk-reduction if expensive improvements are undertaken. It is contended that the majority of problems associated with small rural water supplies are caused by faecal contamination.

It is very easy for legislators in particular, and the public in general to assume that most waterborne diseases are a thing of the past. The vast majority of the population is provided with mains water of nearly uniform excellence. This blinds people to the problems of such water supplies.

2 Methodology

The spring supplies studied were chosen as supplies known to be contaminated and have been the subject of previous investigations (Petrie and Cram[10,11]). Other samples were taken from a spring supply in North Devon, known to be contaminated by Radon. Samples were taken from the supplies during episodes of known contamination, at the inlet (influent water), the outlet (effluent water) and different levels below the water surface. Further samples were taken with the influent water in different positions, at the top, the base and centre of the collection vessel.

2.1 Determination of microbiological Contaminants

2.1.1Faecal Coliforms Faecal coliforms are the most generally accepted indicator of faecal pollution. They are the primary microbiological standard laid down in water quality regulations. They are thought of as the simplest and most direct indicator of potentially pathogenic material transmitted via the faeco-oral route. The laboratory used for the analyses has carried out confirmatory tests on the samples and all the reported faecal coliforms in this study have been confirmed in accordance with guidance in Report 71, section 7.7.6.1 (HMSO[12]). The use of faecal coliforms has been subject to some criticism (Gleeson and Gray[13]). Therefore other organisms have been used as potential alternatives.

One of the problems with coliform indicators is that they are subject to comparatively rapid die off due to environmental stress. Therefore they are often considered less than adequate as a measure of remote or historic faecal contamination. The traditional organism for identifying this type of contamination is *Clostridium perfringens*, a spore forming bacteria of exclusively faecal origin. The spores can be considered as an approximation of the *cryptosporidium* oocyst.

2.1.2 *Faecal streptococci* *Faecal streptococci* were chosen as another potential indicator. They are more resistant to environmental stress than coliforms and generally persist longer in the environment, although not as long as *Clostridium perfringens.* Thus their presence will not so readily give rise to over reaction to past pollution events.

2.1.3 *Cryptosporidium* This is a small, usually 4 to 6 μm, protozoan parasite of the coccidia genus (Casemore[14]). It has a worldwide distribution and is found in a vast number of hosts including birds, fish and mammals. There are several species of the organism but the only one which appears to infect man is *Cryptosporidium parvum.* The organism causes an unpleasant, self-limiting, gastrointestinal illness which may last up to twenty-eight days, but is usually of seven to fourteen days duration. Patients will modally get seven or eight separate symptoms, the most common being diarrhoea (93%) and loss of appetite (84%) (Casemore[14]). Two thirds of the people in the UK contracting the illness (Cryptosporidiosis) are children. The organism is excreted from hosts in faeces in cyst form, known as an oocyst, and in particular, infected young animals are known to excrete up to 10^{10} oocysts a day (Carrington[15]). Once the cyst is ingested by a suitable host it releases four sporozoites into the small intestine which then begin the asexual stage of the life cycle and eventually initiate the symptoms of the disease. The infective dose is unknown but is below ten and some experts think it may be as low as one (Donnelly[16]). The organism was first discovered in the stomach lining of a mouse in 1907 and was considered to be of minor interest to human health. Consequently very little work was done on it until the first human outbreak of cryptosporidiosis in 1976. It was, in fact, only found to be infective to humans in 1971. It is now thought to be responsible for up to 500 million infections worldwide every year.

Determination of Cryptosporidium contamination was by flow cytometry.

2.1.4 *Giardia lamblia.* It should be noted that a second waterborne protozoan parasite which causes severe diarrhoeal disease is *Giardia lamblia.* This causes a food poisoning like disease called giardiasis which is associated with drinking raw water. Although not reported very often in the UK (there is only one reported outbreak from a small rural water supply - Constantine *et al*[17]), it is especially common in the US. A study in the UK by Gilmour *et al.*[18], found that 46% of raw potable water samples contained cysts, and that 33% of the positive samples included viable cysts. Many of the properties of *Giardia* are similar to *Cryptosporidium.* Many of the problems associated with *Cryptosporidium* will equally apply to *Giardia lamblia*

2.2 Determination of inorganic contamination

Standard laboratory procedures were used for the determination of iron, manganese, lead, aluminium, copper, nitrates, and phosphates.

2.3 Radon

A contaminant not dealt with by regulations which could result in more severe problems to small rural water supplies than to "mains" supplies is radon. Radon is an alpha emitting radioactive gas with a half-life of 3.82 days. It is highly soluble in water. Milvy and Cothern[18] calculate that 17 000 fatal cancers in the US occur over a 70 year period from exposure to radon originally present in drinking water.

Standard procedures were used for determining radon contamination.

3 Results

3.1 Estimation of microbiological contamination

Factors likely to effect the distribution of microbilogical contamination were monitored during the course of this study. The results replicate those of earlier studies (Petrie and Cram [10,11]). During dry weather systems remained free from contamination by faecal coliforms. Significant, but reduced levels of *Faecal streptococci* and *Clostridium perfringens*, were measured. These results were mirrored in the influent waters. Effluent waters contained some faecal contamination at the beginning of such dry spells, but the levels of contamination fell as the dry spells continued. The faecal coliform concentrations of stored and effluent waters slowly reduced to zero during protracted dry spells. The effect of moving the position of the influent water was clearly demonstrated. For all measured microbiological contaminants parameters the stratification of contaminants was more pronounced, and the zone of least contamination more clearly defined when influent waters were intoduced to the top of the collection vessel (Fig 1). There was little difference between influent waters being introduced at the base of the tank, or midway up the vessel. In both cases the resident waters were more homogeneous.

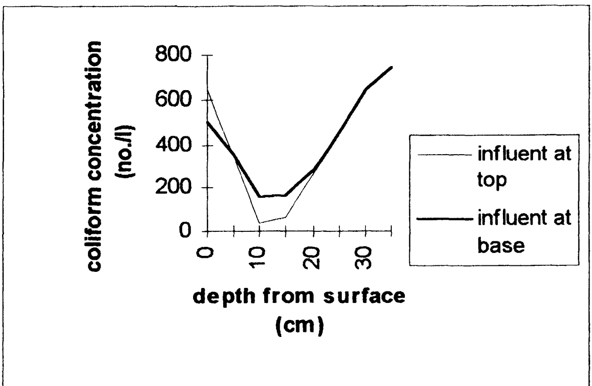

Figure 1. Vertical Distribution of faecal contamination.

3.2 Estimation of inorganic contamination

As in previous studies (Petrie and Cram[10,11]), it is demonstrated that at times of low stream flow stratification of contamination occurs. Stratification is more pronounced when influent water is introduced to the top of the collection vessel than at the base or misway. (Fig 2). This was true for all measured inorganic contaminants measured.

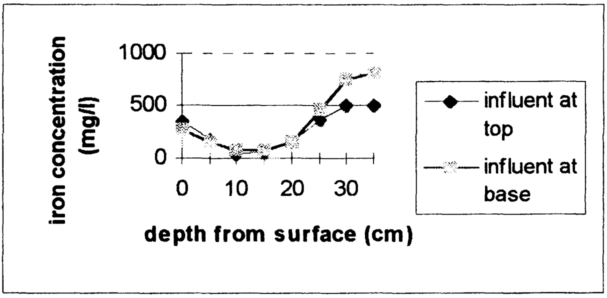

Figure 2. Vertical distribution of inorganic contamination. (Iron).

3.3 Estimation of radon contamination

A stratification of radon contamination is demonstrated during dry weather conditions with low stream flow. The most marked effect on contamination levels is brought about by introducing influent waters to the top of the collection vessel. (Fig 3).

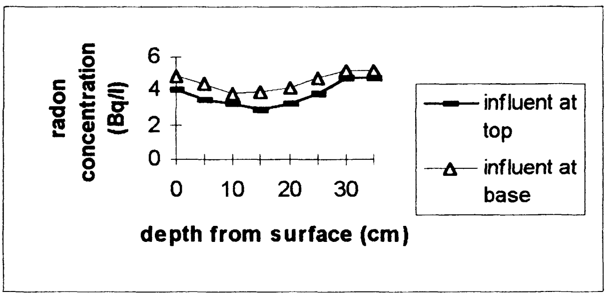

Figure 3. Vertical distribution of Radon.

This reduces overall contamination levels and also increases the zone of least contamination. There is little difference between contamination for influent waters introduced to the base or mid-point of the vessel. Unlike other contaminants a high stream flow produces a reduction in contamination by radon.

4 Discussion

Petrie and Cram[11] demonstrated that there was a pronounced increase in contamination during fast stream flow. This is usually associated with rainfall events. These results were confirmed with the exception of contamination by radon which was reduced under such circumstances. This is probably caused by increased aeration in the turbulent waters.

Petrie and Cram[12] further demonstrated a pronounced stratification of contaminants within the collection vessels of systems and that there was an identifiable region or zone of least contamination. This stratification has been confirmed for all contaminants measured, including radon.

Where influent waters are introduced at the top of the collection vessel the stratification is increased markedly in comparison to it being introduced elsewhere in the vessel. The introduction of influent water to the top of the vessel also reduces contamination by radon, through increased aeration.

These findings have implications for the design of collection and storage systems. Where possible only dry weather flow, i.e. waters with low spring flow, should be collected. Where this is not possible, waters with high spring flow should be diverted to a second vessel, allowed to settle, and then fed back through the primary vessel at low flow rates. (This scenario would most probably pertain in third world countries where water is scarce).

In all cases influent water should be introduced to the top of collection vessels. This has the effect of reducing radon contamination, if any, and increasing stratification of contaminants within the vessel. Effluent water should be taken from the zone of least contamination within the collection vessel.

The combined effect of the measures outlined above has shown reductions of microbiological contamination of some 80% and of inorganic contamination of between 50 and 80%. In terms of microbiological contamination, the design features have the effect of greatly reducing the contamination of the effluent water by cryptosporidium, an organism which is very difficult to remove in small supply treatment systems. In terms of inorganic contamination, in some cases the use of these design features was sufficient to allow water previously outside quality parameters to be brought within the regulations. In the developed countries the adoption of such design features would ensure a smoothing of contaminant load to treatment systems further downstream, rendering them more efficient. In the developing world such design systems would provide a purely mechanical primary filter system capable of reducing greatly the contamination of water, and so reducing the health risks to those consuming the water.

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