Review of the potential impacts of climate change on wastewater networks and treatment plants in Aotearoa New Zealand, and implications for public health

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

AR5	IPCC Fifth Assessment Report (2013/2014)
AR6	IPCC Sixth Assessment Report (2021/2022)
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
ENSO	El Niño Southern Oscillation
GHG	Greenhouse gas
HABs	Harmful algal blooms
IPCC	Intergovernmental Panel on Climate Change
OWMS	Onsite wastewater management system
PED	Potential evapotranspiration deficit
Radiative forcing	A measure of the energy absorbed and retained in the lower atmosphere. Technically, it is the change in the net irradiance (expressed in W/m^2, and including both shortwave energy from the sun and long-wave energy from greenhouse gases) at the tropopause, due to a change in an external driver of climate change (eg, a change in the concentration of carbon dioxide or the output of the sun).
RCP	Representative concentration pathway. A greenhouse gas concentration scenario identified by its total radiative forcing at 2100 relative to 1750.
SAM	Southern Annular Mode
SLR	Sea level rise
SSP	Shared socioeconomic pathway. A scenario of projected global socioeconomic changes and associated climate policies up to the year 2100.
WWTP	Wastewater treatment plant
WG1	Working Group 1 (of the IPCC Sixth Assessment Report team)

EXECUTIVE SUMMARY

Well-functioning wastewater systems provide a critical service to society and play a key role in protecting environmental and public health. In Aotearoa New Zealand, cities and larger towns are serviced by centralised wastewater conveyance and treatment systems ranging from basic pond-based systems to advanced, tertiary treatment systems, while those living in rural areas typically rely on onsite wastewater management systems (OWMSs) such as septic tanks. Other sanitary infrastructure such as pit latrines or vault toilets may be used at more remote locations such as camping grounds or picnic areas. All of these wastewater treatment systems are vulnerable to the impacts of climate change, with potentially serious implications for public health.

The projected climate change hazards that are expected to impact on wastewater systems in New Zealand are sea level rise, coastal flooding and erosion, changing precipitation patterns including both more intense rainfall events (with associated surface and river flooding) and more severe drought, and increasing ambient temperatures. These climate hazards may occur individually or in combination. The impacts of these climate hazards may be direct or indirect, occur abruptly or progress slowly, and may resolve quickly or require extensive, expensive and prolonged remediation. Key impacts are likely to include increased frequency and/or volume of wastewater overflow from sewers; increasing instances of treatment bypass at the wastewater treatment plant (WWTP); cracking, rupture or corrosion of sewer pipes; damage to pumps and pump stations; damage to screens and other WWTP components by silt or debris; reduced treatment efficacy due to impacts on biological or physical treatment processes; inundation of and damage to WWTP infrastructure; power outages and damage to electrical systems; lack of access to, or servicing of, the WWTP or septic tanks caused by damage to roading; reduced treatment capacity of soils due to increased soil saturation; increased production of malodorous gases; and/or coastal erosion or flooding permanently undermining or inundating the sewer network or WWTP. Additional indirect impacts on wastewater systems may include climate-driven changes in the receiving environment that make them more susceptible to adverse impacts of receiving wastewater effluent. Some climate hazards may also yield benefits such as increased vertical separation distance between effluent drainage fields and groundwater tables.

The impacts of climate change will be experienced differently by different wastewater systems around the country, being influenced by regional variation in current and future climate, co-occurring climate hazards, the design and condition of the network, the treatment processes employed, and the influence of local geography that could either minimise or exacerbate risk. The impacts for a certain climate change scenario on a given wastewater system may therefore range from a brief, localised event or minor change in treatment efficacy, to widespread disruption or failure of wastewater services. Wastewater systems that are likely to experience the most significant impacts include those with aging or poorly designed or maintained infrastructure, that are located in low-lying or erosion-prone areas of the coast or in river floodplains, have combined storm and sanitary sewers or sewer networks that are predominantly gravity-operated, or are in regions that are projected to experience increasing frequency of high-rainfall events. In addition, aspects of a system that convey resilience to certain climate hazards may also pose vulnerabilities: for example, highly mechanised or advanced WWTPs may be less sensitive to changes in temperature or influent quality, but be more severely impacted and take longer to reinstate following inundation. As there is little redundancy in most wastewater networks, failure at key points (especially the WWTP) can render the entire network dysfunctional. Depending on the nature of the impact(s) and the wastewater system, a small number of individuals or an entire community may be affected.

The public health implications of climate change impacts on wastewater treatment systems can be considered by first grouping together similar impacts or consequences for the wastewater system. Key ‘impact themes’ can therefore be summarised as increasing instances of untreated or inadequately-treated wastewater being discharged to the environment; increased sensitivity of receiving environments to the impacts of wastewater discharge; disruption or loss of acceptable sanitation services; changes in sanitation behaviours; and increased production of nuisance gases. In turn, these impact themes highlight that public health implications generally fit within two overarching categories: health outcomes associated with environmental contamination or degradation, and health outcomes resulting from lack of access to adequate sanitation.

The most significant public health implication of climate-driven impacts on wastewater systems is the increased transmission of infectious disease, due to increased exposure to pathogens (especially faecal pathogens). The specific health outcomes are a function of the particular pathogen(s) to which a person is exposed, the amount to which they are exposed, the route of exposure and their general health and immune status. Depending on the climate hazard(s) and its impact on a given wastewater system, exposure routes could include direct contact with faeces, spilled wastewater, or contaminated floodwaters; consumption of contaminated drinking-water, mahinga kai gathered from contaminated environments or crops irrigated with contaminated waters; recreation in contaminated receiving environments, particularly aquatic environments such as rivers and coastal beaches; or inhalation of bioaerosols. The loss or reduction of sanitation services may also expose people to infectious pathogens through the use of inappropriate emergency toilet facilities, or through adoption of unsafe sanitary behaviours such as open defecation or reduced hand hygiene. The primary health outcome associated with faecal pathogens is self-limiting gastrointestinal illness, but severe illness, debilitating sequelae or death do occur. Contact with non-faecal pathogens that may be present in wastewater or as a result of poor hygiene can cause upper respiratory tract, skin, wound, eye, ear, nose and throat infections. Health risks associated with exposure to chemical wastewater contaminants are unlikely to be an immediate concern, but could be relevant for cases of chronic exposure.

The impacts of climate change on wastewater systems can also have significant adverse impacts on mental and social wellbeing. The loss of, or reduced access to, adequate or appropriate sanitation is associated with poor mental and psychosocial outcomes including anxiety, stress, shame, disgust, and anger. Environmental degradation due to wastewater overflow or inadequate treatment of effluents prevents the use of blue or green space amenities that provide considerable benefits to mental and physical wellbeing and social cohesion. Environmental degradation is also linked to ‘psychoterric illness,’ causing grief, anger, anxiety, or hopelessness and undermining notions of place-based, cultural or self-identity. This is likely to be especially profound for tāngata whenua, who have a whakapapa connection to their environment, and to which a large part of their identity, wellbeing and cultural practice is tied.

The impacts of climate change on wastewater systems and the associated public health implications are likely to disproportionately affect vulnerable and disadvantaged socioeconomic groups, and may form extensive cascades of additional health, social, cultural, environmental and economic implications.

1. INTRODUCTION

1.1 BACKGROUND

Wastewater treatment systems provide essential services to communities. However, these systems are increasingly being recognised as vulnerable to the impacts of climate change, including rising sea levels and groundwater tables, coastal erosion, increased frequency and intensity of storm and rainfall events, flooding, drought, changing wind patterns and increasing ambient temperatures (Kirchoff and Watson 2019; MfE 2020b; Li et al. 2023). These impacts of climate change may occur as individual hazards, or as co-occurring and compounding hazards, with both direct and indirect impacts on wastewater networks and treatment systems. In turn, these impacts on various elements of the wastewater network and treatment system may be wide-ranging, with potentially complex, cascading and serious implications for human and environmental health (Lawrence et al. 2020; Hughes et al. 2021). Climate change will also exacerbate existing issues relating to aging and/or poorly designed or maintained wastewater infrastructure (Kirchoff and Watson 2019; Hughes et al. 2021).

In New Zealand, numerous changes in climate are already being observed (MfE 2018; IPCC 2021; Bodeker et al. 2022; MfE 2024), and the recent National Climate Change Risk Assessment identified ‘potentially extreme consequences’ of climate change on wastewater and stormwater infrastructure and service provision by 2050 (MfE 2020a, 2020b). However, much of the literature on the vulnerabilities of wastewater treatment systems to climate change comprises single-hazard studies or a high-level overview of the potential impacts on wastewater infrastructure as part of a broader discussion of the societal impacts of climate change (Hughes et al. 2021). Comprehensive assessments of the potential impacts of climate change across the whole wastewater network and treatment system, together with the potential implications of these impacts for public health, are lacking.

1.2 APPROACH AND SCOPE

The objective of this report is to assess the potential impacts of climate change on wastewater treatment systems in the Aotearoa New Zealand context, with a specific focus on those impacts that may have implications for human health. It will draw on key national and international documents, including up-to-date scientific literature, modelling and projections, and white and grey literature to:

- Review the nature and extent of climatic changes being projected for New Zealand.
- Review the potential impacts of those climatic changes on wastewater infrastructure and treatment processes that are relevant to New Zealand, focusing on municipal wastewater systems, but with comments where relevant on onsite wastewater management systems (eg, septic tanks).
- Assess the potential implications for public health that may result from the identified impacts on wastewater treatment systems.

In addition, the following points have also been identified as potential impacts on wastewater treatment plants (WWTPs) and/or sources of human health risk associated with climate change, but are out of scope of this review:

- Noting that WWTPs can be significant emitters of greenhouse gases (GHG) such as carbon dioxide, methane and nitrous oxide, potential impacts on the operation of WWTPs associated with the need to accommodate GHG emission targets (eg, to reduce the production of GHG in line with the Zero Carbon Amendment Act).
- Potential impacts on the operation of WWTPs associated with increasing costs, such as those resulting from increased energy usage (eg, during periods of high wastewater flow related to increased rainfall, or the possibility of more stringent effluent quality requirements being set to protect increasingly sensitive receiving environments) or the need to undertake adaptation or repair work.
- Specific hazards relating to wastewater reuse, as a response to climate change-driven water scarcity.
- Specific hazards associated with industrial WWTPs (ie, separate treatment plants for the treatment of effluents associated dairy production, meat works, wood processing etc).
- Specific issues relating to separated stormwater networks.
- Specific hazards relating to occupational or workplace exposures to wastewater.
- Changing or cascading risks associated with other, non-climate hazards (eg, whether rising coastal groundwater tables linked to sea level rise may increase the vulnerability of underground wastewater systems to damage from earthquake-induced liquefaction).

2. OVERVIEW OF WASTEWATER TREATMENT SYSTEMS IN NEW ZEALAND

This section is intended as a high-level overview of wastewater treatment systems and technologies in Aotearoa New Zealand, to provide context and enable discussion of the vulnerabilities of these systems in the following sections. It draws heavily on data compiled by Beca, GHD and Boffa Miskell in their national review of the wastewater sector (GHD and Boffa-Miskell 2019; Beca et al. 2020), as well as other relevant data, such as the Water New Zealand National Performance Review (Water New Zealand 2023).

2.1 WASTEWATER TREATMENT IN NEW ZEALAND

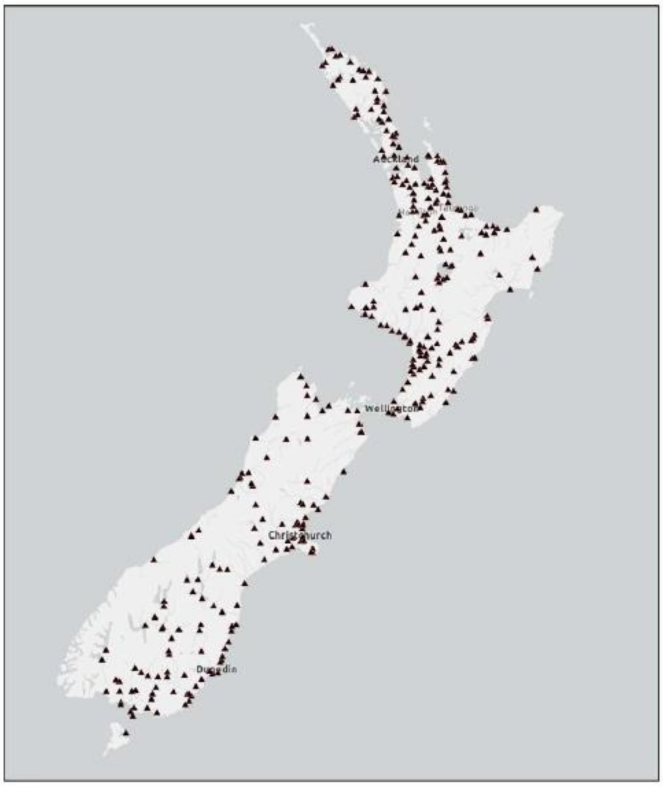
Most cities and towns in Aotearoa New Zealand are serviced by centralised wastewater treatment plants (WWTPs), where wastewater is conveyed from homes, businesses, public facilities and some industrial sites, through a reticulated sewer network to a central location for treatment and disposal (GHD and Boffa-Miskell 2018). The complexity and condition of these sewer networks is variable, with many containing both old and new sections as the communities they service grow and expand. Many networks use gravity to move wastewater to the treatment plant, but pressurised systems are increasingly being used, both in new developments and retrofitted to older networks (GHD and Boffa-Miskell 2018). Following collection, a variety of different treatment technologies and disposal strategies are utilised by different WWTPs around the country that reflect the catchment and context (eg, population size, proximity to coast or waterways, climate etc). Small towns may use decentralised systems where individual dwellings or facilities (or several of these together) are serviced by a separate on-site wastewater treatment system (GHD and Boffa-Miskell 2018).

2.1.1 Municipal wastewater treatment

As a part of the recent wastewater sector review (GHD and Boffa Miskell 2019; Beca et al. 2020), a stocktake of municipal wastewater treatment plants was carried out, and determined that there were 318 active municipal WWTPs in New Zealand. Figure 1 and Table 1 show the distribution of these facilities across the country. While the majority of these plants service small populations (ie, fewer than 5,000 people), approximately 88% of the serviced population[1] is connected to a so-called large or major plant (Table 2).

The estimated total wastewater flow for all of New Zealand's municipal WWTPs is approximately 1.5 million m^3 (1.5 billion litres) per day, of which an estimated 29% comes from the Auckland region, followed by Canterbury (16%) and Wellington (13%).

[1] "Serviced population" describes the New Zealand population that is connected to a reticulated wastewater network and treatment system.



Reproduced from Beca et al. (2020).

Figure 1: Locations of municipal wastewater treatment plants in New Zealand.

Table 1: Number of wastewater treatment plants in New Zealand, by region.

Region	No. WWTPs
Auckland	17
Bay of Plenty	17
Canterbury	42
Gisborne	2
Hawkes Bay	10
Manawatu-Wanganui	39
Marlborough	4
Nelson	1
Northland	30
Otago	33
Southland	23
Taranaki	10
Tasman	8
Waikato	54
Wellington	15
West Coast	13

Reproduced from Beca et al. (2020).

Table 2: Number of wastewater treatment plants in New Zealand, by serviced population.

<table>
<tr><th>WWTP class size</th><th>No. of plants</th><th>% population serviced</th></tr>
<tr><td><1000</td><td rowspan="2">248</td><td>1</td></tr>
<tr><td>1,000-5,000</td><td>5</td></tr>
<tr><td>5,001-10,000</td><td>26</td><td>4</td></tr>
<tr><td>10,001-100,000</td><td rowspan="2">44</td><td>34</td></tr>
<tr><td>>100,000</td><td>54</td></tr>
</table>

Reproduced from Beca et al. (2020).

For those WWTPs where data is available on the receiving environment to which treated effluents are discharged, 143 WWTPs discharge their effluents to a river, 109 discharge to land, and 64 discharge to sea (Beca et al. 2020). When the distribution across receiving environments is considered on a population-basis, 74% of the serviced population are connected to a wastewater network that discharges to the sea, reflecting the coastal locations of New Zealand’s main centres. A further 16% of the serviced population are connected to a network that discharges to a river, and 8% to a network that discharges to land (Beca et al. 2020).

A variety of wastewater treatment technologies are used in New Zealand, including activated sludge processes, tricking filters, aerated lagoons, facultative ponds, wetlands and recirculating filters (Beca et al. 2020; Table 3). The majority of WWTPs are pond-based systems; their simple construction and operation meant they were the common form of wastewater treatment system constructed between the 1960s and 1980s (Beca et al. 2020). However, pond-based systems are more commonly associated with smaller centres, servicing approximately 17% of the serviced population. Instead, activated sludge processes – which are able to achieve greater treatment efficacy and have lower land requirements – are the main treatment type used in newly constructed plants and those in larger population centres. Approximately 74% of the serviced population is connected to a system that utilises activated sludge (Beca et al. 2020). Additional detail on these different processes is provided in Beca et al. (2020).

Industrial and manufacturing facilities often have their own on-site facilities for treating process wastewater before discharging it directly to the environment. However, some industrial facilities may discharge to the local council-operated wastewater network; for example, municipal WWTPs in Whanganui, Morrinsville, Fielding and Blenheim receive significant inputs from nearby industrial facilities. These WWTPs have specific provisions to manage the different characteristics of influent that reflects the high percentage of trade waste entering the facility (Beca et al. 2020).

Table 3: Overview of the different types of technologies used in New Zealand wastewater treatment plants.

Treatment	WSAA Group*	Classification	Examples	No. facilities	% of facilities	% serviced population
Activated sludge	Type 1	AS process with primary treatment, digesters and on-site cogeneration	Mangere, Chapel Street (Tauranga)	5	2	48.7
	Type 2	AS process with primary treatment, digesters and no onsite cogeneration	Westport	1	<1	0.1
	Type 3	AS process with no primary treatment nor anaerobic digesters	Moa Point (Wellington), Shotover (Queenstown)	51	16	25.1
Trickling filters	Type 4.1	Trickling filters	Taupo	22	7	7.9
	Type 4.2	Trickling filters combined with activated AS process	Tokoroa	4	1	2.4
Ponds and lagoons	Type 5.1	Aerated lagoons and oxidation ponds with high intensity aeration	Blenheim	37	11	6.2
	Type 5.2	Facultative ponds and wetlands	Huntly	168	53	9.3
Others	Type 6	Recirculating filters	Whakamaru	17	5	0.1
	Others	Septic tanks, Imhoff tanks, worm farm	Oamaru Bay	16	5	0.2

AS – Activated Sludge. *Water Services Association of Australia (WSAA) technologies groupings are used to benchmark energy efficiency for similar process configurations.

Reproduced from Beca et al. (2020).

2.1.2 Influence of stormwater and groundwater on municipal wastewater networks

The majority of reticulated wastewater networks are separated from the stormwater network, a system of gutters and drains that collect surface runoff generated by rainfall (and in some areas/seasons, snowmelt) and discharge it untreated to nearby waterways, retention basins or wetlands. However, in some precincts with older infrastructure, wastewater and stormwater conveyance systems may be combined, carrying both wastewater and stormwater to the treatment plant in a 'combined sewer.' These systems are prone to 'combined sewer overflows' (CSOs), whereby the additional flow during periods of heavy rain overwhelms the hydraulic capacity of the network and results in the combined wastewater-stormwater stream being discharged untreated to the environment at designated overflow points and/or uncontrolled points such as manholes (GHD and Boffa-Miskell 2019; Beca et al. 2020; Hughes et al. 2021; Water New Zealand 2023). As such, combined sewer systems are no longer being constructed, and existing networks are being replaced as opportunities present (GHD and Boffa-Miskell 2019).

Even where wastewater and stormwater systems are separated, stormwater may enter the wastewater network[2] directly through flooded manholes and gully traps (ie, inflow), or illegal cross-connections between the two networks, resulting in 'wet weather overflows.' Similarly, groundwater may infiltrate into the wastewater network through cracked or broken pipes, poorly fitted connections or degraded pipe joins and seals, adding to the total flow (Cahoon and Hanke 2019). For some wastewater networks, inflow and infiltration can be a significant source of extraneous, non-sewage flow into the wastewater treatment plant (Cahoon and Hanke 2019). 'Dry weather overflows' occur independently of the influence of stormwater, for example, as a result of blockages or pump failure.

In addition to overflow events, stormwater inflow and/or groundwater infiltration can also cause issues at the WWTP by increasing the volume of wastewater requiring treatment or changing the characteristics of the wastewater, which can influence overall treatment efficacy (Cahoon and Hanke 2019; Beca et al. 2020; Coxon and Eaton 2022).

2.1.3 Onsite wastewater treatment systems

An estimated 21% of the New Zealand population is not connected to a reticulated sewerage system (Beca et al. 2020), the majority of whom live in rural areas. These homes (and other buildings such as marae, campgrounds, schools, etc) are serviced by an onsite wastewater management system (OWMS), which collects and treats all of the wastewater flow for the dwelling or facility, before discharging treated effluent to land on the property. The proportion of the local population that is connected to a OWMS rather than a municipal network differs regionally across the country, reflecting geographic differences in urban to rural living (Table 4).

Domestic OWMSs typically consist of primary treatment provided by septic tanks that are buried underground, with fats and oils separated by floatation and solids by settling, and the effluent from the 'clear middle zone' discharged to the environment via a percolation or drainage bed (Beca et al. 2020). Increasingly, secondary treatment is being installed as part

[2] Wastewater conveyance networks that are separated from direct stormwater inputs may also be referred to as 'sanitary sewers,' to distinguish from combined sewers.

of new OWMSs, which may include aerobic activated sludge, contact media, sand and textile filters or specialised membranes (Beca et al. 2020). The treatment performance of OWMSs in New Zealand is highly variable, being influenced by an array of factors including local climate, geology, system design and installation, and the age and maintenance of the system. Failure rates in different communities are estimated to range from 15 to 50% of systems (MfE 2008).

There are several other types of toilet systems that are used in certain situations in New Zealand, including vault toilets and pit latrines ('long drops') such as those used by the Department of Conservation for toilet facilities at campsites, picnic areas and backcountry huts. These systems are designed for managing human sanitary waste only, rather than wider domestic wastewater. Although they are typically small in scale (eg, often one or two toilets) and in relatively remote locations, there is potential for localised impacts on environmental and human health where these systems are overloaded (eg at highly popular locations) or are not operating effectively (eg, through damage or poor design).

Table 4: Estimated usage of onsite wastewater management systems (OWMSs) in different regions of New Zealand.

Region	Territorial Authority	% population not on reticulated wastewater
Northland	Far North	64
	Kaipara	63
	Whangārei	40
Auckland	Auckland	6
Waikato	Hauraki	44
	Waipā	34
	Taupō	29
	Hamilton	0
Bay of Plenty	Whakatāne	39
	Western Bay of Plenty	27
	Rotorua	11
	Tauranga	10
Hawkes Bay	Hastings	29
	Napier	0
Manawatū-Whanganui	Ruapehu	43
	Tararua	40
	Manawatū	39
	Whanganui	17
	Palmerston North	2
Taranaki	Stratford	42
	New Plymouth	24
Wellington	Masterton	22
	Kāpiti Coast	12
	Wellington Water	9
Marlborough	Marlborough	31
Nelson	Nelson	0
Tasman	Tasman	39
Canterbury	Selwyn	38
	Ashburton	38
	Waimakariri	37
	Timaru	37
	Mackenzie	12
	Christchurch	11
Otago	Clutha	41
	Waitaki	34
	Queenstown-Lakes	24
	Central Otago	21
	Dunedin	18
West Coast	Grey	26
Southland	Gore	12
	Invercargill	1
	Southland	0
Overall New Zealand		**21**

Note that data is only presented for territorial authorities that participated in the Water New Zealand 2018/2019 National Performance Review, so some authorities are not represented.

Reproduced from Beca et al. (2020).

3. CLIMATE CHANGE PROJECTIONS FOR NEW ZEALAND

The climate is changing; it is internationally accepted that human activity, principally through the emission of greenhouse gasses (GHGs), has caused warming of the Earth's climate (MfE 2018; IPCC 2021, 2023). Widespread changes in the atmosphere, ocean, cryosphere and biosphere have occurred, resulting in changes to weather patterns, climate extremes, and substantial and increasingly irreversible loss of ecosystems around the world (IPCC 2023). Consequent adverse impacts on food and water security, human health and key infrastructure are already being documented (IPCC 2023).

In 2021, the Intergovernmental Panel on Climate Change (IPCC) published the Working Group 1 (WG1) contribution (IPCC 2021) to its *Sixth Assessment Report (AR6)*, which was released in 2023 (IPCC 2023). Key findings[3] from those reports include:

- Each of the last four decades has been successively warmer than any decade that preceded it since 1950. Mean global surface temperatures between 2011–2020 were 1.09 [0.95 to 1.20] °C higher than in 1850–1900. It is *virtually certain* that hot temperature extremes have become more frequent and intense across most land regions since the 1950s, with cold temperature extremes being less frequent and severe.
- Between 1901 and 2018, global mean sea level increased 0.20 [0.15 to 0.25] metres, with the average rate of sea level rise (SLR) increasing from 1.3 [0.6 to 2.1] mm per year between 1904 and 1971, to 1.9 [0.8 to 2.6] mm per year between 1971 and 2006, and further to 3.7 [3.2 to 4.2] mm per year between 2006 and 2018.
- Globally-averaged precipitation over land has *likely* increased since 1950, with a faster rate of increase since the 1980s (*medium confidence*). The frequency and intensity of heavy rainfall events have increased since the 1950s for most land areas where there is sufficient data (*high confidence*). Mid-latitude storm tracks have *likely* shifted poleward in both hemispheres since the 1980s.
- Continued GHG emission will further affect all major components of the climate system and intensify the global water cycle; with each additional increment of warming, changes in extremes will become larger. Global surface temperature will continue to increase until at least mid-century under all emissions scenarios considered, and is *more likely than not* to exceed warming of 1.5 °C in the near term

[3] Findings are formulated as statements of fact with an associated level of confidence or an assessed level of likelihood, using IPCC-calibrated language. Levels of confidence may be expressed using one of five qualifiers: *very low, low, medium, high* or *very high*, and are typeset in italics within the main text. The assessed likelihood of a given outcome may be described as *virtually certain* (99-100% probability), *very likely* (90-100% probability), *likely* (66-100% probability), *about as likely as not* (33-66% probability), *unlikely* (0-33% probability) *or very unlikely* (0-10% probability). Assessed likelihood is also typeset in italics. Unless otherwise stated, values within square parentheses [x to y] are used to indicate the assessed *very likely* range (ie, 90% probability interval) (IPCC 2021). Further information is included in Appendix A.

(2021–2040) under a low GHG emissions scenario (SSP1-2.6), and more likely again at higher emissions scenarios (ie, SSP2-4.5 through SSP5-8.5).

- Many changes in the climate system become larger in direct relation to increased global warming, including the increased frequency and intensity of hot extremes, heavy precipitation, and agricultural and ecological droughts; increased proportion of intense tropical cyclones; and reductions in sea ice, snow cover and permafrost. For any given level of warming, every region is projected to increasingly experience multiple, concurrent changes in climatic impact drivers. Risks, impacts and losses will escalate, and climatic and non-climatic risks will increasingly interact, creating compounding and cascading risks that are increasingly complex and difficult to manage.
- Some future changes with long response timescales (eg, decades or longer) are unavoidable/irreversible, although they can be limited through rapid, significant and sustained reductions in GHG emissions. For example, SLR is *virtually certain* to continue until at least 2100, and there is *high confidence* of continued rise for centuries thereafter, due to deep ocean warming and ice sheet melt. The impacts of such changes must therefore be planned for.

3.1 CLIMATE CHANGE PROJECTIONS FOR NEW ZEALAND

Natural variation has always played a part in New Zealand's climate and will continue to do so; however, climate change is expected to shift the range and pattern of this variability (MfE 2020b). In 2018, the New Zealand Ministry for the Environment (MfE) published their report *Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment* (MfE 2018). These projections drew heavily on global climate model simulations from the IPCC's earlier *Fifth Assessment Report (AR5)* (IPCC 2013), together with New Zealand regional climate modelling undertaken by the National Institute of Water and Atmospheric Research (NIWA) by downscaling outputs from IPCC AR5 models (also referred to as the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations). The more recent *AR6* report (IPCC 2023) features updated understanding of climate systems and climate change based on an updated set of climate models and projections (CMIP6 simulations), and uses a new way to forecast emissions patterns (eg, Shared Socioeconomic Pathways (SSPs) rather than Representative Concentrations Pathways (RCPs))[4]. However, the IPCC Assessment Reports are primarily global assessments, with global-regional scale summaries (eg, for Australasia); whilst associated sub-regional maps and summaries are available for the New Zealand and Tasman Sea region[5], the data provide limited information on projected change at a level that is useful for local assessment.

The unique and varied geography of New Zealand and the influence of local climate phenomena such as the El Niño Southern Oscillation means that downscaling of global climate models to detailed regional models is required to understand spatial variation in climatic impact-drivers. Updated local-scale projections for New Zealand are currently being

[4] The differences between SSPs and RCPs are described briefly in Appendix A.
[5] https://interactive-atlas.ipcc.ch/

prepared using the AR6/CIMP6 climate models, and are expected to be published in 2024, with detailed assessments of those projections to follow (Bodeker et al. 2022). In the interim, a combination of documents can be used to understand atmospheric climate change projections for New Zealand: Bodeker et al. (2022) distils the New Zealand-relevant information from the AR6 report (specifically, the data from Working Group 1, IPCC 2021) and the associated interactive maps and atlases. However, Bodeker et al. (2022) note that the new knowledge from AR6 is unlikely to fundamentally change the existing projections for New Zealand, thus the projections described in the Ministry for the Environment (2018) report can continue to be used to summarise climate change projections utilising regional downscaling.

With regards to sea level rise and coastal hazards, the Ministry for the Environment first published its *Coastal Hazards and Climate Change: Guidance for Local Government* in 2017 (MfE 2017) to support the assessment of hazard, risk and vulnerability, and associated decision-making. The recent update to this guidance (MfE 2022, 2024) incorporates updated sea level rise projections for New Zealand based on data from *AR6* that had been downscaled to New Zealand, combined with data on vertical land movement for New Zealand coastlines. These locally-relevant projections for relative sea level rise stand to better inform local and regional planning decision-making (MfE 2024).

The following section is intended as a high-level summary of the projected climate change effects and outcomes in New Zealand. The main features of these projections are summarised in Table 5 for quick reference, with additional detail in the following subsections. Detailed temporal and spatial patterns and magnitudes of temperature and precipitation change are described in detail in MfE (2018).

Table 5: Main features of New Zealand climate change predictions.

Climate variable	Nature of change	Magnitude of change	Spatial or seasonal variation
Mean temperature	Progressive increase with concentration. Only for RCP2.6 does the warming trend peak then decline.	By 2040, from +0.7°C (RCP2.6) to +1.0°C (RCP8.5) By 2090, +0.7°C to +3.0°C By 2110, +0.7°C to 3.7°C	Warming is greatest at higher elevations. Warming greater over summer/autumn, and least over winter/spring.
Minimum and maximum temperatures	As per mean temperature	Maximum increases faster than minimum. Diurnal range increases by up to 2°C by 2090 (RCP8.5)	Warming is greatest at higher elevations, particularly marked for maximum temperature
Daily temperature extremes: hot	Increase in number of hot days (maximum temperature ≥25°C)	By 2040, a 40% (RCP2.6) to 100% (RCP8.5) increase. By 2090, a 40% (RCP2.6) to 300% (RCP8.5) increase.	Percentage changes similar in different locations, but number hot days increase in the hottest regions.
Daily temperature extremes: cold	Decrease in number of cold nights (minimum temperature ≤0°C)	By 2040, a 30% (RCP2.6) to 50% (RCP8.5) decrease. By 2090, a 30% (RCP2.6) to 90% (RCP8.5) decrease	Percentage changes similar in different locations, but number cold days decrease in the coldest regions.
Mean precipitation	Varies around the country and with season. Annual pattern of increases in west and south of New Zealand, and decreases in north and east.	Substantial variation around the country, increase in magnitude with increased emissions scenario.	Winter decrease in Gisborne, Hawkes Bay, Canterbury. Winter increase in Nelson, West Coast, Otago, Southland. Spring decrease in Auckland, Northland and Bay of Plenty.
Daily precipitation extremes: dry days	More dry days throughout the North Island and inland South Island	By 2090 (RCP8.5), up to 10 or more dry days per year (a ~5% increase).	Increase in dry days is most marked in the north and east of North Island, during winter and spring.
Daily precipitation: very wet days	Increased moderately extreme daily rainfall, especially where mean rainfall increases	More than 20% increase in 99th percentile of daily rainfall by 2090 (RCP8.5) in southwest of South Island. A few percent decrease in north and east of North Island.	Increase in western regions and in south of South Island. Decrease in extremes in parts of northern and eastern North Island.
Very extreme precipitation events: greater than 2-year average recurrence interval	Increase everywhere	Percentage increase per degree of warming ranges from 5% for 5-day duration events to 14% for 1-hour duration events.	Little robust regional variability. Possibly larger increases in the very north and very south of the country.
Snow	Decrease.	Snow days per year reduce by 30 days or more by 2090 (RCP8.5)	Larger decreases confined to higher altitudes or southern regions of South Island.
Drought	Increase in severity and frequency	By 2090 (RCP8.5), up to 50mm increase in potential evapotranspiration deficit.	Increases are most marked in already dry areas.

Table 5 continued. Main features of New Zealand climate change predictions.

Climate variable	Nature of change	Magnitude of change	Spatial or seasonal variation
Pressure and air circulation	Varies with season	Generally, the changes are only a few hectopascals, but spatial pattern matters	More northeasterly airflow in summer. Stronger westerlies in winter.
Extreme wind speeds	General increase	Up to 10% or more in some parts of the country	Most robust increases occur in southern half of the North Island and throughout the South Island
Storms	Likely poleward shift of mid-latitude cyclones; possible small reduction in frequency	More analysis is needed	
Solar radiation	Varies around the country and with season	Seasonal changes generally lie between -5% and +5%.	By 2090, the West Coast (RCP8.5) shows the largest changes: summer increase (5%) and winter decrease (5%).
Relative humidity	Decrease overall	Up to 5% or more by 2090 (RCP8.5), especially in the South Island.	Largest decreases in South Island in spring and summer
Sea level rise[6]	Increasing, with rate of SLR accelerating. Will result in increased frequency of nuisance and extreme coastal flooding, and permanent inundation	By 2100, SLR will increase 0.4m (SSP1-2.6) to 1.1m (SSP8.5H$^+$) compared with 1995-2014 average. By 2150, an increase of 0.7m (SSP1-2.6) to 2.0 (SSP8.5H$^+$)	Relative or net SLR will vary spatially due to the influence of local vertical land movements.

Reproduced from MfE (2018), based on regionally downscaled predictions from AR5 climate models.

[6] From MfE (2022).

3.2 TEMPERATURE

3.2.1 Mean air temperature

There is growing evidence for increasing air temperatures in New Zealand: mean annual air temperature increased 1.1 °C between 1909 and 2016, with seven of the nine years between 2013 and 2021 amongst the warmest on record, including 2021 as the highest on record (Bodeker et al. 2022). Projections from AR6 suggest that annual mean air temperature for New Zealand, and Australasia as a whole, will increase during the 21st century (*virtually certain*) (Table 6). The extent of warming increases with time and the strength of radiative forcing, with a sustainable emissions scenario (ie, SSP1) showing stabilisation of temperature through the end of the century, and an intensive development scenario (SSP5) showing accelerated warming (Bodeker et al. 2022). The increase in air temperature in New Zealand is projected to be slightly lower than the global average, due to the influence of the surrounding oceans on New Zealand's climate (Bodeker et al. 2022). There is a seasonal pattern to warming projections, whereby warming is greater for the summer period than for winter or spring (MfE 2018; Bodeker et al. 2022).

Regional climate model projections allow for detailed representation of physical processes and local biogeography that impact climate locally. Detailed projections for both seasonal and annual mean temperatures across 15 New Zealand regions are provided in MfE (2018). Overall, they show that a rise in temperature above present day is *virtually certain* (99-100%) for all regions by 2040 and 2090, with the exception of the South Island under a low emissions scenario (RCP2.6), where warming is considered *very likely* (90-100%). Regional temperature projections are relatively uniform across the country but do show a small gradient from north to south and east to west, with the greatest rates of warming in the north-eastern North Island (MfE 2018). Warming is generally less over coastal areas, being tempered by cooler ocean temperatures, and greatest over inland areas and at higher elevations (MfE 2018).

Table 6: Projected changes in annual mean air temperature (over land and sea) for the New Zealand region (over land and sea), relative to the mean for the period 1995-2014.

Emissions scenario	Mid-century	End of Century
SSP1-2.6	+0.75 °C [0.39 to 1.06 °C]	+0.8 °C [0.47 to 1.46 °C]
SSP2-4.5	+1.0 °C [0.60 to 1.32 °C]	+1.6 °C [1.03 to 2.26 °C]
SSP5-8.5	+1.3 °C [0.91 to 1.66 °C]	+3.1 °C [2.20 to 4.05 °C]

Values in parentheses indicate the 10-90 percentile range spanned by the ensemble of CMIP6 models.

Reproduced from Bodeker et al. (2022).

3.2.2 Minimum and maximum daily temperatures

Dynamical downscaling from regional climate models provides detail on daily temperature fluctuation (MfE 2018). In general, as the average temperature increases, so too does the projected number of days where the maximum temperature exceeds 25 °C, while the number of days where the minimum temperature falls below 0 °C decreases. Trends for both minimum and maximum daily temperature are positive across all 15 regions of New Zealand, although there is regional variation. Under RCP8.5, the number of hot days in different regions may increase by 34 to 135% by 2040, and 128 to 634% by 2090 (MfE 2020b). The frequency of cold days (or rather, frosty nights) is projected to decline on average 49% by 2040 and 86% by 2090 at RCP8.5 (MfE 2020b).

Maximum daily temperatures are projected to increase more rapidly than minimum daily temperatures, resulting in an increase in diurnal temperature range. This increase in daily temperature range will be largest in spring and summer over the eastern North Island and much of the South Island. The northern North Island may see a decrease in diurnal temperature range however, as minimum temperatures increase more rapidly than daily maximum temperatures (MfE 2018).

3.2.3 Hot and cold temperature extremes

New Zealand has experienced an increasing frequency and severity of hot extremes since the 1950s (*likely)* (Bodeker et al. 2022), with the number of annual heatwave days increasing at 18 of 30 monitored sites around New Zealand between 1972 and 2019 (MfE and Stats NZ 2020). Conversely, there have been less frequent and intense cold extremes since the 1950s (*likely*) (Bodeker et al. 2022), with the number of frost days decreasing at 12 of 30 monitored sites during the 1972-2019 period (MfE and Stats NZ 2020).

As annual and seasonal mean temperatures increase over time, similar changes in temperature extremes would be expected (ie, an increase in high temperature extremes and a decrease in low temperature extremes). Indeed, AR6 projects an increased frequency and intensity of annual hottest daily maximum temperature for New Zealand, and a decrease in the frequency and intensity of the annual coldest daily minimum temperature; the extent of these changes is predicted to be more pronounced as the extent of overall warming increases (ie, the changes become larger with the shift from 1.5 to 2 to 4 °C of overall warming) (Bodeker et al. 2022).

MfE (2018) note that natural variability and the influence of weather patterns such as El Niño make it difficult for climate models to predict trends for hot and cold extremes, and that land-atmosphere feedback strongly modulates extremes on a regional and local scale. Regional climate modelling was used to estimate the number of ‘high temperature’ days (≥25 °C) and ‘low temperature’ days (or nights, ≤0 °C) per year across 15 regions of New Zealand. Hot days are forecast to increase across the country at all RCPs, with the increase being most pronounced in northern New Zealand (MfE 2018). For example, by 2090, the Auckland region is expected to increase from 19.7 by 11 days a year for RCP2.6, and by 70 days for RCP8.5; while Southland is projected to increase from 7.6 to 9.7 at RCP2.4 and 24.0 (the same as Northland, currently), under RCP8.5. The frequency of cold days (more accurately, cold nights) decreases across the country, ranging from a reduction of approximately 50% at 2090 under RCP2.6, to 70-80% reduction throughout the South Island at RCP8.5.

3.3 PRECIPITATION

3.3.1 Mean rainfall

Historical data suggests that increases in annual rainfall have been observed between 1960 and 2019 in the south and west of the South Island and the east of the North Island, while the northeast of the South Island and western and northern North Island have experienced decreasing rainfall, although in general these trends are not statistically significant (MfE and Stats NZ 2020; Bodeker et al. 2022).

Projected changes in mean annual rainfall show a marked seasonality and variability across regions, showing a similar pattern to observed trends, with an increase in annual precipitation in the south and west of New Zealand (*medium confidence*) (Bodeker et al. 2022). For a number of regions, there is no clear direction of any change in rainfall, although where changes are projected, the magnitude of change (both positive and negative) generally increases with the time and strength of radiative forcing (MfE 2018). Seasonal projections suggest winter and spring rainfall will increase in the south and west of the country (*medium confidence*), with less rainfall in the east and north, caused by increased westerly winds over New Zealand (MfE 2018; Bodeker et al. 2022). The greatest changes are projected for the West Coast, where winter rainfall may increase up to 30% under RCP8.5 by 2090 (MfE 2018). Summer rainfall will increase in the east of both the North and South Islands, with reduced rainfall in the west and central North Island (me*dium confidence*) (Bodeker et al. 2022).

3.3.2 Precipitation extremes

Data presented in MfE (2018) describes projections for both high and low precipitation extremes. The number of dry days (defined as <1 mm rainfall) is projected to increase with time and RCP for much of the North Island and high-country inland regions of the South Island, and decreases on the west and east coastal regions of the South Island; these changes are consistent with projected trends in mean rainfall (MfE 2018).

The frequency of moderately extreme rainfall (determined from the 99th percentile of precipitation on days in which rain is recorded) is *likely* to increase over much of the South Island with time and increasing RCP. Changes in the frequency of moderately extreme rainfall in the North Island are projected to be small and erratic; this is likely to reflect, at least in part, the relatively short period (20 years) of data from which extremes are modelled (MfE 2018). Additional simulations predict that the magnitude of rare rainfall events (with return periods >2 years) increases in most regions, particularly for short-duration events (<6 hours) (MfE 2018).

3.3.3 Flooding

There is *medium confidence* of an increase in river flooding (Bodeker et al. 2022), with projections indicating that the 1-in-50-year and 1-in-100-year flood peaks in many parts of the country could increase 5-10% by 2050 (noting, however, that there is large variation between models and emissions scenarios). A decrease in return periods for specific flood levels is also predicted (Bodeker et al. 2022). Rising sea levels and groundwater tables will also interact with changes in precipitation patterns to significantly impact on both general and river flooding (MfE 2023). For example, a modest sea level rise of 0.3-0.4m would convert what is currently a rare storm-tide inundation (eg with a 1% annual exceedance probability) to an event that would occur on average once a year (MfE 2017).

3.3.4 Landslides

The potential for landslides and rockslides increases with increases in total precipitation rates and intensity. The occurrence of landslides is therefore projected to increase in areas where increases in precipitation are projected (*low confidence*) (Bodeker et al. 2022).

3.4 DROUGHT

Historical data shows that trends in meteorological, agricultural and hydrological drought in New Zealand are inconsistent, with some regions showing increased drying and others decreased drying (MfE and Stats NZ 2020; Bodeker et al. 2022). However, projections from AR6 show that aridity is projected to increase in the north and east of New Zealand (*medium confidence*) and decrease in the south and west (*medium confidence*) (Bodeker et al. 2022).

Regional climate modelling suggests that the number of dry days (ie, <1mm precipitation) will increase throughout the North Island and inland areas of the South Island, with the greatest increase – up to 10 additional dry days per year by 2090 at RCP8.5 – seen in the north and eastern North Island during winter and spring. Drought severity[7] is projected to increase in most of the country, except for Taranaki, Manawatu, Southland and West Coast, and drought intensity[8] is projected to increase with radiative forcing and time. Changes in potential evapotranspiration deficit (PED), a measure of drought intensity and duration, is also projected to increase considerably, especially for drought-prone northern and eastern North Island and northeastern and central areas of the South Island in the lee of the Main Divide, indicating long-term drying (MfE 2018; Bodeker et al. 2022).

3.5 STORMS

It is *likely* that the global frequency of tropical and extra-tropical cyclones will either decrease slightly or remain unchanged through to 2100 (MfE 2018). However, it is *likely* that the average and maximum rain rates and wind speeds associated with tropical cyclones, extra-tropical cyclones and atmospheric rivers, and the occurrence of severe convective storms in some regions (*high confidence*), will increase as global temperatures increase (MfE 2018; Bodeker et al. 2022). As such, these storms may have greater potential to cause damage when making landfall (MfE 2018). There is *low confidence* in region-specific projections for storm frequency and intensity in New Zealand, which can show high levels of variation between locations (MfE 2018).

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[7] Drought severity is how dry a drought event is.

[8] Drought intensity is a measure of severity, scaled by its duration. It is measured in potential evaporation deficit (PED), the cumulative sum of the difference between potential evapotranspiration and precipitation over a 12 month period.

3.6 WIND AND PRESSURE

Mean wind patterns are projected to become more north-easterly over summer, especially in the south-east of New Zealand, with westerly winds becoming more intense over winter (*low confidence*) (MfE 2018, 2023; Bodeker et al. 2022). Downscaling from regional climate models project that for most RPCs and time periods, the southern half of the North Island and all of the South Island will have stronger extreme daily wind speeds – especially in the eastern South Island, with an increase of 10% or greater possible in Marlborough and Canterbury by 2100 under RCP8.5. A decrease in extreme winds is projected for the North Island from Northland to Bay of Plenty (MfE 2018).

3.7 ENSO AND SAM PATTERNS

The future of the El Niño Southern Oscillation (ENSO) cycle remains uncertain, as to its effects on the Aotearoa New Zealand region. However, ENSO is expected to continue as a dominant feature of climate variability (Bodeker et al. 2022). The Southern Annular Mode (SAM) is the north-south movement of the westerly jet stream and storm track across the Southern Ocean, and for the past forty years has tended towards a 'positive state' linked to higher surface pressure and warmer, drier conditions for most regions. Projections for future SAM are uncertain and will depend on GHG emissions and ozone hole recovery; high emission scenarios are like to favour a continuing positive stage, where low emissions and ozone recovery will tend towards a negative SAM pattern, associated with more unsettled weather, with cooler conditions and higher precipitation in many areas (although drier in eastern North Island and northeastern South Island) (Bodeker et al. 2022).

3.8 FIRE

Days with very high and extreme fire weather increased at 12 of 28 monitored sites and decreased at 8 between 1997 and 2019 (MfE and Stats NZ 2020; Bodeker et al. 2022). On average, the four main drivers of wildfire– increased temperature, decreased relative humidity, increased wind speeds and decreased rainfall – are all expected to change in ways that promote an increase in wildfire risk (MfE 2020b). Fire weather indicators are projected to increase in many parts of New Zealand (*medium confidence*) (Bodeker et al. 2022), with Watt et al. (2019) projecting the number of very high to extreme fire risk days could increase by up to 83% by 2090, particularly along the eastern coasts.

3.9 SEA LEVEL RISE

Recent projections show that global sea level rise is accelerating due to the increasing rate of loss of land ice (ie, glaciers and ice sheets), in particular the Greenland and Antarctic ice sheets, and that coastal risks are *virtually certain* to increase through 2100 due to already committed sea level rise (IPCC 2021).

In New Zealand, sea levels rose 0.21 metres on average between 1901 and 2020, with the rate of SLR approximately doubling since 1960 (MfE 2024). Data shows that New Zealand has experienced an increase in nuisance and extreme coastal flooding since 2000 as a result of increasing sea levels, and this is projected to become more frequent by mid-century with continued SLR (*very high confidence*) (MfE 2017, 2022, 2024). Projections show that by 2100, mean sea levels may rise by between 0.4 and 1.1 metres relative to a 1995-2014 baseline, depending on carbon emissions and polar ice sheet dynamics, increasing to between 0.7 and 2.0 metres by 2150 (Table 7) (MfE 2022).

In addition, much of the New Zealand coastline experiences some degree of vertical land movement (VLM). In areas (local or regional) where coastal land is subsiding, sea level rise will be exacerbated, while regions experiencing uplift will experience lesser impact from SLR. Areas that exhibit significant subsidence and thus may be at greater risk from SLR include the southern North Island (Wairarapa, parts of Hawkes Bay, Wellington) and the Northern South Island (Tasman Bay, Collingwood, eastern Marlborough, the Kaikoura Peninsula), while the central Bay of Plenty, Bluff, Fiordland, South Westland, East Cape and parts of the Coromandel exhibit significant uplift (MfE 2022, 2024). Detailed projections for ‘relative sea-level rise’ that accounts for both SLR and local VLM were released in 2022 and are available online.[9]

Table 7: Projections for national sea level rise (above a 1995-2014 baseline), based on *medium confidence* projections for a range of emissions scenarios.

Year	Emissions scenario				
	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP-8.5H+
2005*	0	0	0	0	0
2020	0.06	0.06	0.06	0.06	0.09
2030	0.11	0.11	0.11	0.11	0.15
2040	0.15	0.16	0.16	0.18	0.23
2050	0.20	0.22	0.24	0.26	0.32
2060	0.24	0.28	0.31	0.34	0.43
2070	0.29	0.35	0.40	0.44	0.57
2080	0.34	0.42	0.50	0.56	0.72
2090	0.38	0.49	0.61	0.69	0.90
2100	0.44	0.57	0.73	0.83	1.09
2110	0.50	0.66	0.83	0.95	1.28
2120	0.55	0.74	0.95	1.08	1.47
2130	0.60	0.81	1.07	1.21	1.66
2140	0.64	0.89	1.19	1.34	1.84
2150	0.68	0.96	1.30	1.46	2.01

*mean sea level for the period 1995-2014 used as baseline.

Reproduced from MfE (2022).

[9] https://www.searise.nz/maps-2

3.10 GROUNDWATER

Climate change will impact the availability and recharge of groundwater and water table elevation. There are no projections for groundwater levels under AR6, however regional assessments show a decrease in available groundwater under RCP4.5 and RCP8.5, with projections for groundwater recharge and level generally following rainfall projections (Bodeker et al. 2022).

3.11 OTHER EFFECTS

3.11.1 Glacier volume

Estimates of glacial volume between 1978 and 2020 suggest a 35% loss, with studies suggesting the rate of glacial thinning during 2015-2019 was seven-fold higher than in 2000-2004. New Zealand glaciers are projected to lose a further 36±44% and 77±27% under RCP2.6 and RCP8.5 respectively, relative to their 2015 mass (Bodeker et al. 2022).

3.11.2 Seasonal snow

The overall cover and depth of snow is projected to further decrease in New Zealand, with a projected decline in the number of annual 'snow days'[10] in all regions, most notably in areas that currently experience a higher number of snow days, such as the high-country and inland basins of the South Island, which may experience 30 fewer snow days by 2100 at RCP8.5 (MfE 2018; Bodeker et al. 2022). There is, however greater, potential for heavy snowfall events in in special circumstances, as a warmer atmosphere is capable of holding more moisture, to be released as snow when temperatures do fall (MfE 2018). Snow storage will also reduce due to warmer ambient temperatures, and with effects on the seasonality of snow melt and river flow (MfE 2018).

3.11.3 Relative humidity and solar radiation

Nelson-Marlborough and Central Otago currently experience the highest levels of solar radiation during summer, with peak levels occurring in the northern North Island and Nelson-Marlborough over winter. Regional climate models project summer levels of solar radiation may increase across the country, with the exception of coastal Canterbury, while over winter, levels may decrease in the western North Island and west and south of the South Island, and increase in the eastern North Island (MfE 2018).

Relative humidity may reduce almost everywhere as temperatures increases, especially in the South Island (MfE 2018); the exception is likely to be the West Coast, especially over winter, as a result of increased rainfall, and reduced sunshine (MfE 2018).

[10] Snow days were defined as precipitation days where the mean temperature was below freezing.

4. CLIMATE CHANGE IMPACTS ON WASTEWATER SYSTEMS

4.1 THE IMPACTS OF CLIMATE CHANGE HAZARDS ON MUNICIPAL WASTEWATER SYSTEMS

Well-functioning wastewater systems – including wastewater collection and conveyance networks, pump stations and treatment plants, as well as onsite waste management systems – provide a critical service to society and play a key role in protecting environmental and public health (Howard et al. 2016; Kirchoff and Watson 2019). Different elements of the wastewater network are vulnerable to different aspects or outcomes of climate change, also known as climate hazards. The impacts of these climate change hazards on wastewater systems may range from minor changes in treatment efficiency to widespread disruption or failure of services (Hyde-Smith et al. 2022).

The impacts of climate change on the wastewater sector may be direct or indirect (Zouboulis and Tolkou 2015; Diack et al. 2022). Direct impacts affect the functionality and operation of the wastewater network, such as damage to infrastructure resulting from hydraulic overloading or flooding, or reduced water flow through a network due to drought or water conservation. Indirect impacts are more difficult to pre-empt but are likely to be extensive, and can include treatment inefficiency and associated cost, implications for wastewater reuse, or increased sensitivity of receiving environments to the adverse impacts of effluent discharge (Diack et al. 2022). Impacts may emerge abruptly (eg, wet-weather overflows) or occur slowly (eg, corrosion of pipes and pumps), and be short-term in nature (eg, power outages) or require prolonged and extensive remediation (eg, pipe replacement or WWTP relocation) (Lawrence et al. 2020; Hyde-Smith et al. 2022). There may be multiple impacts happening simultaneously, at the same and/or multiple locations (Lawrence et al. 2020). While there is the potential for both positive and negative impacts of climate change on wastewater and sanitation systems (Howard et al. 2016), the majority of studies have focused on understanding the significant potential for negative impacts, which may have profound and far-reaching implications for human and ecological health.

The key climate change hazards expected to have direct impacts on wastewater systems in New Zealand include sea level rise, storm surges and coastal erosion, changing precipitation patterns, coastal and inland flooding, and increases in temperature and drought frequency (MfE 2020b). However, the impacts of climate change on wastewater networks and treatment systems will be experienced somewhat differently around the country due to geographical variation in climate and some projected climate changes, differences in the design and condition of the wastewater network, different treatment technologies, and the influence local geography that could minimise or exacerbate risk (eg, proximity to the coast or river/flood zone). Key impacts on the wastewater network associated with these climate hazards are discussed below, and summarised in Table 8.

4.1.1 Impacts of more intense and/or prolonged rainfall

Increasing frequency, intensity and/or duration of rainfall are primary concerns for wastewater networks, as stormwaters flow directly into the network through connections with the stormwater system (eg, in combined networks or through inappropriate cross connections) or through surface openings such as manholes, or infiltrates the sewer system through cracked pipes or leaky joins (Flood and Cahoon 2011; Zouboulis and Tolkou 2015; Hughes et al. 2021). Whilst the design of the sewage collection system assumes some degree of inflow and infiltration (Flood and Cahoon 2011), it is possible – and in some systems, commonplace – for this increase in flow to hydraulically overload sewer pipes and/or pump capacity, leading to the overflow of sewage into the environment, or back-up into pump stations and inspection chambers (Hyde Smith et al. 2022). Numerous studies have linked an increase in the frequency or volume of sewer overflow events with higher pollutant concentrations in receiving waters (Weyrauch et al 2010; Abdellatif et al. 2014; Kleidorfer et al. 2014; Goore Bi et al. 2015; Hyde-Smith et al. 2022). Excessive inflow and infiltration can also mechanically strain collection systems, causing pipes to rupture and sewage to leak into the surrounding soils, and potentially into groundwaters (Blumenau et al. 2011; Flood and Cahoon 2011; Diack et al. 2022). Sands, silts and debris carried in stormwaters can cause sedimentation and blockages within the wastewater conveyance system, again with the potential to cause overflows or to damage pipes or pumps (Langefeld et al. 2013; Hyde-Smith et al. 2022; Li et al. 2023).

The increased volume of wastewater within the network also stands to overwhelm the hydraulic capacity of the WWTP, leading to the discharge of untreated or inadequately treated wastewater to the environment, while excessive mechanical strain or the presence of silts and debris can cause physical damage to infrastructure such as screens (Hughes et al. 2021). Further, inflow and infiltration will alter the composition of influent wastewater through dilution, the presence of stormwater-associated contaminants, and changes in in-sewer processes (Wilen et al. 2006). The specifics of these changes are heavily influenced by nature of the rainfall event (eg, duration, intensity, antecedence dry period), the wastewater network (eg, separated or combined with storm sewers, extent of infiltration) and the catchment (eg, size, land use); both increases and decreases in total suspended solids (TSS), biological demand (BOD), chemical oxygen demand (COD) and ammonia are reported for variable combinations of these factors (Lessard and Beck 1990; Rouleau et al. 1997; Giokas et al. 2002; Wilen et al. 2006; Mines et al. 2007; Langefeld et al. 2013; Rashid and Liu 2020). Wastewater properties, including ionic strength, temperature, pH and organic content affect biological processes at the WWTP such as nitrification, denitrification and degradation of organic materials, as well as affecting the physical properties and behaviour of sludge flocs and particulates in the water column, and may therefore affect treatment efficacy or efficiency (Wilen et al. 2006; Plosz et al. 2009). Changes in hydraulic conditions within the WWTP may also affect effluent quality due to reduced retention time and impairment of processes such as settling of sediments (Giokas et al. 2002; Plosz et al. 2009; Phillips et al. 2012; Hughes et al. 2021). Research has shown that WWTP effluent quality can deteriorate during periods of high inflow into the plant; while contaminant concentrations may be reduced through dilution, overall contaminant loads are usually higher in rainfall-impacted effluents due to the presence of stormwater contaminants and reduced treatment (Hughes et al. 2021).

All types of wastewater networks are vulnerable to impacts associated with increased rainfall, though the severity of impacts will differ between different networks. For example, combined stormwater and wastewater systems will be most vulnerable since they directly receive stormwaters during rainfall events, while separated systems will be less so, especially relatively new or well-maintained systems that will experience less infiltration (Hughes et al. 2021; Li et al. 2023). Pressurised networks will also be less vulnerable, since maintenance issues such as cracking or corrosion result in a loss of pressure that impacts system performance, meaning these issues tend to be rapidly identified and addressed (Hughes et al. 2021).

Flooding associated with periods of intense rainfall (ie, pluvial flooding[11], but potentially fluvial flooding[12] for WWTPs located in proximity to rivers) also presents a direct risk to sewer and treatment plant infrastructure and operation. In particular, wastewater treatment plants are usually located in low-lying areas to facilitate efficient conveyance of sewage to, and discharge from the plant; however, this can also be a contributing factor to increased flood risk for WWTPs. Floodwaters may inundate a WWTP causing disruption or cessation, of services; for example, the Awatoto WWTP in Napier required complete shutdown and opening of the bypass valve after being inundated by floodwaters during Cyclone Gabrielle.[13] Flooding-related power outages can cause the failure of pumps within pressurised sections of the sewer network resulting in backflow and/or localised flooding, or the failure of equipment within the WWTP, especially in more technically-advanced or mechanised plants (eg, aeration systems), resulting in reduced treatment efficacy (Hughes et al. 2021; Hyde-Smith et al. 2022). Water damage to electrical systems within the network can mean systems remain offline even after power itself has been restored.

Soil subsidence and/or land slips associated with heavy rainfall have the potential to cause significant damage or rupture of sewer pipes, resulting in untreated sewage leaking to the environment. Flooding or slips can also disrupt operational procedures if roading and related infrastructure is damaged in such a way as to prevent the necessary personnel or equipment access to the treatment plant, including in both the short term (eg, day-to-day operation or securing facilities during extreme weather events) and longer term (eg, faecal sludge management) (WHO 2019).

4.1.2 Impacts of declining rainfall or drought

Reductions in rainfall or periods of drought may adversely affect wastewater conveyance and treatment systems in a number of ways, through changes in both wastewater quantity and quality. Reduced rainfall will reduce inflow and infiltration into the wastewater network, reducing overall wastewater volume and flow. In addition, efforts to reduce water usage during periods of drought through water conservation behaviours (eg, short showers or reduced toilet flushing) and indoor efficiency measures (eg, installation of water-efficient

[11] Pluvial flooding, also known as surface water flooding, occurs when an urban drainage system is overwhelmed and water flows out into the streets and nearby structures and spaces. It occurs independently of an overflowing waterbody.

[12] Fluvial flooding, also known as riverine flooding, occurs when the water level in a river, lake or stream rises and breaks its banks, overflowing onto adjacent low-lying areas.

[13] https://www.nzherald.co.nz/hawkes-bay-today/news/cyclone-gabrielle-the-inside-story-of-how-workers-saved-napier-from-a-catastrophic-wastewater-failure/VTSQDHWQJFCRND24SPOQFCQ7MQ/.

plumbing fixtures and appliances) will further reduce the volume of water entering the network, although not the contaminant load (Zouboulis and Tolkou 2015; Chapelle et al. 2019; Hyde-Smith et al. 2022; Li et al. 2023). This reduced water volume results in a ‘higher strength’ wastewater within the network, with higher contaminant concentrations and greater salinity (Zouboulis and Tolkou 2015; Tran et al. 2017; Hyde-Smith et al. 2022). These changes in wastewater quality make sewer pipes and pumps more susceptible to corrosion, especially when increasing ambient temperature also occurs (Zouboulis and Tolkou 2015; Li et al. 2023). In addition, reduced flow through the conveyance system can also allow solids to accumulate, increasing the risk of blockages and associated overflow events or pipe damage, and therefore increasing requirements for network cleaning or replacement of parts (Zouboulis and Tolkou 2015; WHO 2019; Hyde-Smith et al. 2022). Residence time of wastewaters within the sewer network are increased due to low flow, potentially leading to stagnation; together with the buildup of solids, this can result in oxygen-poor conditions that encourage the growth of anaerobic bacteria that produce compounds such as hydrogen sulfide, accelerating the deterioration of concrete and steel pipes and pump station components, and causing highly unpleasant, nuisance odours (Chapelle et al. 2019; Hyde-Smith et al. 2022; Li et al 2023).

As described above for increased rainfall, changes in influent wastewater quality and quantity may also present challenges at the WWTP and its ability to effectively treat wastewaters. Under conditions of reduced rainfall or drought, the increased strength of influent wastewater may cause issues with corrosion of treatment plant elements such as pumps, valves or tanks (Tran et al. 2017; Chapelle et al. 2019). Higher concentrations of contaminants in influent wastewater are often reflected in higher concentrations in treatment plant effluent, standard wastewater processes are not designed to remove many of these contaminants – especially emerging contaminants – effectively (Tran et al. 2017). In addition, changes in the physicochemical characteristics of the wastewater may adversely affect microbial communities responsible for biological treatment processes, or physical removal processes such as sedimentation, further reducing treatment efficacy. The need to treat a more concentrated wastewater matrix, together with changes in process efficiency, may have implications for treatment costs or require additional processes be installed to help attain requisite effluent quality.

In addition to impacts resulting from changes in wastewater quantity or quality, reduced rainfall and associated changes in aridity and humidity can change the moisture content within soils, leading to soil movement (eg cracking seen during droughts) and increasing the risk of pipe cracking and joint breakage, especially where soils have a high clay content or systems are poorly maintained. Damage to pipes could then result in wastewater leaking into the environment (Pocock and Joubert 2018; WHO 2019; Hyde-Smith et al. 2022).

New Zealand has yet to experience drought conditions severe enough to impact wastewater systems, however, as drought severity is projected to increase in many areas, so too will exposure of these systems (MfE 2020b). The potential for reduced rainfall and drought conditions to impact wastewater systems can be demonstrated by the 2012-2016 California droughts. A survey of 133 wastewater agencies across the state (Chapelle et al. 2019) found that, as a result of the lack of rainfall and an average 25% reduction in water usage:

- flow through the network and to the WWTPs declined 10-25%, however, some WWTPs reported a 50% reduction in inflow;

- more than 60 WWTPs reported changes in influent and/or effluent quality, including increased BOD, nutrient concentrations, ammonia load, total suspended solids and salinity;
- more than 25% of agencies reported increased solids deposition within the collection system, and 20% reported increased corrosion;
- more than 33% of agencies reported challenges in treating wastewater, including damage to WWTP equipment and reduced efficacy of treatment or disinfection; and
- increased costs associated with treatment, operation and maintenance of the plant and capital improvements to address challenges resulting from low flow and/or changes in influent quality were reported.

Reduced rainfall and periods of drought may also impact receiving environments – particularly freshwater environments, making them more vulnerable to adverse effects associated with wastewater discharge. For example, reduced flow through river systems may reduce their ability to effectively dilute effluents, leading to the contamination of water and biota or increased nutrient loads that can exacerbate algal blooms (Zouboulis and Tolkou 2015; Pocock and Jobert 2018; Chapelle et al 2019). More stringent requirements on effluent quality or the installation of additional treatment processes may be required to protect receiving environments and ensure water quality objectives are met, with concomitant increase in operational costs, particularly where the deterioration of treatment efficacy and effluent quality is also observed (Zouboulis and Tolkou 2015; Pocock and Joubert 2018).

On the other hand, it should also be noted that reduced rainfall may confer some benefits to wastewater systems. For example, the frequency and volume of combined sewer and wet-weather sanitary sewer overflows will be reduced, although this may be offset by the higher concentrations of contaminants present in overflows that occur following prolonged periods of dry weather (Langefeld et al. 2013), and by the reduced capacity of some receiving environments to dilute overflowing wastewaters (Hyde-Smith et al. 2022). Lower groundwater tables associated with reduced rainfall recharge would also increase the vertical separation distance between discharged wastewater (both as treated effluents discharged to land and wastewater leaks) and the water table, reducing the risk of groundwater contamination (WHO 2019; Hyde-Smith et al. 2022).

4.1.3 Impacts of increasing ambient temperatures

The impacts of increasing ambient temperatures on wastewater networks and treatment processes may be both positive and negative (Zouboulis and Tolkou 2015; Li et al 2023). In particular, increasing ambient temperatures may improve the efficiency of certain treatment processes at the WWTP (von Sperling 2007; Zouboulis and Tolkou 2015; WHO 2019). Biological reactions are highly influenced by temperature, and naturally occur faster at warmer temperatures (assuming these remain within the functional range of the microorganism). Climate change-driven increases in ambient temperature, and therefore of wastewater temperature within a WWTP, may therefore increase microbial activity within secondary treatment processes, enhancing the efficiency of contaminants conversion and removal processes, and improving the quality of final effluent (Abdullah and Farahat 2020; Li et al. 2023). However, as not all contaminants are removed by such processes, changes in temperature may only enhance removal of certain contaminants. Increased treatment efficiency may also reduce the energy usage and/or land requirements of a treatment plant, or enable the use of processes that are only appropriate for warmer climates, such as anaerobic reactors (Zouboulis and Toulkou 2015; Hughes et al. 2021; Li et al. 2023). The temperature-sensitivity of treatment processes is greatest for systems that are ‘natural’ and less mechanised (von Sperling 2007; Zouboulis and Toulkou 2015), and changes in temperature are thus likely to be most relevant to the large number of pond-based systems in New Zealand. Processes that have greater technological input such as activated sludge and aerobic biofilm reactors are less dependent on ambient temperature and are thus less likely to be affected (von Sperling 2007; Pocock and Joubert 2018). There may, however, be certain cases where an increase in ambient temperature reduces treatment efficacy or efficiency, though in New Zealand these may be limited and highly seasonal; for example, Plosz et al. (2009) reported an increase in snowmelt due to warmer temperatures reduced the temperature of wastewater entering a treatment plant in Norway and in turn, reduced treatment efficiency (as determined by nitrogen removal).

Increasing temperatures may also have negative effects on the wastewater network. As warmer temperatures increase microbial reaction rates, this includes reactions that produce compounds such as hydrogen sulfide, which accelerates the corrosion of concrete in pipes and other infrastructure around the WWTP (Aghdam et al. 2023; Li et al. 2023). In addition, while domestic wastewater usually has a benign, musty odour, these reactions result in the production of highly unpleasant and potentially toxic gases, including hydrogen sulfide, dimethyl sulfide and methyl mercaptan, with negative impacts for nearby residents and employees of the WWTP (Hughes et al. 2021; Aghdam et al. 2023; Li et al. 2023).

Finally, increasing ambient temperatures may pose a threat to receiving environments, particularly freshwater environments, exacerbating the potential adverse effects of effluent discharge, especially when temperature change co-occurs with reduced rainfall that reduced baseflow**.** For example, increasing temperature may lead to the proliferation of algal blooms or increased survival of pathogens in the environment, presenting both environmental and human health risks (Major et al. 2011; Levy et al. 2018; WHO 2019; Mora et al. 2022).

4.1.4 Impacts of more intense storms

More intense storms may impact wastewater networks in several ways. Intense rainfall associated with storm systems may overwhelm network capacity through inflow and infiltration, leading to sewer overflow, mechanical stress and damage to pipes and pumps, or compromising treatment efficacy and resulting in the discharge of untreated or partially treated wastewater to the environment, as described above. Storm-related floodwaters may also carry high volumes of silt and debris that can cause blockages within the sewer network or damage WWTP infrastructure such as primary screens (Hughes et al. 2021; Hyde-Smith et al. 2022). Flooding-related power outages and damage to electrical equipment can cause the failure of pump stations or other key infrastructure within the WWTP (Hyde-Smith et al. 2022). General inundation of a WWTP may result in loss of services.

High winds associated with storm events also present risks to the wastewater treatment network. High winds can uproot trees, damaging sewer pipes in the process and resulting in sewage leaks and/or potential for infiltration of stormwaters (Hughes et al. 2021). High winds may also damage essential infrastructure such as power lines, causing power outages that directly impact pressurised networks that require pumps to convey wastewater through to the treatment plant. At the WWTP, treatment processes requiring electrical input (eg aerators, pumps for activated sludge processes) may also be compromised by such outages, causing disruption to the operation of the plant and reduced treatment efficacy (Hughes et al. 2021).

As storm systems in coastal areas have the potential to generate significant storm surges, the impacts of storm events must also be considered in the context of the sea level rise and coastal flooding (discussed below) (Major et al. 2011; Zouboulis and Tolkou 2015; Diack et al. 2022). Storm surges are a temporary rise in coastal sea level due to low atmospheric pressure and strong winds, that can physically damage infrastructure through increased inflow and infiltration, inundation, wave action, coastal erosion and corrosion by saline floodwaters, or cause power failures that impact pump station or treatment plant operation and processes (Major et al. 2011; Diack et al. 2022). For wastewater networks discharging to sea, the WWTP and outfall – as the terminal components of the network and thus being located on the coastal margin – may be at significant risk from storm surges. In New Zealand some 64 WWTP, including those of our largest cities – Auckland, Wellington, Christchurch, Tauranga, Dunedin – are all located in coastal areas, and therefore potentially at risk from inundation or damage by storm surges or coastal erosion (Beca et al. 2020; MfE 2020b).

4.1.5 Impacts sea level rise and rising groundwater tables

Sea level rise poses a significant risk to wastewater networks and treatment plants, and may increase the risks and exacerbate impacts associated with other climate drivers such as storm surges, coastal erosion, or coastal or pluvial flooding (Flood and Cahoon 2011; WHO 2019; Hughes et al. 2021; Li et al. 2023; Zhou and Hawken 2023). Many WWTPs are located in low-lying areas along the coast, allowing conveyance and discharge of effluents to occur under gravity thus minimising the reliance on pumps, as well as ensuring efficient discharge of effluents to receiving waterbodies; however, this makes them especially vulnerable to the impacts of SLR (Hummel et al. 2018; Li et al. 2023; Zhou and Hawken 2023). Further, as wastewater networks tend to be highly centralised with little redundancy built in, and are dependent on other infrastructure which may also be at risk, they are particularly vulnerable compared to other coastal infrastructure (Kool et al. 2020; Zhou and Hawken 2023). Approximately 4% of New Zealand's WWTP are located within 1 km of a segment of coastline considered to be highly sensitive to coastal inundation, and 7% within 1 km of coastline considered highly sensitive to erosion (Beca et al. 2020; Kool et al. 2020). Rising sea levels can also raise the coastal groundwater table, which may in turn lead to a rise in inland groundwater tables (Hyde-Smith et al. 2022; Li et al. 2023). Many studies consider the impacts of SLR on infrastructure in relative isolation; few consider the additional impacts of concurrently rising groundwater tables, which can more than double the area inundated by SLR (Hummell et al. 2018). The specific impacts of SLR will depend on the extent of SLR, localised vertical land movement, and the location of the wastewater network and treatment plant (ie, whether coastal or inland) (Flood and Cahoon 2011).

Rising sea levels can cause extensive coastal inundation and flooding (both nuisance and permanent) and coastal erosion, especially when combined with storm surges (as described above) (Kool et al. 2020). Increased inflow from inundation and flooding, and infiltration from rising groundwater tables may add considerable flow to the wastewater network, reducing the effective capacity of the sewer network and leading to increased risk of sewer overflows, or causing blockages or physical damage to pipes and pumps in a similar way as described for rain-associated floodwaters (Flood and Cahoon 2011; Hyde-Smith et al. 2021; Li et al. 2023). Leaking sewage pipes increase the risk of contamination of groundwater, especially as the groundwater table rises as well (Hughes et al. 2021). Similarly, the increased volume of wastewater within the network may challenge the capacity of the WWTP, increasing the risk of overflow of untreated wastewater to the environment, or reducing treatment efficacy or efficiency by reducing residence time or disrupting processes such as settling, as discussed above for rainfall-associated flow. In addition, rising groundwater levels can exert uplift on pipes causing rupture or changes in flow, while inundation of gravity-fed pipes can cause a hydraulic loss of head and pumping pressure, resulting in sewage ponding and backing up in low-lying areas of the network or into homes (Hughes et al. 2021; Zhou and Hawken 2023). Pressurised parts of the network will be more mildly affected by groundwater intrusion or loss of hydraulic head than older, poorly maintained or gravity-fed sections, which may experience increased wear on pumps due to increased pumping requirements or the need to retrofit pumps to certain parts of the network (Zouboulis and Tolkou 2015; Kool et al. 2020; Hughes et al. 2021). Loss of hydraulic head or pressure may also prevent WWTP outfalls from functioning correctly, impeding underwater effluent discharge or allowing backflow of effluents and receiving waters into the plant, requiring more powerful pumps to overcome increased pressure above the outfall location (Hummel et al. 2018; Zhou and Hawken 2023).

The inflow and ingress of saline coastal floodwaters can cause corrosion issues for both steel and concrete components including pipes, pumps and valves across both the conveyance network and at the WWTP, as a result of hydrogen sulfide and chloride formation (Flood and Cahoon 2011; WHO 2019; Hughes et al. 2021; Li et al. 2023). Sulfide gas production is also associated with unpleasant odours (Cahoon and Hanke 2019). The ingress of saline waters into wastewater systems is already being observed in New Zealand with the salinity of wastewater in Dunedin increasing at high tide, for example (Hughes et al. 2021). Changes in the characteristics of influent wastewater – particularly salinity – may also affect the efficacy or efficiency of biological treatment processes, by impacting the functional microbial communities at the treatment plant (eg in activated sludges and biofilms), inhibiting their activity and reducing performance (Cahoon and Hanke 2019; Rodrigues et al. 2021; Li et al. 2022; Li et al. 2023).

Some WWTPs apply biosolids and sludge to land for dewatering, which relies on a groundwater table that is sufficiently deep to allow the infiltration of excess water and attenuation of contaminants. Increased coastal flooding and inundation or a rising groundwater table will greatly reduce (or potentially, completely remove) the capacity of soils to support dewatering without the risk of ponding or contaminant migration into groundwaters (Hughes et al. 2021).

Ultimately, SLR can significantly impact the life expectancy of a wastewater network, with infrastructure at low elevations potentially experiencing permanent inundation and/or significant reduction in functionality, so that it requires the installation of expensive protective structures such as levees, or the relocation of the entire WWTP (Flood and Cahoon 2011; Hummel et al. 2018; Hughes et al. 2021).

Table 8: Summary of potential impacts of key climate hazards for New Zealand on municipal and onsite wastewater treatment systems.

Increased rainfall	
Increased inflow and infiltration into the sewer network	Hydraulic capacity of sewer pipes or pump stations exceeded, leading to overflow of untreated wastewater to the environment or backflow of wastewaters and flooding of inspection chambers and basements
	Mechanical strain on pipes, joints etc causes cracking or rupture, allowing wastewater to leak into surrounding soils.
Silt, sand, debris from stormwater or floodwater enters sewer	Blocked pipes result in the overflow of untreated wastewater to the environment or backflow into inspection chambers
	Sediments or debris cause physical damage or increased wear on components such as pumps, reducing component lifespan or leading to failure
Increased volume of influent wastewater arriving at WWTP	Hydraulic capacity of WWTP exceeded, leading to treatment bypass or uncontrolled overflow, and the release of untreated or partially-treated wastewater to the environment
	Mechanical strain on influent pipes can result in rupture and leaks or spills of untreated wastewater
	Treatment efficacy reduced due to reduced retention time within the WWTP
Changes in characteristics of influent wastewater arriving at WWTP	Sediments and debris in influent can damage WWTP such as screens and pumps, causing loss of function and/or disruption to service
	Treatment efficacy reduced due to the effects on new physicochemical parameters on biological processes (eg biological reactions) and physical processes (eg sedimentation, flocculation)
Flooding and inundation of infrastructure	Flood-related power outages cause failure of pump stations, possibly leading to wastewater backing up in the sewer network
	Flood-related power outages cause the failure of treatment systems (eg aeration, pumps for AS movement etc), leading to reduced treatment efficacy
	Inundation of the WWTP may result in cessation of plant function or widespread dispersion of sewage-contaminated floodwaters
	Inundation of pit latrines or vault toilets, leading to loss of amenity, contamination of floodwater or increased contaminant transport through soils.
Slips, subsidence	Damage or rupture of sewer pipes, leading to leaking of untreated wastewater to the environment.
	Damage to roading or related infrastructure prevents staff/equipment access to the WWTP for both immediate operational requirements and longer-term maintenance requirements (eg faecal sludge management)
Increased base flow through rivers, streams	Greater capacity of the receiving environments to dilute discharged WWTP effluents
Increased soil moisture/saturation	Reduced treatment efficiency for OWMS that rely on unsaturated soils for filtration and attenuation of pathogens and other contaminants
	Reduced capacity of soils to support land-based disposal or sludge dewatering, due to increased mobility of contaminants through saturated soils to groundwater or surface waters

Table 8 continued. Summary of potential impacts of key climate hazards for New Zealand on municipal and onsite wastewater treatment systems.

Reduced rainfall, drought	
Reduced wastewater volumes in sewer network (reduced inflow and infiltration, water conservation)	Low wastewater flow allows settling/accumulation of solids and sediments that can block or damage pipes, leading to overflow
	Reduced frequency and volume of overflow CSO or wet weather SSO events
	Increased residence time and possible stagnation of WW within the sewer, creating anaerobic conditions that promote production of corrosive and malodorous substances
Changes in characteristics of influent wastewater arriving at WWTP	More concentrated wastewater with higher salinity produces compounds that accelerate the corrosion of concrete pipes and metal elements in pumps, valves etc.
	More concentrated wastewater impacts microbial communities at the WWTP, reducing efficiency of biological treatment processes
Reduced soil moisture	Loss of soil moisture and increased aridity increases soil movements that put mechanical stress on pipes, leading to cracked pipes and potential sewage leaks
	Increased capacity of soils to treat discharged effluents from OWSM by improving filtration and contaminant attenuation, and enhancing microbial die-off by desiccation
Reduced base flow through rivers, streams, lower lake levels	Reduced flow through receiving environments make them more vulnerable to adverse impacts of wastewater effluent discharge (eutrophication, algal blooms, contamination of water or kai).
Lower groundwater tables due to reduced recharge	Increased vertical separation distance between groundwater levels and wastewater discharge (sludge dewatering, OWMS
Increasing ambient temperature	
Increasing temperature of wastewater	Increased microbial activity in-sewer and at the WWTP produces higher levels of sulfides and other corrosive that accelerate corrosion of concrete pipes and other plant componentry
	Increased microbial activity in-sewer and at the WWTP produces higher levels of sulfides, mercaptans and other compounds that have highly unpleasant odours
	Increased microbial activity at the WWTP improves efficiency of some treatment processes, increasing removal of some (but not all) contaminants
	Increased microbial activity at the WWTP improves efficiency of some treatment processes, reducing energy and/or land requirements for the plant
Increasing temperature of receiving waters	Increasing water temperature may promote the environmental persistence of some pathogens, and reduce environmental persistence of others.
	Increasing water temperatures can help support proliferation of harmful algal blooms, especially in conjunction with reduced base flow
Increased intensity of storm events, extreme winds	
Wind damage to trees, powerlines etc	High winds uproot trees, which can cause cracking or rupture of sewer pipes, leading to sewage leaks or spills
	Fallen trees or damaged lines cause power outages that lead to failure of pump stations, possibly leading to backup of wastewater in the sewer network
	Fallen trees or damaged lines cause power outages that lead to failure of pump stations, possibly leading to failure of treatment processes (eg, aeration, pumps for AS movement etc), leading to reduced treatment efficiency.
	Wind damage to superstructure of toilet facilities (especially for pit latrines or vault toilets), causing loss of amenity
Rainfall and flood damage	As described above for the section on increased rainfall
Storm surges	Wave impact damage and/or rupture of pipes, pump stations, treatment plants or outfalls in immediate proximity of the coast, causing sewage spills and/or loss of services
	Coastal erosion undermines the integrity of sewer pipes, pump stations, treatment plants or outfalls in immediate proximity of the coast, causing sewage spills and/or loss of service
	Inundation and flooding of sewer pipes, pump stations or treatment plants in coastal areas

Table 8 continued. Summary of potential impacts of key climate hazards for New Zealand on municipal and onsite wastewater treatment systems.

Rising sea levels and groundwater tables	
Inundation of coastal areas	Nuisance and/or permanent flooding of pump stations or WWTP may result in disruption or cessation of function, or widespread dispersion of sewage-contaminated floodwaters
	Repeated and extensive or permanent inundation of coastal WWTPs may require relocation of the plant as a worst-case scenario
	Loss of pressure head in low-lying areas leading to sewage backup and ponding, or reduced function of WWTP outfall
Increased inflow and infiltration	Increased inflow and infiltration into sewer pipes, reducing the capacity of the network to manage rainfall-associated inputs, and increasing the frequency and volume of sewage overflow events
	Increased inflow and infiltration into sewer pipes, increasing costs and energy requirements to treat additional volumes of wastewater arriving at WWTP
	Inflow and infiltration of coastal waters or brackish groundwaters increases the salinity of wastewaters, causing corrosion of pumps and other network elements
	Inflow and infiltration of coastal waters or brackish groundwaters increases the salinity of wastewaters, impacting microbial communities and reducing treatment efficacy
Rising coastal water tables	Floatation and damage to underground structures such as septic tanks and pipes, leading to sewage leaking into soils
	Increased soil saturation, reducing the capacity of soils to treat effluents from OWMS or WWTP that discharge to land and increasing transport of contaminants through soils to groundwater or surface waters
	Inundation of pit latrines or vault toilets, causing loss of amenity and increasing transport of contaminants from pit/vault through the soil
Exacerbates impact of pluvial or fluvial flooding	Increased risk and extent of damage or loss of function caused by flooding and inundation of sewer, pump stations, WWTP occurring through rainfall or river flooding
Exacerbates impact of storm surges	Increased risk and extent of damage to sewer, pump stations WWTP, outfalls occurring through wave impact or coastal erosion

4.2 THE IMPACTS OF CLIMATE CHANGE HAZARDS ON ONSITE WASTEWATER MANAGEMENT SYSTEMS

At a basic level, onsite wastewater treatment occurs as wastewater percolates through the unsaturated portion of the soil, where conditions including soil moisture, soil texture, residence time, volume of unsaturated soils (ie, vertical separation distance), oxygen availability and temperature influence the removal of microbial and chemical contaminants (Cooper et al. 2016). Many of the climate hazards and impacts described above for municipal wastewater treatment systems will therefore also be relevant to onsite wastewater management systems used in New Zealand, with the potential to affect both infrastructure and treatment processes. Overall, climate change is expected to reduce the functionality of many OWMS, with implications for human and ecosystem health (Vorhees et al. 2022).

Increased soil moisture content resulting from increased rainfall, coastal inundation and/or rising groundwater tables reduces the hydraulic drainage capacity of the soils (Leonard and Gilpin 2006). Discharging wastewater effluents to soils in excess of this capacity results in effluents rising to the surface and ponding. Wastewater that has ponded on saturated soils presents a high risk to human health, given the likely proximity to dwellings and that there will have been little to no opportunity for removal of microbial pathogens and other contaminants (Leonard and Gilpin 2006). Rising groundwater tables and flooding associated with intense rainfall, storm and flood events and/or sea level rise may also adversely affect treatment systems by directly damaging buried structures, for example, by inundating the pit or vault in pit latrines and vault toilets, respectively, causing sewage overflow and rendering the toilet facility unusable (Cooper et al. 2016). Rising groundwaters can also cause floatation of pipes or septic tanks, causing cracking or damage to pipe or joints that subsequently leak sewage into the soils (Hughes et al. 2021; Hyde-Smith et al. 2022).

Increases in soil moisture can also cause changes in onsite wastewater treatment processes. For example, higher soil moisture can increase microbial survival and reduce microbial attachment to soil particles, reducing mechanical filtration and sorption processes and increasing microbial transport through soils, thereby increasing the potential for pathogens to reach groundwater or nearby surface waters (Amador et al. 2014; Cooper et al. 2016; Hughes et al. 2021; Hyde-Smith et al. 2022). In addition, diffusion of atmospheric oxygen into soils is reduced as moisture content increases, making wetter soils less aerobic; this reduces the efficiency of nitrification and thus nitrogen removal, although subsequent microbial denitrification may be enhanced by reduced oxygen availability (Amador et al. 2014; Cooper et al. 2016). Wetter soils may also increase the reduction of metals by microbes, causing phosphorous attached to soil particles to be solubilised and leach into groundwaters (Amador et al. 2014; Cooper et al. 2016). Decomposition of organic carbon may also be affected, reducing BOD removal (Cooper et al. 2016). Importantly, the reduced filtration and removal capacity of soils with higher moisture content will be exacerbated by rising groundwater tables and the consequent reduction in vertical separation distance between the wastewater discharge field and groundwater (ie reduction in the volume of unsaturated soils available for treatment) – one of the key determinants of the capacity of a OWMS in providing adequate wastewater treatment (Leonard and Gilpin 2006; Hummell et al. 2011, 2017; Amador et al. 2014; Vorhees et al. 2022). While OWMS can tolerate infrequent and brief spikes in water saturation from rainfall or groundwater movements, prolonged changes in soil saturation will have negative effects on the ongoing efficacy of wastewater treatment (Vorhees et al. 2022).

For regions that are expected to become drier, reduced rainfall or periods of drought may reduce the availability of water for domestic use, requiring water conservation measures such as reduced flushing of toilets or frequency or duration of bathing, and resulting in a more concentrated influent to the OWMS (Amador et al. 2014). Septic tanks are sensitive to changes in influent quality, and may therefore discharge a poorer quality effluent. In addition, some systems may experience increased corrosion and/or odour associated with the more concentrated influents. Reduced flushing of toilets (eg after defecation but not urination) can lead to greater volumes of toilet paper in each flush and increase the risk of pipe blockages. Movement, settling and erosion of low-moisture soils during drought may also cause structural damage to pit latrines or cracking in pipes and tanks of septic tank systems (Hyde-Smith et al. 2022). Soil cracking may also create preferential flow pathways through which wastewater can move rapidly with minimal filtration or treatment. On the other hand, however, lower groundwater levels associated with reduced rainfall may be beneficial in terms of increasing vertical separation distance and thus the volume of soils available to provide treatment, reducing the risk of groundwater contamination from wastewater being discharged to soils and soakage fields.

Increasing ambient temperatures may affect the treatment efficacy of OWMS, though whether these are positive or negative changes, and the implications for the removal of specific contaminants will likely depend on the extent of temperature change and the impact of other climate drivers such as changing precipitation or rising water tables (Amador et al. 2014). Increasing soil temperatures result in both reduced oxygen solubility and increased microbial oxygen consumption, reducing the oxygen available for aerobic treatment processes such as nitrification (Cooper et al. 2016; Hyde-Smith et al. 2022). However, as modest increases in temperature will increase microbial activity within the septic system and within the soil, this may enhance the removal of other contaminants such as BOD (Viraraghavan 1976; Hyde-Smith et al. 2022), although lower BOD may in turn limit nitrogen removal by denitrification (Cooper et al. 2016), and reduced oxygen availability can lead to low redox conditions that reduce the capacity for phosphorous removal (Cooper et al. 2016). Modest changes in temperature may also increase survival of some faecal pathogens in the environment, while more significant temperature increases have been shown to increase bacterial and viral mortality (Morales et al. 2015; Cooper et al. 2016). Increased ambient temperatures, especially extreme temperatures and heatwaves may lead to the malfunction of some systems, and the increased production of malodorous gases including hydrogen sulfide, making pit latrines and vault toilets in particular highly unpleasant to use (WHO 2019).

Power outages resulting from storm damage or flooding can cause failure in systems that use a pump for flushing toilets or moving effluent from the septic tank to the drainage field. High winds or storms may cause damage to the superstructure of pit latrines or vault toilets; depending on the extent of damage, this may result in the loss of access to toilet facilities. Damage to roading and related infrastructure caused by flooding (pluvial, fluvial and/or coastal inundation), slips or erosion may prevent access by maintenance services that are required to ensure the system operates effectively (eg periodic access by vacuum trucks is required to pump effluents and prevent overflow of holding tanks or remove faecal sludge).

5. POTENTIAL IMPLICATIONS FOR PUBLIC HEALTH

Climate change presents a fundamental threat to human health in its own right, posing both new challenges and exacerbating existing health problems for many,[14] including those relating to urban water systems and sanitation (Major et al. 2011; WHO 2019). Although there are numerous ways in which climate change hazards may impact on the integrity and functionality of both municipal and onsite wastewater treatment systems, the consequences of these impacts may be summarised in several main themes:

- increasing instances of wastewater overflows, spills or leaks that discharge untreated or partially-treated sewage or wastewater to the environment (including soils, surface water, groundwater and coastal waters, as well as public spaces, private properties and homes);
- increased sensitivity of receiving environments to adverse impacts of wastewater discharge and/or potential for increased persistence of microbial contaminants;
- disruption or loss of access to acceptable or appropriate toilet or sanitation facilities;
- changes in sanitation behaviours, potentially leading to unsafe practices; and
- increased production of malodourous and nuisance gases.

In turn, these common ‘impact themes’ have several key implications for public health. The WHO (2019) notes that these generally fit within two overarching categories:

- increased risk of disease or illness resulting from exposure to pathogens or hazardous substances through increased environmental contamination; and
- increased risk of disease or illness resulting from lack of access to adequate sanitation where systems are damaged or destroyed.

To date, much of the research on the relationship between sanitation and public health has focused on infectious disease and related sequelae, such as diarrhoea, vomiting and malnutrition (Sclar et al. 2018). However, there is increasing recognition that water insecurity and inadequate or inappropriate sanitation are linked to emotional distress, anxiety, depression and other mental and psychosocial health outcomes (Bisung and Elliot 2017). In particular, psychosocial health emphasises an individual’s perception of, and response to, social and environmental conditions, and the relationship between their current and anticipated living conditions (Bisung and Elliot 2017). Indeed, the WHO define health not as the absence of disease, but as a state of “compete physical, mental and social wellbeing,”[15] and Health NZ note that a key element of public health is the promotion of health and wellbeing.[16] Mental disorders are a major public health challenge globally, with well-established links to (both as a precursor to, and a consequence of) chronic somatic conditions such as cardiovascular disease and diabetes (WHO 2021a). Thus, a more holistic

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14 https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
15 https://www.who.int/about/accountability/governance/constitution
16 https://www.tewhatuora.govt.nz/for-health-professionals/health-workforce-development/public-health-workforce-development/about-public-health/

review of the potential public health implications of these climate change-driven impacts on wastewater systems is explored in the sections below, and summarised in Figure 2.

Climate-sensitive health risks, including those associated with wastewater and sanitation, will disproportionately affect the most vulnerable and disadvantaged socioeconomic groups and communities, including women, children, the elderly, ethnic minorities, those experiencing poverty or with limited access to healthcare, displaced persons, and those with underlying health conditions[17] (WHO 2019). It is also important to note that the health implications described can in turn be associated with extensive cascades of further health, social, cultural and economic implications (Lawrence et al. 2020; Hughes et al. 2021). For example, diarrhoeal illness can cause nutritional deficiency and poor physical development in children and/or poor school attendance that impacts academic development and learning, with potential implications for quality of life into adulthood (WHO 2019), while illness in adults can lead to reduced capacity for work, resulting in financial pressure and associated stresses. Because of the complexity of these cascades and the way they interact with other climatic, environmental, social, and economic factors, there are potentially numerous implications that arise from these cascades that are difficult or impossible to predict (Lawrence et al. 2020). The discussion below does not attempt to resolve these indirect and cascading implications, and should therefore be considered a starting point for continued dialogue, rather than an exhaustive list.

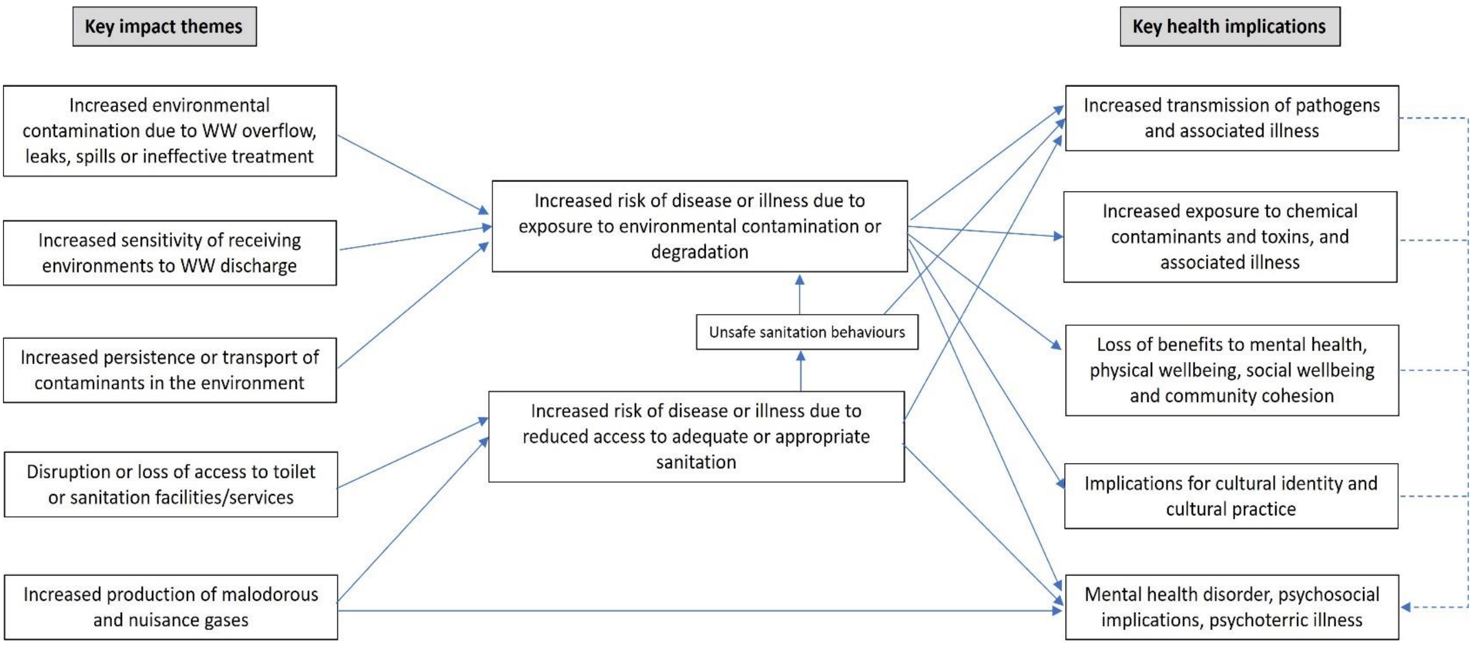

Figure 2: Links between key 'impact themes' or common types of impact on wastewater networks and onsite wastewater management systems from climate change hazards, and their implications for public health. [WW – wastewater]

[17] https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health

5.1 PUBLIC HEALTH IMPLICATONS OF UNTREATED AND PARTIALLY-TREATED WASTEWATER BEING DISCHARGED TO THE ENVIRONMENT

Wastewater contains a myriad of microbiological and chemical contaminants that may pose a risk to human health, including pathogens, heavy metals, pharmaceuticals, industrial chemicals, hydrocarbons, pesticides and microplastics; exposure to untreated or poorly treated wastewaters therefore presents an immediate threat to public health (Botturi et al. 2020; Coxon and Eaton 2022; Sojobi and Zayed 2022). The health outcomes of exposure to wastewater are a function of the specific contaminant(s) present in the wastewater that an individual is exposed to, the amount they are exposed to (ie, dose, duration and frequency), the route of exposure (eg, ingested, inhaled or through contact with the skin or mucous membranes), and the overall health of the individual (WHO 2019). Individuals with lower inherent immunity, including children, elderly, pregnant women and individuals with underlying health conditions, are at greater risk of experiencing adverse health outcomes.

As described in the previous chapter, there are multiple ways in which climate hazards can adversely impact municipal or onsite wastewater management systems and cause the discharge of untreated or partially treated wastewater to the environment. These include sanitary or combined sewer overflows, treatment bypass or overflow at the WWTP, leaks or spills from cracked or ruptured sewer pipes or septic tanks, backup/backflow through pump stations, manholes or into private property and homes. Depending on the nature of the discharge, it could contaminate waterways or coastal environments (ie, rivers, lakes and beaches), roadways and footpaths, public spaces such as parks, residential yards or homes, floodwaters, or seep into groundwaters. The discharge and associated exposure risk may be brief in duration, for example, an overflow after a short period of intense rainfall, or may persist for extended periods, such as the discharge of raw wastewater from Napier for several weeks following Cyclone Gabrielle before partial treatment could be reinstated.[18,19]

People are at risk of exposure to contaminants from wastewater via a number of routes, including direct contact with the spill/overflow or contaminated floodwaters, consumption of drinking water where groundwater or surface water supplies have been contaminated, recreational use of aquatic environments that have been contaminated, or the consumption of shellfish or other mahinga kai harvested from contaminated aquatic environments or crops that have irrigated with contaminated water (Table 9) (Jagai et al. 2017). Depending on the scale and nature of wastewater discharge, the potential for exposure and adverse health outcomes can range from a small number of individuals to a whole community (Jagai et al. 2017; Rothenberg et al. 2023).

[18] https://www.napier.govt.nz/our-council/recommissioning-napiers-wastewater-treatment-plant/
[19] https://www.stuff.co.nz/national/131422429/untreated-napier-sewage-to-be-piped-into-sea-for-another-week-or-possibly-two?rm=a

Table 9: Potential routes for public exposure to untreated or partially-treated wastewater that has been discharged to the environment due to climate-driven impacts.

Environmental exposure	Specific activities or routes of exposure
Direct contact with overflow/spill/floodwater	• Dermal contact • Accidental ingestion via splashing (eg navigating floodwaters, children playing in floodwaters) • Accidental ingestion via hand-to-mouth contact (eg after contact with discharge or floodwaters, after contact during flood clean-up, children playing in contaminated soils or sands) • Inhalation of aerosols produced by overflow
Consumption of contaminated drinking water	• Ingestion of contaminated water (potentially in large volumes) if wastewater contaminates ground or surface source waters
Recreational use of contaminated rivers, lakes, beaches etc	• Accidental ingestion during swimming or other recreation, or hand-to-mouth contact • Dermal contact, including skin and mucous membranes in the eyes, nose, ears and throat, as well as wounds if present • Inhalation of aerosols produced by splashing or wave action
Collection/consumption of shellfish and other wild foods from contaminated aquatic environments	• Ingestion of contaminated foods • Dermal contact (during collection) • Accidental ingestion (via splashing or hand-to-mouth during collection)
Consumption of crops that have been in contact with contaminated water (eg floodwater, contamination of irrigation supply)	• Ingestion of contaminated foods

5.1.1 Exposure to pathogens and infectious disease

Infectious disease is the most significant and most quantified health risk associated with inadequate sanitation and wastewater management, and thus will be the most significant implication for public health associated with climate change-driven impacts on wastewater networks. Wastewater contains an array of bacterial (eg *Campylobacter, Salmonella, Shigella, Aeromonas*, *Pseudomonas, Staphylococcus, Vibrio, Yersinia*), viral (eg norovirus, adenoviruses, enteroviruses, rotavirus, hepatitis A), protozoan (eg *Giardia intestinalis, Cryptosporidium*) and fungal (eg *Candida*) pathogens. These organisms can cause a wide range of illnesses ranging from mild and self-limiting gastrointestinal illness, upper respiratory tract infections, skin and wound infections and eye, ear, nose and throat infections, to severe cases of gastroenteritis, chronic and debilitating sequelae, or death (MfE and MoH 2003; Jagai et al. 2017; Botturi et al. 2020; WHO 2021b, 2022). Some pathogens, particularly viruses, can have very low infectious doses, making them highly infectious; this means a person can easily be infected after environmental exposure, with secondary transmission readily occurring through person-to-person contact (WHO 2021b).

Although the vast majority of the pathogens of concern in wastewater are enteric, some are able to persist in the environment for a period of time. For example, norovirus in groundwater can remain infectious for at least 61 days, meaning it can present a risk for a long period even after the wastewater discharge has ceased (Campos and Lees 2014). Other pathogens are capable of persisting in shellfish, or in sands and sediments and become resuspended with those sediments during future high-flow events or during use of environments for recreation (eg during wading or swimming). Similarly, depending on the receiving environment, pathogens can be highly mobile, with one New Zealand study detecting norovirus in oysters up to 24 kilometres from the wastewater outfall that was their probable source (Greening, cited in Campos and Lees 2014). Thus, if environmental conditions permit, pathogens can present a risk to public health for a long period of time after wastewater discharge has ceased, and/or over a large geographic area; changing climatic conditions that promote survival or transport will exacerbate these risks (Sojobi and Zayeed 2022).

There are numerous cases reported globally whereby dysfunction or failure of wastewater or sanitation systems has resulted in increased prevalence or outbreaks of illness; although they have not necessarily been caused by climate change (or in some cases, by climate hazards at all), they highlight the potential for significant adverse public health outcomes as a result of untreated or inadequately treated wastewater being released to the environment. Yet despite this extensive literature, it likely represents a small proportion of the actual burden of disease, as most cases of illness associated with exposure to wastewater discharge are not reported.[20] A small number of examples are highlighted below.

Contaminated drinking water

In New Zealand, 53 cases of acute gastrointestinal illness were reported in patrons of a restaurant and hotel following contamination of the drinking-water bore by the wastewater disposal field (Jack et al. 2014), while 218 staff and patrons of a ski resort contracted gastrointestinal illness after the drinking-water supply was contaminated by sewage from an overflowing septic tank (Hewitt et al. 2007). In Canada, 108 diners contracted viral gastroenteritis when a restaurant's drinking water was contaminated with sewage from a nearby sewage pit (Beller et al. 1997). In Sweden, an estimated 27,000 people became ill with cryptosporidiosis, with the likely source of contamination being wastewater leaking from an apartment building to the stormwater system, which in turn discharged to a lake close to where drinking-water was sourced (Widerström et al. 2014). In Ohio, contamination of drinking water wells linked to improper sewage disposal and leaking septic tanks resulted in an outbreak of 1,450 cases gastrointestinal illness attributed to multiple pathogens, including *Campylobacter jejuni*, *Salmonella* Typhimurium and *Giardia intestinalis* (O'Rielly et al. 2007).

[20] https://intel.cph.co.nz/media/36222/darfield%20waterborne%20outbreak%20nz%20pub%20hlth%20report%20dec%202012.pdf

Contaminated recreational waters

Epidemiological and quantitative microbial risk assessment studies have shown significantly increased incidence of illness, including gastrointestinal, respiratory, ear, eye and skin or wound infections in individuals who engage in recreational activities in waters that are impacted by wastewater discharges (MfE and MoH 2003; Sinclair et al. 2009; Soller et al. 2010; Wade et al. 2010; Colford et al. 2012). For example, at least 338 of 1,100 swimmers reported gastrointestinal illness after an open water swimming event in the River Thames in London, which is routinely impacted by untreated wastewater during CSO events, with *Giardia* and *Cryptosporidium* identified in several of the few available stool samples (Hall et al. 2017). Similarly, 352 of 838 competitors at a Danish triathlon reported gastrointestinal illness after swimming in urban coastal waters impacted by sewage overflows following heavy rainfall, with *Campylobacter*, *Giardia* and pathogenic *E. coli* detected in clinical samples (Harder-Lauridsen et al. 2013).

Contaminated shellfish and mahinga kai

Most bivalve shellfish, including key mahinga kai species such as mussels, cockles and pipi, are filter-feeders, filtering plankton and other particulates from the water column. This feeding method confers a tendency to accumulate environmental contaminants in their tissues, including microorganisms, to hundreds or thousands of times greater than those in the environment (Lees 2000; Simmons et al. 2001). Outbreaks of illness associated with the consumption of shellfish harvested from sewage-impacted waters are well documented internationally (Potasman et al. 2002; Campos et al. 2024). In China, an unprecedented outbreak of 290,000 cases of hepatitis A occurred as a result of the consumption of clams harvested from sewage-contaminated growing-waters (Tang et al. 1991). In Australia, diners at a private function became ill with norovirus after eating oysters harvested from an estuary as it re-opened following a sewage spill (Huppatz et al. 2008). In New Zealand, outbreaks of norovirus in Auckland and Waikato were traced to oysters harvested from an area of the Coromandel where waters were impacted by a leaking sewage pipe (Wall et al 2011). Shellfish that are consumed raw or lightly cooked, and that are consumed whole, present the greatest risk to consumers. Other mahinga kai that is consumed without or with minimal cooking (eg watercress) or where the gonad or viscera are consumed (including non-bivalve foods such as pāua, kina or crayfish) can also present a risk of pathogen transmission (Edmonds and Hawke 2007; Coxon 2018).

Other exposures

Proximity to bioaerosols from CSO effluents showed a tendency towards increased risks of asthma and skin and soft tissue infections in children residing near sewer overflow sites (Brokamp et al. 2017). A number of studies have also reported higher rates of Emergency Department visits for gastrointestinal illness in the days following sanitary or combined sewer overflow events, without further investigating the specific route of exposure (Redman et al. 2007; Donovan et al. 2008; Drayna et al. 2010; Jagai et al. 2015, 2017; Brokamp et al. 2017; Miller et al. 2022; Rothenberg et al. 2023).

5.1.2 Exposure to harmful chemicals and toxins

Chemical contaminants in wastewater may also be hazardous to human health, although there is considerably less literature assessing potential exposure or risk that results from environmental contamination due to failing wastewater systems. In contrast to microbial pathogens, the concentrations of chemical contaminants present in wastewater and the resultant dose from a single environmental exposure is typically considerably less than those associated with toxicity during acute exposure; rather, the health risks associated with environmental exposure to chemicals typically relate to chronic exposure, for example, when a drinking-water supply becomes persistently contaminated (WHO 2022). Regular consumption of shellfish or other mahinga kai from contaminated receiving waters may also be a key route of exposure, since many compounds, particularly heavy metals and organic contaminants with lipophilic properties, can bioaccumulate in the tissues of shellfish to concentrations many times higher than those in the surrounding waters, and are not destroyed or removed by cooking (Vandermeersch et al. 2015; Stewart et al. 2016; Coxon 2018).

The chemical contaminants that may be present in wastewater and their concentrations can be heavily influenced by the nature of the wastewater catchment, including factors such as population size and density, land use, and the presence of industrial or agricultural activities (Coxon and Eaton 2022). Contaminants of potential health concern include heavy metals (including arsenic, mercury, lead and cadmium), nutrients (especially nitrate), endocrine-disrupting compounds (eg, bisphenol A, various surfactants), pharmaceuticals and microplastics (UN Habitat 2023). The immense variety of potential chemicals compounds, their structure, environmental fate and their potential influence on human health, means they may elicit an incredibly wide array of health effects, with different degrees of toxicity; however, chronic exposure to a number of contaminants have been linked to non-communicable disease including neurological damage, liver and kidney damage, fertility and reproductive issues, and cancer (Jonas Rena et al. 2016; IPCC 2022; Sojobi and Zayed 2022; WHO 2022). Current data, although limited for many emerging contaminants, suggests that while these contaminants may be detected in drinking waters (eg Rozman et al. 2017; Kibuye et al. 2019), the concentrations are below levels that present concern for human health (WHO 2012, 2019; UN Habitat 2023); however, these data tend to focus on large, municipal supplies during business-as-usual, and may not include emergency situations such as large-scale discharge of inadequately treated wastewater, or the impacts on small or private supplies such as bores. Instances of contamination are reported for drinking water supplies where other (ie non-wastewater) sources of contamination have been identified (eg lead in Karitāne and Waikouaiti[21]).

Chemicals that function as environmental nutrients, particularly nitrogen and phosphorous, can also have indirect health implications by driving the eutrophication of receiving environments and promoting proliferation of cyanobacteria or algae responsible for harmful algal blooms (HABs), especially where climatic conditions favour warm temperatures and low rainfall and thus baseflow in rivers and streams (Kessouri et al. 2021; WHO 2021b; UN-Habitat 2023). The cyanobacteria and algae responsible for these blooms produce a variety of toxins, and people may be exposed to these when using waterways for recreation (eg via

[21] https://www.dunedin.govt.nz/__data/assets/pdf_file/0006/828366/Waikouaiti-Metals-Investigation-Report.pdf

ingestion of water, inhalation of aerosols or spray, or contact with skin and mucous membranes), or more commonly, through the consumption of foods harvested from HAB-impacted environments[22,23] (WHO 2021b). The symptoms and syndromes associated with exposure to HABs are determined by the specific organism and hence toxin that a person is exposed to, but can include nausea, vomiting, abdominal pain, diarrhoea, muscle weakness, malaise, fever, numbness and tingling in the face or extremities, dizziness, headaches, respiratory distress, dermatitis, and lesions (WHO 2021b). Severe cases of different syndromes include visual disturbances, loss of short-term memory, tremor, seizures, paralysis, respiratory distress, cardiac arrythmia and death. [24]

5.1.3 Environmental degradation and loss of access/use

The contamination and degradation of receiving environments through the discharge or overflow of untreated or partially treated wastewater, or the reduced assimilative capacity of an environment to receive wastewater discharge (eg through low base flow) can also have negative affects on mental health and psychological wellbeing.

Green and blue spaces[25] support increased psychological wellbeing and reduce risk factors and burdens of some mental illnesses, by reducing harm from environmental stressors such as air pollution, noise and heat; promoting restoration and recovery of physiological or psychological resources that are diminished or depleted through everyday stresses; facilitation of physical activity and recreation; and providing opportunities for social contact and community cohesion (WHO 2016; Kruize et al. 2019; Filipova et al. 2020). However, the 'perceived quality' of these spaces is important in determining their use and the user experience; degradation of these environments discourages their use, reduces enjoyment, or prevents spaces being used for certain recreational or related activities (WHO 2016; Filipova et al. 2020). For example, riverside parks or beaches that are increasingly impacted by the discharge of untreated or partially-treated wastewater may no longer be acceptable for swimming, picnicking, or dog-walking, with the loss of mental health and social and community benefits associated with such use (Kruize et al. 2019). The inability to use such spaces may be more keenly felt when climate drivers also cause an increased desire to do so, such as being unable to use recreational swimming spots during heatwaves, or may aggravate inequalities in a broader sense if impacted sites are more commonly utilised by lower income or other socioeconomic groups (Kruize et al. 2019).

Beyond the loss of benefits that would otherwise be provided by green or blue spaces, is the potential for 'psychoterric illness,' whereby peoples' mental wellbeing is threatened by the severance of healthy links between themselves and their home environment (Albrecht et al. 2007). The bond between people and their environment often serves a functional purpose in

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[22] Contact with harmful algal blooms in streams of coastal waters is reported to cause illness in people, but reports are less frequent and symptoms tend to be less severe when compared with shellfish-associated poisonings. However, algal blooms in waterways can be fatal for wildlife, livestock and pets, and is therefore still a potential source of distress for people using these environments.
[23] https://www.mpi.govt.nz/fishing-aquaculture/recreational-fishing/where-unsafe-to-collect-shellfish/what-toxic-shellfish-poisoning/
[24] https://www.mpi.govt.nz/fishing-aquaculture/recreational-fishing/where-unsafe-to-collect-shellfish/what-toxic-shellfish-poisoning/
[25] Green spaces include parks, recreational areas, grasslands and forests. Blue spaces include rivers, lakes, and coastal beaches.

the fulfilment of needs linked to solace, security, belonging, self-esteem and identity (Thoma et al. 2021), and profound changes in or degradation of these environments may result in ecological grief (the grief felt in relation to experienced or anticipated losses, including of species, ecosystems and meaningful landscapes) and solastalgia (the pain or distresses caused by the loss of, or inability to derive, solace from one's home environment due to negatively perceived state). Environmental grief and solastalgia are observed in populations globally, and are associated with undermined notions of place-based, cultural and self-identity, cumulative and chronic place-based distress, amplified mental health disorders, and heightened perceived risk of depression and suicide (Thoma et al. 2021). These conditions tend to be experienced more acutely by indigenous communities and those who have deep connections with their natural environments (Albrecht et al. 2007; Thoma et al. 2021); this is likely true for Māori too, in the context of their whakapapa connections to their environment.

5.1.4 Te Ao Māori and cultural implications

For Māori, wai[26] is taonga,[27] and an essential ingredient of life. It is a living entity, being both the source of life for all things, and a gift from the Atua[28] to sustain that life. As such, all waters have their own mauri,[29] mana[30], and hau,[31] and it is the responsibility of tāngata whenua[32] to protect and nurture it. Moreover, Māori have a whakapapa[33] connection to their environment, and thus water, as part of that environment, is an integral part of Māori wellbeing and identity – physically, spiritually and culturally (Pauling and Ataria 2010; Durie et al. 2017).

In te ao Māori, places, materials or activities associated with human waste, sanitation or menstruation are tapu[34] and there is extensive tikanga[35] to ensure the appropriate separation and handling of waste to protect people's health and wellbeing (Pauling and Ataria 2010; Ataria et al. 2016). The release of wastewater – as overflow, spills, or even treated effluents – to water degrades the mauri of receiving waters, and is thus highly offensive to Māori (Pauling and Ataria 2010; Durie et al. 2017; Afoa and Brockbank 2019). The tapu of wastewater is extended to the receiving waters, such that these environments become unsafe in a cultural sense, regardless of their status by formal health standards or regulations. These sites become unsafe for use as drinking water sources or for food preparation, bathing, recreation, mahinga kai, and other cultural rituals (Pauling and Ataria 2010; Afoa and Brockbank 2019). This loss of access in turn affects the ability of tāngata whenua to gain physical sustenance through mahinga kai[36] or engage in cultural or spiritual practices, and detracts from core Māori values of kaitiakitanga[37] and manaakitanga.[38] These

[26] wai - water
[27] taonga – a treasure
[28] Atua - gods
[29] mauri – essence
[30] mana – authority, status, spiritual power
[31] hau – vitality
[32] tāngata whenua – indigenous people of the land
[33] whakapapa – genealogy
[34] tapu – sacred, prohibited, restricted, forbidden, spiritually dangerous
[35] tikanga – custom, procedure, principle, values, social norm
[36] mahinga kai – traditionally-harvested foods, as well as the ecosystems, and resources and practices used in producing, procuring and protecting them.
[37] kaitiakitanga - guardianship, stewardship
[38] manaakitanga – to care and provide for manuhiri/guests

losses stand to have significant negative effects on Māori physical, mental, cultural, spiritual and social wellbeing (Pauling and Ataria 2010; Drurie et al. 2017; Afoa and Brockbank 2019).

5.2 PUBLIC HEALTH IMPLICATONS OF REDUCED OR LOSS OF ACCESS TO ACCEPTABLE SANITATION

Loss of access to toilet and sanitation facilities may result from the damage or loss of a wastewater system component that prevents its use, such as the rupture of a sewer pipe during a landslip or the destruction of a latrine pit. Less severe impacts may reduce the capacity or efficacy of the network in a way that allow it to continue operating but under reduced function, such as where damage at a WWTP reduces its capacity to handle and/or treat influent wastewater, requiring significant reductions in the number and volume of discharges to sewer that are not absolutely essential. For example, in several recent examples of extreme rainfall in the North Island, including the Auckland Anniversary floods and Cyclone Gabrielle, stormwater inflow, flooding and slips caused inundation and overflow of the sewer and treatment plants, damaged equipment and electrical systems in pump stations and treatment plants, and cracked and severed sewer pipes. Residents were asked to reduce the volume of wastewater they discharged to the network by reducing the duration of showers, avoiding doing laundry or dishes, or only flushing the toilet 'as necessary,' to minimise pressure on the system and the chance/volume of further spills or overflows.[39,40,41,42,43,44] Residents directly impacted by sewer rupture were supported directly by their local council to implement an alternative facility.

5.2.1 Loss of access to appropriate or acceptable toilet facilities

In the event that toilet facilities could not be used, alternative facilities would be required. This could include an emergency bucket, composting or chemical toilet constructed by or deployed to individual households, respectively, or an informal latrine dug into a backyard or garden.[45] As sanitary waste, especially faeces, can contain infectious pathogens as discussed above, extreme care is required when using emergency toilet facilities to ensure that sanitary waste is contained and disposed of appropriately to minimise exposure to and transmission of pathogens. Anecdotal evidence from the use of chemical toilets following the Canterbury earthquakes in 2010 and 2011 found that some members of the community, especially older people, had difficulties in transporting and emptying their chemical toilets at community-based collection points, putting them at greater risk of coming into contact with sanitary waste or of being unable to use their chemical toilet. Informal latrines would likely be

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39 https://www.dpmc.govt.nz/sites/default/files/2023-11/pr-info-related-floods-3-a.pdf
40 https://www.nzherald.co.nz/hawkes-bay-today/news/hawkes-bay-deluge-napier-residents-told-not-to-shower-avoid-flushing-toilets/KV7DCYQXPHMWL5PMNKYO4ZI65Y/
41 https://www.stuff.co.nz/national/300806160/cyclone-gabrielle-what-you-need-to-know-in-your-region
42 https://www.watercare.co.nz/About-us/News-media/Cyclone-Gabrielle-Water-and-wastewater-updates
43 https://www.nzherald.co.nz/hawkes-bay-today/news/cyclone-gabrielle-dannevirke-wastewater-plant-overwhelmed/MLLK7PH3VBHGDFDNMVUVTLXB4E/
44 https://www.phcc.org.nz/briefing/water-infrastructure-failures-cyclone-gabrielle-show-low-resilience-climate-change
45 https://www.wremo.nz/get-ready/home-ready/emergency-toilets

inappropriate in situations arising from rain- or flood-damage to the network, due to the inability of saturated soils to remediate sewage and the increased risk of contaminant transport, or in situations where bedrock prevented digging a pit of sufficient depth or in high-density, hilly suburbs. The provision of shared community facilities may also be an option, as seen with the deployment of port-a-loos after the Canterbury earthquakes; however, while these types of facilities are familiar and therefore may be more acceptable than garden or bucket toilets, they may present additional physical and psychosocial challenges that pose a risk to public health. For example, adequate servicing, cleaning and emptying of wastes is essential to prevent community transmission of pathogens (DoH 2024), and learnings from the Canterbury earthquakes[46] showed that it was difficult to manage the volume of waste and general cleanliness in an emergency setting, at scale and over a period of time. Challenges such as having to walk some distance to a toilet, especially in the wet, cold or at night, or anxiety as discussed below, may also discourage their use.

Extreme consequences of loss of access to toilet facilities could result in a shift towards unsafe sanitary behaviours such as open urination and defecation. Vulnerable members of society who are unable to access alternative toilet facilities (eg homeless individuals unable to access a chemical or bucket toilet, or older or disabled people unable to empty them) may be forced to resort to open urination and defecation. Open defecation in particular can have particularly severe public health impacts through the widespread exposure to infectious microorganisms, either through direct contact of through environmental contamination of water, and thus transmission of illness. Most of the literature regarding open defecation relates to low-income countries, where confounding challenges include a poor water supply, and shows clear relationships between open defecation and significant burdens of disease, as well as adverse pregnancy outcomes, environmental enteropathy, developmental issues including stunting and impaired cognition, and violence against women and girls (Mara 2017).

In addition to the risks associated with infectious disease, there is increasing recognition that inadequate sanitation is associated with negative impacts on mental and social wellbeing (Bisung and Elliot 2017; Sclar et al. 2018; Kimutai et al. 2023). While much of the literature has focused on low-income settings, where access to sanitation is poor and practices like open defecation are common, similar themes are reported around the use of toilets and sanitation facilities in high income countries (especially public or shared toilets) and could be increasingly relevant in high-income settings where facilities that people were accustomed to using become unavailable. In particular, issues around the privacy and safety dimensions of wellbeing are impacted, with increased levels of anxiety, shame, embarrassment and fear, and loss of dignity. For example, these can arise from shame and embarrassment around being seen to go to the toilet or 'leaving evidence' of their visit if they cannot flush the toilet; fear of having their privacy violated or being 'walked in on'; fear for one's safety (whether perceived or real) while using a facility, especially if needing to use a shared facility; or anxiety about having to wait in a queue, especially if someone is unwell or has an underlying health condition. In situations arising from the loss of access to normal facilities, there may be additional feelings of repulsion or disgust, that progress to anger, resentment, frustration and mental fatigue if the situation is ongoing. Individual factors such as gender identity, culture, physical ability, life stage, and socioeconomic status can influence the perceptions

[46] https://www.wremo.nz/get-ready/home-ready/emergency-toilets

and experiences a person has around privacy and safety when accessing sanitation, especially in emergency settings. Stresses around access to sanitation are felt particularly strongly by women, and may be amplified during menstruation (Sclar et al. 2018).

Loss of access to accessible sanitation facilities, especially toilet facilities, may disproportionately impact vulnerable members of the community, including individuals with disability or illness or the elderly, who may experience increased risk to their physical and mental wellbeing if alternative services such as port-a-loos or bucket or garden toilets are not appropriate for their needs (Sclar et al. 2018). For example, people with visual impairment or limited mobility may have a greater risk of falling (or experience fear of falling) or have to touch unsanitary surfaces to manoeuvre in difficult spaces. Impractical or inaccessible facilities may also lead to mental distress, anxiety and loss of dignity as people are forced to negotiate these spaces or are excluded from them, requiring them to toilet themselves in other days (eg open defecation) that may be damaging to their self-respect and psychosocial wellbeing (Sclar et al. 2018).

Loss of access to facilities could also include the loss of ‘acceptable’ facilities, whereby facilities are impacted by climate change in such a way as to make them highly unpleasant or unacceptable to use. For example, an increase in unpleasant odours associated with certain types of toilet facility – notably pit latrines or vault or composting toilets – may create aversion or avoidance of their use, and promote antisocial or unsafe sanitation behaviours (WHO 2019). This could also occur where alternative toilet facilities are considered unacceptable. People may ‘hold on’ to avoid using a facility emitting high levels of odour, use a facility in haste with less attention to proper hygiene, or opt for open urination or defecation, which may lead to the deterioration of public spaces. While high levels of open urination may cause unpleasant odours associated with ammonia, the issue of open defecation in particular poses a health risk to others through potential contact with faeces, or the contamination of nearby waterways.

5.2.2 Reduced handwashing

Reduced handwashing and hand hygiene could occur as a result of climate-related damage to wastewater infrastructure that prevents or severely limits the discharge of wastewater to the network. For example, handwashing facilities are not always available in the immediate proximity of community-based emergency toilets (eg, port-a-loos), although alternatives such as hand sanitisers may be available. Further, handbasins may be unable to be used if washwater cannot go down the sink, requiring an alternative arrangement for use after using the bathroom or prior to food preparation or eating meals. In addition, while not strictly a result of impacts on the wastewater network, drought-induced water conservation behaviours may also result in reduced prevalence or duration of handwashing (March et al. 2013; Hyde-Smith et al. 2022). Handwashing and hand hygiene is a key intervention in preventing the transmission of faecal pathogens and therefore reducing the incidence of gastrointestinal illness infections (Curtis and Cairncross 2003; Aiello et al. 2008; Freeman et al. 2014); the contamination of bathroom surfaces (eg toilet bowls and seats, sinks, walls, door handles, floors) is well documented, as are outbreaks of illness including norovirus, hepatitis A, *Salmonella* and *Shigella*, where toilet use and bathroom fomites are identified as sources of infection (Goforth et al. 2020; Abney et al. 2021). Handwashing can also be effective in reducing the spread of other illnesses, such as respiratory infections (Curtis and

Cairncross 2003; Aiello et al. 2008; Freeman et al. 2014). Reduced or absence of handwashing may be increasingly risky in situations where communal toilet facilities are required, as people may be increasingly exposed to pathogens from a number of individuals outside of their household.

5.2.3 Reduced bathing

Lack of access to appropriate sanitation can also prevent or reduce people's ability to wash or bathe to the extent to which they feel appropriate or have been accustomed (Bisung and Elliot 2017). In most cases, instances of reduced or restricted bathing (eg showering less frequently and/or for much shorter duration) are unlikely to present a direct health risk,[47] although they may have negative impacts on psychosocial health if people are unable to observe routines, practices or social norms in which they 'feel clean' or 'presentable' such as hair-washing, shaving and grooming, particularly if restrictions are in place for prolonged periods. Extreme cases of reduced bathing could lead to poor hygiene and associated skin conditions such as dermatitis neglecta.

5.2.4 Reduced toilet flushing

In times of water scarcity, or where wastewater infrastructure has sustained significant damage, reduced toilet flushing may occur (Hyde-Smith et al. 2022). For example, the phrase 'if its yellow, let it mellow; if it's brown, flush it down' is often used to promote water conservation by flushing toilets after defecation but not urination. Similarly, requests may be made by water authorities during or following extreme weather events, that residents avoid flushing their toilets unless "absolutely necessary," in order to relieve pressure on the network where it is at capacity and at risk of overflow,[48] or where rupture, damage or inundation has occurred to pipes, pump stations or treatment plants.[49,50,51,52] Aerosolisation of infectious microbes during toilet flushing is well-documented, with transmission occurring by inhalation or fomite contamination (Abney et al. 2021; Goforth et al. 2024); however, whether there are changes in the risk associated with aerosols produced from the 'collective flush' of more concentrated urine is unclear. In most cases, urine is a sterile body fluid, so the risk of pathogen transmission is generally assumed to be low. Such measures may, however, be associated with negative psychosocial and mental health associated with both the perception of unsanitary conditions, and feelings of shame or embarrassment, especially around shared toilet facilities such as those in workplaces.

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[47] https://www.health.harvard.edu/blog/showering-daily-is-it-necessary-2019062617193.
[48] https://www.nzherald.co.nz/hawkes-bay-today/news/hawkes-bay-deluge-napier-residents-told-not-to-shower-avoid-flushing-toilets/KV7DCYQXPHMWL5PMNKYO4ZI65Y/
[49] https://www.stuff.co.nz/national/300806160/cyclone-gabrielle-what-you-need-to-know-in-your-region
[50] https://www.watercare.co.nz/About-us/News-media/Cyclone-Gabrielle-Water-and-wastewater-updates
[51] https://www.nzherald.co.nz/hawkes-bay-today/news/cyclone-gabrielle-dannevirke-wastewater-plant-overwhelmed/MLLK7PH3VBHGDFDNMVUVTLXB4E/
[52] https://www.phcc.org.nz/briefing/water-infrastructure-failures-cyclone-gabrielle-show-low-resilience-climate-change

5.3 PUBLIC HEALTH IMPLICATONS OF INCREASED PRODUCTION OF MALODOROUS AND NUISANCE GASES

Human sanitary waste and wastewater networks can be sources of various odorous and potentially toxic gases, including hydrogen sulfide, methyl mercaptan, dimethyl sulfide, dimethyl disulfide, and ammonia that disperse to the surrounding atmosphere (Beghi et al. 2012; Aghdamn et al. 2023). While the concentrations to which the public are exposed are almost always well below toxic levels, the low odour detection thresholds for these compounds means they may be sufficient for people to smell their distinctive odours, which are often described as rotten eggs, rotting vegetables, fishy, pungent, garlicy, or sour (Schiffman et al. 2000; Cain and Cometto-Muniz 2004; Piccardo et al. 2022; Czarnota et al. 2023). As climate change scenarios such as increasing temperature, heatwaves and droughts can lead to increased production of these compounds, the geographic range (and hence number of people) affected by odour may increase, or the intensity of odour may increase for those in close proximity to treatment plants.

Whether malodour and olfactory nuisance (ie, annoying bad smells) is a public health issue or a social issue is debated (Piccardo et al. 2022). The perceived ‘meaning’ of the odour can be important in whether a person finds an odour acceptable, and in turn, their response to it. Odours associated with wastewater can carry perceptions of unsanitary conditions and a reduced quality of (and potentially, risk from) one’s environment (Schiffman et al. 2000; Aghdam et al. 2023). Prolonged or repeated exposure to unpleasant odours can therefore have negative effects on mental wellbeing, including anxiety, stress, fear, frustration or anger, and there are anecdotal reports of physical symptoms such as nausea, headaches, shortness of breath, and irritation of the eyes and nose (Schiffman et al. 2000; Cain and Cometto-Muniz 2004; Czarnota et al. 2023). There is no clinical data to link odour itself to illness and the symptoms involved have no pathology, suggesting that physical symptoms arise through a hormonal response to the psychological symptoms, such as an increase in cortisol levels (Cain and Cometto-Muniz 2004). The data suggests that individuals with certain chronic conditions, such as asthma or migraine, are more susceptible to this affect (Schiffman et al. 2000; Cain and Cometto-Muniz 2004). The phenomenon of chemesthesis, where some vapours can induce a sensory response described as ‘feeling’ the presence of a chemical (eg, sensations of sharpness or irritation in the nose), may also contribute to developing anxiety or experience of symptoms (Cain and Cometto-Muniz 2004).

An increase in unpleasant odours associated with certain types of toilet facility, notably pit latrines or vault or composting toilets, may create avoidance of their use and/or promote antisocial or unsafe sanitation behaviours (WHO 2019). These are discussed above in the context of ‘loss of acceptable sanitation facilities.’

6. CONCLUSIONS

Wastewater treatment systems provide a critical service to society and play a key role in protecting environmental and human health. In Aotearoa New Zealand, these systems range from reticulated collection and conveyance systems with advanced and highly-mechanised treatment plants that provide for high levels of wastewater treatment from large populations, to small reticulated systems with basic, pond-based treatment, to small onsite management systems (ie, septic tanks) or occasionally, rudimentary systems like pit latrines or vault toilets. All of these systems are vulnerable to various impacts of climate change. Among the changes in climate that have been projected for New Zealand, the key climate hazards that are expected to impact wastewater treatment systems are sea level rise, storm surges and coastal erosion, increasing frequency of intense rainfall events, coastal and inland flooding, and increasing temperatures and drought frequency. The hazards may occur individually or in combination.

The impacts of climate change on wastewater systems will be experienced differently around Aotearoa New Zealand, depending on regional variation in current and future climate, the design and condition of the network, and the influence of local geography that could minimise or exacerbate risk. Key impacts are likely to include increased frequency and/or volume of wastewater overflow from sewers or treatment bypass at the WWTP; cracking, rupture or corrosion of sewer pipes; damage to pumps and pump stations; damage to screens and other treatment plant elements; impacts on the microbial communities that facilitate biological treatment processes, which may increase or decrease treatment efficiency; inundation of and damage to WWTP infrastructure; power outages and damage to electrical systems; lack of access to the WWTP caused by damage to roading or related infrastructure; or coastal erosion undermining the sewer network or WWTP. These impacts will exacerbate challenges already being experienced by aging or poorly designed networks. Additional indirect impacts on wastewater systems may include climate-driven changes in the receiving environment that make them more susceptible to adverse impacts of receiving wastewater effluent, or are conducive to increased pathogen survival in the environment.

The most significant public health implication of climate-driven impacts on wastewater systems is the increased transmission of infectious disease, due to increased exposure to pathogens (especially faecal pathogens). The extent and route(s) of public exposure will depend on the climate hazard(s) experienced and their impact on a given wastewater system but could include direct contact with wastewater or contaminated floodwaters; consumption of contaminated drinking-water, mahinga kai or crops; recreational use of contaminated receiving environments, especially aquatic environments; loss of access to appropriate sanitation facilities; or adoption of unsafe sanitary behaviours. The primary health outcomes associated with faecal pathogens is self-limiting gastrointestinal illness, but severe illness, debilitating sequelae or death do occur, with increased risk for vulnerable individuals. Contact with other pathogens that may be present in wastewater or as a result of poor hygiene can cause upper respiratory tract, skin, wound, eye, ear, nose and throat infections. The impacts of climate change on wastewater systems can also have significant adverse impacts on mental and social wellbeing, as people experience the degradation of their environments and loss of amenity, or are required to use unappealing or inaccessible sanitation facilities or adjust behaviours or expectations. Additional impacts on cultural wellbeing are likely to be relevant for tāngata whenua.

APPENDIX A: IPCC REPORTS AND DEFINITIONS

A.1 IPCC usage of confidence and likelihood terminology

In the IPCC Assessment Reports (ie, AR5, AR6) confidence is expressed qualitatively, to tell us how certain we are that a scientific finding is valid. The level of confidence is determined by the type, amount, quality and consistency of the evidence (Bodeker et al. 2022).

The certainty of a scientific finding is then described using the likelihood of an occurrence or outcome. These findings are assessed probabilistically using observations, modelling or expert judgement.

These definitions of confidence and certainty are used throughout IPPC documents, and are typically conserved through other relevant documentation (eg MfE 2018, Bodeker et al. 2022). The terminology used and associated degree of certainty of likelihood are shown in Table A.1.

Table A.1. IPPC terminology to describe confidence and likelihood of climate change outcomes and projections.

Confidence Terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance
Likelihood terminology	**Likelihood of an occurrence/outcome**
Virtually certain	>99% probability
Extremely likely	>95% probability
Very likely	>90% probability
Likely	>66% probability
More likely than not	>50% probability
About as likely as not	33 to 66% probability
Unlikely	<33% probability
Very unlikely	<10% probability
Extremely unlikely	<5% probability
Exceptionally unlikely	<1% probability

A.2 Key differences between IPCC AR5 and AR6 reports

The IPCCs AR6 report contains the most up-to-date physical understanding of the climate system and climate change and updated climate models and projections.

SSPs v RCPs

To produce projections of future climate change, global climate models require a number of possible future scenarios of greenhouse gas emissions and aerosol concentrations (Bodeker et al. 2022). The AR5 and AR6 reports differ in the way scenarios were used.

The AR5 report (IPCC 2013) used scenarios characterised by Representative Concentration Pathways (RCPs). These RCPs were based on a range of potential greenhouse gas and aerosol concentration pathways that might occur in the future. Four RCPs were examined, each one being named for the radiative forcing (in W m^2) reached at the year 2100: RCP2.6, RCP4.6, RCP6.0, RCP8.5. Radiative forcing is the difference between the energy entering our atmosphere and the energy leaving it; for any number greater than zero, atmospheric temperature can increase (MfE 2023).

The AR6 report (IPCC 2023) used Shared Socioeconomic Pathways (SSPs), where different emissions scenarios may originate from a wide range of socioeconomic drivers, such as population growth and urbanisation, technological development and economic development (Bodeker et al. 2022). SSPs can provide narratives for energy use, control of air pollution, land use and GHG emissions, described along a spectrum of social actions: sustainability (SSP1), middle of the road (SSP2), regional rivalry (SSP3), inequality (SSP4) and fossil-fuel intensive development (SSP5). In AR6, these SSPs were combined with RCPs, to produce five scenarios spanning a range of societal and climatic futures that were therefore used to project climate change and assess impacts and risks. While some RCP- and SSP-based scenarios reach the same radiative forcing by 2100, the GHG concentration pathways taken to reach that radiative forcing could be different.

CMIP5 v CMIP6

The Coupled Model Intercomparison Project (CMIP) is a World Climate Research Programme project that coordinates climate model experiments, with the goal to improve scientific knowledge of the Earth systems. The AR6 Report assesses results from CMIP Phase 6 (CMIP6). CMIP6 is the next generation of climate models, has finer spatial resolutions, additional Earth system processes including biochemical systems and ice sheets, and better constrains parameters of cloud processes. Additionally, SSPs determined the emission scenarios which were put into CMIP6 whereas the inputs from CMIP5 were solely emission scenarios. This extra step resulted in the improvement of the simulation of large-scale indicators of climate change and many other aspects of the climate system (MfE 2023).

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