SUPPORTING COMMUNITY RECOVERY FROM CYCLONE GABRIELLE: CONTAMINATION RESULTING FROM FLOODING EVENTS

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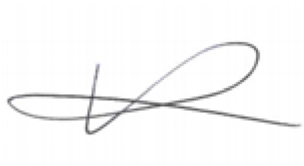

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ACRONYMS AND ABBREVIATIONS

AAS	Atomic absorption spectroscopy
ADI	Acceptable daily intake
AES	Atomic emission spectroscopy
AGI	Acute gastrointestinal illness
aOR	Adjusted odds ratio
APVMA	Australian Pesticide and Veterinary Medicine Authority
BRANZ	Building Research Association of New Zealand
bw	Body weight
CCA	Copper chrome arsenic
CEFS	Center for Environmental Farming Systems
CI	Confidence interval
CFU	Colony-forming unit
DDT	Dichlorodiphenyltrichloroethane
DNA	Deoxyribose nucleic acid
ED	Emergency department
EMT	Emergency medical team
ENT	respiratory and otolaryngology (ear, nose and throat)
ER	Emergency room
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FIB	Faecal indicator bacteria
GC-MS	Gas chromatography-mass spectrometry
JMPR	Joint FAO/WHO Meeting on Pesticide Residues
JRC	Joint Research Centre of the European Commission
HAIL	Hazardous activities and industries list

OR	Odds ratio
MfE	Ministry for the Environment
MPN	Most probable number
NIWA	National Institute of Water and Atmospheric Research
PAH	Polycyclic aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PCR	Polymerase chain reaction
PM_x	Particulate matter with a diameter less than x micrometres
PRR	Prevalence rate ratio
REL	Reference exposure limit
SGV	Soil guideline values
STEC	Shiga toxin-producing *Escherichia coli*
STH	Soil-transmitted helminth
TPH	Total petroleum hydrocarbons
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VOC	Volatile organic compound
WES	Workplace exposure standard
WHO	World Health Organization
WWTP	Wastewater treatment plant
XRF	X-ray fluorescence

EXECUTIVE SUMMARY

The unpredictable, episodic nature of major floods restricts our ability to perform well planned and controlled studies of the impact of floods on chemical and microbiological determinants of public health. Floods cannot make contamination but can move contamination from a contained environment to an uncontained environment. Examples of this would be the failure of WWTPs and the spread of human sewage to the surrounding environment or the movements of contaminated sediment from a riverbed to adjoining land and communities.

Cyclone Gabrielle (13-14 February 2023) adversely impacted areas of Hawkes Bay, Tairāwhiti and to a lesser degree Northland, Auckland and the Wairarapa. Impacts included inundation of land with floodwater of unknown composition and deposition of flood-carried silt/sediment onto public and private land. The current study examined the evidence for conditions that could result in adverse human health effects in the aftermath of Cyclone Gabrielle. The evidence examined was primarily focused on flood debris, usually referred to as silt.

Based on the scientific literature, there have been convincing reports of disease outbreaks or increases in the incidence of diseases due to flooding events. However, the specific route of exposure to the causative agent is not always apparent. The weight of evidence suggests that adverse health effects are most commonly associated with direct contact with flood water or due to circumstances secondary to the flood. For example, crowding in evacuation centres may lead to person-to-person transmission of diseases. A single study identified an association between the incidence of cryptosporidiosis and contact with flood debris, rather than contact with flood water.

With respect to contaminants in flood-deposited silt, in many cases the lack of baseline concentrations makes results difficult to interpret. In general, increases of chemical contaminant concentrations in silt/soil due to flooding events was linked to known or suspected contamination scenarios, such as deposition of river sediments where those sediments were known to be highly polluted. There is suggestive evidence that, in the absence of existing sources of contamination, material deposited during flooding is likely to be no more contaminated than existing soils and may be less contaminated.

Results from microbiological examinations are even more difficult to interpret. In general, concentrations of faecal indicator bacteria and pathogens decrease in surface silts/soils over time following the flooding event. This is likely due to the adverse effects of desiccation and solar radiation on microbial survival. However, it is not clear from most of the studies whether faecal indicator bacteria and pathogens were introduced as a result of the flooding or whether their presence predated the flooding event.

A large amount of chemical and microbiological testing of flood-deposited silt was carried out following Cyclone Gabrielle. In all cases the results of analyses of chemical contaminants in flood-deposited silt give no cause for public health concerns. Contaminants were either not detected or their mean concentrations were consistent with background levels and within soil guideline levels. A small number of elevated concentrations were detected but at locations where their occurrence was explainable.

Microbial analysis of silt samples was limited in the range of organisms examined and in the degree of follow-up carried out. However, some of the highest concentrations of faecal indicator bacteria detected were in proximity to the Napier wastewater treatment plant.

There is little evidence that sampling and analysis was informed by known sources of contaminants and their likely movement into deposited silt. The exception to this statement is the microbial analyses performed in proximity to the Napier wastewater treatment plant in Awatoto. A greater focus in this area and application of faecal source marker and pathogen analyses would have been useful in defining the extent of the contamination and the associated human health risks due to the WWTP being overwhelmed by the flood waters.

The network of air quality monitoring devices deployed in the Hawkes Bay region during September 2023 to March 2024 have provided a wealth of information of airborne dust in the region. While high short-term concentrations of dust and associated crystalline silica were observed, the overall body of data suggests a low level of concern for silicosis resulting from exposure to airborne dust. The non-detection of asbestos in silt samples indicates that risks from this contaminant in airborne dust are likely to be negligible.

1 INTRODUCTION

1.1 BACKGROUND

Flooding events resulting in chemical or microbiological contamination have the potential to affect public health, either through contact with primary (soil or water) or secondary media (water-affected homes). Flooding may lead to release of dangerous from storage or remobilisation of chemicals from environment sinks, such as sediments (Crawford et al 2022; Euripidou and Murray 2004). Chemicals and infectious microorganisms may be present in runoff from residential, industrial, agricultural, and waste facilities entering surface water bodies and residential areas (Yard et al 2014).

Unexpected chemical hazards might be present in soil after flooding, e.g. as a result of flood waters moving through chemical stores, houses, industrial areas, contaminated (HAIL) sites, wastewater plants, and vehicles/machinery. The range of chemicals potentially present depends on the volume and strength of the floodwaters and the surrounding land use and infrastructure. While dilution and overland flow are likely to reduce risk, any remaining residues require assessment on a location-by-location basis, and the capacity for this proposed work to provide useful evidence to inform on chemical risks is limited.

During flooding events pathogenic microorganisms can potentially be transferred to land due to:

- Overflow from human on-site (septic tank), centralised (wastewater treatment plant) sewage treatment facilities or damaged or overflowing reticulated sewage networks,
- Surface transfer of animal faecal material from pastoral lands or areas where animal faeces can become concentrated (e.g. feedlots, dairy sheds, effluent ponds, barns, abattoirs),
- The presence and decomposition of animal carcasses
- The presence of legionella associated with timber waste and ponding, and
- Resuspension of contaminated sediments with subsequent deposition onto land.

However, there is also potential for contaminants to be removed from land by the flooding process, and subsequent dehydration or exposure to UV and it is the balance between these two sets of processes that will dictate the level of microbiological contamination post-flooding.

1.2 NEW ZEALAND CONTEXT

Flooding is the most frequent natural disaster in Aotearoa New Zealand (Royal Society of New Zealand 2016), with much of the population living in flood-prone areas, and many of New Zealand's towns and cities built on floodplains (Royal Society of New Zealand 2016; 2017). Increased frequency and amount of rainfall, and increased intensity and occurrence of tropical cyclones are likely to occur due to climate change (Royal Society of New Zealand 2016).

Cyclone Gabrielle (13-14 February 2023) adversely impacted areas of Hawkes Bay, Tairāwhiti and to a lesser degree Northland, Auckland and the Wairarapa (Murray 2023). Impacts included inundation of land with floodwater of unknown composition and deposition of flood-carried silt/sediment onto public and private land. Both of these phenomena potentially introduced chemical and/or microbiological hazards, which may remain after the flood water has receded. Assessing such flood-associated changes on soils is generally hampered by the lack of suitable baseline (pre-flooding) information on soil status.

1.2.1 Health Impacts

Heavy rainfall events in New Zealand have been associated with increased hospital admissions for children with gastroenteritis (Lai et al 2020). An increase in cases of leptospirosis in Hawke's Bay was observed following Cyclone Gabrielle, believed to have resulted from contact with flood waters on livestock farms (Anonymous 2023).

Internationally, respiratory illnesses have been noted to increase after flooding, for example associated with an increase in dust mite allergens (Curtis et al 1997; March 2002), and respiratory issues from damp and mouldy housing (Prezant and Douwes 2011). After Hurricane Katrina those returning to communities were exposed to contamination and have experienced health issues including respiratory dysfunctions due to mould exposures and subsequent "Katrina cough" (Adeola and Picou 2012).

1.2.2 Equity and Resilience

The impacts of natural hazards such as floods on people's health and well-being are not experienced equally, with structurally disadvantaged population groups experiencing greater impacts from natural hazards. Due to the structural disadvantage experienced, these population groups may have fewer resources to prepare for, cope with, and recover from natural hazards (Lowe et al 2013; Mason et al 2021; Prezant and Douwes 2011).

Communities experiencing structural disadvantage, including Māori, Pasifika, disabled people, low-income households and those in marginal housing were among those hit hardest in 2023 floods (Jones et al 2023). This may have short- and long-term effects on the health of those communities. In the USA, Adeola and Picou (2012) found that gender, older age and lack of social capital significantly predicted health problems relating to Hurricane Katrina.

Those most at risk from health effects may vary during and post flood, Lowe et al (2013) found that females, elderly and children were at greater risk of psychological and physical health effects during floods, whereas post-flood males and the elderly were at increased risk of physical health effects and females appeared to be at greater risk of psychological health effects.

In the aftermath of recent natural disasters in Aotearoa New Zealand, iwi- and hapū-led responses have played a leading role, both immediately after extreme weather events and during the longer-term recovery phase (Jones et al 2023). While many aspects of communities require development to increase resilience to natural disasters, an important part of building resilience in future will be growing the capacity of iwi, hapū, marae and other Māori communities to prepare for and participate in response activities. Alongside this, strengthening Tiriti-based partnerships and local participatory planning, and upholding the right to self-determination for tangata whenua is essential (Jones et al 2023).

1.3 SCOPE OF THE CURRENT PROJECT

The current project includes three components intended to support those affected by Cyclone Gabrielle and inform recovery efforts. These three components are:

- Consolidation and analysis of existing silt testing information. A large amount of testing of flood-deposited silt occurred following Cyclone Gabrielle. The current project consolidated and assessed these data to inform ongoing risks.

- Silt analysis for respirable hazards. As silt dries and becomes airborne as dust respiratory hazards, such as asbestos and crystalline silica may become greater issues. Representative silt samples were collected from the Hawkes Bay region and analysed for these hazards.
- Literature review. This review aimed to consolidate what has already been observed on chemical and microbiological hazards associated with silt, and the impact of flooding events on soil chemical and microbiological hazards, including respiratory hazards from dried silt dispersed as airborne dust. The review can be a resource to support Public Health Officials working with communities recovering from the effects of Cyclone Gabrielle and other future events of a similar nature.

The review does not cover in detail:

- mould and endotoxins, fungi and other similar airborne contaminants that may occur as secondary hazards due to inundation of residential properties
- impact on crops and food, including stock and seafood and health risk related to food consumption post event
- microplastics

Publicly available literature was sourced from scientific citation databases (Web of Science, Pub Med) and searches of specific websites including New Zealand and International government agencies and local government.

1.3.1 Terminology

The material deposited by flooding events may be referred to using several different terms. General terms such as ‘debris’, ‘detritus’ and ‘contamination’ may be used. These terms acknowledge that flooding may deposit a non-homogeneous range of materials. However, the primary focus of the current report is the potential public health risks associated with the soil-like material deposited by flooding, which was generally referred to as ‘silt’ in the aftermath of Cyclone Gabrielle. Throughout this report ‘flood-deposited silt’ will be used to describe soil-like material deposited over the existing landscape. The term ‘soil’ will be used to describe non-deposited ‘native’ soils and the term ‘flood-affected soil’ used to describe soils that have been impacted by flood water, without deposition of silt. Where other terms are used the reason for this has been clarified.

2 SAMPLING PROTOCOLS

2.1 SILT SAMPLING AND ANALYSIS

Numerous guideline documents exist in various jurisdictions for the sampling of soils and/or sediments. Many of these guidelines are intended for the sampling of soils from known or suspected contaminated sites. However, none were identified that were specific to the situation encountered post-flooding, where a layer of silt has been deposited on top of the existing soil.

No single method applies to all monitoring and assessment needs, and considerations should include: the known or likely distribution of the substance of interest in the environment, its physico-chemical properties, statistical methods, variation in time, advantages and disadvantages of grab or composite samples, and detection limits (EPA Victoria 2009; USEPA 2012). A suitable laboratory should be identified and contacted for clarification of container types, transport, preservation and sample times.

2.1.1 Sampling patterns

In New Zealand, soil testing is widely used to manage soil nutrients, and sampling along transects is a standard approach (Knowles and Dawson 2018). A transect might run across the whole area of interest, or if the site is non-homogenous, several transects might be set up within the area of interest to capture this variability. Grid sampling might be used where in-depth knowledge of a particular area is required. This involves dividing an area up into equal sized cells and either preparing a composite of subsamples from within each cell or collecting a sample at equidistant points based on the grid pattern. These techniques are also applicable to the sampling of flood-deposited silt.

2.1.2 Selection of sampling locations

The selection of sample locations can be based on judgement or probability (Pennock et al 2006). Judgement sampling relies on someone having good knowledge of the sample region and selecting sites that suit a particular purpose. Judgement sampling would be useful if the intent is to sample the worst flood affected areas, or locations nearest possible contamination sources (e.g. closest to animal rearing operations or stream/riverbanks). Statistics, such as mean values, can be calculated from the test results generated through judgement sampling but the samples are not representative of the whole sample region.

Judgement sampling plans may include consideration of:

- Sites with known or potential public health considerations, such as sites in proximity to wastewater treatment plants or chemical stores,
- Representative sites, or
- Sites representing concerns from the community due to the presence of vulnerable or marginalised populations, such as marae or aged care facilities, or proximity to known contamination sources, such as sites on the hazardous activities and industries list (HAIL).

Probability sampling relies on methods that maximise randomness. Random sampling is rarely practical for field studies and transects or grids are usually used (as introduced above), and zig-zag lines might also be set up (Pennock et al 2006). The location of the transect should ideally be random but usually transects or grids are set up in a way that most effectively answers a research question.

2.1.3 Sample collection

A range of soil sampling methods were reported in the literature.

Microbiological studies

The flooding of potential sources of pathogenic microbes, including livestock facilities, sewage treatment plants and septic tanks, as well as overland discharges from sewers, can result in microbial contamination of previously unaffected sites. Pathogens levels decrease as the silt deposits dry (Presley et al 2006; Provin et al 2008).The microbial biomass of a normal soil is highest in the upper 0-10 cm layer, and around the roots of plants (Unger et al 2009). The following paragraphs highlight the diversity of sampling methods used or, in some cases, the lack of information provided on how sampling was carried out, in studies of the microbiology of flood-deposited silt.

To monitor the spatial and temporal differences in *E. coli* and *Salmonella* in produce fields after flooding, one group of researchers deployed both drag swabs and core samples at each sample site (Bergholz et al 2016). A sample site was a 30 m by 30 m square ("quadrangle"). These squares were positioned at 76 m intervals along multiple transects. A drag swab sample was collected by taking a sterile swab pre-moistened with laboratory media, attaching a sterile string, dragging the swab for five passes through the square and then around the perimeter of the square, then replacing the swab back into its bag. Core samples were collected to 4 cm deep, from one point in the square. The corer was not sanitised between use, instead "To minimize cross-contamination, the soil probe was conditioned to each quadrangle by first extruding and discarding five soil cores prior to collection of soil for analysis." The *E. coli* prevalence values from the core samples were higher than those from the drag swabs. Thus, the drag swabs covered a wider area at each site but the core samples were more sensitive. This study does not mention deposition of silt and the soil samples appear to have been of the existing soil that had been inundated.

In another post-flood study of crop growing areas, researchers selected sampling sites in each field by following a zig-zag pattern starting from one of the field's sides (Castro-Ibáñez et al 2015). At each sampling site, the top 5 cm of soil was collected from an area of 20 cm diameter, using a spade. It was not reported if the spade was sterilised between samples. Again, the soil collected appear to have been of existing soil, rather than deposited silt.

In another post-flood study, the researchers collected both composite soil samples, collected from up to five locational transects representing 10 subsamples each across identified field(s), and single grab samples, collected in a grid-like pattern at pre-set locations across each study area (Rock et al 2023). No differences between the two methods were observed upon testing for microbiological measures. Approximately 500 g of soil samples were collected at a depth of up to 15 cm using disposable sterile scoops, and deposited in individual sterile Whirl-Pak bags. Soil samples were stored on ice at 4°C for up to 36 hours until transport to the laboratory. Samples taken appear to be of native soil rather than deposited silt.

In a New Zealand study on flooded-affected horticultural land (Graeme Fletcher, Plant and Food Research, personal communication) composite samples were created by collecting five small samples from a 1 m x 1 m plot. A diagonal line was taken across the longest axis of the field from one corner to another (adapting to the field boundaries as needed). Samples were taken at the start and end of this line, then at three points of equal distance along the transect. All samples were collected using sterile equipment. The samples were packed with ice packs and sent to the laboratory within 24 hours of collection.

Chemical studies

Typical chemical analytes considered in flood-deposited silt or flood-affected soils have included pesticides, hydrocarbons and heavy metals (Provin et al 2008). The target for the sampling and subsequent analyses may impose particular requirements on the sampling.

Soils and silt were sampled immediately after flooding in the Middle Vistula Gap, Poland and analysed for metals and polycyclic aromatic hydrocarbons (PAH) (Maliszewska-Kordybach et al 2012). Samples were taken to represent an area of approximately 2 km^2 or 0.5 km^2, depending on the site. Samples were collected from the flood-deposited silt layer (0-2 cm), the surface soil layer (0-30 cm) and the lower soil layer (30-60 cm). No further details of the sampling method were provided.

Analysis of soils for heavy metals following flooding in Houston was based on single composite samples, taken using a grid sampling method across a 200 x 200 m area (Han et al 2022). A 30 cm Lamotte soil sampling tube (2.5 cm core diameter) was used to collect topsoil (0-30 cm) samples. Final samples were the composite of two samples taken approximately 1-2 m apart.

In the aftermath of Hurricane Katrina soil samples were collected for analysis for metals and volatile organic compounds (VOC) (Harmon and Wyatt 2008). Samples were collected from the top 10 cm using disposable scoops modified from plastic syringes. Soils were sampled directly into glass vials for VOC analysis (10 g) or into separate containers for metals analysis (50 g). Plastic scoops were changed between sampling locations to prevent cross-contamination. There was no indication that the soil samples included soil-deposited silt.

Also following Hurricane Katrina, soil and silt samples were collected for the analysis of lead and arsenic (Schwab et al 2007). Where silt deposition was apparent, samples were collected from the entire deposition layer (15 and 20 cm). In regions where no flooding had occurred or no silt deposition was observed, samples were taken from the top 6 cm of soil. Samples were stored in 120 mL polypropylene bottles. No further details of sampling equipment were provided.

New Orleans soils were again sampled and analysed for arsenic after 18 months of recovery from Hurricane Katrina (Rotkin-Ellman et al 2010). Surface samples were selected to include soil most likely to represent a source of exposure and where visual inspection indicated the presence of silt. Samples consisted of the top 1 cm of soil, taken within a 10 cm diameter sampling marker. Samples were collected using a stainless-steel trowel directly into glass jars.

2.1.4 Analytes

A wide range of microbial and chemical analytes have been analysed in soil and silt samples collected after flooding events.

Microbiological

Microbiological analyses of flooding-affected media may focus on faecal indicator organisms, as markers for the potential faecal contamination of the environment, are pathogens, as a direct indication of disease risk.

Indicator organisms analysed for in flood-deposited silt or flood-affected soils include:
- Total coliforms (Castro-Ibáñez et al 2015)
- Faecal coliforms (Casteel et al 2006)

- *Escherichia coli* (Bergholz et al 2016; Castro-Ibáñez et al 2015; Rock et al 2023)
- Somatic coliphage (Casteel et al 2006)
- Male-specific coliphage (Casteel et al 2006)
- *Clostridium perfringens* spores (Casteel et al 2006)
- Enterococci (Strauch et al 2005)

Pathogens analysed for in flood-deposited silt or flood-affected soils include:

- *Salmonella enterica* (Bergholz et al 2016; Castro-Ibáñez et al 2015; Rock et al 2023)
- Pathogenic *E. coli* (Castro-Ibáñez et al 2015; Rock et al 2023)
- *Listeria monocytogenes* (Castro-Ibáñez et al 2015)
- *Leptospira* spp. (Wójcik-Fatla et al 2014)
- *Clostridium perfringens* (Strauch et al 2005)
- *Pseudomonas aeruginosa* (Strauch et al 2005)

Chemical

- Contaminant elements ('heavy metals'), including aluminium, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, nickel, silver, tin, vanadium, zinc (Ciesielczuk et al 2014; Han et al 2022; Harmon and Wyatt 2008; Keita et al 2021; Le Gall et al 2018; Lintern et al 2016; Maliszewska-Kordybach et al 2012; Mandigo et al 2016; Mielke et al 2017; Rotkin-Ellman et al 2010; Schwab et al 2007; Vácha et al 2003; Weber et al 2023)
- Other elements, including sodium, phosphorus (Keita et al 2021)
- Anions, including bromide, chloride, fluoride, nitrate, nitrite, phosphate, sulphate (Harmon and Wyatt 2008)
- Polycyclic aromatic hydrocarbons (Ciesielczuk et al 2014; Maliszewska-Kordybach et al 2012; Mandigo et al 2016; Pulkrabová et al 2008; Vácha et al 2003)
- Volatile organic compounds (Harmon and Wyatt 2008; Vácha et al 2003)
- Organochlorine compounds, including legacy pesticides (DDT, HCH), dioxins and PCBs (Mandigo et al 2016; Martins et al 2005; Pulkrabová et al 2008; Vácha et al 2003)
- Petroleum hydrocarbons (Vácha et al 2003)

2.2 SUMMARY

It is clear from the previous sections that there is no 'standard' approach to the sampling and analysis of flood deposited silt and flood-affected soils. However, the literature highlights certain issues that should be considered:

Selection of sampling sites. Available information on potential sources of contamination within the affected zone should be reviewed, in particular, the known or likely contamination status of sediments in rivers associated with flooding. For example, if the river is receiving industrial or mining inputs upstream, associated contaminants may be present in flood-deposited silt.

The selection of sampling sites should also consider the direction of floodwater flow from potential sources of contamination to potential locations of deposition.

Unless existing information is available on baseline or background levels of contamination, control sites should also be identified that have not been affected by flooding and silt deposition.

Sampling patterns. There does not appear to be any preference in previous studies for particular sampling patterns. However, those responsible for the design of a sampling plan should be aware of the various options (grid, transect, zigzag, etc.) and consider which is most appropriate.

Sample type. Samples may be single samples or composites of sub-samples from a particular location. While composite samples are a good means of ensuring that the sample taken is representative of a particular location, the dynamics of a flooding event suggest that the composition of silt samples shown be reasonably uniform at a particular location. There needs to be clarity concerning whether collected samples are of flood-deposited silt flood-affected soils or a mixture of both.

Sampling technique. Although deposited silt may affect the composition of underlying soil, public health concerns will primarily relate to the deposited silt, as this will be the material that the general public and those involved in recovery will come in contact with. Consequently, the sampling technique applied should be such that it can discriminate between the deposited silt and the underlying soil. Sampling equipment should either be disposable, with one set used at each distinct site, or consideration should be given to cleaning or conditioning of sampling equipment between sampling locations, to ensure no cross-contamination between samples from different sites.

Sample containers should be appropriate for the intended analytes and discussion with the intended analytical laboratory should be undertaken prior to sampling. The time between sampling and delivery of samples to the analytical laboratory should be as short as practically possible.

Analytes. Analytes will be discussed in greater detail later in this report. However, in general analyses should not be performed unless there is knowledge of background concentrations or a suitable risk-based guideline concentration to compare results against.

3 FLOOD-RELATED CONTAMINATION

3.1 INTRODUCTION

Floods are the most common type of disaster globally (Alderman et al 2012; de Freitas and Ximenes 2012). The frequency of flooding events is expected to increase due to climate change factors such as rising sea levels, more frequent and extreme rainfall and other extreme events (de Freitas and Ximenes 2012; Diaz et al 2020; Du et al 2010; Haines et al 2006), and increasing urbanisation meaning more people are exposed to flooding events (Du et al 2010; Paterson et al 2018).

There are a range of mechanisms and exposure routes by which flooding events can result in adverse health effects in human populations. The following review focuses on increases in diseases caused by chemical or microbiological contamination of the environment by flooding events. Additionally, evidence will be reviewed on floods as a cause of increased levels of chemical and microbiological hazards in the affected environment that may result in health effects after the immediate flooding incident.

3.2 IMPACT OF FLOODING ON DISEASE INCIDENCE

A systematic review of epidemiological evidence for impacts of floods on human health was conducted, including articles from the period 2004-2011 (Alderman et al 2012). The review concluded that evidence linking exposure to chemicals released by flooding events and human health was inconclusive. An increased risk of disease outbreaks has been reported after floods, including gastrointestinal diseases, cholera, paratyphoid fever and leptospirosis. However, these outbreaks appear to be related to contact with contaminated water, rather than deposited debris. Chronic adverse effects were generally related to non-direct factors, such as deterioration in mental health, interruption of medication supplies, and malnutrition due to interrupted food supplies.

The studies summarised below are largely restricted to those conducted in developed countries, as these were considered to be most relevant to New Zealand. While diseases such as cholera and typhoid fever have been reported after floods in developing countries, these diseases have not been reported in association with floods in developed countries (Ahern et al 2005).

No New Zealand-specific studies on increases in disease incidence following cyclone or flooding events were identified. While an increase in leptospirosis cases in Hawkes Bay was noted following Cyclone Gabrielle (Anonymous 2023), these findings were not part of a controlled study.

3.2.1 Gastrointestinal disease

The Growing Up in New Zealand (GUiNZ, born 2009-2010) prospective cohort was used as the basis for a case-crossover study to examine associations between heavy rainfall events and first-time paediatric hospitalisation for ‘waterborne diseases’ (Lai et al 2020). A range of lag periods between the rainfall event and hospitalisation was examined. Hospitalisation for a relevant condition was significantly associated with heavy rain 2 days before the hospitalisation (hazard index 1.73, 95% CI 1.10-2.70) but not for other lag periods. Associations were significant for rainfall events at the 94th percentile (16.3 mm) or greater.

Flooding of the Mississippi and Missouri Rivers in 1993 resulted in initiation of an additional surveillance system, based around emergency shelters and hospital emergency departments (Schmidt et al 1993). No acute disease outbreaks were identified through the emergency centre surveillance. During a 6-week period, 524 flood-related conditions were reported through the emergency department system, with details collected through a standardised questionnaire. The main categories of conditions were injuries (250, 47.7%) and illnesses (233, 44.5%). Of the 233 reported illnesses, gastroenteritis (40, 17%), rashes/dermatitis (38, 16%), heat-related (31, 13%), and "other conditions" (47, 20%) were most frequently reported.

In the aftermath of tropical storm Alison in Texas in 2001, a survey was conduct of affected households (*n* = 420) (Waring et al 2002). Household illness that occurred after the onset of flooding, was reported from 54 (12.9%) surveyed households. Residents of flooded houses were significantly more likely to report an illness than residents of non-flooded houses. Diarrhoea/stomach conditions was the only specific illness significantly associated with residing in a flooded home.

In a study conducted in the US territory of Puerto Rico, the impact of flooding on gastrointestinal illness was examined by examining medical insurance claims in a 7-day period following a high rainfall (90+ percentile) event (De Jesus Crespo et al 2019). The best model for the available data estimated a 17% increase in the odds of gastrointestinal illness following heavy rain events. However, the mechanism of infection preceding the illness was not examined.

The impact of large-scale flooding in North Carolina, USA following Hurricanes Matthew (October 2016) and Florence (September 2018) on incidence of acute gastrointestinal illness (AGI) was examined (Quist et al 2022). Controlled interrupted time series analysis was used to compare AGI emergency department (ED) visits in a three-week period following the Hurricane in areas with one-third or more flood coverage to expected rates (no flooding). This analysis suggested an 11% increase in AGI ED visits (rate ratio = 1.11, 95% CI 1.00-1.23). The effect was strongest among American Indians and those aged 64 and over after Florence and among Black patients after both hurricanes.

Severe flooding occurred in the midwestern US in 2001 (Wade et al 2004). Since November 2000, information on gastrointestinal symptoms had been coincidentally collected from an affected community (*n* = 1110 individuals). An increase in the incidence of AGI was observed during the flood period (rate ratio = 1.29, 95% CI 1.06-1.58). Tap water consumption was not related to AGI but contact with flood water was, particularly amongst children.

A case-crossover study was conducted to investigate the association between flooding and emergency room visits for gastrointestinal illness (ER-GI) in Massachusetts for the years 2003 through 2007 (Wade et al 2014). Records of ER-GI and floods were correlated, considering three hazard periods of the visit: 0–4 days post-flood; 5–9 days; and 10–14 days. Controls were selected by matching with cases on day of the week of presentation with two weeks lead or lag time from the ER-GI visit. A total of 270,457 ER-GI visits and 129 floods occurred in Massachusetts over the study period. Across all counties, flooding was associated with an increased risk for ER-GI in the 0–4 day period after flooding (odds ratio: 1.08, 95%CI 1.03–1.12); but not the 5–9 days or the 10–14 days after. The nature of the study meant that no information was collected on the contact of the cases with floodwater or flood debris.

In some cases, illness may be due to conditions created by the flooding event, rather than directly caused by the flooding event. For example, following Hurricane Katrina evacuees were housed in evacuation centres, including one megashelter (Reliant Park) that housed more than 27,000 people (Yee et al 2007). Surveillance conducted through the associated Reliant Park Medical Clinic identified >1000 patients treated at the clinic for gastroenteritis over an 11-day period, which was 17% of all clinic visits. Norovirus was the only enteric pathogen identified. The incidence of gastroenteritis among the evacuees residing in the Reliant Park Complex was estimated to be 4.6 visits per 1000 persons per day, with approximately 10-fold higher rates for evacuees who resided there for nine days.

A county-level analysis of six infectious diseases (cryptosporidiosis, giardiasis, legionellosis, STEC infection, salmonellosis and shigellosis) in relation to storm events was carried out in the USA for the period 1996-2018 (Lynch and Shaman 2023). Storm-related rainfall exposure was associated with a 48% (95%CI 27%–69%) increase in STEC infections in the week following the storms, while a 42% (95%CI 22%–62%) increase in legionellosis two weeks after storms was observed. Cryptosporidiosis cases increased 52% (95% CI 42%–62%) during storm weeks but declined over ensuing weeks. The differences in the periods over which the associations were observed may be associated with differences in the incubation periods for the pathogens, although documented incubation periods for these organisms cover quite broad ranges (MoH 2012). No significant increases in the other diseases included in the study were found. The methodology used did not allow greater definition of individuals' exposure to flood water or flood-deposited silt.

Following flooding in the city of Halle, Germany in 2013 an increase in cases of cryptosporidiosis was observed (Gertler et al 2015). A case-control study was conducted amongst kindergarten children. Compared to controls (*n* = 61), cases (*n* = 20) were more likely to have visited areas that had been flooded (odds ratio: 4.9; 95%CI 1.4-18) and the zoo (odds ratio: 2.6; 95%CI 0.9-7.6). Visits to the floodplain remained the sole significant risk factor (odds ratio: 5.5; 95%CI 1.4-22) in a multivariate analysis. Only a single genotype (IbA9G2) of *C. hominis* was isolated from case clinical samples. This study is interesting in that contact with dried flooded areas, rather than contaminated flood water appears to have been the transmission route for infection. The outbreak is estimated to have begun six weeks after the flooding event.

A case-crossover study was conducted to investigate the association between flooding and emergency room and outpatient visits for *Clostridium difficile* infection in Massachusetts for the years 2003 through 2007 (Lin et al 2015). A total of 1575 *C. difficile* infections and 129 floods occurred in Massachusetts over the study period. ER and outpatient visits for *C. difficile* infections were elevated in the 7–13 day period after flooding (odds ratio: 1.69, 95%CI 0.84–3.37); but not for shorter or longer time periods. The association reached statistical significance for males. The study authors speculated that the observed lag period may be due to a combination of the long environmental survival of *C. difficile* spores and the incubation period for the organism.

Following extensive flooding in Queensland, Australia during December 2010 and January 2011, four individuals from a small community in central Queensland were hospitalised with leptospirosis (Smith et al 2013). Five additional cases were subsequently identified from around Central Queensland. Serovar Arborea (*Leptospira borgpetersenii* serovar Arborea) was presumptively found to be responsible for leptospirosis in seven of nine confirmed cases. Serovars Hardjo and Australis were identified in samples from the two other cases. All cases had exposure to flood water.

3.2.2 Skin and wound diseases

Skin diseases presumably occur through contact with infected floodwater or flood debris and may disproportionately affect the lower limbs. Following Typhoon Morakat in southern

Taiwan, medical records of presentations with cellulitis at two emergency departments were reviewed for the 30-day period before then typhoon and the 30 days after (Lin et al 2013). The number of cellulitis cases increased from 183 before the typhoon to 344, peaking 3-4 days post-flood and lasting for three weeks. The proportion of patients reporting water immersion of the affected limb increased from 6 to 37% (odds ratio: 9.0, 95%CI 4.7-17.2). Microbiological analyses found that infections with *Enterococcus* spp. and Gram-negative bacilli (*Aeromonas hydrophila, Escherichia coli, Klebsiella pneumoniae, Enterobacter cloacae,* and *Proteus mirabilis*) were more prevalence amongst cases with water immersion.

Analysis of emergency medical team (EMT) consultation records (*n* = 3617) in the period following the West Japan Heavy Rain 2018 event found the greatest number of consultations occurred on days 5-12 of the response (Chimed-Ochir et al 2022). The most commonly reported health effects were skin disease (17.3%), wounds (14.3%), stress-related symptoms (10.0%), conjunctivitis (6.3%) and acute respiratory infections (5.4%). Acute gastrointestinal disease only accounted for 1.6% of consultations. It was suggested that respiratory infections may have been due to the high level of crowding in evacuation shelters, rather than as a direct consequence of the floods. Analysis of medical clinic records following the same flooding event identified a similar range of health effects (Hashimoto et al 2023).

A study of inpatient discharges and outpatient consultations for diarrhoea, acute respiratory infections, skin infections, injuries, non-communicable diseases and vector-borne diseases in 11 districts of Cambodia was conducted in relation to flooding, as assessed by satellite data (Saulnier et al 2018). At the time of flooding and three months after, small to moderate increases in healthcare facility visits for skin infections, acute respiratory infections, and diarrhoea were noted, while no associations were seen at one to two months. However, few of the associations reached the level of statistical significance and a plausible explanation for associations at three months but not one or two months is not apparent.

In the aftermath of Hurricane Katrina, 22 *Vibrio* infections (*V. parahaemolyticus, V. vulnificus* and non-toxigenic *V. cholerae*) were reported in two affected states (Engelthaler et al 2005). Cases included 18 wound-associated and four non-wound-associated illnesses. Although exposure information was not available for all cases, it was speculated that the wound-associated cases probably resulted from contact of existing wounds with contaminated floodwater. The majority of the wound-associated cases (13/18, 72%) had underlying conditions that may have increased their risk of serious infections.

3.2.3 Parasitic diseases

A study of the prevalence of and risk factors for soil-transmitted helminth (STH) in school-aged children (*n* = 435) in Assam, India identified flooding of the home within the last year as a risk factor (Deka et al 2021). For infection with any STH, the odds ratio for the home having been flooded was 2.2 (95% CI 1.3-2.6).

3.2.4 Respiratory diseases

A survey of respiratory and otolaryngology (ENT) symptoms was carried out 8-10 months after Spring floods in Quebec, Canada (Landaverde et al 2022). Respondents were classified as flooded, disrupted or unaffected. Significantly more ENT symptoms were reported by flooded (adjusted odds ratio: 3.18; 95%CI 2.45–4.14) and disrupted (aOR: 1.76; 95%CI 1.45–2.14) respondents than unaffected, with similar results for respiratory symptoms amongst flooded (aOR: 3.41; 95%CI 2.45–4.75) and disrupted (aOR: 1.45; 95%CI 1.10–1.91) than the unaffected respondents. Because of the long period between the flooding event and the survey, it is uncertain whether the self-reported symptoms were due to flood-associated infectious agents or a more complex aetiology.

A questionnaire-based survey was carried out of adverse health effects amongst firefighters involved in the response to Hurricane Katrina (Tak et al 2007). The questionnaire was completed by 525 firefighters (77% response rate), with 201 (38%) reporting new-onset respiratory symptoms, including sinus congestion (145 (28%)), throat irritation (92 (17%)), and cough (124 (24%)). Skin rash was more prevalent than respiratory symptoms, with 258 (49%) respondents reporting these symptoms. The majority of respondents (414, 79%) reported skin contact with floodwater, with 165 (32%) reporting contact with floodwater on multiple days. Firefighters who had floodwater contact with skin and either nose/mouth or eyes (224, 44%) had an increased rate of new-onset upper respiratory symptoms (prevalence ratio: 1.9, 95%CI 1.1-3.1), and skin rash (prevalence ratio: 2.1, 95%CI 1.4-3.2) compared to those not exposed to floodwater.

In a study amongst restoration workers in New Orleans, after Hurricane Katrina, respiratory symptoms were frequently reported, included episodes of transient fever/cough (29%), sinus symptoms (48%), pneumonia (3.7%), and new onset asthma (4.5%) (Rando et al 2012). Prevalence rate ratios for sinus symptoms (PRR = 1.3; 95%CI 1.1-1.7) and fever and cough (PRR = 1.7; 95%CI 1.3-2.4) were statistically significantly elevated for those who did restoration work, with prevalence of symptoms increasing with the number of hours worked. PRR for new onset asthma and pneumonia were elevated but were not statistically significant.

3.2.5 Non-communicable diseases

In a rare analysis of the chemical impacts of flooding, children's blood lead levels for matched census tracts were analysed from pre-Hurricane Katrina and 10 years post-Katrina (Mielke et al 2017). For over 38,000 lead analyses pre-Katrina and over 17,000 analyses post-Katrina, the median (range) of blood lead concentrations were 5.0 (3.0-10.8) µg/dL and 1.9 (<1.0-6.8) µg/dL, pre- and post-Katrina, respectively. Soil lead levels decreased during the same period (see section 3.3.1).

In a further analysis of the impact of Hurricane Katrina and Hurricane Rita on soil lead and disease prevalence, Zahran et al (2014) examined changes in soil lead pre-Hurricanes Katrina and Rita (2000) and post these hurricanes (2006) on a zip code basis and merged the findings with information on eclampsia risk in mothers from the same zip codes. A one standard deviation increase in soil lead was associated with an increase in the odds of eclampsia by a factor of 1.48 (95%CI 1.31-1.66). Reductions in soil lead following the 2005 flooding of New Orleans in certain zip codes (-387.9 to -33.6 mg/kg) were associated with a significant decline in eclampsia risk (odds ratio: 0.619, 95%CI 0.397-0.963).

3.3 SUMMARY

There have been convincing reports of disease outbreaks or increases in the incidence of diseases due to flooding events. However, the specific route of exposure to the causative agent is not always apparent. The weight of evidence suggests that adverse health effects are most commonly associated with direct contact with flood water or due to circumstances secondary to the flood, such as, crowding in evacuation centres, leading to person-to-person transmission of diseases. The study of Gertler et al (2015) is perhaps unique in this respect, in associating incidence of cryptosporidiosis to contact with flood debris, rather than contact with flood water.

The study of Mielke et al (2017) suggests potential beneficial aspects for human health due to flooding event, with children's blood lead levels decreasing in the 10-year period following Hurricane Katrina. However, the decrease in blood lead levels is likely to be multi-factorial. For example, in the 10 years following the hurricane there was substantial replacement of housing, with the new housing lacking risk factors for elevated blood lead levels, such as old lead-based paint.

4 HAZARD IDENTIFICATION

4.1 MICROBIOLOGICAL HAZARDS

Assessment of microbiological hazards in floodwater, flood-affected soil or flood-deposited silt may focus on specific microbial pathogens but more often assessments examine faecal indicator bacteria, such as faecal coliforms or *Escherichia coli* as indicators of the potential presence of pathogenic organisms.

No previous New Zealand studies of microbiological hazards in flood-deposited silt or flood affected soils were identified. A limited study of liquefaction silt, carried out in the aftermath of the 22 February 2011 Christchurch earthquake found low concentration of *E. coli* (<10 MPN/g) (ESR 2011). Enteric viruses (rotavirus and enterovirus) and viral indicators (MS2 phage) were not detected. However, it should be noted that the characteristics of liquefaction silt and flood-deposited silt are likely to be quite different.

Surface water samples (*n* = 15) were collected during floods in Kentucky in 2011 and approximately 10 weeks after flooding had ceased (*n* = 8) (Yard et al 2014). Samples were analysed for a range of pathogens and indicator organisms (Table 1). For all organisms the prevalence and/or the mean concentration was greater in floodwater than in the same waterways post-flood. The authors of the study noted that no pre-flood baseline for these measures was available.

Table 1. Microbial indicators and pathogens in surface water collected during flood and post-flood, Kentucky, 2011

Indicator/pathogen (/100 mL)	Percent of samples above LOD		Geometric mean concentration	
	May (Flood)	July (Post-flood)	May (Flood)	July (Post-flood)
Total coliforms	100	100	2340	420
Escherichia coli	100	100	285	13
Enterococci	100	100	335	30
Salmonella	100	38	NQ	NQ
Cryptosporidium	85	62	NQ	NQ
Campylobacter	62	12	NQ	NQ
E. coli O157:H7	15	0	NQ	NQ
Adenovirus	77	12	NQ	NQ

LOD: limit of detection, NQ: not quantified

Wójcik-Fatla et al (2014) sampled soils (*n* = 40) and water (*n* = 40) from areas in eastern Poland exposed to flooding and soils (*n* = 68) and water (*n* = 64) from areas not exposed to flooding. The samples taken appear to have been soil rather than silt. The presence of *Leptospira* DNA was determined by nested-PCR. *Leptospira* DNA was only detected in two samples of flood exposed water (5%) and none of the other water or soil samples. However, these detections were insufficient to conclude that the prevalence of *Leptospira* in environmental media in the two areas was significantly different.

To test the hypothesis that *Leptospira* may grow in flooded soils, Yanagihara et al (2022) inoculated bottles containing water and soil at a ratio of 2.5:1 with various pathogenic and saprophytic strains of *Leptospira*. The organism was found to grow in the water soil mix but not in water or soil individually.

Following flooding in the south-east of Spain during 2012, four fields of iceberg lettuce (*Latuca sativa*) were sampled 1, 2, 3, 5 and 7 weeks after flooding (Castro-Ibáñez et al

2015). Surface soil (0-5 cm depth), lettuces and irrigation water were sampled on each occasion. Total coliforms and *E. coli* were enumerated in all samples. All samples were analysed for *Salmonella* spp., pathogenic *E. coli* (O157:H7, O26, O103, O111, O145) and *L. monocytogenes* using enrichment and PCR detection, followed by culture confirmation. Only results of soil testing are discussed here. Total coliform concentrations were approximately 5 log CFU/g at week 1. From week 2 onwards, concentrations were in the range 3-4 log CFU/g. These levels were described as normal for the area. The concentrations of *E. coli* at week 1 were 3-4 log CFU/g). *E. coli* were not detected in soils at weeks 3 and 5 (<2 log CFU/g). *E. coli* were detected in some soil samples at week 7, with the highest concentration being approximately 2.8 log CFU/g. The authors of the study concluded that this was unrelated to the flooding event and was possibly sporadic faecal contamination from wildlife. One week after the flood most samples of soil were positive for *Salmonella* by PCR. However, only 2/4 soil samples were culture positive for *Salmonella. Salmonella* was not detected in soil at later time points. Pathogenic *E. coli* were detected by PCR in soil samples taken at week 1, 2 and 7 but viable bacteria were not recovered from any of these samples. Soils were not tested for *L. monocytogenes* as this organism is a normal part of the microflora in some soils.

The Center for Environmental Farming Systems (CEFS), North Carolina, USA was affected by flooding during Hurricanes Dennis, Floyd and Irene in September-October 1999 (Casteel et al 2006). Soil samples (<15 cm depth, *n* = 29) had previously been taken from CEFS in March 1999. A further 28 samples were taken in October 1999. Table 2 summarises the results of microbiological analyses of the two sets of soil samples. Coliphage are used as indicators for human enteric viruses.

Table 2. Comparison of soil microbiology at Center for Environmental Farming Systems, North Carolina before and after a series of flooding events

Microbiological parameter	Frequency of detection, positive/total (percent)		Mean $\log_{10}$ MPN/100 g dry soil (95% confidence interval	
	March 1999	October 1999	March 1999	October 1999
Total coliforms	27/29 (93)	19/28 (68)	4.0 (3.7-4.1)	4.1 (3.7-4.3)
Faecal coliforms	2/29 (7)	1/28 (4)	3.5 (2.6-3.7)	4.0 (3.2-4.6)
E. coli	2/29 (7)	1/28 (4)	3.5 (2.6-3.7)	4.0 (3.2-4.6)
Somatic coliphage	0/29 (0)	3/28 (11)	-	1.1 (<0.47-1.7)
Male-specific coliphage	4/29 (14)	0/28 (0)	0.9 (<0.47-1.1)	-
Clostridium perfringens spores	29/29 (100)	24/28 (86)	4.7 (4.5-4.8)	6.6 (6.1-6.8)

Of the various indicators of potential faecal (human or animal) contamination, only levels of *C. perfringens* spores were significantly higher in post-flood samples compared to pre-flood samples. It is of interest to note that levels of *E. coli* were similar between pre- and post-flooding soil samples. Following Cyclone Gabrielle, *E. coli* was used as the primary indicator of faecal contamination of silt in Hawkes Bay.

Samples (water, surface soil and drag swabs) were taken on two fresh produce farms in New York State affected by flooding as a result of Hurricane Irene in August 2011 (Bergholz et al 2016). Qualitative testing (presence/absence) was carried out for *E. coli* and *Salmonella*. Fields were sampled at 21, 44 and 238 days post-flood. *E. coli* prevalence in all sample types decreased between 21 and 44 days but only the prevalence in drag swabs decreased appreciably between 44 and 238 days. While *E. coli* were not enumerated, the genetic diversity among isolates at each time point reduced, suggesting die-off of less resilient strains. Sites closest to nearby surface water (canal, river, stream) were more likely to yield *E. coli*. *Salmonella* were detected in 4/209 drag swab samples and 2/90 soil samples, with all positive samples being from visibly moist soils. From combined soil and water sampling, it was observed that the proportion of samples positive for *Salmonella* decreased from day 21 (4.7%) to day 44 (2.5%) but increased again by day 238 (4.6%) after a period of rainfall. The lack of quantitative data on microbial concentrations and the lack of pre-flood information makes the information from this study of limited use.

Over a 90-day period following flooding in the Salinas growing area of California, four ranches were visited six times and flood-affected soil samples obtained from these sites were tested for total coliforms, faecal coliforms, *E. coli*, STEC and *Salmonella* (Rock et al 2023). During this time, a second flood occurred. The full results of this study were not available but the available data showed that the concentrations of all three faecal indicator bacteria (FIB) generally decreased over time, although the actual reduction in numbers was not large (<1 log) nor always significant. From the examples shown it could be seen that the concentration of faecal coliforms in some samples was >100 MPN/g soil and *E. coli* concentrations were in the range 1-100 MPN/g soil. The concentration of *E. coli* was found to be positively correlated with soil moisture. *Salmonella* was detected in approximately 5% of soil samples collected after the first flood, and 3% after the second flood. The prevalence of STEC was higher among samples collected after the second flood compared to those collected after the first flood. Soils flooded by tributaries or creeks through overland flow were more likely to be STEC-positive compared to sites adjacent to the Salinas River. Water samples confirmed the STEC was more likely to be present in these tributaries. The researchers concluded that faecal coliform bacteria are not suitable for indicating pathogen risk because their concentrations were variable across space and time and not correlated to the presence of STEC or salmonellae.

4.2 CHEMICAL HAZARDS

Flood waters may release chemicals that are already stored in the environment, such as those sequestered in sediments. Toxic exposure-related health impacts are likely to be greatest in populations living near known sources of chemicals, such as flood-impacted industrial or agricultural areas (Du et al 2010; Euripidou and Murray 2004; Fox et al 2009). However, the relationship between flood-related chemical contamination incidents and population morbidity and mortality remains inconclusive (Euripidou and Murray 2004).

4.2.1 Elemental contaminants (heavy metals)

Due the ease of analysis, so called heavy metals are often a focus of post-flooding chemical testing.

During intensive flooding in Poland in May–June 2010, the floodplains in the Little Poland Vistula Gap were waterlogged for over a month (Maliszewska-Kordybach et al 2012). Forty soil samples were collected from two territories on opposite sides of the river Vistula immediately after the flood event. Samples were taken from the upper (0–30 cm) soil layer together with four samples from the 30–60 cm depth layer. Eight samples of flood-deposited silt (thickness, 2 cm) were also taken. Analysed metals (As, Ba, Cr, Sn, Zn, Cd, Co, Cu, Ni, Pb) at all the sampling points were at concentrations below the Polish legal limits for agricultural soils. In both areas, the median contents of Zn (10.3–10.6 mg/kg), Pb (9.2–10.7 mg/kg), and Cd (0.03 mg/kg) were well below the mean concentrations of those contaminants in arable soils at the national and European levels.

Following Hurricane Harvey (2017), surface soil samples were collected from 10 communities in Harris County, the county containing Houston (Han et al 2022). The communities were divided into low- and high-impact, based on the seriousness of flooding during the hurricane. There was some evidence of higher soil concentrations of Cu, Pb and

Zn in the high impact communities, however, no baseline was available to determine if this was due to flooding or due to pre-existing contamination.

Further analysis of heavy metals was carried out on surface soil samples from 16 bayou[1] sites in Harris Country following Hurricane Harvey (Keita et al 2021). With the exception of one site, soil concentrations of Cr, Cu and Pb were below background levels. Background levels were very similar to mean values determined in areas affected by Cyclone Gabrielle in New Zealand. Zn concentrations of soils were mostly above background. The authors of this study did not specifically comment on these two issues and their significance and relationship to the flooding is uncertain.

In the aftermath of Hurricane Katrina, soil samples were taken from a New Orleans neighbourhood (Chalmette) that was completely inundated during the hurricane (Harmon and Wyatt 2008). Heavy metal concentrations were below human health screening values and were mostly at or below background levels. Some anions (chloride, nitrate and sulphate) were elevated in flooded soils relative to an unflooded background sample. While the authors did not comment on this, an associated map suggests that seawater incursion may have occurred and could be responsible for elevated anion levels.

In the immediate aftermath of Hurricane Katrina, surface sediment/soil samples were collected from 36 outdoor locations and 6 indoor locations in New Orleans and analysed for lead and arsenic (Schwab et al 2007). Where flood deposition had occurred samples were taken from the full silt layer. Where deposition had not occurred, samples were of the top 6 cm of soil. Silt concentrations were in the range 27-292 and 1.2-31.8 mg/kg, for lead and arsenic respectively. Soil concentration (not flood-affected) were 39-453 and 7.6-12.1 mg/kg, respectively for lead and arsenic. Lead concentrations were able to be compared to concentrations found in an extensive survey carried out in the mid-1990s. Patterns of lead contamination found after the hurricane were similar to those reported in the earlier survey. Arsenic concentrations were similar across sites and consistent with reported background levels. It was concluded that the flooding did not have a significant impact on silt concentrations of lead and arsenic and resulted in no greater risk from these contaminants to the public than was present before the hurricane.

Following Hurricane Katrina in 2005 approximately 80 residential sites were identified from USEPA sampling with elevated concentrations of arsenic (>12 mg/kg) (Rotkin-Ellman et al 2010). Where possible, sites were selected where there was visual evidence of residual silt. Of the sites sampled, 70 were able to be location-matched to archived soil samples taken in 1998-1999. The mean concentration in the post-flood samples was 23.4 mg/kg compared to 3.7 mg/kg in the archived samples. All post-flood samples contained higher arsenic concentrations than the corresponding archived samples, although there was no significant correlation between the two sets of concentrations. After an 18-month hurricane recovery period, sites were resampled and the mean arsenic concentration was found to have decreased to approximately the archived sample level (3.3 mg/kg). The authors of this study speculated that the decrease in arsenic concentrations during the recovery period may have been due to physical removal of arsenic-contaminated silt. It was suggested that the elevated arsenic levels following the flood may have been due to the widespread use of copper chrome arsenic (CCA) timber in residential construction in New Orleans prior to 2003 and mobilisation of contaminated soil from under houses and decks.

Matched soil samples from pre-Hurricane Katrina and 10 years post-Katrina were analysed for lead (method not stated) (Mielke et al 2017). For over 3000 soil analyses from each time period, the median (range) of soil lead concentrations were 289 (11-1800) mg/kg and 142 (10-1100) mg/kg, pre- and post-Katrina, respectively.

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[1] Bayou is a term mainly used in the southern USA to describe a creek, secondary watercourse of minor river that is a tributary to another body of water

Following Hurricane Sandy, which caused flooding in areas of New Jersey and New York in October 2012, soil samples were collected for analysis for lead and arsenic by x-ray fluorescence (XRF) (Mandigo et al 2016). Initial samples were collected by volunteers, following a ‘citizen science’ approach, while a later sampling was conducted by the research team. While mean concentrations of lead and arsenic were consistent with background levels, where background levels were available, the highest concentrations of both elements were found in samples taken close to known contaminated (Superfund) sites. For example, mean lead and arsenic concentrations in samples from an uncontaminated region (Rockaway Peninsula; 148 and 7 mg/kg, respectively) were substantial lower than concentrations in samples near a Superfund site (Newtown Creek; 523 and 24 mg/kg, respectively).

Following the 2016 Seine River flooding in France, ‘lag’ flood-deposited silt samples were collected and analysed for a range of heavy metals (As, Cd, Cr, Cu, Ni, Pb, Sb and Zn) (Le Gall et al 2018). All mean concentrations were similar to or lower than concentrations in historical sediment samples taken from the same locale. It is uncertain whether this reflects a lower level of contaminants in flood-deposited silt or the progressive decontamination of the Seine basin over the preceding period.

In August 2002, agricultural soils were flooded in the Vltava and Labe river basins in the Czech Republic (Vácha et al 2003). Soil samples (5-15 cm depth) were taken from 15 locations, with top layer sediment (5 mm) taken from one of the locations. It seems probably that ‘top layer sediment’ was flood-deposited silt. Concentrations of various contaminants, including elemental species (As, Be, Cd, Co, Cr, Cu, Hg, Mn, Ni, Pb, V and Zn) were determined and concentrations compared to those in soil samples from the same locations taken in 1992. Concentrations were not directly reported in this publication, but concentrations were categorised against a ‘prevention’ limit and an ‘indication’ limit. While the results of this survey are somewhat difficult to discern from the publication, it appears that only V concentrations were higher in soils following the flooding than in the 1992 survey. The authors of the study concluded that there was no risk of crop contamination with elemental contaminants due to the flooding event.

Heavy flooding in the west of Germany in 2021 resulted in deposition of large amounts of silt across the town of Eschweiler (Weber et al 2023). Samples of freshly-deposited silt were collected and analysed for elemental species by XRF. The silts were found to be moderately to heavily enriched in Zn>Cu>Pb>Cd>Sn compared to background soil concentrations. An assessment of exposure to sediment-borne metals through inhalation and ingestion by humans revealed that the tolerable daily intake was exceeded for Pb. However, it should be noted that this catchment is impacted by historical mining activity.

Following flooding of the Odra River in Poland in 1997, soil samples were taken from sites inundated for 1 day (N), 2-4 days (G) and 2 weeks (Z) (Ciesielczuk et al 2014). A control (non-flooded) sample (U) was also taken. Metals concentrations were determined by atomic emission or atomic absorption spectrometry (AES or AAS). While none of the metal concentrations determined were considered to be a cause for concern, a clear pattern was shown. Samples from site N contained substantially lower concentration of all metals than the control site. However, concentrations of all metals increased with increasing period of inundation. The site inundated for 2 weeks contained the highest concentration of all metals. For example, the lead concentration at the control site was 15 mg/kg dry weight, while at site N, G and Z the concentrations were 1.7, 3.4 and 22 mg/kg dry weight, respectively.

Sediment cores (1-2 m) were taken from two lakes (billabongs) in the floodplain of the Yarra River, Victoria, Australia (Lintern et al 2016). Sediment layers deposited during flooding events (silt) were identified and the heavy metal concentrations of flood and non-flood layers were determined by XRF. In cores from both billabongs[2], arsenic concentrations were high in the flood-borne silts, possibly due to historical upstream gold mining activity. In Bolin Billabong, metal levels were similar in flood and non-flood deposits. In Willsmere Billabong, copper, lead and zinc levels were generally lower in flood-borne silts in the core compared to non-flood sediments.

4.2.2 Environmental contaminants

In addition to analysis of heavy metals following flooding in Poland in May–June 2010, samples of soil and silt were also analysed for PAHs (Maliszewska-Kordybach et al 2012). The median contents of nine PAHs specified in the Polish regulations were below regulatory limits and median contents of Σ16 PAHs (0.21– 0.35 mg/kg) were well below the mean concentrations of those contaminants in arable soils at the national and European levels.

In the aftermath of Hurricane Katrina, soil samples were taken from a New Orleans neighbourhood (Chalmette) that was completely inundated during the hurricane (Harmon and Wyatt 2008). Levels of volatile organic contaminants (VOC) were below human health screening values and were mostly at or below background levels. The presence of petrochemical industry in the area makes it difficult to determine if the presence of these VOCs was hurricane-related or pre-existing.

In August 2002, agricultural soils were flooded in the Vltava and Labe river basins in the Czech Republic (Vácha et al 2003). Soil samples (5-15 cm depth) were taken from 15 locations, with top layer sediment (5 mm) taken from one of the locations. It seems probably that 'top layer sediment' was flood-deposited silt. Concentrations of various organic contaminants, including polyaromatic hydrocarbons (PAH), organochlorine compounds (polychlorinated biphenyls (PCBs), dioxins and DDT) and petroleum hydrocarbons were assessed. For PAH, PCBs and dioxins the highest post-flood concentrations were found in the silt sample. Overall, PAH and PCB concentrations in soil samples were lower post-flood than at the time of the 1992 survey, while DDT concentrations appeared to be higher. Results for dioxins and petroleum hydrocarbons showed no clear pattern.

Following Hurricane Sandy, which caused flooding in areas of New Jersey and New York in October 2012, soil samples were collected for analysis for PAH and total PCBs (Mandigo et al 2016). Initial samples were collected by volunteers, following a 'citizen science' approach, while a later sampling was conducted by the research team. The initial samples were described as 'wet sediment' and are likely to be of flood-deposited silt. The later samples were taken from sites as close as possible to the original collection sites and, although described as soil, are likely to be impacted by flood-deposited silt. The highest concentrations of PAH were found near areas of high traffic volume and did not appear to be influenced by the flooding event. PCB concentrations were generally acceptable, but the highest concentrations determined were in samples close to known contaminated sites.

Following flooding in the Czech Republic in 2002, a study was conducted to characterise the profile of organic contaminants (PAH and organochlorine compounds) in flooded and non-flooded soils and in river sediment (Pulkrabová et al 2008). While the authors of this study did not explicitly say that their soil samples included flood-deposited silt, this appears likely from the broader description of the flooding event. Concentrations in all three sample types were determined in each of the four years following the floods. The highest concentrations of all contaminants were in the river sediments, with no obvious pattern in concentrations over the four years of the study. Flooded soils contained markedly higher organic contaminant concentrations than non-flooded soils. However, while the contaminant content of non-flooded soil remained largely constant over time, the concentrations of most organic contaminants in flooded soils decreased over the four-year monitoring period. For example,

[2] Billabong is an Australian term for a blind channel leading out from a river or a usually dry streambed that is filled seasonally

the concentration of total PCBs in river sediments was in the range 60-85 µg/kg dry weight over the monitoring period, while the concentration in non-flooded soil was in the range 2.2-3.4 µg/kg dry weight. In flooded soils, the concentration of total PCBs decreased from 7.2 µg/kg dry weight in 2003 to 5.3 µg/kg dry weight in 2006. While the study authors do not comment on the mechanism for the contamination patterns seen, they are suggestive of contamination of flooded soil by river sediments.

The Guadiana River in Portugal experienced exceptional floods during January 2001 (Martins et al 2005). Analysis of the PCB content of surface sediments from the estuarine area at the river mouth generally showed low concentrations (<1.1 µg/kg), consistent with the absence of industrial activity in the river catchment. Silt deposited on the riverbanks during the flood contained higher PCB concentration (0.8-1.8 µg/kg), which the authors of the study ascribed to the accumulation of outputs from diffuse sources in the river catchment. It should be noted that the differences in the reported PCB concentrations between estuarine sediments and flood-deposited silt were not large.

Following flooding of the Odra River in Poland in 1997, soil samples were taken from sites inundated for 1 day (N), 2-4 days (G) and 2 weeks (Z) (Ciesielczuk et al 2014). A control (non-flooded) sample (U) was also taken. PAH were determined in all samples by gas chromatography-mass spectrometry (GC-MS). For some PAH, the highest concentrations were seen in the control sample. While the concentrations of PAH in samples N and G were generally much lower than the control sample, total PAH at site Z (2.2 mg/kg dry weight) was high than in the control sample (1.6 mg/kg dry weight).

4.3 SUMMARY

The finding of the various studies summarised in the previous sections provide a less than consistent picture. In many cases, the lack of baseline concentrations make results difficult to interpret. It should also be noted that the studies include a mixture of studies that examined flood-affected soils and studies that examined flood-deposited silts. In general, increases of chemical contaminant concentrations in silt/soil due to flooding events was linked to known or suspected contamination scenarios, such as deposition of river sediments where those sediments were known to be highly polluted. There is suggestive evidence that, in the absence of existing sources of contamination, material deposited during flooding is likely to be no more contaminated than existing soils and may be less contaminated.

Results from microbiological examination are even more difficult to interpret. In general, concentrations of FIBs and pathogens decrease in surface silts/soils with time following the flooding event. This is likely due to the adverse effects of desiccation and solar radiation on microbial survival. However, it is not clear from most of the studies whether FIBs and pathogens were introduced as a result of the flooding or whether their presence predated the flooding event.

5 HAZARDS IN CYCLONE-DEPOSITED SILT

Following Cyclone Gabrielle a large number of samples of SILT were collected and analysed for a range of chemical and microbiological hazards. As part of the current study, results from approximately 900 SILT samples from the Hawkes Bay and Tairāwhiti were reviewed and incorporated into a database.

For many of these hazards, soil guideline values (SGV) have been established by the Ministry for the Environment (MfE) (MfE 2011). SGVs are established by considering soil exposure from direct ingestion, from adherence of soil to skin (dermal exposure) and from uptake of hazards from the soil into edible plants. The methodology considers the background exposure to the hazard, usually from the diet, and establishes a soil concentration of the hazard that would not result in exceedance of health-based guidance values (exposure limits). SGVs are established for up to six scenarios; rural residential/lifestyle block, standard residential, high-density residential, recreational, commercial/industrial indoor worker, and commercial/industrial outdoor worker/maintenance.

5.1 ELEMENTAL CONTAMINANTS

Elemental contaminants, sometimes referred to as heavy metals, were the most frequently determined hazards in silt samples, with more than 700 samples analysed for arsenic (As), cadmium (Cd) chromium (Cr), copper (Cu), lead (Pb), nickel (Ni), and zinc (Zn). A smaller number of samples (approximately 40) were also analysed for manganese (Mn) and mercury (Hg). Summary statistics for these analyses, background soil levels for the region (where available) and SGVs are summarised in Table 3. It should be noted that the background levels are the upper 95th percentile confidence limits of the 95th percentile of the distribution of soil elemental concentrations (Cavanagh 2014).

Table 3. Summary of elemental contaminant levels in flood-deposited silt from Cyclone Gabrielle

Parameter	As	Cd[a]	Cr	Cu	Mn	Pb	Hg	Ni	Zn
Number of samples	724	713	724	722	37	724	37	724	724
Mean concentration (mg/kg)	5.2	0.088	16.8	9.4	201	11.6	0.015	12.7	56
Median concentration (mg/kg)	5	0.05	15	8	187	9.5	ND	11	47
Minimum concentration (mg/kg)	1	0.01	0.34	1.8	135	1.9	ND	6	17
Maximum concentration (mg/kg)	22	4.3	39	151	310	210	0.25	40	1750
95th percentile concentration (mg/kg)	9	0.22	27	20	292	20	0.11	20	86
Hawkes Bay background (mg/kg)	9	0.7	24	32		27		17	105
SGV, range (mg/kg)	17-80	0.82-1300	290-6300	NL	NL	160-3300	200-4200	NL	NL

All results and SGVs are on a dry weight basis

As: arsenic, Cd: cadmium, Cr: chromium, Cu: copper, Mn: manganese, Pb: lead, Hg: mercury, Ni: nickel, Zn: zinc, SGV: soil guideline value (MfE 2011), NL: no limit

[a] Cadmium was not detected in most samples and for the calculation of summary statistics those samples were assigned a concentration equal to the limit of detection (0.05 mg/kg, in most cases)

Mean concentrations of elemental contaminants in Cyclone Gabrielle silt were all below background soil levels for Hawkes Bay, where background levels were available. As would be expected from the derivation of the background concentrations, they are similar to or less than the 95th percentile of the distribution of elemental contaminant concentrations measured in silt samples. Maximum concentrations were generally above background levels and for some elements (As, Cd, Pb) were above the most stringent of the SGVs. These SGVs relate to a scenario where 25% of produce consumed by affected individuals is grown in the soil under assessment. However, such high concentrations were very rare, occurring in two samples each for arsenic and cadmium and one sample for lead. The two samples of silt with elevated cadmium concentrations (1.1 and 4.3 mg/kg) were both from industrial sites and are well below the SGV for a commercial/industrial site (1300 mg/kg). The elevated lead concentration (210 mg/kg) and one of the elevated arsenic concentrations (22 mg/kg) were in samples taken from silt repositories. These sites were sampled on a number of occasions, with no other samples containing similarly high concentrations. The other elevated arsenic concentration (20 mg/kg) was from a rural residential location and may indicate historical use of arsenic-containing agricultural chemicals.

In general, the concentrations of elemental contaminants in flood-deposited silt samples appear entirely typical of the concentrations of these elements in Hawkes Bay soil.

5.2 PETROLEUM HYDROCARBONS

Petroleum hydrocarbons are conventionally classified according to their carbon chain length and results from flood-deposited silt are reported in terms of the concentrations of C_7-C_9, C_{10}-C_{14}, C_{15}-C_{38} and total petroleum hydrocarbons (TPH). MfE has established soil acceptance criteria for petroleum hydrocarbons (MfE 1999). The criteria depend on the soil type, the depth of the soil sample and the intended use of the site (residential, commercial/industrial or agricultural). For sandy silt residential soils at the soil surface, criteria are:

- C_7-C_9 500 mg/kg
- C_{10}-C_{14} 510 mg/kg
- C_{15}-C_{38} >20,000 mg/kg

Petroleum hydrocarbons were analysed for in 155 cyclone debris samples.

The lighter hydrocarbons (C_7-C_9 and C_{10}-C_{14}) were only detected in samples of flood-deposited silt from a single industrial site, with maximum concentrations of 133 and 100 mg/kg, respectively. The soil acceptance criteria for sandy silt soil at a commercial/industrial site are 500 and 1700 mg/kg, respectively. The heavier hydrocarbons (C_{15}-C_{38}) were detected in 24 of 155 flood-deposited silt samples (15%) with concentrations in the range 20-16,100 mg/kg. Positive samples were mainly from industrial sites and the contamination may have been pre-existing. None of the petroleum hydrocarbon concentrations reported exceeded the MfE soil acceptance criteria.

5.3 ENVIRONMENTAL CONTAMINANTS

5.3.1 Legacy pesticides

Organochlorine pesticides, such as DDT and dieldrin were used in New Zealand during the period (approximately) 1950-1980s. The extreme environmental stability of these chemicals means that they can still be detected in some New Zealand soils.

These compounds were analysed for in 378 debris samples. While some samples were analysed individually, the majority were analysed as composites of three or four individual silt samples. DDT was not detected in any silt samples, while dieldrin was detected at a concentration of 0.021 mg/kg in a composite of three samples from the Waiohiki Golf Course silt repository. MfE have established SGVs for dieldrin in the range 1.1-160 mg/kg (MfE 2011), at least 50-fold higher than the levels detected in flood-deposited silt.

5.3.2 Polychlorinated biphenyls

Polychlorinated biphenyls (PCBs) are also highly stable organochlorine compounds. Total PCBs were analysed for in 36 samples (mainly industrial sites), without any detections.

5.3.3 Phenols

Phenol was analysed for in 40 flood-deposited silt samples from industrial sites in the Awatoto area. Phenol was detected in three samples with concentrations in the range 3.8-30 mg/kg. No SGVs have been established for phenol in New Zealand. The UK Environment Agency established land-use specific SGVs of 420, 280 and 3200 mg/kg dry weight for phenol in residential, allotment and commercial land, respectively. These SGVs suggest that the concentrations of phenol detected at industrial sites in Awatoto are not of human health concern.

Cresols (methyl-substituted phenols) were also detected at the industrial sites where phenol was detected, with concentrations in the range 3-27 mg/kg. The EU Joint Research Centre (JRC) reviewed methods and values for soil screening values within the EU (EU JRC 2007). Soil screening values were reported from three countries (Italy, Poland and Spain), with values in the range 25-100 mg/kg dry weight for industrial soil use. This suggests that the levels of cresols detected in flood-deposited silt are unlikely to be a cause for concern.

5.4 PESTICIDE RESIDUES

More than 300 flood-deposited silt samples were analysed for pesticide residues, either through a multi-residue pesticide screen, an acid herbicide pesticide screen or both. Ten pesticides were detected either in single samples or in a small number of samples. Results of positive detections are summarised in Table 4.

Table 4. Pesticide residues detected in flood-deposited silt from Cyclone Gabrielle

Pesticide residue	Sample type (number of different sites)	Number of detections	Concentration(s) detected (mg/kg)
Diuron	Silt repository (1)	1 (composite of 4 samples)	0.07
Linuron	Silt repository (1)	1 (composite of 4 samples)	0.16
Captan	Silt repository (1)	1 (composite of 3 samples)	0.17
Permethrin	Industrial (1)	10	0.04, 0.05, 0.05, 0.07, 0.09, 0.09, 0.12, 0.18, ,0.59, 0.61
Propiconazole	Industrial (1)	1	0.18
Alachlor	Agriculture (1)	1	0.082
Cyhalothrin	Agriculture (1)	1	0.027
Metribuzin	Agriculture (1)	1	0.049
Procymidone	Agriculture (1)	1	0.20
Pendimethalin	Agriculture (1)	1	0.024

No New Zealand SGVs have been established for these pesticides. However, given that direct ingestion of soil is generally the major component of exposure estimates in the derivation of the SGVs, a soil ingestion-based risk assessment approach was used to assess the toxicological significance of these residues. Exposure estimates were derived for a 13 kg child ingesting 50 mg/day of soil. Exposure estimates were compared to acceptable daily intakes (ADIs) established by the Joint FAO/WHO Meeting on Pesticide Residues (JMPR). Results of these assessments are included in Table 5.

Table 5. Assessment of risks associated with ingestion of cyclone debris containing pesticide residues

Pesticide residue	ADI (mg/kg bw)[a]	Residue concentration (mg/kg)	Exposure estimate (mg/kg bw per day)	Hazard quotient (% of ADI)
Diuron	0.007[b]	0.07	2.7×10^{-7}	0.004
Linuron	0.01[b]	0.16	6.2×10^{-7}	0.006
Captan	0.1	0.17	6.5×10^{-7}	0.0007
Permethrin	0.05	0.61	2.3×10^{-6}	0.005
Propiconazole	0.07	0.18	6.9×10^{-7}	0.001
Alachlor	0.0025[c]	0.082	3.1×10^{-7}	0.01
Cyhalothrin	0.02	0.027	1.0×10^{-7}	0.0005
Metribuzin	0.02[b]	0.049	1.9×10^{-7}	0.0009
Procymidone	0.1	0.20	7.7×10^{-7}	0.0008
Pendimethalin	0.1	0.024	9.2×10^{-8}	0.00009

ADI: acceptable daily intake

[a] Unless otherwise stated, ADIs are those established by the Joint FAO/WHO Meeting on Pesticide Residues (JMPR, https://apps.who.int/pesticide-residues-jmpr-database/). JMPR expresses ADIs as a range from zero to an upper limit. Only the upper limits are reported here. JMPR only establishes ADIs for pesticides applied to food and ADIs for herbicides were sourced elsewhere.

[b] Australian Pesticide and Veterinary Medicine Authority (APVMA), Acceptable daily intakes (ADI) for agricultural and veterinary chemical used in food producing crops or animals

[c] Secretariat of the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade, Decision Guidance Document – Alachlor

The hazard quotients associated with the pesticide residues detected in Cyclone Gabrielle flood-deposited silt are negligible and these residues would not be a cause for concern.

5.5 FAECAL INDICATOR BACTERIA

Approximately 280 flood-deposited silt samples were analysed for the faecal indicator bacteria (FIBs), faecal coliforms and *Escherichia coli.* Concentrations ranged from not detected to >16,000 MPN/g. Repeated analyses were available for a limited number of sites. Twenty-three sites were sampled and tested for FIBs on 9 March 2023 and again on 16 March 2023. Table 6 gives the *E. coli* results for these 23 sites. It should be noted that in most cases the faecal coliform and *E. coli* results were identical.

Table 6. *Escherichia coli* concentrations in flood silt samples collected on 9 and 16 March 2023

Site code	Site type	Location	*Escherichia coli* concentration (MPN/g)	
			9 March 2023	16 March 2023
A2-1	Residential	Awatoto	9200	1600
A3-1	Residential	Awatoto	9200	920
A6-1	Residential	Awatoto	5400	1600
U2-1	Residential (rural)	Awatoto	5400	2400

Site code	Site type	Location	*Escherichia coli* concentration (MPN/g)	
U5-1	Residential (rural)	Awatoto	>16,000	5400
U9-1	Residential (rural)	Awatoto	9200	2400
U13-1	Residential (rural)	Awatoto	16,000	3500
B1-1	Industrial	Awatoto	5400	2400
D1-1	Industrial	Awatoto	5400	3500
D1-2	Industrial	Awatoto	5400	2400
F1-1	Industrial	Awatoto	3500	3500
G1-1	Industrial	Awatoto	16,000	2400
G1-2	Industrial	Awatoto	16,000	2400
G1-3	Industrial	Awatoto	16,000	1600
I1-1	Industrial	Awatoto	5400	2400
J1-1	Industrial	Awatoto	5400	5400
J1-2	Industrial	Awatoto	3500	350
L1-1	Industrial	Awatoto	9200	2400
L1-2	Industrial	Awatoto	16,000	5400
N1-1	Industrial	Awatoto	5400	2400
P1-1	Industrial	Awatoto	1100	3500
P1-2	Industrial	Awatoto	540	2400
Q1-1	Industrial	Awatoto	5400	2400

With the exception of site P1, *E. coli* concentration remained unchanged or decreased in the week between sampling events. Decreases in bacterial concentrations ranged between 35 and 90%.

While no analyses for specific pathogens or faecal source markers were carried out on these samples, the proximity of the sampling locations to the Napier wastewater treatment plant (WWTP) suggests that the WWTP may have contributed to the elevated *E. coli* concentrations. It should be noted that industrial sites G1 and L1 were two of the closest sites to the WWTP and had the highest initial *E. coli* concentrations of the industrial sites. However, industrial site I1 was similarly close to the WWTP, while J1 was the WWTP. Both of these sites contained silts with lower *E. coli* concentrations, suggesting that other determinants than proximity to the WWTP contributed to *E. coli* levels.

5.6 SUMMARY

The vast majority of the results of analyses of chemical contaminants in flood-deposited silt give no cause for public health concerns. Contaminants were either not detected or their concentrations were consistent with background levels and within soil guideline levels. A small number of elevated concentrations of metals (arsenic, cadmium and lead) were either associated with industrial sites, seen in single samples from silt repositories or associated with rural sites, where this occurrence may be due to historical agrichemical use.

Microbial analysis of flood-deposited silt samples was limited in the range of organisms examined and in the degree of follow-up carried out. Where repeat samples were taken at the same site, concentrations of FIBs mostly decreased with time.

There is little evidence that sampling and analysis was informed by known sources of contaminants and their likely movement into flood-deposited silt. The exception to this statement is the microbial analyses performed in proximity to the Napier WWTP in Awatoto. A greater focus in this area and application of faecal source marker and pathogen analyses would have been useful in defining the extent of the contamination and the associated human health risks due to the WWTP being overwhelmed by the flood waters.

6 AIR QUALITY RISK ASSESSMENT

Asbestos and crystalline silica were identified as potential respirable hazards in flood-deposited silt in Hawkes Bay from Cyclone Gabrielle.

Asbestos may enter the environment through the decomposition of asbestos-containing building materials (Bardsley 2015). The main potential adverse health effect related to low exposures is mesothelioma, a cancer of the thin tissues that surround the lungs. Mesothelioma is associated with much lower cumulative exposures to asbestos fibres than lung cancer or other asbestos-related lung diseases, such as asbestosis. Most asbestos-containing building materials used in New Zealand houses contain mainly chrysotile asbestos, which represents a lower risk of mesothelioma than other asbestos types. While there is no absolutely safe level of asbestos exposure, asbestos fibres are present in the environment in very low concentrations, and therefore some exposure is unavoidable.

Studies of exposure to respirable crystalline silica in occupational settings (e.g., mining and stone cutting) have demonstrated adverse respiratory health effects. High concentrations acutely cause cough and shortness of breath. Chronic, lower occupational exposures to silica can produce silicosis, characterised by development of silicotic nodules and by scarring of the lung (Collins et al 2005). Soils and silt naturally contain crystalline silica, mainly in the form of quartz (Swanepoel et al 2011).

Adverse effects from respirable crystalline silica are rare in non-occupational settings (Swanepoel et al 2011). However, due to the quantity of silt deposited in the Hawkes Bay region and the likelihood of this becoming airborne as dust, further investigations were carried out.

6.1 COMPOSITION OF FLOOD-DEPOSITED SILT FROM HAWKES BAY

Samples of flood-deposited silt (n = 39) were collected from locations in Hawkes Bay during the period 29 September 2023 to 6 October 2023. Samples were analysed for asbestos (Capital Environmental Services) and for mineral composition by x-ray diffraction (Agon Environmental, Fullerton, South Australia). Asbestos was not detected in any of the silt samples analysed. Results of the mineral analyses are summarised in Table 7.

The inorganic component of soil is classified on the basis of particle size into sand (0.1-2 mm), silt (0.002-0.1 mm) and clay (<0.002 mm).[3] Samples of Hawkes Bay flood-deposited silt (n = 3) were subjected to particle size analysis by sieve and hydrometer analyses. All samples were predominantly silt (50-65%), with lower amounts of sand (10-50%) and clay (trace-25%).

Silt is reported to usually be composed of quartz, feldspars, chlorites and mica.[4] Noting that muscovite is a form of mica, all of these minerals are represented in the Hawkes Bay flood-deposited silt samples. Quartz is also a common component of sand. All samples of flood-deposited silt from Hawkes Bay contained quartz (mean 32%, range 16-45%).

3 https://bio.libretexts.org/Bookshelves/Microbiology/Microbiology_(Boundless)/16%3A_Microbial_Ecology/16.02%3A_Soil_and_Plant_Microbiology/16.2A%3A_Soil_Composition Accessed 21 March 2024

4 https://www.mindat.org/min-49428.html Accessed 21 March 2024

6.2 EXPOSURE LIMITS FOR RESPIRABLE CRYSTALLINE SILICA

Collins et al (2005) established a chronic reference exposure level (REL) for crystalline silica of 3 μg/m^3. The REL is a concentration, at or below which no adverse health effects are anticipated in the general human population from long-term (up to lifetime) exposure. Consequently, the REL is most appropriate for comparison to the mean concentration of crystalline silica in air over time. The REL was based on the development of silicosis in a cohort of South African gold miners (Hnizdo and Sluis-Cremer 1993).

The REL value is an order of magnitude lower than the New Zealand workplace exposure standard (WES) for crystalline silica of 0.05 mg/m^3 (50 μg/m^3) as a time-weighted average (WorkSafe 2022). This difference is appropriate considering that the WES relates to occupational exposure (8 hours/day, 5 days/week), compared to continuous lifetime exposure for the REL.

6.3 CHARACTERISATION OF EXPOSURE TO RESPIRABLE CRYSTALLINE SILICA

The National Institute of Water and Atmospheric Research (NIWA) established a network of portable airborne particulate equipment in the Hawkes Bay.[5] The network included 18 devices in the Esk Valley and 18 in the Tūtaekurī Valley. Real-time laser-based particle monitors measured PM_1, $PM_{2.5}$ and PM_{10} (particle matter smaller than 1, 2.5 and 10 microns, respectively) over 17-minute intervals. Data were converted into estimates of dust concentrations. Outputs from the monitoring were reported in terms of:

- The number of dust events per day. The number of 17-minute periods for which the airborne dust concentration exceeded 10 μg/m^3, and
- The mean airborne dust concentration across dust events for a given day.

The results from the particle monitoring were used to calculate the mean dust concentration for the two valleys per day and across the entire monitoring period. To convert dust concentrations to crystalline silica concentrations, it was assumed that airborne dust would have a negligible moisture content and that the crystalline silica content of the dust was equivalent to its quartz content (mean = 32%). This is consistent with the approach taken in other studies. For example, Hnizdo and Sluis-Cremer (1993) estimated that 30% of dust that South African miners were exposed to was crystalline silica. In a study of air quality in New York following Hurricane Sandy, the silica content of air samples was equated to the quartz content (Freund et al 2014). Results are summarised in Table 8.

Mean exposure to respirable crystalline silica across the complete monitoring period was well below the REL for both Esk and Tūtaekurī Valleys. It should further be noted that the monitoring was conducted over the high-risk seasons for dust production, while the REL is applicable to lifetime exposure. Exposure to dust and silica is likely to be at a lower level through the Autumn and Winter periods and overall exposure to silica will be lower than indicated in Table 8. Additionally, all monitoring sites were outdoors and time spent indoors is likely to result in lower exposure to silica than estimated in this study.

Peak dust concentrations and associated silica concentrations were well above the REL level. However, these high concentrations generally only occurred for short time periods. For example, the overall maximum dust concentration (3850 μg/m^3) occurred in a single 17-minute sample, with no dust reported for the preceding and following 17-minute time periods. No daily mean silica concentration (maximum 7.5 μg/m^3 of dust or 2.4 μg/m^3 of

[5] https://niwa.co.nz/atmosphere/research-projects/assessing-post-cyclone-air-quality-across-tair%C4%81whiti-and-hawkes-bay Accessed 21 March 2024

crystalline silica) in either valley exceeded the REL of 3 µg/m^3. The highest daily mean silica concentration was in the Esk Valley on 31 October 2023.

Unsurprisingly, the sampling site with the highest mean dust concentration (3.9 µg/m^3 of dust or 1.2 µg/m^3 of crystalline silica) was at one of the silt repositories (Moteo Pa).

6.4 SUMMARY

The network of air quality monitoring devices deployed in the Hawkes Bay region during September 2023 to March 2024 have provided a wealth of information of airborne dust in the region. While high short-term concentrations of dust and associated crystalline silica were observed, the REL is a concentration of crystalline silica in air that is without appreciable risk over a lifetime of exposure. The overall body of data and the associated long-term mean concentrations of crystalline silica suggest that exposure is well below the REL and represent a low level of concern for silicosis resulting from exposure to airborne dust.

Table 7. Mineral content of flood-deposited silt samples from Hawkes Bay, September-October 2023

Sample date	Location	Minerals (%, dry weight basis)								
		Quartz	Albite	K-feldspar	Amphibole	Muscovite	Chlorite	Clay	Laumontite	Calcite
29/09/2023	Waiohiki Marae EIT Bridge	41	41	4	2	7	3		2	
29/09/2023	Tutaekuri River Lennox Park Brackenridge	32	55	4	2	5	2			
29/09/2023	Pakowhai Gilligan Road area	16	30			6	3	45		
29/09/2023	Taradale Tukaekuri Recreation Reserve	36	45	6	3	6	3			1
29/09/2023	Esk Valley Whirinaki WTP area	38	48	2	3	6	2			1
29/09/2023	Esk Valley Top near side stream	44	44	3	2	5	2			
29/09/2023	Esk Valley River confluence 3/4 way up valley	40	47	5	3	4	1			
29/09/2023	Esk Valley SH5 / Waipunga Road big silt pile	35	51	3	2	6	2			1
29/09/2023	Esk Valley Hukarere Marae Bridge area	38	50	3	3	3	2			1
29/09/2023	Eskdale School area	38	49	5	2	3	2			1
29/09/2023	Esk Valley lower Petane Cemetary	39	49	5	1	3	2			1
30/09/2023	Awatoto Ravensdown - NCC WWTP area	16	27	1		5	2	48		1
30/09/2023	Waitangi / Clive Regional Park	20	33			7	4	35		1
30/09/2023	Tukituki Haumoana Recreational area	24	36	2		3	2	30	2	1
30/09/2023	Tukituki Havelock North River Recreation area	22	40			4	2	30	1	1
30/09/2023	Ngaruroro River Omaha / Fernhill	22	37	1		6	3	30	1	
1/10/2023	Puketapu Tutaekuri River area near town	34	53	4	3	3	2			1
1/10/2023	Puketapu Tutaekuri River middle Recreational area	39	48	5	2	4	2			
1/10/2023	Tutaekuri / Mangaone River confluence	43	46	2	3	4	2			
1/10/2023	Rissington Dartmor Mangaone River silt processing area	34	52	6	2	3	2			1
1/10/2023	Omaruni / Moteo Pa / Tutaekuri River silt processing area	33	48	6	3	7	3			
4/10/2023	Pakowhai Silt task force processig site	25	37	2	2	6	3	20		5

Sample date	Location	Minerals (%, dry weight basis)								
		Quartz	Albite	K-feldspar	Amphibole	Muscovite	Chlorite	Clay	Laumontite	Calcite
4/10/2023	Whirinaki recreational area	20	33			4	3	40		
4/10/2023	SH5 Esk Valley middle Silt task force processing site	34	40	2	2	4	2	15		1
4/10/2023	Top of Esk Valley Silt task force processing site	45	40	5	3	4	2			1
4/10/2023	Bottom Esk Valley Silt task force processing site	41	48	4	2	2	2			1
4/10/2023	Pahowhai dog recreational / cycling area	33	54	4	3	4	2			
5/10/2023	Ngaruroro River Recreational area by river / bridge	34	50	10		3	2		1	
5/10/2023	Tongoio Lower Valley	32	40	3	1	2	1	10		11
5/10/2023	Tongoio Upper valley silt processing site	34	40	6	2	1	1			16
5/10/2023	Frasertown School area	22	43			1	1	30		3
5/10/2023	Opoutama Blue Bay River area	28	33	2		1	1	35		
5/10/2023	Nuhaka River bridge area	33	54	4		2	2			5
5/10/2023	Wairoa Ruatuniwha Marae area	25	42	9		2	2	15		5
5/10/2023	Wairoa main street across road on riverbank	31	32	2		3	1	28		3
5/10/2023	Tutira School area	36	56	2	3	2	1			
6/10/2023	Tukituki River Pourerere Event Centre bridge area	34	56	5		2	2		1	
6/10/2023	Waipawa town bridge recreational area	25	66	2	1	3	2		1	
6/10/2023	Waipukurau town bridge recreational area	26	48	1		2	2	20	1	
6/10/2023	Porangahau Marae town bridge recreational area	34	26	4		3	1	28		4

Table 8. Summary of airborne dust monitoring in the Esk and Tūtaekurī valleys, September 2023 to March 2024

Month	Esk Valley		Tūtaekurī Valley	
	Dust concentration, mean (range), µg/m^3	Crystalline silica[a] concentration, mean (range), µg/m^3	Dust concentration, mean (range), µg/m^3	Crystalline silica[a] concentration, mean (range), µg/m^3
Sept 2023	0.78 (0-42)	0.25 (0-13)	0.79 (0-116)	0.25 (0-37)
Oct 2023	1.75 (0-161)	0.56 (0-51)	1.62 (0-612)	0.52 (0-196)
Nov 2023	1.37 (0-133)	0.44 (0-43)	1.15 (0-372)	0.37 (0-119)
Dec 2023	1.28 (0-104)	0.41 (0-33)	1.09 (0-470)	0.35 (0-150)
Jan 2024	1.12 (0-157)	0.36 (0-50)	1.08 (0-399)	0.35 (0-128)
Feb 2024	1.16 (0-171)	0.37 (0-55)	1.31 (0-3850)	0.42 (0-1230)
Mar 2024	1.37 (0-112)	0.44 (0-36)	1.29 (0-224)	0.41 (0-72)
Total	1.30 (0-171)	0.42 (0-55)	1.22 (0-3850)	0.39 (0-1230)

[a] Based on a mean quartz content of 32%

7 CONCLUSIONS

The current study examined the evidence for conditions that could result in adverse human health effects in the aftermath of Cyclone Gabrielle. The evidence examined was primarily focused on flood-deposited silt.

A review of the literature highlighted that there is no ‘standard’ approach to the sampling and analysis of flood-deposited silt and flood-affected soil. However, the literature highlights certain issues that should be considered, such as, the basis for the selection of sampling sites, sampling patterns, sample types, sampling techniques and analytes to be included.

There have been convincing reports of disease outbreaks or increases in the incidence of diseases due to flooding events. However, the specific route of exposure to the causative agent is not always apparent. The weight of evidence suggests that adverse health effects are most commonly associated with direct contact with flood water or due to circumstances secondary to the flood, such as, crowding in evacuation centres, leading to person-to-person transmission of diseases. The study of Gertler et al (2015) is perhaps unique in this respect, in associating incidence of cryptosporidiosis to contact with the flood-affected environment, rather than contact with flood water.

The study of Mielke et al (2017) suggests potential beneficial aspects for human health due to flooding event, with children’s blood lead levels decreasing in the 10-year period following Hurricane Katrina. However, the decrease in blood lead levels is likely to be multi-factorial. For example, in the 10 years following the hurricane there was substantial replacement of housing, with the new housing lacking risk factors for elevated blood lead levels, such as old lead-based paint.

With respect to contaminants in flood-deposited silt, in many cases the lack of baseline concentrations makes results difficult to interpret. In general, increases of chemical contaminant concentrations in flood-deposited silt or flood-affected soil was linked to known or suspected contamination scenarios, such as deposition of river sediments where those sediments were known to be highly polluted. There is suggestive evidence that, in the absence of existing sources of contamination, silt deposited during flooding is likely to be no more contaminated than existing soils and may be less contaminated.

Results from microbiological examination are even more difficult to interpret. In general, concentrations of FIBs and pathogens decrease in surface silts/soils with time following the flooding event. This is likely due to the adverse effects of desiccation and solar radiation on microbial survival. However, it is not clear from most of the studies whether FIBs and pathogens were introduced as a result of the flooding or whether their presence predated the flooding event.

A large amount of chemical and microbiological testing of flood-deposited silt was carried out following Cyclone Gabrielle. In all cases the results of analyses of chemical contaminants in flood-deposited silt give no cause for public health concerns. Contaminants were either not detected or their mean concentrations were consistent with background levels and within soil guideline levels.

Microbial analysis of silt samples was limited in the range of organisms examined and in the degree of follow-up carried out. However, some of the highest concentrations of FIBs detected were in proximity to the Napier WWTP.

There is little evidence that sampling and analysis was informed by known sources of contaminants and their likely movement into flood-deposited silt. The exception to this statement is the microbial analyses performed in proximity to the Napier WWTP in Awatoto. A greater focus in this area and application of faecal source marker and pathogen analyses would have been useful in defining the extent of the contamination and the associated human health risks due to the WWTP being overwhelmed by the flood waters.

The network of air quality monitoring devices deployed in the Hawkes Bay region during September 2023 to March 2024 have provided a wealth of information of airborne dust in the region. While high short-term concentration of dust and associated crystalline silica were observed, the overall body of data suggests a low level of concern for silicosis resulting from exposure to airborne dust.

7.1 AREAS WHERE FURTHER INFORMATION IS REQUIRED

The unpredictable, episodic nature of major floods restricts our ability to perform well planned and controlled studies of the impact of floods on chemical and microbiological determinants of public health. Floods cannot make contamination but can move contamination from a contained environment to an uncontained environment. Examples of this would be the failure of WWTPs and the spread of human sewage to the surrounding environment or the movements of contaminated sediment from a riverbed to adjoining land and communities.

In this respect, advance knowledge of sources of contained contamination and the characteristics of those contaminants is pivotal to an effective environmental health response to a major flood. Knowledge of such sites and a check of their condition following a flood would allow greater direction of the location of sampling and the scope of analyses to be performed. Consideration should also be given to the proximity of sources of contamination to vulnerable or marginalised populations.

The scientific literature suggests movement of contaminants from a contained site to the surrounding environment will only be apparent over relatively short distances, with dilution mitigating contamination at greater distances from the source. Sampling and analysis efforts could generate greatest value in demarcating the spread of contamination. While some sources of contamination may remain unknown, information on the location and characteristics of such sources is a prime requirement for being prepared for an environmental health response to a major flooding event.

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