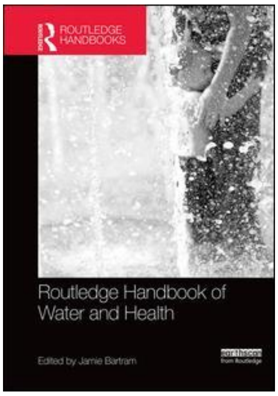

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BRADLEY CLASSIFICATION OF DISEASE TRANSMISSION ROUTES FOR WATER-RELATED HAZARDS*

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Learning objectives

1 Understand the purposes and value of a disease classification system.
2 Recognize and explain the 'Bradley Classification' of water-related disease.
3 Understand an updated interpretation of the 'Bradley Classification', since its first description, and appreciate its comprehensive validity, wide applicability and future relevance worldwide.

Disease classification

A classification is literally 'The action or process of classifying something according to shared qualities or characteristics' (Oxford Dictionaries, 2014), the definition of which goes on to provide as an example 'the classification of disease according to symptoms'. However, disease classification can be based on diverse perspectives and many group

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diseases according to their underlying processes (e.g. infective, allergic, metabolic, neoplastic); the primary organs affected (genitourinary, respiratory, gastrointestinal); immediate cause (toxic, microbial, genetic); and, for externally caused diseases, the type of exposure or source of the hazard (airborne, water borne, endemic, zoonotic). Infectious diseases may be classified according to the broad classification of the infecting agents (viral, bacterial, protozoal) or even by the genus of infective agents (mycobacterial, treponemal). Other classification systems may also be used for various reasons especially when intending to stress the importance of a group of diseases such as the 'neglected tropical diseases' or means of transmission such as faecal–oral diseases.

A classification is useful only in as much as it enhances understanding, communication and effective action, in this case towards disease prevention. The process and outcome of classification are useful in clarifying and making subject to criticism our 'view of the world'. In doing so and when well conducted they tend to improve comprehension, enhance the real and perceived 'balance' among perspectives and encourage critical reflection. Classifications serve to increase order, to make complex matters tractable and to encourage reflection on the principal dimensions of a theme. The process of classification often forces explicit recognition of influences that may otherwise be unrecognized or implicit.

'Water-related disease' is a diverse assemblage. The hazards or agents that are the direct cause of damage include bacteria, viruses, protozoa, helminthes, chemicals and personal physical factors. They may originate from human or animal excreta, industrial operations or be parts of natural or disturbed ecosystems. The sites of entry include ingestion but also inhalation/aspiration, wounds and perforation of mucous membranes and intact skin. The sites of damage – whether by pathogens or chemical toxins – include every organ of the body. The symptoms are diverse ranging from the acute (self-limiting diarrhoea) to the chronic (cancers, blindness and life-long infections) and recurring (malaria); and are both direct (caused by a pathogen or chemical) and indirect (such as an existing condition aggravated by the physiological effects of the water-related disease or through an intermediate state such as such as malnutrition caused or aggravated by water-related disease). Finally, epidemiological investigation identifies numerous underlying associated factors such as poverty, education, climate, demography, housing and use of basic services. Some of these may be judged to be 'causal' whereas others may be associated through a series of co-factors, and distinguishing among these is complex.

In 1972 White et al. proposed '…a new classification intended to be both more comprehensive and more precise in predicting the likely effects of changes in water supply on infective diseases' (White et al., 1972, p162), noting that 'All infections related to water supplies are included – that is, all those likely to change in incidence or severity as a result of changing water supplies.' The classification has become widely known as the 'Bradley Classification'. It comprises four broad and non-exclusive classes of water-related disease: water borne; water washed; water based; and diseases with a water-related insect vector (Figure 3.1).

A review of Figure 3.1 and the associated text of the 'Drawers of Water' study show that the classification reflects a careful handling of multiple perspectives, accounting for aspects of transmission, control and disease consequences. Evidently the sense of 'supply' – and hence the scope of the definition – was broad, including water resource-related concerns and was not restricted to a narrow interpretation of drinking water or household water.

A CLASSIFICATION OF INFECTIVE DISEASES RELATED TO WATER

Category	Example
I. Waterborne	
a) Classical	Typhoid
b) Nonclassical	Infectious hepatitis
II. Water-washed	
a) Superficial	Trachoma, Scabies
b) Intestinal	*Shigella* dysentery
III. Water-based	
a) Water-multiplied percutaneous	Bilharziasis
b) Ingested	Guinea worm
IV. Water-related insect vectors	
a) Water-biting	Gambian sleeping sickness
b) Water-breeding	Onchocerciasis

Figure 3.1 Facsimile of the table presenting a 'Classification of Infective Diseases Related to Water'

Source: White et al., 1972

Water-borne disease

White et al. (1972) describe this class as 'where water acts as a passive vehicle for the infecting agent' (p162).

Definition/explanation

The water-borne class is, for many, the most intuitive and comprises those diseases caused by the ingestion of pathogens in water. It is fundamentally concerned with water quality and safety. Chapter 4 of this volume provides an overview of the diverse viral, bacterial, protozoal and helminthic causes of water-borne disease. While water-borne disease can be manifest as, sometimes large, outbreaks, the ability of public health surveillance systems to detect such events, even in countries with advanced health information systems, is very low and in fact the majority of water-borne disease is not associated with identified outbreaks.

Recognized links and complexities

The great majority of the agents of water-borne disease can also be transmitted by other means, all leading to ingestion. As such it overlaps with the concept of faecal–oral disease transmission (Figure 3.2). Hygiene, and especially hand washing at critical times, is an important preventive measure and is also reflected in the water-washed class of water-related diseases; and in the facts that some agents and diseases may be both water-borne and water-washed.

Changes over time requiring interpretation or implying modification of the class

Several important considerations have emerged or been clarified since 1972 that impact our interpretation of water-borne disease. These include knowledge of: a greater number of

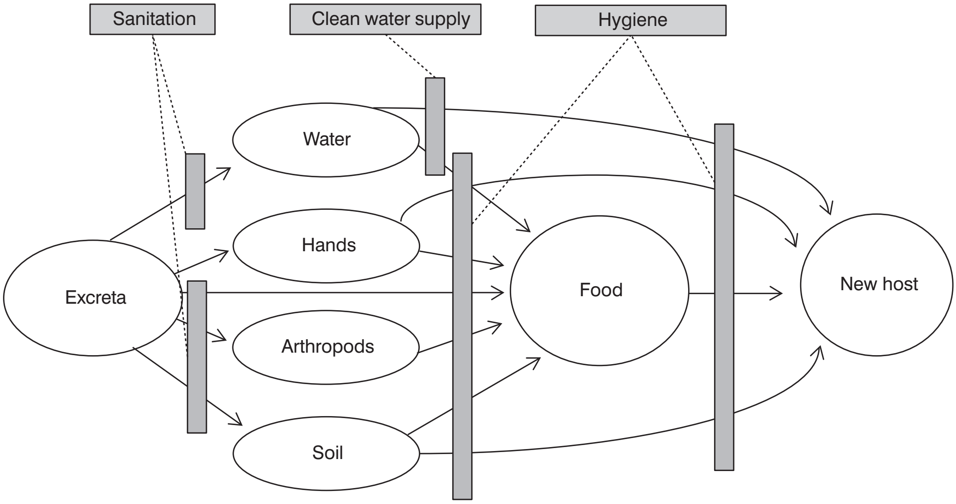

Figure 3.2 Faecal–oral disease transmission

This representation reflects the original terminology of Wagner and Lanoix (1958). It is popularly referred to as the 'F diagram' and depicted with water as Fluids, arthropods as 'Flies', hands as 'Fingers' and sometimes with the addition of Fomites.

causal agents; deterioration of water quality between source and use; the risks of animal and human faecal pollution; and understanding of chemical hazards

Knowledge of, and the perceived importance of, some individual causal agents has developed. Two agents which were historically important causes of mortality, cholera (caused primarily by toxigenic strains of the bacterium *Vibrio cholerae*) and typhoid (caused by the bacterium *Salmonella* Typhi), have declined in global importance but remain locally important where outbreaks occur. They were described by White et al. (1972) as having become established as the 'types' for discussion of water-borne diseases and criticized as not being representative in that role, which remains true today. Other agents have been recognized, including several viruses, such as rotavirus and norovirus (caliciviruses). For some viruses, while water-borne transmission may contribute to disease spread, water quality management is unlikely to provide an effective control measure as other routes of transmission dominate. Other recognized agents include the protozoans *Giardia* spp and *Cryptosporidium* spp, both of which have an environmentally resistant cyst form, the latter of which is small and has challenged some of the water treatment processes that are widespread in industrialized nations. The range of now-recognized water-borne disease agents is summarized in Table 3.1. This list is considerably longer than that of White et al. (1972).

Since the original development of the Bradley Classification, much attention has been paid to deterioration in water quality between 'source' and use. This includes aspects of primary relevance to low and middle income countries (LMICs) such as faecal pollution in water transport and household storage (Wright et al., 2004; Shields et al., 2014). Debate has included concern about the relative importance of intra-household versus community excreta exposure (VanDerslice and Briscoe, 1993; Baum et al., 2013) and the value of household water treatment and safe storage as a health intervention (Clasen et al., 2009; Schmidt and Cairncross, 2009; Hunter, 2009). While this attention does not fundamentally

Table 3.1 Pathogens transmitted through drinking water

Pathogen	*Health significance*	*Persistence in water supplies*	*Resistance to chlorine*	*Relative infectivity*	*Important animal source*
Bacteria					
Aeromonas hydrophila	Moderate	May multiply	Low	High	No
Burkholderia pseudomallei	High	May multiply	Low	Low	No
Campylobacter jejuni, *C.coli*	High	Moderate	Low	Moderate	Yes
Escherichia coli – pathogenic	High	Moderate	Low	Low	Yes
E. coli – Enterohaemorrhagic, e.g. E. coli O157	High	Moderate	Low	High	Yes
Francisella tularensis	High	Long	Moderate	High	Yes
Helicobacter pylori	Pending	Short	Pendng	Pending	Yes
Legionella pneumophila	High	May multiply	Low	Moderate	No
Leptospira interrogans	High	Long	Low	High	Yes
Mycobacteria (non-tuberculous, *M. avium* complex, MAC)	Low	May multiply	High	Low	No
Salmonella Typhi	High	Moderate	Low	Low	No
Other salmonellae	High	May multiply	Low	Low	Yes
Shigella dysenteriae, S. flexneri, S. mansoni	High	Short	Low	High	No
Vibrio cholerae	High	Short to long	Low	Low	No
Viruses					
Adenoviridae (adenoviruses)	Moderate	Long	Moderate	High	No
Astroviridae (astroviruses)	Moderate	Long	Moderate	High	No

Caliciviridae (noroviruses, sapoviruses)	High	Long	Moderate	High	Potentially
Hepeviridae (hepatitis E viruses)	High	Long	Moderate	High	Potentially
Picornaviridae (enterovirus, parechovirus, hepatitis A viruses)	High	Long	Moderate	High	No
Reoviridae (rotaviruses)	High	Long	Moderate	High	No
Protozoa					
Acanthamoeba spp.	High	May multiply	Low	High	No
Cryptosporidium hominis, C. parvum	High	Long	High	High	Yes
Cyclospora cayetanensis	High	Long	High	High	No
Entamoeba histolytica	High	Moderate	High	High	No
Giardia intestinalis	High	Moderate	High	High	Yes
Naegleria fowleri	High	May multiply	Low	Moderate	No
Toxoplasma gondii	High	Moderate	Long	High	Yes
Helminths					
Dracunculus medinensis	High	Moderate	Moderate	High	No
Fasciola hepatica, F. Gigantica	Pending	Pending	Pending	Pending	Yes
Schistosoma mansoni, S.japonicum, S.mekongi, S.intercalatum, S. haematobium	High	Short	Moderate	High	Yes

Source: Adapted from WHO, 2011, p119

alter our understanding of water-borne disease, it does modify the frame of reference with which we analyse and interpret associated evidence.

White et al. (1972) note that '… animal pollution with fecal coliforms has different implications from human pollution'. Since that time the increase in numbers of livestock has continued. Large numbers may be kept close to human populations, the management of the excreta is often poor and water provides a connection between animal and human populations. Disease agents of concern because of animal to human disease transmission (e.g. *Crysptosporidium*) have been of increasing concern (reviewed in Cotruvo et al., 2004 and Dufour et al., 2012). These issues increase the scope for concern about water-related zoonoses and the range of agents of concern may increase further as understanding grows in the future. The importance of this for transmission relates to control measures in that close-to-source measures will vary between human faecal sources (sanitation) and animal sources (livestock including feedlot management and animal access to water resources).

Chemical hazards were not addressed in the original classification. This was a conscious decision:

> Conditions usually considered noninfective, such as cancer and artherosclerotic heart disease, also are believed to vary with water quality, but the relations are subtle and are poorly understood as yet. It is rarely possible by available technical means to control non-infective disease (apart from dental caries) by changing the quality of domestic water …
>
> *White et al., 1972, pp 161–162*

Since that time greatly increased attention has been paid to chemical exposure and human health including exposure through drinking water, reflected in the inclusion of an increasing number of individual chemical hazards in consecutive editions of WHO's *Guidelines for Drinking-water Quality* (WHO, 1984, 1993, 2008, 2011). Nevertheless a limited number of agents are credible contributors to substantive disease burden at a global scale, potentially only fluoride and arsenic and possibly lead. But many others may be of local or national concern depending on industrial processes, agricultural practices, geology, water treatment and distribution methods and other factors (Thompson et al., 2007 and Chapter 10). This is reflected in extensive regulations in many LMIC and industrialized countries. A major change has taken place since 1972 in that the claim that 'It is rarely possible by technical means to control [chemical hazards in water]' does not hold true. In the same way that there are multiple routes of transmission of pathogens through the faecal–oral route, so chemical exposure may be through multiple means including foodstuffs and inhalation as well as ingestion with water; and in the same way that multiple transmission routes of pathogens must be understood for efficient and effective intervention, so must diverse contributions to overall chemical exposure be understood. These typically depend on major contaminant-source type categories (Chapter 25).

Exposure and disease burden

Until recently, inhabiting a dwelling for which water was collected from an 'improved source' was used as an indicator of access to, or use of, safe water. On this basis, according to WHO and UNICEF, some 11 per cent or 780 million of the global population did not use an improved source in 2010, with the greatest number of the unserved in Asia and the highest proportion of the unserved in sub-Saharan Africa. More recent literature correcting for the proportion of dwellings in which water tests show no faecal indicator bacteria in a one-off test increase these figures to 28 per cent or 1.9 billion (in 2012, Bain et al., 2014). Further correction to account for the sanitary status of the water source itself increases them further to 47 per cent or 3 billion (Onda et al., 2012). These figures do not fully account for water quality variability. Data on water safety in other settings such as schools, workplaces, markets and health care settings (Cronk et al., 2015) are very limited but would increase these figures further still.

A recent estimate of the burden of diarrhoeal disease from exposure to inadequate drinking water sanitation and hygiene in LMICs concluded that 842 000 million diarrhoea deaths (1.5 per cent of the total disease burden and 58 per cent of diarrhoeal diseases) were caused by this cluster of risk factors. It is difficult to disentangle the various components of faecal–oral disease transmission, especially water-borne and water-washed disease (Prüss-Ustün et al., 2014).

The disease burden, including that associated with some faecal–oral diseases, includes a number of sequelae (i.e. delayed and often chronic effects consequent to the original infection) that should be taken into consideration. An example is Guillain-Barré syndrome. This is an adverse neurological outcome that affects a small proportion of people following a viral or bacterial infection such as campylobacteriosis. The long-term debilitating effects, while experienced by only a proportion of those infected, weigh heavily.

Water-washed disease

White et al. (1972) describe this class as comprising ‘infections that decrease as a result of increasing the volume of available water’ and also provide a formal operational definition: ‘water washed infections are those whose incidence or severity can be reduced by augmenting the availability of water without improving its quality’ (p162).

Definition/explanation

The water-washed disease class is fundamentally concerned with access to and use of water for personal, food and domestic hygiene. In contrast to water-borne disease, the role of water is in prevention of disease transmission rather than as a vehicle for carriage of pathogens. Water-washed diseases may be conveniently divided into two types. The first comprises faecal–oral diseases, which may also be water- and food-borne, because water serves both as a vehicle for their transmission and is necessary for adequate personal and food hygiene whereby both sufficient water and safe water are necessary for effective prevention. The second includes diseases such as trachoma (*Chlamydia trachomatis*), skin sepsis (diverse bacterial causes) and yaws (*Treponema pertenue*) where transmission is person to person and hygiene also plays a role in prevention.

Recognized links and complexities

White et al. (1972) wisely side-stepped the issue of behavior by defining the class in terms of water availability, rather than extend the definition to encompass the fact of its use. Monitoring activities over the subsequent period have provided information on water access and use (Bartram et al., 2014) but study and monitoring of actual behaviors has proven problematic: suitable indicators are hard to identify and data collection is fraught with bias (Freeman et al., 2014). Indeed the relationships among access, reliability, use and behavior are complex and poorly understood.

White et al. (1972) note that 'water has many uses, several affecting health and it seems clear that the volume employed for each activity will affect health. We do not know the quantitative relationships …' That statement remains substantively true today, despite the studies that have taken place in the interim, although broad bands of relative adequacy for different purposes from personal hydration to domestic hygiene have been described (Howard and Bartram, 2003).

Also originating from the 'Drawers of Water' study was a depiction of the relationship of domestic water use according to the time/distance for water collection. The 'plateau curve', refined by Cairncross (1990), suggested that water use was plentiful when the source was very close to the dwelling; plateaued at around 20 litres per capita per day where a water collection trip took around 5 to 30 minutes and declined further thereafter. Recent work has confirmed much greater domestic water use when water is accessed 'on plot', but evidence for the decline when the collection burden is excessive is elusive and this now affects a small and declining population (Evans et al., 2013). Similarly there is some evidence for greater health benefits associated with dwelling-level water access (idem) and it seems likely that future policy, such as the Sustainable Development Goals (Chapter 43), will give greater emphasis to this level of access.

The notion of availability (or access) – the fundamental basis on which the class is identified – has proven complex (Bradley and Bartram, 2013). In addition to varying degrees of access (above), complexity includes the facts that access is normally defined at a household level and applied to all associated persons equally, but the experience of access varies between individuals within households; and access is also experienced and may be restricted in extra-household settings (Cronk et al., 2015).

Changes over time requiring interpretation or implying modification of the class

On trachoma, White et al. (1972) said that while '… most workers think that making water more readily available reduces the amount of clinical trachoma, little precise data is available' and that 'Most ophthalmologists would hold that prevalence [of trachoma] is also reduced by a readily available water supply, but as yet there is limited evidence to support this view.' Certainty about the role of water, sanitation and hygiene (WaSH) has increased: Stocks et al. (2014) confirm its importance in trachoma elimination; and it is reflected in the SAFE strategy for eradication of blinding trachoma (Surgery, Antibiotics, Facial cleanliness and Environment) but it has received limited attention in large-scale eradication efforts.

There are three areas in which new information or an evolving understanding of the issue affects the class of water-washed disease: hydration (reviewed in Howard and Bartram, 2003); the impact of personal hygiene; and water carriage.

There is now strong evidence that good personal hygiene is associated with decreased transmission of non-faecal–oral, as well as faecal–oral water-washed diseases. These include some respiratory diseases with large global disease burdens such as pneumonia (Aiello et al., 2008; Freeman et al., 2014).

The process involved in having to fetch water each day can also have adverse impacts on health. There is substantive evidence for skeletal injury associated with water carriage (Chapter 7), and suggestive evidence for violence on persons collecting water from shared community sources. In addition some work has shown that infectious diseases such as meningococcal disease has spread in refugee camps along the routes that people walk to fetch water (Santaniello-Newton and Hunter, 2004). While different in cause and exposure, these are associated with water access, and remedial measures are primarily related to enhancing access levels to that of the household. Other evidence suggests that this level of water access is associated with health benefits (Kayser et al., 2013; Cumming et al., 2014). As such they fit well in this class despite the word 'washed' in the titular description being inappropriate.

Exposure and disease burden

The water-washed disease class is fundamentally concerned with water access, which is monitored at a household level by WHO and UNICEF, suggesting that 56 per cent of the global population live in households with water 'on plot' (normally a piped supply) and a further 33 per cent use an 'improved source' such as a protected community source. Although these data do not account for relative accessibility, the great majority of these sources are within 30 minutes' collection time. These two categories of access serve as indicators of relative household water use (Evans et al., 2013).

Freeman et al. (2014) estimate that approximately 19 per cent of the world population washes their hands with soap after contact with excreta and that hand washing reduces the risk of diarrhoeal disease by 23 per cent (after adjustment for unblinded studies).

Water-based disease

White et al. (1972) describe this class as 'where a necessary part of the life cycle of the infecting agent takes place in an aquatic animal' (p162).

Definition/explanation

The water-based disease class is concerned with those agents of disease that pass an obligatory part of their life cycle in water. Infection may be through ingestion – as is the case with dracunculiasis – which therefore overlaps with the water-borne class; or may be across the intact or damaged (abraded, wounded) skin (percutaneous) – as is the case with schistosomiasis and leptospirosis. These are normally disease agents with more-or-less complex life cycles. Chapter 5 describes the cause, transmission and prevention of schistosomiasis.

Recognized links and complexities

White et al. (1972) divide the water-based class into two: the first comprising the helminths (schistosomes), which they consider 'water multiplying' because of proliferation in the intermediate snail host; and the second comprising guinea worm (*Dracunculus medinensis*), whose larvae infect aquatic crustaceans but do not multiply in them.

Unlike the agents associated with water-borne and water-washed disease, the helminth causes of water-based disease do not elicit protective immunity and may be associated with cumulative auto-infection. For example, someone excreting schistosomes who contaminates their own water source may (if there are suitable snail hosts present) be further infected through water contact and thereby increase their own wormload. This is important because the severity of disease is related to the intensity of infection.

Changes over time requiring interpretation or implying modification of the class

There are three important new considerations that affect the water-based disease class. These are the potential inclusion of leptospires, toxic cyanobacteria and recreational water contact.

White et al. (1972) state that the agents of water-based disease 'are all helminths, parasitic worms' and place leptospires only in the water-borne class. Leptospires enter water bodies from the urine of some rodent species and may infect humans percutaneously as well as following ingestion. Disease is sometimes associated with flooding which causes distribution of rodent urine (and associated leptospires), human exposure to water and physical injury including skin cuts and abrasions. On the basis that transmission can be associated with water contact; that the alternative/intermediate hosts are water-associated (albeit not necessarily so); and that prevention is through management of water bodies and human contact with them, they are a natural component of this class

Interest in toxic cyanobacteria emerged in the 1990s with the recognition that these organisms – that are prokaryotes (like bacteria) but photosynthetic (like eukaryotic algae) – can produce a range of potent toxins of human health concern and recognition of substantive health impacts in unusual cases where they have overgrown in drinking-water sources (Chorus and Bartram, 1999; see also Chapter 9). Disease outbreaks have been associated with ingestion, and cyanobacterial toxins are therefore included among water-borne chemical hazards (see above). However, while contact-related injury has largely been limited to animals, there is cause for human health concern and contact is discouraged where blooms occur. Since risk management relates to management of water resources, and of human contact with these agents, they are best classified with other water-based diseases.

Another newly identified agent in this class is *Naeglaria fowleri*, a rare and almost always fatal cause of primary amoebic meningitis. Interest in these organisms has been fueled by concerns about the effects of global climate change.

A further exposure that may be argued to fit in the water-based class is associated with recreational or bathing use of natural water bodies contaminated with human or animal excreta. The agents of concern do not conform to the 'complex life cycle' criterion and transmission is by ingestion. However, disease prevention relates to water resource management and control of human contact with water resources. While an argument may be made for a water-based classification, on balance we believe they fit more properly as water borne.

Here we conclude that while a complex life cycle is a frequent characteristic of water-based disease agents it is not a necessary characteristic in their definition. In arguing this we note that this relates to the aspect of disease *transmission* which is common among these agents.

The relevance of the water-based class may increase as water storage at large and small scales increases in response to population growth, increased wealth and climate change (Bradley and Bos, nd).

Exposure and disease burden

For the agents reflected in the original classification, exposure leading to disease is associated with collection of water from unprotected open sources such as rivers, lakes, ponds and streams – either through ingestion or physical contact (wading into infested waters and percutaneous infection). Around 2 per cent of the global population collects drinking water from such sources (WHO and UNICEF, 2014). To this number must be added those for whom water contact is associated with productive activity, especially irrigated agriculture and its association with schistosomiasis.

The global burden of dracunculiasis has declined substantively in response to global eradication efforts and it may become the first parasitic disease to be eradicated (WHO, 2014).

Diseases with a water-related insect vector

White et al. (1972) describe this class as 'those infections spread by insects that breed in water or bite near it' (p162) and note that 'Many tropical infections have insect vectors, and the larvae of many insects are aquatic. There thus grows up a relationship between water and many vectorborne diseases.'

Definition/explanation

The title of this class is largely self-explanatory. The disease agent itself may have no relationship itself with water; rather its insect vector either breeds in or bites near water bodies. The relationship to water is determined by the insect vector, with some preferring stagnant polluted waters and others preferring clean, fast moving waters. Globally malaria is the most important of this class, which also includes Bancroftian filariasis, onchocerciasis, dengue, yellow fever and other arboviral infections all of which are transmitted by insects with aquatic larvae. Tsetse flies, which transmit Gambian sleeping sickness, are found near rivers but do not breed in water. Chapter 6 of this volume describes the cause, transmission and prevention of some vector-borne diseases.

Recognized links and complexities

In many cases there are multiple vector insects that can transmit each of these diseases and disease epidemiology is strongly related to the locally prevalent vectors. In addition and contrary to the general assumption that it is degraded or polluted environments that favor vector proliferation, the *Simulium* flies (blackflies) that transmit onchocerciasis breed in clear mountain streams.

Some of the agents in this class have increased their range and/or disease burden (e.g. dengue).

Both general and water-related disease prevention may relate to reducing insect vector load or to reducing human exposure to insects. In some settings large-scale drainage has been very effective in disease prevention and this is true both in parts of Europe and in the south of the United States of America against malaria. Exhaustive elimination of small water containers (such as abandoned car tyres) has value in settings where they provide a suitable breeding site for the prevalent vector and where exhaustive intervention is feasible. Where biting occurs near water bodies (e.g. *Simulium*, tsetse flies), access to improved or household water may reduce exposure. Where vectors breed in household water storage containers, application of insecticides, both chemical and biological (*Bacillus thuringiensis*), to such containers is sometimes practiced (WHO, 2011). Since the development of the Bradley Classification, use of large-scale insecticide (including DDT) applications has grown and waned in popularity. General preventive measures also include case treatment, prophylaxis (including immunization) and the use of insecticide-treated bed nets.

Changes over time requiring interpretation or implying modification of the class

There is widespread interest in this class in anticipation of the impacts of climate change on vector distributions (Caminade et al., 2014).

Future value of a water-related disease classification

As noted above, a classification is useful only in as much as it enhances understanding, communication and effective action, in this case towards prevention of water-related disease.

The value of the Bradley Classification for educational purposes is self-evident from the frequency with which it is cited in teaching materials, and from its use in communication and fostering action, for example in framing and implementing health impact assessments (Chapter 53).

Experience using the classification in teaching and in policy work suggest that its perceived weaknesses include the non-exclusive nature of its classes (the fact that many diseases can be both water borne and water washed for instance is sometimes a cause of consternation); the fact that some diseases that are not referred to in the original text have emerged, re-emerged or increased in importance or visibility; and the fact that some disease causes and health outcomes that were recognized at the time (such as chemical toxins and water carriage effects) were not explicitly incorporated despite its declared comprehensive intentions.

It is noteworthy that an attempt to describe mutually exclusive classes (Feachem et al., 1977) was not well-received. Similarly an attempt to classify sanitation/excreta-related disease (Feachem et al., 1983) stumbled on technical complexity and ultimately failed to secure the widespread adoption and use of its water-related counterpart.

The success of the classification, founded on its simplicity and its successful marriage of aspects of transmission and of prevention, leads to the question of its comprehensive applicability and future value.

The Bradley Classification emerged from work in rural settings in developing regions on one continent and this has contributed to a perception that it has limited applicability in an increasingly industrialized and urbanized world. Thus despite having been demonstrated to have enduring value and utility, it is sometimes perceived as of limited global relevance rather than as providing a unifying framework. Indeed its wider applicability was suggested but not assumed, 'Although it was made necessary by the particular characteristics of the small, heavily polluted sources of the African tropics, it may have wider relevance, at any rate within tropical areas' (White et al., 1972, p163).

While it is evident that the original classification was intended to be comprehensive – 'All infections related to water supplies are included' (White et al., 1972, pp162–163) – the fact that we are readily able to incorporate both infectious diseases that have emerged or re-emerged since development of the classification, and importantly also to incorporate other water-related health outcomes of diverse non-infectious nature relating to chemical hazards, behaviors and physical injury, suggests potential comprehensiveness.

In light of actual changes in our world – in its ecosystems and in the status of access to water supplies – and changes in our understanding of water-related disease, alongside demonstration of the universal value of such a classification, suggests that the further development and application of the classification has value.

Need for new classes

It has been previously suggested (Bradley, 2009) that an additional class to accommodate aerosol-transmitted disease would be desirable. At the time of description of the original classification, inhalation-related causes were not considered. The principal hazard of concern is *Legionella* bacteria, the causal agents of legionellosis, that multiple in biofilms, especially in engineered water systems (plumbing, evaporative cooling) where nutrient and temperature conditions support their growth. They survive and multiply within a number of free-living protozoa in a way analogous to the 'complex life cycles' of many water-based diseases. *Legionella* infection occurs after inhalation of droplets or aerosols containing the bacteria that are small enough to enter the lungs, such that water serves as a medium for disease transmission analogous to the water-borne class. *Legionella* therefore already overlaps the water-borne and water-based classes from the point of view of transmission. However, management of water for disease prevention has two dimensions – minimization of proliferation (reinforcing the water-borne characterization, although concern is especially related to complex plumbed systems) and minimization of the creation and dispersal of droplets/aerosols (which is not reflected in any current class). Thus from a *transmission* perspective *Legionella* can be accommodated in the current classification, but from the perspective of *prevention* this is insufficient.

Other bacteria of health significance that multiply in water include some that were already recognized at the time of development of the Bradley Classification (such as *Pseudomonas aeruginosa*) and some that have been subsequently identified (such as *Mycobacterium avium* complex). These may be argued to meet in part the definition of water-based disease in that they proliferate in water, although in several of these cases it is unclear whether the complex life cycle generalization is observed. All of these may also be seen as water borne, as infection occurs through ingestion (except *Pseudomonas* which causes a number of infections of other sites). However, these classifications also seem insufficient in that they reflect transmission but not prevention perspectives.

As noted above, the Bradley Classification reflects a careful handling of multiple perspectives, accounting for aspects of transmission, control and disease consequences. The agents described above may be accommodated in the classification either in its original form or through the addition of a new 'inhalation' class but we consider that such a modification would allow the transmission perspective to dominate to the detriment of prevention. Here we therefore propose the addition of an alternative class to reflect the risks arising from *engineered water systems*. Such a class would capture risks that arise within those systems and for which action on the system itself is the, or one of the, principal preventive measures. Such a class would accommodate agents that multiply in plumbing systems (the bacteria noted here). It would also better capture the chemical hazards that arise from plumbing materials (such as lead and vinyl chloride monomer) which are also water borne but for which conventional water quality interventions, such as central water treatment, are inappropriate.

A further argument in favor of such a new class derives from the health hazards arising from radon. Radon is a radio-active gas emitted especially from granitic geologies and which tends to accumulate in the basements of dwellings. It is also found in water from associated aquifers. Piped drinking water supply into dwellings may contribute to accumulation in dwellings as the gas is released in water use in showers, dishwashers and washing machines. The global disease burden remains unclear, as does the contribution of water to household radon accumulation. It may be argued to be water borne since the water medium leads, albeit

Table 3.2 Proposal for a modified classification

	Original Bradley Classification		*Proposed clarifications and modifications*	
Class	*Sub-classes*	*Examples*	*Revised sub-classes*	*Additional examples*⋆
Water borne	Classical	Typhoid	Infectious	*Cryptosporidium*, *Giardia* and several viruses are important additions (see Table 3.1 for an extensive list); faecal–oral diseases associated with bathing/recreational water use
	Nonclassical	Infectious hepatitis		
			Toxic chemicals	Arsenic, fluoride (toxic effects at high exposures), lead
			Nutrient minerals	Fluoride (beneficial effects at moderate exposures)
Water access-related disease (formerly water washed)	Superficial	Trachoma, scabies	Superficial	
	Intestinal	Shigella dysentery	Intestinal	
			Respiratory	Pneumonia
			Hydration	
			Injury and violence associated with water collection	
Water based	Water multiplied percutaneaous	Bilharziasis	Contact	Leptospires, *Naeglaria fowleri*
	Ingested	Guinea worm	Ingested	Toxic algae and their toxins
Water-related insect vectors	Water biting	Gambian sleeping sickness	No change	Malaria
	Water breeding	Onchocerciasis	No change	
Engineered water system associated (new proposed class)			Inhaled	*Legionella*, radon
			Ingested	MAC
			Contact	*Pseudomonas*

⋆ Sequelae of infectious disease apply to all infectious agents indirectly, to human exposure. It would also logically fall into an 'inhalation' class, but once again while suitable from a transmission perspective this has little relevance to prevention.

Finally, White et al. (1972) briefly note the potential association of water hardness with arterial disease (footnote to p162) and make mention of fluorine (fluoride) in the context of its adverse effects when exposure is excessive. There is strong evidence for a protective role for fluoride against dental caries, and addition of fluoride to water supplies in areas where natural concentrations are very low is recommended by the World Health Organization and practiced in some countries. There is suggestive evidence for a protective effect of higher water hardness or components associated with water hardness. While these may all be characterized as water quality issues they reflect nutritional inadequacy rather than toxicity and there may be an argument that they be accommodated in a new sub-class of water-borne disease or an entirely new sub-class for essential minerals.

Summary

We propose here a series of explanations, refinements and modifications to the Bradley Classification that would consolidate and secure its comprehensive nature, general applicability and future relevance. Our proposals are summarized in Table 3.2, which we believe is faithful to White et al.'s (1972) original intent: to propose a '… classification intended to be both more comprehensive and more precise in predicting the likely effects of changes in water supply …'

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