

Hydro-epidemiology: the emergence of a research agenda

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Abstract There is a growing international awareness of the health risks associated with water, and particularly in developing countries. For example: (i) a child dies in Africa every 30s due to malaria—a disease related to stagnant water, (ii) every year flooding causes many deaths world-wide, with infant mortality due to diarrhea from contaminated flood waters posing the biggest threat, and (iii) poor sanitation and its relation to hepatitis A continues to be a serious problem. A revealing measure of the extent of such global problems is that more than half of the hospital beds in the world today are occupied by people with water-related diseases. Addressing these issues mandates an interdisciplinary approach by the world's scientific and engineering community. In this spirit a workshop was held in Phoenix to provide a forum where epidemiologists, hydraulics researchers and other stakeholders of varied backgrounds (e.g., policy makers, environmental groups etc.) could all participate in a debate on a future agenda for hydro-epidemiology. The principal outcome of the workshop was a significant appreciation of the potential for interdisciplinary research and development in hydro-epidemiology and the major contribution that hydraulics professionals could offer, in partnership with the public health community, in addressing such water related disease control and prevention challenges.

This report derives from papers presented at a three day workshop (2–4th December) on Hydro-epidemiology held during the Fifth International Symposium on Environmental Hydraulics in Tempe, Arizona, held during December 2007. The invited and submitted papers have been condensed and synthesized to identify current activity and potential research contributions at the interface area between the environmental hydraulics and public health communities.

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1 Rationale for the workshop

The title of this workshop was chosen because there is no discipline or community of scientists who would identify with or, more importantly, claim ownership of the term ‘hydro-epidemiology’. This field of study resides at the interface between the physical science communities; i.e. containing engineers, physicists, chemists and environmental science professionals, and the medical and public health communities concerned with disease transmission, health impact assessment and mitigation. The former is focused on the drive to understand and, where possible, model the physical processes relating to the transport, transformation and storage of toxicants and pathogens in the water column, whilst the latter is concerned with understanding their impacts within human populations and appropriate responses to observed and/or predicted patterns of illness. There are, however, very few international scientific forums where these communities can meet and communicate to encourage integration of effort between these, largely discrete, academic and practitioner communities. The workshop organizers hold chairs in Environment and Health (Kay) and Hydro-environmental Engineering (Falconer) and they invited key practitioners and academics to present examples of current work at this interface, with the joint aims of: (i) scoping the current baseline of activity; and (ii) identifying priority stakeholder needs and opportunities for this emerging research agenda. This report does not attempt to repeat the verbal presentations of all workshop speakers, rather, it seeks to identify cross cutting themes identified by speakers and other participants. These are used to summarize outcomes (i) and (ii) above. Presentations of the workshop can be accessed via:- <http://www.aber.ac.uk/iges/staff/kaydavid.shtml>

2 Some preliminaries

The most significant disease burden world-wide derives from the risks of pathogen transmission in food and drinking water often contaminated through poor sanitation and sewage disposal [10,25,39,50,54,55]. This risks impact particularly the poorest people in developing nations where the very young and very old are the principal groups affected [11,12,18,29,30,56]. Intervention strategies have centred on traditional engineered barriers to the faecal-oral route of infection [5,9,22,23] and some work has been reported on their cost-effectiveness [16–18].

However, the scientific attention focused on this most significant global disease burden is dwarfed by that devoted to clinical and surgical interventions possible only, or principally, in developed nations where medical technology, and professional support, is available to the general populations. In such nations, the disease burden from water and sanitation is certainly lower, but it still represents a significant driver within the lower overall disease risks experienced [6,13,47].

The hydraulic community has led developments in modelling bacterial concentrations in environmental waters [33] and sewage treatment systems [15,24,37,52,61,63,64,69]. In some notable contributions, the links to defined health outcomes have also been addressed in modelling investigations [31,41,42]. However, these efforts have principally focused on process optimisation within waste water treatment systems and outfall design for marine/lacustrine disposal of sewage effluents.

A significant science vacuum is becoming evident in the area of terrestrial hydraulic and catchment modelling of bacterial and other faecal pathogen concentrations [46]. Attention in this area has been highlighted by new regulatory paradigms for water quality management being implemented in the United States and the European Union.

In the EU, the imperative to understand the processes driving catchment microbial dynamics has emerged as the regulatory implications of the Water Framework Directive (WFD) 2000/60/EC have become clear [3]. This Directive requires member states to identify ‘*pressures and impacts*’ [14] then design a ‘*programme of measures*’ (Article 11) to ensure compliance with the microbiological standards set out in daughter directives such as the original Bathing Water Directive 76/160/EEC [2] and new World Health Organisation health-based standards for bathing waters recently agreed by the EU Parliament [4,44,67]. Article 1(2) of the new Bathing Water Directive (2006/07/EU) states “*The purpose of this Directive is to preserve, protect and improve the quality of the environment and to protect human health by complementing Directive 2000/60/EC*”, further reinforcing the central place of microbiological water quality and catchment microbial flux analysis within the WFD strategy for water quality improvement. As EU members address the problem of designing new ‘programmes of measures’ to effect protection of impacted waters the absence of a literature and/or operational modelling tools able to guide policy decisions and underpin evidence-based interventions to effect pollution reduction are becoming all too apparent. This contrast with, for example, catchment-based modelling tools which have been applied to parallel catchment processes driving nutrient and sediment fluxes

This science gap was noted in a recent review for the UK Government of the evidence-base available to underpin UK agricultural diffuse pollution control. This assessment [32] noted the emerging policy imperative to understand and predict catchment microbial fluxes and they described this area as ‘*the challenge of the 21st Century*’ (Page 4). They also noted the lack of research and regulatory attention to the microbial pollution area when compared to, for example, the nutrient parameters (see for example: [34] and [35,36]).

In the United States of America, the *Clean Water Act* enshrines many of the same principles as the WFD [38]. Where water quality is defined as *impaired*, i.e. fails to reach target levels, the *Clean Water Act* requires that a Total Maximum Daily Load (TMDL) assessment is undertaken to rectify the impairment (i.e. parallel to the WFD Article 11 ‘*programme of measures*’). Some 64,918 water quality ‘*impairments*’ were reported between October 1995 and April 26th 2008 and 33,381 TMDLs were approved by USEPA over the same period. The top 5 reasons for water quality impairment to date are (i) pathogens (in reality bacterial faecal indicator organisms (FIOs))—9,191 impairments; (ii) mercury—8,845 impairments; (iii) other metals—6,446 impairments; (iv) sediment—6,381 impairments, and (v) organic enrichment and oxygen depletion 4,902 impairments.

It is interesting to note that microbial water quality ‘*impairments*’ were the second most common reasons for US TMDL studies after metal pollution, suggesting a higher US prominence for this area than, for example, nutrients, pesticides and oxygen demand which have all received far more attention, to date, by the UK regulators and policy makers addressing the implementation of the Water Framework Directive [20,21].

Kay et al. [45] reviewed the operation of microbial TMDLs in California and concluded that the longer US regulatory experience with examination of catchment microbial dynamics, through TMDL assessments, had not, to date, produced more operationally useful empirical science or modelling approaches which could be applied in the UK. In effect, many US authorities were defining FIO ‘*discharge*’ concentration limits for discharges to streams and coastal waters (in TMDL terminology the ‘*concentration-based pollutant allocations*’) which were simply set at the environmental ‘*receiving water*’ concentrations required for

recreational and shellfish harvesting waters for relevant discharges (i.e. a geometric mean faecal coliform concentration in agricultural and surface drainage discharges to tributary streams of $<200,100\text{ ml}^{-1}$ and a 90th percentile for faecal coliforms in direct discharge to the coastal water of $<43,100\text{ ml}^{-1}$). Waste water treatment plants and boats were required to achieve a faecal coliform median of zero 100 ml^{-1} . The examples chosen did not address the spatial and temporal characteristics of the inputs or their fluxes which are more relevant than ‘concentration’. Nor was the feasibility of achieving these criteria addressed. Additionally, sampling programmes were recommended which could not capture data on the hydrological events which studies world-wide have suggested account for $>90\%$ of the catchment-derived faecal indicator flux from diffuse source pollution [43,49].

An additional international policy driver for catchment microbial dynamics research emerged following the publication of the WHO guidelines for drinking water quality [68]. These advocated a new regulatory paradigm for drinking water protection based on ‘*water safety planning*’. This mirrors the Hazard Assessment Critical Control Point (HACCP) approaches commonly applied in food processing industries and more recently applied to bathing beach management and shellfish protection through ‘*profiling*’ of coastal bathing and shellfish harvesting waters [48,66,67]. This development has generated the requirement for water undertakers to assess microbiological risks in water supply gathering grounds. Much of the early research and scientific information in this area has been driven by Australian water undertakers and research scientists and can be traced back to perceived risks from chlorine resistant protozoan parasites, principally *Cryptosporidium* spp. which have led to studies of both FIOs and pathogens in Australian water supply gathering grounds [7,8,19,26–28,57–60]. Water undertakers in the EU are now applying similar approaches which imply maintenance of source water quality through the protection of gathering grounds. This is, in effect, a re-invention of the ‘multiple barrier’ approach to public health protection which was dismantled with the introduction of multiple use catchment policies in the developed economies and the consequential heavy reliance on treatment plant and supply system integrity to maintain water quality almost 60 years ago [1,51]. Such a reinvention might also be prompted in part by the assessment of land condition by the Statutory body in England, namely Natural England (previously called English Nature), and the designation of significant areas of water supply catchments as ‘unsatisfactory’.

Thus, science and policy landscape for the emerging hydro-epidemiology community addressing the interface between hydro-environmental modelling and public health through development of catchment and nearshore microbial dynamics is developing rapidly. New challenges are opening up as the government and regulatory communities seek to develop an evidence-base to underpin emerging policy imperatives following from new regulatory paradigms and drivers. It is into this challenging landscape that the participants of the Hydro-epidemiology workshop ventured in December 2007.

3 Emerging themes

3.1 Hydroinformatics

A unifying concept available to this diverse community was the maturing tool kit which has become known as ‘hydroinformatics’. The applications and contribution of this approach were outlined by Prof Arthur Mynett, of the Netherlands, across a spectrum of applications covering coastal flooding, fisheries management, environmental impact assessment and the management of harmful algal blooms (HABs). Satellite data acquisition systems

and catchment-based modelling tools, such as SWAT, were shown to provide integrated solutions to problems identified during Water Framework Directive implementation in the EU and parallel problems world-wide. Prof Nigel Wright developed similar themes from a UNESCO-IHE perspective, exemplified by the concept that the water professional should seek both to ‘assess vulnerability and increase resilience’. The use of the ‘Flood Vulnerability Index’ was explained using innovative applications of computational fluid dynamics and GIS modelling of flooding scenarios. The episodic nature of these risks was noted, together with the crucial importance of scale issues in model design and uncertainty assessment.

3.2 Technocentric/ecocentric paradigms

These authoritative, and intensely ‘technocentric’, perspectives were contrasted by Prof S Karandikar, of India, who explained the place and utility of feasible multi-stage mitigation measures. He noted at the outset that, in 2004:

More than half the hospital beds in the world are filled by people with water-related diseases. This clearly demonstrates the link between water targets and health targets

The solutions proposed were set into a more ‘ecocentric’ paradigm, drawing on the work of James Lovelock and the ‘Gaia’ hypothesis which envisages the earth as a living entity in which many, if not all, of the negative feedback systems which are essential to global stability are dependent on microbial metabolism and community diversity. This ecocentric paradigm was considered essential to successful adaptation of human populations, to the impending environmental changes which will result from anthropogenic effects on the global climate. The most pressing problems were defined as:

- population stabilization;
- poverty alleviation; and
- life-style modification.

Adverse health impact was seen as the most significant threat during the emerging period of rapid environmental change, driven by anthropogenic impacts on the global climate.

3.3 Continental-scale water resource management

Taking the ecocentric paradigm forward with a continental scale case study from the Ganges-Brahmaputra-Meghna basin Dr Chowdhury Farouque, of Bangladesh, examined the interaction of politics, water and sediment abstractions and downstream sediment delivery to communities in Bangladesh. He noted that the:

massive inter-basin water transfer project of India looms as a serious threat to the ecology of the region and survival of Bangladesh as an economically sustainable nation

He predicted a 2–3 m water level reduction in the Ganges and Brahmaputra if abstraction plans are implemented and urged trans-boundary cooperation between all riparian states to effect integrated management of this globally important water resource system.

3.4 Catchment paradigms in a developing nation

A case study of urban domestic sanitation in Bogata, Colombia, was outlined by Dr Luis Camacho, of Columbia. Some 90% of wastewater is discharged to streams without treatment,

producing very high FIO concentrations in Bogota and Magdalena rivers commonly exceeding 10^5 to 10^6 *E. coli* 100ml^{-1} through urban areas. An integrated catchment approach to water quality and quantity management was seen as the most appropriate paradigm. A series of largely technocentric tools of catchment modelling with GIS data capture and multicriteria modelling of environmental, socio-economic and infrastructure constraints was explored to prioritize interventions.

3.5 Not all fluids are aqueous

Aerosol transmission of pathogens is a well established cause of disease in animals [65] and humans [53,62] with well established control strategies [40]. It is perhaps surprising therefore that the hydraulics professionals have been less involved in gaseous pathway research than in aquatic systems. This was redressed by Prof Joseph Lee, of Hong Kong, who reported a linked empirical and hydraulic modelling investigation of the airborne transmission of the severe acute respiratory syndrome (SARS) virus in high rise accommodation at Amoy Gardens in Hong Kong. The virus moved upwards within the building's utilities shaft and entered apartment units on the upper floors of Block E in Amoy Gardens. Horizontal spreading of the infection was then detected to other units in Block E by air movement between apartment units, then, after the plume reached the top of the shaft in Block E, the virus was spread to some units in Block B, C, and D by the northeasterly wind. This presentation provided an excellent illustration of the potential contribution which can be made by the hydrodynamic modelling community in providing exploratory and explanatory tools for epidemiological investigation, particularly in the context of real-time outbreak management where decisions are made which have immediate health significance, with catastrophic implications if the wrong outbreak control steps are taken. Thus, the illustration of the hydraulics contribution in broadening the 'outbreak control teams' disciplinary armory was a valuable contribution by this scientist.

4 Conclusions

The workshop generated a lively and informed debate from its international participants, who spanned disciplinary and socio-economic boundaries. The principal outcome was a significant improvement in awareness in the informed practitioners, who gained a new appreciation of the potential for interdisciplinary inputs and the significant contribution that hydraulics professionals could offer in partnership with the public health community which traditionally addresses disease control and prevention.

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