Pathogens and groundwater

(Contributed by Brian Morris, formerly of British Geological Survey)

The pathogen side: sources, transport factors.

In the UK most waterborne disease-causing micro-organisms found in surface waters and groundwater are spread by the microbiological contamination of water by faeces or urine originating from humans or animals. The main threats are cholera, typhoid, paratyphoid, infectious hepatitis, leptospirosis, gastroenteritis, cryptosporidiosis and amoebic and bacillary dysentery. The ability of soils and underlying geological formations to retard or eliminate the onward transmission of the pathogenic[1] organisms that are the agents of such infections is a vital asset and is one of the reasons for the longstanding preference both in Britain and elsewhere for groundwater for drinking water supply and other sensitive uses.

Pathogenic organisms include bacteria, viruses, protozoa and metazoa, and these are not only present in very large numbers at the ground surface but also span a large size range, so the ability of the subsurface to act as a barrier to their transmission is correspondingly variable. For example, faecal matter contains on average 10^9 bacteria/gram (although not all are pathogenic) while faeces from infected individuals may contain as many as 10^6 PFU/gram of enteroviruses and 10^{10} PFU/gram rotaviruses. Raw sewage and septic tank effluent may have about 10^6/100 ml of micro-organisms, mostly faecal coliforms, and farm waste slurry pits even more. The size range of protozoa, bacteria and viruses extends over c. 5 orders of magnitude, from 10^{-3} to 10^{-8} m (Fig.1).

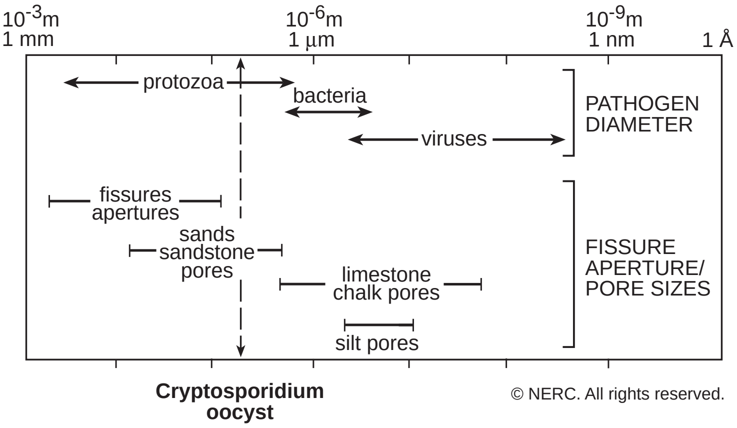

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Fig.1. Pathogen diameters compared to aquifer matrix apertures

Just like other groundwater contaminants, the length of time it will take for a microbiological load generated by an activity at the surface to travel to the point of abstraction is important. This is not only because microbial populations degrade naturally with time but also because long travel times maximise the opportunity for other attenuation mechanisms to operate, some of which will also detain or remove pathogenic micro-organisms.

The soil is the first barrier to pathogen contamination of aquifers, as these micro-organisms are subject to naturally occurring attenuation processes that occur as soon as they pass below the ground surface. If the recharge enters via a natural soil profile, this can be a potentially effective attenuation system, as soils are usually aerated by soil fauna and are biologically very active ecosystems where natural removal by grazing, predation and die-off can occur. In such aerobic environments bacterially-mediated degradation can be both rapid and effective, not only for disease-causing organisms but also for many other pollutants, especially those soils which have high clay and/or humus content that provide opportunities for sorption. Also, in most soils the relatively large size of most protozoan and metazoan pathogens like helminthic parasites means that in addition to predation by other microorganisms, they are likely to be removed by filtration mechanisms. The protozoan *Cryptosporidium* is an exception in that at oocyst stage, its size (4-6 µm diameter) is only marginally greater than bacteria, which together with viruses may potentially be transported with percolating effluent to groundwater through soil/rock pores.

For bacteria, the main mechanism for removal by filtration seems to be retention at the infiltration surface due to physical clogging and retention by a biologically active layer (the '*schmutzdecke*'). Once this biofilm zone is passed there is little evidence of physical removal except in fine-grained strata where pore diameters are smaller than the actual organism. It is for this reason that the role of the soil in pathogen

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[1] Pathogen: micro-organism able to cause disease

attenuation is important; once below the top metre or so, the ability of many UK aquifers to physically detain bacteria, viruses and oocysts is limited, and residence time becomes the principal means of attenuation, a factor also related to thickness of unsaturated zone (see later).

Fig. 2 illustrates qualitatively the relative importance of various mechanisms both in the soil, then above, at, and below the groundwater table. Many other waterborne pollutants are subject to such naturally occurring attenuation processes.

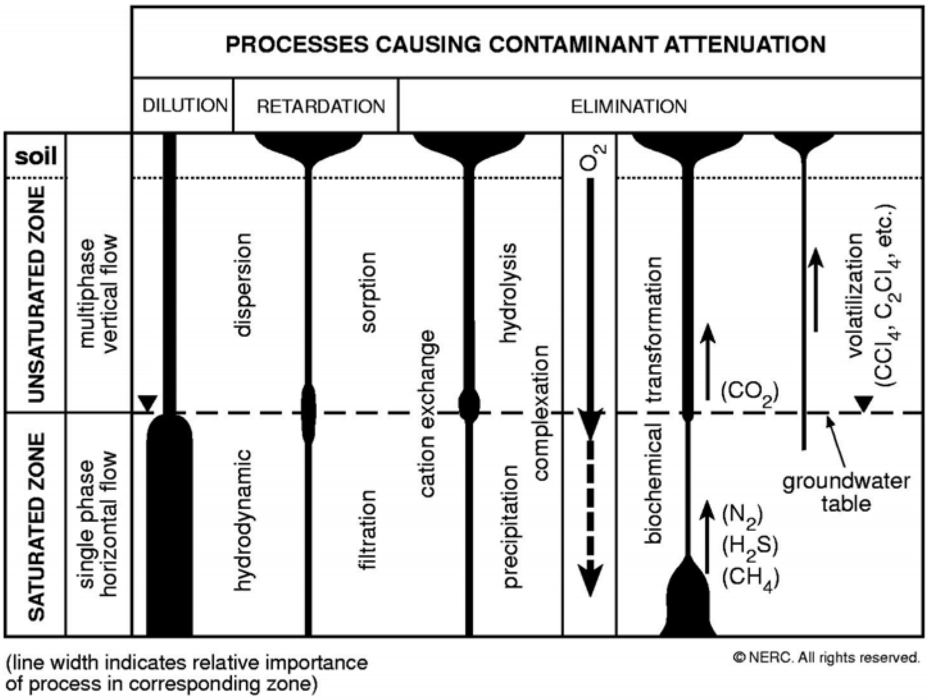

Fig. 2. Processes promoting contaminant attenuation in groundwater systems (Foster & Hirata after Gowler 1983).

However, some microbial contaminants enter the subsurface directly, via structures designed to by-pass the soil zone such as septic tanks, latrines, soakaways or older (unlined) farm waste storage silos. Being designed to dispose of waterborne wastes quickly, such structures will almost invariably impose a higher hydraulic loading, or surcharge, than contaminants entering via the soil zone. These two factors of soil zone bypass and hydraulic loading potentially limit pathogen removal ability because Fig. 1 shows that in many aquifer settings the typical matrix aperture range is not in itself able to provide a physical filtration barrier. The increased percolation velocities that result bring about a corresponding reduction in residence times and thus diminish the potential for contaminant degradation. Analogous infiltration situations can occur beneath heavily-leaking sewerage systems and also along the influent (losing) reaches of watercourses, especially where the flow regime and underlying alluvial deposits result in a silt-free permeable stream-bed.

Sewer leakage also typically (but not invariably) occurs in the unsaturated zone. However, there is accumulating evidence from sewer exfiltration studies in Germany and elsewhere (e.g. Wolf et al, 2005) that the undisturbed colmation[2] and biofilm layers that build up in the soil/fill around the outside of leaking pipes, joints and other sewer ruptures and clog matrix pores are very effective at limiting microbial migration. A similar mechanism would occur beneath well-constructed septic tank drainage fields.

Apart from retention, the other important factor affecting the fate of microbes in the subsurface is the interaction of flow travel time with pathogen survival rates. The survival of bacteria in groundwater is generally thought to be limited; 90% reduction may be expected at 20ºC within about 10 days, although a few may persist for 200 days or more as a result of the absence of ultraviolet light, lower temperature (UK groundwater is typically around 10-12ºC) and less competition for nutrients (Fig. 3). Laboratory viral studies on groundwater samples in the USA demonstrated persistence of both poliovirus and echovirus for up to 28 days at 12 ºC before a 1 log reduction was achieved (Yates et al, 1985). The lifecycle of some protozoan parasites, such as *Cryptosporidium* and *Giardia* includes an environmentally hardy cyst stage. Viability in the subsurface of the protozoan *Cryptosporidium* has not been extensively studied but as oocysts are reported to survive dormant for months in moist soil or up to a year in clean water, typically

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[2] Clogging layer of fine sediment

they are likely to show survival rates at least two orders of magnitude longer than corresponding faecal-derived bacterial pathogens. This would account for the widespread detection of oocysts in a recent national monitoring programme (see later)

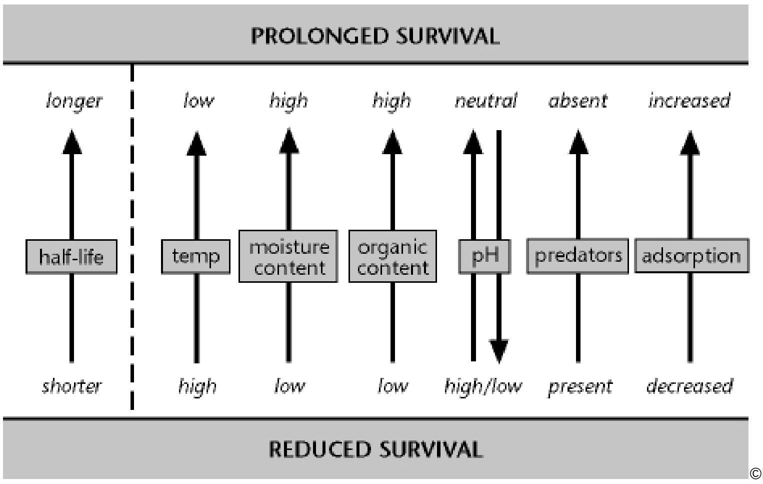

Fig. 3. Factors affecting microbe survival and half-life (from Coombs et al 2000)

Contaminant attenuation processes at depth in the unsaturated zone can be especially important in rural communities with on-site domestic or agricultural wastewater disposal via septic tanks, where high bacterial loadings are associated with other metabolic wastes such as nitrogen compounds. Like the soil profile, a thick unsaturated zone offers aerobic conditions in which more numerous and more metabolically active aerobic bacterial populations can bring about faster biological degradation than under conditions of anaerobic decomposition[3]. Intergranular unsaturated zone vertical flow is also typically slower than its saturated zone equivalent.

A recent research study of a septic tank installation in Hampshire permitted assessment of its impact on the underlying Chalk aquifer by means of 5 dedicated boreholes located in the vicinity of the drainage field (Environment Agency 2007). At the site the unsaturated zone was approximately 7.5-9.5 m thick and the drains lie about 1.5-2 m below ground level in weathered Upper Chalk. Total coliform and faecal coliform sampling and analysis was conducted on pore waters, depth samples from the saturated zone during drilling and pumped samples during a subsequent 10-month period of monitoring. The results suggested a very low impact on the underlying aquifer with the two boreholes positioned directly below the outflow pipes recording total coliform counts in the range <2-25 cfu/100ml (excluding one sample probably contaminated during the drilling process).

However it should be noted that in some situations (e.g. where weathering effects are less intense so that original rock structures remain), the effects of fissures can be even more important in the unsaturated zone than below the water table, because significant by-pass flow can occur along vertical fractures activated after major recharge events. This by-pass flow can be very fast compared to typical intergranular flow rates.

Faecal coliforms, faecal streptococci and *Clostridium* bacteria have all been used as indicators of pollution from sanitation and farm waste disposal. For more information on microbiological contaminants in groundwater, see West et al 1998 and Coombs et al 2000.

The groundwater side: settings, flow

While many aquifer settings provide raw water of high purity with respect to pathogens, this will not be the case when:

- The aquifer system is of a type that will not permit recharge to undergo an adequate residence time before reaching the supply. These could be aquifers where flow is along well-developed fracture systems, or gravel deposits where flow is intergranular but the permeability and groundwater velocities are very high.
- The aquifer is under the local influence of surface water. Examples include shallow boreholes or infiltration gallery systems adjacent to rivers (where the formation is acting mainly as a prefilter), and situations where the supply is effectively tapping ‘surface water temporarily underground’. The latter includes all springs, wells and boreholes in karstic limestone areas, rural supplies fed by field land-

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[3] Note however that both anaerobic and facultative bacteria have a bioremedial degradation role, being for example used conjunctively in some wastewater treatment systems.

drains and some catchpit systems drawing from very shallow-circulation spring systems.

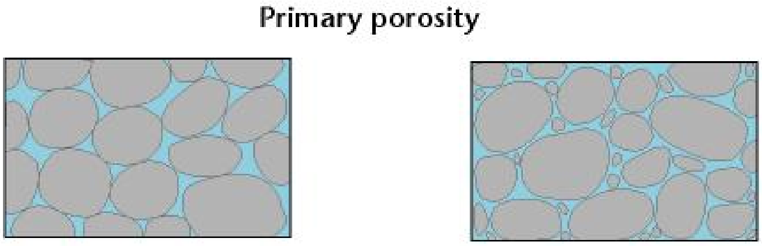
- The location, design, construction or operation of the borehole, well or spring tapping the aquifer permits water of recent origin to ‘short-circuit’ and mix with the main flow system, thus contaminating pristine groundwater from the aquifer. Examples include runoff entering via abandoned wells or shafts, or by overland flow to a spring box due to inadequate cut-off wall/bund, or ingress down a borehole annulus from defective casing or inadequate sanitary seal. A variant on this setting is where the screen design of the borehole or the well permits mixing-in of contaminated water from an upper level, either an overlying superficial aquifer or a separate shallow flow system. This latter occurrence is most likely in older wells in hardrock areas, where the deeper formation is poorly permeable and yield potential uncertain (see later).

In England and Wales, as elsewhere, such situations are not uncommon because of the diversity of aquifers and designs for the almost 2700 sources that provide water for potable use (Table 1).

Table 1 Groundwater public supply sources (from Environment Agency NAL database, 2009)

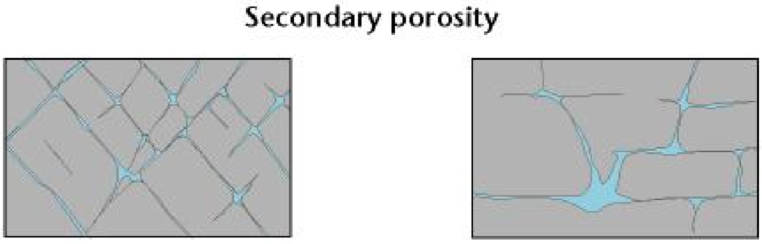
Source type	*No. of public supplies*
Boreholes	2249
Wells	254
Springs and spring complexes	86
Mineshafts and mine adits	22
Other (catchpits, infiltration galleries, wellpoints)	77
Total	2688

Clearly, an aquifer’s productivity depends on the fundamental characteristics of being able to both store and transmit water and these qualities vary (Fig. 4). Unconsolidated granular sediments (i), such as sands or gravels contain pore space between the grains and thus the water content can exceed 30% of their volume, but this reduces progressively both with the proportion of finer materials such as silt or clay and with cementation of the grains (ii). In highly consolidated rocks (iii) groundwater is found only in fractures and rarely exceeds 1% of the volume of the rock mass. However, in the case of limestones (iv), these fractures may become enlarged, by solution and preferential flow, to form fissures and caverns. Even then the total storage is relatively small compared to unconsolidated aquifers, and one result is that there is less water available to dilute contaminant pulses.



(a) unconsolidated well-sorted sand; high porosity

(b) sand porosity reduced by admixture of fines or cementation



(c) Consolidated rock rendered porous by fracturing e.g. crystalline basement

(d) Consolidated fractured rock with porosity increased by solution

Fig. 4. Rock texture and porosity of typical aquifer materials (modified from Meinzer, 1923)

A number of major British aquifers are a combination of types (ii) and (iii) or (ii) and (iv) in that the rock matrix provides a certain proportion of the total storage capacity of the system, while the fractures provide the dominant flow-path. Examples of these dual porosity aquifers include the Chalk, some Jurassic limestones, the Permo-Triassic sandstones and the Magnesian Limestone (Fig. 5).

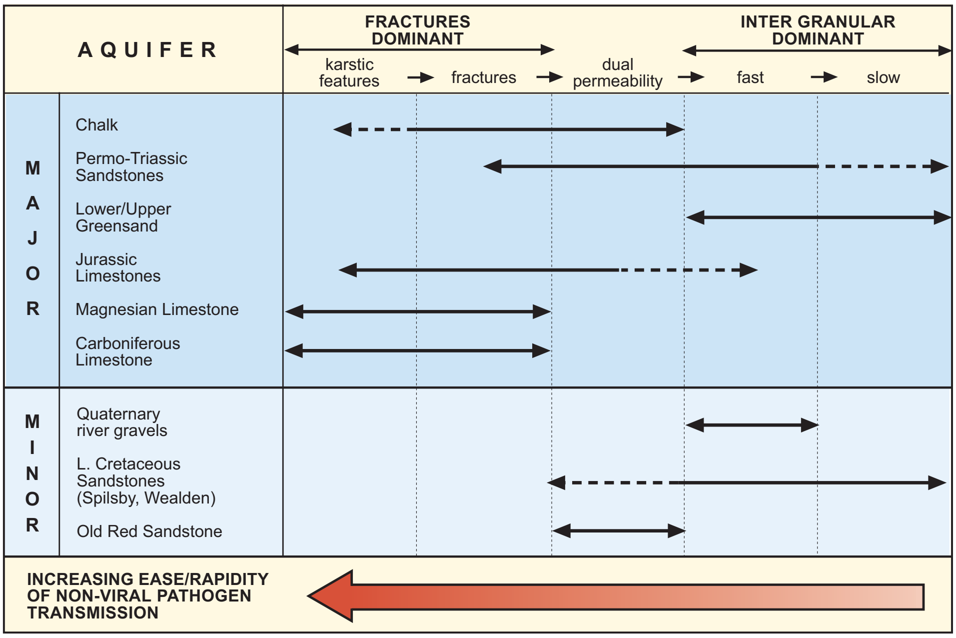


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Fig. 5. Nature of flow in major British Aquifers

This arrangement greatly modifies pollutant movement (Fig. 6), the water in the matrix being relatively immobile compared with that in the fissures:

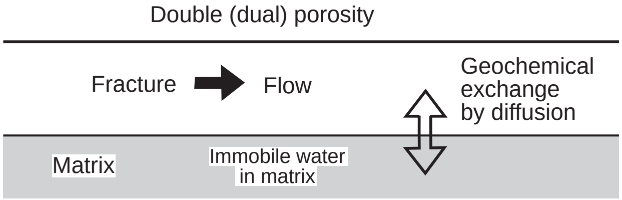

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Fig. 6. Schematic representation of double porosity aquifer (modified from Barker 1993)

All of these groundwater settings are found in the aquifers of Britain, but consolidated rock aquifers comprise the most important group for both public and private water supply. These include not only the six major aquifer systems[4] most used for public water supply, but also the more than 160 other locally important aquifers distributed throughout England and Wales which are also tapped for drinking water supplies (Jones *et al* 2000).

Often, recharge and flow in these aquifers conforms to the typical regional flow setting shown in Fig. 7, with dynamic groundwater systems in which water moves continuously in slow motion down gradient from areas of recharge to areas of discharge. In the larger aquifer systems, years or even decades may elapse in the passage of water through this subterranean part of the hydrological cycle. Such flow rates do not normally exceed a few m/day and compare to rates of up to 1 m/second for riverflow. There are, however, some fracture-flow aquifers such as the karstic limestones (including localised valley-axis zones of the Chalk with well-developed solution-enhanced fracture systems) where flow along major fissure systems can be as rapid as 1 km/day. Thus supplies located in different aquifers, or in different parts of the same aquifer can tap water of widely different residence time. This is an important factor for control of the migration of disease-causing micro-organisms, which degrade over time.

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[4] the Chalk, the Permo-Triassic sandstones, the Upper and Lower Greensand, the Magnesian Limestone, the Jurassic limestones and the Carboniferous Limestone

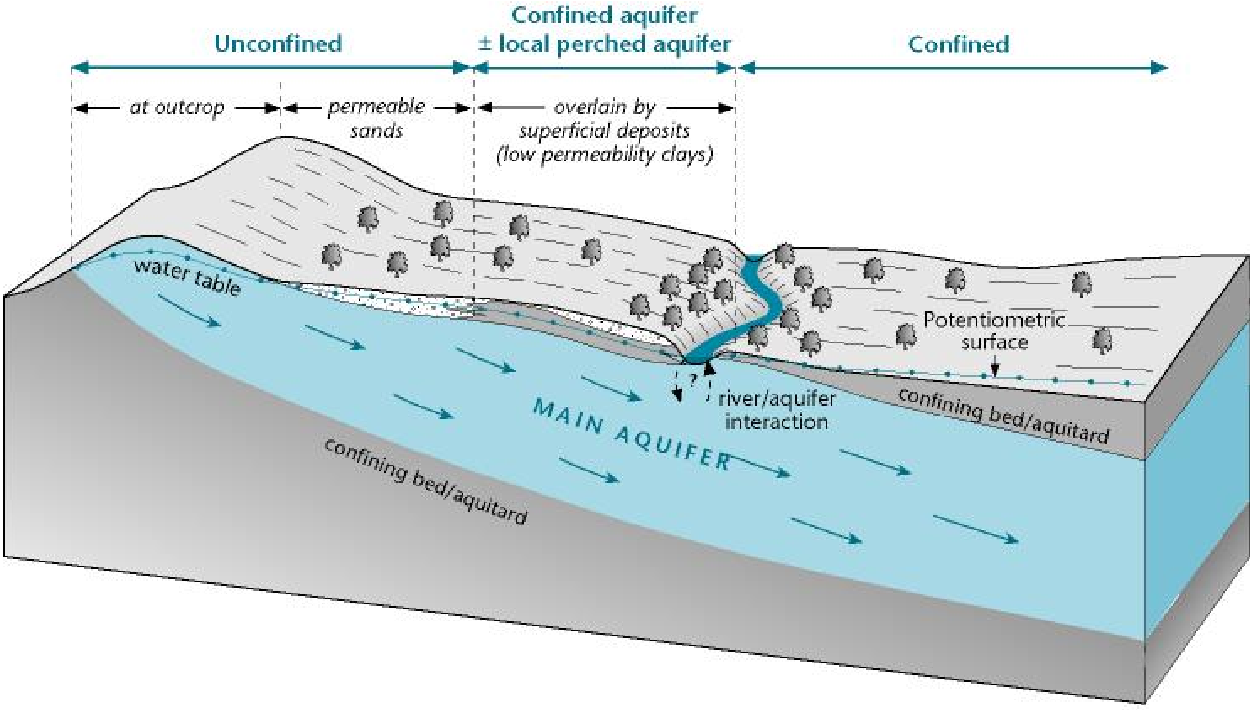


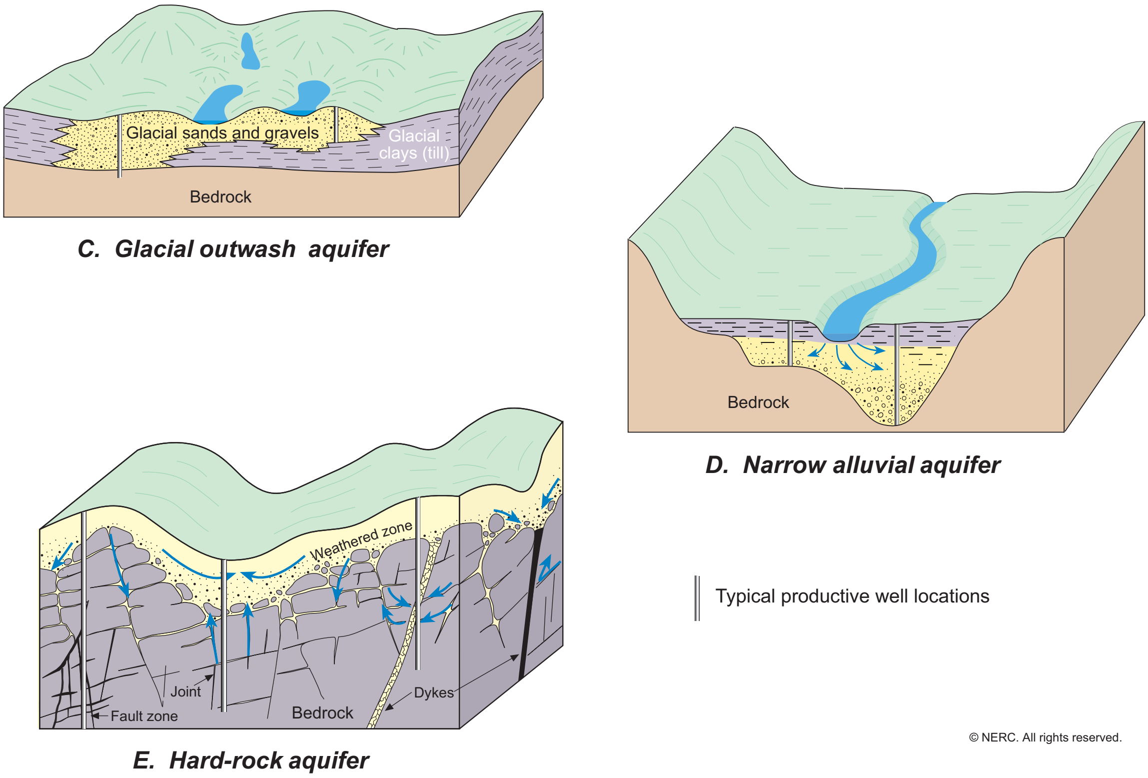
Fig. 7. Typical major aquifer situations in the UK

The characteristic geological feature of layering is present in both confined and unconfined aquifer systems. As well as controlling the yield, design and depth of the wells that tap such systems, layering is hydraulically important because the presence of beds with different permeability affects the rate at which contaminants entering below the ground surface can move into the aquifer.

Even in crystalline and very old sedimentary rocks, where structural and other controls dominate the effects of any original bedding, layering occurs as weathering processes enlarge fractures and introduce interstices near to the ground surface in rocks of otherwise very low permeability.

This is especially important for the many areas of Britain that are underlain by older poorly permeable hard rock formations. Although these are too low-yield to be considered as aquifers, they may be sufficiently productive in favourable circumstances to provide a few m^3/day of water, sufficient to support domestic-scale supplies (for an individual dwelling, farm, retail outlet or small camp-site). Many such rural supplies are present throughout the UK. These typically tap quite shallow depths (often less than 30m) and may draw at least some of their water from patches of much more recent glacial or alluvial deposits overlying the much older hard rock formations. In this setting, the overlying thin superficial layer of recent river or glacial deposits, if permeable, can provide a temporary storage medium for rainfall recharge, thereby increasing the productivity and apparent storage of the underlying bedrock (Fig. 8). It results in much more localised flow systems because the aquifer is limited in vertical or lateral extent, as in the case of relatively recent glacial (C) or alluvial (D) sediments, or because the bedrock is highly consolidated and usable water only occurs either in certain fracture situations or in a thin weathered zone near the ground surface (E) (Morris & Tyson, 2003).

Residence times in such aquifers are much less predictable either because the degree of interconnection with nearby rivers or lakes is uncertain or because there is more scope for rapid by-pass flow along fracture networks. Typically the shortest residence times (hours→days→weeks) occur in limestones where solutionally enlarged fissures or conduits (*karstic features*) are well developed.



C. *Glacial outwash aquifer*

D. *Narrow alluvial aquifer*

E. *Hard-rock aquifer*

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Fig. 8. Localised groundwater flow systems in minor aquifers (adapted from Freeze & Cherry 1979, Davis & De Wiest 1966)

Pathogen problems in groundwater supplies: examples

In the USA, poor microbiological quality of groundwater systems has caused many disease outbreaks. A review by Macler and Merkle (2000) reported the initial results of a major public health study of the occurrence of pathogens in U.S. groundwater supplies involving the sampling of 244 public water-supply wells prior to any treatment. About 50% of wells initially considered more vulnerable to contamination and 40% of wells considered less vulnerable were positive for one or more faecal indicators (total coliform bacteria, *E. coli*, enterococci, viruses infecting coliform bacteria, and human viruses). Craun and Calderon (1997) reported that between 1971 and 1994, 58% of U.S. waterborne disease outbreaks (356 in number) were caused by contaminated groundwater systems. 70% of these outbreaks were considered to be due to contamination of the groundwater source as opposed to the distribution system. To put this in context, groundwater is very extensively employed in the USA for both public and private water supply, with over 20 million domestic boreholes in regular use, many of which have no precautionary disinfection barrier.

In England and Wales, Fewtrell and Kay (1996) compiled a list of 18 outbreaks of waterborne disease associated with private water supplies between 1970-94 in which over 1388 people were affected. The figure is almost certainly an underestimate because no data from 1987-93 were available and under-reporting is an inherent problem. The authors' survey of 91 private supplies (all but two of which were groundwater-based) showed almost 50% of the supplies failing to meet national microbiological standards for faecal indicators (total coliforms, faecal coliforms and faecal streptococci). The survey sampled a range of groundwater settings, testing sites in 10 local authority areas in England. In Scotland, Benton *et al* (1989) reported that private supplies caused 21 out of 57 waterborne disease outbreaks between 1945 and 1987 (37%). These 21 outbreaks gave rise to at least 9362 cases (Lamb *et al*, 1998).

The special hazard for small groundwater supplies: the multiple barrier approach

Being generally smaller and less well-equipped than public supplies, and subject to less stringent surveillance and regulatory requirements, private groundwater supplies by their very nature are more likely to suffer water quality failures. Pathogens are the contaminant group of most concern to small supplies for the following reasons:

(i) Long travel times favour the natural elimination/attenuation of micro-organisms, but most private supplies will have a very limited catchment area. The volume of aquifer involved is relatively small and as geological formations are not uniform, very localised variations in properties such as fracture densities or apertures could disproportionately reduce recharge residence times.

(ii) Very many small supplies either have an installed disinfection system not maintained to a standard which would guarantee a safe supply at all times or lack any precautionary system at all. The onus to attenuate the pathogens present in recharge from any origin is then in effect placed on the subsurface, with the resource acting as the sole barrier. This is unlike drinking-water systems sourced from surface water, where there is a presumption that microbial contamination is always present, and treatment is accordingly designed to include multiple barriers. It also differs from groundwater public supplies, where operational timetables and precautionary disinfection regimes are strictly controlled, monitored and regulated.

(iii) Not all groundwater sources function the same, because different hydraulic structures may, by accident or design, draw water preferentially from various aquifer horizons. Those designs such as infiltration galleries, shallow wells and some springs, which pose a greater risk because they draw in water with short travel times from the recharge point, are also commonly used for small supplies. In general, these structures, together with collector wells in riverine gravels and shallow adited wells are more vulnerable to microbiological contamination than deep boreholes (Fig. 9).

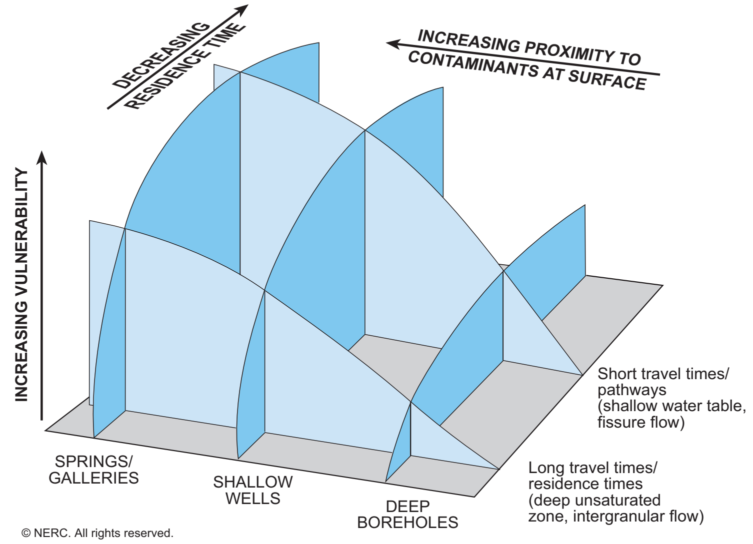

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Fig. 9. Relationship of vulnerability residence time and type of abstraction to microbial hazard (from Ball et al, 1997)

(iv) Some protozoan parasites like *Cryptosporidium* and *Giardia* are environmentally hardy, have low infectivity thresholds and are known to survive longer than many pathogenic bacteria. These pathogens may need to undergo an extended residence time in the subsurface before becoming non-viable. Regular consumers of groundwater contaminated at low concentrations may have a developed immunity that does not extend to visitors e.g. on-farm holiday accommodation, caravan and campsite situations.

(v) Age deterioration, poor wellhead hygiene or defects in design may provide localised pollution pathways from nearby septic tanks or cess/slurry pits (Fig 10)

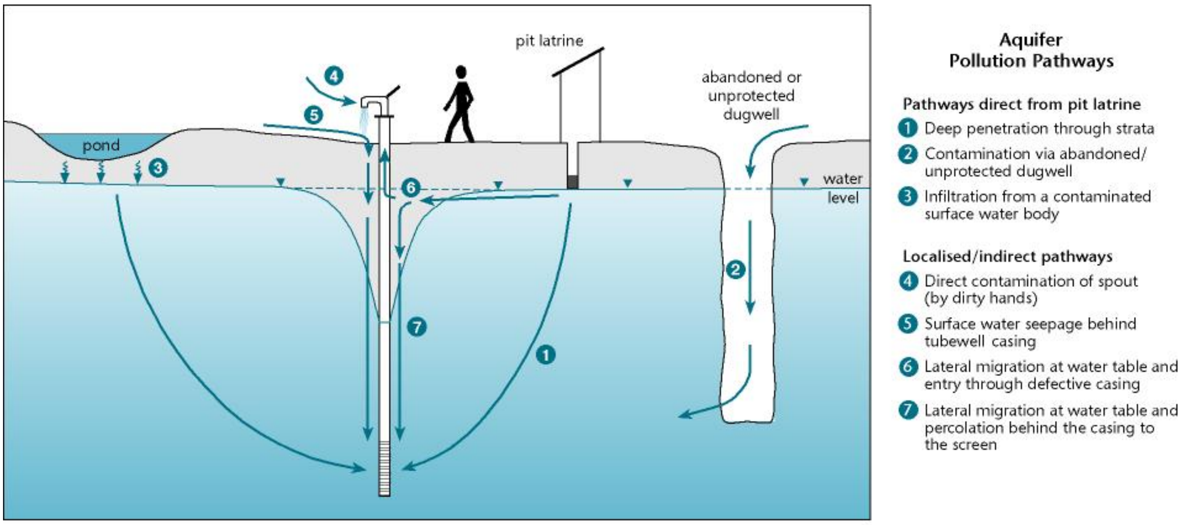


Fig 10 Groundwater supply pollution pathways by on-site sanitation (ARGOSS manual, 2001)

Private supplies would benefit from developing multiple barriers to minimise risk of exposure to pathogenic organisms. This is a management approach that has been proposed in the USA as part of the development by the Environmental Protection Agency (EPA) of a Groundwater Disinfection Rule to protect public water systems (Macler 1996, Macler and Merkle 2000, Wireman and Job 1998). Table 2 lists the four groups of barriers and relates them to operational conditions in England and Wales. The system is attractive because no single barrier is effective, by itself, in eliminating pathogens from the source-pathway-receptor route.

Table 2. Multiple barrier practices to control pathogen infection of private groundwater supplies (adapted from Macler and Merkle, 2000)

Pathogen barrier group	*Typical measures*	*Comments/Ways to introduce barrier into private water supply systems in England & Wales*
Source-water protection barriers	- Aquifer or wellhead protection programme - Specified minimum setback distances for faecal sources from supply - Using hydrogeological criteria for well siting - Monitoring raw water quality	-EA's Policy and Practice for the protection of groundwater - voluntary code - Could be based on 50-day Inner Protection Zone or sanitary control zone - Only possible for new or replacement supplies - Reactive:only shows infection after it has occurred. Useful to validate sanitary survey results
Borehole, well and spring water-system integrity barriers	- Sanitary surveys with mandatory take-up of improvements - Well construction codes	- Cost-effective and verifiable especially in conjunction with aquifer susceptibility rating; maximises operator involvement in improving own supply - No UK code; NWWA (1984) and US-EPA (1975) codes in USA are possible models
Operations and system maintenance barriers	- Well-pump-piping-storage disinfection - Periodic flushing of distribution system - Disinfection of new/repaired mains - Cross-connection control programmes - Operator registration or certification	- These measures adopted by public water supply agencies more widely than by private operators but could all be adapted to small supply operational scale.
Disinfection requirements	- Specified disinfection concentration x contact time values - Microbial kill/reduction values - Specified minimum disinfectant or chlorine residual in distribution systems	- Guidance measures need to keep abreast of disinfection technology development, especially of non-chlorination systems now increasingly used for small supplies.

Pathogen risk assessment for small groundwater supplies

Pathogen risk assessment for a small private supply has to be not only fast and robust (to be workable) but also simple and transparent (to enable operators to identify and correct identified hazards where practicable). Combined use of a sanitary survey and aquifer susceptibility rating would be one approach, as the results from each can be combined to provide a simple qualitative assessment of the risk that the raw water reaching the supply may at some period contain pathogenic micro-organisms.

A sanitary survey is an effective way to identify hazards, and such surveys have long been regarded (Lloyd and Helmer, 1991) as more useful guides to assessing potential pollution problems than single or very infrequent microbiological water quality analyses, because the latter can only indicate problems at the time of testing. The sanitary survey form for boreholes provided in the appendix to this article could be employed. This is modified from similar questionnaires in Lloyd and Helmer 1991, Lamb et al 1998 and Hodson 1996 and could be extended to include an evaluation of the standard of maintenance and efficacy of associated precautionary disinfection and other treatment plant.

A complementary tool is the aquifer pathogen pollution susceptibility rating, derived by following a flowchart (Fig. 11). The flowchart can be used for small private water supplies tapping either known aquifers or those low-yielding formations not usually described as aquifers, although in practice the procedure for each would be slightly different. Typically both sanitary survey and susceptibility rating would be conducted by an environmental health officer (to achieve consistency) in collaboration with the operator (to encourage adoption of improvement measures) with the joint aim of identifying whether short travel time pathways exist between a potential source of pollution and the well or spring intake which is the raw water receptor.

The sanitary survey results and the susceptibility rating can be related to each other transparently in a simple matrix (Figure 12) to provide a pathogen risk assessment for a given supply. The procedure would provide the environmental health officer with a means to identify deficiencies and highlight those actions where the owner/operator could significantly reduce risk by removing/mitigating identified hazards.

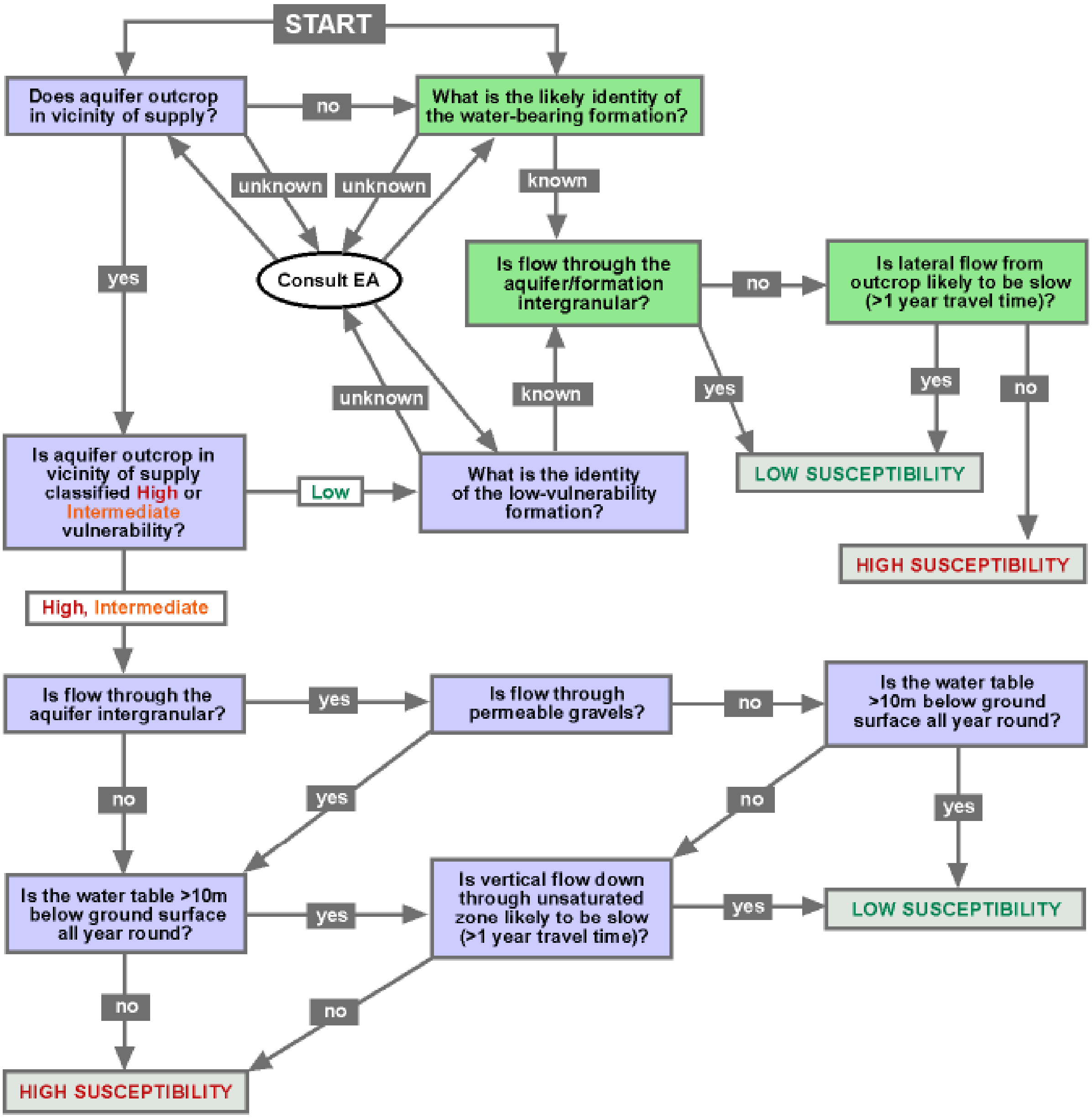
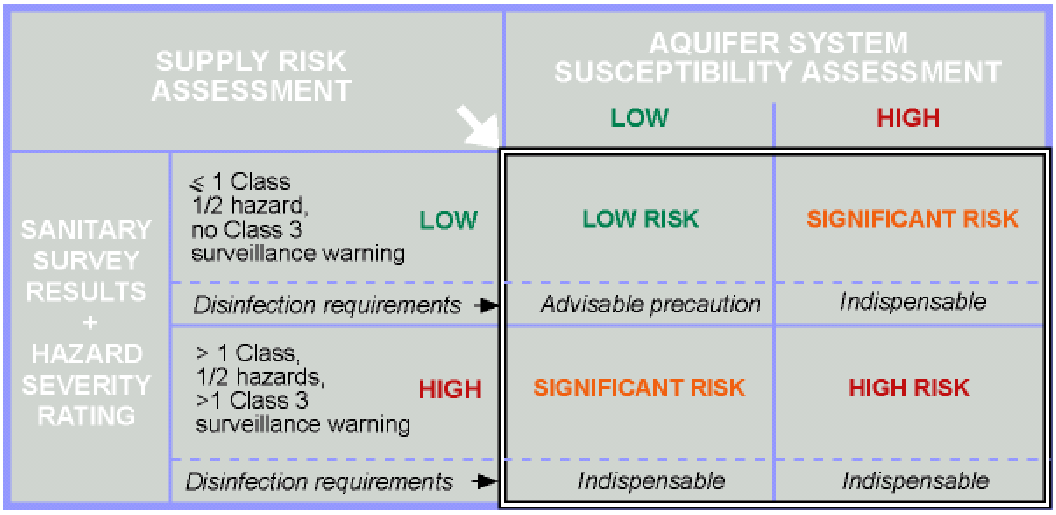


Fig. 11. aquifer pathogen pollution susceptibility-rating (from Morris, 2001)



SUPPLY RISK ASSESSMENT			AQUIFER SYSTEM SUSCEPTIBILITY ASSESSMENT LOW	AQUIFER SYSTEM SUSCEPTIBILITY ASSESSMENT HIGH
SANITARY SURVEY RESULTS + HAZARD SEVERITY RATING	≤ 1 Class 1/2 hazard, no Class 3 surveillance warning	LOW	LOW RISK	SIGNIFICANT RISK
	Disinfection requirements →		*Advisable precaution*	*Indispensable*
	> 1 Class, 1/2 hazards, >1 Class 3 surveillance warning	HIGH	SIGNIFICANT RISK	HIGH RISK
	Disinfection requirements →		*Indispensable*	*Indispensable*

Fig. 12. Pathogen risk assessment matrix (from Morris, 2001)

The special concerns over *Cryptosporidium* in groundwater supplies: a regulatory case history

Background: Increasing awareness that the 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 for waterborne outbreaks of cryptosporidiosis. In the UK Bodley-Tickell et al (1997) found *Cryptosporidium* in almost 70% of rural surface waters tested, demonstrating a constant threat to public water supplies drawn from surface waters. A large outbreak in Oxford and Swindon in 1989 focused attention on the parasite's presence as a waterborne problem and stimulated much development during the early 1990s of precautionary treatment and protocols to reduce the threat to surface water-derived supplies to acceptable levels (Badenoch, 1990, 1995). The realisation that *Cryptosporidium* contamination of groundwaters used for public supply can also occur was only more recently 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 the use of simpler treatment facilities (typically precautionary disinfection by chlorination, ozonation or ultra-violet irradiation) than those needed for surface water sources. The low infective dose threshold and the resistance of *Cryptosporidium* to such common disinfection methods makes a breakthrough of infectious oocycts a real hazard if raw groundwater has become contaminated.

That contamination can occur is now undoubted, and Hancock et al (1997) noted that in the 12 most recent outbreaks at that time of waterborne cryptosporidiosis in the USA 33% were traced to contaminated wells; 17 of 74 wells in their survey contained *Cryptosporidium* (average 4.1 oocysts per 10 litres). In the UK an outbreak in north London in 1997 with 345 confirmed cases of cryptosporidiosis was traced to a groundwater supply (DWI, 1998). The implications of this outbreak were significant because in that year (Table 3) almost 5000 Ml/d or about three-quarters of all licensed groundwater abstraction in England and Wales was used for public supply, providing water for the equivalent of 20 million population. 26 of the 28 water undertakings in England and Wales rely on groundwater for part or all of their supply.

Table 3 Role of groundwater in water supply in England & Wales 1997-2006 (modified from DEFRA 2009)

Year	*Public water supply Ml/d*	*Private water supply Ml/d*	*Other uses Ml/d*	*Public & private water supply as % of all licensed abstraction*
1997	4999	85	1,709	75
1998	5042	86	1,525	77
1999	5019	43	1,799	74
2000	4937	55	1,520	77
2001	4941	38	1,505	77
2002	4976	26	1,515	77
2003	5099	27	1,420	78
2004	4918	26	1,347	79
2005	5027	24	1,349	79
2006	4833	28	1,347	78

The north London outbreak and other suspected *Cryptosporidium* contamination events associated with groundwater supplies led to new regulations being introduced in 1999 with the intention of controlling the risk to public water supplies of contamination by the pathogen. The new statute (the Drinking Water Supply [Water Quality] [Amendment] Regulations SI 1999 No. 1524) required water companies to set a treatment standard of an average of <1 oocyst per 10 L of water supplied and to conduct a risk assessment for each of their treatment works to help conform with this standard. To verify compliance with the treatment standard for those works where the assessment established that there was a significant risk, it was required that water leaving the works be continuously sampled and analysed daily for Cryptosporidium oocysts.

The 1999 Risk assessment exercise: The assessments found about one-fifth (332) of the 1481 treatment works in operation in England and Wales in 1999 as being at significant risk, about one half of which were plants treating groundwater. 19 of the 28 water undertakings were affected, the 175 groundwater at-risk works being geographically widely spread and drawing from a dozen nationally, regionally or locally significant aquifer systems (Morris & Cunningham 2005). An analysis of their distribution showed that works tapping the Chalk were the largest single aquifer category (Fig. 13) and springs draining fracture-flow systems the most common at-risk design type (Table 4).

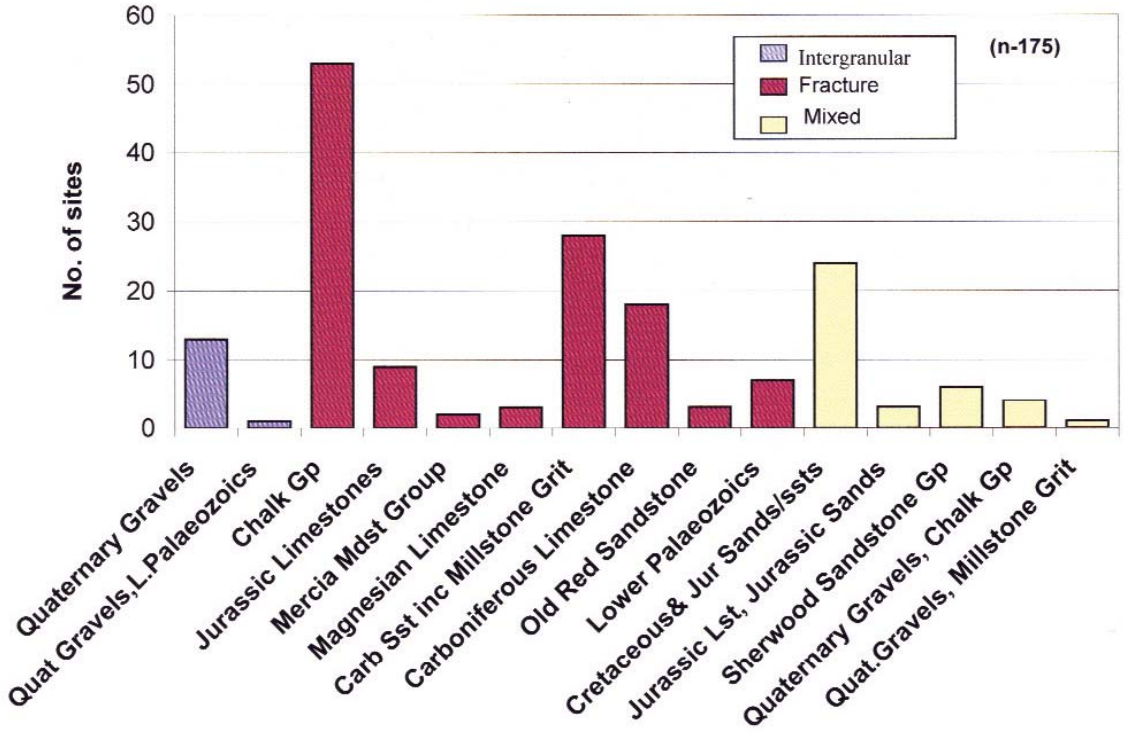


Fig. 13. At-risk groundwater treatment works in England and Wales by aquifer and flow type (from Morris & Cunningham 2005)

Table 4. At-risk groundwater treatment works in England & Wales by supply type (from Morris & Cunningham 2005)

Class and % of total	*Supply type*	*No.*
Drilled well systems 29%	Borehole(s) alone	50
Borehole-enhanced well or well and adit systems 9%	Borehole(s) and well(s) Borehole(s),well(s) & adit(s)	6 10
Other systems 62%	Excavated Well(s) (large diameter vertical wellshafts) Well(s) with adit(s) (sub-horizontal excavated shaft or gallery) Spring(s) Spring(s) with well(s) & shallow borehole(s) Mine gallery or adited spring	9 15 76 6 3
	Total	175

It was generally accepted at the time the risk assessments were conducted that they were semi-qualitative, one of the several limiting factors being the need to rely on existing surveillance results that were mostly from non-*Cryptosporidium* microbiological indicators. Nevertheless, the number and extent of groundwater public supplies identified as at risk came as a surprise to the industry.

Once the risk-assessment process had been completed, water companies with ‘at significant risk’ groundwater treatment works (GWTWs) had three risk reduction options (DWI 1999):

- shut down the supply,
- install a plant capable of meeting the new treatment standard of continuous removal of particles >1 µm in diameter, for which a timetable for installation had to be agreed with the DWI, or
- implement continuous monitoring under strict chain-of-custody rules.

All three options were variously adopted by water companies for the at-risk GWTWs that they identified under their chosen assessment procedure. The choice of option for a given GWTW depended not only on its specific operational setting and the availability of an alternative not-at-risk supply but also on the asset management strategy of the water utility. More than a quarter (27%) of the works were immediately eliminated either by abandonment or by placing on long-term standby (not operating but not formally taken out of production), while a similar percentage (24%) were scheduled for treatment modifications, generally membrane filtration plant installation. Generally the preferred option for works tapping major aquifers like the Chalk and the Jurassic limestones was to keep the works operational, with a significant number modified for particle removal treatment. Such works were often served by boreholes, wells, adits or a combination thereof. In contrast, spring-fed works, a number of which tend to be sited on upland areas and less productive aquifers, were more commonly placed on standby or abandoned (as well as scheduled for additional treatment). Thus, less than half of the at-risk works continued in operation unchanged and thereby became subject to the continuous monitoring requirement from 1999 onwards (including some treatment upgrade works that temporarily had to be monitored in the period before commissioning the new plant).

Results of oocyst monitoring: By the end of 2005, the resultant national monitoring database, maintained by the DWI, contained almost 275,000 sample results, about a third of which were provided from groundwater-only treatment works. The 5½-year monitoring period covered winter recharge months both significantly wetter than and significantly drier than average. Some 89 different treatment works recorded 2812 samples that were at or above the minimum oocyst detection limit (typically 0.01/10 L), representing about 3% of all samples. The monitoring programme had produced widespread detections of oocysts in GWTWs, tapping a wide range of British aquifers of different lithologies and flow conditions. Once thought to be an exceptional occurrence in groundwater, oocyst positives were recorded in 83% of the works that were monitored.

However, most positives were at very low concentrations and only six samples (from three sites) exceeded the treatment standard, all during 2001. The annual 90th percentile oocyst concentration showed that in all years, the positive concentrations detected were overwhelmingly <0.1 oocysts per 10 L. The three exceedence sites were a mine gallery and spring complex in the Carboniferous Limestone and a spring complex in Lower Palaeozoic slates, all in the Pennines.

Public health benefit: The risk screening process and the results of the risk assessments themselves obliged water companies to scrutinise those sources that, either through the prior microbiological surveillance record or from an evaluation of the hazard settings and treatment facilities, had demonstrated that they might be significantly at risk of oocyst transmission in excess of the new regulations. This stimulated water companies into risk-reduction measures that included the removal from production of about a quarter of the sources and the installation of additional treatment measures in another quarter. As these measures were substantially completed within 18 months of the statute coming into force, it is reasonable to infer that, as a result of the screening exercise, the array of works monitored since 2001, although diverse, is weighted in favour of lower-risk sources compared with the initial candidate list.

Interpretation of the results was complicated by a number of factors but broadly vindicated the screening and monitoring measures as a preventive health success, albeit at an estimated cost (2000-2005) to the consumer of about £12 million. For more information on *Cryptosporidium* and groundwater for water supply see Morris & Foster (2000), Morris & Cunningham (2005) and Morris & Whitehead (2007).

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