Climate Risk Management 31 (2021) 100262

Contents lists available at ScienceDirect

Climate Risk Management

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

Impacts and implications of climate change on wastewater systems: A New Zealand perspective

James Hughes [a,*], Katherine Cowper-Heays [a], Erica Olesson [a], Rob Bell [b], Adolf Stroombergen [c]

[a] *Tonkin + Taylor, PO Box 5271, Victoria Street West, Auckland 1142, New Zealand*
[b] *National Institute of Water and Atmospheric Research, PO Box 11115, Hamilton 3251, New Zealand*
[c] *Infometrics, PO Box 25309, Wellington 6140, New Zealand*

ARTICLE INFO

Keywords:
Wastewater
Climate change impacts
Local government
Risk
Resilience
Adaptation
Decision-making

ABSTRACT

Wastewater systems provide a critical service to society, and their vulnerability to the impacts of climate change. places the health and sanitation of many communities at risk. The impacts of climate change on wastewater systems are numerous and can lead to wide ranging implications over changing timescales. This paper considers the significance of the impacts and implications, how they will be distributed across different groups, how they will manifest in different contexts and locations, and conclude by proposing a range of guiding principles for local government decision makers.

The research firstly considered direct climate-related impacts on a range of wastewater system elements (including reticulated wastewater systems, on-site wastewater systems and treatment plants), in both urban and *peri*-urban settings in New Zealand. The impacts identified for each aspect of the wastewater network were found to fit within three broad impact themes; nuisance flooding spills and odour, water quality deterioration due to increased uncontrolled discharges and damage to infrastructure.

The research shows that the immediate and long-term implications resulting from these impacts are likely to be experienced widely across the social, cultural, environmental and economic domains. Examples include loss and damage to assets - leading to disruption to communities, water quality deterioration with consequential social, environmental, economic and cultural effects, public health risks, and economic costs related to damages, foregone production and insurance. Cultural implications are of particular importance in a New Zealand context, given the strong connection of Māori to the environment and water.

1. Introduction

Urban wastewater systems provide an essential service to communities in developed countries. The widespread development of wastewater reticulation and treatment systems over the last 150 years has resulted in major improvements in public health, with reduced mortality and disease outbreaks, as well as significant reductions in environmental pollution (Weil, 2016). Despite these improvements, urban wastewater systems, like any engineered system, can malfunction or fail when stressed beyond their historic

* Corresponding author.
E-mail address: jhughes@tonkintaylor.co.nz (J. Hughes).

https://doi.org/10.1016/j.crm.2020.100262
Received 3 June 2020; Received in revised form 3 November 2020; Accepted 28 November 2020
Available online 3 December 2020

design thresholds or functional condition. Failure can result from internal factors relating to poor condition materials, or an external hazard event such as a heavy rainfall event or earthquake. Consequential disruptions can lead to a range of potentially serious implications to receiving environments and public health. This is common across many developed countries on a regular basis; for example sewage contamination resulting from combined sewer overflow following significant wet weather events in the United States (Olds, et al., 2018), or following an external shock event such as the 2012 Christchurch Earthquake, which caused extensive damage to the wastewater network resulting in widespread pollution including contamination of drinking water (Zare, 2012).

The focus for this paper is on hazards exacerbated by climate change which present increased risk for many of New Zealand's settlements and their utility services, both coastal and inland (Ministry for the Environment, 2020a; 2020b). As with the rest of the world, the effects from climate change are already being felt in New Zealand (Ministry for the Environment & StatsNZ, 2017). These include sea-level rise, increased temperatures and dry spells, more frequent extreme rainfall events, more intense storms, and more prolonged and intense westerly winds and thus more frequent and heavier coastal or ocean swells (Ministry for the Environment, 2018). The individual hazards will compound and cascade across critical services and communities (Lawrence et al., 2020). The increased frequency of drought, flooding, coastal erosion and higher groundwater levels will have significant consequential impacts on the built environment, critical infrastructure as well as on social and economic activities (Stephenson, 2018). Compound hazards, such as the co-occurrence of extreme coastal waters, riverine flooding on top of sea-level rise, have been shown to exacerbate flooding, increasing the vulnerability of lowland coastal assets and communities (Moftakhari et al., 2017; Ganguli & Merz, 2019).

Climate change adaptation is increasingly being recognised as important for managing the performance and location of wastewater systems, which means that understanding the science and local knowledge is key for adaptation strategies (Kettle, et al., 2014). Impact assessments are a necessary step in the process of planning for addressing climate impacts (Danilenko et al., 2010). However it has been recognised that a coordinated and comprehensive study of the impacts of climate change on wastewater, relevant to local climate and geographic constraints, is lacking in New Zealand (White, et al., 2017). This study responds to this gap by delivering a systematic review of the impacts of climate change on wastewater systems, and an assessment of the implications that arise from these.

First, we provide the background and context, and discuss the framing and approach used in this study. Second, we systematically identify the key impacts of climate change on wastewater systems and discuss the direct and indirect social, cultural, environmental, and economic implications. Third, we develop decision-making principles for infrastructure owners and managers, typically local government. Finally, we conclude and make recommendations for further research.

1.1. Background and context

In New Zealand temperatures are warming in response to increased atmospheric greenhouse gas (GHG) concentrations (Ministry for the Environment, 2018). Future warming will depend on the success of efforts to curb global GHG emissions. The magnitude of rise in global mean temperatures this century is commensurate with the emissions trajectories in coming decades and significant changes in intensity and frequency of rainfall is projected, but with some uncertainties. In New Zealand, there is a clear trend of wet areas getting wetter, and dry areas getting drier and on average, an increase of rainfall in the west and decrease in the east (RSNZ, 2016; Caloiero, 2017; Ministry for the Environment, 2018). More extreme variability is also projected, with droughts and rainfall events becoming more severe or frequent. For rainfall this could range from no change, up to a fourfold increase in the frequency of heavy rainfall events by 2070 (RSNZ, 2016; Carey-Smith et al., 2018). As sea-level rises, increasing *frequency* and *depth* of extreme coastal flooding, will exceed thresholds relative to present day levels (Paulik et al., 2020a).

Many of New Zealand's urban areas are located around low-lying coasts and harbours or clustered on river floodplains. Within towns and cities with reticulated networks, the most significant wastewater infrastructure is often located where gravity flows concentrate at the coastal or riverine edges (Paulik et al., 2020b). Existing wastewater systems, which are often aging and designed based on past climate, have potential to be significantly impacted beyond the historic functional design requirements of the system. Damage will come from increasing occurrence of individual and compound hazards including with earthquakes and other ground instability.

Cascading impacts of climate change have been highlighted as having complex and far reaching potential impacts across sectors due to their interdependencies and feedbacks with implications for community wellbeing, adaptive capacity and governance (Lawrence et al., 2020). The possibility of cascades highlights the benefit in understanding both direct climate-related impacts and indirect and cascading implications. This reinforces that to adapt to climate change a complete understanding of impacts and implications is essential. Further, a wastewater system services people and their activities which means that service levels (not just vulnerabilities of individual assets in isolation) are at risk from climate change hazards. Furthermore, maintenance of service levels will never provide fail safe systems because the uncertainties mean that there will always be a residual risk remaining (Gibbs, 2015).

A comprehensive assessment of impacts (to both wastewater reticulation and treatment systems) and system-wide implications has not been undertaken either internationally or in a New Zealand context, to the best of our knowledge. An extensive body of New Zealand based and international literature comprising case studies and single-issue studies inform the impacts and implications discussed in this research. General consideration of the impacts of climate change on wastewater systems have been discussed in international assessments highlighting broader societal impacts of climate change, including damage to infrastructure and reduced service levels (Revi, et al., 2014; Major et al., 2011; Aboulnaga et al., 2019). Similar overviews exist in New Zealand, where a number of high-level studies have identified potential impacts of climate change on New Zealand's infrastructure (Ministry for the Environment, 2008a; NIWA et al., 2012; RSNZ, 2016), including increased inflows, overflows and blockages.

Of particular note is a high level summary of direct and indirect impacts of climate change on stormwater and wastewater systems by White et al., (2017). This study provided useful foundational context for this research and identified a range of impacts, including reduced capacity in pipe networks, exposed or damaged pipes, and increased wastewater discharges. Other studies have identified that such damages will have implications for design (Tolkou and Zouboulis, 2015; ONeil, 2010), and economic costs (Neunteufel et al., 2015). The majority of relevant literature are case studies or single-issue international studies. Many of these identify decreased performance of wastewater system components under extreme weather (Marleni et al., 2012; Yuan, 2010a, 2010b; Tran et al., 2017; Budicin, 2016; Naidoo & Moolman, 2016; Pocock & Joubert, 2017; Plosz et al., 2009; Langeveld et al., 2013; Hummel et al., 2018) and an increasing risk of wastewater overflows (Olds, et al., 2018; Benotti et al., 2010) resulting in worsened water quality (Semandeni-Davies et al., 2008; Komatsu et al., 2007) with implications for public health (Curtis et al., 2017; World Health Organisation, 2013; Stanke, 2012; Boholm & Prutzer, 2017), and economic performance of businesses (Wang et al., 2017; Fauzel et al., 2017).

Recognition of indigenous and customary knowledge is acknowledged to be best practice in the development of impact assessments and other climate and disaster planning (UNDRR, 2015). Indigenous people can be disproportionately vulnerable to the impacts of climate change due to their unique relationship with the natural environment, socioeconomic deprivation and increased susceptibility to disease (Jones, 2019; Lansbury et al., 2020). Conversely, Indigenous knowledge and customs can be a valuable tool in responding to impacts of climate change, for example through diverse approaches to adaptation, unique cultural governance and practices, and increased awareness of environmental change (Hiwasaki et al., 2014; Nursey-Bray et al., 2019). The cultural implications of the impacts of climate change are explored in the context of New Zealand's Indigenous Māori society. This draws mainly on case studies and research informed through dialogue, focused on addressing vulnerability or informing decision-making regarding resource management (Durette et al., 2009; King et al., 2012a, 2012b). Māori, as the people of the land, or 'tangata whenua', have a traditional relationship with their ancestral lands, waters, sacred places and other treasures, or 'taonga', and many Māori have place attachment in low-lying coastal areas (Bradley, 2016; Morgan, 2006). Of particular note, in considering wastewater management and disposal, Māori view wastewater and its impacts on cultural practices and the environment in a holistic manner, generally irrespective of the methods of treatment (Ministry for the Environment, 2003).

This research has been conducted in a New Zealand context, in recognition of the importance of local knowledge and Indigenous knowledge in gathering information for adaptation strategies. However, many of the issues discussed in this research will be relevant when considering impacts and implications of climate change on wastewater systems in urban areas outside New Zealand.

2. Framing and approach

Given the increasing effects of climate change on the built environment, it is becoming necessary to understand what infrastructure will likely be *exposed* and *vulnerable* to climate hazards. The IPCC (Oppenheimer, et al., 2014) describes hazard, exposure and vulnerability as overlapping factors which combine to create *risk* associated with climate change. Risk can manifest in *impacts* which can lead to downstream *implications* across social, cultural, environmental, and economic domains. These terms are defined below.

- Impacts: The "effects on natural and human systems" of extreme weather, climate events and climate change (ISO, 2019) and defined in this report as the direct (first order) effect from a climate-related risk.
- Implications: The indirect (second/third order, and cascading) effects, resulting from the impact. This relates primarily to changes to environmental, social, economic and cultural values following an impact.

An example of the relationship between risk, impacts and implications is presented in Table 1, to provide context and to demonstrate how decision-making may apply in the wastewater context. This example demonstrates how sea-level rise can lead to rising groundwater (hazard) that can impact underground pipes (exposure), and depending on pipe material (vulnerability), can lead to an impact (damage), as well as a range of implications including reduced levels of service.

New Zealand specific climate projections were reviewed and the key climate hazards and stressors with the highest relevance to wastewater system impacts include: *increased rainfall, decreased rainfall, sea-level rise, increased temperature and increased wind* (Ministry for the Environment, 2008a, 2018). These hazards and stressors provide the structure for this paper.

Typically, wastewater systems comprise a network of pipes (reticulation) that collect and convey wastewater from urban centres or towns to a wastewater treatment facility. When assessing the impacts and implications of climate change on wastewater systems, we

Table 1
Example summary of relationship between sea-level rise risk, impact, implications and decision making.

Risk	Impact	Implication	Deciding, acting & review
Hazard × exposure × vulnerability	The direct (first order) impact from a risk source	Change to environmental, social, economic and cultural value following an impact	Decisions to reduce the risk
Example: Groundwater rise:			
The potential for groundwater to rise, over time, affecting underground pipes	Pipe corrosion, damage or failure Increased infiltration into networks Ground heave/ flotation	Increased service provider costs to repair damages, causing economic losses Reduced levels of service Deterioration of water quality from saline intrusion	Understanding impacts and implications, combined with consideration of climate change uncertainty can lead to prioritisation of interventions to mitigate risk (Stephens, Bell, & Lawrence, 2017).

considered the following components of the wastewater system; *wastewater conveyance systems including pump stations, wastewater treatment plants and on-site wastewater treatment plants*.

Our research was conducted in three phases; identification of impacts, identification of implications and development of guiding principles for local government decision makers. Data collection and analysis for impacts and implications was conducted in five steps: 1 Initial literature review of impacts and implications; 2 workshop with key stakeholders; 3 detailed literature review of impacts and implications with follow up expert elicitation; 4 sense-making and analysis of impacts and implications by the research team; 5 development of guiding principles by the research team.

The potential impacts for each wastewater system component and implications were examined through a day long workshop comprising participants (n = 14) from central government, policy advisers, water service providers, asset managers, academic and institutional researchers, local government, engineering consultants and economic consultants. The group of specialists present at the initial workshop, along with one additional specialist who contributed at a later stage, formed an expert Technical Reference Group (TRG) which subsequently provided ongoing consultation. During the workshop the severity of each climate impact was assessed by the experts and categorised as low, medium or high. This allowed a focused discussion and follow up study on those impacts which were deemed the most severe (medium and high severity).

Following the workshop, the impacts and the resulting social, cultural, environmental, and economic implications were further

Table 2
Summary of impacts of climate change on various wastewater system elements.

Wastewater system element	Climate hazards / stressor Increased rainfall	Reduced rainfall	Sea-level rise	Temperature	Wind
Wastewater conveyance (all types; separated and combined gravity and pressure)	Increased overflows Increased blockages and breakages	Corrosion due to low flows resulting in increased concentration Blockages or siltation when combined with increased temp, and reduced water use.	Pipes float due to increased groundwater level causing cracking Corrosion Groundwater ingress leading to loss of functionality and capacity Erosion/inundation causing damage to infrastructure	Increased odours	Increased blockages and breakages associated with rainfall events or storms
Pump stations	Increased overflows Increased blockages	Corrosion due to low flows resulting in increased concentration	Corrosion Flotation Inundation Flooding causing a reduction in the service zone of the pump station	Blockages due to user behaviour changes in hot weather (e.g. flushing of wet wipes)	Increased blockages, breakages and outages associated with rainfall events or storms
Wastewater treatment plant (WWTP) – general	Increased inflows leading to more frequent bypassing. Storm related power outages and road closures	Increased strength of influent risking breach of toxicity levels	Flooding and infrastructure damage Raised groundwater table preventing sludge management dewatering Outfalls may be impacted Increased pumping heads for outfalls	Performance of biological systems, oxidation ponds and sludge management varies with temperature Odours (due to higher temperatures)	Increased blockages and breakages associated with rainfall events or storms
On-site wastewater	Soakage performance affected when soils are waterlogged Floatation of below ground chambers Soil structure damage reducing soakage performance Ecological changes to soakage fields	Ecological changes to soakage fields	Soakage performance affected when soils are waterlogged Floatation of below ground chambers Soil structure damage reducing soakage performance Ecological changes to soakage fields	Performance varies with temperature Odours increase	–

explored through a literature review. The identified impacts were grouped the into common 'impact themes' to provide a structure for the examination of the implications. These themes were chosen by grouping all the impacts that create a similar physical result out of the climate change impacts discussed in the literature review and stakeholder engagement.

Identification of implications followed the logic modelling or theory of change approach, which aims to describe causal relationships between situations (in this case climate impacts) through to outcomes affecting wellbeing (Mayne, 2015). This included considering implications from the perspective a wide range of stakeholders, including individuals, community groups, the broad community, local businesses, business supply chains, and local government. The implications were elicited through literature review and consultation with the TRG. Implications were synthesised and grouped according to the most relevant domain of environment, social, cultural, and economic (while recognising implications often reflect multiple domains). Linkages were assessed between the implications, such as directional links where one implication acts as a trigger for another, or feedback loops where two implications may mutually reinforce each other. Each implication was mapped against the previously identified impacts and the timeframe the implication would typically occur, as a short, medium, or long timeframe following the impact (or a combination).

The impacts, impact themes and implications are summarised into 'bow tie' diagrams, which show the various relationships between climate hazards, impacts, and implications. Arrows within the bow-tie diagrams demonstrate linkages between direct implications and indirect implications and show feedback loops which are characteristic of cascading effects (Lawrence et al. (2020)). Key implications were those deemed by the authors to be more significant and overarching and are generally indirect. For the social and cultural domains, the key implications generally relate to those that play out over the longer term.

Finally, a series of guiding principles to assist decision-makers were developed to enable them to manage and respond to the identified impacts and implications.

3. Impacts of climate change on wastewater systems

The potential impacts of climate change on wastewater systems that were identified by the TRG are listed in Table 2, along with the assessment of severity. The following discussion of impacts is focused on those which were identified as having medium to high severity. We acknowledge that impacts will be experienced differently depending on location around New Zealand due to geographical variation in climate and climate change.

3.1. Impacts on wastewater conveyance systems

The impacts of climate change on wastewater conveyance systems that were identified as having a medium and high severity in Table 2 are discussed in this section. Pipeline conveyance systems include systems where stormwater overflow is conveyed in the wastewater pipe, termed 'combined', and systems where separate pipe networks are used to convey stormwater and wastewater, termed 'separated'. Conveyance within pipe networks can rely on either gravity to drive wastewater flow or using pumping to drive wastewater under a pressure or vacuum (negative pressure) system, thereby allowing conveyance uphill as well as down. Often pumped systems will form a small section of the network within a larger gravity system. The materials used in pressurised and vacuum pipes must be flexible and durable to ensure the pipes are fully sealed to maintain pressure.

3.1.1. Impacts of increased rainfall on wastewater pipeline conveyance systems

The most significant impact of increased rainfall on wastewater conveyance systems were identified to be increased overflows, and blockages and breakages. Increased rainfall intensity and extreme events are likely to lead to increased occurrence of inflow and infiltration (I&I) into wastewater networks. This occurs due to stormwater directly entering combined networks or infiltrating the sewer network through cracks, poorly constructed or corroded manholes and direct connections (Ministry for the Environment, 2008b; ONeil, 2010). While all types of conveyance systems face similar impacts from climate change, they each have particular features that influence the severity of the impact. Combined systems are the most vulnerable to I&I and will most readily cause uncontrolled discharge of untreated wastewater to the environment as they receive stormwater overflow during high rainfall events. Separated systems are also exposed to I&I through infiltration, but are considered to be less vulnerable as stormwater inflow volumes are lower and they are typically constructed more recently, and therefore have tighter seals between joints, and less cracks and corrosion that often develops with age. Cracks in a pressure system are more quickly detectable, as a loss of pressure to the system seriously affects system performance, therefore are much less vulnerable to I&I.

As wet weather overflow events increase in frequency and volume it is likely that there will be increased instances of serious environmental contamination (Olds, et al., 2018). Increased severe weather may also cause pipe damage due to flooding and erosion. Wind velocities are often associated with increased severe weather events associated with climate change. Increasing wind velocities will be location-specific but with a trend nationally to increased westerlies. This will result in changes in rainfall over complex topography – increases upwind of hills and ranges, and may compound some of the issues associated with increasing rainfall (Ministry for the Environment, 2008b). High winds will cause blockage or damage due to wind fall and increased accumulation of debris in pump stations and screens, particularly in combined systems. Wind damage to infrastructure such as powerlines can indirectly impact pressurised systems that are dependent on power to convey wastewater (ONeil, 2010).

3.1.2. Impacts of reduced rainfall and increased temperature on wastewater pipeline conveyance systems

The most significant impacts on conveyance systems resulting from reduced rainfall and increased temperatures were corrosion, odour and blockages. Guidance from the government highlights that longer dry spells will increase the likelihood of blockages and related dry weather overflows (Ministry for the Environment, 2008b). The related impacts of drought on the wastewater system have been studied in places such as Australia, South Africa and California, which have experienced prolonged drought. During such times, water restrictions are typically enacted. This, compounded with less infiltration from stormwater and groundwater sources results in flow reductions and higher temperatures in wastewater flow (Marleni et al., 2012; ONeil, 2010). Reduced wastewater inflow results in an increase in wastewater concentration, because the solids content of wastewater remains the same but the contaminant dilution capacity decreases. Thus, 'high-strength' wastewater occurs, which contains higher pollutant concentrations, including pathogens (Tolkou and Zouboulis, 2015). This can result in increased likelihood of blockage, odour and corrosion of the reticulated wastewater network (Marleni et al., 2012; Naidoo & Moolman, 2016; DeZellar & Maier, 1980). The most common causes of blockage are the build-up of fats, oils and greases (FOGs), debris, solids deposition and tree root intrusion, all of which can be accelerated in times of drought. Reduction in water usage can result in insufficient water to move waste and solids through the system if self-cleansing velocities are not achieved (Naidoo & Moolman, 2016).

Low flows can cause deposition of solids and thus more extensive anaerobic decomposition resulting in production malodourous compounds such as hydrogen sulphide (H_2S), volatile organics, sulphur compounds and nitrogenous compounds (Yuan, 2010; Pocock & Joubert, 2017). Increased wastewater concentration and increased temperature increase the likelihood of these emissions during times of drought. Of particular concern is H_2S, due to its odour nuisance, threat to public health and potential to enhance corrosion in sewer pipes (Yuan, 2010; Marleni et al., 2012). Pipe corrosion is influenced by pipe age and condition and occurs predominantly in metal or concrete pipes, rather than plastic (PVC, PE) (Marleni et al., 2012).

Reduced rainfall can increase the likelihood of aquifer contamination, as lower rates of aquifer recharge (due to less frequent rainfall) reduce the dilution of pollutants (Neunteufel et al., 2015). This, in turn, can pose a risk to public health and the environment.

3.1.3. Impacts of sea-level rise on wastewater pipeline conveyance systems

Sea-level rise, storm surges and coastal erosion can cause inundation and damage to pipelines, affecting the serviceability of the system (Hummel, Berry, & Stacey, 2018). Fully submerged gravity pipelines may lead to sewer back-up in homes and may contribute to wastewater contamination of the coast (Kettle, et al., 2014).

Sea-level rise will raise coastal water tables which may influence inland groundwater levels (May, 2020; Befus et al., 2020). Increased infiltration of groundwater into wastewater systems due to a raised groundwater table will particularly affect older systems which are more likely to have cracks and other points of entry for groundwater. Salt-water intrusion and inundation adversely affect conveyance capacities and may contribute to corrosion. In New Zealand, this is already occurring in locations such as South Dunedin where the groundwater table is thought to be kept artificially low due to infiltration into the stormwater and wastewater network. Testing has found high salinity in the wastewater system during high tide (Water New Zealand, 2015).

3.2. Impact of climate change on wastewater pump stations

Pump stations are part of the broader wastewater system and therefore many of the issues discussed above that affect pipes, also affect the pumping station, such as overloading under increased rainfall, salinity impacts from rising groundwater, and blockages arising from build-up of fats oils and grease. Increased wind severity and lightning strike associated with more extreme stormy conditions can damage exposed structures, cut off power supply or damage controls (ONeil, 2010).

As temperature ranges shift, the operational temperature range of infrastructure will change. This may expose elements to heat extremes causing overheating or increased community demand for water, translating to shifts in wastewater constitution and odour impacts (ONeil, 2010). Increased inflow and infiltration due to increased rainfall intensity and raised groundwater tables may lead to increased pumping volume requirements for pump stations. These conditions can lead to increased wear within pump stations (Kettle, et al., 2014).

3.3. Impacts on wastewater treatment plants and processes

Increased and decreased rainfall, sea level rise and increased temperature extremes are expected to have a medium or high severity of impact on WWTPs (refer Table 2). The concentration of pollutants in the wastewater *influent* is a combination of the load and the volume of water with which the pollutant is mixed (Henze, van Loosdrecht, Ekama, & Brdjanovic, 2008). How the wastewater *effluent* characteristics will change under climate change will depend on the type and design of WWTP processes. Depending on how these can cope with changes to influent quality (for example, as a result of changing water temperature, water usage/conservation measures and flow patterns), will result in potentially negative effects within receiving environments – such as nutrient enrichment (eutrophication) and ultimately the reduction in the capacity for the receiving environment to accommodate contaminant loads, termed '*assimilative capacity*' (Chapra, 2008).

3.3.1. Impacts of increased rainfall on treatment plants / processes

Increased inflows and power outages were identified to be the most significant impacts likely to affect treatment plants and processes. Increased rainfall will result in larger volumes and peak inflows into WWTPs due to flow from combined systems and I&I. While the volume or 'flow' of the wastewater increases due to increased stormwater infiltration, the Total Suspended Solids (TSS) of the wastewater remains the same, resulting in a dilution of the influent to the WWTP which can affect biological treatment processes. Research has shown that treated effluent quality can deteriorate during periods of increased inflows into activated sludge secondary treatment systems, and was primarily attributed to decreased detention times in the treatment processes (Mines, Lackey, & Behrend, 2007; Plosz, Liltved, & Ratnaweera, 2009). The impact of increased rainfall when combined with an extended dry period can further aggravate the impacts of increased rainfall on WWTPs, and has been shown to contribute to extended biologic overloading, putting stress on the WWTP processes and ultimately resulting in increased combined sewage overflow (Langeveld et al., 2013).

High flows can carry debris associated with storm events, which can reach the treatment plant and cause blockages or damage screens. High inflows can affect the hydraulic performance of the system or overwhelm the infrastructure completely. During extreme weather, system bypasses can be activated, diverting flows past part or all of the treatment process. This causes partially treated or untreated wastewater to directly enter the receiving environment (Langeveld et al., 2013; Tolkou and Zouboulis, 2015; Watercare, 2020). This can cause public health concerns and result in the closure of swimming beaches as well as contamination of drinking water supplies (Boholm & Prutzer, 2017).

As with other types of infrastructure, high winds and storminess can raise the likelihood of windfall from trees. This raises the risk of power outages, causing disruption to the operation of plants and reliance on back-up generator systems. Additionally, storm-related road closures can prevent access to treatment plants.

3.3.2. Impacts of decreased rainfall on treatment plants/processes

The most significant impact to wastewater treatment plants and process from a decrease in rainfall was identified to be increased strength of wastewater influent risking breach of toxicity levels.

Decreased rainfall and drought conditions reduce the amount of water that flows into WWTPs, through less I&I and potential lower household water consumption (as a result of the implementation of water conservation strategies). An increased occurrence of low flows will lead to decreased contaminant dilution capacity, and thus higher pollutant concentrations, including pathogens (Tolkou and Zouboulis, 2015). The volume or 'flow' of the water decreases, but the waste load remains the same, creating 'high-strength wastewater.'

High-strength wastewater flow can cause problems for WWTPs. The increase in concentration of fats, oils, grease, organic and solid matter can result in blockages, early system corrosion and/or severe health and environmental impacts (Pocock & Joubert, 2017). This higher concentration and reduced flow could see interrelated problems occur. Firstly, the sedimentation of solids in the reticulation pipes up stream of the WWTP can be suddenly released as a slug once flows resume, which can be problematic as most WWTPs struggle to process erratic loads. Secondly, longer detention times during conveyance can trigger extensive anaerobic decomposition to occur prior to the WWTP, resulting in changed influent properties which the WWTP may process less effectively (Pocock & Joubert, 2017). Thirdly, salinity levels can increase as influent pollution concentrations increase, which adversely affects treatment effectiveness, effluent quality and operational costs (Tran et al., 2017).

Lower flows and higher strength wastewater are likely to affect each plant differently, depending on the type and capacity of the individual plant. Plants that rely on trickling filters are expected to be more affected by higher concentrations of pollutants, particularly in winter when efficiencies normally decrease due to slower biological reaction rates at lower temperatures. Plants which incorporate activated sludge systems may benefit positively, due to increase retention times in process tasks and consequential increased solid removal within the clarifiers (Pocock & Joubert, 2017).

3.3.3. Impacts of sea-level rise on treatment plants / processes

Flooding, reduced capacity for outflow and raised groundwater tables, all related to sea level rise, are likely to result in significant impacts on WWTPs. WWTPs are typically located on low-lying coastal land, to minimize the cost of collecting wastewater and discharging treated effluent, which makes them particularly exposed to coastal flooding from sea-level rise (Hummel, Berry, & Stacey, 2018). Rising sea level also increases the risk of compound flooding (e.g. combined coastal, pluvial and fluvial events and/or raised groundwater levels). With it, the potential for direct damage to WWTPs increases, which may cause disruption to WWTP processes, necessitate repair or protection works, and eventually may lead to abandonment of stranded assets (Hummel, Berry, & Stacey, 2018). Rising receiving-water levels may result in the need to change from gravity to pumped effluent through outfalls, or higher heads for existing pumped systems, thereby increasing energy requirements (Tolkou and Zouboulis, 2015).

Some wastewater treatment plants practise land-based dewatering of wastewater sludge. Dewatering relies on a groundwater table at a sufficient depth below ground level to allow excess water to infiltrate. A rising groundwater table will compromise the capacity for dewatering.

3.3.4. Impacts of increased temperature extremes on treatment plants / processes

Performance varying with temperature, and increased odours was identified to be the greatest impact on WWTP and processes due to increased temperature extremes. Generally, fresh wastewater, particularly residential wastewater, produces a benign musty odour. Wastewater composition transforms in the wastewater network, which produces malodorous compounds (Marleni et al., 2012). Increased strength of wastewater and changes in WWTP performance may result during warmer temperatures, and are likely to increase odour, or change the WWTP process inputs or effluent characteristics.

Increased temperature may change WWTP processes as biological reactions naturally occur much faster in higher temperatures. Given the secondary treatment phase within WWTPs relies on these biological reactions, warmer temperatures would decrease land requirements, enhance conversion processes, increase removal efficiencies and make the utilisation of some treatment processes feasible (Tolkou and Zouboulis, 2015). During 'sludge digestion', the sludge is required to be heated to 37 °C. A rise in ambient temperature would mean less energy is required for this heating. Processes such as activated sludge and aerobic biofilm reactors are less dependent on temperature, as a result of higher technological input and mechanization (Pocock & Joubert, 2017) and therefore would be less affected.

Another potential impact of a warmer climate is higher evaporation rates, as with increased temperature the water-holding capacity of the atmosphere increases. For WWTPs this could mean the final discharge standards for effluent become stricter, due to increased salinity in receiving water bodies (Pocock & Joubert, 2017).

3.4. Impacts on on-site wastewater systems

The most significant impacts of climate change on on-site wastewater systems are identified to be changes to the soakage field performance resulting from groundwater, ecological and soil structure changes, floating, performance varying with temperature, and increased odours. Increased rainfall intensity and sea-level rise will raise groundwater tables and increase the likelihood of saturated soil. This, in turn, prevents effective treatment of wastewater, resulting in elevated pathogens, nutrients and biochemical oxygen demand (BOD) (Cooper, Loomis, & Amador, 2015). Additionally, higher soil temperatures can result in lower oxygen solubility and higher soil microbial oxygen consumption, resulting in further reduction in levels of oxygen available for wastewater treatment (Amador, Loomis, & Kalen, 2014).

Changes in groundwater levels may cause damage to buried structures, pipes and connections particularly in expansive soils which are expand and contract with changes in groundwater level. Cracking of buried structures may be caused if settlement occurs, causing leakage or system failure. Conversely, if groundwater levels rise, this can result in changes in buoyancy of buried structures and may cause floatation (Auckland Council, 2015a; 2015b).

3.5. Impacts summary

As well as the identified impacts of climate change, many existing problems with wastewater systems are likely to be exacerbated. Existing problems relate to aging infrastructure, poorly designed infrastructure, or infrastructure that is designed to meet outdated environmental or service standards (NIWA et al., 2012). New Zealand on-site wastewater disposal systems are dominated by septic tanks, which generally treat effluent to a minimum standard. Many systems are ageing and while all systems require ongoing maintenance, it has been identified that in many cases this is not carried out (Ministry for the Environment, 2008c). Climate change impacts will potentially exacerbate existing issues with poor performing or poorly maintained systems.

In order to characterise and further explore impacts and their implications, three main summary impact themes for wastewater have been developed and are listed below. These themes were chosen by grouping the impacts discussed for each of the wastewater system components above into similar types of impacts, termed 'impact themes'. The identified impact themes are:

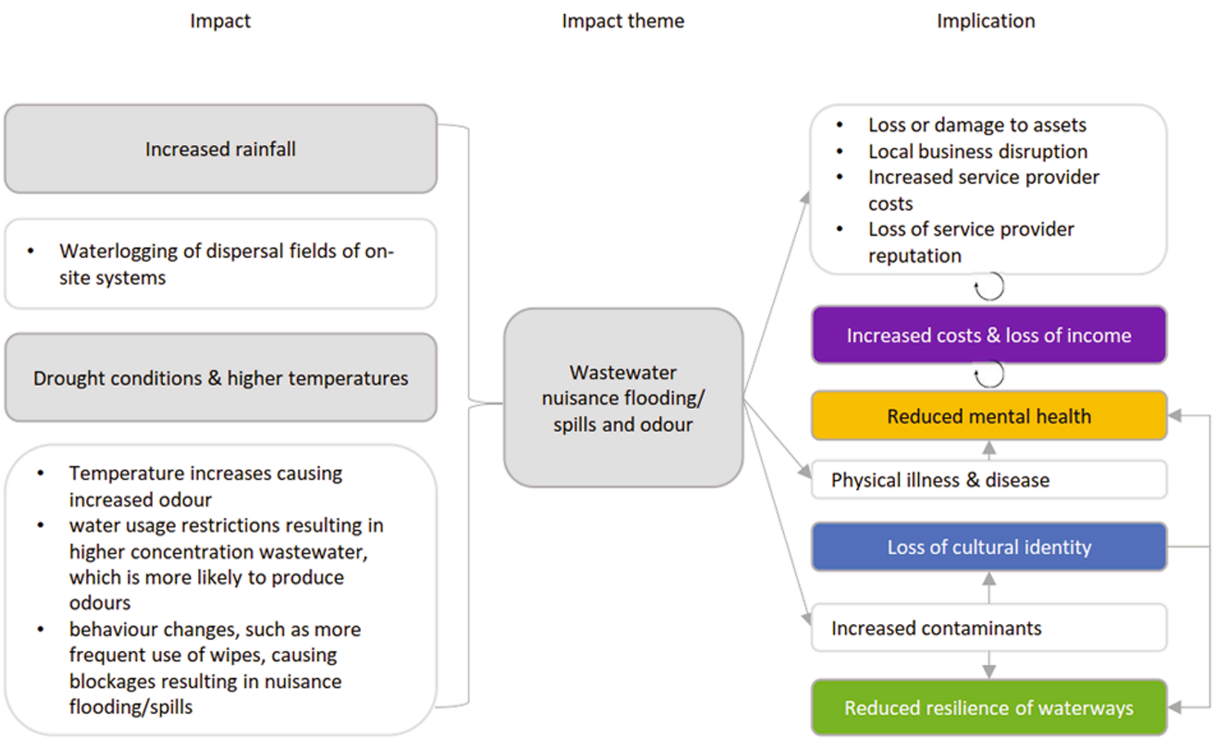

Fig. 1. Summary of impacts resulting in nuisance flooding, spills and odour and the associated implications. Key implications are denoted with coloured boxes relating to the social (yellow), environmental (green), cultural (blue) and economic domains (purple). Arrows identify relationships between implications, where one implication can be a precursor to another. Circular arrows indicate feedback loops, indicating a cyclical relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- Wastewater nuisance flooding, spills and odour
- Water quality deterioration due to worsening impacts of wastewater discharges
- Damage to infrastructure leading to disruption to wastewater services

4. Implications of climate change for wastewater systems across four domains

The sections below present a discussion of the social, environmental, cultural, and economic implications arising from the identified impact themes. Implication maps in the form of 'bow-tie' diagrams for each of the impact themes show the various relationships between climate hazards, impacts and implications. Relationships between implications are identified, including those that occur during or immediately after a climate change impact, and cascading implications over the medium to long term, including those from gradually evolving stressors for example sea level rise. As described in Lawrence et al. (2020) many of these implications move across space and organisations as a cascade. For example, a loss in community facilities such as loss of access to waterways due to poor water quality can, among other implications, contribute to a reduction in community cohesion. This in turn is known to contribute to reduction in mental health of individuals, which has further economic implications. As mental health is the long-term implication from the loss of community facilities, and other implications also lead to this reduction, mental health is identified as a key implication in the bow-tie diagrams, and relationships between mental health and other implications is indicated through linking arrows and feedback loops. It is noted that as cascades move through social cultural, environmental, and economic domains they can combine or compound because of external policy decisions or concurrent impacts and implications, some of which are beyond the scope of this research.

4.1. Implications arising from wastewater nuisance flooding, spills and odour

Nuisance flooding, spills and odour arising from the impact of climate change on wastewater systems is expected to arise primarily from increased rainfall. We define nuisance flooding for the purpose of our discussion as wastewater flooding that is not related to waterways, for example flooding arising from a waterlogged on-site wastewater field. Wastewater flooding resulting in the reduced resilience of waterways and assimilative capacity is discussed in Section 4.2. The key implications arising from nuisance flooding, spills and odour are the loss of income and increased costs for residents and business owners; reduced mental health for residents and impacting the community as a whole and loss of cultural identity, as shown in Fig. 1.

Disruption to businesses and residents is an immediate implication of wastewater nuisance flooding or spills (Curtis, Fair, Wistow,

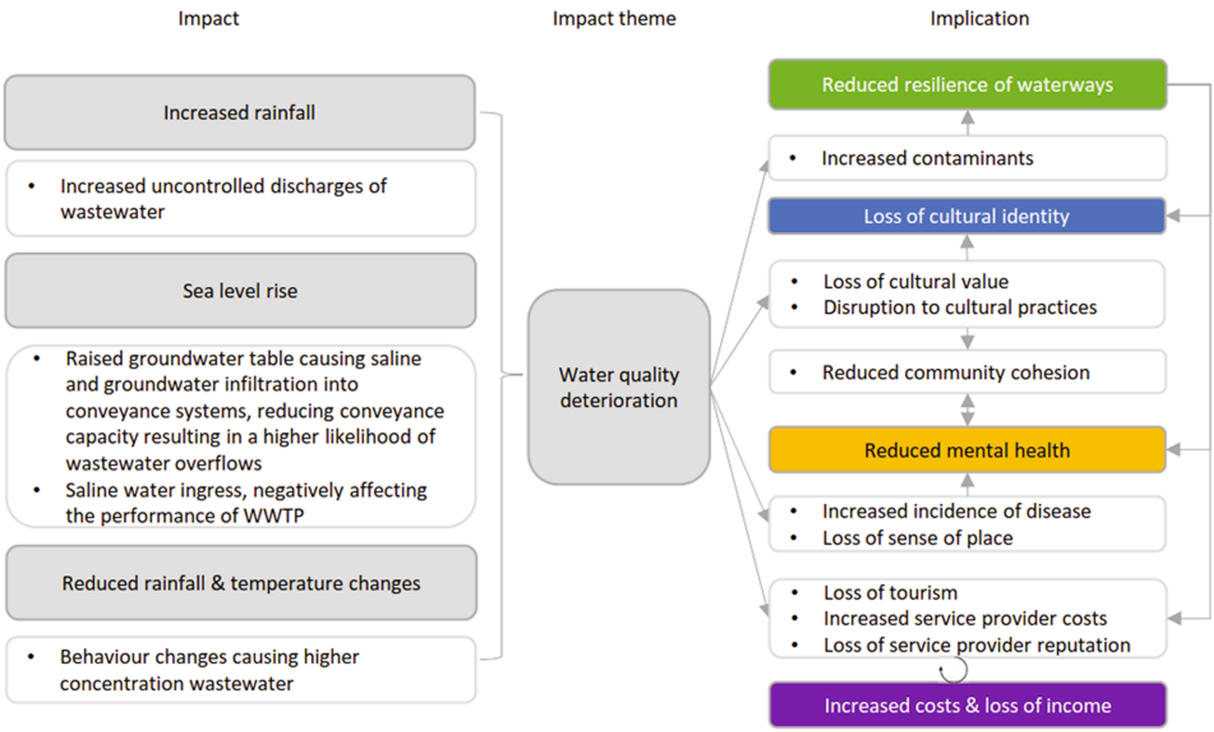

Fig. 2. Summary of impacts resulting in water quality deterioration and the associated social, cultural, environmental and economic implications. Key implications are denoted with coloured boxes relating to the social (yellow), environmental (green), cultural (blue) and economic domains (purple). Arrows identify relationships between implications, where one implication can be a precursor to another. Circular arrows indicate feedback loops, indicating a cyclical relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Val, & Oven, 2017; World Health Organisation, 2013). Clean-up activities are likely to cause temporary closure of businesses and roads, and nuisance flooding and spills may also result in the evacuation of homes. Businesses may incur clean-up costs, and a loss of income due to foregone production (Surminski & Hankinson, 2018; Wang, Zeng, & Zhong, 2017; Fatoric, Moren-Alegret, Niven, & Tan, 2017; Fauzel, Seetanah, Sannassee, & Nunkoo, 2017).

Exposure of residents to untreated wastewater resulting from spills poses an immediate threat to public health and associated deteriorating water quality can also be a source of illness over the short and medium term infections (World Health Organisation, 2013; Zhang, 2010; The National Institute for Occupational Safety and Health, 2012). Repeated exposure to odour can lead to respiratory disorders and have a negative impact on mood (Schiffman & Williams, 2005; Bay of Plenty Regional Council, 2012; Shusterman, 1992).These implications can lead to further reduced mental health in the community over the medium to longer term.

Wastewater spills or overflows can lead directly to an immediate loss of cultural values as Māori have a cultural aversion to the discharge of raw (or treated) human wastewater to natural waterways, as well as the transportation of wastewater past marae, urupā and other sacred areas (Bradley, 2016). Within a traditional Māori world-view, places or activities related to human waste are deemed to be 'tapu' or spiritually dangerous (Bradley, 2016). The implications of contamination of cultural land through wastewater flooding, spills or odour may be exacerbated because of the special relationship that Māori have with the land; the health and well-being of Māori people is often dependent on the condition of their local natural resources and environment (Manning, 2015; NZIER, 2003; Smith, 2014; King et al., 2010; Jones, 2019). Loss of cultural values due to the degradation of cultural sites in turn can lead to reduction in mental health of Māori (King et al., 2012a, 2012b) and is also important for the broader community, who may lose community cohesion that has been tied to physical sites (Carmichael, et al., 2018).

4.2. Implications arising from water quality deterioration due to increased uncontrolled wastewater discharges

Water quality deterioration due to increased uncontrolled wastewater discharges is expected to arise from increased rainfall, sea-level rise, reduced rainfall and increased temperature extremes, and will potentially coincide with a reduction in assimilative capacity of receiving environments. The key implications for the impact theme of water quality deterioration are: reduced resilience of waterways, reduced mental health for residents and impacting the community as a whole; loss of cultural identity; and loss of income and increased costs for service providers, residents and business owners, as shown in Fig. 2.

Water quality deterioration leads to the key implication of reduced resilience of waterways which will occur primarily in response to the increased discharge of wastewater contaminants during high rainfall. Increased nutrients entering waterways as a result of spills can promote algal growth and increase toxicity (Sinha et al., 2017; ANZECC, 2000). These direct implications are immediate and may also lead to a disruption in the aquatic ecosystem over the medium term, or coupled with increased air temperatures can lead to an increased frequency of phytoplankton blooms and subsequent alteration of the trophic balance (Komatsu et al., 2007). Over the longer term, this leads to reduced resilience of the waterways to recover from events. The capacity for the receiving water to accommodate treated wastewater discharges may be reduced if reductions in base flows within receiving watercourses negatively impact water quality, therefore decreasing the assimilative capacity of the receiving water (Whitehead et al., 2009; WERF, 2009). A better understanding of the assimilative capacity of sensitive receiving environments under climate change conditions will thus be a critical component in informing the design of WWTPs that discharge to sensitive environments.

Reduced resilience of waterways related to the discharge of raw wastewater causes a significant loss of cultural values for Māori (Section 4.1). Increased pathogens from human waste will lead to restrictions on recreational water activities which has implications for gathering kaimoana (sea food) in the wider region, which is an important cultural practice for Māori (Durette et al., 2009; Potangaroa, 2010). Reduced resilience of waterways has implications for other traditional land, river and sea based activities, which can lead to a loss in traditional and a loss of connection to cultural identity over the medium to long term for Māori (King et al., 2012a, 2012b) as well as other indigenous cultures (Downing & Cuerrier, 2011; Carmichael, et al., 2018).

In addition to social health issues related to exposure to wastewater spills (refer Section 4.1), exposure to unsafe water due to wastewater contamination presents a heightened risk of infection such as faecal-oral disease, vector-borne diseases, asthma, skin rashes, and poisoning (Vardoulakis, et al., 2015; Ahern et al., 2005). Reduced amenity of waterways can disrupt place-based activities in the community, which can lead to *solastalgia*, or a loss of sense of place, over the short to medium term (Berry et al., 2010). These implications can lead to further reduced mental health in the community over the medium to longer term (Albrecht et al., 2007).

Increased preventive maintenance and water quality management costs are likely to be incurred by service providers in the short to medium term as a response to any rising water quality deterioration. These costs may be passed on to the community through rates and taxes, all of which may contribute to a loss of service provider reputation. Water quality deterioration is also likely to result in a loss of tourism within or to New Zealand, which is known for its 'clean, green' image. This may result in medium and long term economic impact (Wang et al., 2017; Fatoric et al., 2017).

4.3. Implications arising from damage to wastewater infrastructure

Damage to wastewater infrastructure is expected to arise from increased rainfall, sea-level rise, reduced rainfall and increased temperature extremes. These damages will result in increased maintenance, repair and disruption to wastewater services due to system component failure which will occur at a local and community wide scale. The key implications for the impact theme of damage to wastewater infrastructure are: loss of income and increased costs for residents and business owners; reduced mental health for residents and impacting the community as a whole; loss of cultural identity; and environmental damage and reduced resilience of waterways, as shown in Fig. 3.

Disruption to residents and businesses is an immediate implication of event-based damage to wastewater infrastructure. Loss of services to residents is likely to cause stress (Stanke, 2012), and due to wastewater systems not working (toilets not flushing, showers unusable etc.) temporary evacuations of homes may be required. Repair works are likely to cause temporary closure of businesses and schools, incurring repair costs and loss of income due to foregone production until wastewater services are functional. Chronic damage to infrastructure, such as higher strength wastewater causing corrosion, will require increased maintenance, repair and running costs. These costs are likely to be incurred by service providers in the short to medium term but may be passed on to the community through rates and taxes, all of which may contribute to a loss of service provider reputation. Home owners, residents, and business owners, are likely to face increasing insurance premiums due to increased and/or ongoing damage (Surminski & Hankinson, 2018), and in the worst cases, it may not be possible to renew insurance to cover losses from future events (Salmeemul et al., 2007).

Damage can lead to increased incidence of disease or excess nutrients entering waterways. This is particularly acute in gravity conveyance, where breakages or leaks can be difficult to detect, or where on-site wastewater treatment devices are affected, as these systems are usually subject to much less frequent performance monitoring relative to wastewater treatment plants. Significant implications for social, cultural, economic and environmental domains have been identified as arising from exposure to wastewater contamination and water quality reduction (see Section 4.1 and Section 4.2).

Damage to wastewater infrastructure will occur in both existing urban areas, and areas where proposed urban expansion may become inappropriate due to a changing risk profile such as in close proximity to the coast (Ministry for the Environment, 2008b). Climate change may result in existing wastewater systems becoming unable to provide adequate service, as the conditions for which they were designed change. For example, this may occur through sea level rise flooding WWTPs and pipes, repeated storm damage, or increased flooding in combined wastewater pipes.

Service withdrawal and managed retreat may be considered if loss of land or ongoing damage to wastewater infrastructure is likely (Hanna et al., 2017; Haasnoot et al., 2013). This is associated with extensive cascading social, environmental, cultural and economic

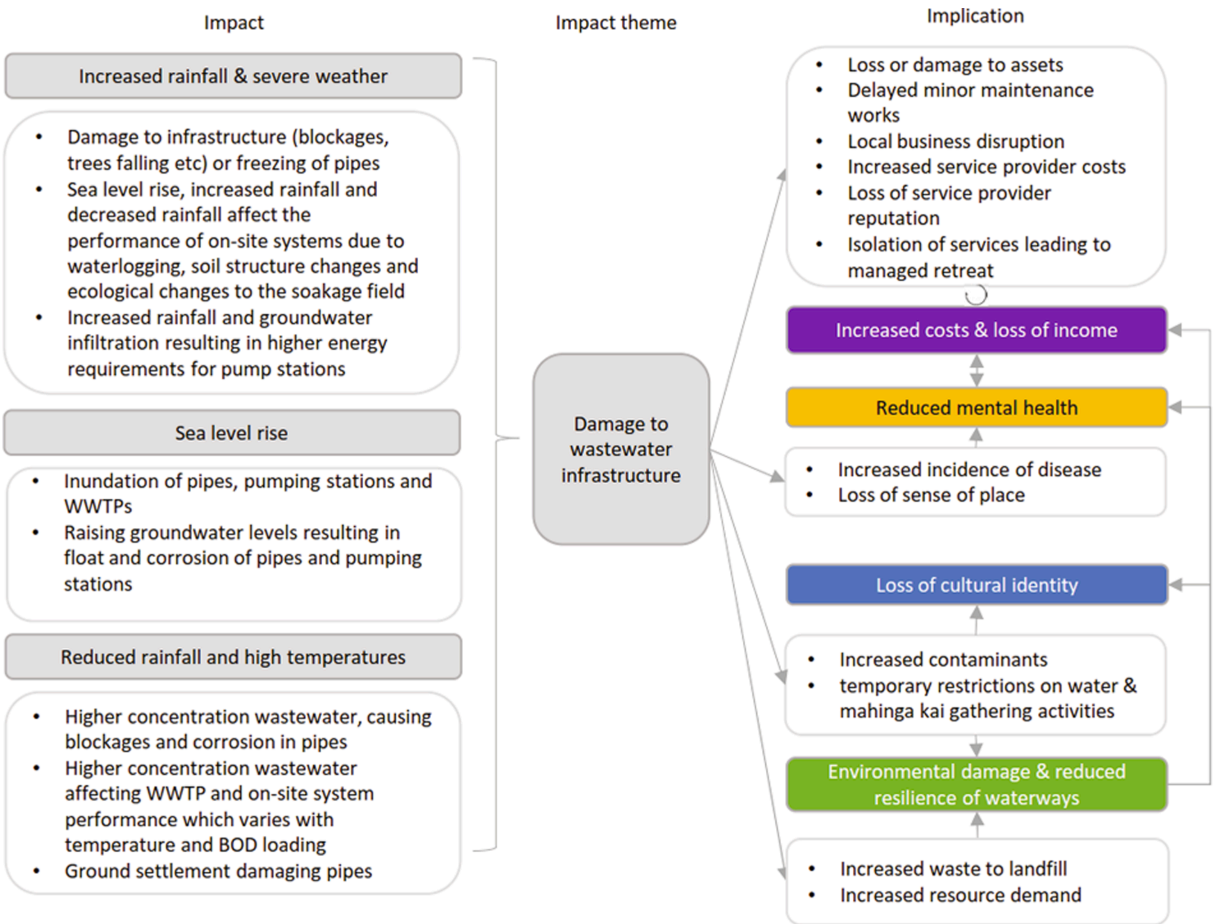

Fig. 3. Summary of impacts resulting in damage to infrastructure and the associated social, cultural, environmental, and economic implications. Key implications are denoted with coloured boxes relating to the social (yellow), environmental (green), cultural (blue) and economic domains (purple). Arrows identify relationships between implications, where one implication can be a precursor to another. Circular arrows indicate feedback loops, indicating a cyclical relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

implications that are unique in the way they exhibit over the long term. Retreat, once implemented is a way of permanently reducing hazard exposure, thereby reducing the impact of climate change in the long term (Hino et al., 2017). The scale of retreat i.e. whether infrastructure can be moved back from the coast in the first instance, or whether whole communities need to be relocated, has an influence on the implications which arise. Property rights, protection of the status quo, large up-front costs, logistic difficulties and political complexity have been identified as significant social and economic drivers that favour staying in place in a New Zealand context (Hanna et al., 2020). Despite its goal to reduce physical harm from hazards, managed retreat can be extremely socially and culturally disruptive for the communities affected, and has significant cultural implications for Māori facing retreat from ancestral land (King et al., 2012a, 2012b). Experiences from relocation of Pacific indigenous communities has identified difficulty in overcoming culturally sensitive issues such as place attachment, land rights, community consensus and governance (Dannenberg et al., 2019). Residents experiencing managed retreat may experience the loss of community, identity and employment and be unable to afford to purchase a house of comparable value (in economic and sentimental term). These issues and additional psychological stress associated with coping with uncertainty and change may lead to reduced mental health (Hanna et al., 2020; Dannenberg et al., 2019). Economic implications of relocating wastewater infrastructure are significant, however costs are also associated with continuous repair and maintenance associated with remaining in place, retrofit options to protect the system, or measures to accommodate sea-level rise, which still have an element of residual risk (Kool, 2020). As demonstrated in Kool et al. (2020), dynamic adaptive pathway planning for the retreat 2-waters services is useful to balance these drivers.

5. Discussion and recommendations

The propagation of impacts into numerous interrelated and cascading social, cultural, economic and environmental implications is significant as it indicates how far the implications of climate change may reach when considering wastewater in isolation. Many of the identified impacts will occur simultaneously throughout the wastewater system both due to compound hazards and due to multiple vulnerable components within the system. Further, impacts and implications from climate change on other systems and sectors will place a significant burden on society. Many of the implications identified in this research are central issues within mainstream contemporary New Zealand; key implications such as reduced mental health and resilience of waterways are the subject of extensive policy reform through creation of the Mental Health and Wellbeing Commission, and updates to the National Policy Statement on Freshwater Management (Ministry for the Environment, 2020a; 2020b). The loss of cultural identity is also of critical concern in the context of ongoing historical impacts of colonization for Māori, under which breaches of promises made under the foundational settlement agreement the 'Treaty of Waitangi' are still being resolved. We identify that climate change will place further stress on these important issues.

Improved understanding of impacts and implications of climate change is essential for building the confidence of wastewater sector decision makers, when developing policy and in adaptive planning. A good understanding of climate hazards or stressors; a good understanding of direct impacts; and a good understanding of cascading implications allows decision makers to project future impacts and implications and prioritise response options to minimise risk and future impacts and implications. Ensuring a cohesive government and institutional environment for decision making is key to strengthening community and individual climate change responses (Signh et al., 2018). When considering approaches and principles for adaptive management, it is important to recognise the range of interrelated issues and initiatives within a national and sectoral context – some of which may present additional risk, while others may provide opportunities for co-beneficial outcomes if considered collectively.

New Zealand is in the early stages of planning to adapt to climate change, but recent years have seen some significant steps towards acknowledging national climate risk (Ministry for the Environment, 2020a; 2020b) and developing strategies to adapt to climate change (New Zealand Government, 2019). These steps are in alignment with recommendations from the New Zealand Climate Change Adaptation Working Group (2018). These national scale recommendations provide principles to guide, support and help sustain actions for climate change adaptation, as well as actions for immediate and ongoing action. It is within this context of evolving action to mitigate and adapt to the effects of climate change that this research sits. Based on the findings from this research and informed by the wider context of adaptation within New Zealand, a range of guiding principles for local government decision-makers has been developed.

5.1. *Guiding principles for local government decision makers*

The following series of guiding principles were developed based on a number of common themes which arose from a detailed a literature review and the researchers' understanding of key contextual issues within New Zealand. These drew on a range of sources including; recommendations from the Climate Change Technical Working Group (Climate Change Adaptation Technical Working Group, 2018) – which provides recommendations to guide effective adaptation at a national scale; The New Zealand Auditor General's assessment of managing stormwater systems to reduce flood risk (Controller and Auditor General, 2018) – which provides recommendations on how to manage stormwater systems to protect people and property from the risk of flooding; the New Zealand Government's Living Standards Framework (New Zealand Treasury, 2018) - which uses the four capitals of social, human, natural and financial to measure intergenerational wellbeing; the Local Government New Zealand position statement (LGNZ, 2017) - which highlights the need for collaboration within and across the sector, the need to incorporate climate change impacts/implications into decision-making; the National Policy Statement for Freshwater Management (Ministry for the Environment, 2020a; 2020b) - which prioritises the health and wellbeing of waterbodies and freshwater ecosystems; and the Australian National Climate Resilience and Adaptation Strategy (Australian Government, 2015) - which developed a series of guiding principles including shared responsibility,

Table 3
Guiding principles for local government decisionmakers.

Principle	Why this is important	Examples of application
Principle 1: Factor climate risk into decisions	Consideration of the current and future climate in all decisions for wastewater infrastructure is needed to ensure continuity of service. This includes decisions for asset management, renewals, and planning	• Understanding and monitoring climate change risk and performance for wastewater assets, along with monitoring changes in community, indigenous tribe and subtribe (iwi/hapū) and stakeholder perceptions of the levels of service. • Reviewing and updating design standards to incorporate latest knowledge on the impacts of climate change and eventually moving to adaptive design standards (e.g. (Ayyub, 2018) • Incorporating climate risk and funding models into the asset management plans and infrastructure strategies and ensure resilience / adaptation measures are identified. • Local and central government agencies working together, within and across the sector, to understand and agree on best practice and develop a plan to improve maturity of practice from 'awareness' to 'advanced performance' (IPWEA, 2015) in risk and resilience planning and decision-making. This would shift asset management focus from response-based action to anticipatory action that reduces risks ahead of reaching adaptation thresholds. • Developing and regularly updating climate change adaptation plans for infrastructure and communities. • Identifying key critical assets (such as low-lying WWTPs) that will require adaptive measures for continued performance, with agreed adaptive management plans and timeframes.
Principle 2: Base decisions on evidence and current national guidance, supported by sound data and local knowledge	This is the basis of informed decision making and best practice in participatory democracy. Using the best available information in education, community consultation, planning and decision making is vital. It includes incorporating reliable sources of scientific information about climate change scenarios, impacts and implications, as well as local and indigenous knowledge.	• Ensuring a robust environmental / natural hazard monitoring plan that captures relevant data on an ongoing basis, at an appropriate frequency and granularity - in order to enable planning for both gradual and event-based climate hazards. This includes monitoring water quality, rainfall, runoff and groundwater levels and the magnitude and frequency of various levels of events consistently and in an ongoing manner to quantify changes driven by climate change. • Monitoring of environmental changes and use of indigenous knowledge (matauranga[1] Māori) to inform an understanding of changes, and to inform decision-making, and solutions. • Ongoing monitoring of wastewater network and asset performance, including outages and sewer overflows. • Ensuring that asset information is up to date and available, and exposure of assets to climate hazards/stressors is monitored. • Communicating risk to communities in a transparent and ongoing manner.
Principle 3: Cooperation and collaboration	Identifying and advancing opportunities for collaboration, as well as addressing internal structural and policy barriers or misalignments, will enable improved decision-making. This involves including local and central government, business, communities, lifeline services, indigenous representatives, researchers and other experts, who all have a role to play. In particular, it is important that the knowledge and experience of those affected is respected and they are involved in decision-making.	• Better co-ordination and integration of effort within and across councils to create efficiencies in data collection and analysis, and to share practice and resources. This was highlighted by LGNZ (2019) with specific mention of: variation across councils in terms of asset and financial data availability, as well as systems and formats in which the data is held; and lack of integration

(continued on next page)

Table 3 (*continued*)

Principle	Why this is important	Examples of application
		between spatial infrastructure data and financial information. • Sharing of best practice in climate risk assessments, adaptation planning, and wastewater management and design. • Looking for opportunities for regional / national collaboration for projects that have benefits across multiple local government authorities. For example, common design guidelines, data gathering to benefit multiple local government authorities, common systems and adaptation approaches. • Engaging with stakeholders according to best practice (such as that developed by the International Association for Public Participation (2014)) and endeavouring to meaningfully collaborate with stakeholders. • Identify and address structural and policy misalignments with local government authorities with respect to management of wastewater systems.
Principle 4: Stewardship (kaitiakitanga[2]) and precaution	Each person and organisation has a duty of care to safeguard the life-supporting capacity of our people and environment (kaitiakitanga), on which we all depend. There is clear and compelling evidence for the need to act now on climate change and to adopt a precautionary approach because of the irreversible nature and scale of most of the risks involved (Abram, et al., 2019; IPCC, 2018; IPCC, 2014b).	• Shifting planning and asset management focus from response-based action to anticipatory planning and action where possible to avoid reaching adaptation thresholds where impacts become intolerable. • Embedding climate resilient (e.g. *water sensitive)* design approaches within council standards and developing upskilling and education initiatives around this, incorporating indigenous knowledge (matauranga Māori) principles where applicable. • Ensuring that the management of wastewater is considered within broader land use, ecological, social and cultural constraints. • Upholding a) the rights of indigenous peoples; which in a New Zealand context includes honouring the Treaty of Waitangi, b) intergenerational sustainability, and c) the principles of ecologically sustainable development (Preston, 2016) in designing adaptation and mitigation approaches.
Principle 5: Prioritise the most vulnerable	It is important that adaptation responses support those who are most vulnerable to climate change impacts as it is these groups in our community who are often disproportionately affected by climate change and natural hazards.	• Identifying vulnerable communities and working with them to understand climate hazards that may affect them, and developing response and adaptation strategies that are acceptable, effective and recognise the unique social/ cultural/economic circumstances of each community.
Principle 6: Long term, adaptive thinking	Long-term thinking, policies and actions are necessary to ensure the reasonably foreseeable needs of current and future generations are met, this includes adopting adaptive planning (Lawrence, Bell, & Stroombergen, 2019), and performing regular monitoring and review of actions.	• Careful development of adaptation options and plans which consider the range of possible future scenarios, including unintended consequences, maladaptation, lock-in etc. • Consideration of a range of 'typologies' of adaptation options, from hard physical defences, to flexible/modular solutions, to emergency response / early warning systems – as well as appropriate pathways/signals/triggers for each agreed option (Ministry for the Environment, 2017). • Consideration and awareness of broader implications of insurance and un-insurability due to climate change. Councils, asset owners and

(*continued on next page*)

Table 3 (*continued*)

Principle	Why this is important	Examples of application
		communities must be aware of their insurability and liability, with mechanisms in place to manage the changing risks. More generally, lenders, property owners and developers should evaluate property security in a way which places less reliance on backward looking valuation models and considers long-term changes in risks arising from climate change. • Securing funding sources to ensure the risks of climate change are well understood, and that investment can be made to maintain an acceptable level of service.
Principle 7: Prioritise actions with multiple benefits or which have 'low-regrets'	Prioritising actions that are worth doing regardless of the impacts of climate change may enable the realisation of multiple benefits. These include those for the environment, for managing coastal processes, for the affordable and efficient provision of infrastructure, for nature-based amenity and for more socially cohesive settlements.	• Identifying actions which meet other national / sectoral challenges such as freshwater quality, aging infrastructure, biodiversity or GHG reduction. • Considering nature-based systems based on water sensitive principles (Auckland Council, 2015).

[1] matauranga Māori translates to Māori knowledge. It relates to the body of knowledge originating from Māori ancestors, including the Māori world view and perspectives, Māori creativity and cultural practices.

[2] Kaitiakitanga means guardianship and protection in Māori language. It is a way of managing the environment, based on the Māori world view

factoring climate risk into decisions, assisting the most vulnerable, evidenced based decision-making; collaborative and values-based choices; and regular review of actions over time.

Adopting the proposed principles in Table 3 and described further below will best enable local government to manage the impacts of climate change both broadly and also specifically for wastewater systems. Examples of application of the guiding principles in decision making for wastewater infrastructure including asset management, renewals, and planning are include

6. Conclusion

Much of New Zealand's wastewater infrastructure is vulnerable to the hazards associated with a changing climate. The nature of existing wastewater systems, often designed on past climate and sea-level criteria, mean that they will be significantly impacted in a wide variety of ways including the increasing occurrence of compounding hazards and cascading impacts. It is expected that climate change will impact all elements of wastewater systems, and the essential functions they provide in protecting the health of communities and natural environments.

Sea-level rise and changes in rainfall are expected to lead to impacts with high severity, with further impacts of medium and low severity expected from wind and temperature increases. Impacts will range from capacity and levels of service impacts, to effects on treatment performance and water quality of receiving environments. Impacts are expected to concentrate in low lying areas that are exposed to coastal and inland flooding but will also be distributed throughout the system as increased temperature, groundwater changes and user behaviour changes result in system-wide impacts. Although originating from a range of climate drivers and occurring throughout the geographically dispersed wastewater system, the impacts that have been identified can be simplified by grouping into three categories. Each of these 'impact themes' propagate numerous interrelated and cascading social, cultural, economic and environmental implications.

Many of these impacts are already emerging and action will be required now, in order to mitigate worsening impacts. Local government authorities therefore need to be aware of climate impacts and risks in order to make important long-term decisions relating to their infrastructure. These decisions need to be considered along with other current and future pressures relating to land use, growth and renewals, as well as the real possibility of insurance retreat over the medium to longer term.

The principles developed in this paper (Table 3) are designed to support councils and asset owners or managers to proactively respond to emerging climate risks to their wastewater systems, as well as assisting them with adaptation decision-making under a changing climate.

The findings in this paper provide an evidence base to understand not only the *impacts* but the consequential and potentially far-reaching *implications* across the economic, environmental, cultural and social domains.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors were funded by the New Zealand Deep South National Science Challenge *Stormwater, wastewater and climate change: Impacts on our economy, environment, culture and society project* through the Ministry of Business, Innovation and Employment. The authors thank all the research participants for their contributions. The authors also thank the useful feedback received from three anonymous reviewers.

References

Aboulnaga, M. M., Elwan, A. F., Elsharouny, M. R., & Aboulnaga, M. M. (2019). Climate Change Impacts on Urban Areas and Infrastructure. In: Urban Climate Change Adaptation in Developing Countries. Switzerland : Springer, Cham. doi:https://doi.org/10.1007/978-3-030-05405-2_3.

Abram, N., Gattuso, J.-P., Prakash, A., Cheng, L., Chidichimo, M. P., Crate, S., . . . K, v. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M.Weyer (eds.)]. In press. IPCC.

Ahern, M., Sari Kovats, R., Wilkinson, P., Few, R., Matthies, F., 2005. Global Health Impacts of Floods: Epidemiologic Evidence. Epidemiol. Rev. 27 (1), 36–46. https://doi.org/10.1093/epirev/mxi004.

Albrecht, G., Sartore, G., Kelly, B., Stain, H.J., 2007. Solastalgia: The distress caused by environmental change. Australasian Psychiatry(15), S95–S98. https://doi.org/10.1080/10398560701701288.

Amador, J., Loomis, G., Kalen, D., 2014. Soil-based Onsite Wastewater Treatment and the Challenges of Climate Change. *Innovation in Soil-Based onsite wastewater treatment*. Soil Science Society of America, Albuquerque, pp. 6–11.

ANZECC. (2000). Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy. Canberra, Australia: Australian and New Zealand Environment and Conservation Council. Agriculture and Resource Management Councils of Australia and New Zealand. Retrieved from https://www.waterquality.gov.au/anz-guidelines.

Council, A., 2015a. Code of Practice for Land Development and Subdivision Chapter 4 Stormwater. Auckland Council, Auckland.

Council, A., 2015b. Water Sensitive Design Manual. Retrieved from, Auckland Council http://www.aucklanddesignmanual.co.nz/regulations/technical-guidance/wsd.

Australian Government, 2015. National Climate Resilience and Adaptation Strategy. Retrieved from, Australian Government https://www.environment.gov.au/climate-change/adaptation/strategy.

Ayyub, B., 2018. Climate-resilient infrastructure: Adaptive design and risk management. Committee on Adaption to a Changing CLimate, ASCE Manuals and Reports on Engineering Practice 140. https://doi.org/10.1061/9780784415191.

Bay of Plenty Regional Council, 2012. A review of odour properties of H2S - Odour Threshold Investigation 2012. Bay of Plenty Regional Council, Whakatane.

Befus, K., Barnard, P., Hoover, D., Finzi Hart, J., Voss, C., 2020. Increasing threat of coastal groundwater hazards from sea-level rise in California. Nat. Clim. Change 10, 946–952. https://doi.org/10.1038/s41558-020-0874-1.

Benotti, M.J., Stanford, B.D., Snyder, S.A., 2010. Impact of Drought on Wastewater Contaminants in an Urban Water Supply. J. Environ. Qual. 39 (4), 1196–1200. https://doi.org/10.2134/jeq2009.0072.

Berry, H.L., Bowen, K., Kjellstrom, T., 2010. Climate change and mental health: a causal pathways framework. Int J Public Health 55 (1), 123–132. https://doi.org/10.1007/s00038-009-0112-0.

Boholm, A., Prutzer, M., 2017. Experts' understandings of drinking water risk management in a climate change scenario. Clim. Risk Manage. 16, 133–144. https://doi.org/10.1016/j.crm.2017.01.003.

Bradley, J., 2016. Maori cultural considerations in developing and operating wastewater systems: Case history experiences. WaterNZ, Wellington.

Budicin, A., 2016. Analysis of drought associated impacts on the city of San Bernardina Municipal Water Department's wastewater flow rates and consitituent concentrations. California State University, San Bernardino, California. Retrieved from https://scholarworks.lib.csusb.edu/etd/319/.

Caloiero, T., 2017. Drought analysis in New Zealand using the standardized precipitation index. Environmental Earth Sciences 569. https://doi.org/10.1007/s12665-017-6909-x.

Carey-Smith, T., Henderson, R., Singh, S., 2018. High Intensity Rainfall Design System Version 4. NIWA, Wellington.

Carmichael, B., Wilson, G., Namarnyilk, I., Nadji, S., Brockwell, S., Webb, B., Bird, D., 2018. Local and Indigenous management of climate change risks to archaeological sites. Mitig Adapt Strateg Glob Change 23, 231–255. https://doi.org/10.1007/s11027-016-9734-8.

Chapra, S.C., 2008. Surface water-quality modelling. Waveland Press Inc., Illinois. Retrieved from https://www.researchgate.net/publication/48447645_Surface_Water-Quality_Modeling.

Climate Change Adaptation Technical Working Group. (2018). Adapting to Climate Change in New Zealand. Recommendations form the Climate Change Adaptation Technical Working Group. Wellington: Climate Change Adaptation Technical Working Group, Ministry for the Environment New Zealand. doi:ISBN: 978-1-98-852547-1.

Controller and Auditor General Managing stormwater systems to reduce the risk of flooding 2018 Controller and Auditor General, Government of New Zealand Wellington ISBN 978-0-478-44299-1.

Cooper, J., Loomis, W., Amador, J., 2015. Reduced water quality treatment functions of soil-based onsite wastewater treatment systems due to climate change. *Onsite Wastewater Mega-Conference*. NOWRA, Virginia Beach.

Curtis, S., Fair, A., Wistow, J., Val, D.V., Oven, K., 2017. Impact of extreme weather events and climate change for health and social care systems. Environmental Health 16 (1), 23–32. https://doi.org/10.1186/s12940-017-0324-3.

Danilenko, A., Dickson, E., Jacobsen, M., 2010. World Bank. Climate Change and Urban Water Utilities : Challenges and Opportunities No. 50.

Dannenberg, A., Frumkin, H., Hess, J., Ebi, K., 2019. Managed retreat as a strategy for climate change adaptation in small communities: public health implications. Clim. Change 153, 1–14. https://doi.org/10.1007/s10584-019-02382-0.

DeZellar, J., Maier, W., 1980. Effects of water conservation on sanitary sewers and wastewater treatment plants. Retrieved from Water pollution controll federation 76–88. https://www.jstor.org/stable/25040552.

Downing, A., Cuerrier, A., 2011. Social and economic impacts of climate change on the First Nations and Inuit of Canada. Retrieved from Indian Journal of Traditional Knowledge 10 (1), 57–70. https://pdfs.semanticscholar.org/0230/2b6430553b2315f19fc57adc973f615afb90.pdf.

Durette, M., Nesus, G., Barcham, M., 2009. Maori perspectives on water allocation. Report prepared for MfE by Nesus & associates ltd., Wellington. Retrieved from https://mfe.govt.nz/sites/default/files/MaoriPerspectivesonWaterAllocationFINAL.pdf.

Fatoric, S., Moren-Alegret, R., Niven, R.J., Tan, G., 2017. Living with climate change risks: stakeholders' employment and coastal relocation in mediterranean climate regions of Australia and Spain. Environ Syst Decis 37, 276–288. https://doi.org/10.1007/s10669-017-9629-6.

Fauzel, S., Seetanah, B., Sannassee, R., Nunkoo, R., 2017. Conference Proceedings of BEST EN Think Tank XVII: Innovation and Progress in Sustainable Tourism. James Cook University, page, Townsville. Retrieved from https://researchonline.jcu.edu.au/50855/.

Ganguli, P., Merz, B., 2019. Extreme coastal water levels exacerbate fluvial flood hazards in northwestern Europe. Sci. Rep. 9, 13165. https://doi.org/10.1038/s41598-019-49822-6.

Gibbs, M.T., 2015. Guiding principles for infrastructure climate change risk and adaptation studies. Civil Engineering and Environmental Systems 32 (3), 206–215. https://doi.org/10.1080/10286608.2015.1025385.

Haasnoot, M., Kwakkel, J., Walker, W., ter Maat, J., 2013. Dynamic adaptive policy pathways: A method forcrafting robust decisions for a deeply uncertain world. Global Environ. Change 23, 485–498. https://doi.org/10.1016/j.gloenvcha.2012.12.006.

Hanna, C., White, I., Glavovic, B., 2017. Managed retreat in New Zealand: revealing the terminology, approaches and direction of local planning instruments. University of Waikato, New.

Hanna, C., White, I., Glavovic, B., 2020. The uncertainty contagion: Revealing the interrelated cascading uncertainties of managed retreat. Sustainability 12, 736.

Henze, M., van Loosdrecht, M., Ekama, G., Brdjanovic, D., 2008. Biological Wastewater Treatment: Principles. IWA Publising, Modelling and Design. Retrieved from https://www.researchgate.net/publication/274255669_Biological_Wastewater_Treatment_Principles_Modeling_and_Design.

Hino, M., Field, C., Mach, K., 2017. Managed retreat as a response to natural hazard risk. Nat. Clim. Change 7, 364–370. https://doi.org/10.1038/nclimate3252.

L. Hiwasaki E. Luna Syamsidik, & Shaw, R. Process for integrating local and indigenous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities International Journal of Disaster Risk Reduction 10 2014 15 27 10.1016/j.ijdrr.2014.07.007.

Hummel, M.A., Berry, M.S., Stacey, M.T., 2018. Sea level rise impacts on wastewater treatment systems along the U.S. coasts. Earth's Future 6, 622–633. https://doi.org/10.1002/2017EF000805.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. World Meteorological Organization, Geneva, Switzerland.

IPWEA, 2015. International Infrastructure Management Manual (IIMM). Retrieved from, IPWEA https://www.ipwea.org/publications/ipweabookshop/iimm.

ISO, 2019. ISO14090:2019 Adaptation to climate change — Principles, requirements and guidelines. Retrieved from, International Organization for Standardization https://www.iso.org/standard/68507.html.

Jones, R., 2019. Climate change and Indigenous Health Promotion. Global Health Promotion 73–81. https://doi.org/10.1177/1757975919829713.

Kettle, N.P., Dow, K., Tuler, S., Webler, T., Whitehead, J., Miller, K.M., 2014. Integrating scientific and local knowledge to inform risk-based management approaches for climate adaptation. Clim. Risk Manage. 4 (5), 17–31. https://doi.org/10.1016/j.crm.2014.07.001.

King, D., Dalton, W., Bind, J., Srinivasan, M.S., Duncan, M., Skipper, A., Baker, M., 2012a. Coastal Adaptation to Climate Variability and Change Examining community risk. vulnerability and endurance at Manaia Settlement. AKL2012-029, Hauraki-Waikato, Aotearoa-New Zealand. Auckland: NIWA Report No.

King, D., Dalton, W., Home, M., Duncan, M., Srinivasan, M., Bind, J., . . . Skipper, A. (2012). Coastal adaptation to climate variability and change: examining community risk, vulnerability and adaptive strategies at Ngaati Huirapa at Arowhenua Paa, Te Umu Kaha (Temuka), New Zealand. NIWA client Report AKL2011-015. 133p. Wellington: NIWA . Retrieved from https://niwa.co.nz/sites/default/files/niwa_report_akl2012-029.pdf.

D. King G. Penny C. Severne The climate change matrix facing Māori society In W. D. Nottage . RAC, Climate change adaptation in New Zealand: future scenarios and some sectoral perspectives 2010 Wellington: New Zealand Climate Change Centre 100 111.

Komatsu, E., Fukushima, T., Harasawa, H., 2007. A modelling approach to forecast the effect of long-term climate change on lake water quality. Ecol. Model. 351–366 https://doi.org/10.1016/j.ecolmodel.2007.07.021.

Kool, R., 2020. Preparing for Sea Level Rise: An Adaptive Managed Retreat Case Study. New Zealand Climate Change Research Institute, Wellington, Auckland.

Kool, R., Lawrence, J., Drews, M., Bell, R., 2020. Preparing for sea-level rise through adaptive managed retreat of a New Zealand stormwater and wastewater network. Infrastructures 5 (11), 92. https://doi.org/10.3390/infrastructures5110092.

Langeveld, J.G., Schilperoort, R., Weijers, S.R., 2013. Climate change and urban wastewater infrastructure: There is more to explore. J. Hydrol. 476, 112–119. https://doi.org/10.1016/j.jhydrol.2012.10.021.

Lansbury Hall, N., Crosby, L., 2020. Climate Change Impacts on Health in Remote Indigenous Communities in Australia. International Journal of Environmental Health Research. https://doi.org/10.1080/09603123.2020.1777948.

Lawrence, J., Bell, R., Stroombergen, A.A., 2019. A Hybrid Process to Address Uncertainty and Changing Climate Risk in Coastal Areas Using Dynamic Adaptive Pathways Planning, Multi-Criteria Decision Analysis & Real Options Analysis: A New Zealand Application. Sustainability 11, 406. https://doi.org/10.3390/su11020406.

Lawrence, J., Blackett, P., Cradock-Henry, N., 2020. Cascading climate change impacts and implications. Clim. Risk Manage. https://doi.org/10.1016/j.crm.2020.100234.

LGNZ, 2017. Local Government Position Statement on Climate Change. Retrieved from. https://www.lgnz.co.nz/assets/Uploads/44591-LGNZ-Climate-Change-wraparound-4-FINAL.pdf.

LGNZ, 2019. Exposed: Climate change and infrastructrue. Retrieved from, LGNZ https://www.lgnz.co.nz/assets/Uploads/6ed34721bd/LGNZ-2019-CC-guidance-document-FULL.pdf.

Major, D.C., Omojola, A., Dettinger, M., Hanson, R.T., Sanchez-Rodriguez, R., 2011. Climate change, water, and wastewater in cities. In: Rosenzweig, C., Solecki, W. D., Hammer, S.A., Mehrotra, S. (Eds.), Climate change and cities: first assessment report of the urban climate change research network), Vol. Cambridge University Press, Cambridge.

Manning, M.L., 2015. Dealing with changing risks: a New Zealand perspective on climate change adaptation. Retrieved from Reg Environ Change 581–594. https://link.springer.com/article/10.1007/s10113-014-0673-1.

Marleni, N., Gray, S., Sharma, A., Burn, S., Muttil, N., 2012. Impact of Water Source Management Practices in Residential Areas on Sewer Networks – A Review. Water Sci. Technol. 624–642, 10.2166/wst.2012.902.

May, C., 2020. Rising groundwater and sea-level rise. Nat. Clim. Change 10, 889–890. https://doi.org/10.1038/s41558-020-0886-x.

Mayne, J., 2015. Useful Theory of Change Models. *Canadian Journal of Program Evaluation / La*. Revue 119–142 doi: 10.3138/cjpe.230 canadienne d'évaluation de programme, 30.2 (Fall / automne).

Mines, R.O., Lackey, L.W., Behrend, G.H., 2007. The impact of rainfall on flows and loadings at Georgia's wastewater treatment plants. Water Air Soil Pollut. 135–157 https://doi.org/10.1007/s11270-006-9220-0.

Ministry for the Environment & StatsNZ, 2017. New Zealand's Environmental Reporting Series: Our atmosphere and climate 2017 ME 1332. Ministry for the Environment & Stats NZ, Wellington. Retrieved from https://www.mfe.govt.nz/publications/environmental-reporting/our-atmosphere-and-climate-2017.

Ministry for the Environment Sustainable Wastewater Management: A handbook for smaller communities Retrieved from https://www.mfe.govt.nz/publications/waste/wastewater-mgmt-jun03 2003.

Ministry for the Environment, 2008. Climate change effects and impacts assesment: A guidance manual for Local Government in New Zealand. Ministry for the Environment, Wellington.

Ministry for the Environment, 2008b. Preparing for climate change: A guide for local government in New Zealand. Ministry for the Environment, Wellington. Retrieved from https://www.mfe.govt.nz/publications/climate-change/preparing-climate-change-guide-local-government-new-zealand.

Ministry for the Environment, 2017. Coastal Hazards and Climate Change Guidance for Local Government. MfE, Wellington. Retrieved from https://www.mfe.govt.nz/publications/climate-change/coastal-hazards-and-climate-change-guidance-local-government.

Ministry for the Environment, 2018. Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessmentt, 2nd Edition. Ministry for the Environment, Wellington. Retrieved from https://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/Climate-change-projections-2nd-edition-final.pdf.

Ministry for the Environment, 2020a. National Climate Change Risk Assessment for Aotearoa New Zealand: Main report – Arotakenga Tūraru mō te Huringa Āhuarangi o Āotearoa: Pūrongo whakatōpū. Ministry for the Environment, Wellington. Retrieved from https://www.mfe.govt.nz/publications/climate-change/national-climate-change-risk-assessment-new-zealand-main-report.

Ministry for the Environment, 2020b. National Policy Statement for Freshwater Management. Ministry for the Environment, Wellington. Retrieved from https://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2020.

Moftakhari, H.R., Salvadori, G., AghaKouchaka, A., Sanders, B.F., Matthew, R.A., 2017. Compounding effects of sea level rise and fluvial flooding. PNAS 114 (37), 9785–9790 www.pnas.org/cgi/doi/10.1073/pnas.1620325114.

Morgan, T., 2006. An indigenous perspective on water recycling. Desalination 187, 127–136. https://doi.org/10.1016/j.desal.2005.04.073.

Naidoo, V., Moolman, V., 2016. April 22). Retrieved from, Excessive water restrictions impact on sewage treatment systems. Engineering News: http://www.engineeringnews.co.za/article/excessive-water-restrictions-might-impact-sewerage-and-sewage-treatment-systems-2016-04-22.

Neunteufel, R., Perfler, R., Schwarz, D., Bachner, G., Bednar-Friedl, B., 2015. Water supply and sanitation. In: Steininger, K., König, M., Bednar-Friedl, B., Kranzl, L., Loibl, W., Prettenthaler, F. (Eds.), Economic Evaluation of Climate Change Impacts Development of a Cross-Sectoral Framework and Results for Austria. Springer International Publishing, Switzerland, pp. 215–234. Retrieved from https://www.springer.com/gp/book/9783319124568.

New Zealand Government. (2019). Climate Change Response (Zero Carbon) Amendment Act 2019. Public Act 2019 No. 61. Wellington: Government of New Zealand. Retrieved from http://www.legislation.govt.nz/act/public/2019/0061/latest/LMS183736.html.

New Zealand Treasury, 2018. Living Standards Framework. Retrieved from. https://treasury.govt.nz/information-and-services/nz-economy/higher-living-standards/our-living-standards-framework.

NIWA, Mwh, GNS, & BRANZ. Impacts of Climate Change on Urban Infrastructure and the Built Environment: Toolbox Handbook 2012 Retrieved from NIWA https://niwa.co.nz/climate/urban-impacts-toolbox.

NIWA; MWH; GNS; BRANZ Impacts of Climate Change on Urban Infrastructure and the Built Environment: Toolbox Handbook Available from: http://www.niwa.co.nz/climate/ 2012.

Nursey-Bray, P.R., Smith, T., Rist, P., 2019. Old ways for new days: Australian Indigenous peoples and climate change. Local Environment 24 (5), 473–786. https://doi.org/10.1080/13549839.2019.1590325.

NZIER, 2003. Māori economic development Te Ōhanga Whanaketanga Māori. New Zealand Institute of Economic Research, Wellington. Retrieved from https://nzier.org.nz/static/media/filer_public/de/31/de315bcb-3188-4760-b21d-348382149aa0/maori_economic_development.pdf.

Olds, H. T., Corsi, R. S., Dila, D. K., Halmo, M. K., Bootsma, J. M., & McLellan, S. L. (2018, July 24). High levels of sewage contamination released from urban areas after storm events: A quantitative survey with sewage specific bacterial indicators. PLOS Medicine. doi:https://doi.org/10.1371/journal.pmed.1002614.

ONeil, J. Climate Change's Impact on the Design of Water, Wastewater, and Stormwater Infrastructure Hydrology Days Retrieved from 79–88 2010.

Oppenheimer, M., Campos, M., Warren, R., Birkmann, J., Luber, G., O'Neill, B., & Takahashi, K. (2014). Emergent risks and key vulnerabilities. In C. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, . . . W. L. L (Eds.), Climate Change 2014: Impacts, Adaptation, and vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 1039-1099). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Retrieved from https://archive.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-FrontMatterA_FINAL.pdf.

Paulik, R., Stephens, S., Bell, R., Wadhwa, S., Popovich, B., 2020a. National-Scale Built-Environment Exposure to 100-Year Extreme Sea Levels and Sea-Level Rise. Sustainability 10 (4). https://doi.org/10.3390/su12041513.

Paulik, R., Stephens, S., Bell, R., Wadhwa, S., Popovich, B., 2020b. National-Scale Built-Environment Exposure to 100-year Extreme Sea Levels and Sea-level Rise. (Special issue "Understanding and Preparing for Uncertainty in. 12 (4), 1513. https://doi.org/10.3390/su12041513.

Plosz, B.G., Liltved, H., Ratnaweera, H., 2009. Climate change impacts on activated sludge wastewater treatment: a case study from Norway. Water Sci Technol. 60 (2), 533–541. https://doi.org/10.2166/wst.2009.386.

Pocock, G., Joubert, H., 2017. Effects of reduction of wastewater volumes on sewerage systems and wastewater treatment Plants. Water Research Comission, Gezina, South Africa. Retrieved from http://www.wrc.org.za/wp-content/uploads/mdocs/2626-1-18.pdf.

Potangaroa, J. (2010). Tuna Kuwharuwharu. An educational resource facts threats and how to help. Wellington: Department of Conservation, Greatwe Wellington Regional Council, Rangitane o Wairarapa Inc. Retrieved from http://www.longfineel.co.nz/wp-content/uploads/2011/06/Tuna-Kuwharuwharu-Longfin-Eel.pdf.

Preston, B.J., 2016. The Judicial Development of Ecologically Sutainable Development. Oslo. https://doi.org/10.4337/9781784714659.

Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R., Pelling, M., . . . Solecki, W. (2014). Urban Areas in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (C. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, . . . L. L. White, Eds.) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA: IPCC.

RSNZ, 2016. Climate Change Implications for New Zealand. Royal Society of New Zealand, Wellington. Retrieved from https://www.royalsociety.org.nz/assets/documents/Climate-change-implications-for-NZ-2016-report-web.pdf.

Salmeemul, H., Kovats, S., Reid, H., Satterwaithe, D., 2007. Reducing risks to cities from disasters and climate change. Environment & Urbanisation 19 (1), 3–15. https://doi.org/10.1177/0956247807078058.

Schiffman, S.S., Williams, C.M., 2005. Science of Odor as a Potential Health Issue. Retrieved from J. Environ. Qual. 34 (1), 129–138. https://pubmed.ncbi.nlm.nih.gov/15647542/.

Semandeni-Davies, A., Hernebring, C., Svensson, G., Gustafsson, L., 2008. The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. J. Hydrol. 350 (1–2), 100–113. https://doi.org/10.1016/j.jhydrol.2007.05.028.

Shusterman, D., 1992. Critical Review: The Health Significance of Environmental Odor Pollution. Environmental Health An International Journal 47 (1), 76–87. https://doi.org/10.1080/00039896.1992.9935948.

Signh, C., Rahman, A., Srinivas, A., Bazaz, A., 2018. Risks and responses in rural India: Implications for local climate change adaptation action. Clim. Risk Manage. 21, 52–68. https://doi.org/10.1016/j.crm.2018.06.001.

Sinha, E., Michalak, A., Balaji, V., 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science 357, 405–408. https://doi.org/10.1126/science.aan2409.

Smith, K.W.-L., 2014. Human health: impacts, adaptation, and co-benefits. In: Field, C.B. (Ed.), Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects, Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 709–754. Retrieved from https://www.ipcc.ch/report/ar5/wg2/.

Stanke, S.M., 2012. The effects of flooding on mental health: Outcomes and recommendations from a review of the literature. PLoS Currents 1. https://doi.org/10.1371/4f9f1fa9c3cae.

Stephens, S.A., Bell, R.G., Lawrence, J., 2017. Applying principles of uncertainty within coastal hazard assessments to better support coastal adaptation. Journal of Marine Science and Engineering 5 (3), 40–60 doi:10.3390/jmse5030040.

Stephenson, J.S., 2018. Communities and Climate Change: Vulnerability to Risisng Seas and More Frequent Flooding. Motu, New Zealand. Retrieved from https://ourarchive.otago.ac.nz/bitstream/handle/10523/8062/Communities-and-Climate-Change-Report2.pdf?sequence=1&isAllowed=y.

Surminski, S., Hankinson, J., 2018. Private-sector action in adaptation: Perspectives on the role of micro, small and medium size enterprises. Retrieved from, UNP (UNEP DTU Partnership) Perspective Series http://www.unepdtu.org/PUBLICATIONS/Perspective-Series-2018.

The National Institute for Occupational Safety and Health, 2012. Preventing Occupational Respiratory Disease from Exposure Caused by Dampness in Office Buildings, Schools, and Other Nonindustrial Buildings. Retrieved from, NIOSH Alert https://www.cdc.gov/niosh/docs/2013-102/pdfs/2013-102.pdf?id=10.26616/NIOSHPUB2013102.

Tolkou, A.K., Zouboulis, A.I., 2015. Effect of Climate Change in WWTPs with a focus on MBR infrastructure. Journal of Desalination and Water Treatment 2344–2354. https://doi.org/10.1080/19443994.2015.1049403.

Tran, Q., Jassby, D., Schwabe, K., 2017. The implications of drought and water conservation on the reuse of municipal wastewater: Recognizing impacts and identifying mitigation possibilities. Retrieved from Water Research 472–481. https://phys.org/news/2017-09-residential-drought-hinder-wastewater-reuse.html.

UNDRR, 2015. Sendai Framework for Disaster Risk Reduction 2015–2030. UNDSIR, Sendai, Japan.

Vardoulakis, S., Dimitroulopoulou, C., Thomas, J., Lai, K.-M., Taylor, J., Myers, I., Wilkinson, P., 2015. Impact of climate change on the domestic indoor environment and associated health risks in the UK. Environmental International 85, 299–313. https://doi.org/10.1016/j.envint.2015.09.010.

Wang, L.-E., Zeng, Y., Zhong, L., 2017. Impact of Climate Change on Tourism on the Qinghai-Tibetan Plateau: Research Based on a Literature Review. MDPI, Sustainability 9, 1–14. https://doi.org/10.3390/su9091539.

Water New Zealand, 2015. Infiltration & Inflow Control Manual: Volume Two Practical Guidelines. Retrieved from. https://www.waternz.org.nz/Folder?Action=View%20File&Folder_id=394&File=II%20Manual%20Volume%202.pdf.

Watercare. (n.d.). Wastewater treatment Process overview information sheet 2. Auckland, NZ: Watercare. Retrieved from https://www.watercare.co.nz/CMSPages/GetAzureFile.aspx?path=~%5Cwatercarepublicweb%5Cmedia%5Cwatercare-media-library%5Cwastewater-collection-treatment%5Cwastewater_treatment_overview.pdf&hash=197289a0ac6a728558b1519f831b90394257069c057e5b56beaa56763392f75.

Weil, D., 2016. Chapter 4: Population and Economic Growth. In: Economic Growth. Routledge, New York, pp. 82–121.

WERF. (2009). Implications of Climate Change for Adaptation by Waterwater and Stormwater Agencies. Report no. CC2R08. Denver, Colorado: Water Research Foundation. Retrieved from https://www.werf.org/a/ka/Search/ResearchProfile.aspx?ReportID=CC2R08.

White, I., Storey, B., Owen, S., Bell, R., Charters, F., Dickie, B., Zammit, C., 2017. Climate Change & Stormwater and Wastewater Systems. Motu Economic and Public Policy Research, Wellington. Retrieved from https://motu.nz/our-work/environment-and-resources/climate-change-impacts/climate-change-and-stormwater-and-wastewater-systems/.

Whitehead, P., Wilby, R.L., Battarbee, R.W., Kernan, M., Wade, A., 2009. A review of the potential impacts of climate change on surface water quality. Hydrol. Sci. J. 101–123 https://doi.org/10.1623/hysj.54.1.101.

World Health Organisation, 2013. Floods in the WHO European Region: health effects and their prevention. World Health Organisation, Copenhagen. Retrieved from http://www.euro.who.int/en/publications/abstracts/floods-in-the-who-european-region-health-effects-and-their-prevention.

Yuan, C., 2010. Impact of drought and water consercation on H2S formation in sewer pipes. Retrieved from Melbourne: Masters Thesis, RMIT University.

Zare, R. (2012). The effect of earthquakes on wastewater pipelines in New Zealand: Evaluation and rehabilitation. PhD Thesis. Auckland: University of Auckland. Retrieved from http://hdl.handle.net/2292/19646.

Zhang, Z., 2010. A review of rising Damp in Masonry Buildings. University of Portsmouth. https://doi.org/10.1016/j.conbuildmat.2010.04.024.