REGENERATIVE STORMWATER MANAGEMENT: A SYSTEMS THINKING APPROACH

J Hodson (Tonkin + Taylor)

ABSTRACT

Stormwater management is a critical aspect of creating sustainable and resilient cities in the face of pressures such as ongoing urbanisation, ageing infrastructure, climate change, loss of productive soils and infrastructure affordability. However, the continued degradation of our waterways is evidence that the prevailing notion of 'sustainable' stormwater management isn't working and a paradigm shift is required. This paper explores the application of systems thinking to the domain of stormwater management, emphasising the importance of adopting a holistic perspective and using non-structural solutions to enhance system resilience and regenerative outcomes (i.e. outcomes that achieve restoration across multiple domains rather than simply the reduction of harm).

Systems thinking is a holistic approach to understanding and solving problems by examining the interconnected relationships and dynamics within systems. Unlike linear thinking (which focuses on isolated cause-and-effect relationships) or reductionist approaches, systems thinking recognises the interdependence of various elements to better understand system behaviour. In this sense, systems thinking is a perspective that can be applied to any technical field and is needed more than ever to develop robust and enduring responses to society's many complex challenges.

Stormwater management in New Zealand in recent decades has typically focused on managing three primary objectives: (1) flooding, (2) stream erosion and (3) water quality. These have typically been managed with the adoption of structural solutions such as pipes and devices such as ponds, while the implementation of approaches such as Water-Sensitive Urban Design (WSUD) has been limited. This approach of focusing on managing the symptoms of changes to the water cycle (runoff quality and quantity) rather than root causes (e.g. increases in impervious area) has contributed to an urban environment characterised by high imperviousness that results in poor stormwater outcomes as well as a host of non-stormwater related city planning issues.

However, as urbanisation continues at a historic pace and local government faces increasing financial pressure, can we really continue to rely on (attempting to) engineering our way out of the problem? The conventional approach to stormwater management, with a heavy reliance on engineered devices and infrastructure, has led to residual environmental effects (as demonstrated by the continued degradation of our waterways), low levels of resilience, and high embodied carbon emissions. Is this approach *really* sustainable?

Approaches such as WSUD and sponge cities are discussed as examples of a systems thinking approach that can provide more robust and resilient solutions than conventional stormwater management (when applied well). However, incorrect implementation and limited uptake of these approaches shows that these frameworks are not enough on their own without further system interventions.

This paper seeks to use a systems thinking lens to examine the current approach to stormwater management in New Zealand, why it is falling short, and examples of systemic responses that could lead to better outcomes. The aim of this paper is to equip stormwater practitioners with some of the language, tools and principles of systems thinking in the context of stormwater management to aid with a shift toward regenerative solutions.

KEYWORDS

Stormwater management, systems thinking, regenerative design, water sensitive urban design, WSUD, sponge cities, resilience.

1 INTRODUCTION

Stormwater management is a critical aspect of creating sustainable and resilient urban environments that address pressures such as urbanisation, climate change, infrastructure affordability and degrading water quality. Stormwater management in the 20th century (referred to in this paper as the 'historical approach') has been characterised by a reductionist approach that focused solely on conveying runoff away from urban areas as quickly as possible. This was often achieved using hard engineering approaches such as pipes and lined drainage channels without adequately considering the broader environmental and social impacts. In Greater Wellington for example, it is estimated that more than 95% of waterways in the city are now piped underground (Greater Wellington, 2022). Consequently, this often led to unintended consequences such as increased flooding, degraded water quality, eroded streams and diminished biodiversity and habitat in urban ecosystems.

Since then, stormwater management in many countries, including New Zealand has advanced to include a broader set of objectives. In addition to flooding, the field of stormwater engineering now focusses on mitigation of other effects that arise from the creation of impervious area such as water quality and stream erosion. The stormwater engineering 'toolbox' has also expanded with time beyond pipes and concrete channels to include more treatment devices such as ponds, swales, and raingardens.

The implicit assumption within the industry and government appears to be that, armed with this wider range of tools and interventions, we can now continue to create impervious area to cater for our ever-growing urban areas in a way that is 'sustainable'. At a development scale, sustainable stormwater management typically means the adoption of hard and soft engineering devices that aim to not make things worse with regards to environmental outcomes. However, when the starting point is a degraded water cycle from historical human intervention, is simply sustaining the current degraded state of our catchments what we should be aiming for? Even if current regulatory frameworks or financial constraints limit us to an approach of simply aiming to minimise harm, our current approach to stormwater management arguably can not even meet this low bar as water quality continues to degrade in many locations. Given current predictions in the growth of New Zealand's urban areas in the coming decades, the relationship between stormwater management and urban development requires a much more critical examination.

While current stormwater management practices (referred to in this paper as the 'conventional approach') have made significant strides towards embracing more holistic approaches, they are probably closer to the conventional approach than we would like to admit. This similarity is apparent in the underlying paradigm of solutionism (i.e. the tendency to think that complex problems have simple technological or engineering solutions), linear thinking and poor environmental outcomes. This approach of predominantly focusing on managing the symptoms of changes to the water cycle (runoff quality and quantity) rather than root causes (e.g. increases in impervious area) has contributed to an urban environment characterised by high imperviousness that results in poor stormwater outcomes as well as a host of non-stormwater related city planning issues. The heavy reliance on engineered devices and infrastructure can also lead to high embodied carbon emissions in stormwater systems as well as considerable upfront and ongoing financial cost. Systems thinking offers an alternative way of viewing the challenge of stormwater management in the 21st century.

This paper seeks to use a systems thinking lens to examine the current approach to stormwater management in New Zealand, why it is falling short, and examples of systemic responses that could lead to better outcomes. The aim of this paper is to equip stormwater practitioners with some of the language, tools and principles of systems thinking in the context of stormwater management to aid with a shift toward regenerative solutions.

2 UNDERSTANDING SYSTEMS THINKING

2.1 LINEAR THINKING: THE LIMITATIONS OF CAUSE AND EFFECT

To understand the principles of systems thinking, it is important to first examine the prevailing paradigm of linear thinking which is particularly prominent in Western society. Linear thinking is characterised by the tendency to break down complex phenomena into singular components, analysing them methodically. In linear thinking, there is typically a clear cause-and-effect relationship between ideas or actions, and the focus is on step-by-step progression towards a goal or solution. Previous experiences and historical data are heavily relied upon to inform decisions and predict outcomes.

Linear thinking proves invaluable for engineers in cognitive tasks like designing culverts, where the problem can be isolated and solved with a straightforward methodical approach. However, its inherent limitations become apparent when dealing with complex systems comprising multiple variables, interrelated components and delayed feedbacks. Linear thinking often tends to oversimplify complex problems by breaking them down into isolated parts. This reductionist approach tends to overlook the systemic nature of problems, focusing solely on surface-level behaviours or symptoms.

While linear thinking aids in analysing discrete events and their sequence, it offers little insight into the underlying processes and causal relationships. Quick fixes aimed at addressing symptoms often fail to address the root causes, which can often lead to perverse outcomes or externalising costs to other parts of the system or into the future. Unintended consequences can also result from failing to recognise the presence of feedback loops, where the outcomes of one step can influence previous steps or future decisions.

In an increasingly interconnected world, where issues are multifaceted and dynamic, relying solely on linear thinking is inadequate. As such, there is a pressing need to embrace a new paradigm — one that acknowledges the complexity of systems and fosters a more holistic approach to problem-solving. That's where systems thinking comes in.

2.2 WHAT IS SYSTEMS THINKING?

Systems are prevalent in everyday life. A system can be defined as a group of interacting or interrelated elements that act as a unified whole. Without interdependency between elements they just remain a collection of parts not a system (e.g. fruit in a fruit bowl).

Systems can be naturally occurring biological or ecological systems such as the human body. In the human body bone, blood, muscle, fat and nerve cells interact in innumerable ways to sustain life. The human body also illustrates that systems can sit within other systems. Collections of cells form various organs which operate as a system that then interact together to form the larger system of the human body. Systems can also be artificial such as a city where elements such as buildings, roads, utilities, businesses all interact in a dynamic way. A city also illustrates that systems are not just physical. A city also involves the interaction of many social, cultural, political and economic elements that also affect the built environment.

Systems thinking is a holistic approach to understanding and solving problems by examining the interconnected relationships and dynamics within systems. It is also a diagnostic tool that allows one to examine problems more completely and accurately before acting. Systems thinking involves going beyond acting simply in response to isolated events to identifying patterns of behaviour over time and then identifying the structures and paradigms that lead to those patterns of behaviour (this is a common systems thinking framework known as the iceberg model – refer Figure 1 below – in which the conventional approach of just treating the symptoms is represented by the top level) to develop robust and integrated solutions. Systems thinking is a perspective or paradigm that can be applied to any technical field and it is important to keep in mind that there is no one definition of a systems thinking approach.

Systems thinking is critically important in today's globalised world due to the increasing complexity and interconnectedness of the problems we face - a phenomenon often referred to as 'wicked' problems. These wicked problems are characterised by their multifaceted nature, with interconnected causes and unpredictable outcomes. The worldview that 'everything is connected' is more than just a pithy quote. It is wisdom from te ao Māori and other indigenous cultures that is crucial for addressing the challenges that face us in the 21st century.

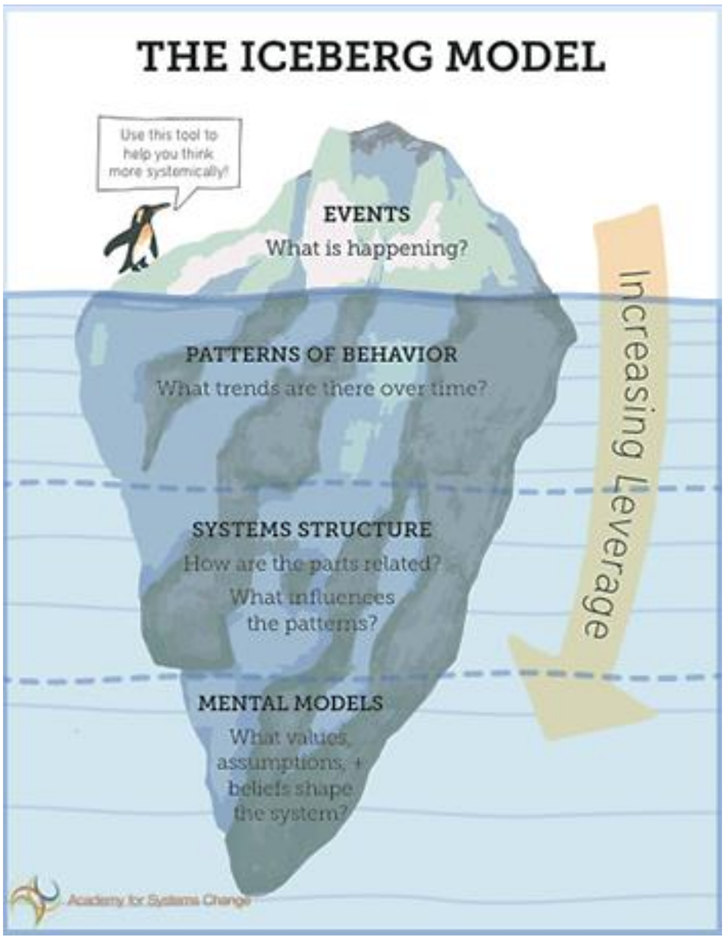

Figure 1: Iceberg model of systems thinking (source: Academy for Systems Change)

2.3 RESILIENCE IN THE CONTEXT OF SYSTEMS THINKING

Resilience is an increasingly important idea in infrastructure systems, particularly as cities face increasing uncertainties related to climate change and extreme weather events. In the context of systems thinking, resilient systems are those that can adapt to changing conditions, absorb disturbances, and continue to provide effective services over time. Some factors that are characteristic of resilient systems include:

- **Decentralisation** – a decentralised system (one that is more distributed rather than having central nodes) means there a less critical points of potential failure and buffers the spreading of failure through the system e.g. at-source stormwater management throughout the catchment rather than centralised end of pipe solutions.
- **Diversity** – increased diversity creates more ways that a system can respond to a given event and reduces the ability of shocks to cascade through the system e.g. using a variety of different native plants in a stormwater treatment device rather than a narrow range of species.
- **Self-sufficiency** – the fewer the dependencies the system has on particular inputs, the less vulnerability to change and the greater its ability to adapt to change successfully e.g. gravity stormwater systems are more resilient than rather than pumped systems which rely on electricity to function during extreme weather events.
- **Learning/adaptation** – learning from how the system responds to shocks in past events helps builds adaptive capacity and resilience to future challenges in the system e.g. dynamic adaptive management approaches.

3 ASSESSING CONVENTIONAL STORMWATER MANAGEMENT WITH A SYSTEMS THINKING LENS

3.1 CAUSAL LOOPS

Causal loops are a common systems thinking tool to begin to analyse the behaviour of a system and various feedbacks (a process also known as system mapping). Causal loop diagrams involve identifying elements within a system, the relationships between those elements and the nature of those relationships. Causal loop diagrams can be used to tell a story about complex issues, making our understanding of the interrelationships within a system's structure more explicit.

Below a simple causal loop diagram is given as an example showing the relationship between infiltration, rainfall and runoff (refer Figure 2). The arrow with a (+) between rainfall and runoff indicates that there is a positively correlated relationship between the two variables. That is as rainfall increases, runoff will also increase (sometimes also denoted as an 's'). The arrow with a (-) between infiltration and runoff indicates that there is a negatively correlated relationship between the two variables. That is as infiltration/evapotranspiration increases, runoff will decrease (sometimes also denoted as an 'o'). This is a simple example that is built on in the sections below into a full causal loop diagram for conventional stormwater management.

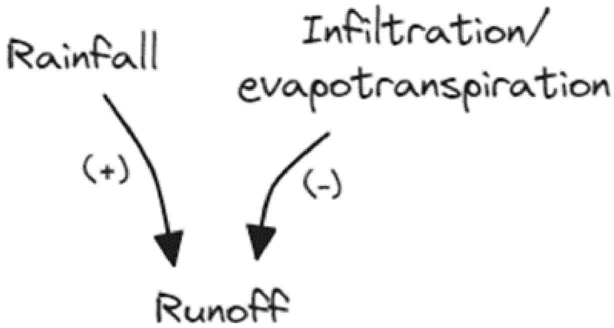

Figure 2: Example of interactions in a causal loop diagram

3.2 SYSTEM MAPPING OF CONVENTIONAL STORMWATER MANAGEMENT PRACTICES

As part of this paper a simple causal loop diagram for the general elements that make up the physical system of stormwater management in New Zealand has been developed (refer Figure 3). The purpose of this causal loop diagram is to begin to understand the general dynamics of the conventional stormwater management approach to see where it may be falling short and where practitioners can best intervene in the system to improve outcomes. With this purpose in mind, it is worth highlighting the fact there is no one correct way to represent any system and this is just one representation. Specifically, this causal loop diagram is limited only to stormwater management and doesn't represent how this system interacts with the wider city infrastructure and urban water system. The causal loop diagram is also generally limited to physical manifestations of the stormwater system. While some non-physical elements are included where they directly impact on physical elements (e.g. building code regulations), other social and economic elements (i.e. interactions of human behaviour) of the system have been excluded for the sake of simplicity. As with every systems mapping exercise, one has to draw the boundaries of the system somewhere. Figure 3 presents part of the causal loop diagram which is discussed below then subsequently built on with additional elements and interactions.

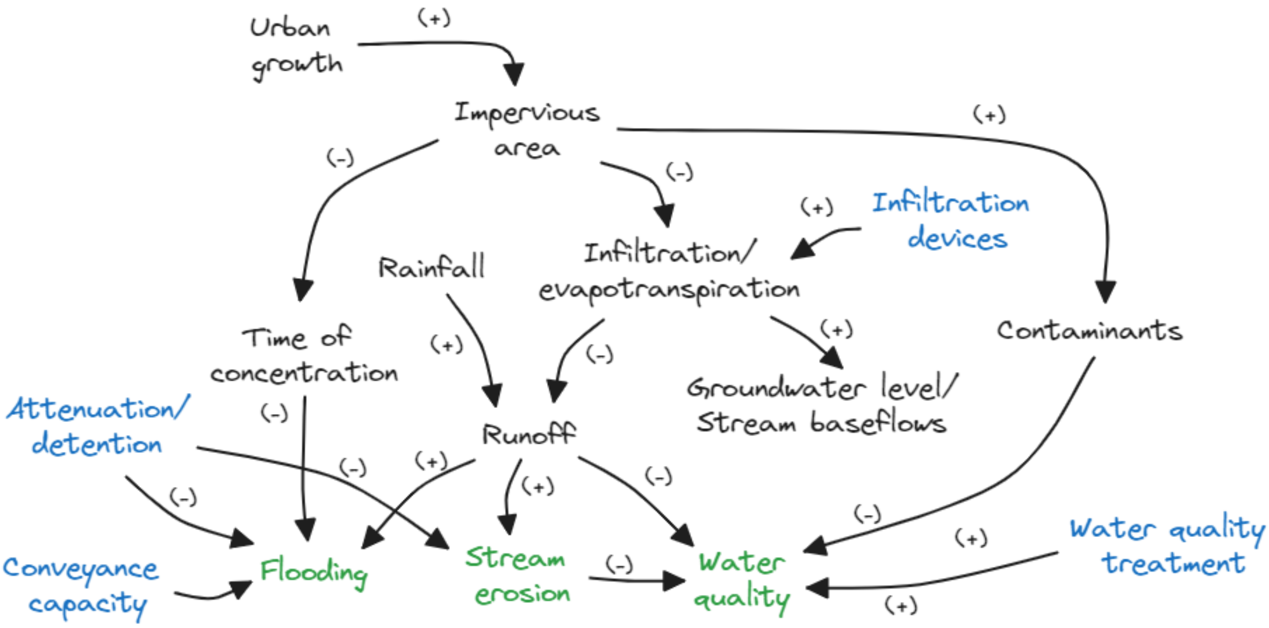

Figure 3: Causal loop diagram for conventional stormwater management

To begin understanding the dynamics within the causal loop diagram presented, the node 'urban growth' is a good starting point. A change in this node (i.e. as urban growth occurs) and resulting interactions paint a familiar story for stormwater professionals. Urban growth in the form of new houses and roads and other infrastructure typically requires additional impervious area. Creation of impervious area has several implications for the water cycle. Primarily it reduces the amount of water that enters soils (i.e. infiltration) and evapotranspiration, thereby increasing the amount of runoff. As runoff increases the causal loop diagram shows that flooding increases, stream erosion increases and water quality decreases. These nodes (shown in green in Figure 3) are the three primary effects that conventional stormwater management typically seeks to mitigate in a New Zealand context.

Impervious area is also associated with a decrease in time of concentration of catchments. That is, impervious areas are typically less hydraulically rough leading to runoff reaching the bottom of the catchment faster, resulting in higher peak runoff rates and increased flooding. In addition to an increased amount of runoff above ground, an increase in impervious area also leads to a reduction in the recharge of groundwater which either feeds deep aquifers or reappear as stream base flows. Impervious area is also correlated with an increase in contaminants that end up in receiving environments which decreases water quality (although it is worth pointing out that impervious area is not necessarily the source of these contaminants).

In order to address these effects, conventional stormwater management has centred around a variety of structural engineering solutions (shown in blue in Figure 3). These structural solutions are generally grouped according to their function as follows:

- **Attenuation/detention** (e.g. ponds, wetlands, dry detention basins and detention tanks) – temporary capture and release of runoff to mitigate increases in flooding and stream erosion.
- **Conveyance capacity** (e.g. pipes, overland flow paths) – conveyance of runoff to mitigate increases in flooding and for service level drainage in smaller events.

- **Water quality treatment** (e.g. wetlands, swales, raingardens, proprietary filters) – capture and treatment of typical urban contaminants of concern using physical processes (settlement, filtration) or chemical and biological processes occurring in soil and plant matter.
- **Infiltration devices** (e.g. soakholes, raingardens) – permanent capture of runoff and infiltration into the ground to mitigate reductions in groundwater recharge and stream baseflows.

Given the ability of ponds and wetlands to achieve all three of the primary stormwater management objectives, as well as for cost reasons, a centralised pond or wetland is often the default approach for greenfield urban development in New Zealand and decentralised devices are not as common.

Infiltration has been historically used in New Zealand as an alternative to reticulated stormwater networks where areas of sand or volcanic soils/rock exist which provide very high infiltration rates. However, mitigating the effect of impervious area on groundwater recharge/stream baseflows has only been adopted by a handful of councils (e.g. Auckland Council). It is the author’s experience that there is no requirement to mitigate this effect across the majority of territorial authorities.

3.3 LIMITATIONS AND FEEDBACKS

While the causal loop diagram presented above (Figure 3) is the typical narrative around stormwater management it also misses many important elements in the system. Figure 4 below shows the causal loop presented in Figure 3 above with additional elements and interactions added. These are discussed in further detail below.

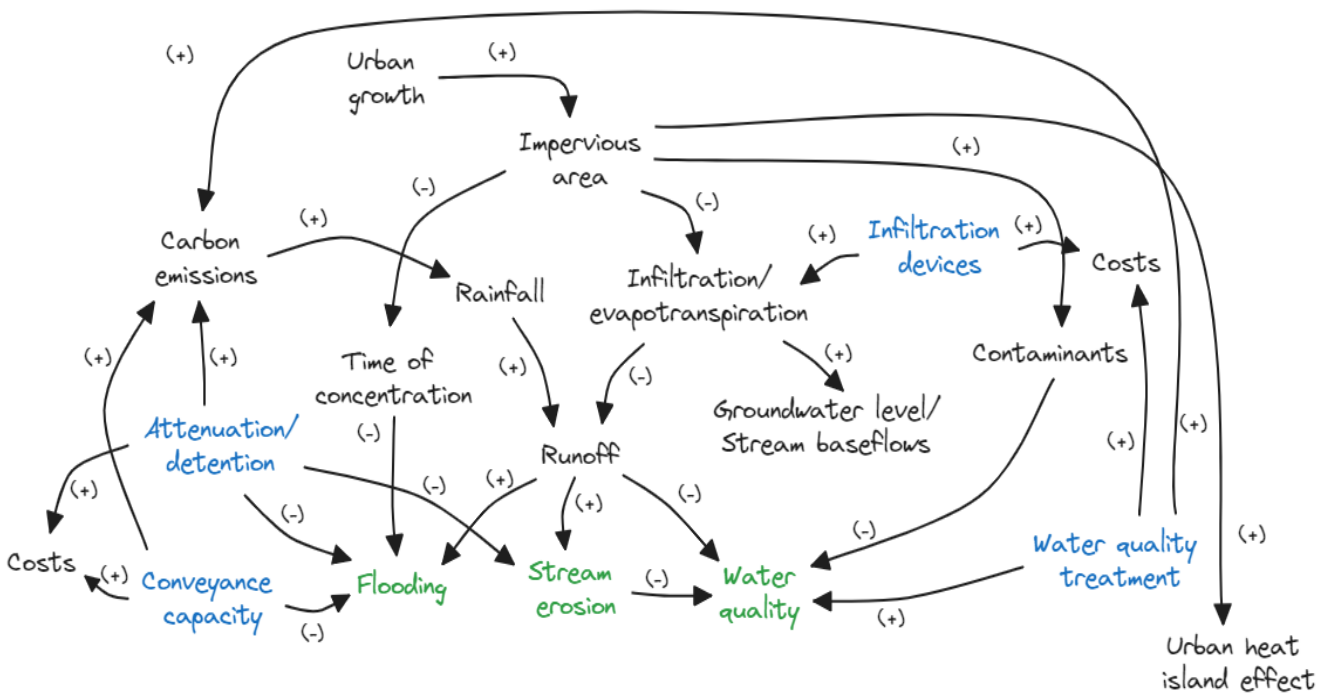

Figure 4: Causal loop diagram for conventional stormwater management with feedbacks added

In terms of feedbacks from the implementation of structural engineering solutions, an obvious one is associated financial costs, which can be significant. One feedback that is often less considered is the associated carbon emissions of structural solutions. This includes embodied carbon emissions in steel and concrete (considered hard to abate emissions) and also carbon emissions associated with construction. A link is also made with rainfall to recognise the fact that carbon emissions contribute to climate change which is directly linked with an increase in rainfall intensities. This becomes a self-reinforcing feedback loop where the carbon emissions associated with larger pipes and other structural solutions actually contribute (even if modestly) to the higher rainfall intensities which they are intended to address.

As the climate change occurs another increasingly important factor in cities will be the urban heat island effect. The urban heat island effect describes the increase in heat in urban areas due to the fact the impervious areas such as buildings, roads and pavements absorb heat from the sun more readily than natural pervious surfaces. This contributes towards an increase in the temperature of runoff that can adversely affect receiving environments. These surfaces also retain heat and can release it later in the day leading to prolonged heat exposure.

Another limitation of structural treatment devices is the fact that while they can mitigate the stormwater effects to a certain degree, they do not complete eliminate them. Residual effects of stormwater management devices can include the following:

- **Nonattenuation of smaller peak flows** – attenuation is often designed for large infrequent events with very "peaky" design rainfall patterns. This means that outlets from attenuation storage areas can be very large and still achieve throttling of the large predicted peak flows. However peak flows in actual rainfall events can often be much lower and the same level of throttling is not achieved. This could result in increases in downstream flood levels relative to the pre-developed state (Groves et. al, 2020).
- **Partial removal of contaminants** – water quality treatment is designed around the principle of removing a certain percentage of contaminants within stormwater runoff (historically 80% removal of total suspended solids). However, a percentage of contaminants are not removed and can be conveyed to the downstream environment.
- **Emerging contaminants** – water quality treatment is focussed on removal of 'urban contaminants of concern' (typically heavy metals, total suspended solids and nutrients). Research on the ability for these devices to remove emerging contaminants such as PFAS, pharmaceuticals and micro/nano plastics is limited (Bodus et al. 2024).
- **Coincidence of peak flows** – when attenuation of peak flows is only considered at the site scale without proper consideration of the catchment scale there is a risk of worsening downstream flooding. This phenomenon, known as 'coincidence of peak flows', can occur where increased site runoff volume and changes in runoff timing can result in flood levels being increased downstream even when peak flows for the site are reduced to pre-development levels (Lewis et. al, 2015).
- **Cumulative effects** – at a site scale the aim of stormwater management is to mitigate effects such that they are negligible or 'no more than minor'. At a catchment scale these negligible effects are cumulative and can end up being significant.
- **Increase in runoff volume** – even when measures like extended detention are provided there can still be a large increase in runoff volume from development that has effects in the receiving environment. Phillips and Lillis (2018) presented a case study in Hamilton where a site with best practice extended detention still resulted in a four-fold increase in runoff volume being discharged.

- **Over-design events** – structural solutions such as pipes and attenuation devices are often designed for a particular return period event. In over-design events their functionality can be limited and a different set of structural solutions and non-structural solutions is required.
- **Unmitigated water cycle effects** – some stormwater effects are not mandated by particular councils to be mitigated. This is usually the case for reductions in infiltration which can affect aquifer recharge and stream baseflows. Auckland Council aim to address these effects with their SMAF rules but many councils only require water quality, flooding and stream erosion to be addressed. It is also the case for increased temperature of runoff. Many guideline documents are silent on how to mitigate it and, where guidance is provided, enforcement is often lacking.

3.4 REDEFINING STORMWATER MANAGEMENT OBJECTIVES

Another important aspect of systems thinking is understanding the goals of the system. As discussed above the traditional objectives for stormwater management have been on managing flooding, stream erosion and water quality. However, one could argue that these three objectives are really proxies for what we ultimately wish to achieve, namely avoiding degrading receiving environment health and reducing risk of property/asset damage and risk to public safety. Going one level further these bottom lines can all be seen as all contributing first and foremost to the goal of human health and well-being. These other objectives have been added to an expanded version of the causal loop diagram below (refer orange elements in Figure 5 below).

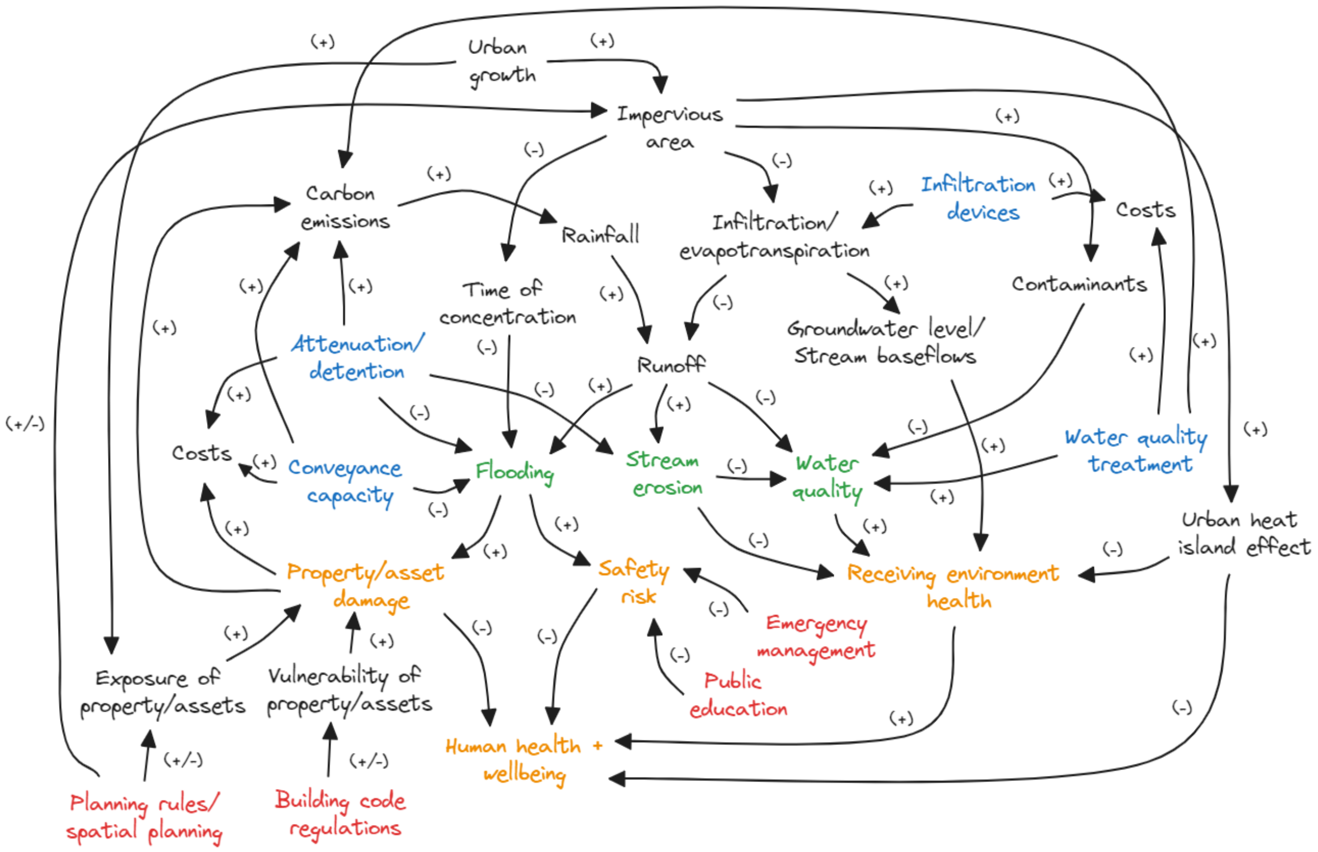

Figure 5: Causal loop diagram for conventional stormwater management with feedbacks and non-structural management approaches added

This clarification of system goals is an important one. At best failing to recognise the ultimate goals of stormwater management result in costly sub optimal solutions; at worst it can result in achieving proxies while actually making things worse. An example of this is adopting a peak flow control mitigation approach on a site scale that results in coincidence of peak flows and worsening of flooding at a catchment level.

A shift from focusing on proxies to the ultimate desired outcomes is also important as it facilitates consideration of a broader set of solutions, beyond purely structural ones. To illustrate this, a number of non-structural solutions that can influence these end objectives have also been added to the causal loop diagram in red (refer Figure 5).

In the example of managing flood risk, there is an increasing acknowledgement that it is impractical to try and 'fix' flooding especially in over design flood events. Rather, flood risk can be effectively managed with a combination of structural solutions and non-structural solutions like emergency management and public education to reduce safety risk. Property and asset damage can also be limited in flood events by addressing the vulnerability and exposure of assets with regulations such as the building code and good spatial planning/planning rules in addition to structural solutions. Structural solutions can also be designed better when focussed on these end outcomes rather than proxies (e.g. designing to fail safely rather than attempting to be fail safe with approaches such as property flood resilience (PFR)). Figure 6 below shows how structural and non-structural approaches can be used together effectively to manage flood risk.

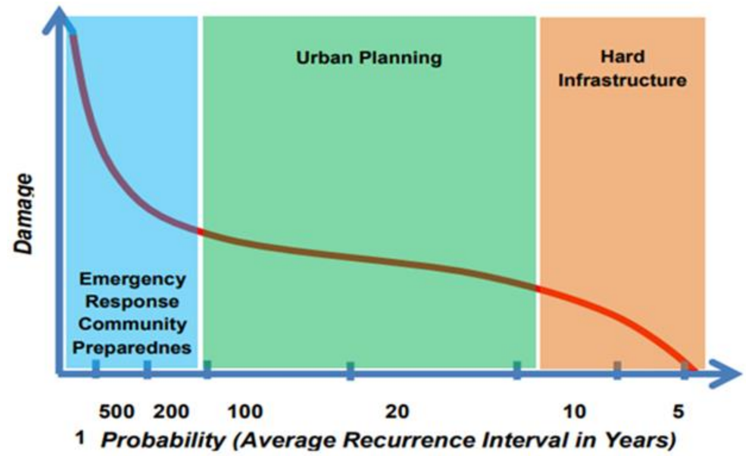

Figure 6: Indicative flood risk profile and broad categories of how the risk is managed (source: Wellington Water, 2018)

3.5 SHIFTING FROM SYMPTOMS TO ROOT CAUSES

Ultimately the heavy focus on structural solutions to mitigate stormwater effects is focussed on addressing the symptoms of urban development not its root cause, namely the creation of impervious areas. While frameworks such a water sensitive design (discussed in Section 4) advocate for a source control approach of limiting impervious area, generally application of this principle is limited.

Overall, the conventional approach to stormwater management, with a heavy reliance on engineered devices and infrastructure, has led to residual environmental effects, low levels of resilience, high financial costs and high embodied carbon emissions. Its focus on treating symptoms of increased impervious area perpetuates an urban form with a high level of imperviousness. Further discussion on the interaction of these urban development approaches with stormwater management is provided in Section 5.

Yet despite this, the conventional approach is often labelled as 'sustainable' as long as 'green' engineered devices such as raingardens are used. While this is a step in the right direction, a regenerative stormwater management approach involves an integrated and holistic suite of structural and non-structural approaches such as those laid out in frameworks like Water Sensitive Urban Design (WSUD) and sponge cities.

4 EXISTING STORMWATER FRAMEWORKS THAT APPLY SYSTEMS THINKING

The limitations of the conventional approach described above have long been acknowledged and a number of existing stormwater management frameworks have been developed in response that are based on a systems thinking approach. In this section WSUD and sponge cities are discussed as prominent examples of emerging approaches in a New Zealand context.

WSUD originated in Australia in the 1990's as a response to urban water management challenges, aiming to integrate sustainable water practices into urban planning and development. WSUD is defined by Auckland Council as:

'An approach to freshwater management, it is applied to land use planning and development at complementary scales including region, catchment, development and site. Water sensitive design seeks to protect and enhance natural freshwater systems, sustainably manage water resources, and mimic natural processes to achieve enhanced outcomes for ecosystems and our communities' (Lewis et. al, 2015).

With regards to stormwater management, it primarily focussed on promoting interdisciplinary planning and design, protecting and enhancing the values and functions of natural ecosystems, addressing stormwater effects as close to the source as possible and mimicking natural systems and processes for stormwater management. Key aspects of WSUD that align with a systems thinking approach include:

- **Holistic planning** – WSUD aims to integrate urban water management with urban spatial planning and design. There is a strong emphasis on minimising effective impervious areas and advocates for 'clustering of development'.
- **Integration of three waters** – WSUD integrates various components of the urban water cycle, including stormwater management, water supply, wastewater treatment, and water reuse. By considering these elements as interconnected parts of a larger system, WSUD seeks to optimise the use of water resources and minimise environmental impacts.
- **Stakeholder engagement and interdisciplinary approach** – WSUD emphasises stakeholder engagement and collaboration across disciplines and sectors to co-create solutions that reflect diverse perspectives and priorities. By involving communities, policymakers, developers, indigenous people groups and water professionals in the planning and design process, WSUD ensures that interventions are contextually appropriate and socially equitable.
- **Broader objectives** – WSUD aims to achieve multiple objectives beyond traditional water management goals, such as enhancing biodiversity, improving urban aesthetics, and promoting community well-being. By addressing a range of social, environmental, and economic considerations, WSUD reflects a comprehensive understanding of urban systems and their interactions.

- **Ecosystem approach** – WSUD adopts an ecosystem-based approach to water management, recognising the interconnectedness of human and natural systems. By restoring or enhancing natural water systems, such as wetlands, green spaces, and riparian corridors, WSUD enhances ecosystem services, improves water quality, and supports biodiversity.

The systems thinking basis of WSUD is also acknowledged by key champions of the movement such as Tony Wong (Wong, 2020)

Sponge cities are urban areas designed to effectively manage stormwater through the integration of green infrastructure, decentralised water management techniques, and ecological principles. The concept of sponge cities originates from China's response to urban flooding and water pollution challenges, particularly in rapidly growing cities facing increased urbanisation and climate change impacts.

Following extreme rainfall events in 2023 the Helen Clarke Foundation commissioned a report recommending the adoption of a sponge city approach in New Zealand. The report, titled 'Sponge Cities: Can they help us survive more intense rainfall?' (Mercier, 2023), presented the following sponge city management approaches:

- Creating or improving parks and green spaces to make them more absorbent, improve water retaining capacity and biodiversity.
- Increasing wetland areas and daylighting streams.
- Protecting and restoring overland flow paths.
- Improving the connectivity of the urban water system and urban green spaces, to allow unimpeded water flows and create corridors for wildlife.
- Introducing green infrastructure such as rain gardens, green roofs and rainwater harvesting systems.
- Using porous materials to construct permeable roads, carparks, and pavements.

The report points out that sponge city approach is not only about cities becoming more absorbent, but also includes an acceptance that cities must make space for water. This can include things like managed retreat, no longer building on floodplains and adopting approaches like 'making space for the river'.

Sponge cities exemplify a systems thinking approach by addressing stormwater management as part of a broader urban system, considering the interconnectedness of various elements and their interactions. Key characteristics of sponge cities that reflect systems thinking principles include:

- **Holistic planning** – Sponge cities adopt a holistic approach to urban planning, considering the entire urban water cycle and its interactions with other systems such as transportation, land use, and green space. By integrating water management with urban design and development, sponge cities seek to optimise the use of space and resources while enhancing overall urban liveability.
- **Co-benefits** – Sponge cities aim to achieve multiple objectives beyond traditional stormwater management, including flood prevention, water quality improvement, urban heat island mitigation, biodiversity enhancement, and recreational opportunities. By addressing diverse social, environmental, and economic goals, sponge cities reflect a comprehensive understanding of urban systems and their interdependencies.

- **Nature-based solutions** – Sponge cities prioritise nature-based solutions, such as green roofs, rain gardens, permeable pavements, wetlands, and urban forests, to mimic natural hydrological processes and enhance water infiltration, retention, and purification. These green infrastructure elements not only help manage stormwater but also provide additional benefits such as habitat creation, carbon sequestration, and aesthetic enhancement.
- **Decentralised management** – Sponge cities emphasise decentralised water management techniques that distribute stormwater management functions across multiple locations and scales. By diversifying approaches and reducing reliance on centralised infrastructure, sponge cities improve system resilience and adaptability to changing conditions, such as extreme weather events and urban expansion.
- **Community engagement** – Sponge cities actively engage stakeholders, including residents, businesses, policymakers, and water professionals, in the planning, design, implementation, and maintenance of stormwater management solutions. By fostering collaboration and co-creation, sponge cities ensure that interventions are contextually appropriate, socially inclusive, and culturally sensitive.

Both these approaches provide holistic and integrated frameworks to managing urban water that is based on system thinking principles. WSUD in particular is now commonly referred to in stormwater management guidelines and planning regulations in New Zealand. However, in practice actual implementation of WSUD has been low.

Ira et. al (2018) identified factors like perceived higher costs, a lack of regulatory framework and a lack of adequate design guidelines as barriers for implementation of WSUD in New Zealand. Also, when it is implemented, it is often done so in a reductionist manner. It often involves engineers working in a silo with a heavy focus of use of devices associated with WSUD such as swales and raingardens and less as an actual philosophical approach to minimising impacts on the water cycle. Non-structural approaches and a focus on minimising additional impervious area are often ignored entirely under the banner of WSUD.

This can lead to many concluding that WSUD is more expensive than conventional stormwater management. As Ira et. al (2015) concluded from a study on economic benefits of WSUD: *'the literature suggests that savings realized in WSD developments are generally related to **"avoided" costs** of site earthworking, preparation, concreting and piping rather than the costs of the stormwater management devices themselves'*. While a reductionist approach to WSUD may be more expensive than conventional stormwater management, it can be cheaper when its non-structural management approaches are adopted.

5 INTERACTION OF URBAN FORM AND STORMWATER MANAGEMENT

A systems thinking approach to stormwater management recognises that we cannot separate urban form from how we manage stormwater. As discussed above, existing stormwater management frameworks like sponge cities and WSUD emphasise the need to consider the integrated nature of urban design and urban water management and highlight the importance of minimising impervious surfaces. Integration of resource management, infrastructure planning and urban spatial planning is not a new idea but one that is still not generally being done well in New Zealand. Understanding the interaction between urban form and stormwater management is crucially important to the future of how we build our cities and is explored briefly in this section.

5.1 URBAN SPRAWL VS COMPACT DEVELOPMENT

Generally urban growth can occur in one of two ways; greenfield growth on the periphery of cities (i.e. urban sprawl) or intensification or brownfields development within existing city boundaries (i.e. compact development). The downsides of continued urban sprawl across various domains are well documented in literature and aren't repeated here. With regards to stormwater management there are two key disadvantages worth highlighting to demonstrate why it is not generally considered a sustainable approach to urban development:

- Greenfield growth results in much higher upfront network infrastructure costs than intensification. A 2021 report prepared by PWC and Sense Partners found that unrecovered costs for infrastructure like transportation and three waters was more than double for greenfield development when compared to intensification in New Zealand (Price Waterhouse Cooper and Sense Partners, 2021). Intensification also results in a much higher ratepayer base to bear the cost of ongoing maintenance, relative to the extent of the new or upgraded infrastructure (Smart Growth America, 2013).
- Extending urban areas generally results in a worsening of catchment health. Research shows that when catchment imperviousness reaches 10-20% stream health begins to degrade rapidly (Arnold Jr and Gibbens, 1996, Herald, 2003). Even best practice conventional stormwater management cannot fully mitigate the hydrological effects of development for greenfield development (Phillips and Lillis, 2018).

One of the key recommendations from the Sponge City Report (Mercier, 2023) is to *'encourage "upwards" development in preference to "outwards" sprawl and "infilling" back yards, to leave more green space available to absorb water'*. Compact development/intensification offers the following opportunities for stormwater management:

- Compact development is more efficient in terms of the impervious area required per capita (e.g. more people are accommodated per m^2 of roof area in an apartment vs a standalone dwelling). This provides more efficiency in the number of ratepayers financing the structural solutions to deal with the runoff from these impervious surfaces.
- Redevelopment of existing urban areas provides an opportunity to retrofit devices that don't currently exist, thereby improving stormwater outcomes.
- Compact development leads to an urban form that can more easily accommodate approaches like green roofs.
- Compact development generally increases the viability of high-quality public transport and infrastructure for active transport modes. Aside from the carbon emissions benefits, a shift away from car-dependant urban development would decrease the amount of stormwater contaminants and would reduce the impervious footprint required for roads and carparks. Up to 35% of impervious surfaces are located on non-rateable land, and 60% of expenditure associated with pollution control is required because of pollution caused by motor vehicles (Ira, 2012). A shift away from the predominant paradigm of making space for cars could help achieve 'making space for water'.

However, there is also an inherent tension between intensification and green space. Without adequate planning and controls, intensification can increase the amount of impervious area and reduce the green space available for stormwater management (e.g. adding additional housing in backyards). Without adequate source control and at source management this can result in complicated and expensive upgrades of the public stormwater network to enable development. Also, if urban transport planning is not well integrated as part of holistic urban planning, then intensification can also lead to the opposite effect discussed above – the number of cars increases leading to a greater area occupied by roads and carparks.

5.2 THE NEW ZEALAND CONTEXT

In New Zealand the data shows that our cities are both sprawling and intensifying.

Urban land cover has increased from 207,000ha in 1996 to 237,000ha in 2018 (Stats NZ, 2021) representing almost 1400 ha of greenfield expansion each year. When considering respective population totals during this period, urban land cover per capita averaged around 540m^2 per person. In 2018, the average urban land cover per capita had decreased to 480m^2 per person. In other words, urban areas have continued to grow as the national population has increased, but at a slower rate (signalling intensification is occurring).

A shift towards intensification is also reflected in data for new residential building consents(refer Figure 7 below). Prior to 2014, standalone housing generally comprised up to 70% of building consents (Stats NZ 2022). This has steadily declined over the last decade with standalone housing now only making up 30% of new building consents and townhouses comprising 50%. Analysis undertaken by the Parliamentary Commissioner for the Environment found that 75% of all titles created within Greater Wellington since 2016 were within the pre-existing urban footprint (Parliamentary Commissioner for the Environment, 2024). The equivalent figures in Auckland and Hamilton are approximately 70% and 60%, respectively.

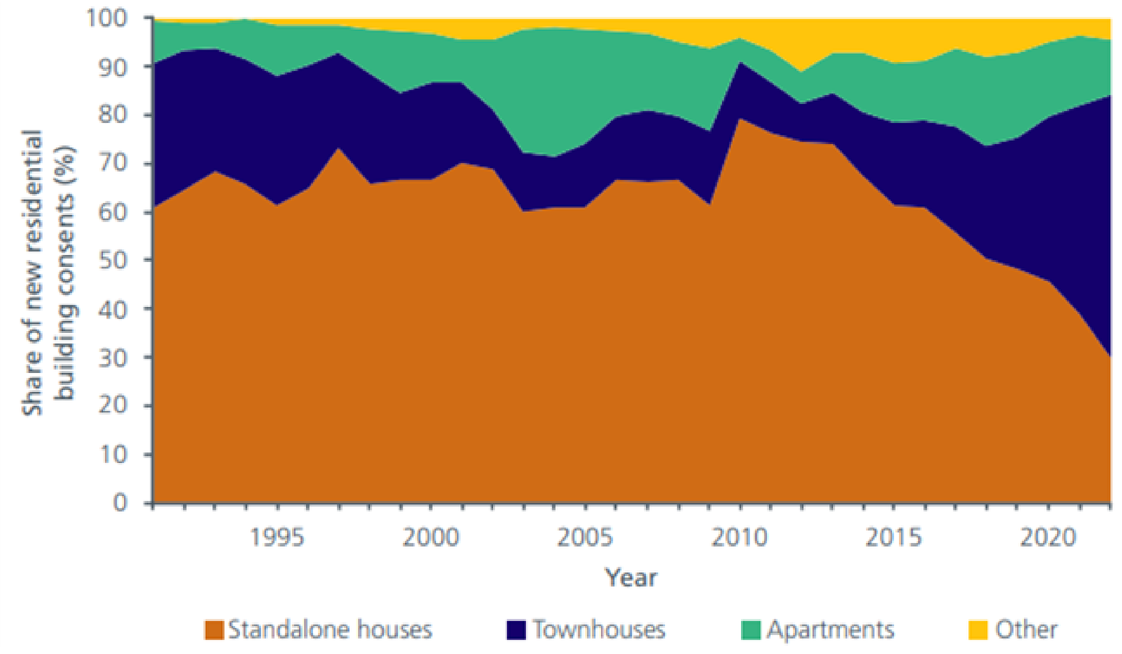

Figure 7: Building typology of new residential building consents in New Zealand 1991-2022 (source: Stats NZ, 2022)

However, this intensification is happening at the expense of green space. Between 1980 and 2016 green space per person fell 30% in Auckland, and at least 20% in Hamilton – primarily on private land (Parliamentary Commissioner for the Environment, 2023). This reduction in green space has also resulted in a reduction in tree cover in our urban centres. According to Global Forest Watch, Auckland has lost as much as 19% of its tree cover in the past twenty years, Dunedin 24%, Greater Wellington around 11% and Christchurch 13% (Global Forest Watch). Also, despite this move towards intensification, the number of cars per capita continues to increase in New Zealand. The number of vehicles per 1,000 people increased from approximately 700 in the year 2000 to 889 in 2021 Te Manatū Waka Ministry of Transport, 2022). New Zealand now has one of the highest rates of vehicle ownership in the world (Te Manatū Waka Ministry of Transport, 2022).

The trend towards intensification predates the implementation of two recent central government policy initiatives designed to encourage additional housing supply through intensification in the largest urban centres. The National Policy Statement on Urban Development (NPS-UD), will provide additional means to enable development 'upwards' in areas close to existing centres and public transport nodes. The Medium Density Residential Standards (MDRS), will allow development 'inwards' across significant areas these urban areas. Under the MDRS, three homes of up to three storeys can be built on most sites without the need for resource consent from local councils. At the same time, the National Policy Statement for Highly Productive Land and the wetlands provisions in the National Policy Statement for Freshwater Management will further constrain development outwards.

The MDRS only requires that a minimum of 20% of a development site be retained as landscaped area, meaning that 80% of sites will be able to be impervious area. Both the MDRS and NPS-UD identify public open space as a qualifying matter, meaning that councils can choose to exclude it from up-zoning and development. The Parliamentary Commissioner for the Environment recently prepared a report titled 'Are We Building Harder, Hotter Cities? – The Vital Importance of Urban Green Spaces' (Parliamentary Commissioner for the Environment, 2023). The report noted:

'While both the NPS-UD and MDRS identify accessibility to natural spaces and open spaces as a key element of "well-functioning urban environments", neither provides any guidance, tools or additional funding sources to help councils achieve that. It is telling that the NPS-UD classifies public open space as "additional" infrastructure – something that councils need only be satisfied "is likely to be available".'

This presents a very real risk that intensification under current regulatory frameworks could lead to a reduction in urban green space and a loss of the 'environmental services' it provides in regard to stormwater management.

5.3 OUR CITIES NEED TO BE COMPACT AND GREEN

Greenfield development results in higher unrecovered infrastructure costs for councils and provides a lower ratepayer base for funding ongoing maintenance of stormwater infrastructure. The conventional stormwater management approach for this type of development results in a high level of imperviousness which result in significant changes to the water cycle. Centralised structural devices are employed to mitigate these effects but often there are a number of residual effects that contribute to environmental degradation.

Intensification provides an opportunity for councils to achieve urban growth that is both more efficient in terms of impervious area per person and more cost effective in terms of infrastructure delivery. However, without a change in paradigm to source control and at source treatment approaches intensification could also lead to the same poor environmental outcomes.

A systems thinking approach to stormwater management requires an integration of resource management, infrastructure planning and urban spatial planning. Regenerative stormwater management requires cities that are simultaneously compact and green. Green space is not just a 'nice to have' but plays a crucial role in stormwater management in urban environments. While a tension does exist between achieving both compact and green cities, various literature and frameworks exist on how both can be achieved (Artmann et. al, 2017). There are also various examples internationally of what this could look like in practice.

Superblocks, are an example of compact and green urban planning pioneered in Barcelona, Spain aimed at reclaiming streets and public spaces from vehicular traffic to create more liveable and sustainable neighbourhoods. These larger units group several city blocks together, restricting through-traffic and allowing only local access for residents, businesses, and essential services. Superblocks promote safer, more pleasant environments for walking, cycling, and socializing, while reducing noise, air pollution, and traffic congestion. They also encourage the creation of green spaces, parks, and community facilities within the blocks providing space for stormwater management and fostering social interaction, community cohesion, and public health. It is estimated that by adopting the superblocks model 70% of space dedicated to traffic could be liberated for other uses, while only reducing total car travel by 15% (OECD, 2021).

6 CONCLUSION

Systems thinking is a holistic approach to understanding and solving problems by examining the interconnected relationships and dynamics within systems. Systems thinking is a diagnostic tool that allows one to examine problems more completely and accurately before acting. In this sense systems thinking is a paradigm and it must be acknowledged that there is no one way to apply it to stormwater management.

Multi-dimensional and complex problems require holistic and integrated solutions – there is no silver bullet or one right answer. Structural solutions such as pipes and treatment devices do have their place. However, using them as a panacea for addressing stormwater effects at the 'bottom of the cliff' results in residual environmental effects, low resilience, and high embodied carbon emissions. A shift from focusing on proxies (such as runoff water quality, stream erosion and flooding/peak flows) to ultimate bottom lines (such as receiving environment health, property/asset damage, safety risk and human health and wellbeing) shifts the focus from single-purpose treatment devices to a holistic suite of structural and non-structural management approaches that maximise benefits.

The current financial pressure on local government in New Zealand make it essential that more emphasis is placed on non-structural solutions. The often-quoted infrastructure funding gap of up to $180 billion in New Zealand comes from a 2021 Sense Partners report (Sense Partners, 2021). However, the actual conclusion of that report seems to have been lost in the public discourse: *'the size of the challenge is too large to fix by simply investing more. Adding more infrastructure doesn't always lead to better economic outcomes either. For example, more roads can also lead to more driving and hence more congestion, which* *is a cost to society. Rather, we need to invest more as well as reduce demand, increase efficiency and do better integrated spatial planning…we cannot build our way out.'*.

A systems thinking approach to stormwater management recognises that we cannot separate urban form from how we manage stormwater. Existing stormwater management frameworks like sponge cities and WSUD emphasise the need to consider the integrated nature of urban design and urban water management and highlight the importance of source control and at source management. However, incorrect implementation and limited uptake of these approaches shows that these frameworks are not enough on their own without further system interventions. Compact cities are needed to address population growth and a host of other issues facing cities in the 21st century. However, it is crucial that compact doesn't come at the cost of urban green space which plays a key role in stormwater management.

This shift in approach will require an understanding of some of the key paradigms and socio-economic factors driving both human behaviour on an individual level but also the emergent behaviour of how cities evolve as complex adaptive systems. Stormwater professionals should be a part of a multi-disciplinary effort to achieve system change through a combination of regulation, incentives and education and further work is required in this space. Systems thinking is a tool which can be used to minimise the risk that interventions result in unintended consequences.

An integrated, systems thinking approach to stormwater management goes beyond simply aiming to minimise harm but can actually achieve restoration across multiple domains beyond stormwater. This change in paradigm for the future of our cities is best captured by the vision of the Regenerative Cites movement:

'The planning of new cities, as well as the retrofit of existing cities, needs to undergo a profound paradigm shift. Mere 'sustainable development' is not enough. To be compatible with natural systems, cities need to move away from linear systems of resource use and learn to operate as closed-loop, circular systems. To ensure their long-term future, they need to develop an environmentally enhancing, restorative relationship between themselves and the natural systems on which they still depend.'

-'Creating Regenerative Cities' by Herbert Girardet (Girardet, 2015)

REFERENCES

Arnold Jr, C. L and Gibbons, C. J. (1996) 'Impervious Surface Coverage: The Emergence of a Key Environmental Indicator', Journal of the American Planning Association, 62:2, 243-258.

Artmann, M., Kohler, M., Meinel, G., Gan, J. and Ioja, I. (2017) 'How smart growth and green infrastructure can mutually support each other - A conceptual framework for compact and green cities'. Ecological Indicators, 2017, 96, pp.10 - 22.

Bodus, B., O'Malley, K., Dieter, G., Gunawardana, C. and McDonald, W. (2024) 'Review of emerging contaminants in green stormwater infrastructure: Antibiotic resistance genes, microplastics, tire wear particles, PFAS, and temperature, Science of The Total Environment, Volume 906.

Girardet, H. (2015) Creating Regenerative Cities, 1st Edition, Routledge, London.

Global Forest Watch. "Interactive Charts" https://globalforestwatch.org/dashboards/. [accessed 2 April 2024].

Greater Welllington (2022) 'What lies beneath? Monitoring our urban streams', https://www.gw.govt.nz/your-region/news/what-lies-beneath-monitoring-our-urban-streams/ [accessed 6 April 2024].

Groves, M., Hellberg, B., Schicker, B. and Bird, W. (2020) 'Does your detention meet your intention?', proceedings of the 2020 Water New Zealand Stormwater Conference.

Herald, J. R. (2003) 'Pointing the way to reducing stormwater impacts on urban streams'. Proceedings of the 3rd South Pacific Conference on Stormwater and Aquatic Resource Protection, Auckland, New Zealand, 14– 16 May 2003.

Ira, S. (2012), 'A Review of Alternative Funding Solutions for Stormwater Management', Prepared by Koru Environmental Consultants Ltd. for Auckland Council. Auckland Council Technical Report 2014/008, January 2014.

Ira, S., Batstone, C. and Moores, J. (2015) 'Does Water Sensitive Design Deliver Beneficial Net Economic Outcomes?', Proceedings of the 2015 Asia Pacific Stormwater Conference.

Ira, S., Simcock, R., Moores, J. and Batstone, C. (2018) 'You Want WSUD With That? Identifying and Breaking Barriers to Uptake', proceedings of the 2018 Water New Zealand Stormwater Conference.

Lewis, M., James, J., Shaver, E., Blackbourn, S., Leahy, A., Seyb, R., Simcock, R., Wihongi, P., Sides, E. and Coste, C. (2015). 'Water Sensitive Design for Stormwater'. Auckland Council Guideline Document GD2015/004. Prepared by Boffa Miskell for Auckland Council.

Mercier, K. (2023) 'Sponge Cities: Can They Help Us Survive More Intense Rainfall', Helen Clark Foundation.

Parliamentary Commissioner for the Environment (2023) 'Are We Building Harder, Hotter Cities?'.

Phillips, A. and Lillis, M. (2018) 'Confronting the Residual Effects of Development on Stormwater', proceedings of the 2018 Water New Zealand Stormwater Conference.

Price Waterhouse Cooper and Sense Partners (2021) 'Cost-benefit analysis for the proposed Medium Density Residential Standards'.

OECD (2021), Transport Strategies for Net-Zero Systems by Design, OECD Publishing, Paris, https://doi.org/10.1787/0a20f779-en.

Sense Partners (2021), 'New Zealand's Infrastructure Challenge: Quantifying the Gap and Path to Close it, October 2021.

Smart Growth America (2013) 'Building Better Budgets: A National Examination of the Fiscal Benefits of Smart Growth Development'. May 2013.

Stats NZ (2021). Urban land cover. https://www.stats.govt.nz/indicators/urban-land-cover [accessed 2 April 2024].

Stats NZ (2022) Building consents. Infoshare table. Wellington: Stats NZ.

Te Manatū Waka Ministry of Transport (2022) Annual Fleet Statistics 2021.

Wellington Water (2018) Three Waters Strategy: Wellington Metropolitan Region.

Wong, T. H. F., Rogers, B. C. and Brown, R. R. (2020) 'Transforming Cities Through Water-Sensitive Principles and Practices'. One Earth, 3(4), 436–447.