  Journal of Water Supply: Research and Technology—AQUA | 51.8 | 2002

Copper in drinking water supplies and gastrointestinal illness in England and Wales: a risk assessment

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ABSTRACT

This paper examines possible health risks from copper in drinking water supplies in England and Wales, with particular reference to gastrointestinal illness. This is done within the standard risk characterisation model, coupled with the use of an outline quality audit framework to examine the strength of the findings. The hazard source is identified in terms of naturally occurring and anthropogenic contributions, leading to monitored levels of copper in drinking water supplies. Dose response is estimated from scientific evidence for gastrointestinal effects from copper ingestion. Exposure is estimated by extrapolation from available data. It is shown from the overall risk characterisation that there is a 1 in 17,000 probability of exposure to levels of copper above 3 mg/l. Of the population exposed to elevated copper levels in their drinking water, 20% are likely to become ill. The outline quality audit ratings provide guidance on interpretation of these findings.

Key words | copper, drinking water, health effects, quality audit, risk assessment

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INTRODUCTION

The purpose of this paper is to estimate risks of gastrointestinal illness from elevated levels (3 mg/l or over) of copper in public drinking water supplies in England and Wales, and to couple this with an indication of the strength of that estimate. The widespread use of copper in domestic plumbing, together with its acknowledged emetic effects, suggest the need for undertaking a systematic assessment of risk. It is noted, in passing, that this (the first published) risk assessment post-dates new World Health Organization (WHO) guidelines and European Union (EU) legislation relating to this metal (see also Fewtrell *et al.* 2001*a*). The WHO guideline value of 2 mg/l has been adopted by the EU and from 25 December 2003, will be applied to drinking water in England and Wales. It is suggested that the core of the approach demonstrated in this paper could be used as an exemplar for risk assessment and related outline quality audits for other cases of waterborne risk.

RISK CHARACTERISATION

The general model for risk assessment provided by the USA National Research Council represents risk characterisation (the core scientific process of estimating risk) as the integration of three distinct stages (National Research Council 1983).

Hazard assessment

This stage investigates the nature and strength of evidence that an environmental agent can potentially cause harm (i.e. is recognisable as a hazard source). The evidence may come from tests on animals, coupled with inferences about possible human effects; or from case studies of people known to have been exposed to the agent of interest; or from human volunteer experiments.

Table 1 | Quality audit framework (adapted from Macgill *et al.* 2000)

Aspect	Criterion	Question	Assessment	Score
Observation	Measure	How close a match is there between what is being observed and the measure adopted to observe it?	Primary	4
			Standard	3
			Convenience	2
			Symbolic	1
			Inertia	0
	Data	How strong is the empirical content?	Bespoke/ideal	4
			Direct/good	3
			Calculated/limited	2
			Educated guess	1
			Uneducated guess	0
	Sensitivity	How critical is the measure to the stability of the result?	Strong	4
			Resilient	3
			Variable	2
			Weak	1
			Wild	0
Method	Theory	How strong is the theoretical base?	Laws	4
			Well-tested theories	3
			Emerging theories/comp. models	2
			Hypothesis/statistical processing	1
			Working definitions	0
	Robustness	How robust is the result to changes in methodological specification?	Strong	4
			Resilient	3
			Variable	2
			Weak	1
			Wild	0

Table 1 | (*Continued*)

Aspect	Criterion	Question	Assessment	Score
Output	Accuracy	Has a true representation of the real world been achieved?	Absolute	4
			High	3
			Plausible	2
			Doubtful	1
			Poor	0
	Precision	Is the degree of precision adequate and appropriate?	Excellent	4
			Good	3
			Fair	2
			Poor	1
			False/unknowable	0
Peer review	Standing	How widely reviewed and accepted is the process and the outcome?	Wide and accepted	4
			Moderate and accepted	3
			Limited review and/or medium acceptance	2
			Little review and/or little acceptance	1
			No review and/or not accepted	0
	State of the Art	What is the degree of peer consensus about the state of the art of the field?	Gold standard	4
			Good	3
			Competing/developing field	2
			Embryonic field	1
			No opinion	0
Validity	Completeness	How sure are we that the analysis is complete?	Full	4
			Majority	3
			Partial	2
			Little	1
			None	0

Also 'scores' under each criterion for unknown (—) and not applicable (na).

Dose-response assessment

This identifies the relationship between the dose of a substance and the extent of any resulting health effects. Calibration of dose-response models may lead to the identification of critical threshold levels below which there are no observed adverse effects, or alternatively to representation of the classic U shape of the dose-response relationship for chemical essential elements (moderate doses beneficial to health; low and high doses both harmful to health). The conclusions from dose-response assessments are often controversial, as there can be large measurement errors, possible misinterpretation of symptoms, and often the conclusions rely on statistical analysis that is vulnerable to manipulation. It is also difficult to be absolutely sure that the observed responses are indeed caused by the substance being tested, and not by some other cause; this is especially true for the majority of human exposure circumstances.

Exposure assessment

This seeks to establish the intensity, duration and frequency of the exposure that a human population experiences. There is a great deal of uncertainty here, owing to difficulties in measuring dilute concentrations of substances far from their originating source, and in predicting population distribution patterns relative to those concentrations.

As the cumulative integration of these three stages, characterisation of risk from copper in drinking water will produce a quantitative estimate of the likelihood and extent of human health impairment resulting from the presence of copper concentrations in public water supplies.

QUALITY AUDIT

The strength of risk characterisation findings (inversely related to degree of uncertainty in the corresponding science) will be different for different risks. For some the corresponding science will be strong and robust, and conclusions can be communicated and used with confidence. For others, there will be uncertainties. Such uncertainties give cause for greater caution in the interpretation and utilisation of findings. Instances of uncertainties at the dose-response stage (Havelaar *et al.* 2000) include:

- Imprecision of population exposure assessment.
- Unknown, and possibly unknowable, shape of the dose-response curves at low, environmental levels of exposure.
- Translation of this information from one species to another as well as from one population to another.
- Internal and external validity of epidemiological results.
- Need to use simple models in the face of limited availability of data.
- Nature and extent of assumptions that are made, both qualitative (which models to use) and quantitative (choice of parameters and parameter values).

In recognition of uncertainties, we have favoured the use of a quality audit framework for systematically representing the strength of risk estimates (Macgill *et al.* 2000; Fewtrell *et al.* 2001*b*). Adapting the work of Funtowicz & Ravetz (1990), this recognises that there is a generic structure to the type of uncertainties associated with the characterisation of waterborne risk, and indeed in other risk assessment contexts. This structure maps onto a checklist of questions that can be used to interrogate, in turn, the five fundamental dimensions of any scientific study, namely:

- Strength of the empirical base.
- Strength of the theoretical base.
- Accuracy and precision of reported findings.
- Standing of the findings among peers.
- Validity of the findings to end-use requirements (a policy context).

The questions are shown in Table 1, together with possible categories of response. This provides a framework for a systematic outline audit of the strength of the science underpinning any chosen element of a risk characterisation process, including any assumptions made. In the present paper this framework is applied to the stages of

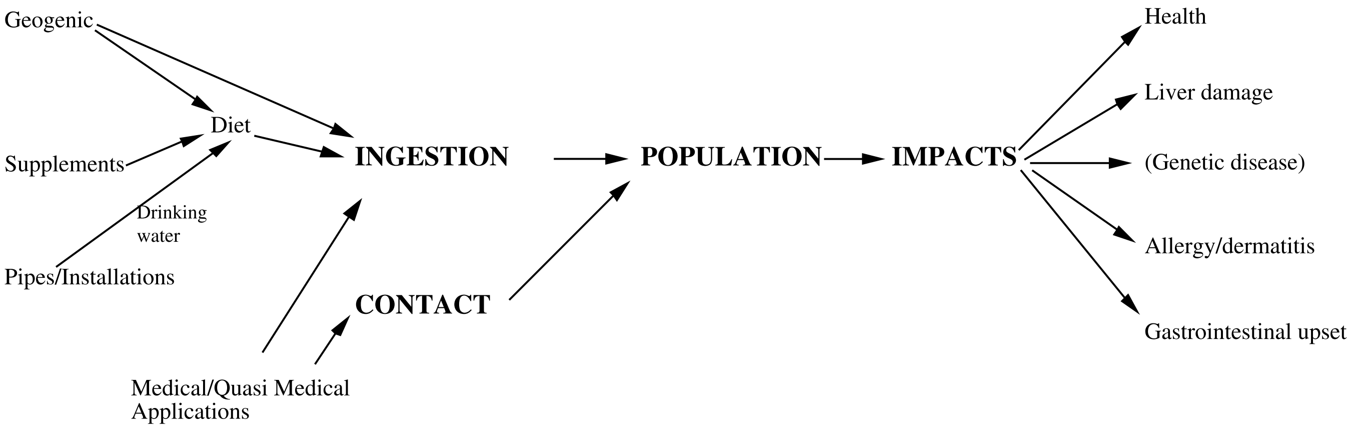

Figure 1 | Logic tree for human exposure to copper.

characterising the risk of copper in drinking water supplies in England and Wales.

HAZARD IDENTIFICATION

Copper can cause a number of toxic effects, including liver damage (generally thought to have a genetic component–Scheinberg & Sternlieb 1994) and gastro-intestinal upsets. Although copper can have negative health impacts it is an essential element and some intake is, therefore, vital for good health. The pathways for human exposure to copper (excluding occupational exposure) are indicated in Figure 1, along with a list of possible impacts. Copper is best known for its gastro-intestinal effects, indeed historically it has been used as an emetic (Karlsson & Noren 1965), and it is this aspect that will be examined further. Ingestion is the only active pathway for gastrointestinal effects and a number of reports of drinking-water-induced copper gastrointestinal toxicity have appeared in the literature (Spitalny *et al.* 1984; Knobeloch *et al.* 1994; Kramer *et al.* 1996), as have others relating to the consumption of copper-contaminated drinks (reviewed in Fitzgerald, 1995).

The concentration of copper occurring naturally in water as a result of soil weathering is low, in the order of a few micrograms (μg) per litre. However, in some countries copper is a major component of water distribution mains, and it is commonly used as a plumbing material. It may be present in the water supply pipe (connecting the water main to the household's external stopcock) and/or in the household piping (connecting the external stopcock to the internal plumbing and/or in the internal plumbing and installations). It has been estimated that the majority of household installations in Great Britain are copper-based (Arens 1999). While copper pipes have a number of useful properties in terms of water distribution they may also, in certain circumstances, lead to the release of copper resulting in potentially high concentrations in drinking water. Indeed, in the UK, domestic plumbing is the principal source of copper in drinking water and levels of copper much above the background concentration of 10 μg/l, are likely to reflect leaching of copper from plumbing fixtures and copper piping. This process depends upon pH, hardness and carbon dioxide content of the water and also the length of time the water is in contact with the pipe or fixture. First draw water, from pipes subject to copper leaching, will have the greatest levels of copper contamination. Clearly, individual exposure will be affected by the extent to which such water is used for cooking and beverage preparation.

Measurement of copper in drinking water is well established and can be done with a high degree of accuracy and confidence in the results. This is reflected by an overall score of 95% in an outline quality audit of the

Table 2 | Exceedences to the UK drinking water copper standard by water supplier and year

Supplier [Pop. supplied[a]]	Year 1990	1991	1992	1993	1994	1995†	1996	1997†	1998	1999
Anglian Water [3,900,000]				1 (1,330)						
Dwr Cymru [2,800,000]	1 (2,980)	1 (3,404)	1 (1,236)							
East Anglian [242,000][b]	1 (96)									
Mid Kent [536,700]	1 (175)									
Mid Southern [729,000]							2 (185)			
North West [6,800,000]			2 (5,176)	1 (4,951)	1 (2,108)		1 (2,486)		1 (1,376)	1 (1,416)
Northumbrian [2,600,000]	1 (1,418)	3 (1,343)								
South Staffordshire [1,200,000]		1 (174)		1 (475)	2 (477)					
Southern Water [2,190,000]				1 (550)						
Suffolk Water [242,000][b]			1 (76)							
Thames Water [7,600,000]				2 (1,091)	2 (1,079)		1 (977)			
Three Valleys [2,300,000]										
Wessex Water [1,200,000]	1 (552)									

( ) represents the number of samples taken. Only those suppliers who record exceedences are shown.
†No recorded failures.
[a]Population figures based on DWI (1998).
[b]East Anglian and Suffolk Water serve the same population (and reflect merger and take-over activity).

determination of copper from drinking water samples using induction coupled plasma mass spectrometry (details not shown).

Current UK legislation (Water Supply (Water Quality) Regulations 1989) lays down that levels of copper in drinking water (as supplied at the consumer's tap) should not exceed 3 mg/l, although this will be reduced to 2 mg/l effective from the end of 2003 (Water Supply (Water Quality) Regulations 2000). Samples are the first litre of water that issues from the consumers' taps during a daytime visit to randomly selected houses. Monitoring data detailing the number of exceedences to the 3 mg/l standard date back (in easily accessible form) to 1990. Information on actual concentrations is not readily available. Table 2 outlines the number of samples exceeding 3 mg/l recorded between 1990 and 1999.

In a 10-year period, 31 samples have been found to exceed 3 mg/l. Requirements are laid down within UK legislation and water companies are audited by the Drinking Water Inspectorate to ensure that they are achieving suitable standards and that methodologies, sampling procedures and so on are appropriate. It is reasonable, therefore, to expect that these data are of good quality and reasonably consistent between different water companies. Their relative strength, as inputs to risk assessment, is represented in the outline quality audit in Table 3. There are some areas of weakness (reflected in the scores of 2 or 2–3 under data availability, sensitivity, accuracy and completeness), but the overall picture is of a reasonable base of evidence.

DOSE-RESPONSE ASSESSMENT

It is well established that copper can cause emetic effects. The degree to which copper in drinking water causes gastrointestinal effects, however, is less clear. As mentioned earlier, a number of incidents have been reported in the literature with values of copper ranging from just over 3 mg/l to over 100 mg/l. While such incident reports are important they generally do not consider confounding factors or document a dose-response relationship.

The first study examining the effects of known copper levels in drinking water was published by Pizarro *et al.* in 1999. In this study, 60 healthy adult women were exposed to differing levels of copper (as copper sulphate) in their drinking water (0, 1, 3 and 5 mg/l) over an 11-week period. Participants were exposed to each copper concentration for 2 weeks, with a 'clear' week (consuming their normal tap water) in between each different intake level. The volunteers were split into four groups, each of which received a different pattern of copper intake (Latin-square design). Water consumption and gastrointestinal symptoms were recorded daily. Gastrointestinal symptoms were recorded by 21 (35%) of the participants sometime during the study (nine had diarrhoea, some with abdominal pain and vomiting, and 12 subjects presented with abdominal pain, nausea or vomiting). The authors report that there was no association between diarrhoea and drinking water copper level. Nausea, abdominal pain and vomiting, however, were significantly related to the copper concentration (Cu≤1 mg/l versus Cu≥3 mg/l – $P<0.01$).

Additionally, on discontinuing consumption of copper-containing water, the symptoms in subjects ingesting 0 mg Cu/1 persisted while the symptoms in the groups ingesting 1, 3 or 5 mg/l Cu disappeared (most of which reappeared on resumption of water intake containing 3 or 5 mg/l Cu). The authors conclude that at concentrations greater than or equal to 3 mg/l, copper is associated with nausea, abdominal pain and vomiting. The same research group extended the dose range in 61 subjects examining doses of copper sulphate between 0 and 12 mg/l in both purified water and an orange flavoured drink (Olivares *et al.* 2001). Mild nausea was the most frequently reported symptom starting at 4 mg/l. When the copper was given as a flavoured drink, nausea was not reported until levels of 8 mg/l and above.

In a larger study of 179 individuals from the United States of America, Northern Ireland and Chile, doses of between 0 and 8 mg/l copper sulphate were given. Statistically significant greater reporting of effects occurred at 6 and 8 mg/l. An acute no-observed-adverse-effect level (NOAEL) was determined as 4 mg/l and a lowest-observed-adverse-effect level (LOAEL) as 6 mg/l (Araya *et al.* 2001).

In addition to acute effects, more long-term gastrointestinal problems have been reported in the literature (Stenhammar 1999; Eife *et al.* 1999). These case reports are not well characterised and will not be considered further here.

Given the anecdotal nature of most of the case reports outlined in the literature, the human volunteer studies outlined above are taken as the scientific evidence for dose-response assessment. Table 4 presents the results of an outline quality audit of this evidence.

EXPOSURE ASSESSMENT

Extensive drinking water data exist in the UK from the monitoring required by legislation. So, exposure assessment is determined here from the number of people in England and Wales served by public drinking water supplied by water companies which have (in 10 years of monitoring) ever recorded a level of greater than 3 mg/l copper at a consumer's tap. Consumers exposed to 3 mg/l

Table 3 | Outline quality audit of copper monitoring data

Observation			
	Measure	Copper is being measured in drinking water samples derived from the consumer's tap.	
		Primary	4
	Data	The sampling regime is not designed for RA* purposes as used here, but is routine monitoring data, and standing times prior to sampling are not fixed.	
		Limited	2
	Sensitivity	This is likely to be reasonable.	
		Variable–Resilient	2–3
Method			
	Theory	The measurement is based upon laws, while the idea that people will be exposed to the level, as measured, is a well-tested theory.	
		Well-tested theory–Laws	3–4
	Robustness	**Resilient–Strong**	3–4
Output			
	Accuracy	Given the country-wide spread of data and the many thousands of samples which have been taken, this is likely to be	
		Plausible–High	2–3
	Precision	It would be nice to have the actual figures for the samples exceeding 3 mg/l, but given the small number of positive samples this is unlikely to add a great deal.	
		Good	3
Peer review			
	Standing	**Wide and accepted**	4
	State of the Art	**Gold standard**	4
Validity			
	Completeness	Despite the large number of samples, only exceedences are recorded and no data are available on samples measuring 3 mg/l.	
		Partial	2
Total			**31**

*RA – risk assessment.

Table 4 | Outline quality audit of copper ingestion and gastrointestinal symptoms

Observation		
Measure	The studies specifically examine exposure to different levels of copper in drinking water and any subsequent symptomology.	
	Primary	4
Data	The studies seem well designed, and have been conducted at three international sites, although the participant numbers are relatively small.	
	Limited–Good	2–3
Sensitivity	It is unlikely that the measure is critical to the stability of the result.	
	Resilient	3
Method		
Theory	Anecdotal evidence suggests that copper in drinking water may result in gastrointestinal upsets, and high doses are known to be emetic, however, these are the first studies to specifically address the issue.	
	Emerging theory	2
Robustness	The studies have been conducted at several sites, therefore the result is felt to be reasonable.	
	Resilient	3
Output		
Accuracy	Accuracy could be improved by repeating with a greater number of participants and further extending the dosing regime. It is, however, plausible to high	
	Plausible–High	2–3
Precision	**Fair**	2
Peer review		
Standing	The studies have been published in peer-review journals.	
	Moderate	3
State of the Art	Given the recent nature of the studies this aspect has been rated	
	Developing–Good	2–3
Validity		
Completeness	Relatively limited sample size with healthy adult volunteers.	
	Partial	2
Total		**26.5**

copper are considered to be at risk of gastrointestinal symptoms.

Table 2 shows that a total of 12 water company areas have recorded copper levels above 3 mg/l between 1990 and 1999 (East Anglian and Suffolk Water covering the same area). These areas represent a population of approximately 32 million. The Drinking Water Inspectorate estimates that public supplies in England and Wales serve approximately 50 million people. Somewhere in the region of 64% of people served by public supplies are therefore potentially at risk of receiving water which may exceed 3 mg/l copper. Table 2 also shows the number of samples taken for copper, by individual water companies, for any one year in which there was an exceedence to the standard. Details on sample numbers where no exceedences were recorded are not readily available.

Over 35,000 samples were analysed of which 31 exceeded 3 mg/l copper; this represents a failure rate of 0.09%. In the absence of better data, the failure rate of 0.09% will be applied to the population potentially at risk (i.e. 32 million), according to the following model:

P_{cu}	Population calculated to be at risk from elevated copper levels
$P_{WaterCo.}$	Population exposed to copper levels greater than 3 mg/l. This figure is calculated from the population served by a water company reporting a copper failure.
S_{cu}	This represents the number of samples that have exceeded the level of 3 mg/l as a function of the number of the annual number of samples taken in each water company area reporting a failure.
M	Monitoring period in years.
P_T	Population in England and Wales served by public supplies. DWI estimates this figure to be 50,000,000.

$$P_{cu} = P_T / \frac{(P_{WaterCo.} \times S_{cu})}{M}$$

It is calculated from the above model that there is a probability of 1 in 17,360 (rounded to 1 in 17,000 to reflect a more appropriate degree of precision) of exposure to drinking water containing copper levels greater than 3 mg/l. An outline quality audit of this estimate is given in Table 5. It is an area ripe for further research and development, as quantitative assessment of waterborne risk becomes more widely practised.

RISK CHARACTERISATION

Although 1 in 17,000 is the probability of exposure to copper levels in drinking water greater than 3 mg/l, gastrointestinal symptoms are unlikely to result in all cases. Pizarro *et al*. (1999) reported that 12 out of 60 people (or 20%) exhibited gastrointestinal symptoms as a result of copper ingestion. If it is assumed that this proportion is applicable more widely, then the probability of gastrointestinal symptoms would be 1 in 85,000 as a result of ingesting copper in drinking water in England and Wales. This does not, however, account for possible sensitive subgroups (such as children for example) because no research has examined such groups. Nor does it account for people regularly using first draw water or those who flavour water in a way that alters the copper susceptibility threshold (Olivares *et al*. 2001).

The degree of confidence that can be placed in the estimate of 1 in 85,000 as a true representation of the risk to the general public in England and Wales from copper in drinking water is indicated by the outline quality audits in Tables 4 and 5. Ratings from Table 3 have been used as an input to Table 5 so are not considered further at this stage. The scores of 26.5 and 21 (respectively) out of a possible 40 equate to 66.25% and 52.5%. If we take intervals of 20% as convenient benchmarks for an interpretative scale (80% + excellent; 60–80% good; 40–60% moderate; 20–40% weak; 0–20% poor) then these ratings come out as being 'good' and 'moderate' respectively. This, in turn, accords with the authors' intuitive understanding of the current state of knowledge about copper-related health risk. For the purposes of wider accountability, it is important to be able to refer to a formally verifiable statement of this understanding, as provided through Tables 4 and 5, and not merely to rely on intuition and informal judgement.

Table 5 | Outline quality audit of exposure assessment model

Observation		
Measure	Copper in water is being measured at the consumer's tap on a random basis. Number of samples taken is dependent on the size of population served by the supply and whether there is a known problem.	
	Standard	3
Data	Data are not specifically designed in the context of a risk assessment and are considered to be limited (see Table 3).	
	Limited	2
Sensitivity	Samples are taken on a random basis, but are unlikely to represent true first draw samples, therefore may underestimate peak values.	
	Variable	2
Method		
Theory	The notion that exposure is related to the levels of a substance determined from a large number of random samples and the overall population figures is a	
	Well-tested theory	3
Robustness	Targeting the sampling towards new properties with copper plumbing could change the result. To the best of our knowledge no work has been conducted to establish how well a random sampling program characterises the actual distribution of copper.	
	Variable	2
Output		
Accuracy	It is likely that a fair representation of the real world is achieved using this method.	
	Plausible	2
Precision	Precision is adequate, knowing total sample numbers and actual copper concentrations for the whole of England and Wales would be better.	
	Fair	2
Peer review		
Standing	Specific exercise has not been conducted before, but the logic follows the lines of other risk assessment exercises.	
	Limited review	2
State of the Art	To the best of our knowledge this is the first time this has been attempted.	
	Embryonic	1
Validity		
Completeness	The lack of information on first draw water copper concentrations and extent to which people use first draw water leaves a knowledge gap. The validity of moving from household to population estimate is also unknown.	
	Partial	2
Total		**21**

DISCUSSION AND CONCLUSIONS

It is noted that the exposure measure is based on a very small number of positive samples and that the applicability of extrapolating these 'household' events to a population level is unknown—resulting in an overall rating of 'moderate' for this aspect. In light of these issues it could be argued that the positive samples reflect 'one off' high values, due to a short-term problem or new pipework, and therefore over-estimate the population exposure level. Conversely, it could be argued that due to the sampling regime (which does not require a fixed, or even any, standing time) the positive values may represent the tip of the iceberg and many more people may be exposed to copper at levels greater than 3 mg/l on at least an occasional basis, although it has been suggested that random daytime sampling may result in a higher average than proportional sampling. The exposure measure could be improved by characterising the distribution of copper in drinking water supplies under a range of circumstances (geographical areas) for typical situations.

The risk assessment given above focuses on acute gastrointestinal effects, which have been best characterised in terms of a dose–response relationship. Other, more severe effects, such as liver disease, are thought to have a genetic component and established genetic defects such as Wilson's disease will occur even with restricted copper intake. These, therefore, are not amenable to risk assessment at this stage and are probably not relevant on a general public basis.

A risk level of 1 in 85,000 (for a relatively mild effect) falls within what is taken by a number of regulatory authorities to be 'acceptable' levels, such as the acceptable level of infection from drinking water of 1 in 10,000 adopted in the United States (Macler & Regli 1993). As such, bearing in mind the 'moderate' confidence that can be placed in the risk assessment, the current standard of 3 mg/l would seem to be adequate, although it should be noted that this will be reduced to 2 mg/l at the end of 2003 in line with WHO guidelines.

The core of the approach adopted in this paper results in a clear and easily understood output. It is suggested that it could be used as an exemplar for risk assessment and related outline quality audits for other cases of waterborne risk.

ACKNOWLEDGEMENTS

This work was funded by a grant from EPSRC. Thanks are also due to Alan Godfree, Gary O'Neill, Nigel Lightfoot, Mike Waite, David Drury and Paula Hopkins.

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First received 4 June 2001; accepted in revised form 5 June 2002