Science of the Total Environment 485–486 (2014) 666–680

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# The impact of major earthquakes and subsequent sewage discharges on the microbial quality of water and sediments in an urban river

Megan L. Devane [a,b,*], Elaine M. Moriarty [a], David Wood [a], Jenny Webster-Brown [b], Brent J. Gilpin [a]

[a] Institute of Environmental Science and Research Limited, Christchurch Science Centre, PO Box 29-181, Christchurch, New Zealand
[b] Waterways Centre for Freshwater Management, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

## HIGHLIGHTS

- *E. coli* was a better predictor of pathogens than *C. perfringens*.
- F-RNA phage, alongside *E. coli*, is a potential indicator of untreated human sewage.
- Protozoa persisted in river sediments after cessation of sewage discharges.
- F-RNA phage and *Campylobacter* did not accumulate in sediments.
- Sediment re-suspension increases health risk from re-mobilisation of pathogens.

## ARTICLE INFO

*Article history:*
Received 21 October 2013
Received in revised form 6 March 2014
Accepted 9 March 2014
Available online 22 April 2014

Editor: D. Barcelo

*Keywords:*
Pathogens
Indicators
*Cryptosporidium*
*Giardia*

## ABSTRACT

A series of large earthquakes struck the city of Christchurch, New Zealand in 2010–2011. Major damage sustained by the sewerage infrastructure required direct discharge of up to 38,000 $m^3$/day of raw sewage into the Avon River of Christchurch for approximately six months. This allowed evaluation of the relationship between concentrations of indicator microorganisms (*Escherichia coli*, *Clostridium perfringens* and F-RNA phage) and pathogens (*Campylobacter*, *Giardia* and *Cryptosporidium*) in recreational water and sediment both during and post-cessation of sewage discharges.

*Giardia* was the pathogen found most frequently in river water and sediment, although *Campylobacter* was found at higher levels in water samples. *E. coli* levels in water above 550 CFU/100 mL were associated with increased likelihood of detection of *Campylobacter*, *Giardia* and *Cryptosporidium*, supporting the use of *E. coli* as a reliable indicator for public health risk. The strength of the correlation of microbial indicators with pathogen detection in water decreased in the following order: *E. coli* > F-RNA phage > *C. perfringens*.

All the microorganisms assayed in this study could be recovered from sediments. *C. perfringens* was observed to accumulate in sediments, which may have confounded its usefulness as an indicator of fresh sewage discharge. F-RNA phage, however, did not appear to accumulate in sediment and in conjunction with *E. coli*, may have potential as an indicator of recent human sewage discharge in freshwater. There is evidence to support the low-level persistence of *Cryptosporidium* and *Giardia*, but not *Campylobacter*, in river sediments after cessation of sewage discharges. In the event of disturbances of the sediment, it is highly probable that there could be re-mobilisation of microorganisms beyond the sediment–water exchange processes occurring under base flow conditions. Re-suspension events do, therefore, increase the potential risk to human health for those who participate in recreational and work-related activities in the river environment.



## 1. Introduction

In 2010 and 2011, the province of Canterbury in New Zealand (NZ) experienced a series of damaging earthquakes. All four earthquakes (magnitude 6.0–7.1) and aftershocks were shallow (5–11 km depth), which increased the damaging effect of the ground movement. The municipal sewage treatment plant, sited in the East of the city (Fig. 1) and pump stations in the area, suffered major damage after the February 2011 earthquake (magnitude 6.3) due to liquefaction and physical disturbance. The damage caused extreme disruption to water, wastewater and stormwater infrastructure throughout much of Christchurch. This resulted in the discharge of large volumes of raw sewage directly into the city's rivers, the Avon and Heathcote, and the estuary (Fig. 1) from February 2011 until October 2011.

* Corresponding author at: Institute of Environmental Science and Research (ESR) Ltd, P.O. Box 29-181, Christchurch, New Zealand. Tel.: +64 3 3510044; fax: +64 3 3510010.
*E-mail address:* megan.devane@esr.cri.nz (M.L. Devane).

http://dx.doi.org/10.1016/j.scitotenv.2014.03.027
0048-9697/

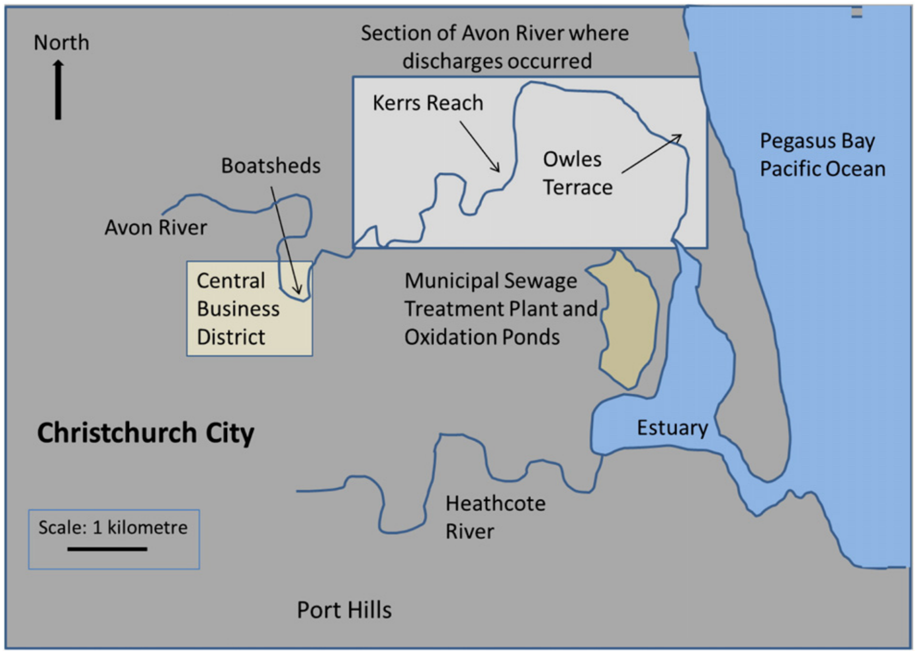


**Fig. 1.** Sample collection locations along the Avon River.

Wastewater can contain a number of pathogenic organisms including *Campylobacter* spp., *Escherichia coli* O157, *Cryptosporidium* spp., and *Giardia* spp. which when ingested can cause severe illness and, in some cases, death (Leclerc et al., 2002). When untreated sewage contaminates rivers or oceans, waterborne transmission of these pathogens can occur to those who use the water for swimming, boating, fishing and shellfish-gathering (Cornelisen et al., 2011).

Microbial water quality is assessed primarily by testing for the indicator bacteria *E. coli* and enterococci in freshwater and enterococci in saline waters. The *New Zealand Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas* (Ministry for the Environment (MfE) and Ministry of Health (MoH), 2003) state that fresh water containing less than 260 *E. coli* per 100 mL (alert level) is acceptable for recreation such as swimming, but that concentrations higher than 550 *E. coli* per 100 mL are not acceptable (action level). These indicator bacteria usually do not cause disease themselves, but they are prevalent in faecal material and sewage, and therefore indicate the presence of pathogenic organisms that can be transmitted by the faecal–oral route (Yates, 2007). Methods for the detection of these indicator organisms in waters are rapid, simple and relatively cheap to perform in the laboratory (Yates, 2007).

In fresh, untreated sewage, *E. coli* and enterococci are considered to be good indicators of potential risk to human health from pathogenic bacteria and protozoa (United States Environmental Protection Agency (USEPA), 1996). Once sewage discharge occurs into receiving waters, however, a range of physical and environmental factors including river dilution, movement within a river, storage in sediments, and the intrinsic characteristics of the microorganisms may, over time, alter the relationship between these indicator bacteria and the pathogens of concern (Sinclair et al., 2012).

Studies have shown that even in the absence of recent faecal inputs, the faecal indicator *E. coli* can occur in soil, vegetation and algal mats in waterbodies as part of the natural microflora (Byappanahalli and Fujioka, 2004, Byappanahalli et al., 2003a, 2003b). Research has identified naturalised populations of these indicators in tropical and sub-tropical environments (Byappanahalli et al., 2012a; Desmarais et al., 2002, Solo-Gabriele et al., 2000), and temperate climates (Byappanahalli et al., 2006a, 2006b; Whitman and Nevers, 2003; Whitman et al., 2003). There is increasing evidence of *E. coli*'s potential to not only persist in extra-intestinal environments but also actively grow in soil environments and algal mats across the climate spectrum of tropical to temperate locations (Byappanahalli and Fujioka, 2004; Byappanahalli et al., 2003b, 2012a; Desmarais et al., 2002). Genotypic and phenotypic studies in various climates have shown that the populations of *E. coli* and enterococci isolated from soils cluster by location into genotypically distinct but diverse populations, suggesting *E. coli* in the natural environment come from multiple sources but are divergent from animals and bird sources in the same geographical location (Byappanahalli et al., 2012b; Fujioka and Byanppanahalli, 2001; Ilshii et al., 2006). These factors call into question *E. coli*'s ability to perform as an indicator of faecal contamination in an aquatic environment, when naturalised sources of *E. coli* from resuspended sediments and macrophytes; and from vegetative and soil run-off, may impact a watercourse confounding the correlation between indicator and pathogen.

Due to the persistence and potential for growth of *E. coli* in the environment, additional indicators have been recommended as surrogates for sewage contamination such as *Clostridium perfringens* and coliphages for monitoring of tropical aquatic environments (Fujioka, 2001; Vithanage et al., 2011). F-RNA phage have also been proposed as useful indicators of fresh faecal contamination in tropical waters (Fung et al., 2007). It has been suggested that better predictability of pathogens may require a suite of indicator organisms (Harwood et al., 2005) to minimise false-negative tests where bacterial indicator concentrations are low in the presence of detectable pathogens (Wilkinson et al., 2006).

Effective wastewater treatment removes or inactivates wastewater-derived pathogens before they enter natural waterways. However, the severe damage to the wastewater system in Christchurch after the February 2011 earthquakes led to the initial discharge of up to 38,000 $m^3$/day of raw sewage into the Avon River, representing up to 23% of total river flow, with volumes decreasing over the ensuing six months. The Avon River rises from a groundwater spring in the west within the city boundary and traverses the urban environment of Christchurch City providing a popular destination for recreational and tourist activities. The microorganisms in the discharged sewage may have remained suspended in the water column to eventually reach the Avon–Heathcote Estuary (Fig. 1), or may have been deposited into the riverbed sediment.

The process of deposition and re-suspension of microorganisms to and from sediments is poorly understood. There is also limited information about the rates of microbial survival in sediments, although reduced oxygen levels and protection from sunlight may allow microorganisms