Cryptosporidium contamination hazard assessment and risk management for British groundwater sources

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Abstract Contamination of aquifers by *Cryptosporidium* oocysts has only recently been recognised as a risk to the security of important groundwater-based drinking water supplies in the UK. The predominance of dual porosity aquifers with complex flow systems, the fact that UK water utilities hardly ever own or control the catchments overlying the aquifer supplying their abstractions and the diverse designs of the wells/springs themselves renders hazard assessment necessary but not simple. A tripartite approach is proposed which is a modification of standard contaminant transport source→pathway→receptor principles. The complex interaction of factors and uncertainty of underpinning data greatly limit the applicability of a strictly numerical approach to risk assessment. Instead the importance is emphasised of understanding the blend of hydrogeological and operational factors which makes each site and its setting unique.
Keywords *Cryptosporidium*; pathogen transport; groundwater contamination; aquifer protection; hazard assessment; risk assessment

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Background to concerns

Increasing awareness that oocysts of the protozoan parasite *Cryptosporidium* are not only widely found in the environment but also can survive for long periods outside their host raises the risk of occurrence of waterborne outbreaks of cryptosporidiosis.In the USA LeChevallier and Norton (1995) record a *Cryptosporidium* prevalence rate of 60% in American Water System-monitored rivers and lakes, in Germany Wagner-Wiening *et al.* (1998) found oocysts in almost 40% of lake waters sampled, and in it UK Bodley-Tickell *et al.* (1997) found *Cryptosporidium* in almost 70% of rural surface waters tested. Such statistics demonstrate a constant threat to public water supplies drawn from surface waters.In the UK, a large outbreak in Oxford and Swindon in 1989 (Richardson *et al.*, 1991) focused attention on the parasite's presence as a waterborne problem and stimulated much recent development of precautionary treatment methods and protocols designed to reduce the threat to acceptable levels (Badenoch, 1990,1995).

In contrast, the risks to some groundwaters used for drinking water supply have until recently not been adequately appreciated for the reason that water from most aquifers is of much higher bacteriological quality and lower turbidity than surface water sources. These advantages have traditionally allowed safe use of simple treatment facilities (typically precautionary disinfection by chlorination or ultra-violet irradiation) rather than those needed for surface water sources. The resistance of *Cryptosporidium* to such common disinfection methods makes a breakthrough of infectious oocysts a real hazard if raw groundwater tapped by the source has become contaminated.

That contamination can occur is now undoubted, and Hancock et al (1997) noted that in the 12 most recent outbreaks of waterborne cryptosporidiosis in the USA 33% were traced to contaminated wells; 17 of 74 wells in their survey contained *Cryptosporidium* (average 41 oocysts per 100 litres). In the UK an outbreak in north London with 345 confirmed cases of cryptosporidiosis in 1997 was traced to a groundwater supply (DWI, 1998), and events associated with groundwater sources providing public supplies in England average more than one per year (Table 1).

Groundwater has an important role in England and Wales, where it provides 32% of all public supplies and up to 50% in much of southern, central and eastern England (DETR, 1997). As a result, 83% of all licensed groundwater use is for this purpose. Additionally, most of 90,000 or more private water supplies draw on groundwater, as does the rapidly-expanding bottled spring and mineral water industry. In Scotland and Northern Ireland groundwater, while much less important, satisfies many strategic rural needs, including 30% by number of all Scottish public supplies (Ball *et al.*, 1997). So there are ample public health concerns of *Cryptosporidium* hazard to the aquifers used for such supplies.

Potential for *Cryptosporidium* transport in British aquifers

Types of aquifer and groundwater supply

The aquifer systems tapped by more than 2,200 public supply sources in England and Wales are comprised principally of consolidated rocks. About 85% of the 2010 million m^3/year pumped in 1995 (DETR 1997) was drawn from the fine-grained limestone of the Cretaceous Chalk and from sandstones of Permo-Triassic age, but other major aquifer systems include the Cretaceous Lower Greensand of southern England, the Permian Magnesian Limestone of central and northern England and carbonate aquifers of Jurassic and Carboniferous age. In addition, more than one hundred other formations, including Quaternary fluvio-glacial gravels provide locally important public and private potable supplies. The majority of these sources are wells or boreholes, but there are several hundred licensed public spring supplies. Over a hundred of the wells have adit systems, mostly located in the Chalk of southern and eastern England. Many of the latter are highly productive: the average yield per source for 72 of these adited systems is over 10.7 Ml/d (Environment Agency, *pers. comm*).

Groundwater flow regimes and pathogen movement

The principal UK aquifers are of the dual-porosity type, in which much of the total storage capacity of the system is provided by interstices in the rock matrix, while fractures provide the dominant flow-path (Figure 1).

This condition greatly influences pollutant movement, the water in the matrix being relatively immobile compared with that in the fissures. Both the Chalk and the Permo-Triassic

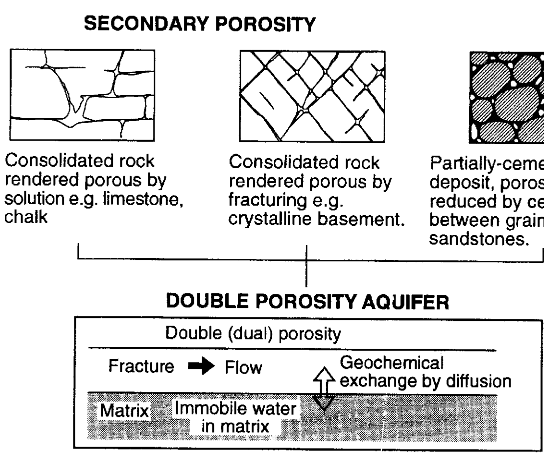

Figure 1 Flow and storage in UK aquifers

sandstones are of this type. Yet other aquifers store and transmit water predominantly through linked fractures. In some carbonate aquifers solution effects have produced karstic systems in which flow velocities can be measured in many metres per day. Of the relatively small proportion of British aquifer systems in which intergranular flow provides the water for supplies, Quaternary alluvial and fluvio-glacial deposits are the most prominent despite their limited areal extent. Even in these formations groundwater velocities can be sufficiently high under abstraction conditions to make for rapid travel times from point of recharge to well.

Where flow through the matrix predominates, the aquifer can provide a mechanism for pathogen attenuation by filtration. This is most likely to occur close to the ground surface as a result of physical clogging and by retention on a biologically-active layer present in the soil and the uppermost part of the unsaturated zone. Where flow also occurs along fractures such a biofilm may also be present as a coating on fracture faces and be more or less effective depending on aperture sizes. Once this zone is passed there is less evidence of physical removal except in fine-grained strata where pore-neck diameters are smaller than the actual organism.

It is for this reason that the role of the soil in pathogen attenuation is important; once below the top metre or so, the ability of many aquifers to physically detain oocysts is limited.*Cryptosporidium* oocysts are physically larger than the typical 1 μm pore-size of the Chalk aquifer but they are within the pore-size range of arenaceous aquifers like the Permo-Triassic sandstones and almost certainly smaller than the fissure and micro-fissure/bedding plane aperture systems which dominate groundwater transmission.

Once below the soil zone, physical filtration in intergranular-flow aquifers can be effective in alluvial deposits, where silts or fine sands interbedded with coarse-grained sands and gravels provide the hydrogeological equivalent of a slow-sand filter. However, in the absence of such horizons, physical retention in the coarse-grained high permeability horizons is limited because the small size of oocysts (4–6 μm) is significantly less than the median pore-neck diameters and only marginally greater than that of many bacteria (Figure 2).

A further barrier to most waterborne pathogen survival can be provided by the tortuosity of flow-paths. These act to extend residence times so that natural die-off can provide attenuation and eventual elimination. In this way, matrix flow through the subsurface can deal effectively with high microbial populations such as those in septic tank effluent and farm waste slurry pit drainage (10^6/100 ml of faecal coliforms or more). However *Cryptosporidium*'s high persistence compared with other bacterial pathogens can pose a problem. Subsurface viability of *Cryptosporidium* has not been extensively studied,

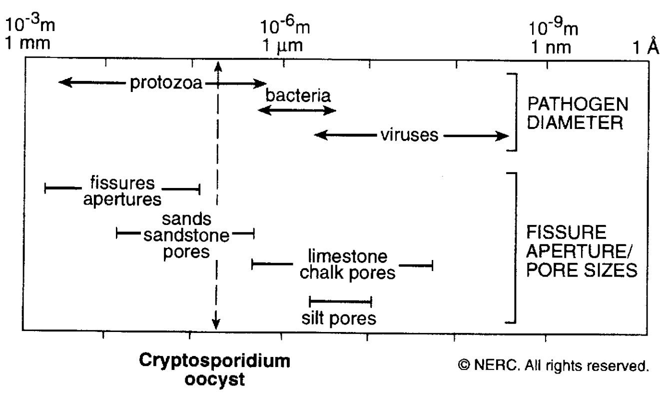

Figure 2 Pathogen diameters compared to aquifer matrix apertures

oocysts are reported to survive dormant for months in moist soil or up to a year in clean water (Badenoch 1990), and it would appear that they are likely to show survival rates at least an order of magnitude longer than corresponding faecal-derived bacteria.

Special considerations for dual-porosity aquifers

For the dual porosity aquifers that provide the bulk of British groundwater supplies, the issue of groundwater travel times is complex. Water passing through the matrix and having a very long residence time drains to the fractures which make consolidated aquifers productive. Some of these same fractures may also receive recent recharge from the surface which has by-passed the rock mass and is circulating in the active fracture system. As a result, a source may draw groundwater recharged over a wide time-period, depending on the local flow regime, the geometry of the well and the detailed hydrogeology in the near-well part of the catchment.

For the practical purposes of groundwater protection and hazard assessment, in most British aquifers the relative importance of the rapid recharge element is a key issue, because unlike other groundwater pollutants, microbial contaminants are usually self-limiting and auto-remediating, albeit at a slower rate in the case of *Cryptosporidium.* A significant threat from this pathogen is not posed by the mere existence of a subsurface pathway- it must transmit polluted water from the surface to a spring or well over a hydrogeologically short residence-time, which is more likely to be measured in days or weeks than in years.

It is a tacit but entirely reasonable assumption of the hazard assessment procedures proposed in this paper that only a relatively small proportion of British groundwater sources do receive such short-residence-time groundwater from their catchments, and that these produce the raw waters at risk.

Occurrence of *Cryptosporidium* in British groundwaters

The list of incidents associated with groundwater supplies in England and Wales for 1990–1997 (Table 1) permits comparison with the general observations described below.

Table 1 Suspected *Cryptosporidium* groundwater contamination events in England since 1990 (Bouchier, 1998)

Year of occurrence	Aquifer lithology	Aquifer flow type	Supply source type	Comments
1990–1991	River gravels over chalk	Intergranular/ dual porosity	Well with adits	Adjacent to river
1992, 1995	River gravels	Intergranular	Collector well used conjunctively with surface water	Adjacent to river
1992	Sandstone	Dual porosity	Well with adits	Contaminated grazed field runoff to wellhead, possibleseptic tank leakage in wellhead area
1995	Chalk	Dual porosity	Well with adits	–
1995, 1996	Sandstone	Fissure	Aditd spring	–
1997	Chalk	Dual porosity	Single borehole	Grazed catchment, losing stream with sewage effluent discharge close to borehole
1997	Sandstone, karstic limestone	Fissure	Adit of former mine	Possible slurry pit leakage
1997	Chalk	Dual porosity	Well with adits	Adjacent to river
1997	Gravels	Intergranular	Collector well	Very shallow well in thin gravel on flood plain, seasonal flooding and gravel pits adjacent

The following features are notable:

- all main aquifer types (fissure flow, dual porosity and intergranular flow) are represented;
- the Chalk, the most productive and widely used aquifer, is the most prominent; its extensive exploitation as a water resource may explain this observation;
- intergranular aquifers are only affected in settings where the residence time in the aquifer is likely to be very short (eg in river gravels close to a surface watercourse);
- both rural and part-rural/part-urban catchments are involved, although the former predominate;
- adited wells, collectors, springs and former mines with adits are particularly vulnerable settings, accounting for eight of the nine reported incidents; this feature appears to be more significant than mere proximity to a watercourse.

It is suspected that significant under-reporting of incidents may also have occurred in the past, not least due to the absence until recently of consistent and reliable industry-wide analytical procedures. However, on available recent evidence, the authors conclude that *Cryptosporidium* contamination of raw groundwater abstracted for public or private use is an unusual but by no means rare occurrence.

Development of a hazard assessment scheme

Given the risk of an outbreak from an infected supply to the public, the National Expert Group on *Cryptosporidium* in Water Supplies has recommended that British water utilities should evaluate potential risk of raw water contamination for the groundwater sources that they operate (Bouchier, 1998). There has arisn therefore a need to develop a practical methodology for the initial groundwater hazard assessment stage of a full risk evaluation, with the aim of providing a tool for water utilities (and other providers of water to the public such as bottled water suppliers) to estimate and therefore manage risk to the integrity of supplies.

Conceptual basis

Pathogen hazard to a groundwater supply can be assessed using a tripartite approach which is analogous to the standard source→pathway→receptor principles applied to other contaminant transport problems. In the case of *Cryptosporidium*, this means accounting three sets of factors (Figure 3):

(i) **Source factors:** what activities are taking place on the catchment which might generate a load, that is what *catchment predisposing factors* may be present?

(ii) **Pathway factors:** what inherent features of the groundwater setting might render a particular aquifer or area of aquifer prone to receive and rapidly transmit oocysts to a groundwater source, that is what *hydrogeological predisposing factors* are at work?

(iii) **Receptor factors:** what aspects of the groundwater supply source as a hydraulic structure might increase the chances of intercepting contaminated raw water which has already entered the subsurface, that is what *well or spring design/construction predisposing factors* may be operating?

A typical hazard assessment for a groundwater supply and its catchment would use available data and involve:

- identification of the source, pathway and receptor factors particular to that supply
- a semi-quantitative/qualitative factor evaluation and ranking, using a simple indexing scheme
- a compilation of existing water quality data to look for evidence to verify the above evaluations
- a concise assessment of how factors interact, with recommendations for follow-up verification or additional work to check uncertainties.

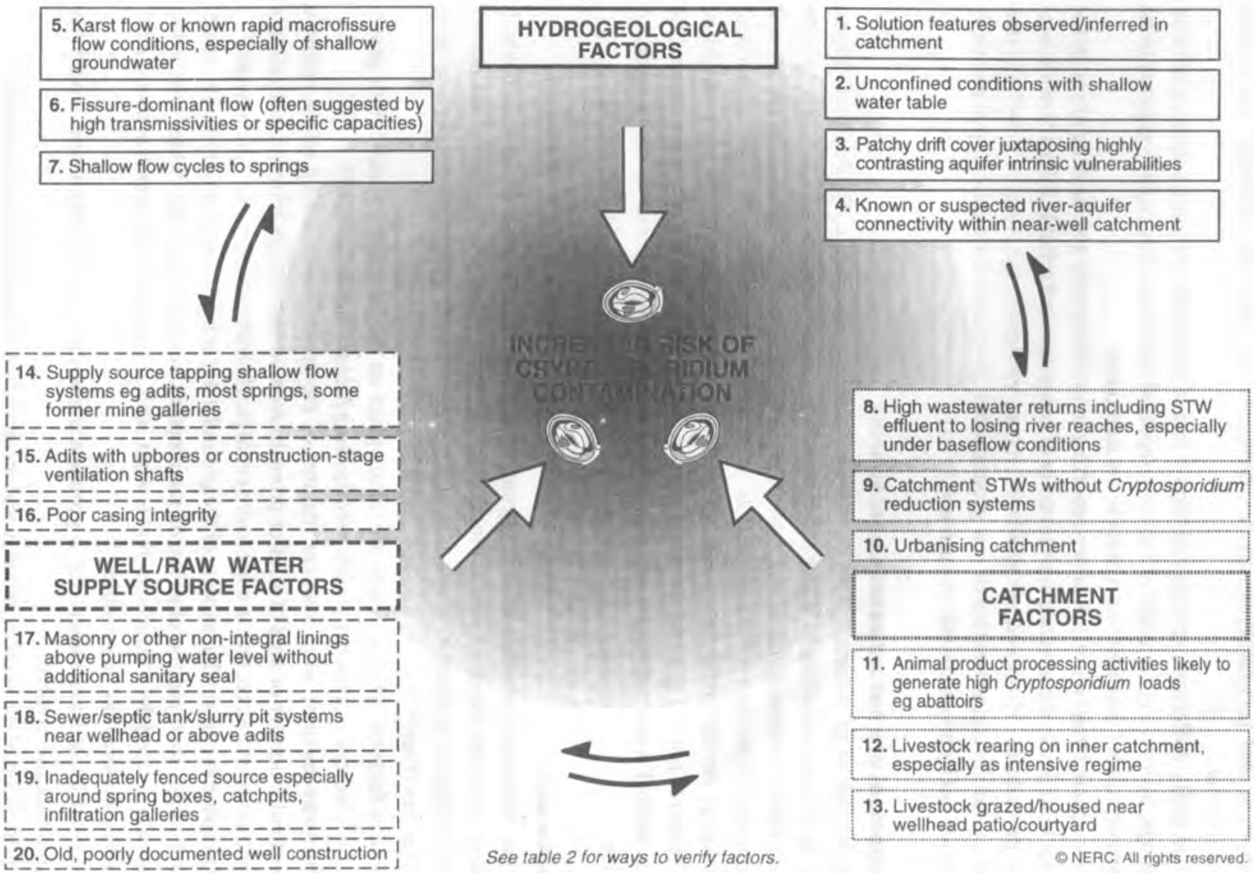

Figure 3 *Cryptosporidium* groundwater contamination hazard factors: conceptualisation

Table 2 Verification techniques for hazard factors (see also Figure 3)

Predisposing factors		**Ways to verify**
Hydrogeological (pathway)	1	Photogrammetry+field mapping
	2	Well water monitoring
	3	Field mapping, shallow drilling
	4	Flow gauging, modelling, hydrochemistry
	5	Field mapping, farm surveys
	6	Downhole fluid/flow logging, pumping test analysis
	7	Tracing, hydrochemistry, fluid logging
Catchment (source)	8	Hydrochemistry, microbiology, hydrometry
	9	System efficiency evaluation
	10, 11, 12	Cadastral, economic activity, farm surveys
	13	Site inspection
Water-supply (Receptor)	14,15	Check site plans, site inspection, tracing
	16,17	CCTV, geophysical logging, check site plans
	18, 19	Site inspection
	20	Check site plans/Nat. Well Record Archive at BGS

The original hazard assessment would be periodically updated as more information became available on the groundwater setting, operational regime and land-use activities. A typical groundwater setting appraisal is shown pictorially in Figure 4, while techniques to verify the factors identified in the preliminary assessment are described in Table 2.

The pathway term is pivotal in a groundwater hazard assessment because even if there is a significant *Cryptosporidium* source (loading) in the catchment, hazard is still low if there is no likely rapid-transit route to the well/spring supply. However the prominence of wells with adits and spring sources in the list of incidents shown in Table 1 shows that source sanitary integrity remains an important consideration.

Vulnerability mapping

As most British water utilities do not own or control the land which is the catchment to their groundwater abstractions, there is a need to identify areas of "extreme vulnerability" in such catchments. Limited in area (ha. rather than km^2), they would typically comprise solution, lost drainage or other karstic or pseudo-karstic features where rapid entry of recharge or runoff to the aquifer is known or suspected to occur. Being so limited in area, catchment activity control measures could be much more easily negotiated with land users than if restrictions were sought for the entire catchment to the supply.

England and Wales are fortunate in having working approximations to the groundwater catchments of more than 2,000 of its public supplies, thanks to the National Groundwater Protection Programme operated by the Environment Agency (NRA 1992, EA 1998). Depending on the definition method adopted (by modelling or by manual means), the Programme can provide the typical catchment (best-estimate zone) or a slightly larger area which takes account of uncertainty in aquifer and hydrological parameters (the zone of uncertainty). Use of either helps to narrow down the hazard survey area.

Arguments against an over-prescriptive approach

One practical problem in developing a robust ranking is how to assess the relative importance of each factor. For some factors, even the preliminary step of assigning a simple qualitative ranking (e.g. low, medium, high risk, equal weight) can require careful interpretation.

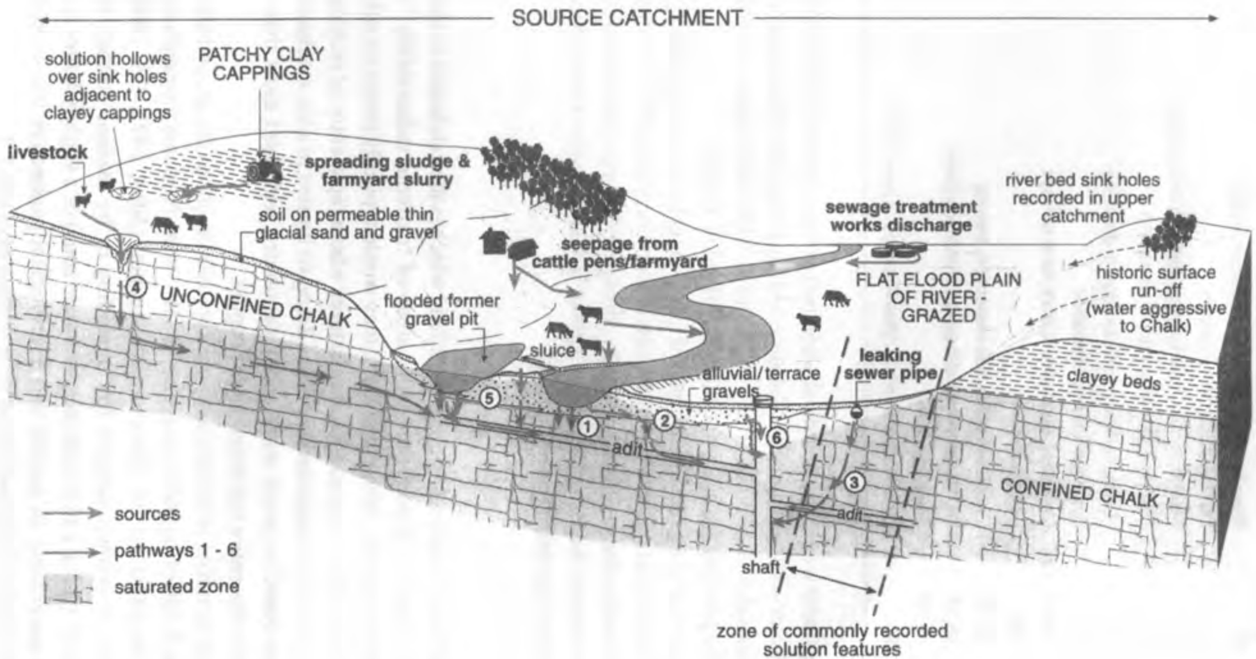

Figure 4 *Cryptosporidium* hazard factor assessment for a typical British chalk setting

To take one simple example, a preliminary risk classification would assess a given aquifer as of intergranular or fracture flow type (Factor 6 in Figure 3). When applied to the UK's most important aquifer the Chalk, it would be tempting but over-simplistic to classify all of the Chalk as high hazard on the basis that in this exceptionally fine-grained limestone all effective flow is through the fractures. Yet in many catchments the transmissivity in similar thicknesses of saturated Chalk is known to vary by over two orders of magnitude, from 100–1000 m^2/d along valley axes to perhaps only 1–10 m^2/d on the interfluves. Productive sources are often located in the former zone but most of their catchment may stretch into the latter, and there are innumerable possible permutations. So it is not surprising to find that in practice there are many Chalk sources which consistently produce microbiologically very high quality water, and also some which have irregular problems evidenced by erratic but at times significant faecal and total coliform counts. To be useful, the classifier would need to reach a view on how important karstic or near-karstic flow might be in the upper part of the saturated aquifer in that catchment, and classify accordingly.

The assessment of relative weights is even more fraught with problems. While it is true that not all predisposing factors are of equal importance it is difficult to objectively justify scheme divisions and weightings because often these are based not on verifiable field study results but rather on empirical, frequently subjective, rules which are not universally applicable. For instance, depth to water table would be a factor to consider in unconfined aquifers (Factor 2 in Figure 3), but where does one place the hazard divisions? 0–15 m and >15 m? Or 0–10 m, 11 m–20 m and >20 m? Or some other scheme? And what multiplier to apply for the top division? And so on.

A recent water industry guide issued in the UK (Hall and Young, 1998) has proposed a cumulative ranking incorporating a simple multiplier to introduce weighting to *Cryptosporidium* hazard assessment. The authors of this paper offer no alternative scheme but rather caution against over-reliance on a numerical procedure which, while reasonable, is essentially subjective. We would stress the need to focus instead on the water supply itself and its unique hydrogeological and operational setting, applying a simple ranking which does not obscure paucity or doubtful quality of the original data on which the assessment is based. Such an approach is currently being applied with some success to *Cryptosporidium* hazard assessments for a number of English water companies.

Adapting hazard assessments to management needs

While there is some overlap between hydrogeological (pathway) and supply source (receptor) factors, the key difference is that for a given groundwater source those relating to the hydrogeology are inherent and cannot be altered short of relocating the source to a less vulnerable site. In contrast, land/activity control measures could drastically reduce likely contaminant loadings to the subsurface, while a critical appraisal of potentially hazardous well design characteristics could further reduce the likelihood of encountering oocysts in sufficient numbers to trigger a disease outbreak. In the UK active cooperation between water utility and environmental regulator would facilitate introduction of catchment mitigation measures.

As an alternative, more passive, strategy, a water utility could employ the hazard factor evaluations merely as a means to identify those sources where additional precautionary raw water treatment measures would be advisable and to decide where a more intensive (and therefore more costly) monitoring regime should be put in place. An assessment could provide a justification for investment in risk management strategies to the water utility's price regulator or to shareholder representatives, given the significant capital and running costs of the modular microfiltration plant needed to provide a treatment barrier at source.

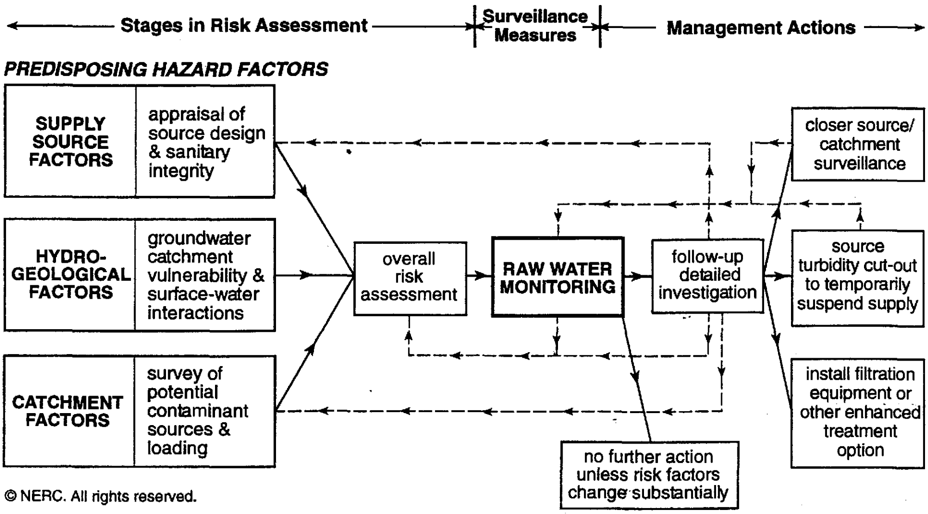

Figure 5 How hazard assessment helps *Cryptosporidium* risk management

A typical decision flow chart for groundwater *Cryptosporidium* risk management is shown in Figure 5.

Conclusions and recommendations

The long survivability and hardiness of oocysts outside their hosts means that, as a contaminant of groundwater, *Cryptosporidium* probably cannot be treated exactly the same as other microbial pathogens in that it is not as short-lived and rapidly attenuated as bacteria, nor as sensitive to relatively adverse environmental conditions as most viruses. We say probably because to date the survival, transport and viability of oocysts once they have passed below the soil zone into the unsaturated and saturated zones does not appear to have been investigated. This is a much-needed area of research.

Meanwhile a tripartite hazard assessment aimed at understanding and integrating the pathway, source and receptor factors affecting movement of oocysts is proposed as a practical tool enabling drinking water providers to start to assess the risk to their supplies and to develop risk management strategies.

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