Assessment of Monitoring Requirements for Drinking Water
ASSESSMENT OF MONITORING REQUIREMENTS FOR DRINKING WATER

Final Report to the Department of the Environment

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EXECUTIVE SUMMARY

BACKGROUND


The Department of the Environment let a contract to WRc to examine the present Regulations in England and Wales, to advise on how well they implement the Directive with respect to monitoring and whether the discretionary parts give adequate consumer protection.

METHOD

A detailed comparison was made between parts IV and V of the Regulations and the requirements of the Directive, especially in relation to the point of sampling and sampling frequencies.

Results from statutory monitoring were obtained from nine selected water companies and were subjected to statistical analysis. In addition further information and views on monitoring were obtained from the companies by means of a questionnaire.

RESULTS

Comparison of the Regulations with the Directive

Detailed comparison of the Regulations with the Directive indicates that they meet the mandatory requirements of the Directive and in many respects are more comprehensive. The Directive states imprecisely that the water should be monitored 'at the point where it is made available to the user'. The Regulations require this to be at a tap unless a supply point has been authorised for specific parameters.

The Regulations introduced the concept of a maximum size of supply zone, whereas this is not limited in the Directive.

Statistical Evaluation of the Parameters

A concept of 'predictable' and 'unpredictable' parameters has been developed based on historical data. Of the 41 parameters for which adequate data exist, approximately half can be defined at present as 'predictable'.
Sampling Frequencies

The report examines the probability of detecting non-compliance at the frequencies used in the Regulations. The report shows, for example, that, assuming a true rate of compliance of 98%, the standard frequencies in the Regulations give a probability of detecting failure of 2% for the parameters in 'Table 4', and 90% for the much increased frequencies for microbiological parameters in 'Table 6', at the largest zone size. The probability increases as sampling frequency increases and compliance decreases.

The standard frequency for "Table 4" parameters is judged to be too low and it is recommended that the minimum sampling frequency should be increased to four per year.

The report presents a statistical approach for judging when reduced frequencies can be used for ‘predictable’ parameters, based on past results.

Relating the frequency of sampling to zone size is shown to be a valid approach for parameters which can change in distribution but that fixed number sampling is more appropriate for other parameters. Additionally it is shown that there is no statistical reason why the zone size limit should not be increased.

The present rule for increasing sampling frequency where failures occur is questioned in terms of cost-effective monitoring. More emphasis should be placed on other follow-up actions to be taken when exceedences occur.

Sampling Locations

In principle, fixed point sampling should be specified except for parameters which tend to give exceedences at particular locations in distribution. The scope for fixed point sampling should be explored further. However, there is some evidence that the number of parameters specified for random sampling in the Regulations could be increased.

There is considerable advantage in monitoring at authorised supply points for parameters whose concentrations do not change in distribution and there is a case for extending this approach to zones where supplies are blended.

Sampling Times

Data supplied by water companies did not allow an examination of parameter behaviour out of normal working hours. However, seasonality should be covered by advice in the Guidance Document.

PRACTICAL IMPLICATIONS

Overall the monitoring requirements in the Regulations implement the content and spirit of the Directive and compare well with regimes known to exist in other Member States. There are some areas, however, which could benefit from re-appraisal.

- Given adequate historical data, parameters can be classed as ‘predictable’ or ‘unpredictable’. This distinction, together with a knowledge of whether
concentrations change in distribution, could assist in the development of monitoring strategy.

- Some of the frequencies in the current Regulations may need to be reviewed. The present rule for increasing sampling when exceedences occur should also be reviewed.

- Monitoring effort could also be released by greater use of authorised supply points for parameters whose concentrations do not change in distribution.

- Statistical support is given in the report for reduced frequency of sampling provided adequate historical data exist for 'predictable' parameters.

- Fixed point sampling should be allowed for all parameters except those which tend to exceed the PCV at particular locations in distribution.

- Sampling frequencies proportional to zone sizes are appropriate for those parameters which exceed the PCV in distribution rather than at source or as a result of problems in treatment.

- There is no statistical case for limiting zone size.
1. INTRODUCTION

1.1 Background


The Department of the Environment placed a contract (PEC 7/7/429) with WRc to examine how well the current Regulations implement the content and spirit of the Directive and to explore whether the discretionary aspects of the monitoring regime included in the Regulations provide the most effective protection to the consumer, taking into account technical and financial factors.

The project was undertaken by making a detailed comparison between parts IV and V of the Regulations and the requirements of the Directive, especially in relation to the point of sampling and sampling frequencies. The Department nominated ten water companies to participate in the project by supplying monitoring data and information and opinions on sampling regimes. Results from statutory monitoring were obtained from nine of the selected water companies, transferred to a computer database and subjected to statistical analysis. In addition, further information and views on monitoring were obtained from the companies by means of questionnaire.

1.2 Guide to the Report

The implementation of the Directive by the Regulations is considered in Section 3.

The Regulations lay down provisions which should safeguard the quality of public water supplies. Sampling rules therefore should provide a probability of detecting failure to comply with the Regulations that (i) is high enough to give water undertakers the incentive to treat and supply water to a high standard, and (ii) is consistent between parameters and between zones. Sampling frequency should also, of course, be sufficient to enable consumers to have confidence in the quality of their supply.

Sections 5 to 7 examine the implications of this approach in terms of the likelihood of detecting PCV exceedences, given the sampling frequencies and zone size bands defined by the Regulations. As a necessary introduction to these sections, the concept of 'predictable' and 'unpredictable' parameters is introduced in Section 4.
These sections are based on two elements:

- data provided by nine water companies, which is summarised in Appendices A and B, and
- statistical theory, which is described in Appendices C to G.

The detailed application of the conclusions from Sections 5 to 7 is discussed in Section 8, taking account of comments from the ten water companies. These comments were obtained:

- at the beginning of the project during structured interviews with water company staff, and
- towards the end, when their comments on provisional recommendations were sought.

The questionnaire used during the first interviews is reproduced as Appendix H. A number of other issues that arose from discussions with the water companies are also considered in Section 8.

Finally the main conclusions and recommendations are given in Section 9.
2. OBJECTIVES

The objectives of the project written into the contract were:

(a) To assess how well the monitoring requirements of the Regulations meet the requirements of the Directive.

(b) To assess the suitability of the frequencies for determining compliance with Prescribed Concentrations and Values (PCVs) taking into account the degree of confidence possible in the information obtained using those frequencies and, where appropriate, to recommend changes to the regulatory frequencies.

(c) To assess the relative merits of fixed and random sampling points and, if appropriate, recommend changes to the Regulations in respect of the way sampling locations are selected.

(d) To assess the implications of water companies’ sampling practices regarding the spread of sampling times, both within the day and within the year and, where appropriate, make recommendations for changes in the temporal spread of sampling.

(e) To assess any difficulties water companies may report in meeting the present sampling and monitoring requirements, and invite comments on the likely implications of any measures proposed as a result of this review.

(f) To consider the cost effectiveness of the existing monitoring requirements and report upon the implications of any changes that are proposed.
3. IMPLEMENTATION OF THE DIRECTIVE BY THE REGULATIONS

3.1 Introduction

The Directive is implemented in England and Wales by the Regulations. Guidance on the application of the Regulations is provided in "Guidance on safeguarding the quality of public water supplies" (HMSO 1989c) ("the Guidance Document").

The requirements of the Directive and the Regulations may be considered under four headings:

1. Where to take samples?
2. Which parameters to measure?
3. What limits apply to these parameters?
4. How often to sample?

3.2 Location of sampling points

The Directive simply states that "All water intended for human consumption shall be monitored at the point where it is made available to the user" (Article 12.2), and that the points of sampling shall be determined by the competent national authorities (Article 12.3).

The Regulations define a "sampling point" as being a consumer's tap (regulation 2). Regulation 11 requires all samples to be randomly selected for Cu, Pb and Zn, and at least 50% to be randomly selected for total and faecal coliforms, colony counts and residual chlorine. Sampling at service reservoirs (regulation 17) and treatment works (regulation 18) is required in addition to sampling points, and this could be considered to go beyond the Directive's formal requirements.

Regulation 20 requires analysis of sources that are new, or have not been used for six months or more and, in this respect too, the Regulations may go beyond the strict requirements of the Directive.

Under regulation 12, supply points may be authorised, at which specified parameters may be sampled. "only if he [the Secretary of State] is satisfied that the analysis of samples taken from a point other than a sampling point will produce data which are unlikely to differ in any significant respect from the data that would be produced .... from sampling points".

The Directive sets no limit on the size of a supply area and includes frequencies for supplies up to five million population. However, the Regulations set a limit of 50 000
people resident: this restriction should ensure that samples were taken from all parts of large, complex distribution systems.

3.3 Parameters and limits

The Directive requires "values to be fixed" in National legislation for the parameters shown in its Annex I, except those for which no value is stated there (Article 7). These values must be less than or the same as those in the "maximum admissible concentration" column.

Monitoring is required to conform to Annex II of the Directive, which defines which parameters are to be monitored, and at what frequencies. Annex II specifically requires relatively frequent monitoring of:

(a) taste and odour (qualitative);
(b) conductivity or other physico-chemical parameter, residual chlorine (or other disinfectant);
(c) faecal coliforms plus total coliforms or total counts at 22 °C and 37 °C;

and less frequently for:

(a) taste and odour (quantitative), turbidity;
(b) temperature, pH;
(c) nitrates, nitrites, ammonia;
(d) total counts at 22 °C and 37 °C.

Other parameters, to be monitored "periodically", are to be determined by the competent national authority, "taking account of all factors which might affect the quality of water....". There appears therefore to be some discretion allowed over whether monitoring is required for all the parameters listed in Annex I. However, Article 7.6 might be interpreted as removing this scope for discretion: "Member states shall take the steps necessary to ensure that water intended for human consumption at least meets the requirements specified in Annex I".

The Regulations closely follow the Directive, in listing all the parameters from Annex I as Tables A to E, and setting concentration limits corresponding to those in the Directive. Furthermore, four parameters are added with values based on the World Health Organization’s 1984 guidelines for drinking water quality (WHO 1984).

However, the parameters for which sampling frequencies are defined (in Tables 1 to 7) omit six from the Annex I list, none of them mentioned by name in Annex II. The Guidance Document confirms that routine measurement is not required but gives circumstances in which some of them might be measured. The reasons for not monitoring routinely are given below.
(a) Kjeldahl nitrogen (C23). In drinking water this parameter would be expected to be near or below the limit of detection, using the method described in the Directive. This parameter is not considered relevant to drinking water quality in normal circumstances.

(b) Substances extractable in chloroform (C27). This is an outdated method, giving little information relevant to the quality of drinking water.

(c) Dissolved or emulsified hydrocarbons (C28). This parameter is not well defined in the Directive, and the suggested analytical method does not enable measurements to be made at the level required. Measurement of individual hydrocarbons of potential concern for human health may be a sensible option when hydrocarbons are thought to be present.

(d) Phenols (C29). The parameter defined is not meaningful, and the method of measurement suggested in the Directive cannot detect phenols at the MAC level. Individual phenols could be measured when their presence is suspected.

(e) Faecal streptococci (E59). This is regarded by some as an additional indicator to faecal and total coliforms; others regard it as essentially a parameter of operational value only. Routine measurement is not therefore justified but examination may be instituted when 'presumptive' coliforms are detected.

(f) Sulphite reducing clostridia (E60). This is very useful for operational control but not a prime measure of drinking water quality. However, examination may be made for this organism where 'presumptive' coliforms are detected.

3.4 Sampling frequency

The Regulations follow Annex II of the Directive for specified parameters, with some minor upward adjustments of the numbers. The increased frequency of sampling that is required by regulation 13(8) after a parameter exceeds its PCV (MAC) is not required by the Directive. The allowances for reduced monitoring in the Regulations conform with the requirements of the Directive, both in terms of the frequencies and the exclusion of microbiological parameters for tap samples.

The Guidance Document requires "at risk" zones for lead to be identified from at least 20 and preferably more than 50 samples. The PCV for lead is 50 μg l\(^{-1}\) in the first litre of water from the consumer's tap, while the Directive MAC is 50 μg l\(^{-1}\) after flushing. In both these respects the Regulations are more demanding than the Directive,
4. STATISTICAL BEHAVIOUR OF PARAMETERS

4.1 Patterns of variability with time and position

The total variability shown by a parameter is a combination of:

(i) systematic temporal variations
    - seasonality, for example, or long-term trend;

(ii) systematic spatial variations
    - due to distance from supply point, for example, or presence/absence of lead
      plumbing; and

(iii) random short-term sampling variations and analytical error.

The description 'predictable' is used in this report to denote a parameter for which the
variations over time and space are either slight, or regular and well understood. The
random component of variation should be adequately represented by a probability
distribution such as the Normal or the logNormal. For a 'predictable' parameter, a
historical sequence of values all grouped within a particular concentration range will give
added assurance that such values are likely to continue into the future.

An 'unpredictable' parameter, in contrast, is one which is subject to occasional
unpredictable bursts or spikes of extreme behaviour. These may arise in any of the three
components listed above. For such parameters, a very good historical level of observed
compliance offers no assurance that this will continue in the future.

The pattern of PCV exceedences of both predictable and unpredictable parameters may
take different forms, as illustrated in Figures 4.1a to 4.1d. In all these figures, the origin is
at the top left hand corner, the horizontal axis represents time, and the vertical
(downwards) axis represents location, from source through treatment and into
distribution. The shaded areas represent times and locations where there is a significant
risk of a PCV exceedence.

Figure 4.1(a) Occasional problems at the source(s) or in treatment pass through into the
distribution system. For example, high pesticide concentrations may
occur at particular times of year, or a bacteriological failure in treated
water ex-works may occur occasionally.

Figure 4.1(b) There may be chronic problems with the source water quality, and
treatment (or blending) not yet adequate to overcome them. A possible
effect is high nitrate concentrations.

Figure 4.1(c) Continuous or intermittent problems may occur at particular locations,
caused perhaps by lead plumbing or the presence of particulate metals in
certain mains.
Figure 4.1a  Times and locations at risk of poor quality - intermittent problems at source or at treatment works

Figure 4.1b  Times and locations at risk of poor quality - chronic problems at source or at treatment works

Figure 4.1c  Times and locations at risk of poor quality - at a small number of consumer properties

Figure 4.1d  Times and locations at risk of poor quality - isolated events
Figure 4.1(d) Isolated exceedences occur, apparently limited to a particular sampling occasion. They may be caused by sample contamination or analytical error.

The production of diagrams like these for specific situations would require information for all times and positions. In practice, of course, samples are taken at comparatively few times and positions, and the conclusions that are reached will depend, not just on the measured concentrations, but also on a wider understanding of the behaviour of the parameters in question.

4.2 Classification of Parameters

Table 4.1 shows a classification of parameters into ‘predictable’ and ‘unpredictable’. This is based on evidence from the data (summarised in Appendix B), and is confirmed by practical experience. There are insufficient data to confirm predictability for all parameters included in “Table 4” of the Regulations except total hardness and alkalinity.

Table 4.1  Predictability of parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Regulation table</th>
<th>WRc code</th>
<th>Units¹</th>
<th>PCV²</th>
<th>Predictable?³</th>
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<tbody>
<tr>
<td>Conductivity</td>
<td>1</td>
<td>101</td>
<td>μS/cm</td>
<td>1500</td>
<td>Y</td>
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<tr>
<td>Odour¹</td>
<td>1</td>
<td>102</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste⁴</td>
<td>1</td>
<td>103</td>
<td></td>
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<td></td>
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<tr>
<td>Odour</td>
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<td>201</td>
<td>Dilution number</td>
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<tr>
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<td>202</td>
<td>Dilution number</td>
<td>3</td>
<td>N</td>
</tr>
<tr>
<td>Turbidity</td>
<td>2</td>
<td>203</td>
<td>Formazin units</td>
<td>4</td>
<td>N</td>
</tr>
<tr>
<td>Temperature</td>
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<td>204</td>
<td>°C</td>
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<td>Y</td>
</tr>
<tr>
<td>pH</td>
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<td>205</td>
<td>pH value</td>
<td>9.5 max.</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.5 min.</td>
<td></td>
</tr>
<tr>
<td>Nitrate</td>
<td>2</td>
<td>206</td>
<td>mg NO₃ I⁻¹</td>
<td>50</td>
<td>Y</td>
</tr>
<tr>
<td>Nitrite</td>
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<td>mg NO₂ I⁻¹</td>
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<td>Ammonium</td>
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<td>mg NH₄ I⁻¹</td>
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<tr>
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<tr>
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<td>mg l⁻¹ Pt/Co scale⁵</td>
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<td>Trivalent methanes⁶</td>
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<td>305</td>
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<td>Tetrachloromethane</td>
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<td>Tetrachloroethene</td>
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<td>µg l⁻¹</td>
<td>10</td>
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<tr>
<td>Cu</td>
<td>3</td>
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<td>µg Cu I⁻¹</td>
<td>3000</td>
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</tr>
<tr>
<td>Pb</td>
<td>3</td>
<td>310</td>
<td>µg Pb I⁻¹</td>
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Table 4.1 continued/2

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<thead>
<tr>
<th>Parameter</th>
<th>Regulation table</th>
<th>WRc code</th>
<th>Units$^1$</th>
<th>PCV$^2$</th>
<th>Predictable?$^3$</th>
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<tbody>
<tr>
<td>Zn</td>
<td>3</td>
<td>311</td>
<td>µg Zn l$^{-1}$</td>
<td>5000</td>
<td>N</td>
</tr>
<tr>
<td>Pesticides</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(a) individual</td>
<td>3</td>
<td>312</td>
<td>µg l$^{-1}$</td>
<td>0.1</td>
<td>N</td>
</tr>
<tr>
<td>(b) total</td>
<td>3</td>
<td>316</td>
<td>mg l$^{-1}$</td>
<td>0.5</td>
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</tr>
<tr>
<td>Benzo 3,4 pyrene</td>
<td>3</td>
<td>319</td>
<td>µg l$^{-1}$</td>
<td>10</td>
<td>N</td>
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<tr>
<td>PAHs (total)$^4$</td>
<td>3</td>
<td>401</td>
<td>mg Cl l$^{-1}$</td>
<td>400</td>
<td>Y</td>
</tr>
<tr>
<td>Chloride</td>
<td>4</td>
<td>402</td>
<td>mg SO$_4$ l$^{-1}$</td>
<td>250</td>
<td>Y</td>
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<tr>
<td>Sulphate</td>
<td>4</td>
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<td>mg Ca l$^{-1}$</td>
<td>250</td>
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<td>Mg</td>
<td>4</td>
<td>405</td>
<td>mg Na l$^{-1}$</td>
<td>150</td>
<td>Y</td>
</tr>
<tr>
<td>Na</td>
<td>4</td>
<td>406</td>
<td>mg K l$^{-1}$</td>
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<td>Y</td>
</tr>
<tr>
<td>Dry residues</td>
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<td>407</td>
<td>mg l$^{-1}$</td>
<td>1500</td>
<td>Y</td>
</tr>
<tr>
<td>Oxidisability</td>
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<td>408</td>
<td>mg O$_2$ l$^{-1}$</td>
<td>5</td>
<td>&lt;</td>
</tr>
<tr>
<td>TOC</td>
<td>4</td>
<td>409</td>
<td>mg Cl l$^{-1}$</td>
<td>5</td>
<td>&lt;</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>410</td>
<td>µg B l$^{-1}$</td>
<td>2000</td>
<td>&lt;</td>
</tr>
<tr>
<td>Surfactants</td>
<td>4</td>
<td>411</td>
<td>µg l$^{-1}$</td>
<td>200</td>
<td>&lt;</td>
</tr>
<tr>
<td>P</td>
<td>4</td>
<td>412</td>
<td>µg P l$^{-1}$</td>
<td>2200</td>
<td>Y</td>
</tr>
<tr>
<td>Fluoride</td>
<td>4</td>
<td>413</td>
<td>µg F l$^{-1}$</td>
<td>1500</td>
<td>Y</td>
</tr>
<tr>
<td>Ba</td>
<td>4</td>
<td>414</td>
<td>µg Ba l$^{-1}$</td>
<td>1000</td>
<td>&lt;</td>
</tr>
<tr>
<td>Ag</td>
<td>4</td>
<td>415</td>
<td>µg Ag l$^{-1}$</td>
<td>10</td>
<td>&lt;</td>
</tr>
<tr>
<td>As</td>
<td>4</td>
<td>416</td>
<td>µg As l$^{-1}$</td>
<td>50</td>
<td>&lt;</td>
</tr>
<tr>
<td>Cd</td>
<td>4</td>
<td>417</td>
<td>µg Cu l$^{-1}$</td>
<td>5</td>
<td>&lt;</td>
</tr>
<tr>
<td>Cyanide</td>
<td>4</td>
<td>418</td>
<td>µg CN l$^{-1}$</td>
<td>50</td>
<td>&lt;</td>
</tr>
<tr>
<td>Cr</td>
<td>4</td>
<td>419</td>
<td>µg Cr l$^{-1}$</td>
<td>50</td>
<td>&lt;</td>
</tr>
<tr>
<td>Hg</td>
<td>4</td>
<td>420</td>
<td>µg Hg l$^{-1}$</td>
<td>1</td>
<td>&lt;</td>
</tr>
<tr>
<td>Ni</td>
<td>4</td>
<td>421</td>
<td>µg Ni l$^{-1}$</td>
<td>50</td>
<td>&lt;</td>
</tr>
<tr>
<td>Sb</td>
<td>4</td>
<td>422</td>
<td>µg Sb l$^{-1}$</td>
<td>10</td>
<td>&lt;</td>
</tr>
<tr>
<td>Se</td>
<td>4</td>
<td>423</td>
<td>µg Se l$^{-1}$</td>
<td>10</td>
<td>&lt;</td>
</tr>
<tr>
<td>Hardness</td>
<td>4</td>
<td>424</td>
<td>mg Ca l$^{-1}$</td>
<td>60 min.</td>
<td>Y</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>4</td>
<td>425</td>
<td>mg HCO$_3$ l$^{-1}$</td>
<td>30 min.</td>
<td>Y</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>6</td>
<td>601</td>
<td>number/100 ml</td>
<td>0</td>
<td>N</td>
</tr>
<tr>
<td>Faecal coliforms</td>
<td>6</td>
<td>602</td>
<td>number/100 ml</td>
<td>0</td>
<td>N</td>
</tr>
<tr>
<td>Residual disinfectant</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- free chlorine</td>
<td>6</td>
<td>603</td>
<td>mg Cl$_2$ l$^{-1}$</td>
<td>-</td>
<td>N</td>
</tr>
<tr>
<td>- total chlorine</td>
<td>6</td>
<td>604</td>
<td>mg Cl$_2$ l$^{-1}$</td>
<td>-</td>
<td>N</td>
</tr>
<tr>
<td>Colony counts</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 1 day</td>
<td>6</td>
<td>605</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 2 day</td>
<td>6</td>
<td>606</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 3 day</td>
<td>6</td>
<td>607</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Notes to Table 4.1

1. mg = milligrams, μg = micrograms, ng = nanograms.

2. PCV = prescribed concentration or value.

3. Y = yes, N = no, < = no evidence of unpredictability, but too few data to confirm predictability. The basis of a "yes" is that the standard deviation is less than 50% of the mean in over 90% of the sets of data examined, with a minimum of 20 cases.

4. Qualitative

5. This unit is the same as "Hazen".

6. Trihalomethanes is the sum of:

   trichloromethane, 301
   dichlorobromomethane, 302
   dibromochloromethane, 303
   tribromomethane. 304

   The limit applies to a 3 month rolling average.

7. Total PAHs is the sum of:

   fluoranthene, 313
   benzo 3,4 fluoranthene, 314
   benzo 11,12 fluoranthene, 315
   benzo 3,4 pyrene, 316
   benzo 1,12 perylene, 317
   indeno (1,2,3-cd) pyrene. 318
5. SAMPLING FREQUENCIES

5.1 Terminology

In order to select sampling frequencies on anything other than arbitrary or pragmatic grounds, it is necessary to have a way of quantifying the degree of information conveyed by any given monitoring programme. This in turn demands clear and unambiguous definitions of the various concepts involved in measuring that information. In this section, accordingly, the following key terms are defined and briefly discussed:

- observed compliance;
- true compliance;
- failed tap-years; and
- probability of detection.

The discussion applies generally to any particular parameter of interest.

5.1.1 Observed and True compliance

Suppose that 100 samples were taken from a supply point at random occasions over a 12-month period, and that 97 of those samples met the PCV (for some particular parameter). The ‘observed compliance’ with that PCV would therefore be 97/100, or 97%.

Suppose now that an automatic sampler were used to take 10 000 samples over that 12-month period, out of which 9 721 samples met the PCV. This would give a much more precise measure of the underlying rate of compliance, namely 97.21%. And generally, as the number of samples becomes indefinitely large the observed compliance figure will tend to the ‘true compliance’. In practice, of course, the true compliance can never be known. However, this is the measure that truly describes the quality of the water being supplied to the consumers in that supply area. This, therefore, is the measure that all monitoring programmes must primarily be attempting to illuminate.

5.1.2 Non-compliance and failed tap-years

In the above example, the estimated non-compliance value of 3% has a straightforward interpretation: it is the proportion of time that water from the supply point is failing to meet the given PCV.

Suppose, however, that the 100 samples had instead been taken at the same moment in time at 100 randomly chosen properties in the supply zone. The estimated 3% non-compliance figure would now have a quite different interpretation: it would indicate that the water from about 3% of the taps in the zone was (at that moment) failing the PCV.
In practice, much of the regulatory monitoring programme in a zone involves samples that are spread both through time and spatially. It follows that the estimated rate of non-compliance in any one instance may be the consequence of both temporal and spatial failures. Thus:

- at one extreme, a 3% non-compliance figure may arise because all consumers receive non-compliant water for 3% of the time, as depicted earlier in Figure 4.1(a);

- at the other extreme, it may arise because 3% of taps permanently supply non-compliant water (see Figure 4.1(b)); whilst

- in other situations the non-compliance will arise through a combination of both effects, as depicted by the shaded area in Figures 4.1(c) and 4.1(d).

In all these cases the extent of the non-compliance is shown by the size of the shaded area in the figure. Thus, as each figure has the dimensions ‘taps’ (down) by ‘years’ (across) the non-compliance can always be expressed quantitatively as the number (or proportion) of ‘failed tap-years’.\(^1\)

### 5.1.3 Probability of detection

Where the true % compliance for the water in a zone or at a supply point is less than 100% (in respect of a particular parameter), there will be some chance that the monitoring programme obtains at least one PCV failure and so correctly identifies the non-compliance. This chance is termed the ‘probability of detection’, and is the primary yardstick for judging the statistical effectiveness of any given sampling programme. To this end, the methodology presented in Appendices C and D provides quantitative links between:

- the number of random samples to be taken;

- the true % compliance in the population of water being sampled; and

- the resulting probability of detection.

### 5.2 Effectiveness of the current regulatory frequencies

Monitoring should ensure a probability of detecting failure that is (i) high enough to give water undertakers the incentive to supply good quality water, and (ii) consistent between parameters and zones. This requirement is made more specific in this section, using the example of a zone with a population between 20 000 and 35 000. The true compliance is

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\(^1\) The phrase ‘failed consumer-years’ was also considered as a general term for quantifying the extent of non-compliance. However, the more impersonal ‘failed tap-years’ was felt more suitable. For this reason, in subsequent discussions involving zone size, ‘number of consumers’ and ‘number of taps’ will be regarded as interchangeable quantities for the purpose of illustration.
taken to be 98%, and the desired probability of detecting non-compliance at least 10% per year. The formula on which the following table is based is given in Appendix C.

**Table 5.1 Effectiveness of current regulatory frequencies**  
*True non-compliance 2%, source Table C.1*

<table>
<thead>
<tr>
<th>Table in the Regulations</th>
<th>Frequency (Samples/yr)</th>
<th>Probability of detecting failure within 1 year %</th>
<th>Time to 50% probability of detection (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>57</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>10 (Standard)</td>
<td>18</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>36 (Increased)</td>
<td>52</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>4 (Standard)</td>
<td>8</td>
<td>8.5</td>
</tr>
<tr>
<td></td>
<td>12 (Increased)</td>
<td>22</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>1 (Standard)</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>12 (Increased)</td>
<td>22</td>
<td>2.8</td>
</tr>
<tr>
<td>6</td>
<td>60</td>
<td>70</td>
<td>0.5</td>
</tr>
</tbody>
</table>

It is clear from Table 5.1 that the probability of detection is low for "Table 3" and "Table 4" parameters at the standard sampling frequency.

5.3 **A reduced frequency for predictable parameters at low concentrations**

A sampling frequency of two per year can, however, be justified in situations where the parameters are predictable and their concentrations are well below the PCV (Appendix D). The phrase ‘well below the PCV’ can be quantified from Appendix D as:

Equation 1: \[ \text{Mean} + R \times \text{Standard deviation} < \text{PCV} \]

where the value of R is between 3 and 5 depending on the desired degree of confidence and the number of samples available. A value of 4 can be justified if there are 2 measured values (Table D.6).

From data provided by the water companies, it appears that typically the standard deviation is one third of the mean for several "Table 4" parameters, with an upper limit just over 0.4. Table 5.2 shows the result of substituting different ratios into the above formula.
Table 5.2  Rejection limits for mean values of predictable parameters

<table>
<thead>
<tr>
<th>St.Dev./Mean</th>
<th>Rejection limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.56 × PCV</td>
</tr>
<tr>
<td>0.3</td>
<td>0.45 × PCV</td>
</tr>
<tr>
<td>0.4</td>
<td>0.38 × PCV</td>
</tr>
<tr>
<td>0.5</td>
<td>0.33 × PCV</td>
</tr>
</tbody>
</table>

In order to justify a reduced frequency, it would be necessary to show from past data that equation 1 is satisfied. At the same time, the ratio of the standard deviation to the mean would be calculated. The reduced sampling frequency of 2 would operate as long as:

- the mean each year was less than the rejection limit; and
- the difference between the two measurements was less than 3 standard deviations (Appendix D.7), the standard deviation being estimated from data up to, but not including, the year in question.

5.4 Sampling frequency and zone size

5.4.1 Tables 1 and 6 of the Regulations

For parameters in Tables 1 and 6 of the Regulations, the standard frequency is proportional to the zone size for populations of 5000 and above (pro-rata sampling). It is shown in Appendix E that the effect of this is to give an equal probability of detecting failures amounting to the same number of 'tap-years' but higher protection of individuals in larger zones. This is illustrated in Figures 5.1 and 5.5.

For zones in the smallest category (population up to 500) the probability of detecting a failure of the same number of tap-years is higher. However, the risk that any one consumer might suffer an undetected PCV failure is also high (Appendix E). This is illustrated in Figures 5.6 and 5.7.

This is potentially significant if water entering the distribution system fails a PCV intermittently, as the lower standard sampling frequencies in small zones mean a lower probability of detecting failure. However, the bacteriological parameters ("Table 6") are sampled at least weekly at treatment works and service reservoirs, as well as in the distribution system, thus providing additional protection to the consumer for non-chemical parameters.
Figure 5.2  Probability of detecting a PCV exceedence - Table 2 Parameters

Key
■ 2% true non-compliance
□ 250 tap-years true non-compliance
Figure 5.3 Probability of detecting a PCV exceedence - Table 3 Parameters
Figure 5.4  Probability of detecting a PCV exceedence - Table 4 Parameters
Figure 5.5  Probability of detecting a PCV exceedence - Table 6 Parameters
Figure 5.6  True non-compliance that would be found with 10/50/90% confidence - Table 1 Parameters
Figure 5.7  True non-compliance that would be found with 10/50/90% confidence - Table 6 Parameters
5.4.2 Tables 3 and 4 of the Regulations

For Tables 3 and 4, the standard frequency is independent of the zone size (fixed number sampling), so that there is always the same rather low probability of detection of a given % non-compliance irrespective of zone population (Figures 5.3 and 5.4).

The probability of detecting a failure of a given number of tap years is smaller in larger zones. Stated another way, extensive failures in distribution may go undetected in large zones (Figures 5.8 and 5.9).

5.4.3 Table 2 of the Regulations

This represents an intermediate case (Figure 5.2).

To summarise, pro-rata sampling is appropriate for parameters that can fail in the distribution system (Figure 4.1c), while fixed number sampling is appropriate for parameters that do not change in distribution, and whose failures would be caused by source and/or treatment problems (Figure 4.1a).

5.5 The effectiveness of increased sampling

The Regulations provide for increased sampling frequencies following a PCV failure, and in certain other circumstances. The effectiveness of this provision is considered from a statistical viewpoint in Appendix F.

From the data made available to WRc, it appeared that increased frequencies usually provided little extra information and sometimes consumed significant extra resources. This is confirmed by Appendix F, which shows that:

- if the standard frequency is high enough to give a reasonable probability of detecting a failure, the increased frequency is unnecessary; whereas

- if the standard frequency is low, so that the probability of detecting a failure is low, the increased frequency rule is unlikely to be applied in any case.

Clearly any PCV failure should be (and is) investigated by the water supplier. The form of an investigation will vary, and the water supplier is probably in the best position to decide what action, if any, is appropriate.
Figure 5.8  Tap-years true non-compliance that would be found with 10/50/90% confidence - Table 3 Parameters
Figure 5.9 Tap-years true non-compliance that would be found with 10/50/90% confidence - Table 4 Parameters
6. SAMPLING LOCATIONS

6.1 Random and fixed sampling points

Several problems are associated with sampling from random taps:

- the occupants of houses may not be present;
- concern on the part of occupants about admitting water company samplers to their homes, even with official passes;
- concern over the safety of water company staff in certain areas; and
- the difficulty of obtaining an uncontaminated sample, particularly where mixer taps or taps with plastic inserts are common.

Some of the companies surveyed recognise the problems, but believe that they can be overcome. One of these requires its samplers to leave a letter explaining why it is necessary to take samples of water, and inviting the householder to contact the company’s Quality Manager, and to comment on the quality of their water supply.

Others would like to be permitted to use only fixed taps that they had installed themselves. This point is discussed later (in Section 8.2.1). It is however clear that fixed taps should be permitted unless there are good reasons for requiring randomness.

Parameters for which failures tend to occur at generally unknown locations in the distribution system should be sampled randomly. Examination of available data, including "Schedule 4" summaries, suggests that such parameters include coliforms, copper, lead, zinc and also iron, aluminium, manganese and PAHs. Sampling only at fixed taps would run the risk of perpetually missing locations prone to failure.

The Regulations require all sampling points for copper, lead and zinc, and 50% of the sampling points for bacteriological parameters to be chosen randomly. This requirement is certainly appropriate. Consideration should be given to requiring random sampling points for iron, aluminium, manganese and PAHs.

6.2 Supply points versus samples from the distribution system

The Regulations permit the authorisation of supply points for a large number of parameters. However, authorisations appear to have been made only for pesticides. Three topics are discussed in this section:

- the potential benefits of taking samples from supply points;
- parameters for which the authorisation should be permitted; and
- whether supply points should be authorised for zones where blending of different waters occurs.
6.2.1 Benefits of supply points

Clearly, supply points should only be authorised for parameters for which there is evidence of no concentration change (except from mixing) as water passes through the distribution system. Where this is the case, more cost-effective sampling can be achieved from supply points.

6.2.2 Which parameters?

Limited data were available to WRc to compare the concentrations of parameters in water entering, and within, a distribution system. This was because, with the exception of microbiological parameters, regulatory sampling has generally been done either in the distribution system, or at a supply point, but not at both. However, Water company H has measured the concentrations of many parameters in water leaving its treatment works, and provided data for six of its zones. These data indicate that many parameters do not change their concentration significantly.

WRc obtained few data on this subject for pesticides. However, water company I indicated that measured concentrations in raw water were similar to those in the distribution systems receiving this water.

6.2.3 Authorised supply points for zones with blending

The Guidance Document (Para. 12(2)) does not permit authorisation of a supply point for a zone in which blending of waters takes place "unless the water undertaker can demonstrate... that the different waters contain similar and relatively constant concentrations of the respective parameters".

An argument for permitting authorisation of supply points where blending takes place, whatever the concentrations, can be made as follows:

- Supply points are considered only for parameters that are shown not to change in treated water, except through mixing.

- Blending of different waters would therefore result in a concentration that was a weighted average of the individual concentrations. This weighted average will never be greater than the largest individual concentration.

- Measured concentrations from taps within the zone contain less information than concentrations at supply points, because high concentrations within the zone could have come from any of the supply points, while measurements at supply points allow the source of a problem to be more easily identified.

- In situations where a small number of supplies serve a large conurbation, authorisation of the supply points would allow more useful information to be obtained at the same cost, possibly even at less cost.

For example, if three supplies serve 15 zones with a population of 500 000, then at the standard frequency without authorised supply points it would be necessary to take $4 \times 15$ or $60$ pesticide samples, at various points in the systems and at various
times. These would represent different and possibly unknown degrees of blending between the sources, and detection of a pesticide would require investigation of all three sources.

If three supply points were authorised, then up to 20 samples from each point could be analysed for the same or less cost. If a pesticide were detected, then the source would be identified immediately. Furthermore the results of the analyses would allow trends in pesticide concentrations to be examined.
7. SPREAD OF SAMPLING TIMES

While several parameters showed evidence of some seasonal variation (Table B.3), there were no unexpected effects. The Regulations require regular sampling throughout the year to cover any seasonal variations.

Most companies sample during the normal working day for five days per week, although it is sometimes necessary to sample at weekends. Because of this, no data were available to confirm the widely held view that there are no major daily or weekly cycles in the quality of water in distribution systems. Clearly, however, where there are lead service pipes the concentration of lead in the water that is drawn off after a prolonged period of standing may be high.

Any requirement to sample routinely outside the normal working week would entail additional cost if automatic monitoring was not available.
8. DISCUSSION

In this section, the detailed application of the conclusions of the preceding sections is discussed. The response of water company representatives to a second questionnaire are taken into account, and used to assess the effects of proposed changes on operations and analysis costs.

8.1 Sampling frequencies

8.1.1 Minimum standard frequency

The Regulatory frequencies may be judged on whether they give an adequate probability of detecting PCV exceedences that is consistent between zones and parameters.

On this basis, the standard frequency of one per year for "Table 4" parameters is too low. The criterion used in Section 5, of at least a 10% probability per year of detecting true non-compliance of 2%, would require a minimum of five samples per year. Since scheduling of either four or six samples per year would fit the existing sampling patterns better, there are two sensible options:

(a) Require a minimum standard sampling frequency of at least six per year, whatever the parameter or zone size. This would have the effect of increasing the standard frequencies for "Table 3" parameters, "Table 1" parameters up to 500 population, and "Table 2" parameters up to 10 000 population, as well as for "Table 4" parameters. It would provide a 12% probability per year (approximately 1 in 8) of detecting a true non-compliance of 2%.

(b) Require a minimum standard sampling frequency of at least four per year, whatever the parameter or zone size. While this would affect "Table 4" parameters only, it should be noted that a suite of "Table 4" analyses is comparatively costly. It would provide an 8% probability per year (approximately 1 in 12) of detecting a true non-compliance of 2%.

8.1.2 Reduced frequencies

The Regulations currently permit reduced frequencies for parameters in Tables 1, 2, 3 and 5, provided all samples over three successive years contain less than 0.5 of the PCV.

A case can indeed be made for sampling ‘predictable’ parameters, whose concentration is well below the PCV (typically less than 0.4 of the PCV), at a reduced frequency. This should be two per year rather than one, in order to provide a check each year that the variability remains low.

Reduced frequencies should not be permitted for any ‘unpredictable’ parameter, or for any ‘predictable’ parameter whose mean concentration is not below approximately 0.4 of the PCV.
Pesticide analysis is expensive. Although pesticides are not 'predictable' parameters, a different case can be made for reduced frequencies. Pesticide applications are normally seasonal and it may therefore be possible, for surface water sources, to identify a period of the year of (say) 2 to 3 months, when the source is most at risk of pollution - and outside which period the risk is negligible.

Many companies stated that they monitor raw water sources for pesticides more frequently than the current regulatory frequencies for sampling in distribution, and that this provides an understanding of seasonal variations.

A case can therefore be made for Regulatory sampling of pesticides at a reduced frequency, provided (i) the measured concentrations from Regulatory samples have been low (less than say 0.3 of the PCV), and (ii) evidence can be provided, from raw water sampling and use patterns, for a restricted season that will encompass any risk of source pollution.

8.1.3 Increased frequencies

It is concluded from Appendix F that the increased sampling frequencies that are required following a PCV failure serve little useful purpose. This conclusion was reinforced by comments from several water companies.

One company suggested that, instead of the increased frequency rule, as the investigations that follow a PCV exceedence are open to audit by the DWI, each company could use its judgement on what investigation and follow-up action was required, while still allowing DWI to maintain its regulatory rôle.

Companies commented that this would make the scheduling of sampling significantly easier.

The comment was also made that high sampling frequencies are appropriate for health-related parameters monitored at supply points, particularly where water treatment or blending is used to reduce the level of the contaminant. This is considered further in the sub-section on authorised supply points.

8.1.4 Operating and cost implications

The implications of the proposed changes in sampling frequency vary between companies, depending on the extent to which reduced or increased frequencies are currently used.

The number of sampling occasions, i.e. the number of times that a sampler calls to take samples, would not be affected by the proposal to increase the minimum standard frequency, as any extra samples would be taken at the same time as samples for "Table 1" and "Table 6" parameters.

The removal of the requirement for increased sampling frequencies following failure would make scheduling easier, and might reduce analysis costs marginally.
A minimum standard frequency of 6 per year would increase the sampling frequency of both Tables 3 and 4, and water companies estimated that this would increase analysis costs by up to 70%. This is consistent with simple calculations (Appendix I). A minimum standard frequency of 4 per year, by itself, would increase the sampling frequency for Table 4 only, and analysis costs would increase by a smaller amount, perhaps in the range 20% to 40%.

These increases would be partially offset by operation of the reduced frequency rule, unless of course the rule is being applied widely already, which appears not to be the case. Additional savings might be made:

- if the increased frequency rule ceased to apply; and/or

- there were greater opportunities for authorised supply points (assuming that the frequencies in Table 5 of the Regulations would apply); and/or

- larger zones were permitted (depending on the sampling frequencies in the larger zones).

Several companies stated that they expected the combined effect of all these changes to be no change in analysis costs. The calculations given in Appendix I confirm that this may well be true if the minimum standard frequency of four per year were adopted. If a minimum standard frequency of six were adopted, an overall increase in analysis costs would probably result.

8.2 Sampling locations

8.2.1 Random sampling

The objectives of random sampling are:

- to provide for the eventual detection of PCV exceedences that tend to occur at particular locations in distribution systems. These include iron, manganese, aluminium and PAHs; as well as the parameters currently required by the Regulations, namely coliforms, copper, lead and zinc;

- to give a fair overall picture of the quality of water supplied to customers.

Adding the first four parameters to the list of those to be sampled at random points would not add to the number of random calls to be made by samplers, as the frequency of calls is determined by the need to sample for coliforms.

The views of water companies on random sampling generally varied from: "We recognise the problems associated with random sampling but believe that they can be overcome." to "We believe that random sampling should no longer be required.". At the time of writing, companies appear to be evenly divided between those in favour of, and those against, random taps.
An alternative to random taps would be representative fixed taps, perhaps installed by the water company, on consumers' premises. Their use instead of random taps would run the risk of missing PCV exceedences in certain parts of the distribution system. The degree of risk would depend on:

(a) the patterns of PCV exceedences in time and location;
(b) how the locations of the fixed taps were chosen;
(c) the number of fixed taps per 5000 population.

Data on the patterns of PCV exceedences for the relevant parameters are limited. However, it is believed to be possible to predict the location of areas with a high risk of bacteriological failures, from predictions of residence time and residual disinfectant concentration. These predictions can be made from a mix of modelling and local knowledge.

Lead, copper and zinc exceedences are usually associated with plumbing inside consumers' properties. Particularly in the case of lead, water companies are generally aware of the areas that they serve where lead plumbing is a significant problem.

Aluminium and manganese in distributed water generally result from deficiencies in water treatment. Any deposits will therefore tend to be greater higher up a distribution system. On the other hand, the causes of iron and PAH exceedences is in the distribution system, and exceedences are more likely lower down. Iron discoloration is believed to be worse where water stands in smaller pipes.

Therefore, the method of choosing the location of fixed taps would be crucial. There would be the potential for more cost effective sampling, in two senses:

- sampling from fixed taps would be cheaper than from random taps; and
- the fixed taps could be located in areas where problems were believed to be more likely.

On the other hand, the cost of setting up the fixed taps would not be negligible, and would include both:

- installation costs; and
- the cost of justifying the locations chosen.

Before reaching a firm recommendation on this matter, it would be necessary to investigate further:

- the failure patterns of the relevant parameters;
- the extent to which areas of high failure risk can be predicted; and
- the costs of setting up fixed taps.
One possible means of making access to private homes easier would be to make appointments in advance, at least in rural areas where ‘next door’ might be some distance away.

### 8.2.2 Authorised supply points

It was concluded in Section 6 that authorised supply points should be permitted for zones in which blending occurs, whether or not "the different waters contain similar and relatively constant concentrations of the respective parameters".

An authorised sampling point under these circumstances has been permitted for one of the ten companies, who state that "this has provided good reliable information". Other companies do not have authorised supply points in this situation.

This proposal received wide support from water companies.

The Regulations (Para. 12(1)) permit the authorisation of supply points for a wide range of parameters, although apparently only pesticides have been the subject of applications.

One company commented that, where a supply point is authorised for pesticides or nitrate, and the achievement of PCVs depends on treatment or blending, a higher sampling frequency than that required by “Table 5” of the Regulations, which may be as low as four, would be desirable.

### 8.3 Other Issues

#### 8.3.1 Trivial and significant PCV exceedences

All companies follow set procedures to distinguish between ‘trivial’ failures (e.g. from a contaminated tap) and ‘significant’ failures to supply wholesome water. In most cases this involves re-sampling from the same house and/or a neighbour; one company routinely collects two samples from neighbours with each random tap sample.

It is recognised that this is a difficult distinction to define precisely. One water company suggested that each water company should be allowed to exercise its judgement, by following the guidance given in Chapter 7 of the Guidance Document and by keeping a record. The DWI might then audit such records in their annual inspection.

There is a discrepancy between the advice in the Guidance Document (Para. 7.15) which states that sampling of pesticides at increased frequency is required after a PCV exceedence has been confirmed by a second sample, while the Regulations (Para. 13(7)), supported by a statement in paragraph 4.6 of the DWI report on "Nitrate, Pesticides and Lead" (DWI 1992), state that the increased frequency is required even if the PCV exceedence is not confirmed. The Guidance Document is incorrect in this respect.
8.3.2 Taste and odour

The Directive requires quantitative tests for taste and odour, and the Regulations incorporate this requirement. Quantitative taste and odour tests have been criticised for being expensive and not useful as a routine test. They may have a rôle when a qualitative taste or odour problem has been identified, although even here the usefulness of the tests has been questioned.

The sampling frequency for these parameters should therefore be the minimum required by the Directive.

8.3.3 Maximum zone size

The maximum zone population permitted by the Regulations is 50 000. It is sometimes necessary to split larger systems to bring populations below this limit.

It is shown in Appendix E.5 that for pro-rata sampling frequencies, the probability of detecting a failure is the same, whether or not a relatively uniform large system is divided into smaller zones. An important rider is that, if the system is split into zones and a failure is detected in one of them, the possibility that other zones are also affected should be considered.

Several companies are in favour of larger zone sizes being permitted, in order to avoid the need to subdivide large systems, serving up to 200 000 people, artificially.

8.3.4 Sampling at service reservoirs

Weekly sampling at service reservoirs is required by regulation 18. The Guidance Document (Para. 2.8) states that, "Where reservoirs are divided into compartments, each compartment should be treated as a separate reservoir and sampled accordingly unless the compartments are interconnected."

It is common for a service reservoir with a single feed to the distribution system to consist of two compartments, to facilitate cleaning. In some situations, the installation of a sampling point for each compartment would require excavation, and be costly and inconvenient. The customers would seem to be protected by sampling from the single feed, and there would appear to be no good reason to require regulatory sampling of water from each compartment separately; guidance to this effect has been issued recently (DWI 1994).

8.3.5 "No significant increase" rules for total organic carbon and colony counts

Appendix G discusses the unhelpful nature of these unquantified limits. The requirement for TOC is based on, but is sharper than, the requirement in the Directive. The similar requirement for total colony counts is not included in the Directive. Any future amendment of the Regulations should include more explicit requirements for these parameters.
8.3.6 Summary statistics

Considerable importance is attached to the appearance of the summary statistics that are derived from the regulatory samples. The possible changes that would result from recommended changes to the sampling frequencies are:

- An increase in the minimum standard frequency to four per year (or perhaps 6) would be likely to increase the overall percent compliance marginally, assuming that the "Table 4" parameters are those for which PCV exceedences are relatively uncommon.

- Reduced frequencies would have a marginal, possibly smaller, effect in the opposite direction.

- If no increased frequencies were required following PCV exceedences, the overall percent compliance would increase, marginally for many companies and significantly for a few.

- If a supply point is authorised for several zones, serving a large number of people, then a PCV exceedence for a single sample will be counted several times.

- If sampling of all parameters from fixed taps were permitted, then the proportion of PCV exceedences would depend strongly on the method of choosing the locations of the fixed taps.
9. CONCLUSIONS AND RECOMMENDATIONS

The letters (a) to (f) refer to the objectives set out in Section 2.

(a) Implementation of the Directive

Generally the Regulations implement the Directive faithfully. They go beyond the Directive in requiring an increased sampling frequency following a PCV exceedence and sampling at random taps for certain parameters, and in setting an upper limit on zone size.

(b) Sampling frequencies

The Regulations are designed to ensure that water companies supply wholesome water. The Regulatory sampling frequencies may therefore be judged on whether they give an adequate probability of detecting PCV exceedences that is consistent between zones and parameters.

On this basis, the standard frequency for sampling "Table 4" parameters is too low. It is recommended that the minimum sampling frequency should be increased to four per year.

A case can be made for sampling at a reduced frequency of (i) ‘predictable’ parameters whose mean concentration is well below the PCV (‘predictable’ is defined in Section 4.1) and (ii) pesticides that are used seasonally.

The requirement for an increased sampling frequency following a PCV exceedence serves little useful purpose and should therefore be reviewed. Exceedences should be followed-up and the action should remain open to audit by DWI.

Sampling frequencies proportional to zone size are appropriate for parameters that tend to exceed their PCV locally in the distribution system. Sampling at a frequency independent of zone size is appropriate for parameters whose failures are due to source and/or treatment problems. However, parameters specified in Annex II of the Directive would continue to require frequencies based on population or volume distributed.

There is no statistical argument against permitting larger zone sizes, provided that the minimum frequencies of sampling specified in the Directive are met.

Parameters may be divided into four classes, to provide a basis for considering sampling frequencies:

(i) Those that are predictable, and whose concentration does not change in the distribution system. Reduced frequencies should be permitted if mean concentrations are low, and authorised sampling points should be permitted.

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Provisionally, nitrate, tetrachloromethane, trichloroethene, tetrachloroethene, trihalomethanes, temperature and most "Table 4" parameters are in this class.

(ii) Those that are unpredictable, and whose concentration is liable to change in the distribution system. Neither reduced frequencies nor authorised sampling points should be permitted. These comprise odour and taste, coliforms, turbidity, nitrite, ammonium, iron, aluminium, manganese, colour, copper, lead, zinc and PAHs.

(iii) Pesticides, that are unpredictable, but whose concentration is not believed to change in distribution. Authorised sampling points should be permitted.

(iv) Predictable parameters whose concentration changes in distribution. Examples are residual disinfectant and possibly pH.

Within each class, higher or lower sampling frequencies could be justified for parameters for which the desired probability of detecting PCV exceedences is higher or lower than the standard figure.

Since quantitative taste and odour tests are believed not to provide useful data, and are expensive, routine sampling should be at the minimum frequency required by the Directive.

(c) **Sampling locations**

The requirement for random sampling from consumers’ taps presents several difficulties including unoccupied premises, concerns of occupants about admitting samplers, concerns over the safety of samplers, and contamination of samples from domestic taps.

Sampling from fixed points is cheaper than from random points, and should therefore be permitted unless there are good reasons for random sampling.

Random sampling should be required for parameters whose PCV exceedences are site-specific in distribution systems. At present this is required for coliforms, copper, lead and zinc but should also be required for iron, manganese, aluminium and PAHs.

For parameters whose concentration does not change in distribution, routine sampling at the point(s) where water enters distribution gives more information than sampling at taps in distribution.

Authorised sampling points should be permitted for zones in which blending of different waters occurs, whether or not the concentrations of the relevant parameters are similar in the different waters.
The proposal to permit sampling at fixed taps for all parameters should be investigated further, in view of the increasing ability of water companies to identify areas where the risk of PCV exceedences is relatively high. The following topics should be investigated:

(i) the failure patterns of the relevant parameters;

(ii) the extent to which areas of high failure risk can be predicted;

(iii) the costs of setting up fixed taps; and

(iv) the implications of fixed tap locations for the overall PCV exceedence rate.

It will then be possible to decide whether and how fixed taps can be located so that major areas at risk of PCV exceedences are not missed, and at the same time sampling costs are minimised.

(d) Sampling times

All water companies contacted have sampled during normal working hours, Monday to Friday. Samples were sometimes taken at weekends, but not outside the normal working day. As a result there is no evidence to confirm or refute the widely held view that any daily or weekly cycles in water quality in distribution systems are insignificant.

(e) Difficulties

The main difficulty reported by water companies was the requirement to sample for certain parameters from random taps. Companies were divided over whether or not the problems associated with fixed taps could or should be overcome.

Two companies suggested that sampling from fixed taps should be permitted for all parameters. Since it is now believed to be possible to define areas of distribution systems where there is a high risk of PCV exceedences, this proposal is worth serious consideration. Clearly the locations of fixed taps would have to be chosen with care, and would have implications for the overall water quality statistics.

For a few parameters the Regulations permit criteria less stringent than 100% PCV compliance - including rolling-mean limits and 'no significant increase'. This statistical diversity, although causing no great difficulties at present represents an unnecessary degree of sophistication, and the opportunity could usefully be taken in any future revision of the Regulations to standardise on the form of such criteria; a clearer definition of compliance for total organic carbon and colony counts would be helpful.
(f) Cost effectiveness

Generally the Regulations have proved to be a cost-effective means of giving water companies the incentive to supply wholesome water. Certain recommendations for improving their effectiveness have been made, whose combined effect is expected not to increase overall sampling and analysis costs.
REFERENCES


APPENDIX A  DATA RECEIVED FROM WATER COMPANIES

For nine of the ten water companies, zones were identified that represented the main types of water source in each company’s area. Data were requested for each of these zones, on the measured concentrations of a range of parameters in distribution, and in some cases at service reservoirs and ex treatment works. The time period for which useful data were available was generally January 1990 to mid 1993. In most cases data were provided on computer disk, although useful data were also provided on paper to overcome problems with creating and/or reading computer files.

In order to reduce the volume of data, the range of parameters was sometimes restricted to those for which (i) a sufficient number of measurements had been made, and (ii) the parameter was detected at a significant level on at least some occasions.

A summary of the zones by water company and source type is given in Table A.1.

Table A.1  Summary of zones

<table>
<thead>
<tr>
<th>Water company</th>
<th>upland reservoir</th>
<th>river</th>
<th>borehole/springs</th>
<th>imported</th>
<th>mixed</th>
<th>Total number of zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
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<tr>
<td>C</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>-</td>
<td>1</td>
<td>8</td>
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<tr>
<td>E</td>
<td>-</td>
<td>2</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>9</td>
</tr>
<tr>
<td>F</td>
<td>-</td>
<td>4</td>
<td>5</td>
<td>-</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
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<td>-</td>
<td>6</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>2</td>
<td>8</td>
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<tr>
<td>J</td>
<td>1</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>6</td>
<td>34</td>
<td>22</td>
<td>-</td>
<td>7</td>
<td>69</td>
</tr>
</tbody>
</table>
APPENDIX B STATISTICAL SUMMARY OF DATA

B.1 INTRODUCTION

B.1.1 Data storage and retrieval system

An efficient data storage and retrieval system was considered vital for this project in view of the large volume of data expected to be received from the ten collaborating water companies. It was decided to use Microsoft Excel, as this offers the facility to store and manage huge quantities of data on spreadsheets which can be accessed in an easy manner from within a Windows environment. Moreover, Excel offers a wide variety of search and sort strategies that can be combined with specific calculations, any of which can be automated through the use of macros.

Given the variety of data formats likely to be encountered, it was necessary for the data processing to include a ‘pre-processing’ stage: in this, the ‘raw’ data files received from a water company were read into a purpose-built program which produced output files of a consistent format for transfer to Excel. The pre-processor program was designed to minimise the need for interaction on the part of the data handler - a key criterion in light of the quantity of data to be processed. Different functions were available within the pre-processor for handling the different styles of data files produced by each water company. The program also kept track of all parameter names and their aliases encountered during the data manipulation, and maintained these in a library file with cross-references to a WRc master list of parameter codes.

All output files from the pre-processor were formatted with dates and times running down the file, and WRc parameter codes running across. Each file was tagged with a WRc code that identified the water company, zone, and site type.

Following the pre-processing stage, files were imported into Excel and converted into spreadsheet format. The contents of all the files for a zone were then assembled into a central spreadsheet; this enabled any desired data subsequently to be extracted in a rapid and efficient manner. Macros were constructed to automate this process as much as possible, and also to facilitate the data extraction according to various search and sort criteria.

B.1.2 General approach

With data being sought from as many as ten different water companies, it was inevitable that the data files provided would follow a wide variety of structures, formats and labelling conventions. Thus a major task upon first receiving a company’s water quality data files was to submit them to the pre-processing operation, as described above. This ensured that:

(i) all data would be identified and stored in one common format; and

(ii) any desired subset of the data could readily be extracted for further statistical analysis.
This preliminary exercise was particularly necessary in view of the huge quantities of data involved, and resulted in the creation of more than sixty Microsoft Excel files - one for each company/zone combination.

Initial summaries of these data files were produced using macros within Excel. For subsequent statistical analysis, data for selected parameters was exported to ASCII files which could then be read by purpose-written Fortran programs.

### B.1.3 Statistical fingerprints

The first of these programs generated a six-line 'statistical fingerprint' for each parameter in each specified data set. (For less-than values, the convention adopted was for them to be taken at face value.) At the same time, the statistical fingerprint information was written to intermediate results files that could be accessed by other programs as required.

An example of a fingerprint summary, relating to Atrazine (WRc parameter code 705) for water company C, zone 01, at treatment works X02, is shown in Table B.1.

#### Table B.1 Statistical fingerprint for Atrazine in data set C01X02

| ---Site:  | C01X02 | ---Atrazine --- | .1 (PCV)----------------------- | 705 |
| N        | 73     | No<:N>PCV       | Min        | Median | Mean | Max | 2:3 | 1:2 | SD | SDD | SRat |
| 73       | 7      | 40              | .02        | .11    | .14  | .9  | 1.2 | 2.0 | .12 | .11 | .91  |
| =Zero:   | 0      | Hist:           | 8 /        | 1 /    | 7 /  | 17 / | //  | 11 /| 6 / | 7 / | 4 /  | 12   |
| Skew     | coeff & sigce; | KSProb; A2EMax | Skew coeff & sigce; | KSProb; A2EMax |
| Raw:     | 3.52   | 1               | .013       | 2.8   | Log: | -.46 | 0   | .458 | 1.2 |

The information contained in the fingerprint table can be described briefly as follows.

The first two rows of the table contain title and header information. The next row declares that there are 73 values, including seven 'less-than' values and 40 PCV failures. Those 73 values range between 0.02 and 0.9, with median 0.11, mean 0.14, and standard deviation 0.12. The '1:2' entry of 2.0 indicates that the maximum is twice the second-largest data value; similarly the '2:3' entry shows that the second-largest value is 1.2 times the third-largest value.

The following row confirms that there were no data values reported as zero; it then shows a frequency table, or tabular histogram, of the 73 data values, grouped in units of 0.25*PCV. For example, there were 17 values in the range 0.075 - 0.100, and 12 values greater than 0.175.
The remaining entries in the table give more specialised information about the nature of the parameter’s systematic and random variability: these are discussed in Sections B.2 to B.4 following.

B.2 SYSTEMATIC TEMPORAL VARIATION

A useful measure of non-randomness in a time series is provided by the SDD:SD ratio, where:

- SD is the conventional standard deviation; and
- SDD (‘successive differences deviation’) is the short-term standard deviation, obtained as:

\[ SDD = \left( \text{standard deviation of successive differences} \right) / 2. \]

For a time series that is entirely random, the SDD/SD ratio will not differ greatly from unity. But where the series contains a systematic component of variation (such as seasonality), the SDD/SD ratio will fall below unity - by an amount dictated by the strength of the systematic variation. The point at which the ratio is statistically significantly less than unity depends on the number of samples and also on the underlying probability distribution of the data. A useful rough guide, however, is to regard values of 0.75 or less as indicative of a genuine effect; and that was the rule used in this project.

In Table B.1, the SD and SDD values are 0.12 and 0.11, giving a ratio of 0.91. In this example, therefore, there is no evidence at all of any underlying seasonal pattern.

‘Useful’ data sets for Atrazine (that is, data sets not consisting largely or entirely of less-than values) were available for a total of 24 zones. To summarise the resulting 24 sets of SD and SDD fingerprint information, program SOFA (Summary Of Fingerprint Analyses) was written. The SOFA output for Atrazine is shown in Table B.2. For each row, the three left-hand numbers show the minimum, median and maximum; the array of (up to 15) numbers on the right then gives a frequency table showing how the individual fingerprint values are spread between the reported minimum and maximum values.

For example, the first row shows that the number of samples varied between 4 and 109 around a median frequency of 12. As the range of values is 109 - 4 = 105, each cell of the frequency table spans a range of 105/14, namely 7.5. Thus the table shows that there were four data sets with sample numbers in the range [4 to 11], 13 data sets in the range [12 to 19]; and so on.

---

1 Where the frequency reported in a cell is ten or more, adjoining entries will often run into one another (as they do here). This does make it a little awkward to read individual frequencies from the table. Clumps of consecutive digits do, however, give a useful visual impression of the relative abundance of the data in those parts of the table. Where, conversely, the values are scattered thinly and some intervening cells are blank, the amount of ‘daylight’ between neighbouring entries again visually reinforces the information conveyed by the numbers themselves.
The second row shows that:

- the overall standard deviations lie between 0 and 0.9 times the PCV;
- the median standard deviation - that is, the standard deviation exceeded in half of the zones - is only 0.12 times the PCV; and
- the standard deviations for the majority of the zones are clustered tightly around that median value.

The other rows can be interpreted similarly. Thus, the SDD:SD ratios range from an unusually low value of 0.54 to a maximum of 1.18, with a median of 0.91 (which happens to correspond to the particular zone summarised earlier in Table B.1). The final row shows that only one of those 24 ratios is in fact less than the 0.75 criterion. The conclusion from this is that there is little or no evidence of seasonality in these particular data sets.

Table B.2  Examples of SDD:SD summaries from program SOFA

<table>
<thead>
<tr>
<th>Param:</th>
<th>Atrazine</th>
<th>.10</th>
<th>No. of sites:</th>
<th>24---------</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.of values</td>
<td>4.00</td>
<td>12.00</td>
<td>109.00</td>
<td>413</td>
</tr>
<tr>
<td>St.dev/PCV</td>
<td>.00</td>
<td>.12</td>
<td>.90</td>
<td>2</td>
</tr>
<tr>
<td>SDD/St.dev</td>
<td>.54</td>
<td>.91</td>
<td>1.18</td>
<td>1</td>
</tr>
<tr>
<td>SDDRat &lt;.75?</td>
<td>.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Param:</th>
<th>Temperature</th>
<th>25.00</th>
<th>No. of sites:</th>
<th>76--------</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.of values</td>
<td>11.00</td>
<td>77.00</td>
<td>582.00</td>
<td>62413</td>
</tr>
<tr>
<td>St.dev/PCV</td>
<td>.02</td>
<td>.17</td>
<td>1.43</td>
<td>24421</td>
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<td>SDD/St.dev</td>
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<td>.58</td>
<td>1.16</td>
<td>3</td>
</tr>
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<td>SDDRat &lt;.75?</td>
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<td>.00</td>
<td>1.00</td>
<td>56</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Param:</th>
<th>Nitrate</th>
<th>50.00</th>
<th>No. of sites:</th>
<th>93--------</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.of values</td>
<td>4.00</td>
<td>32.00</td>
<td>464.00</td>
<td>2245</td>
</tr>
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<td>St.dev/PCV</td>
<td>.00</td>
<td>.04</td>
<td>1.09</td>
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<td>1</td>
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<td>SDDRat &lt;.75?</td>
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<td>1.00</td>
<td>1.00</td>
<td>32</td>
</tr>
</tbody>
</table>
By way of comparison, Table B.2 also shows the corresponding SOFA summaries for two parameters with pronounced seasonality - temperature, and nitrate. For the 76 temperature data sets the SDD:SD ratios are way below unity: they vary around a median value of 0.58, with nearly three-quarters of them meeting the 0.75 criterion of significance. For the nitrate results the median SDD:SD ratio is rather higher; even so, good evidence of seasonality is shown for more than a third of the 93 sites.

Table B.3 similarly summarises the SDD:SD results for all those parameters showing significant seasonality for at least a quarter of the available data sets.
<table>
<thead>
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<th>Param: 101</th>
<th>Condctry</th>
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<th>No.of sites: 67</th>
</tr>
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</tr>
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<td>St.dev/PCV</td>
<td>.01</td>
<td>.03</td>
<td>.13</td>
</tr>
<tr>
<td>SDD/St.dev</td>
<td>.43</td>
<td>.86</td>
<td>1.22</td>
</tr>
<tr>
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<td>.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
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</table>

<table>
<thead>
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<td>77.00</td>
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</tr>
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<td>St.dev/PCV</td>
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<td>.17</td>
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<td>.02</td>
<td>4.44</td>
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</tr>
<tr>
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</tr>
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<td>St.dev/PCV</td>
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<td>1.09</td>
</tr>
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<td>SDD/St.dev</td>
<td>.26</td>
<td>.88</td>
<td>1.23</td>
</tr>
<tr>
<td>SDDRat &lt;.75?</td>
<td>.00</td>
<td>1.00</td>
<td>1.00</td>
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<th>No.of sites: 110</th>
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<td>993.00</td>
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58
B.3 SYSTEMATIC SPATIAL VARIATION

The data sets received during the project presented only limited opportunities for making within-zone spatial comparisons: with few exceptions (such as for the bacteriological parameters), samples for a particular parameter are taken either ex-works or at random (or, less often, fixed) points in the supply zone. Thus appreciable data was rarely available for several different locations through the distribution system.

Some comparisons could nevertheless be made; and program COSM (Comparison Of Site Means) was written to carry out t-tests on all pairs of means for different sampling points. Because of the limited time available, the analysis was only approximate. First, it assumed underlying Normality (though the t-test is fairly insensitive to departures from this assumption). Secondly, no correction was made for possible shared time trends in the data - by, for example, doing paired rather than unpaired comparisons. Again, however, such refinement would have brought only marginal benefit, given the relative size of the random component of variation for virtually all parameters.

Table B.4 shows an example of the output from COSM - for pH in zone 01 of company F. The treatment works sampling point is coded F123x0; the ten service reservoirs are labelled F01s01 to F01s10; and random sampling points in the zone are labelled F01R.

Thus there are 66 possible spatial comparisons, and of these 24 are statistically significant (using a cut-off t value of 2.5). The first row of the table, for example, compares ex-works (1045 values, mean 7.53) and service reservoir s02 (35 values, mean 7.77); and the t value of 8.88 shows that the increase is very highly significant.

In the lower part of the table, the results from the 66 comparisons are plotted in the upper triangular half of a 12-by-12 grid. The diagonal of asterisks marks the edge of the diagram. Above this, significant positive changes (reading from the y-axis to the x-axis labels) are marked by ‘+’, significant negative changes by ‘-’, and non-significant differences left blank. The order of sites down the y-axis corresponds broadly to the direction of flow through the distribution system.

The advantage of summarising the t-tests in this way is that it highlights any systematic spatial patterns that happen to be present in the distribution system. Two patterns are of particular interest:

(i) If nearly all of the symbols are of the same sign, this indicates a persistent spatial increase (+) or decrease (-) in water quality through the system.

(ii) If there is an L-shape of symbols meeting at the diagonal, with the ‘horizontal’ and ‘vertical’ limbs containing opposite signs, this indicates a site whose mean is significantly different from all others in the system.

The first row of the diagram, for example, shows a consistent increase in pH from ex-works to six of the ten service reservoirs, whilst the second row shows that, in comparison with the mean at s01, pH is significantly higher at three other service reservoirs - s02, s03 and s10.
The I-shaped patterns for both s02 and s03, with ‘+’ columns and ‘-’ rows, confirm that mean pH tends to be higher at those two sites than elsewhere. A similar tendency is shown by s10. Finally, the right-most column of ‘-’ symbols indicates a persistent drop in mean pH from service reservoirs to zone.

### Table B.4  Example of the between-site comparisons from program COSM

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Param: 205  pH

|   | F123x0 |   | F01s01 |   | F01s02 |   | F01s03 |   | F01s04 |   | F01s05 |   | F01s06 |   | F01s07 |   | F01s08 |   | F01s09 |   | F01s10 |   | F01R |
|---|--------|---|--------|---|--------|---|--------|---|--------|---|--------|---|--------|---|--------|---|--------|---|--------|---|
| 1 | *      | + | +      | + | +      |   | +      |   | +      |   | +      |   | +      |   | +      |   | +      |   | +      |   | +      |   | +      |   |
| 2 | F01s01 |   | F01s02 |   | F01s03 |   | F01s04 |   | F01s05 |   | F01s06 |   | F01s07 |   | F01s08 |   | F01s09 |   | F01s10 |   | F01R |
| 3 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 4 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 5 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 6 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 7 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 8 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
| 9 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
|10 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
|11 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |
|12 |        |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |         |   |

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Program COSM was applied to all data sets, and the outputs scrutinised for evidence of persistent spatial trends.

B.4 RANDOM VARIATION

For almost all parameters, much the largest component of variability is random scatter rather than systematic variation: this is especially true for data derived from random sampling in the distribution system. For example, it is exceptional to find a parameter whose SDD:SD ratio (see Section B.2) is less than 0.5.

This places great importance on understanding as much as possible about the nature of the non-systematic component of variation. Evidence helping in the judgement as to whether a particular parameter is ‘predictable’ or ‘unpredictable’ is especially useful.

To explore the plausibility (for some parameters, at least) of the Normal or logNormal model of variability, the project has pursued three complementary lines of enquiry:

(i) general goodness-of-fit testing;
(ii) testing of the coefficient of skewness; and
(iii) comparison of observed and predicted maximum values.

These approaches are described and the conclusions summarised in the following three sections.

B.4.1 Goodness-of fit testing

As part of the statistical fingerprinting, each data set was subjected to Kolmogorov-Smirnov goodness-of-fit tests both for Normality and for log-Normality. In Table B.1, for example, the two resulting test probabilities (labelled ‘KSProb’) are 0.013 and 0.458 for ‘Raw’ and ‘Log’ data respectively.

The ‘Raw’ value of 0.013 indicates that the Normality hypothesis can be rejected at close to the 1% level of significance: in other words, it can be stated with almost 99% confidence that the Normal model provides a poor fit. For the ‘Log’ test, however, the KSProb value is comfortably within the acceptable range. This means that the 73 Atrazine values are entirely consistent with the assumption of a logNormal model.

The KSProb values for the 24 ‘useful’ data sets for Atrazine were summarised by program SOFA to produce the output shown in Table B.5. The convention was adopted whereby:

- ‘0’ denotes ‘not significant’; and
- ‘1’ denotes ‘significantly poor fit’.

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Because of possible approximations due to the presence of less-than values, a fairly stringent rejection criterion of 0.01 was used. Thus, in the Atrazine example just discussed, the logNormal model is in fact retained - albeit as a slender possibility. And overall, the Normal and log-Normal models seem to fare equally well: the Normal model is rejected in five of the 24 data sets, and the logNormal in six of the 24.

Table B.5  Examples of Goodness-of-fit summaries from program SOFA

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The table also shows the goodness-of-fit summaries for three other parameters. For turbidity and Fe, the superiority of the logNormal model is apparent: the logNormal hypothesis is rejected for fewer than a quarter of the 111-113 data sets, whilst the Normal hypothesis is rejected in well over half the cases. The chloride example is rather different. Here, both Normal and logNormal models are successful, providing an adequate fit in over 80% of cases. The reason for there being so little difference between the two models for this parameter is that the range of chloride values in any data set tends to be small in relation.
B.4.2 Skewness testing

A further element of the statistical fingerprint produced for each data set was the coefficient of skewness - calculated both for the original, or ‘raw’, data and for the logged data. (For the latter calculation, zero data values were ignored.) In Table B.1, for example, the two skewness values are 3.52 and -0.46 for the ‘Raw’ and ‘Log’ data respectively. Each coefficient was then submitted to an approximate significance test to determine whether it was significantly different from zero - with the result shown by the accompanying ‘sigce’ flag. Thus the ‘1’ and ‘0’ flags indicate that the 3.52 value IS significantly greater than zero, whilst the -0.46 value is NOT significantly less than zero. In other words, the tests support the findings of the goodness-of-fit tests discussed earlier: the Normal model offers a poor representation of the data, but the logNormal model is quite plausible.

Program SOFA was used to summarise the skewness information across the 24 Atrazine data sets, resulting in the output shown in Table B.6. The 24 coefficients vary from -1.1 to 2.9 around a median of 1.2. In reporting the significance test results, the convention was adopted of using ‘0’ to denote skewness coefficients not significantly different from zero, and ‘-1’ and ‘1’ respectively to denote skewness coefficients significantly less than and greater than zero.

The value of -1.1 is in fact statistically significant according to both the Normal and the logNormal model. More usually, however, the skewness coefficients are positive. They are significantly greater than zero, moreover, for about half of the data sets when Normality is assumed, but only 25% of data sets when assuming logNormality.

<table>
<thead>
<tr>
<th>Table B.6</th>
<th>Examples of skewness-testing summaries from program SOFA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Param: 705 Atrazine</td>
<td>0.10</td>
</tr>
<tr>
<td>No. of values</td>
<td>4.00</td>
</tr>
<tr>
<td>Skewness</td>
<td>-1.10</td>
</tr>
<tr>
<td>Skew? (Nor)</td>
<td>-1.00</td>
</tr>
<tr>
<td>Skew? (LgN)</td>
<td>-1.00</td>
</tr>
<tr>
<td>Param: 209 Fe</td>
<td></td>
</tr>
<tr>
<td>No. of values</td>
<td>6.00</td>
</tr>
<tr>
<td>Skewness</td>
<td>-1.90</td>
</tr>
<tr>
<td>Skew? (Nor)</td>
<td>.00</td>
</tr>
<tr>
<td>Skew? (LgN)</td>
<td>.00</td>
</tr>
<tr>
<td>Param: 210 Al</td>
<td></td>
</tr>
<tr>
<td>No. of values</td>
<td>4.00</td>
</tr>
<tr>
<td>Skewness</td>
<td>-.70</td>
</tr>
<tr>
<td>Skew? (Nor)</td>
<td>.00</td>
</tr>
<tr>
<td>Skew? (LgN)</td>
<td>.00</td>
</tr>
</tbody>
</table>
The SOFA summaries for iron and aluminium are also shown in Table B.6. Iron is highly skewed, with a median of 2.5 and coefficients ranging as high as 12.8. The Normal model is accordingly discredited in all but 18 cases out of 113. Two-thirds of these cases, however, are consistent with a logNormal model.

A similar though less pronounced effect is shown by the aluminium summary.

**B.4.3 Actual versus Expected maximum values**

One common difficulty with interpreting the maximum value in a set of data is that it is very dependent upon the number of data values: the greater the amount of data, the greater the maximum is likely to be. A useful way of correcting this effect is to relate the ACTUAL maximum value to the value that would be EXPECTED according to some assumed statistical model. This, accordingly, is the final information provided by the statistical fingerprinting program: the ratio of actual to expected maximum - again assuming Normality and logNormality in turn.

In Table B.1, for example, the ‘A2EMax’ values are 2.8 for the ‘Raw’ data, and 1.2 for the ‘Log’ data. Once again, therefore, the results are consistent with those discussed previously. The actual maximum of 0.9 is nearly three times the value that would be expected assuming Normality - which strongly suggests that Normality is a poor model. For the logNormal assumption, on the other hand, the actual maximum differs by only 20% from the expected value - further support for the adequacy of the logNormal model in this instance.

The SOFA summary of the results for the 24 data sets is shown in Table B.7. This shows that, with only a few exceptions, the A:E ratios are clustered quite tightly around a median of 1.7 for the Normal assumption, and 1.4 for the logNormal assumption.

The table shows examples of A:E maximum performance for two further parameters. The first, pH, exhibits a close agreement with both Normal and logNormal models - as would be expected for a parameter with such a narrow range of variation. The other example, for total PAH, is more typical of the majority of parameters. The Normal model performs poorly, but the logNormal model is a marked improvement, with the actual maximum seriously underestimated in only about a quarter of cases.
Table B.7  Examples of A:E maximum summaries from program SOFA

<table>
<thead>
<tr>
<th>Param: 705</th>
<th>Atrazin</th>
<th>.10</th>
<th>No. of sites: 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of values</td>
<td>4.00</td>
<td>12.00</td>
<td>109.00</td>
</tr>
<tr>
<td>Max/PCV</td>
<td>.00</td>
<td>1.00</td>
<td>3.00</td>
</tr>
<tr>
<td>A:E max(Nor)</td>
<td>.00</td>
<td>1.70</td>
<td>2.30</td>
</tr>
<tr>
<td>A:E max(LgN)</td>
<td>.00</td>
<td>1.40</td>
<td>2.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Param: 205</th>
<th>pH</th>
<th>9.50</th>
<th>No. of sites: 79</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of values</td>
<td>29.00</td>
<td>83.00</td>
<td>1386.00</td>
</tr>
<tr>
<td>Max/PCV</td>
<td>.06</td>
<td>.84</td>
<td>36.84</td>
</tr>
<tr>
<td>A:E max(Nor)</td>
<td>.30</td>
<td>1.10</td>
<td>3.50</td>
</tr>
<tr>
<td>A:E max(LgN)</td>
<td>.10</td>
<td>1.00</td>
<td>2.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Param: 319</th>
<th>Total PAH</th>
<th>.20</th>
<th>No. of sites: 29</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of values</td>
<td>4.00</td>
<td>31.00</td>
<td>102.00</td>
</tr>
<tr>
<td>Max/PCV</td>
<td>.00</td>
<td>.50</td>
<td>4.50</td>
</tr>
<tr>
<td>A:E max(Nor)</td>
<td>.00</td>
<td>1.90</td>
<td>3.00</td>
</tr>
<tr>
<td>A:E max(LgN)</td>
<td>.00</td>
<td>1.40</td>
<td>2.30</td>
</tr>
</tbody>
</table>

B.5 STATISTICAL BEHAVIOUR OF "TABLE 4" PARAMETERS

Certain data were provided on paper, in order to bypass problems with creating and reading computer data files. In particular water companies D and J provided "Schedule 4" summaries that were particularly useful for examining the statistical behaviour of "Table 4" parameters. The standard frequency in the Regulations for these parameters is once per year, but these companies had carried out more frequent sampling. A summary is given in Table B.8.
Table B.8  Summary of behaviour of "Table 4" parameters

<table>
<thead>
<tr>
<th>Zone</th>
<th>Years</th>
<th>Det.</th>
<th>n</th>
<th>min</th>
<th>max</th>
<th>mean</th>
<th>SD</th>
<th>CV</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>1/90-6/93</td>
<td>Cl</td>
<td>14</td>
<td>12</td>
<td>26</td>
<td>17.5</td>
<td>4.11</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO	extsubscript{4}</td>
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<td>50</td>
<td>100</td>
<td>69</td>
<td>14.7</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca</td>
<td>14</td>
<td>29</td>
<td>53</td>
<td>39</td>
<td>7.05</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mg</td>
<td>14</td>
<td>2.8</td>
<td>11</td>
<td>7.3</td>
<td>2.4</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Na</td>
<td>14</td>
<td>7.3</td>
<td>19</td>
<td>11.2</td>
<td>3.4</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>14</td>
<td>1.1</td>
<td>2.1</td>
<td>1.6</td>
<td>0.29</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F\textsuperscript{1}</td>
<td>14</td>
<td>300</td>
<td>1200</td>
<td>630</td>
<td>264</td>
<td>0.42</td>
</tr>
<tr>
<td>J2</td>
<td>1/90-6/93</td>
<td>Cl</td>
<td>16</td>
<td>8</td>
<td>15</td>
<td>11</td>
<td>1.9</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO	extsubscript{4}</td>
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<td>41</td>
<td>8.8</td>
<td>0.22</td>
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<tr>
<td></td>
<td></td>
<td>Ca</td>
<td>16</td>
<td>14</td>
<td>35</td>
<td>25</td>
<td>6.0</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mg</td>
<td>16</td>
<td>1.6</td>
<td>4.6</td>
<td>2.5</td>
<td>0.85</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Na</td>
<td>16</td>
<td>3.9</td>
<td>10</td>
<td>5.6</td>
<td>1.7</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>16</td>
<td>0.5</td>
<td>1.8</td>
<td>0.95</td>
<td>0.37</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>16</td>
<td>40</td>
<td>120</td>
<td>76</td>
<td>23</td>
<td>0.30</td>
</tr>
<tr>
<td>D1</td>
<td>1/90-11/93</td>
<td>Cl</td>
<td>37</td>
<td>32</td>
<td>55</td>
<td>40</td>
<td>&lt;6</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO	extsubscript{4}</td>
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<td>30</td>
<td>179</td>
<td>126</td>
<td>37</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ca</td>
<td>17</td>
<td>72</td>
<td>144</td>
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<td>20</td>
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<td></td>
<td></td>
<td>F</td>
<td>37</td>
<td>630</td>
<td>1260</td>
<td>992</td>
<td>158</td>
<td>0.16</td>
</tr>
<tr>
<td>D2</td>
<td>1/90-11/93</td>
<td>Cl</td>
<td>9</td>
<td>15</td>
<td>24</td>
<td>21</td>
<td>3.0</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>1/93-11/93</td>
<td>F</td>
<td>6</td>
<td>386</td>
<td>1011</td>
<td>789</td>
<td>247</td>
<td>0.31</td>
</tr>
<tr>
<td>D3</td>
<td>1/90-11/93</td>
<td>Cl</td>
<td>9</td>
<td>8</td>
<td>20</td>
<td>13</td>
<td>4.0</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>1/93-11/93</td>
<td>F</td>
<td>6</td>
<td>150</td>
<td>769</td>
<td>1083</td>
<td>368</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Notes:  
SD = Standard Deviation  
CV = Coefficient of Variation, SD/mean

Estimated SD = (max - min) / (2*E(n)), where E(n) is the expected value of the nth order statistic (Biometrika Tables Vol I 1954 table XXVIII)

Note\textsuperscript{1} Use of (max - mean) gives 0.53 instead of 0.42.
APPENDIX C  RELATIONSHIP BETWEEN NUMBER OF SAMPLES AND PROTECTION SECURED - GENERAL CASE

C.1  STATISTICAL PROBLEMS WITH THE MAXIMUM

In general, no monitoring programme based on discrete sampling can ever determine the true underlying maximum with any quantifiable measure of precision and statistical confidence. That is because the locations and times actually sampled constitute only a tiny fraction of the underlying population or entirety of values, and so will almost certainly miss the one particular location and moment in time at which the true maximum occurs.

(Sampling may of course uncover the maximum if the true behaviour of the parameter in question happens to be constant, or very slowly moving in relation to the sampling frequency; but such information can be gained only from externally-supplied knowledge, not from scrutiny of the sample values themselves.)

In this respect, the maximum is uniquely different from all other statistics, such as means, standard deviations, percentiles and proportions. In all those cases, the number of samples can be chosen so as to achieve some desired precision of estimation. But that approach is unavailable for the maximum.¹

It follows from this that no practical amount of monitoring can ever demonstrate that a particular PCV IS being met; it can only hope to reveal cases in which the PCV is NOT being met. The key statistical task, therefore, is to quantify the effectiveness with which any particular monitoring programme can detect NON-compliance.

C.2  STATISTICAL THEORY

One way of proceeding would be to ask:

'How much greater than the PCV must the true maximum be before a given monitoring programme has a high chance of detecting non-compliance?'

Unfortunately, this cannot in general be answered because of the statistical problems associated with the maximum, as mentioned above. There is, however, an alternative approach that has the merit of being straightforward to apply and also entirely general. This involves recasting the question as:

'How much poorer than 100% must the true % compliance be before a given monitoring programme has a high chance of detecting non-compliance?'

¹ One possible compromise, accordingly, is to redefine the 'maximum' as a very high percentile such as the 99.9%ile. This option is developed in Appendix D.
The statistical treatment proceeds as follows. Suppose that n random samples are taken from a population whose true % compliance (with a particular PCV) is 100p%. The probability of all samples meeting the PCV is then given by:

\[ \text{Prob[PCV met]} = p^{**n} \]

(where ‘**’ denotes ‘raised to the power of’).

Thus the probability of detecting non-compliance is:

\[ \text{Prob[PCV failure]} = 1 - p^{**n} \]  \hspace{1cm} (1)

Expression (1) is evaluated in Table C.1 for a range of p and n values.

### Table C.1  Probabilities of detection for various sample numbers and values of true % non-compliance

<table>
<thead>
<tr>
<th>No. of samples</th>
<th>.1</th>
<th>.5</th>
<th>True % non-compliance</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0</th>
<th>10.0</th>
<th>20.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.1</td>
<td>.5</td>
<td>1.0</td>
<td>2.0</td>
<td>5.0</td>
<td>10.0</td>
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<tr>
<td>2</td>
<td>.2</td>
<td>1.0</td>
<td>2.0</td>
<td>4.0</td>
<td>9.8</td>
<td>19.0</td>
<td>36.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>.3</td>
<td>1.5</td>
<td>3.0</td>
<td>5.9</td>
<td>14.3</td>
<td>27.1</td>
<td>48.8</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>.4</td>
<td>2.0</td>
<td>3.9</td>
<td>7.8</td>
<td>18.5</td>
<td>34.4</td>
<td>59.0</td>
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<tr>
<td>6</td>
<td>.6</td>
<td>3.0</td>
<td>5.9</td>
<td>11.4</td>
<td>26.5</td>
<td>46.9</td>
<td>73.8</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.2</td>
<td>5.8</td>
<td>11.4</td>
<td>21.5</td>
<td>46.0</td>
<td>71.8</td>
<td>93.1</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>2.4</td>
<td>11.3</td>
<td>21.4</td>
<td>38.4</td>
<td>70.8</td>
<td>92.0</td>
<td>99.5</td>
<td></td>
</tr>
<tr>
<td>42</td>
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<td>19.0</td>
<td>34.4</td>
<td>57.2</td>
<td>88.4</td>
<td>98.8</td>
<td>100.0</td>
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<tr>
<td>52</td>
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<td>22.9</td>
<td>40.7</td>
<td>65.0</td>
<td>93.1</td>
<td>99.6</td>
<td>100.0</td>
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</tr>
<tr>
<td>60</td>
<td>5.8</td>
<td>26.0</td>
<td>45.3</td>
<td>70.2</td>
<td>95.4</td>
<td>99.8</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>104</td>
<td>9.9</td>
<td>40.6</td>
<td>64.8</td>
<td>87.8</td>
<td>99.5</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>11.3</td>
<td>45.2</td>
<td>70.1</td>
<td>91.1</td>
<td>99.8</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

Take, for example, the third column in the body of the table. This relates to a situation in which the true % non-compliance is 1% - that is, a particular PCV is being exceeded for 1% of the total tap-years in the sampled zone. In such a situation, the probability of detection during a one-year monitoring programme would be:

- 40.7% with weekly random sampling;
- 11.4% with monthly random sampling; and
- 1.0% if only one random sample were taken during the year.
The table may also be viewed 'horizontally', with any one row showing how, for that particular monitoring frequency, the probability of detection increases as the true level of non-compliance worsens. For example, with monthly sampling there is a roughly 50-50 chance of detecting a level of non-compliance as severe as 5%. Even four samples a year is more likely than not to pick up a non-compliance rate of 20%.
APPENDIX D  RELATIONSHIP BETWEEN NUMBER OF SAMPLES AND PROTECTION SECURED - SPECIAL CASE OF NORMALITY

D.1 DEFINITION OF ‘MAXIMUM’

Whatever the parameter, the assumption of Normality can never strictly be upheld because the Normal distribution has an infinite maximum. In a sense this obstacle is more theoretical than practical, as the area under the Normal curve becomes negligible beyond about four standard deviations from the mean. For example, the 99.99%ile - the quantity that would be exceeded only one time in 10 000 random samples - occurs at 3.7 standard deviations above the mean.

Nevertheless, any approach based on the assumption of Normality requires a decision to be taken about the particular high percentile that may for practical purposes be regarded as the maximum.

D.2 STATISTICAL INTRODUCTION

Suppose that a number of samples are taken (perhaps as few as one) and analysed for a particular parameter. It goes without saying that all the sample values are below the PCV, for otherwise non-compliance would be self-evident. Suppose also that the true ‘maximum’ has been defined as the P-%ile. (The inverted commas will be retained in the ensuing discussion to serve as a reminder that the method relates to an ‘inner’ or ‘practical’ substitute rather than the genuine maximum.)

The question now to be posed is: What confidence does an observed compliance of 100% provide that the true ‘maximum’ is below the PCV?

This can be addressed as follows. Suppose it is required to be C% confident that the true ‘maximum’ meets the PCV. Suppose also that:

\[ n = \text{number of random samples taken}, \]
\[ M = \text{the observed mean}, \]
\[ S = \text{the observed standard deviation (if } n > 1), \]
\[ u(P) = \text{standard Normal deviate corresponding to the } P-%ile, \]
\[ u(C) = \text{standard Normal deviate corresponding to a single-sided confidence level of } C\%, \text{ and} \]
\[ t(C) = t\text{-statistic for } n-1 \text{ degrees of freedom and single-sided confidence level of } C\%. \]

What is required now is an expression for the upper confidence limit for the true ‘maximum’. Two ways of obtaining this will be considered below. First, Section D.3 provides a general approach. Section D.4 then provides a simplified method for the case in which the standard deviation may be assumed known.
D.3 CASE A: STANDARD DEVIATION ESTIMATED FROM DATA

A thorough statistical treatment of parametric percentile confidence intervals is complex. However, a much simpler approximate approach is available which is quite adequate, given the other approximations and assumptions involved. This proceeds as follows:

The estimated ‘maximum’ is $M + u(P)*S$.

The sampling variances of $M$ and $S$ are given by:

$$\text{var}(M) = S**2/n, \text{ and (approximately)}$$
$$\text{var}(S) = S**2/(2(n-1))$$

(where ‘**’ denotes ‘raised to the power of’).

Moreover, $M$ and $S$ are statistically independent.

Thus

$$\begin{align*}
\text{var}\left[\text{maximum}\right] &= \\
\text{var}[M + u(P)*S] &= \text{var}(M) + u(P)**2*\text{var}(S) \\
&= S**2\left[1/n + u(P)**2*0.5/(n-1)\right]
\end{align*}$$

and so an approximate upper C% confidence limit for the ‘maximum’ is:

$$M + u(P)*S + t(C)*S*\sqrt{1/n + 0.5*u(P)**2/(n-1)} \quad (1)$$

This quantity must accordingly be less than the PCV for the required confidence of compliance to be achieved.

For the case of the ‘maximum’ defined as the 99.99%ile, Expression (1) is illustrated in Table D.1 for a range of sample numbers ($n$) and confidence levels ($C$). For example, to be 90% confident of compliance with the PCV on the basis of 12 samples, the mean of those 12 samples would have to be at least 4.9 standard deviations below the PCV. The required multiple increases to 6.3 if only four samples are available, but reduces to 4.2 if the mean is based on as many as 52 samples.

Tables D.2 and D.3 provide the corresponding results for two less extreme definitions of the ‘maximum’, namely the 99.9%ile and the 99%ile. With the 99.9%ile definition, for example, the mean of 12 samples must be 4.1 standard deviations below the PCV to be 90% confident of compliance with the PCV. (The corresponding figure in Table D.1 was 4.9.) With a further relaxation of the ‘maximum’ to the 99%ile, the required figure reduces again - to 3.1 standard deviations.
Table D.1  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with (approximately) the stated confidence

* Standard deviation estimated from data.
* 'Maximum' defined as 99.99%ile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the 'maximum' is truly below the PCV.

Table D.2  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with (approximately) the stated confidence.

* Standard deviation estimated from data.
* 'Maximum' defined as 99.9%ile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the 'maximum' is truly below the PCV.
Table D.3  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with (approximately) the stated confidence.

* Standard deviation estimated from data.
* 'Maximum' defined as 99%tile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the 'maximum' is truly below the PCV.

D.4  CASE B: STANDARD DEVIATION ASSUMED KNOWN

If the standard deviation may be assumed to be known, the statistical theory becomes much simpler - and also paves the way for a possible justification of very low sample numbers.

The upper C% confidence limit for the mean is:

\[ M + u(C) \times S/\sqrt{n}. \]

Thus the upper C% confidence limit for the 'maximum' is:

\[ M + u(C) \times S/\sqrt{n} + u(P) \times S = M + S[u(P) + u(C)/\sqrt{n}] \]

This, therefore, is now the quantity that must be less than the PCV for the required confidence of compliance to be achieved.

For the case of the 'maximum' defined as the 99.99%tile, Expression (2) is illustrated in Table D.4 for a range of sample numbers (n) and confidence levels (C). For example, to be 90% confident of compliance with the PCV on the basis of four samples, the mean of those four samples would have to be at least 4.4 standard deviations below the PCV. The required multiple increases to 5.0 if only a single sample is available, but reduces to 3.9 if the mean is based on as many as 52 samples.
Table D.4  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with the stated confidence

* Standard deviation assumed known.
* 'Maximum' defined as 99.99%ile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the 'maximum' is truly below the PCV.

Tables D.5 and D.6 provide the corresponding results for two less extreme definitions of the 'maximum', namely the 99.9%ile and the 99%ile. With the 99.9%ile definition, for example, the mean of four samples must be 3.7 standard deviations below the PCV to be 90% confident of compliance with the PCV. (The corresponding figure in Table D.1 was 4.4.) With a further relaxation of the 'maximum' to the 99%ile, the required figure reduces again - to 3.0 standard deviations.
Table D.5  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with the stated confidence

* Standard deviation assumed known.
* ‘Maximum’ defined as 99.9%ile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the ‘maximum’ is truly below the PCV.

Table D.6  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with stated confidence

* Standard deviation assumed known.
* ‘Maximum’ defined as 99%ile.

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Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the ‘maximum’ is truly below the PCV.
D.5 STATISTICAL POWER OF THE SCHEMES

All of the various schemes summarised in Tables D.1 to D.6 provide the guarantee that if the true ‘maximum’ is exactly equal to the PCV, the probability of the observed mean exceeding the tabulated criterion is the specified ‘confidence of conclusion’ value. Suppose, for example, that:

- the ‘maximum’ is defined as the 99%ile;
- the standard deviation (S) is assumed known;
- 90% confidence is required; and
- the scheme is to be based on two samples.

For these specified conditions, Table D.6 produces a criterion of 3.2. The guarantee then is this: if the true 99%ile is exactly equal to the PCV, there is a 90% probability that the observed mean of two samples will exceed the quantity \[ PCV - 3.2*S \].

It follows from this that:

(i) if the true ‘maximum’ is greater than the PCV, the probability of rejection will be greater than 90%; and

(ii) the true ‘maximum’ must be some way below the PCV before the probability of rejection becomes negligible.

(The term ‘probability of rejection’ is used rather than ‘probability of detection’ to emphasise the point that the schemes described in this appendix are surrogate compliance schemes: it is the sample mean that is being rejected, not a PCV failure being detected.)

The way in which the probability of rejection varies according to the proximity of the true ‘maximum’ to the PCV - a relationship known as the ‘statistical power’ - can be quantified as follows:

From expression (2), the acceptance criterion is:

\[ \text{Observed mean} \leq \text{PCV} - S*[u(P) + u(C)/\sqrt(n)] \].

Suppose that the true mean is \( D \) standard deviations worse than the borderline case in which the ‘maximum’ is equal to the PCV. Then:

\[ \text{true mean} = \text{PCV} - S*[u(P) - D]. \]

The observed mean will be Normally distributed with that true mean and with standard deviation \( S/\sqrt(n) \).
The acceptance criterion therefore corresponds to a standardized Normal deviate of:

\[
    z = \left\{ \begin{array}{l}
        \left[ \text{PCV} - S^*[-u(P) + u(C)/\sqrt{(n)}] \right. - \left[ \text{PCV} - S^*[-u(P)-D] \right] \right. \\
        \left. - u(C) - D^*\sqrt{(n)} \right) \\
        \left. \left[ \text{PCV} - S^*[-u(C) - D^*\sqrt{(n)}] \right. - \left[ \text{PCV} - S^*[-u(\text{max})] \right] \right. \\
        \left. - u(\text{max}) - D^*\sqrt{(n)} \right) \\
    \end{array} \right. \\
\]

Thus the probability of rejection is given by:

\[
    100^*\left[ 1 - \text{CNP}\{-u(C) - D^*\sqrt{(n)}\} \right] \\
\]

where CNP denotes Cumulative Normal Probability.

Expression (3) is evaluated in Table D.7 for a range of sample numbers and for D values stepping in 0.5*S intervals below and above the PCV.

**Table D.7 Statistical power of the '90% confidence' schemes in Table D.6**

<table>
<thead>
<tr>
<th>No. of st.devs below PCV for:</th>
<th>Criteria from Table D.6 for 90% confidence:</th>
</tr>
</thead>
<tbody>
<tr>
<td>True</td>
<td>True</td>
</tr>
<tr>
<td>mean</td>
<td>'max'</td>
</tr>
</tbody>
</table>

| 6.33 | 4.00 | -1.0 | .3 | .0 | .0 | .0 | .0 | .0 |
| 5.83 | 3.50 | -1.0 | 1.3 | .0 | .0 | .0 | .0 | .0 |
| 5.33 | 3.00 | -1.0 | 4.3 | .2 | .0 | .0 | .0 | .0 |
| 4.83 | 2.50 | -1.0 | 11.2 | 1.2 | .1 | .0 | .0 | .0 |
| 4.33 | 2.00 | -1.0 | 23.6 | 6.1 | 1.5 | .3 | .0 | .0 |
| 3.83 | 1.50 | -1.0 | 41.4 | 20.1 | 9.4 | 4.3 | .0 | .0 |
| 3.33 | 1.00 | -1.0 | 61.1 | 44.7 | 32.6 | 23.6 | 1.5 | .0 |
| 2.83 | .50 | -.8 | 78.3 | 71.7 | 66.1 | 61.1 | 32.6 | 12.1 |
| 2.33 | .00 | -.0 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 |
| 1.83 | -.50 | 2.4 | 96.3 | 97.7 | 98.4 | 98.9 | 99.9 | 100.0 |
| 1.33 | -1.00 | 8.2 | 98.9 | 99.6 | 99.9 | 99.9 | 100.0 | 100.0 |

Note: 1. Values in body of table show the probability of rejection for the specified number of samples and true 'maximum'.

2. 'True % NC' stands for 'true % non-compliance'.

To understand the table, it is helpful first to look at the spaced-out row near the foot of the table. This represents the borderline case in which the true mean and true 'maximum' are 2.33 and zero standard deviations respectively below the PCV. The third column shows a true % non-compliance of zero (because the 'maximum' complies exactly with the PCV). The remainder of the row confirms that, whatever the number of samples, the scheme has been designed to give a probability of rejection of 90%.
Now look at the ‘no. of samples – 2’ column. This shows how the probability of rejection decreases with improving quality. For example, when the ‘maximum’ is one standard deviation below the PCV, the probability of rejection falls to 44.7%; with a further decrease in ‘maximum’ to two standard deviations below the PCV, the probability of rejection falls to just 6.1%.

Conversely, a deterioration in the ‘maximum’ to half a standard deviation ABOVE the PCV increases the probability of rejection to 97.7%. Moreover, the true % non-compliance in that situation is still quite small, namely 2.4%. (In this case the true mean is 1.83*S below the PCV. Thus the true compliance with the PCV is 96.6%; and this is 2.4% below the required 99% compliance figure taken in this example to define the ‘maximum’.)

Even with just two samples, therefore, even a relatively small deterioration will be picked up effectively by a Normality-based scheme. And the sensitivity further improves when greater numbers of samples are used.

Other columns in the table can be interpreted in a similar way. One key point to note is the diagonal pattern in the table: this quantifies the way in which the more samples the scheme is based upon, the nearer may the true mean quality be permitted to drift towards the PCV. The case mentioned earlier, for example, which had a 44.7% probability of rejection with means of two samples, has only a slight chance of rejection (1.5%) with means of 12 samples.

D.6 SUMMARY OF ACTUAL MEANS AND STANDARD DEVIATIONS

The approach described in preceding sections does critically rely on the parameter’s mean and standard deviation both being well below the PCV. To help determine the circumstances in which this would be a reasonable assumption, individual means and standard deviations for each parameter were extracted from the zone-by-zone summary files produced by the statistical fingerprinting program (see Appendix B), and a grand plot then produced of standard deviation against mean.

The plot for iron is shown in Table D.8. It summarises a total of 134 sampling locations (a mixture of ex-works, service reservoir, fixed taps and random). The sets of statistics for these 134 sites were derived from a total of 14 028 data values - of which 18% were below-than values.

The chart consists of a 10 × 10 grid running at intervals of 0.1*PCV, with ‘overspill’ areas beyond the two solid PCV lines. The bottom left-hand cell represents the situation in which both mean and standard deviation are less than 0.1*PCV. In this example, 110 of the 174 sites fall into this category. At the other extreme, four sites have standard deviations greater than the PCV - the mean also being greater than the PCV in one case.
Table D.8  Standard deviation v. mean plot for iron

<table>
<thead>
<tr>
<th>St.dev v. Mean summary for parameter 209 : Fe</th>
<th>No. of sites: 134</th>
<th>TotN, &amp; % of Tot&lt;s therein: 14028 18%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PCV</td>
<td></td>
</tr>
<tr>
<td>:</td>
<td>:</td>
<td>:</td>
</tr>
<tr>
<td>1:</td>
<td>1:</td>
<td>1:</td>
</tr>
<tr>
<td>:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^ .9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^ .8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^ .7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>^ .6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>St.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dev.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.4</td>
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<tr>
<td>.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:</td>
<td></td>
<td></td>
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<tr>
<td>:</td>
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<td>:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1 .2 .3 .4 .5 .6 .7 .8 .9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean --->

The values presented in Tables D.1 to D.6 show that, even with modest levels of confidence and definitions of 'maximum', the approach has little chance of practical success unless the standard deviation is 0.2*PCV or less. A convenient way of further summarising Table D.7, therefore, is to quote the totals and percentages in (i) the bottom left-hand cell and (ii) the bottom left-hand quartet of cells. For iron, as seen above, these figures are 48 (64%) and 54 (72%). Similar summaries for all other available parameters, ranked in decreasing order of the '<0.1*PCV’ percentage, are provided in Table D.9.
| Parameter | No. of sites | No. and % of sites for which mean and st.dev are both: |  |  |
|-----------|-------------|---------------------------------------------------------|-----------------|
|           |             | < 0.1*PCV                                              | < 0.2*PCV       |  |
| Zn        | 40          | 40 100%                                                | 40 100%         |  |
| Ba        | 19          | 19 100%                                                | 19 100%         |  |
| Alpha_E   | 19          | 19 100%                                                | 19 100%         |  |
| TCE       | 17          | 17 100%                                                | 17 100%         |  |
| Aminotr   | 6           | 6 100%                                                 | 6 100%          |  |
| Chlororda | 5           | 5 100%                                                 | 5 100%          |  |
| Cu        | 53          | 51 96%                                                 | 52 98%          |  |
| Lindane   | 21          | 20 95%                                                 | 21 100%         |  |
| TetCE     | 17          | 16 94%                                                 | 17 100%         |  |
| P         | 63          | 59 93%                                                 | 60 95%          |  |
| As        | 24          | 21 87%                                                 | 21 87%          |  |
| Dielndri  | 23          | 20 86%                                                 | 21 91%          |  |
| Fe        | 134         | 110 82%                                                | 116 86%         |  |
| Aldrin    | 34          | 28 82%                                                 | 29 85%          |  |
| Cyanide   | 28          | 23 82%                                                 | 23 82%          |  |
| Endrin    | 17          | 14 82%                                                 | 15 88%          |  |
| B3,4P     | 17          | 14 82%                                                 | 15 88%          |  |
| Alpha_H   | 27          | 22 81%                                                 | 23 85%          |  |
| Fluoride  | 35          | 28 80%                                                 | 31 88%          |  |
| Cd        | 26          | 21 80%                                                 | 23 88%          |  |
| TetCM     | 23          | 18 78%                                                 | 22 95%          |  |
| Cr        | 23          | 18 78%                                                 | 20 86%          |  |
| Al        | 97          | 74 76%                                                 | 85 87%          |  |
| Ni        | 26          | 20 76%                                                 | 22 84%          |  |
| Mn        | 126         | 93 73%                                                 | 109 86%         |  |
| Beta En   | 19          | 14 73%                                                 | 19 100%         |  |
| Hg        | 13          | 9 69%                                                  | 10 76%          |  |
| Amm       | 122         | 83 68%                                                 | 105 86%         |  |
| Se        | 29          | 19 65%                                                 | 19 65%          |  |
| Heptach   | 20          | 13 65%                                                 | 14 70%          |  |
| pp_TDE    | 22          | 14 63%                                                 | 14 63%          |  |
| Heptach   | 19          | 12 63%                                                 | 12 63%          |  |
| Taste ql  | 24          | 15 62%                                                 | 15 62%          |  |
| Odour ql  | 24          | 15 62%                                                 | 15 62%          |  |
| pp_DDE    | 22          | 13 59%                                                 | 13 59%          |  |
| Nitrite   | 116         | 65 56%                                                 | 91 78%          |  |
| Na        | 30          | 16 53%                                                 | 22 73%          |  |
| Pb        | 42          | 22 52%                                                 | 25 59%          |  |
| Pesttot   | 14          | 7 50%                                                  | 12 85%          |  |

81
<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of sites</th>
<th>No. and % of sites for which mean and st.dev are both:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt; 0.1*PCV</td>
<td>&lt; 0.2*PCV</td>
</tr>
<tr>
<td>Turbidity</td>
<td>133</td>
<td>64 48%</td>
<td>103 77%</td>
</tr>
<tr>
<td>Ag</td>
<td>23</td>
<td>11 47%</td>
<td>19 82%</td>
</tr>
<tr>
<td>Sb</td>
<td>24</td>
<td>11 45%</td>
<td>12 50%</td>
</tr>
<tr>
<td>Nitrate</td>
<td>117</td>
<td>50 42%</td>
<td>98 83%</td>
</tr>
<tr>
<td>Mg</td>
<td>41</td>
<td>16 39%</td>
<td>27 65%</td>
</tr>
<tr>
<td>Mecopro</td>
<td>26</td>
<td>10 38%</td>
<td>22 84%</td>
</tr>
<tr>
<td>Chloride</td>
<td>54</td>
<td>20 37%</td>
<td>48 88%</td>
</tr>
<tr>
<td>Dichlor</td>
<td>11</td>
<td>4 36%</td>
<td>8 72%</td>
</tr>
<tr>
<td>Total PAH</td>
<td>29</td>
<td>10 34%</td>
<td>18 62%</td>
</tr>
<tr>
<td>Triflur</td>
<td>6</td>
<td>2 33%</td>
<td>6 100%</td>
</tr>
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<td>26</td>
<td>8 30%</td>
<td>14 53%</td>
</tr>
<tr>
<td>pp_DDT</td>
<td>27</td>
<td>7 25%</td>
<td>21 77%</td>
</tr>
<tr>
<td>OxY</td>
<td>27</td>
<td>6 22%</td>
<td>10 37%</td>
</tr>
<tr>
<td>Atrazine</td>
<td>24</td>
<td>5 20%</td>
<td>13 54%</td>
</tr>
<tr>
<td>Taste</td>
<td>43</td>
<td>8 18%</td>
<td>12 27%</td>
</tr>
<tr>
<td>Odour</td>
<td>43</td>
<td>7 16%</td>
<td>11 25%</td>
</tr>
<tr>
<td>Hard</td>
<td>42</td>
<td>7 16%</td>
<td>7 16%</td>
</tr>
<tr>
<td>Alk</td>
<td>43</td>
<td>7 16%</td>
<td>7 16%</td>
</tr>
<tr>
<td>Trietaz</td>
<td>6</td>
<td>1 16%</td>
<td>6 100%</td>
</tr>
<tr>
<td>Clopyra</td>
<td>6</td>
<td>1 16%</td>
<td>6 100%</td>
</tr>
<tr>
<td>Surfnts</td>
<td>19</td>
<td>3 15%</td>
<td>8 42%</td>
</tr>
<tr>
<td>SO4</td>
<td>69</td>
<td>9 13%</td>
<td>22 31%</td>
</tr>
<tr>
<td>Isoprot</td>
<td>23</td>
<td>3 13%</td>
<td>15 65%</td>
</tr>
<tr>
<td>K</td>
<td>40</td>
<td>5 12%</td>
<td>18 45%</td>
</tr>
<tr>
<td>Ca</td>
<td>32</td>
<td>4 12%</td>
<td>11 34%</td>
</tr>
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<td>Simazin</td>
<td>26</td>
<td>3 11%</td>
<td>18 69%</td>
</tr>
<tr>
<td>Col</td>
<td>109</td>
<td>11 10%</td>
<td>47 43%</td>
</tr>
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<td>Condcty</td>
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<td>6 7%</td>
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</tr>
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<td>Dicamba</td>
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<td>3 3%</td>
</tr>
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<td>2 2%</td>
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<td>17 73%</td>
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<tr>
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<td>0 0%</td>
<td>15 88%</td>
</tr>
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<td>0 0%</td>
<td>13 100%</td>
</tr>
<tr>
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<td>13 61%</td>
</tr>
<tr>
<td>Diazino</td>
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<td>0 0%</td>
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</tr>
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<td>11 91%</td>
</tr>
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<td>Malathi</td>
<td>8</td>
<td>0 0%</td>
<td>8 100%</td>
</tr>
<tr>
<td>Dichlor</td>
<td>9</td>
<td>0 0%</td>
<td>8 88%</td>
</tr>
<tr>
<td>Prometr</td>
<td>9</td>
<td>0 0%</td>
<td>8 88%</td>
</tr>
<tr>
<td>Azinpho</td>
<td>14</td>
<td>0 0%</td>
<td>8 57%</td>
</tr>
</tbody>
</table>

82
<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of sites</th>
<th>No. and % of sites for which mean and st.dev are both:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$&lt; 0.1 \times \text{PCV}$</td>
<td>$&lt; 0.2 \times \text{PCV}$</td>
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</tr>
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<td>7</td>
<td>100%</td>
</tr>
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<td>Chlorto</td>
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<td>0%</td>
<td>7</td>
<td>63%</td>
</tr>
<tr>
<td>&quot;&quot;&quot;2,4_D&quot;&quot;&quot;&quot;</td>
<td>14</td>
<td>0</td>
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<td>50%</td>
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<td>100%</td>
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<td>0%</td>
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<td>100%</td>
</tr>
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<td>0%</td>
<td>6</td>
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</tr>
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<td>54%</td>
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<td>30%</td>
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<td>0%</td>
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<td>40%</td>
</tr>
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<td>0%</td>
<td>2</td>
<td>25%</td>
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<td>0%</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>Carbeta</td>
<td>6</td>
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<td>0%</td>
<td>0</td>
<td>0%</td>
</tr>
</tbody>
</table>
APPENDIX E  NUMBERS OF SAMPLES IN RELATION TO
ZONE SIZE

E.1 INTRODUCTION

This appendix addresses the issue of random sampling in a supply zone, with particular
reference to the effect of zone size on the protection provided. To avoid unnecessary
complications, the discussion here will be confined to the Standard range of frequencies.
(The effectiveness of the present mechanisms in the regulations for switching between
Reduced, Standard and Increased frequencies is taken up later in Appendix F.)

The methodology outlined in Appendix C enables the number of samples to be determined
so as to provide the following assurance (where F and C are any desired percentage values):

- If the true % non-compliance is as poor as F%, there must be C% confidence that
the programme will produce at least one PCV failure out of n random samples
(and hence detect the non-compliance).

That methodology applies irrespective of the nature or size of the underlying statistical
population. In the present context, the statistical population can be visualised as a rectangle
of M taps by 365 days, embracing all the locations and moments in time that have an
opportunity of being sampled. Thus, the assurance provided by the programme with C%
certainty is that the ‘worst case’ number of failed tap-years will be no more than F% of
the total 365*M tap-years.

The specific consequences of this general result are explored in the following sections.

E.2 PROTECTION ACHIEVED BY EXISTING SAMPLE NUMBERS

For most parameters, the number of samples stipulated by the Regulations increases broadly
in proportion with zone size (up to the maximum of 50 000 population). This will be
referred to in the following discussion as the ‘pro-rata’ rule.

On the basis of the Appendix C methodology, Table E.1 shows the protection provided for a
standard range of "Table 1" sample numbers and zone sizes. The worst-case values listed in
the table all relate to a figure of 90% confidence.

The table reveals that the pro rata rule built into the Regulations protects against a constant
number of ‘failed tap-years’ whatever the zone size (the only exception to this being Zone
A, which is proportionately over-sampled). This is in fact a general result that is derived in
Annex I at the end of this appendix.

For this particular set of sample numbers, the worst-case number of failed tap-years is
around 1900. If lower or higher confidence is required, the failed tap-years figure will be
correspondingly smaller or larger. This is illustrated by Table E.2, which shows the

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protection provided for confidence levels of 50%, 95% and 99%. (The 90% case is repeated for completeness). Thus, a problem as small as 600 failed tap-years will be detected with about 50% confidence, whereas one as large as 3600 failed tap-years will be detected with 99% confidence.

**Table E.1 Protection provided (at 90% confidence) by pro-rata sample numbers for different zone sizes**

<table>
<thead>
<tr>
<th>Zone population size</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard sampling freq (for Table 1 parameters)</td>
<td>: 500</td>
<td>5000</td>
<td>10000</td>
<td>20000</td>
<td>35000</td>
<td>50000</td>
</tr>
<tr>
<td>: 4</td>
<td>6</td>
<td>12</td>
<td>24</td>
<td>42</td>
<td>60</td>
<td></td>
</tr>
</tbody>
</table>

Worst-case values (at 90% confidence)

| % compliance | : 56.2 | 68.1 | 82.5 | 90.9 | 94.7 | 96.2 |
| % non-compliance | : 43.8 | 31.9 | 17.5 | 9.1 | 5.3 | 3.8 |
| No. of failed tap-years | : 218 | 1593 | 1745 | 1829 | 1867 | 1882 |

One apparent drawback with the pro-rata rule, in that consumers experience a different PROPORTIONAL risk according to the size of zone they live in. Thus, Table E.1 shows that in Zone A, 43.8% - or nearly half - of the consumers could be suffering non-compliant water before a PCV failure was very likely (i.e. the probability of detection is 90%); but in Zone F, the corresponding proportion is only 4%!

Whether or not this is a real point of concern depends very much on how those failures are spread through time and/or spatially - as discussed in the next two sections.

**E.3 CONSEQUENCES OF SPATIAL PROBLEMS IN WATER QUALITY**

Suppose there is a problem associated with a specific part of the distribution system which affects about 2000 consumers. Those consumers would constitute 40% of a small zone (of size 5000), but only 4% of a large zone (of size 50 000). However, the magnitude of that percentage figure is irrelevant. What matters to the consumers is the chance that their particular problem is picked up; and, as Table E.1 shows, a failure lasting for 2000 tap-years is just severe enough to be picked up with better than 90% confidence in any size of zone.
This desirable property of pro-rata random sampling can be summarised as follows:

With pro-rata sampling, a ‘problem pocket’ in the distribution system has roughly the same chance of being detected whether it is contained within a small zone or a large zone.

Table E.2  Protection provided by pro-rata sample numbers (at various levels of confidence) for different zone sizes

<table>
<thead>
<tr>
<th>Zone population size</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard sampling freq (for “Table 1” paras)</td>
<td>500</td>
<td>500</td>
<td>10000</td>
<td>20000</td>
<td>35000</td>
<td>50000</td>
</tr>
</tbody>
</table>

Worst-case values (at 50% confidence)

| % compliance | 84.1 | 89.1 | 94.4 | 97.2 | 98.4 | 98.9 |
| % non-compliance | 15.9 | 10.9 | 5.6 | 2.8 | 1.6 | 1.1 |

No. of failed tap-years

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>79</td>
<td>543</td>
<td>561</td>
<td>569</td>
<td>572</td>
<td>574</td>
</tr>
</tbody>
</table>

Worst-case values (at 90% confidence)

| % compliance | 56.2 | 68.1 | 82.5 | 90.9 | 94.7 | 96.2 |
| % non-compliance | 43.8 | 31.9 | 17.5 | 9.1 | 5.3 | 3.8 |

No. of failed tap-years

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>218</td>
<td>1593</td>
<td>1745</td>
<td>1829</td>
<td>1867</td>
<td>1882</td>
</tr>
</tbody>
</table>

Worst-case values (at 95% confidence)

| % compliance | 47.3 | 60.7 | 77.9 | 88.3 | 93.1 | 95.1 |
| % non-compliance | 52.7 | 39.3 | 22.1 | 11.7 | 6.9 | 4.9 |

No. of failed tap-years

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>263</td>
<td>1965</td>
<td>2209</td>
<td>2346</td>
<td>2409</td>
<td>2435</td>
</tr>
</tbody>
</table>

Worst-case values (at 99% confidence)

| % compliance | 31.6 | 46.4 | 68.1 | 82.5 | 89.6 | 92.6 |
| % non-compliance | 68.4 | 53.6 | 31.9 | 17.5 | 10.4 | 7.4 |

<table>
<thead>
<tr>
<th>No. of failed tap-years</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>341</td>
<td>2679</td>
<td>3187</td>
<td>3491</td>
<td>3634</td>
<td>3694</td>
<td></td>
</tr>
</tbody>
</table>
E.4 CONSEQUENCES OF TEMPORAL PROBLEMS IN WATER QUALITY

Suppose now that there is a persistent problem with the water ENTERING the distribution system, such that a particular PCV is exceeded for 9% of the time during the course of the year. Would a non-compliance rate of this magnitude be detected with 90% confidence?

For a zone of size 20 000, the answer would be ‘yes’. Table E.1 shows that 24 samples would be just sufficient to pick up an underlying non-compliance rate of 9% with 90% confidence. For zones smaller than this, however, the probability of detection is less. In a 5000 zone, for example, the true non-compliance rate must climb to 32% before a failure will be detected with 90% confidence. The converse effect is seen with larger zone sizes. At the maximum zone size of 50 000, for example, a non-compliance rate as low as 3.8% will be detected with 90% confidence.

In this sense, therefore, the consumer does under the current arrangements receive greater protection the larger the zone. Or, putting this the other way round, a consumer’s worst-case risk of exposure to non-compliant water entering supply increases as zone size gets smaller. If this were thought undesirable, the solution would be to have a constant number of samples irrespective of zone size.  

To illustrate this further, suppose that the total amount of sampling shown in Table E.1 were divided equally across Zones A to F (instead of being spread in proportion to zone size). This results in a figure of 24 samples per zone; and the protection that this provides at 90% confidence is shown in Table E.3.

Note that the results for Zone D are the same as in Table E.1, because they derive from 24 samples in each case. But now, the worst-case number of failed tap-years changes in direct proportion to zone size. For Zone F, the number of failed tap days could be as high as 4600 before the problem was likely to be detected; whilst for Zone A (100 times smaller) just 46 failed tap-years would trigger a PCV failure with the same probability (viz 90%).

To summarise, therefore:

With fixed-number sampling, an intermittent problem of given duration in the water supply is equally likely to be detected whatever the zone size. With pro-rata sampling, on the other hand, the greater the zone, the more likely it is for such a problem to be detected.

---

1 This is the principle behind opinion poll sampling: the imprecision in the percentage estimate of any attribute is determined entirely by the number of samples; the size of the sampled population is irrelevant.
Table E.3  Protection provided (at 90% confidence) by fixed sample numbers for different zone sizes

<table>
<thead>
<tr>
<th>Zone size</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pro-rata freq.</td>
<td>500</td>
<td>5000</td>
<td>10000</td>
<td>20000</td>
<td>35000</td>
<td>50000</td>
<td>148</td>
</tr>
<tr>
<td>Fixed freq.</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>24</td>
<td>42</td>
<td>60</td>
<td>144</td>
</tr>
<tr>
<td>Worst-case</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(at 90% conf.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% compliance</td>
<td>90.9</td>
<td>90.9</td>
<td>90.9</td>
<td>90.9</td>
<td>90.9</td>
<td>90.9</td>
<td></td>
</tr>
<tr>
<td>% non-comp.</td>
<td>9.1</td>
<td>9.1</td>
<td>9.1</td>
<td>9.1</td>
<td>9.1</td>
<td>9.1</td>
<td></td>
</tr>
<tr>
<td>No. of failed</td>
<td>46</td>
<td>457</td>
<td>915</td>
<td>1829</td>
<td>3201</td>
<td>4573</td>
<td></td>
</tr>
<tr>
<td>tap-years</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E.5  THE CHOICE OF ZONES

The sub-division of a region into a number of zones according to the supply source has clear advantages whenever there are known - or potential - differences in water quality from one source to another. Any PCV failures that may occur (other than those attributable to local effects in the distribution system) will tend to cluster in a relatively small number of problem zones, thereby facilitating both follow-up investigation and any remedial action that may be necessary.

The benefits of zoning are not so apparent where a single very large supply area is broken down into zones solely on geographical or administrative convenience. This is especially the case when (as at present) the sample numbers are chosen in proportion to zone size. For example, consider the following question:

Which is better: 60 random samples taken in a 50 000 zone, or 12 random samples in each of five separate 10 000 zones?

This can be answered with the help of Table E.1. With a single large zone, the 60 samples protect with 90% confidence against a true non-compliance of 3.8%, or 1882 tap-years failing a particular PCV. With 12 samples in each of the five small zones, on the other hand, the worst-case non-compliance is 17.5%, or 1750 tap-years in each zone. To judge which of these (if either) is preferable, it is helpful to consider the two extremes of problem that can arise: spatial, and temporal.
E.5.1 Spatially-related non-compliance

Suppose the cause of non-compliance is a SPATIAL problem - amounting to, say, 1750 failed tap-years. As seen earlier, it is immaterial whether this occurs in a small zone or a large one: there is roughly a 90% probability of detection in either case. In fact, this continues to hold even when the problem area straddles two neighbouring zones - as the example in Table E.4 shows. As far as spatial problems are concerned, therefore, there are neither advantages nor disadvantages in arbitrarily zoning an area: the exercise is statistically neutral.

Table E.4 Detecting a spatial problem that straddles two zones

Suppose there are 1000 failed tap-years in Zone P and 750 in Zone Q.

1. Probability of failure given two separate zones, P and Q

   In Zone P, the true compliance is 9000/10000, or 90.0%; and so
   \[ \text{Prob}[\text{all 12 samples} < \text{PCV}] = (.90)^{**12} = .282. \]

   In Zone Q, the true compliance is 9250/10000, or 92.5%; and so
   \[ \text{Prob}[\text{all 12 samples} < \text{PCV}] = (.925)^{**12} = .392. \]

   Thus the chance of at least one PCV failure in Zone P or Zone Q is:

   \[ 1 - (.282)\times(.392) = .889 \text{ or } 88.9\% \]

2. Probability of failure given one pooled zone, (P + Q)

   The true compliance over the two pooled zones is 18250/20000, or 91.25%;
   and so

   \[ \text{Prob}[\text{all 24 samples} < \text{PCV}] = (.9125)^{**24} = .111. \]

   The chance of at least one PCV failure is therefore:

   \[ 1 - .111 = .889 \text{ or } 88.9\% \text{ again.} \]

E.5.2 Temporally-related non-compliance

Suppose instead that the cause of non-compliance is TEMPORAL, whereby occasional problems with the water entering supply cause the true compliance to be 96.2% in each of the five zones.
Again, the consequences can be found from the statistical details in Table F.1. When the five small zones are regarded as one large zone of size 50,000, the probability of detection is 90%. In other words, non-compliance as severe as this can be detected with 90% confidence. Now consider each of the five small zones. The probability of detection in any one specific zone is only 37%. However, the chance of AT LEAST ONE of the five zones failing is $1 - (1-.37)^5 = .90$, or 90%; and this is exactly the same as the probability of detection for the single 50,000 zone.

Again, therefore, it transpires that nothing is gained or lost statistically by arbitrarily subdividing an area into zones: the probability of detecting a temporal pattern of non-compliance is the same whether a given amount of sampling is organised across one large zone or a number of smaller zones.

The validity of this conclusion does, however, rely on the assumption that a failure in any one of the five zones will be recognised as indicative of a potentially more widespread problem in that geographical grouping of zones. Put another way, when a single very large zone is required to be arbitrarily sub-divided, it is important that a parameter failure in one of those sub-zones is not regarded solely as information about that one specific sub-zone. Given the wealth of local experience and expertise generally available, there is little danger of this happening in the companies themselves. However, the formal reporting process under the present Regulatory arrangements does place considerable emphasis on the results for individual zones, and this brings the risk of an inappropriate response to PCV failures. In particular, a move to increased frequencies in a single (possibly irrelevant) sub-zone could well be less effective than a less protracted but wider-ranging investigation.
ANNEX I  ACHIEVING A CONSTANT NUMBER OF FAILED TAP-YEARS

Suppose the true compliance in a zone of size Z is 100p%.

Then for n random samples to detect non-compliance with C% confidence, the following must hold:

\[ P^{**n} = 1 - \frac{C}{100} = a, \text{ say, and so} \]
\[ n \log(p) = \log(a). \]

Moreover, the worst-case number of failed tap-years, x, is

\[ x = Z(1-p), \text{ and so} \]
\[ p = 1 - \frac{x}{Z}. \]

The required number of samples, n, can therefore be expressed as:

\[ n = \frac{\log(a)}{\log(1 - \frac{x}{Z})}. \]  \hspace{1cm} (1)

Assuming that x is small in relation to Z, \( \log(1 - \frac{x}{Z}) \) can be approximated by \(-\frac{x}{Z}\), and so expression (1) becomes:

\[ n = \frac{-\log(a)*Z}{x} \]

Thus the number of samples is proportional to zone size.

Numerical illustration:

For C = 90% confidence and x = 2000, a = 0.10, and so

\[ n = \frac{-\log(.10)*Z}{2000} = .00115*Z \]

Thus for zone sizes of 5000, 20 000 and 50 000, the required sample numbers would be 6, 23 and 57.
APPENDIX F  EFFECTIVENESS OF THE 'INCREASED FREQUENCY' RULE

F.1  BACKGROUND

If, during the course of a year’s monitoring at 'Standard' frequency, a parameter value contravenes its PCV, the Regulations in most circumstances require the water undertaker to switch immediately to an 'Increased' frequency for the remainder of the current year and throughout the following year. If all samples in that period then meet the PCV, the frequency reverts to Standard.

As Table F.1 shows, the Increased frequency may be anything from double to 12 times the Standard frequency depending on the parameter type and also (to a lesser extent) zone size. The table also lists the 'Reduced' frequencies that apply, for certain parameters, in cases when all samples over a three-year period have met the relevant PCV. From this lower base level, a subsequent PCV failure will generally trigger a greater proportional change in sample numbers, the most pronounced being the 24-fold increase in sampling required for "Table 3" parameters in zone size 35 000 and above.

F.2  POSSIBLE REASONS FOR AN INCREASED FREQUENCY RULE

In order to evaluate the statistical merits of the Increased frequency trigger mechanism, it is first necessary to consider what such a mechanism might be intended to achieve. It is suggested that two plausible objectives are:

1. to provide confirmatory evidence of a failure to comply; and

2. to provide reassurance that the failure was a ‘one-off’.

Either objective lends itself to quantitative assessment by means of the ‘probability of detection’ measure discussed earlier in the report. More specifically, the Increased frequency rule can be judged quantitatively by its success in meeting (i) or (ii) in comparison with the success achieved when monitoring only at Standard frequencies.

A non-parametric statistical model has been developed to handle the details of the comparison; this is briefly outlined in the next section. The remainder of the appendix then discusses the model’s application to various typical combinations of Standard and Increased frequencies.
## Table F.1 Reduced, Standard and Increased frequencies specified in the Regulations

<table>
<thead>
<tr>
<th>Parameter group</th>
<th>Zone size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
</tr>
</tbody>
</table>

"Table 1" (Gr.W)

<table>
<thead>
<tr>
<th>Reduced freq.</th>
<th>4</th>
<th>4</th>
<th>6</th>
<th>11</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard freq.</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>Increased freq.</td>
<td>12</td>
<td>12</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incr./Reduced</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Incr./Standard</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Table 1" (Surf.W)

<table>
<thead>
<tr>
<th>Reduced freq.</th>
<th>4</th>
<th>6</th>
<th>12</th>
<th>21</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard freq.</td>
<td>4</td>
<td>6</td>
<td>12</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>Increased freq.</td>
<td>12</td>
<td>12</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incr./Reduced</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Incr./Standard</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

"Table 2"

<table>
<thead>
<tr>
<th>Reduced freq.</th>
<th>4</th>
<th>5</th>
<th>5</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard freq.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Increased freq.</td>
<td>12</td>
<td>12</td>
<td>24</td>
<td>24</td>
<td>36</td>
<td>48</td>
</tr>
<tr>
<td>Incr./Reduced</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incr./Standard</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>3.6</td>
<td>4.8</td>
</tr>
</tbody>
</table>

"Table 3"

<table>
<thead>
<tr>
<th>Reduced freq.</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard freq.</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Increased freq.</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Incr./Reduced</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>Incr./Standard</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

"Table 4"

<table>
<thead>
<tr>
<th>Standard freq.</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased freq.</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Incr./Standard</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>
F.3 STATISTICAL METHOD

Suppose that the Standard frequency is \( n \) samples per annum. The model evaluates the following two sampling regimes:

* 'Standard' This defines the 'laissez-faire' or base-line case in which samples continue at the Standard rate irrespective of the outcome in Year 1. Thus Periods 1 & 2 both last for 12 months, and \( 2^*N \) samples are taken in all.

* 'Std+Incr' This proceeds as per the Base scheme unless a failure occurs during Period 1. In that case, Period 2 starts immediately and extends to the end of the following year. Also, the sampling frequency is increased by a factor \( F \) throughout Period 2. The total no. of samples will accordingly be \( 2^*N \) (if no failures occur in Period 1), or otherwise lie between \((1+F)^*N\) and \(1 + F^*(2^*N-1).\)

Now the behaviour of the two schemes can be evaluated. Over the two periods each scheme has four possible outcomes: pass-pass, pass-fail, fail-pass, or fail-fail. For any assumed true compliance rate 100p\%, the probabilities of the four outcomes can be calculated by 'chasing through' the appropriate individual probabilities. With the Standard scheme, for example:

\[
\text{Prob [ first PCV failure occurring ]} \\
\text{[ at exactly the r-th sample ]} = (1-p)^*p^{**}(r-1), \text{ and}
\]

\[
\text{Prob [ zero PCV failures subseq. ]} \\
\text{[ in Period 2 ]} = p^{**}(2n-r).
\]

(Note: ** denotes 'raised to the power of'.)

Under the Standard scheme, therefore, the probability of a failure on the r-th sample in Period 1 followed by a pass in Period 2 is:

\[
\text{Prob [ r-fail, pass ]} = (1-p)^*p^{**}(2n-1).
\]  \( (1) \)

Thus the overall probability of a fail-pass is the sum of Expression (1) over all values of \( r \) from 1 to \( n \).

Program N1N2 has been written to carry out all the statistical details. An example of the output from N1N2 can be seen in Table F.2. This represents the situation in which:

- the true underlying compliance rate is 99\%; and
- the Standard annual sampling frequency of 12; and
- the Increased frequency is 24.
Table F.2  Example of the output from program N1N2

<table>
<thead>
<tr>
<th>N, outcome</th>
<th>N, outcome</th>
<th>Prob. of joint outcome</th>
<th>Conditional prob. of detecting a failure during Period 2 given stated Period 1 outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 pass</td>
<td>12 pass</td>
<td>78.6%</td>
<td>11.4%</td>
</tr>
<tr>
<td>12 fail</td>
<td>12 fail</td>
<td>10.1%</td>
<td></td>
</tr>
<tr>
<td>1 fail</td>
<td>46 pass</td>
<td>.6%</td>
<td></td>
</tr>
<tr>
<td>2 fail</td>
<td>44 pass</td>
<td>.6%</td>
<td></td>
</tr>
<tr>
<td>3 fail</td>
<td>42 pass</td>
<td>.6%</td>
<td></td>
</tr>
<tr>
<td>4 fail</td>
<td>40 pass</td>
<td>.6%</td>
<td></td>
</tr>
<tr>
<td>5 fail</td>
<td>38 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>6 fail</td>
<td>36 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>7 fail</td>
<td>34 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>8 fail</td>
<td>32 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>9 fail</td>
<td>30 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>10 fail</td>
<td>28 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>11 fail</td>
<td>26 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td>12 fail</td>
<td>24 pass</td>
<td>.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>pass</td>
<td>8.0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>fail</td>
<td>3.4%</td>
<td></td>
</tr>
</tbody>
</table>

Total prob. of Period 1 failure: 11.4%

Overall prob. of detecting failure in Period 2:  13.4%

Mean total no. of samples over Periods 1 & 2:  26.0

(Nfact = 1.083)

Prob. of success in Period 2 given failure in Period 1...

at Standard freq: 88.6%

at Increased freq: 70.3%
The first row of the table shows the pass-pass outcome: this has a probability of 78.6%. Immediately below this is the pass-fail case, for which the probability is 10.1%. The sum of these two values, 88.7%, is therefore the overall probability of a pass in Period 1. Thus the probability of a failure in Period 1 is 100 - 88.7 = 11.3%. (Rounding has distorted this slightly: a more precise figure is 11.4%.) Moreover, because the numbers of samples for Periods 1 and 2 are equal, in this part of the table, 11.4% is also the probability of a failure in Period 2.

The more complicated event to consider is where there is a failure in Period 1, because now there are 12 ways in which that can arise. Table F.2 deals with each case in turn. Take, for example, the case of a failure on the third sample. This would trigger the end of Period 1 and the start of an extended Period 2 lasting for 42 samples; and the joint probabilities of fail-pass and fail-fail are 0.6% and 0.3% respectively. The figure of 34.4% in the right-hand column is the CONDITIONAL probability of failure GIVEN THAT the Period 1 failure occurred. This is much higher than the 11.4% figure at the top of the table because there are 42 rather than 12 opportunities for the PCV failure to occur.

In all, the table shows 12 pairs of probabilities representing all the (mutually exclusive) events that begin with a Period 1 failure. These should therefore add up to the overall probability of a failure in Period 1, namely 11.4%; and Program N1N2 confirms this check total. It also shows how it breaks down between fail-pass (8.0%) and fail-fail (3.4%).

The final column of the table quantifies the way in which the probability of detection varies according to what has happened in Period 1. These outcomes are not, of course, all equally likely. Much the most probable occurrence in Period 1 is a pass (88.6%), with each of the other 12 outcomes having a probability of occurrence of only 1% or so. The overall probability of detection in Period 2 can therefore be calculated as a weighted average of the right-hand column values, with weights equal to their probabilities of occurrence. The result of this is 13.4% - a value 2% greater than the detection probability that applies under the Standard sampling regime.

The program also similarly calculates the weighted average number of samples called for by the Std+Incr regime over the two years - 26.0 in this case. Thus the slight increase in the overall probability of detection is accompanied by an increase of about 8% in the required number of samples.

The final two rows of the table provide answers to Objectives (i) and (ii) stated earlier, namely to give reassurance or otherwise that the failure was a ‘one-off’. With Standard sampling, there is a high probability -88.6% - of obtaining no PCV failures in Period 2, and so concluding (incorrectly) that there is no underlying problem. Under the Std+Incr regime, in contrast, the probability of concluding that the problem has disappeared, though still high, does fall substantially - to 70.3%.
F.4 EXTENSION TO OTHER LEVELS OF TRUE COMPLIANCE

The detailed results in Table F.2 relate to just one assumed value of the true % compliance, namely 99%. The N1N2 model has similarly been run for a variety of other true % compliance values (for the moment keeping the Standard and Increased frequencies at 12 and 24). A summary table of the results is presented in Table F.3.

Table F.3 Summary of N1N2 model results for (12,24) frequencies

<table>
<thead>
<tr>
<th>True % compliance</th>
<th>Overall % probability of obtaining a PCV failure in Period 2...</th>
<th>% probability of [fail given prev.fail]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard regime:</td>
<td>Std+Incr regime:</td>
</tr>
<tr>
<td>99.5</td>
<td>5.8</td>
<td>6.4</td>
</tr>
<tr>
<td>99</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>98</td>
<td>21</td>
<td>28</td>
</tr>
<tr>
<td>95</td>
<td>46</td>
<td>63</td>
</tr>
<tr>
<td>90</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>80</td>
<td>93</td>
<td>99</td>
</tr>
</tbody>
</table>

Note: 1. N column shows average number of samples required under Std+Incr regime.
2. Nfact denotes factor by which average number of samples increases under Std+Incr regime.
3. Entries in the two ‘Standard regime’ columns are identical because Period 2 frequencies stay the same whatever happens in Period 1.

In all the cases considered in Table F.3, the true compliance is less than 100% and so the correct outcome would be for the zone to fail. Whether or not this is the ACTUAL outcome, however, depends very much on the severity of the non-compliance. When the true compliance is 99.5%, a Standard frequency programme has a high probability (94%) of incorrectly passing the zone. That is, it will throw up a failure only about one year in 20. But when the non-compliance is as poor as 80%, the Standard programme will almost certainly reach the correct conclusion - that is, fail the zone.

How does the Std+Incr regime improve these detection rates? Again, the answer is that it depends very much on the true level of non-compliance. In the case of 99.5% true compliance, the overall probability of detection increases only slightly - from 5.8 to 6.4%. That is because Increased frequencies are called into play so rarely: the Nfact value of 1.04 shows that there is an expected increase of only 4% in the average number of samples actually required. On the rare occasions that the Increased frequency does get triggered, however, the conditional probability of detection shows almost a three-fold
increase. In other words, the Std+Incr regime is three times as effective as the Standard regime in confirming that a problem does exist. It should be remembered, however, that even the Std+Incr programme is much more likely than not to pass the zone - in which case the frequency will revert to Standard and the chance of detection will drop still further.

At the other extreme, a true compliance of only 90% will almost certainly trigger a confirmatory failure under the Std+Incr regime (97%); but the probability of detection under the Standard regime (72%) is already high enough to produce a zone failure nearly three years in four. Moreover, the extra sampling does now become appreciable: the price of that modest extra assurance amounts now to a 55% increase in the average number of samples.

For the 12,24 combination of frequencies, therefore, the benefits of the Std+Incr regime are most evident only within a fairly narrow range of true compliance values. In the vicinity of 98% true compliance, in particular, a 16% increase in sampling can improve the confirmatory detection rate from one year in five (21%) to one year in two (51%).

F.5 GENERALISATION TO OTHER STANDARD AND INCREASED FREQUENCIES

The summary in Table F.3 relates solely to the case of Standard and Increased frequencies of 12 and 24. To widen the scope of the results, the N1N2 program was run for four other pairs of frequencies typical of many of those in the Regulations, namely: 1,12; 4,24; 6,24; and 4,12. The results are summarised in Table F.4. For completeness, the table also repeats the results for the 12,24 case. Thus the example discussed in the previous section for 90% true compliance can readily be identified in the final column. The quartets of values in other cells of the table are interpreted in exactly the same way.

As the footnote to the table indicates, two measures of effectiveness can be obtained from the table:

- the OVERALL effectiveness of the Std+Incr regime in comparison with the Standard regime can be judged by contrasting the first two PoD% values in any cell of the table. When the true compliance is 98%, for example, the probability of detection is 7.8% with a Standard regime of 4 samples, and increases to 9.4% with a Std+Incr regime of 4 samples increasing to 12.

- The CONDITIONAL effectiveness of the Std+Incr regime is shown by contrasting the first and THIRD PoD% figures in any cell. In the example just mentioned, for example, there is a 28.3% probability of detection with the increased frequency - much better than the 7.8% chance under the Standard frequency - GIVEN THAT THERE HAS BEEN A FAILURE IN PERIOD 1. This can be a misleading comparison, however, in view of the rarity (7.8%) with which a Period 1 failure occurs in the first place!
The general picture painted by Table F.4 is that the additional statistical effectiveness of the Std+Incr regime is marginal - a benefit, moreover, that may take as long as two years to materialise. In addition, the administrative disruption caused by sudden switches from Standard to Increased frequencies should not be forgotten.

Bearing all these points in mind, accordingly, it is suggested that a simpler and preferable approach would be to ensure that the Standard frequencies were chosen in the first place so as to provide an adequate degree of protection against PCV failures.
Table F.4  Summary of N1N2 model results for other frequencies

<table>
<thead>
<tr>
<th>True % compl’ce</th>
<th>Pairs of Standard and Increased frequencies</th>
<th>1,12</th>
<th>4,24</th>
<th>6,24</th>
<th>4,12</th>
<th>12,24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PoD% Nfact</td>
<td>PoD% Nfact</td>
<td>PoD% Nfact</td>
<td>PoD% Nfact</td>
<td>PoD% Nfact</td>
<td>PoD% Nfact</td>
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<td>.5</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
<td>5.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.5</td>
<td>1.03</td>
<td>2.2</td>
<td>1.07</td>
<td>3.3</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
<td>15.2</td>
<td>15.6</td>
<td>7.9</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>1.0</td>
<td>3.9</td>
<td>5.9</td>
<td>3.9</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1</td>
<td>1.06</td>
<td>4.9</td>
<td>1.1</td>
<td>7.2</td>
<td>1.1</td>
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<td></td>
<td>11.4</td>
<td>18.1</td>
<td>18.9</td>
<td>15.3</td>
<td>29.7</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>2.0</td>
<td>7.8</td>
<td>11.4</td>
<td>7.8</td>
<td>21.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>1.1</td>
<td>10.9</td>
<td>1.3</td>
<td>15.8</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>21.5</td>
<td>48.3</td>
<td>49.4</td>
<td>28.3</td>
<td>50.7</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>5.0</td>
<td>18.5</td>
<td>26.5</td>
<td>18.5</td>
<td>46.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7.0</td>
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<td>30.1</td>
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<td>41.2</td>
<td>1.6</td>
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<tr>
<td></td>
<td>46.0</td>
<td>80.9</td>
<td>82.0</td>
<td>56.9</td>
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</tr>
<tr>
<td>90</td>
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<td>46.9</td>
<td>34.4</td>
<td>71.8</td>
<td></td>
</tr>
<tr>
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<td>16.2</td>
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<td>70.3</td>
<td>2.0</td>
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<td>71.8</td>
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<td>96.8</td>
<td>82.1</td>
<td>97.5</td>
<td></td>
</tr>
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<td>80</td>
<td>20.0</td>
<td>59.0</td>
<td>73.8</td>
<td>59.0</td>
<td>93.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>34.6</td>
<td>2.1</td>
<td>83.2</td>
<td>3.1</td>
<td>93.1</td>
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<td>99.9</td>
<td>99.9</td>
<td>97.2</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
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<td>93.8</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
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<td>99.6</td>
<td>4.7</td>
<td>100.0</td>
<td>3.5</td>
</tr>
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<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: 1. The PoD% columns give the Probability of Detection for:
   (i) the Standard frequency regime,
   (ii) the Std+Incr regime (overall); and
   (iii) the Std+Incr regime (conditional on a failure in Period 1)

2. The Nfact columns show the average factor by which the sampling frequency increases in moving from the Standard to the Std+Incr frequency regime.
APPENDIX G  STANDARDS OTHER THAN MAXIMUM-TYPE LIMITS

G.1 INTRODUCTION

Table G.1 gives details of the small number of parameters for which the Regulations permit criteria that are less stringent than 100% PCV compliance. This appendix addresses the statistical behaviour of such schemes.

Table G.1 Parameters for which 100% compliance is not required

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC</td>
<td>No sig. increase over that normally observed.</td>
</tr>
<tr>
<td>Colony counts</td>
<td>No sig. increase over that normally observed.</td>
</tr>
<tr>
<td>Table D parameters</td>
<td>Rolling 12-month mean &lt;= PCV</td>
</tr>
<tr>
<td>THMs</td>
<td>If n is 4 or more: Rolling 3-month mean &lt;= PCV</td>
</tr>
<tr>
<td>Sodium</td>
<td>&gt;=80% of samples over previous 36 months &lt;= PCV</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>If n &gt;= 50: At least 95% of samples must be zero. Otherwise: The most recent 50 must be zero.</td>
</tr>
</tbody>
</table>

G.2 ROLLING MEAN COMPLIANCE

The statistical methodology developed in Appendix D for ‘predictable’ parameters assumed that:

(i) water quality followed an underlying Normal distribution; and

(ii) the PCV limit could be interpreted for practical purposes as a suitably high percentile such as the 99.9%ile.

This approach can readily be adapted to the case of a mean limit simply by defining the limit in (ii) as the 50%ile (which is equivalent to the mean for Normal populations). Moreover, the Central Limit Theorem ensures that assumption (i) will be at least approximately upheld whatever the parameter.

The output from the Appendix D program is shown in Table G.2.
Table G.2  Minimum values of (PCV - mean), in standard deviation units, required to demonstrate compliance with the stated confidence.

* Standard deviation assumed known.
* PCV defined as an arithmetic mean.

<table>
<thead>
<tr>
<th>Confidence of conclusion</th>
<th>No of samples</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>12</th>
<th>24</th>
<th>52</th>
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</thead>
<tbody>
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<td>.0</td>
<td>.0</td>
<td>.0</td>
<td>.0</td>
<td>.0</td>
</tr>
<tr>
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<td>.4</td>
<td>.3</td>
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<td>.1</td>
<td>.1</td>
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<td>.5</td>
<td>.4</td>
<td>.2</td>
<td>.2</td>
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<td>.4</td>
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<td>.2</td>
<td>.2</td>
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<tr>
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<td>1.6</td>
<td>1.2</td>
<td>.9</td>
<td>.8</td>
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<td>.2</td>
<td>.2</td>
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<td>.4</td>
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</tr>
<tr>
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<td>1.2</td>
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<td>1.4</td>
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<td>.4</td>
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<tr>
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<td>1.8</td>
<td>1.5</td>
<td>.9</td>
<td>.6</td>
<td>.4</td>
<td>.4</td>
</tr>
</tbody>
</table>

Note: The table shows the amount (in st.dev. units) by which the sample mean must fall below the PCV to provide the stated confidence that the true mean is below the PCV.

For any given number of samples, Table G.2 shows how far below the PCV the sample mean would need to be in order to achieve various specified levels of confidence. The special case of 50% confidence (see the top row of the table) is where no allowance is made for sampling error, and a straightforward 'face-value' approach is taken to compliance. This in fact is the approach described in Table G.1 for the "Table D" parameters and THMs. Thus, (borderline) compliance is achieved when the observed mean is equal to the PCV mean limit, and there is then only a 50:50 chance that the TRUE mean is below the PCV.

To show the consequences of the face-value approach, the power calculation program from Appendix D was run for the case of 50% confidence. The resulting output is shown in Table G.3. Take, for example, the case of means based on four samples. When the true mean is one standard deviation below the PCV, the probability of detection is only 2.3% - that is, compliance can almost be guaranteed: conversely, detection is very likely (97.7%) when the true mean deteriorates to one standard deviation ABOVE the PCV. But for true means within this concentration band, the compliance response will be indeterminate.
Table G.3  Statistical power of a ‘face-value’ mean compliance rule

<table>
<thead>
<tr>
<th>No. of st.devs below PCV for:</th>
<th>True mean</th>
<th>True % NC</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>12</th>
<th>24</th>
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<td>.0</td>
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<td>.0</td>
</tr>
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<td>.0</td>
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<td>7.9</td>
<td>4.2</td>
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<td>92.1</td>
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<td>97.7</td>
<td>100.0</td>
<td>100.0</td>
<td>.0</td>
</tr>
<tr>
<td>-1.00</td>
<td>39.4</td>
<td>89.4</td>
<td>96.1</td>
<td>98.5</td>
<td>99.4</td>
<td>100.0</td>
<td>100.0</td>
<td>.0</td>
</tr>
<tr>
<td>-1.25</td>
<td>43.3</td>
<td>93.3</td>
<td>98.3</td>
<td>99.5</td>
<td>99.9</td>
<td>100.0</td>
<td>100.0</td>
<td>.0</td>
</tr>
<tr>
<td>-1.50</td>
<td>46.0</td>
<td>96.0</td>
<td>99.3</td>
<td>99.9</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>.0</td>
</tr>
<tr>
<td>-2.00</td>
<td>47.7</td>
<td>97.7</td>
<td>99.8</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>.0</td>
</tr>
</tbody>
</table>

Note: 1. Values in body of table show the probability of rejection for the specified number of samples and true mean.
2. ‘True % NC’ stands for ‘true % non-compliance’.

The results for other sample numbers may be interpreted similarly, and show how the ‘indeterminate concentration band’ narrows with increasing sample numbers. With 12 samples, for example, the compliance outcome will be correct on more than 90% of occasions (i.e. years) whenever the true mean is more than half a standard deviation away from the PCV.

G.3 PERCENTAGE COMPLIANCE

G.3.1 The 80% rule for sodium

The Standard and Increased frequencies for sodium (Table 4 of the Regulations) are 1 and 12 per annum. Over three years, therefore, the total number of samples will lie between 3 and 36 - of which at least 80% must meet the PCV. With 36 samples, for example, at least ‘28.8 values’ must comply - that is, no more than 7 PCV failures are allowed.
Given an observed non-compliance of 20%, how much poorer might the true % non-compliance be? This can be calculated, for any desired level of confidence, by standard binomial sampling theory. For example, given 7 failures out of 36 samples it can be stated with 90% confidence that the true non-compliance is no poorer than 30.5%, and with 99% confidence that it is no poorer than 39.1%.

Similar calculations for other sample numbers in the range 3 to 36 are summarised in Table G.4. These exhibit the saw-tooth pattern characteristic of all % compliance rules, whereby the effectiveness, or ‘power’, of the regime gradually increases with increasing sample numbers, but slips back periodically each time one additional failure is permitted.

<table>
<thead>
<tr>
<th>Number of samples</th>
<th>Max. allowed number of failures</th>
<th>True % non-compliance detectable with:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90% conf.</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>53.6</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>43.8</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>58.4</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>36.8</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>45.0</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>33.7</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>39.3</td>
</tr>
<tr>
<td>19</td>
<td>3</td>
<td>31.9</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>36.1</td>
</tr>
<tr>
<td>24</td>
<td>4</td>
<td>30.6</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>34.0</td>
</tr>
<tr>
<td>29</td>
<td>5</td>
<td>29.7</td>
</tr>
<tr>
<td>30</td>
<td>6</td>
<td>32.5</td>
</tr>
<tr>
<td>34</td>
<td>6</td>
<td>28.9</td>
</tr>
<tr>
<td>35</td>
<td>7</td>
<td>31.3</td>
</tr>
<tr>
<td>36</td>
<td>7</td>
<td>30.5</td>
</tr>
</tbody>
</table>

The broad message from Table G.4 is that compliance with the 80% rule, even when based on several years of increased frequency data, guarantees only that the true non-compliance is probably no worse than about 40%; whilst for smaller sample numbers the true non-compliance may be substantially in excess of 50%. Thus there is little difference in practice between this rule and the more widely applied rolling mean rule — which makes it questionable whether the 80% variant is worth retaining. However, it should be noted that this rule is a requirement of the Directive.
G.3.2 The 95% rule for total coliforms

The binomial approach used to quantify the 80% sodium rule can similarly be applied to the case of the '95% of samples' rule for total coliforms (noting that the rule applies only when 50 or more samples are available). The results are summarised in Table G.5.

The most striking feature to be seen is the sharp discontinuity in the performance of the compliance rule at the point when fewer than 50 samples become available. Compliance on the basis of 50 samples ensures (with 90% confidence) that the true non-compliance is no worse than about 10%. But with 49 samples, the sudden tightening in the compliance rule brings a two-fold reduction - to 4.7% - in the worst-case non-compliance value.

This juxtaposing of percentage and absolute compliance rules is in fact statistically incoherent - as can be illustrated by the following scenario. If, out of 49 samples, just one is found to produce a positive coliform count, the result is failure. But suppose those 49 samples are augmented by one further positive sample. This clearly constitutes a poorer picture than before; and yet the presence of two positive coliforms in 50 samples is deemed a pass!

<table>
<thead>
<tr>
<th>Number of samples</th>
<th>Max. allowed number of failures</th>
<th>True % non-compliance detectable with:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90% conf.</td>
</tr>
<tr>
<td>48</td>
<td>0</td>
<td>4.7</td>
</tr>
<tr>
<td>50</td>
<td>2</td>
<td>10.3</td>
</tr>
<tr>
<td>59</td>
<td>2</td>
<td>8.8</td>
</tr>
<tr>
<td>60</td>
<td>3</td>
<td>10.8</td>
</tr>
<tr>
<td>79</td>
<td>3</td>
<td>8.3</td>
</tr>
<tr>
<td>80</td>
<td>4</td>
<td>9.7</td>
</tr>
<tr>
<td>99</td>
<td>4</td>
<td>7.9</td>
</tr>
<tr>
<td>100</td>
<td>5</td>
<td>9.1</td>
</tr>
<tr>
<td>119</td>
<td>5</td>
<td>7.7</td>
</tr>
<tr>
<td>120</td>
<td>6</td>
<td>8.6</td>
</tr>
</tbody>
</table>

A more consistent mechanism - that is, one whose statistical power was broadly similar at sample numbers both below and above 50 - would be to demand zero failures only below 36 samples, and to permit a single coliform failure for sample numbers between 36 and 49. In particular, a rule that allowed one failure in as few as 36 samples would still ensure with 90% confidence that the true non-compliance was no worse than 10.4%. However, the present rule is a requirement of the Directive.
G.4 NO SIGNIFICANT INCREASES

This form of wording - used both for TOC and for colony counts - is unhelpfully vague. In the first place, the Regulations do not indicate whether 'significant' is to be interpreted as meaning 'statistically significant' or 'practically significant'. Secondly, no guidance is given (whichever interpretation is intended) as to the practical method by which 'significance' is to be judged.

It is accordingly recommended that the 'no significant increase' criterion is replaced, in any revision of the Regulations, by an explicit statement of the criteria that the sample values are required to meet.
APPENDIX H  QUESTIONNAIRE USED IN DISCUSSIONS WITH WATER COMPANIES

1. Location, type and number of samples

1.1 Over a typical year, what is the approximate split in your total number of samples\(^{(1)}\) from the water supply and distribution system?

<table>
<thead>
<tr>
<th>Location</th>
<th>Compliance</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ex-source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk supply(^{(2)})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ex-works</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Service reservoirs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution - fixed points</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distribution - random points</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (specify)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total                     |            |             | 100%  |

Notes
\(^{(1)}\) A single sample is taken from one point at one time. This may be analysed for many parameters. Water purchased from another company.

\(^{(2)}\) Water purchased from another company.

1.3 Do you make operational use of your compliance data? If so, how?

1.4 How are random points chosen?

1.5 How are fixed points chosen?

1.6 Does the water quality data indicate which values are from random and which are from fixed samples? Similarly, compliance and non-compliance?

1.7 How many samples does a sampling officer collect in a typical working day:
* when visiting fixed points?
* when visiting random points?

1.8 What problems are associated with sampling from random points? How severe are they?

1.9 As 1.8, for fixed points.
2. Variations with time and location

2.1 Which parameters do you believe are most/least likely to show some degree of systematic variation through time -
   * seasonally?
   * according to day of week?
   * diurnally?

2.2 How representative is your sampling programme:
   * over the 7 day week?
   * over the 24 hour day?

2.3 Which parameters do you believe are most/least likely to show some degree of systematic variation through the distribution system?

2.4 Which parameters do you believe have a tendency to be 'unpredictable' - that is, cause you to be least confident about predicting their next value given their past history?

2.5 What impact is your mains lining programme having on water quality (if you have one)?

3. Supply zones

3.1 In your company, are supply zones defined:
   * by supply type or source?
   * having regard to perceived problem areas?
   * for geographical convenience?
   * arbitrarily?
   * other criteria?

3.2 Where you have multiple sources supplying a zone, do you often/ever have problems in identifying an 'authorised supply point'?

3.3 In your company, what are the main factors governing differences in drinking water quality (if any) between zones:
   * surface v. groundwater sources?
   * bankside storage v. direct abstraction?
   * urban v. rural?
   * other?

3.4 How important or useful do you find the 'zones' concept in compliance monitoring?
4. Analysis costs

4.1 In your company, what are typical costs of analysis:
   * per pesticide? total pesticides?
   * per PAH? total PAHs?
   * other organics?
   * other parameters? (single out any exceptional costs)

4.2 What is a typical approximate split of total analysis costs?

<table>
<thead>
<tr>
<th>Parameter group</th>
<th>Compliance</th>
<th>Other</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pesticides</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other organics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bacteriological</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Others(^1)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

Note 1 Specify any that require a particularly high proportion of the analysis costs.

5. Pesticides

5.1 Which specific pesticides does your company analyse for, and how are those parameters identified in your data records?

5.2 Is it the practice in your company to correct pesticide analyses for under-recovery?

5.3 How is ‘total pesticides’ calculated?

6. Confidence in the measured concentrations

6.1 For the more problematical parameters (e.g. pesticides), what confidence do you feel can be placed on the sample results? For example:

   Order of magnitude only?
   \(+Y\%\) to \(-X\%\) ?
   Likelihood of false positives?... or false negatives?
   Analytical error a large % of total variation?

6.2 From your AQC results, have there been any noteworthy improvements in analytical error over the past three years - e.g. for pesticides?
6.3 In your view, how severely may results be influenced by the manner in which the sample is taken from the consumer's tap? Are you happy that all practical steps are taken to standardise on sampling protocol?

7. Scheduling

7.1 Do the sampling frequencies prescribed in the regulations give rise to any scheduling problems?

7.2 Would you prefer e.g. daily/weekly/monthly/quarterly frequencies? (Possibly at the price of rather higher overall frequencies.)

7.3 The Regulations prescribe a variety of different monitoring frequencies according to the parameter (and its past history). What practical problems do you find in 'dovetailing' the various monitoring programmes so as to permit an adequate amount of cross-checking between parameters?

8. Compliance interpretation

8.1 For Total organic carbon, how do you interpret the requirement "No significant increase over that normally observed"?

8.2 As 8.1, for Colony counts.

9. General

9.1 How strongly do you agree with this assertion?

Drinking water quality is primarily safeguarded not by the results of sampling, but rather by the integrity of a water company's entire spectrum of activities - engineering, scientific and operational.

9.2 How important a contribution do you believe monitoring makes to the overall level of assurance associated with a drinking water supply?

9.3 What future changes in the monitoring and/or compliance regime would you most - or least - like to see?

9.4 Are there any significant issues with the current regulations that have not already been covered?
APPENDIX I  ESTIMATED ANALYSIS COSTS - THE IMPLICATIONS OF THE RECOMMENDED CHANGES

In this appendix some simple calculations of the impact on analysis costs of the recommended changes to the Regulations are presented. Three cases are considered:

- a zone with a population of 5000 (Tables I.2 and I.3);
- a zone with a population of 40 000 (Tables I.4 and I.5);
- the effect of combining four zones into a big zone with a population of 150 000 (Table I.6).

The analysis costs assumed (Table I.1) are those that local authorities are permitted to charge for carrying out analyses of private water supplies, taken from Schedule 5 of HMSO (1991b). For simplicity, parameters are considered in the groups used in the Regulations, listed there in Tables 1 to 4, and 6.

Several sampling regimes are considered:

- for the current Regulations, standard frequencies, and with Table 3 parameters at reduced and increased frequency;
- for the recommended changes, standard frequencies, and with tables 3 and 4 at reduced frequencies.

The cost implications of the recommended changes are based on a minimum standard frequency of four per year. The extra cost of raising the minimum to six is shown at the foot of the relevant tables.

The results suggest that the overall analysis costs would be unlikely to change significantly if the recommendations were to be adopted (with a minimum standard frequency of four per year), although the implications will vary between water companies, depending on their current mix of zone sizes, and the degree to which increased frequencies apply.

<table>
<thead>
<tr>
<th>Table in the Regulations</th>
<th>Cost per analysis (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>350</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
</tr>
</tbody>
</table>

113
Table I.2  Annual sampling frequencies - Zone population 5000

<table>
<thead>
<tr>
<th>Table</th>
<th>Current Regulations</th>
<th>Recommended changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Increased</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>12</td>
</tr>
</tbody>
</table>

Note*: or 6.

Table I.3  Analysis costs compared - Zone population 5000 (£/year)

<table>
<thead>
<tr>
<th>Current Regulations regime</th>
<th>Cost (£/year)</th>
<th>Recommended changes regime</th>
<th>Cost (£/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>1950</td>
<td>Standard*</td>
<td>3000</td>
</tr>
<tr>
<td>Table 3 reduced</td>
<td>1140</td>
<td>Table 4 reduced</td>
<td>2300</td>
</tr>
<tr>
<td>Table 3 increased</td>
<td>2750</td>
<td>Tables 3 and 4 reduced</td>
<td>1760</td>
</tr>
</tbody>
</table>

Note*: The effect of a minimum frequency of 6 is to add £1220 to the estimated annual analysis costs.

Table I.4  Annual sampling frequencies - Zone population 40 000

<table>
<thead>
<tr>
<th>Table</th>
<th>Current Regulations</th>
<th>Recommended changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Standard</td>
<td>Increased</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>96</td>
</tr>
</tbody>
</table>

Note*: or 6.
<table>
<thead>
<tr>
<th>Current Regulations regime</th>
<th>Cost (£/year)</th>
<th>Recommended changes regime</th>
<th>Cost (£/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>4950</td>
<td>Standard*</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Table 4 reduced</td>
<td>5300</td>
</tr>
<tr>
<td>Table 3 reduced</td>
<td>4140</td>
<td>Tables 3 and 4 reduced</td>
<td>4760</td>
</tr>
<tr>
<td>Table 3 increased</td>
<td>6950</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note *: The effect of a minimum frequency of 6 is to add £1140 to the estimated annual analysis costs.

<table>
<thead>
<tr>
<th>Table</th>
<th>Four zones Frequency</th>
<th>Analysis cost (£/year)</th>
<th>Single large zone Frequency</th>
<th>Analysis cost (£/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180</td>
<td>3600</td>
<td>180</td>
<td>3600</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
<td>1600</td>
<td>30</td>
<td>1200</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>3240</td>
<td>12*</td>
<td>3240</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>1050</td>
<td>4</td>
<td>1400</td>
</tr>
<tr>
<td>6</td>
<td>360</td>
<td>7200</td>
<td>360</td>
<td>7200</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>16690</td>
<td></td>
<td>16640</td>
</tr>
</tbody>
</table>

Note *: assuming two supplies with authorised sampling points