National SCIENCE Challenges

BUILDING BETTER HOMES, TOWNS AND CITIES

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Building Better Homes Towns and Cities National Science Challenge 11

Novel wastewater processing: Impact on our cities, infrastructure and society

Report information sheet

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Novel wastewater processing: Impact on our cities, infrastructure and society

Executive summary

We introduce a future vision of the urban environment in this *Think Piece.* A vision represented by a decentralised system, unlike the current centralised infrastructure. And one where the environment is characterised by a circular economy, with produced resources being re-introduced into the system and low levels of waste.

We use wastewater management as an example to assess this long-term vision of decentralised, circular-economy cities. Wastewater treatment is a vital service that currently uses a highly centralised infrastructure (pipes in the ground, centralised treatment facilities), and processes huge amounts of materials as wastes, which could alternatively be viewed as resources (nutrients, energy, water). The sustainability of the current paradigm is questionable, from the perspective of urban population growth and densification, coupled with issues of water scarcity and quality, loss of vital resources, energy demand, climate change impacts and overall system resilience.

We sought inputs to the *Think Piece* through a workshop, focussed on critiquing the opportunities and implications of the future vision, and a technical literature review.

The work has been distilled into four propositions around societal implications:

Social. A decentralised, circular urban economy which includes wastewater could help people reconnect with each other and their environment. However, acceptance of community level wastewater processing and reuse of resources from wastewater will need to be well managed, as will ensuring social equity for all.

Environmental. A decentralised, circular economy wastewater system will promote environmental sustainability. However, regulations and infrastructure may struggle to keep pace and, in fact, facilitate the move towards a more sustainable system.

Technical. Decentralised, circular economy wastewater systems are an exciting area of innovation and development, but they must take place alongside developments in the infrastructure and social integration of a circular economy.

Systemic. A substantive move towards decentralised, circular wastewater economy will not occur without a substantial buy-in from “the system”. Achieving even the slightest transitional movement will be one of the great challenges faced by those promoting this vision of the future.

Underpinning this, **transitioning from the status-quo** is raised as a significant challenge. A hybrid of decentralised infrastructure and centralised management may be required. New models of operation and ownership are likely to be needed and innovative community organisations could play a role. Health and quality must be continually monitored and ensured, the regulatory system will need maturing. Governance and policy will be needed to incentivise change and de-risk the transition.

Looking forward, we propose extending the scope of conversation around future urban infrastructure within the BBHTC National Science Challenge - beyond wastewater to include all water (potable, waste and storm), energy, transport, and communications, and to “model the future” by translating ideas from this vision into tangible urban examples.

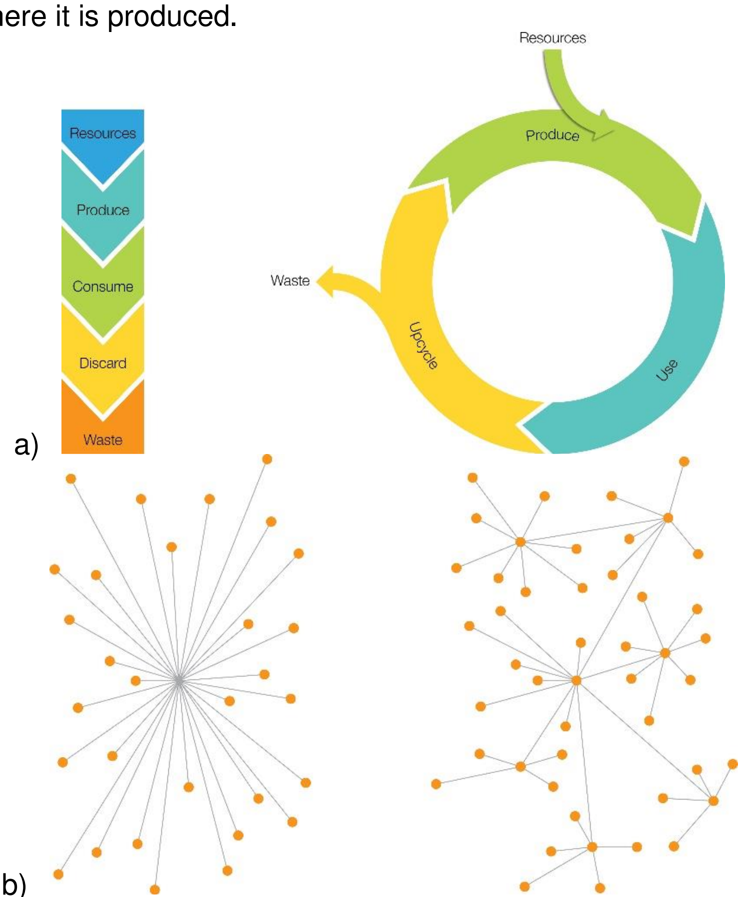
Introduction

Recovering and reusing resources: New ways to process wastewater

Push a button or pull a chain, our toilet waste disappearing out of sight is the last time most of us ever think about what goes down our drains. But an intricate infrastructure system takes care our wastewater. Civil engineers, town planners and waste water treatment experts are busy maintaining pipes and plant, coping with increasing demand and disposing of the end products.

Flushing waste away with water is at least as old as the first cities, and although wastewater treatment has certainly improved over the centuries, the general linear process has remained the same.

There are other ways wastewater treatment could be approached. One is to move from a linear model to a circular model, where waste is considered a resource to be recovered and reused – the principle behind the circular economy (symbolised in the figure below)a). Another option is to move from centralised to decentralised processing, with smaller more localised treatment units (symbolised in figure below) b). Combining the two, we have the vision of a decentralised, circular economy where waste is a resource processed and reused close to where it is produced.



Visualisations of a) linear vs circular economy; b) centralisation vs decentralisation

We describe some potential decentralised circular economy futures for wastewater treatment made possible by increasingly available new technologies in this *Think Piece*. We also consider the potential benefits and trade-offs that a technological shift like this would bring to urban communities and neighbourhood landscapes, and how changes might implemented.

Why we looked at this problem

New Zealand needs innovative, affordable and flexible solutions for the country's homes, towns and cities that will allow us to create built environments that suit the needs of our society. The *Building Better Homes, Towns and Cities: Ko ngā wā kāinga hei papakainga* (BBHTC) National Science Challenge (NSC) was established to work towards this [4].

As the populations of future cities increase, it is a constant challenge to meet people's key needs e.g. safe places to live, a sense of community, ease of mobility and access to healthy food and water. The current response to ever-increasing population is urban sprawl that places more and more pressure on centralised services and does not take into account what it takes to sustain a community in a city.

An alternative to urban sprawl is future cities with denser neighbourhoods. This, overlapped with a strong social driver for high quality community living, provides both opportunity and challenge:

- A decentralised infrastructure that allows for local provision of services and recovery of resources would arguably bring benefits and improve the wellbeing of urban communities, and greater resilience to external events.
- Decentralised cities operating as circular economies will be radically different to today's cities. The infrastructure that holds a city together will be radically affected.

We have been motivated to explore the implications of this alternative vision for the future of New Zealand's urban environment.

What we wanted to achieve

We have used wastewater management as an example to assess this long-term vision of decentralised, circular-economy cities. Wastewater treatment is a vital service. It has a highly centralised infrastructure (pipes in the ground, centralised treatment facilities), and processes huge amounts of materials as wastes that could alternatively be viewed as resources such as nutrients, energy, and water. Further, the infrastructure in many of our cities is aging, and stretched to capacity making wastewater management an excellent candidate for exploring this vision of the future.

Some questions that challenge our current thinking and have motivated the *Think Piece* include: How can typical urban neighbourhoods evolve to take advantage of the reconfigured environment as new, distributed, household-scale wastewater processing options reach maturity? What kinds of changes need to occur in these shorter term horizons? And what are the societal impacts and potential drivers of change?

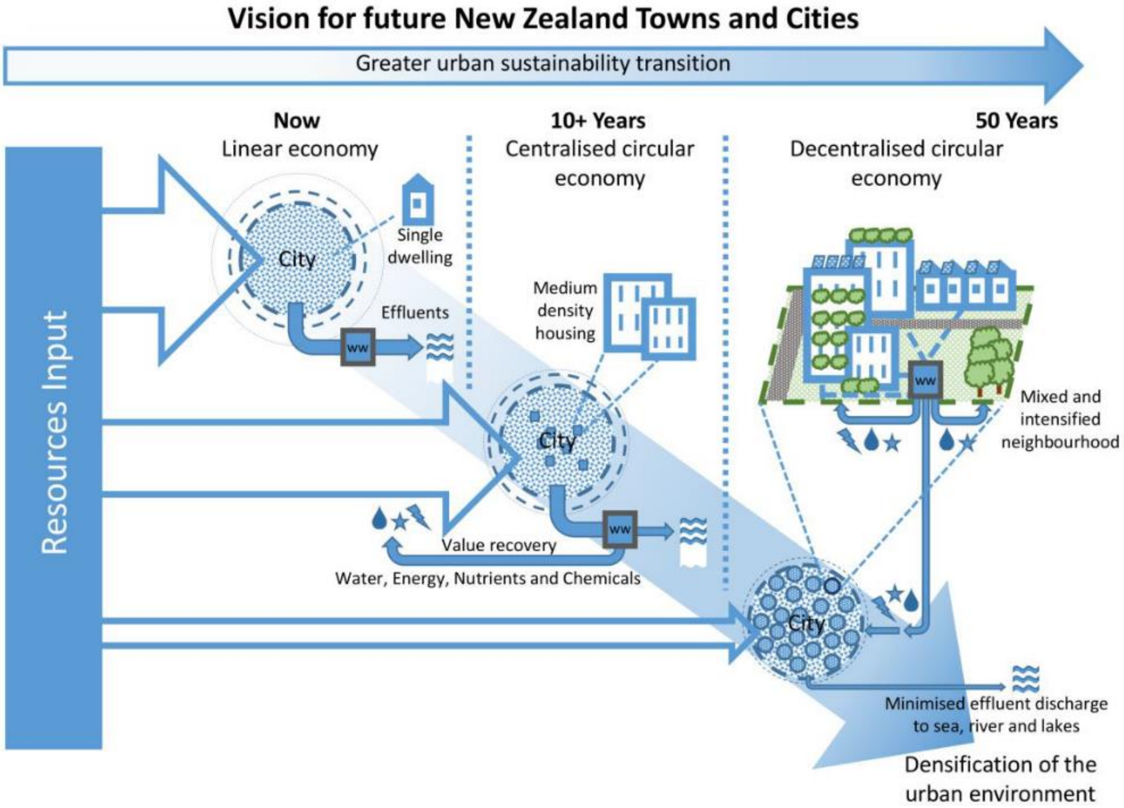
Our aims were to:

- Start a national conversation about interactions between urban living and neighbourhood infrastructure, in particular about the vision of a decentralised circular economy
- Highlight wastewater infrastructure as a platform from which to view the opportunities and challenges that might arise from a transition towards a decentralised, circular economy

- Formulate ideas for future collaboration and research in relation to the transition towards greater urban sustainability that are aligned with and contributing to the multiple Strategic Research Areas/Programmes of the Challenge[1]

A future Vision

Our vision of future urban living that is centred on embracing a combination distributed processing, which minimises centralised infrastructure (applicable over the short term) and resource recovery – long-term integration with localised circular economy. The diagram below illustrates movement towards this goal long-term.



A vision for future New Zealand towns and cities

This vision challenges the linear, urban-sprawl model by proposing a transition towards denser neighbourhoods supported by a distributed infrastructure that allows for the recovery of resources from waste locally. The central premise of the work is that, as novel distributed, household-scale wastewater processing options reach maturity; typical urban neighbourhoods can evolve to take advantage of the reconfigured environment.

In the long-term, localised circular economies can arise out of recovered resources, opening beneficial opportunities for and improved wellbeing within urban communities.

The result is a radically different requirement for new build infrastructure and transformation in the use of the existing municipal infrastructure.

[1] This work aligns with the NSC11 Strategic Research Areas/Programmes (SRAs) – "Future neighbourhoods in cities"; "Improving the architecture of decision-making"; "Supporting success in regional settlements"; and "Kāinga Tahi Kāinga Rua".

Our method

We sought inputs to the *Think Piece* via two main approaches.

1. We engaged stakeholders in a one-day workshop held in Auckland on 26 February 2018. The objective was to start conversations around the posed Vision. Invitees were directly targeted for the perspectives that they could bring to the discussion.

2. We carried out a review of the technical and public literature in relation to sanitation services, distributed wastewater infrastructure, waterless wastewater infrastructure, urban densification, and circular economy and water sensitive cities.

Detailed descriptions of these activities are provided in the appendices. We have distilled the insights from the workshop and the result of the literature review into the opportunities afforded, and the more immediately perceived challenges under the headings of *Social*, *Environment*, *Technical* and *System* implications, and provide real life examples where they exist. Emphasis is applied to *Transitioning* – how we might move from the status quo, and to what the *Next Steps* might be.

Discussion

Social implications

Wastewater systems work within a social context. Moving away from the status-quo of centralised wastewater services thus involves a social movement. Some of the more apparent societal benefits, opportunities and challenges that arose during workshop discussions and were recognised during the literature review are listed in the table below. User acceptance of wastewater re-use is a key part to bringing the vision to reality.

Social implications of the future vision

Benefits and opportunities	Challenges
Individuals	
Improved understanding of the realities of sanitation – increased awareness and reconnection of people and our impact on the environment. Availability of wasteater recovered resources.	Centralised "flush and forget" is easy yet impactful. User acceptance of new ways of dealing with waste – closer interaction with what happens when we flush. Acceptance of waste derived products.
Communities	
New model of wastewater management and service delivery – community more involved/ connected. New business opportunities around resource recovery and reuse – deriving from localised wastewater management needs and from availability of resources Urban self-sufficiency. An identifiable collective, dealing with its own issues, can be very satisfying, and contribute to community-building.	People's acceptance of their involvement in the sanitation service chain and in their role in a community. Community acceptance of the products from wastewater. Social equity must be guaranteed. Cannot have one level of service for the wealthy, and a lower level (or more relatively costly) for the poor.
Urban form and land use	
Reuse of products at point of production will change our urban landscapes Urban forests Proliferation of green spaces New urban microclimates Use of innovative spaces for urban food, crop production.	It is easier to envisage greenfield developments adopting this philosophy, much harder to see how existing urban areas could be "retrofitted". Must avoid unintended competition for space that could occur (e.g. urban farm vs open free space)
Policy, planning, consent	
Opportunity for individuals to beneficially influence quality of the local environment	Human health outcomes must be guaranteed. Service quality cannot be compromised Regulatory framework (national, regional, local) will require attention, to allow for and promote decentralisation and reuse

A decentralised, circular urban economy which includes wastewater could help people reconnect with each other and their environment. However, acceptance of community level wastewater processing and reuse of resources from wastewater will need to be well managed, as will ensuring social equity for all.

Integrated and resilient eco villages

"Regen Villages" plans to build the first of 194 homes in Almere, Netherlands (Oosterwold District) before Christmas of 2018.

Founded by James Erlich, an Entrepreneur in Residence at Stanford Peace Innovation Lab, their website (http://www.regenvillages.com) quotes that the development will contain:

"Desirable off-grid capable neighbourhoods comprised of power positive homes, renewable energy, water management, and waste-to-resource systems that are based upon on-going resiliency research – for thriving families and reduced burdens on local and national governments.

"Engineering and facilitating the development of integrated and resilient neighbourhoods that power and feed self-reliant families around the world.

"IoT [Internet of Things]-integrated infrastructure enable thriving communities with surplus energy, water and organic food in the aggregate become asset classes that can amortize and reduce mortgage payments.

"Partnering with regional land developers, architects, construction, universities and brand manufacturing firms to maximize cost-benefit efficiency that enable global scaling of development projects."

Environmental implications

Sustainable environmental outcomes will be a clear driver of change. Reduction in environmental harm, reinvigoration and improvement of habitat, and addressing climate change will all influence our future urban systems. The major implications that we perceive are described below. New treatment systems will reduce the environmental load of wastewater but need to meet stringent conditions.

Environmental implications of the future vision

Benefits and opportunities	Challenges
Environmental health	
Upgrading wastewater processing to the level that the circular economy requires will drastically lower the environmental harm of any residual emissions. Lower net water demand through a philosophy of use-upgrade-reuse. Aquifer water-take could be drastically lowered; lower take from reservoirs and waterways; fewer water stressed communities.	The new treatment systems must be, at a minimum, as good as today's best available technology. Ultimately, the systems will be required to be energetically neutral, and yield safe (non-pathogenic) products which can be reused within the community (energy, water nutrients). New challenges to be faced by small scale systems - micropollutants (e.g. pharmaceuticals, nanomaterials); heavy metals; noise and odour generated at multiple community level sites New environmental standards will be drivers for change – these will need to be pitched at the right level to encourage innovation whilst maintaining public and environmental health.
Resilience	
The impact of natural disasters (e.g. earthquakes) can be catastrophic on centralised systems – if major pipes or the central plant is compromised, the whole city is put under immediate stress. Decentralised systems may also fail, but the likelihood of complete failure of the all systems is less probable. Climate change: circular systems will have low environmental discharges of greenhouse gases, and improved system resilience to climate-driven catastrophic events	Energy demands may rise at a local level to achieve the required processing. Thus, integration of infrastructure (water, energy, transport etc.) will need to be worked out in a holistic manner.
Urban land use	
New land use opportunities will arise, as a result of localised supply of nutrients, water, energy - horticulture, agriculture - bring peri-urban farms (those on the periphery of cities) right into the city - growing in the vertical rather than horizontal planes (rooftops, walls)	Supply chains may require drastic modification – e.g. local water use/reuse making large sewage infrastructure redundant

A decentralised, circular economy wastewater system will promote environmental sustainability. However, regulations and infrastructure may struggle to keep pace and, in fact, facilitate the move towards a more sustainable system.

Resource recovery and protein farms

Protein from waste 'Black Soldier Fly'
Black Soldier Fly (BSF) larvae can digest faecal waste, with the mature larvae providing an excellent protein source for animal feed. Larvae can reduce solid material by 50-80% and convert up to 20% into larval biomass over 2 weeks. The products of this process are mature larvae, larvae oil and residual soil conditioner. The larvae are 42% crude protein and 29% fat.

Trials for a faecal waste processing plant using BSF technology are underway in South Africa. Chamber waste from urine diversion (UD) double vault toilets is used as feedstock. BSF are bred and the larvae introduced into the waste.

Regional legal restrictions limits its use as feed currently. Taboos around insect consumption also exist in many regions. (www.eawag.ch; Wang et.al. 2017).

Urban farming – containerised farms
Several companies are innovating the use of shipping containers for farming using LED and hydroponic techniques. The containers can be located close to where crops are consumed. Crops can be grown in urban areas. Multiple crop cycles are feasible and the temperature, nutrient and pest control can be intimately managed. Water can be recirculated and therefore reduce overall demand (www.localrootsfarms.com).


Images courtesy of Chu Tai and Alvaro Ibanez on Unsplash

Technology implications

Technical development will be needed to move towards effective decentralised water processing. This includes both treatment technology and the infrastructural demands (energy, communications, new pipework etc.). Some of the identified technology benefits, opportunities and challenges are described below. Although technology for the transition is currently available, the challenge of "how to move" is still being tested.

Technology-related benefits, opportunities and challenges

Benefits and opportunities	Challenges
Infrastructure	
Through onsite treatment and reuse, aging, overloaded infrastructure (pipes, treatment plants) should get relief via decentralised systems. Technical and economic benefit here could be massive. Hybrid systems – combinations of decentralised and centralised treatment may provide the overall optimal approach Sanitation in developing countries is working with limited infrastructure – there may be much to learn from leading edge work going on in this area (e.g. Gates Foundation Toilet Challenge)	Pipes in ground and centralised plants – will they become stranded assets? A new decentralised infrastructure will need to arise, based on local processing and reuse.
Design	
Develop the principle of economy of numbers rather than economy of scale (additive manufacturing, mass production approach) Crossover of technical designs for treatment plants between developing and developed world may be substantial (all based on absence of pipe network infrastructure) Massive opportunity for innovation – novel approaches for value extraction Technology solutions already exist. Economic and social challenges may be more of a bottleneck to a decentralised vision, rather than purely technology demands.	Economic viability of decentralised systems needs to be established No compromise will be allowed on human health or environmental performance of small systems Reliability and maintainability demands will be stringent
Deployment	
Smart systems, the Internet of Things (massive deployment of low cost sensors) brings new opportunities for monitoring and control of decentralised systems Centralised control of decentralised units may be a viable model	Big Data challenges

Decentralised, circular economy wastewater systems are an exciting area of innovation and development, but they must take place alongside developments in the infrastructure and social integration of a circular economy.

Reinvent the Toilet Challenge

The Blue Diversion Autarky Toilet (left) is one of a number of designs emerging from the Bill and Melinda Gates funded, Reinvent the Toilet Challenge. The Challenge is to develop an affordable off-grid toilet for developing countries.

The Blue Diversion Autarky Toilet, which is being developed at Eawag (Switzerland) in collaboration with FHNW (Switzerland) and EOOS (Austria), uses source separation of urine, faeces and water and treats these fractions separately. Calcium hydroxide is doses to urine, which is then concentrated by evaporation. The faeces are treated by hydrothermal oxidation (HTO). Finally, water treatment utilises a gravity driven membrane bioreactor in combination with activated carbon and electrolysis. Water and nutrient recovery are the goals of the toilet.

The Challenge involves numerous organisations around the world with toilets at varying stages of development.

www.autarky.ch

© EOOS and Eawag

Buildings as power stations (energy sector)
Decentralised energy systems suitable for housing has developed rapidly over the last decade. Although photovoltaic technology is often considered, many other technologies are under development.

SPECIFIC is an academic and industrial consortium associated with the Swansea University (Wales). They have a goal of transforming buildings *"…into power stations by enabling them to generate, store and release their own energy"* (www.specific.eu.com). Their research and development programme includes photovoltaics, solar-thermal heat generation and storage, heated coatings and battery technology. Developing so-called Active buildings, live demonstrations of energy saving and generating technologies are provided, capable of moving buildings off-grid or interacting in new and beneficial ways with the grid.

SPECIFIC represents a leading edge example of how developments within one sector (energy, in this case) might drastically change centralised demands, through radical decentralisation – of energy production, in this case. As such, it exemplifies an opportunity for other sectors, including water.

System-related implications

The wider system is likely to have a heavy influence on the potential for realising a decentralised, circular economy. The system can be thought of as the civil environment (planning, regulatory, consenting, development, etc.) within which an urban activity exists. Some of the identified system benefits, opportunities and challenges are described below. Shifts in thinking are required to move from "what is difficult" to "what is possible". The current rise in circular economy thinking aligns well with the challenges here.

System-related benefits, opportunities and challenges

Benefits and opportunities	Challenges
Planning, regulating, consenting	
Modification of risk profiles – less reliance on single massive plant Potential for hybrid system model – combination of decentralised primary/secondary processing, coupled with centralised tertiary treatment Decentralisation is occurring in other sectors – especially the energy sector. What are the steps that occurred to allow this transition? What drivers, and can they be applied to the wastewater/water management sectors?	The regulatory, planning environment is generally complex, slow to change and highly risk averse. Change will require champions at all levels of the system. Need to create an economic framework as a driver for change Modified models for ownership of services compared with centralised systems, e.g. collaborative models New regulatory environment needs to be created to enable wide scale re-use.
Professionals	
New business opportunities - modified business models – lower amounts of large-plant builds, more modular system deployment. Opportunity for faster consenting of development projects – infrastructure managed more internally to the project itself	Paradigm shift in "ownership" required. For example, in a new development in Australia a utility owns and manages the stormwater system from the gutters and rain water tank, to the drain (see example below). Changes to investment demands, models for value recovery
Communities and individuals	
New business opportunities at a local scale Local treatment system operation and maintenance Resource recovery for new value	Social equity Cost concerns – "will it cost more to do it this way?" and "who will pay?"

A substantive move towards decentralised, circular wastewater economy will not occur without a substantial buy-in from "the system". Achieving even the slightest transitional movement will be one of the great challenges to be faced by those promoting this vision of the future.

Decentralised governance of infrastructure

Aquarevo is an urban development of 460 residential dwellings across 42 ha in Melbourne, Australia. The utility provider, South East Water, partnered with Villawood Properties and included a range of stakeholders.

Rainwater from roofs are used for irrigation, toilet flushing and cold water laundry, which reduces (but doesn't eliminate) potable water use. Rainwater may also be used for hot water supply as it undergoes screening, filtration, ultraviolet (UV) and heat treatment before being supplied to hot water taps in the house.

The equipment related to rainwater supply remains the property of South East Water and will be maintained and operated by them for a period of 10 years. The OneBox® monitoring system on the homes allows South East Water to remotely control and monitor supply of the hot water system to homes.

Rainwater tanks, guttering and piping, as well as the treatment system, are also owned by the utility provider. Remote monitoring and operation allows stormwater to be managed, flows controlled in sewers and pre-emption of maintenance needs. Flooding is mitigated as Tank Talk® technology collects forecast data from the Bureau of Meterology and decides if water should be released from rainwater tanks prior to storm events. South East Water have taken on the water management risks and supply, operate and maintain water infrastructure at an allotment scale.

Image courtesy of CRCWSC

Transitioning – how might this be achieved?

How do we transition to a new sanitation paradigm over a 50-year horizon? Significant social and technical barriers to adoption exist. Existing systems and governance are inadequate for radically different decentralised processing. A multi-disciplinary effort, with community engagement to the fore, will needed to effect change. Some of the key transitioning issues are listed below. Communities around the world have started to transition elements of the system; they provide the stepping stones which others can test and follow.

Transitional issues that need addressing

Issue	Transitioning
Governance and policy	
Existing planning system makes implementing novel technologies difficult and expensive	The status-quo uses permitting and consent limits for point source discharges. Diffuse release of effluent from many decentralised units will require new management systems.
Operation by local council may not be appropriate	A wider selection of operators or owners may be possible. Community governance, local corporation, collaborative structures, public or private models are feasible
Maintaining standards	Whether it is disposal of residues to lawn, land or water decentralised systems will need monitoring and managing. With multiple parties a standardisation of equipment and performance would be required.
Acceptability of localised wastewater recycling	Regulatory and monitoring modifications will be required.
Acceptability of food/feeds produced from wastewater resources	Stakeholder dialogue to determine desirability and develop concept. Regulation needs to evolve to allow use. Locate schemes near sites of reuse e.g. aquaculture.
Social	
Perception or cultural concern regarding inappropriate use of wastewater resources– water reuse, food or feed.	Issues will need to be clarified, and solutions developed which gain full acceptance to all.
Decline in social equity through decentralisation	Society shares equal access to public health protection, and this must not be compromised. Governance will need to ensure equal access and quality within a decentralised infrastructure potentially having multiple vendors and service providers.
Unwillingness to adopt alternative systems	Incumbent centralised systems efficiently treat waste and sewerage allows ‘out-of-sight, out-of-mind’ perception. New systems would have to be perceived equally or better to compete.
Increased health risks through comprehensive water reuse	Pharmaceuticals, personal care products. Manufacturers may be required to make them degradable
Technical	
High risk and unproven technology	Community-level demonstrations, focusing on different demographics. Learn decentralisation lessons from energy sector.
Decentralisation	Hybridised model incorporating some centralised control / monitoring may be more optimal
Cost burden	Stranded assets, problem for ratepayers. Who pays and responsibilities for maintenance? Centralised systems can be costly. Phased transition at end of asset life.

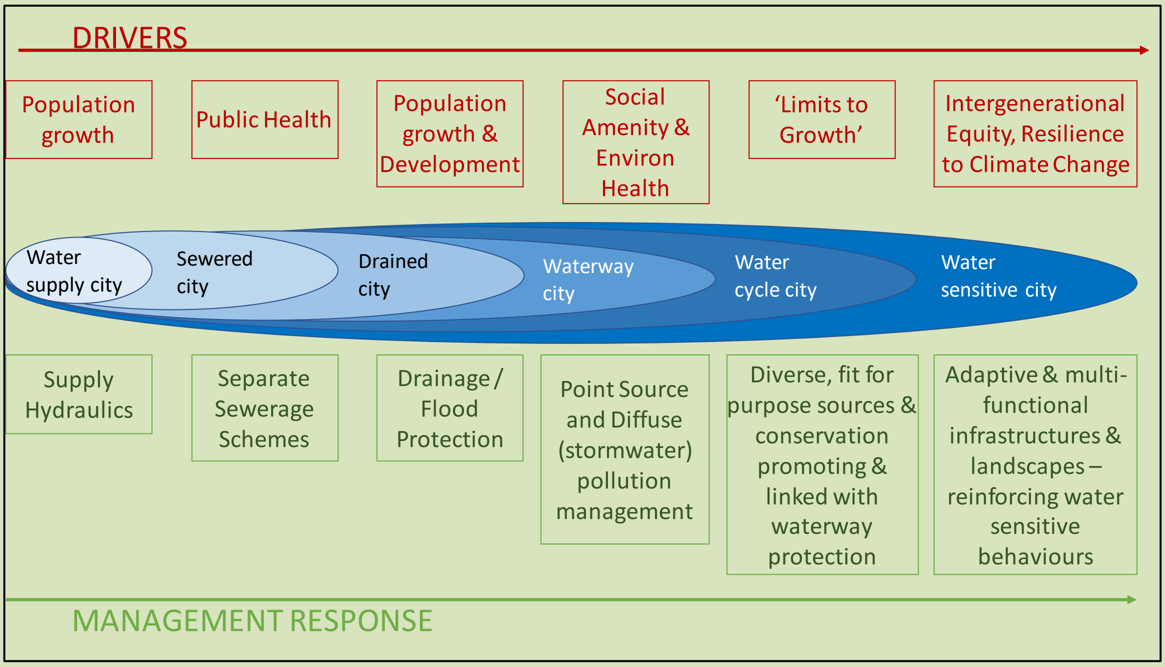
A hybrid of decentralised infrastructure and centralised management may be required. New models of operation and ownership are likely needed, innovative community organisations could play a role. Health and quality must be continually monitored and ensured, the regulatory system will need maturing. Governance and policy to incentivise change and de-risk the transition.

Cooperative Research Centre for Water Sensitive Cities (CRCWSC)

The Australian Cooperative Research Centre for Water Sensitive Cities (CRCWSC) has a purpose which is well aligned with the topic of this *Think Piece*. Their remit is broader than wastewater infrastructure and incorporates management of three waters (drinking water, storm water and wastewater). Amongst their goals are:

- a desire to *'put water at the heart of our cities' biophysical, economic and social wellbeing'*
- To '*bring together global thought leaders to drive cross-disciplinary research into urban planning and water management in Australia and overseas'*
- *'Collaborating with our university, industry, and government partners, we help cities respond to today's pressing water problems for the benefit of current and future generations.'*

The CRCWSC website provides a range of resources. An area of focus has been how to achieve community engagement within the transition process. Mechanisms for socio-institutional pathways for change are part of the programme. Local communities are extensively consulted and drive the implementation as part of diverse stakeholder groups.



Urban Water Transition Phases (adapted from Brown et.al. [2])

Summary and next steps

This *Think Piece* has presented a possible future for wastewater infrastructure New Zealand, focussed on decentralised, circular economy principles. The interaction of social and environmental drivers, linked with new technology capability, could provide a radical change to the current status-quo.

Research is essential to optimise and drive the implementation towards the most positive, utilitarian outcomes for communities. Current threads of international research bring insights to the topic area, but greater value will arise from a more comprehensive and integrated programme. We believe that the multi-disciplinary nature and number of open questions provide fertile areas of future research, and that the implications are real and impactful.

As a result of the *Think Piece,* our recommendations are to:

- Engage with Māori about this future vision for sanitation. In particular, use the *Think Piece* to initiate dialogue with the Māori Science Team within the BBHTC National Science Challenge.
- Establish formal links with local and international experts in circular economy, sustainable development and decentralised infrastructure.
- Establish connections with other National Science Challenges, where similar research is being carried out; particularly “The Deep South” and “Science for Technological Innovation”.
- Extend the scope of conversation around future urban infrastructure within the BBHTC National Science Challenge beyond wastewater to include all water (potable, waste and storm), energy, transport, and communications.
- Explore the opportunity to “model the future” by translating ideas into tangible urban examples.

Ultimately, we recommend establishment of an Infrastructural Strategic Research Programme within the BBHTC National Science Challenge, providing a comprehensive coverage of all services that will help build and maintain liveable cities into New Zealand’s future.

Appendix A: Stakeholder engagement and workshop

We engaged stakeholders via direct contact (visit, phone call and emails) and by organising a specific *Think Piece* Workshop.

We identified stakeholders on the basis of their role and ability to represent a specific target category. We aimed to get a portfolio of stakeholder including representatives from:

- Public Governance and Authorities and planners;
- Local urban communities and Māori;
- Water and waste water service providers;
- Infrastructure engineers;
- Urban and architectural design;
- Built Environment Sustainability experts;
- Researchers (Waste water and urban design).

We set a target of twenty five stakeholders to engage with due to timeframe and funding constraints. However, we envision that a wider number of stakeholders will be engaged in potential future iterations of this project.

We initially engaged stakeholders via email and phone calls, circulating an executive summary of the project's BBHTC context, Vision, rationale and aims.

We organised a workshop in Auckland that was attended by 15 stakeholders. Two stakeholders that could not attend the workshop provided written insight and feedback via email. The workshop included presentations from the Project Team and from individuals representing the Australian CRC for Water Sensitive Cities (CRCWSC). The participants were asked to discuss, critique and provide insights on the Vision from the different perspectives of Governance, Industry and Community, as well as answering specific questions.

We followed-up with email and phone calls, and gathered additional feedback from stakeholders who could not attend the workshop.

Māori engagement

We invited a number of Māori stakeholders to the workshop. However, they were unable to attend. They, and groups contacted subsequent to the workshop, are very willing to contribute and remain engaged in the co-development of alternative wastewater treatments.

Daniel Gapes (*Think Piece* Project Leader) met with Dr Ella Henry (BBHTC's "*Shaping Places: Future Neighbourhoods*" and "Māori Housing Think Tank hui") to discuss the Vision and identify alignment of this *Think Piece* with the "Māori Housing Think Tank hui" Whenu 1, Whenu 2 and Whenu 3. A fruitful discussion was held, illuminating the need to really engage with the BBHTC Māori Science Committee. Dr Henry posed the challenge to use the *Think Piece* to as a provocation – to elicit response from identified stakeholders, of whom Māori are clearly high priority.

Workshop

The objective of the workshop was to bring together leaders from different areas of society who currently work in and around the wastewater or wider urban infrastructure in New

Zealand. Professor Jurg Keller and Dr Paola Leardini from the CRCWSC were invited to provide Australian perspectives of transitioning city infrastructure. The discussions and questions raised during the workshop provide the major thought-leadership outcomes of this *Think Piece*.

Stakeholders unable to attend the workshop were invited to provide feedback on the following key research questions via email:

- What are the essential characteristics of a community structured in this manner?
- What are the demands, technical and otherwise, that will be placed on such an infrastructure?
- What new opportunities does this approach provide – community development, connectedness, increased capacity, resource recovery for community reuse (water, energy, nutrients)?
- What are the major challenges of implementation of this vision?
- How much circularity in wastewater processing is rational at a neighbourhood scale?
- What are the steps along the way that might achieve significant change prior to complete realisation of the vision?
- Does this vision work for greenfield and brownfield application?

Workshop participants:

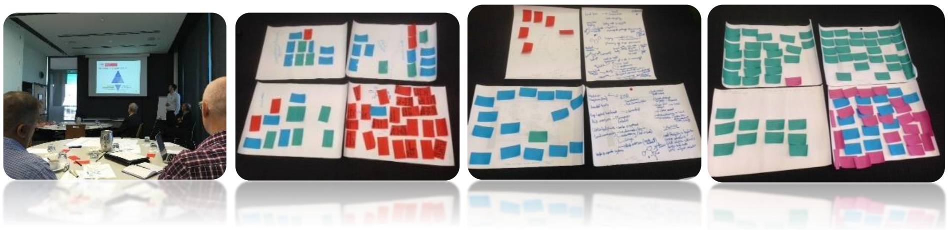
Alyssa Jones	Auckland Council
Amber Garnett	BRANZ
Andrea Stocchero	Scion
Daniel Gapes	Scion
Dr Paola Leardini	School of Architecture Faculty of Engineering, Architecture and IT CRC Water Sensitive Cities
Garry Macdonald	Beca
John Andrews	Scion
John Pfahlert	WaterNZ
Prof Jurg Keller	CRC Water Sensitive Cities, Australia
Kim McGrouther	Scion
Naresh Singhal	Auckland University
Rob Fullerton	BECA
Ruth Berry	BRANZ
Steve Couper	Mott MacDonald
David Boothway	Christchurch City Council
Brian Vass	Terax 2013 Ltd

The people listed below were also invited. Those who were unable to attend (or send a delegate), and expressed an interest in further involvement, were invited to respond to the research questions by email. Responses were received from Peter Trafford and Jerome Partington.
John Mauro (Auckland Council); Greg Offer (Beca); Dr David Dowdell (BRANEW ZEALAND); Lee Bint (BRANZ); Professor Bruce Melville (Centre for Infrastructure Research-University of Auckland); Tony Moore (Christchurch City Council); Rau Hoskins (Design Tribe); Robin Allison (Earthsong Eco-Neighbourhood); ***Peter Trafford (Filtration Technology Ltd)****; Mark Christison (Fulton Hogan); Gen Troop (GreenPeace);* ***Jerome Partington (Jasmax – Living Future Institute)****; Chris Tanner (NIWA); Robert Perry (Sustainable Business Council); Tupara Morrison (Geneva Healthcare); Andrew Alcorn (Sustainability Consultant - Andrew Alcorn & Associates); David Chick, Sarah Adams (Wellington City Council); Rachel Brown, Phil Jones, Georgina Hart (Sustainable Business Network).*

Workshop Structure

The first session of the workshop was designed for laying out the project within NSC11, the vision, and the context for the vision. This was followed by presentations from Australia and NEW ZEALAND to provide some "current state" and "transitioning" examples for the participants.

The participants were then asked to "wear three different hats" for the discussion sessions. Dr Daniel Gapes facilitated the discussion of the vision from the "Individual & Community perspective"; Dr John Andrews led from the "Government/Council perspective"; and Andrea Stocchero led from the "Developer/Planner perspective". The participants were assigned to one table initially then were asked to move to wearing a different hat as the sessions progressed. This process brought the participants out of their normal "expert at work mode" and into alternative thinking spaces. Each table produced "post-it note" comment sheets that were used to inform later discussion.



The workshop, with some of the (raw) work

General outcomes/feel of the workshop

Participants in the first session were encouraged to look into the future but many found this hard as there were critiques and comments around status quo and sunken costs of the current infrastructure. This provided valuable insight into what each participant was bringing to the workshop in terms of past experience and willingness to see a different future.

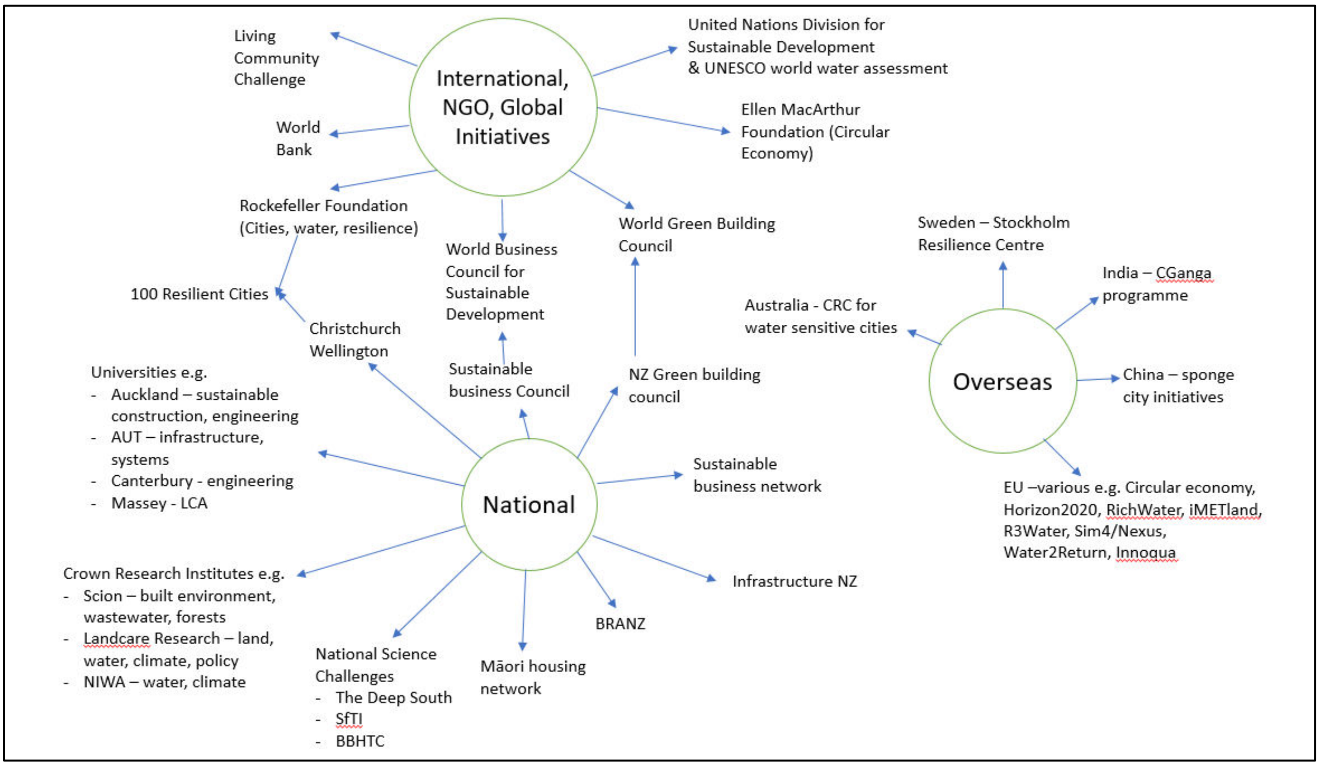
The workshop leaders compelled thinking into the future by asking participants to "see themselves looking out from the window in one of the apartments" in the 2050 vision. From this point, the workshop participants were able to bring "what could be possible" and "what would still remain an issue" to the table.

The changes in table groupings throughout the day enabled different thinking and experiences to come together. By the end of the day, participants were keen to be involved in future activities in this area, particularly in tangible movements towards tackling the governmental and societal issues that would need to be addressed to enable development of new wastewater and other systems within the urban environment. It was clear that urban sprawl and aging centralised infrastructure were coming to tipping points in large New Zealand cities.

Related activity

A variety of organisations have been identified as bringing a relevant focus into the discussion regarding decentralised circular economy, as applied into urban sanitation.

A starting-list of a number of these are described in the figure below with some commentary in the following table.



A selection of organisations with relevant and associated activity

A selection of organisations with relevance to the current Think-piece

Organisation	Purpose
CRC for Water Sensitive Cities ***https://watersensitivecities.org.au/***	To help change the way we design, build and manage our cities and towns by valuing the contribution water makes to economic development and growth, our quality of life, and the ecosystems of which cities are a part.
Living Community Challenge ***https://living-future.org***	To create a symbiotic relationship between people and all aspects of the built environment. In NEW ZEALAND the Vision of Living Future is seen through the Living Building Challenge Collaborative
United Nations Division for Sustainable Development ***https://sustainabledevelopment.un.org***	To provide leadership and catalyse action in promoting and coordinating implementation of internationally agreed development goals, including the seventeen Sustainable Development Goals (SDGs)
World Business Council for Sustainable Development **https://www.wbcsd.org/**	To enable the realization of the Sustainable Development Goals (SDGs) through five work programs to achieve systems transformation. The programmes are "Cities & Mobility", Energy & Circular Economy", Food, Land & Water", "People" and "Redefining value".
100 Resilient Cities ***http://www.100resilientcities.org***	To help cities around the world become more resilient to the physical, social and economic challenges that are a growing part of the 21st century. Christchurch and Wellington have joined into this network and have developed their own Resilience Strategies.
Māori Housing Network ***http://www.tpk.govt.nz/en/whakamahia/maori-housing-network*** ***https://www.tpk.govt.nz/en/a-matou-mohiotanga/housing/a-guide-to-papakainga-housing***	Supports whānau, hapū and iwi with information, advice and practical support to improve whānau housing and develop papakainga housing.
Infrastructure NZ **https://infrastructure.org.nz/**	To advance best practice in the development of world class transport, energy, water, telecommunications and social infrastructure for all New Zealanders.
Sustainable Business Network (SBN) **https://sustainable.org.nz/**	Social enterprise set up to assist New Zealand businesses to succeed through sustainability. Recently launched the Circular Economy Accelerator, with a focus on speeding up adoption of circular economy principles

Literature review

We started the work by carrying out a literature review to supplement the Project Team's existing knowledge and know-how in relation to the status-quo in: sanitation services, distributed wastewater infrastructure, waterless wastewater infrastructure, urban densification, circular economy and water sensitive cities.

Introduction

Is urban wastewater infrastructure sustainable?

The long-term sustainability of the current approach to urban wastewater treatment is questionable. A compelling rationale for change is manifest from the problems or issues associated with the existing system. These issues are broad ranging:

- Water use – flush toilets consume 2 to 10 litres of potable water per flush. Pathogen containing waste is diluted, inflating the hazard and making resource recovery harder.

- Water quality – residual nutrients and emerging contaminants in effluent or biosolid discharges can have adverse impact upon release to the environment

- Wastefulness – nutrient and energy recovery is low. Nitrogen is largely considered a pollutant. Despite phosphorus being a scarce resource, the recovery is limited.

- Cost - wastewater infrastructure in many cities is aging, working beyond capacity and requires substantial investment to maintain or replace.

- Energy intensity – the processing of water and wastewater is energy intensive. Substantial energy is used to convert ammonia to nitrogen gas, also losing nutrients.

- Climate Change – wastewater systems are vulnerable to climate change impacts. Sea level rise, storm events, salinity, drought can damage infrastructure.

- Resilience – natural disasters such as earthquakes, floods and volcanic eruptions can devastate centralised infrastructure. Repairs can be costly and take time to achieve.

- Urban densification – higher population density and increased water run-off will strain the capacity of (often ageing) wastewater and storm water infrastructure, stretching water supply capacity, and providing large quantities of solid waste.

Objectives of the review

This review provides some deeper perspective on this, with insight provided by the currently available literature. The goals of the review were:

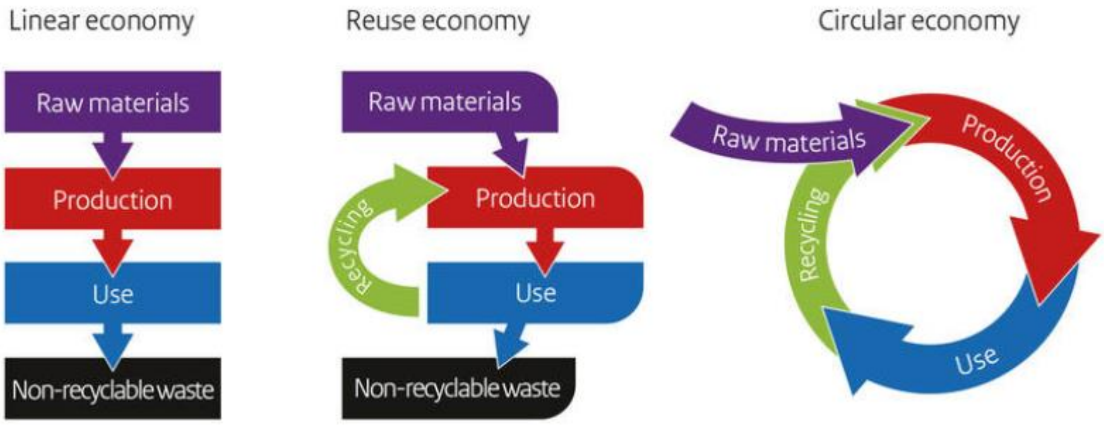
- Provide an overview of key concepts
  - Linear and circular economy.
  - Centralisation and Decentralisation of infrastructure, particularly wastewater.

- Describe the state of urban wastewater treatment
  - Achievements and limitations.
  - New developments, particularly as relevant to circular economy, decentralisation concepts.

Key concepts

Linear and circular economy

For a given entity, be it a group, city or country, the directional nature of its economy describes the way this entity produces, consumes and discards its resources, goods and services. A useful description of different economies is provided in the figure below, depicting a progression from linear to circular economies.



From a Linear through Reuse to a Circular economy (source: Government of the Netherlands [5])

The current economic framework for resource utilisation can be considered linear, i.e. Largely characterised by input of fresh raw materials, their utilisation through a value chain, and discard back into the environment as waste.

This strictly linear produce/consume/discard characterisation may be an oversimplification. Certainly the drive towards more efficient resource use has a pedigree with significant modern history. This can be characterised in large industries like pulp and paper, which embarked on ambitious closed water cycles in the 1970s [6], and the global increase in paper recycling. Industrially, current reuse activity in paper, plastics, metals do show a progression beyond the strictly linear to a reuse economy.

In the NZ urban environment, key resource utilisation is dominated by linearity:

- Treated domestic wastewater is not actively recovered; only in a small number of places in the world actively recover and reuse treated wastewater (e.g. Israel, California, Australia, and Singapore [7])
- Transport energy is based on non-renewable petroleum resources
- Household energy use is almost entirely linear; secondary use of low grade heat is limited to one-off sustainability projects (e.g. [8])
- Built environment is designed for destructive deconstruction; resource recovery rates from demolition are very low [9]
- Food wastage rates are substantial [10]; nearly half of our food produced gets thrown away

Clearly, there is scope for change to this model of produce/consume/ discard.

The realisation of an increasing need to conserve energy and resources is motivating people to transition away from the linear economy, through the Reuse economy and into a circular economy.

The concept of a circular economy represents the most recent attempt to describe an integration of economic activity and environmental wellbeing in a sustainable way. It emphasises redesign of processes and cycling of materials and resources in a cascade of use; minimising resource input and waste leakage from a system [11-13]. The circular economy promotes an attitude of stewardship over ownership [14]. The concept has developed to a significant global profile amongst governments and business enterprise, forming, for example, recent policy passed within the EU [15] and China [16, 17]. Significant advocates include the Ellen MacArthur Foundation, who describe the circular economy as entailing the decoupling of economic activity from the depletion of finite resources, linked with a philosophy of designing out waste production [18]. Three principles of the circular economy are also described:

- Design out waste and pollution.
- Keep products and materials in use.
- Regenerate natural systems.

Adoption of circular economy principles is happening in New Zealand, at both a business [19] and governmental level [20]. The status of circular economy principles in the context of wastewater is described further in latter parts of this review.

Decentralisation

Decentralisation describes a move away from centralised control and authority, towards local responsibility and control. The concept has strong political roots, but has been used across areas including government, management science, political science, public administration, economics and technology [21].

Technological decentralisation is particularly relevant to this review, where an alternative to centralised processing or production of goods or services is described. A number of infrastructural services are affected by decentralisation, including energy and communications.

The International Energy Agency identifies five motivating factors for decentralised or distributed energy production in the electricity industry [22]: i) energy market liberalisation; ii) technology developments allowing the deployment of effective smaller scale systems (microturbines etc.) iii) constraints on construction of new transmission lines; iv) customer demand for highly reliable electricity; and v) concerns about climate change.

These benefits could be generalised to provide useful motivations for the general drivers for technological decentralisation:

- A market that accepts or promotes a decentralised service provision
- Technology that facilitates economic and reliable provision of services
- High costs or other barriers to new or retrofitted centralised services
- Social acceptance of decentralised concepts
- Climate change mitigation or adaption.

The literature pertaining to decentralised wastewater management is discussed below.

Wastewater processing – where is it heading?

The Status Quo

Existing cities are highly dependent upon other cities and hinterlands to supply materials and energy, and to dispose of waste [23]. For a typical city in an average industrialised country, consumptions per capita per year are 150-400 GJ for energy, and 15-25 tonnes for materials [24]. As it is consumed, a large component of the flows of wastewater, solid waste and waste heat are then exported from the urban environment.

Globally, there is an increased trend towards urbanisation. This reflects a growth pattern that will put pressure on the availability of resources and increases in pollution [25].
The collection, transport and treatment of domestic sewage is designed primarily to protect public health. Within urban environments of the developed world, conventional flush toilets are largely ubiquitous. Toilets connect to sewer lines for the transfer of waste. The blackwater (excreta and urine) are flushed through into trunk mains, with sufficient water required to be added to achieve reticulation and prevent blockages.

Centralised sewage treatment facilities vary in complexity and performance. The most common configuration in urban environments is primary settlement followed by secondary treatment. Secondary treatment is often by conventional activated sludge (CAS) through which the chemical oxygen demand (COD) and nitrogen concentrations are drastically reduced. Tertiary treatment may often be added for further polishing of the effluent.

Limitations of the current system

Urban sewerage systems have been immensely successful in many ways, protecting the health of citizens and preventing the pollution of waterways. The activated sludge process, combined with better drinking water, is the main factor behind the increase in average life span in the last century [26]. However, the flush toilet is an illogical form of sanitation from the point of view of water conservation, nutrient recovery and water pollution [27]. Using water to transport waste dilutes and mixes different waste products, some of which are sterile nutrient rich fertilisers, making it difficult to harvest this resource efficiently. Indeed, sewer systems destroy nature's nutrient cycle in which nutrients collected from the land should arguably be returned to the land [28].

The limitations of the current system are discussed below, grouped into i) water use, ii) cost, iii) energy intensity and iv) nutrient losses.

Water Use

A large amount of clean water is used to carry even a small quantity of human excreta. With each flush, 2 to 10 litres of clean water goes down the drain. Dams and irrigation systems are built to bring water to urban areas, only to flush this water down the toilet into an equally expensive sewage system [28]. This has been termed the *political economy of defecation;* the more water you use, the more investment is needed to clean it up. Since we know excreta contains dangerous pathogens, it makes very little sense to dilute pathogens in water [28].

Water Quality

Despite advances in treatment capability, water quality deterioration is a global issue, not exclusively for developing countries where sanitation is of low quality [29]. Chemicals of emerging concern (CEC) are being found in sewage works, often passing unaltered through the treatment process, or accumulating within the sludges produced at the plant [30]

Cost
In many developing countries, high capital and operating costs of sewer systems combined with severe water scarcity means that flush toilets with reticulated sewerage is simply unfeasible [31]. Within developed nations, wastewater infrastructure in many cities is aging, working beyond capacity and the financial cost of upgrading is immense.

Sewerage infrastructure is both costly to install and requires extensive ongoing maintenance. For example, deposition of fat, oil and grease (FOG) is a major cause of sewer blockage [32], and tree roots can damage the pipes. The purchase and installation of gravity sewer components can easily range from US$100-200+ per foot of main line service [33]. Operation and maintenance costs in a US city have been estimated to be in the range of US$951 - $46973 per mile per year [34]. In their recent 2017 Infrastructure Report Card, the American Society of Civil Engineers scored wastewater infrastructure a D+, and describe a US$271 billion requirement for infrastructure spend over the next 25 years [35]. In Auckland, NZ$4.7 billion is currently budgeted in the 10 year plan for capital works associated with water and wastewater [36].

Energy intensity
The processing of water as a whole is energy intensive. Considering urban water supply, water use within households, and wastewater services, these activities consume of 13-18% of the electricity and 18-32% of the natural gas in Australia and the United States, respectively [37]. The energy intensity of the sector may rise further with the trend in many countries to greater desalination and higher quality wastewater discharges.

Wastewater treatment is particularly energy demanding. Aeration for CAS is the most energy intensive part of the process taking up 50-60% of all electricity consumption. However, CAS has a low cost-effectiveness, low recovery potential (partly due to the dilution effects) and a high electricity demand and environmental footprint [38]. Primary treatment in Australia is estimated to use 0.1-0.37 kWh/m^3 with an additional 0.46 kWh/m^3 for conventional activated sludge systems. Advanced wastewater treatment in New Zealand uses an estimated 0.49 kWh/m^3. At a national level, 0.6% of the USA energy is consumed in wastewater treatment plants, in comparison, it is 1% in Sweden and 10% in Israel [39].

Nutrient losses
Currently nutrient recovery in the sector is primarily achieved through application of digestate or composted biosolids to land. Anaerobic digestion is used to recover energy. However, much value is lost in the processing of urban wastewater. Within New Zealand, most biosolids are sent to landfill despite a strong scientific, economic and environmental case for beneficial reuse [40]. The nitrification and denitrification processes in CAS converts ammonia into dinitrogen gas, which is lost to the atmosphere.

All organisms need nutrients to grow. Plants get these nutrients from the soil. Sewage systems bypass the natural flow of nutrients back to the soil and instead dump these nutrients into water [28]. In place of excreta, artificial fertilisers are used to replace the nutrients removed, which take large amounts of energy to produce, and they have well-researched negative environmental effects [41]. At present, 1-2% of the energy consumption on earth is used to fuel the Haber-Bosch process for nitrogen fixation. Only 4-16% of this nitrogen is consumed, with the remainder lost to the environment [42]. Recovery of this nutrient directly from effluent would be far more efficient for society and highlights the wastefulness in the current system.
Approximately 20% of manufactured nitrogen and phosphorus is contained within domestic wastewater. Wastewater also contains 6.5 MJ/kL of chemical energy which is largely wasted [43]. Phosphorus is vital to survival of life, and it is a non-renewable resource that is at high risk of depletion. It is a scarce resource and its mining is overwhelmingly located in the Western Sahara. A 2009 estimate of global phosphorus flows demonstrated that of the estimated 3 million tonnes of phosphorus consumed annually by humans, 1.5 million tonnes

was lost to inland or coastal waters via treated or untreated sewage, and 1.2 million tonnes was lost to landfill or non-arable soil. Only a 0.3 million tonnes (10%) made it back into useful arable soil [44]. Recycling of phosphorus from municipal effluent is going to need to become more important in coming decades [45].

Resilience

Natural disasters such as earthquakes, floods, and volcanic eruptions are devastating in many ways, including the disruption to essential services such as water and wastewater, leading to a state of affairs of ongoing suffering of local inhabitants. Natural disasters such as earthquakes, floods, and volcanic eruptions are devastating in many ways, including the disruption to essential services such as water and wastewater. The Christchurch earthquakes in 2010 and 2011 resulted in damage to 300 km of street sewer pipes, 15 km of sewer mains, 10 pump stations, and the wastewater treatment plant. Repairing damage from these events is taking years [46]. Anaerobic digesters in Christchurch also filled with inorganic residues from liquefaction occurring throughout the city.

New Zealand’s water and wastewater systems have been identified as vulnerable to climate change, with risks including system inundation from sea level rise and storms, damage to infrastructure from higher salty water tables, through to drought-induced blockages and gas build-up within pipe networks [47]. This sits in context with international context around the growing concern regarding the impacts of climate change on water infrastructure [48-60], including arguments for decentralisation as mitigation strategy [61].

Future Urbanisation

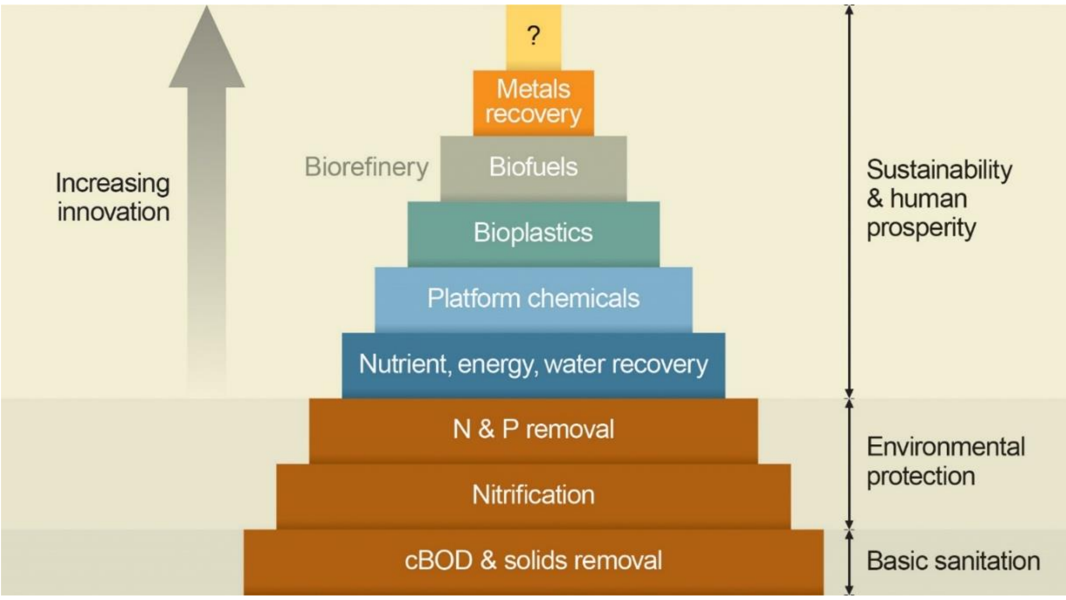
Existing wastewater infrastructure is vulnerable to demographic changes as cities become denser and society more urbanised. The “urban sprawl” that has developed in cities such as Auckland has stretched the capacity of aging wastewater and stormwater infrastructure, as well as adding to growing roading and energy constraints. Auckland is expected to grow to around 2.3 million in 2043. To continue to grow, without introducing a fundamental reform of the current planning system to a Smarter Urban Design platform, has been identified as only exacerbating the current infrastructure issues [62]. In a recent BRANZ report, Helm noted that there is a movement towards medium density housing, with an increase from 19% of the New Zealand housing stock in 2013 to 25% of the housing stock in 2017 [63]. This trend is expected to continue with 33% of the housing stock being medium-density by 2025.

The true cost of uncontrolled sprawl is not fully understood. Urban sprawl and general growth increasingly encroaches upon peri-urban and rural landscapes. Cities' borders are typically where farms that provide produce and where wastewater treatment plants are located. City growth can thus subsume farms and wastewater infrastructure as they spread, undermining food security and raising processing costs. Urban sprawl does not just affect land availability, it also can disrupt water supply, food security and quality of urban environment. [64, 65].

Sprawling development leads to inefficient use of energy and resources. There is more congestion and amenities must be provided to expensive infrastructure, such as roads, pipes and wires to suburbs at a city’s periphery. Urban Designer, Peter Calthorpe [66] talks about a doubling of the urban environment in the next decade and along with that an increase in pollution, energy usage and living costs associated with urban sprawl. The key shift away from sprawl – both low- and high-density – is based on developing city designs focused on human interaction. The principles used include preserving natural environment and history; mixing incomes, culture and land-use; prioritising biking and walking; investing more in transit than freeways; and matching density (and mix) to transit capacity.

Innovations in centralised treatment

Providing sanitation is the most basic achievement of wastewater treatment. However, there is much more value to be recovered (see figure below)



A hierarchy of value recovery from wastes

Many of the identified limitations of current wastewater treatment systems are well recognised, and research has been directed at finding solutions to these. The vast majority of the effort has focussed on modifying the extant centralised processes, rather than on the more radical transition towards decentralised processing. Some of the innovations being evaluated for centralised treatment are discussed below.

Adoption of alternative technologies to recover resources and energy at centralised plants is the focus of significant research [67] [68]. This an alternative vision for better integration within a circular economy where sewage treatment plants become centralised bio-refineries recovering value. Carbon, nitrogen and phosphorus are the key elements from which value recovery is sought. However, the recovery of water is also of importance since many cities are already water poor.

'Partition-release-recover' is a concept to describe the use of biological agents to selectively remove nutrients and carbon from the liquid phase. Partition could be facilitated by heterotrophic bacteria, phototrophic bacteria or algae to bioaccumulate nutrients. Release may be in the form of energy via anaerobic digestion, also through which recovery is attained [43]. Wastewater biofactories see the production of organic acids, polyhydroxyalkanoates (PHA), alginates or cellulose, for example, as a way to recover high value from wastewater resource [43]. Biofuels via lipid formation from volatile fatty acids has been demonstrated [69]. Methods exist for the recovery of phosphorus, for example struvite precipitation can be used to recover phosphorus, which the Ostara Process, amongst others, is currently operating commercially [70].

Energy self-sufficiency in wastewater treatment plants is close to feasible with current technologies. For example, the Sheboygan wastewater treatment plant (USA) uses co-digestion to produce nearly 90% of its electrical demand and 85% of its heat demand [39]. However, new technologies should become available that enable energy neutrality. Emerging technologies such as Annamox have a much lower energy demand, tending towards net-energy-producing system [26], and are able to convert ammonia to dinitrogen gas. Anaerobic treatment processes would replace the existing paradigm of energy intensive aerobic treatment.

Biogas recovery through anaerobic digestion is an established technology used worldwide at wastewater treatment plants. However, future plants would not necessarily direct biogas to energy but upgrade it, along with nutrients into more valuable molecules [42]. Biological methods offer the strongest promise to efficiently recover valuable resources from dilute streams. The next generation of domestic wastewater treatment plants is targeting energy neutrality and complete recovery of nutrients, particularly N and P [43].

Decentralisation and wastewater

Decentralised treatment is often thought in the context of existing technologies such as septic tanks, composting toilets and the like. However, alternative novel technologies can bring about different outcomes. For example, a large number of decentralised plants have been installed worldwide over the last few decades. However, their performance has been judged mediocre at best, partly due to immature technologies but also resulting from poorly aligned regulatory systems [71]. Many decentralised schemes are scaled-down versions of centralised plants, which may have been optimised or developed with different goals in mind.

Over the long-term, a fully decentralised treatment may negate the need for sewerage and could facilitate local reuse of resources. Decentralised systems have the advantage that they can be installed in the short term when needed, thereby reducing the requirement for large-scale investment in sewers and centralised plants. Moreover, they allow the local reuse of water increasing water productivity [71]. Water reuse networks to recycle water offer a more sustainable solution for cities [72].

Earthsong Eco-Neighbourhood in Ranui, Auckland is a neighbourhood that incorporates the principles of sustainable living. The use of a composting toilet installed next to the community building allows the conversion of human waste into pathogen free compost, which smells like rich soil and is safe to use in the garden. Earthsong Neighbourhood has chosen not to use this humanure on the community vegetable gardens for cultural reasons, however the end product is available for the residents to use on private gardens and non-food bearing trees in community space. www.wctnz.co.nz/earthsong-eco-neighbourhood

Image courtesy of Earthsong Eco Neighbourhood

The ability to locally recover nutrients to grow crops [73] or feed-protein [74] could transform the structure of urban communities. Consequently, the circular-economy would be far more integrated into people's daily lives with geographic proximity to food source. Community nutrient recovery will help implement a decentralised circular economy. Ecological Sanitation (EcoSan) is a concept typically applied to the developing world which looks to efficiently capture excreta and reuse it in agriculture. Its goal is environmentally and economically sound management of water, nutrient and energy fluxes [75]. EcoSan is a promising alternative for small scale wastewater treatment and is conceptually aligned to local agriculture within urban environments.

Decentralised toilet systems for treatment are available currently. Many of the low-tech options, such as septic tanks, have a long history but are problematic within dense urban environments. Condominial sewerage systems are prevalent in Brazil. These undertake sewage treatment at the scale of the housing block; having shorter pipe runs and lower cost to centralised systems [76]. Ecologically engineered systems (e.g. The Living Machine) use a series of tanks to incorporate multiple scales of ecological treatment (microorganisms, protozoa, higher animals such as snails and plants). It uses the same basic processes of conventional systems such as sedimentation, filtration, clarification, adsorption, nitrification and denitrification, volatilisation, anaerobic and aerobic decomposition [77].

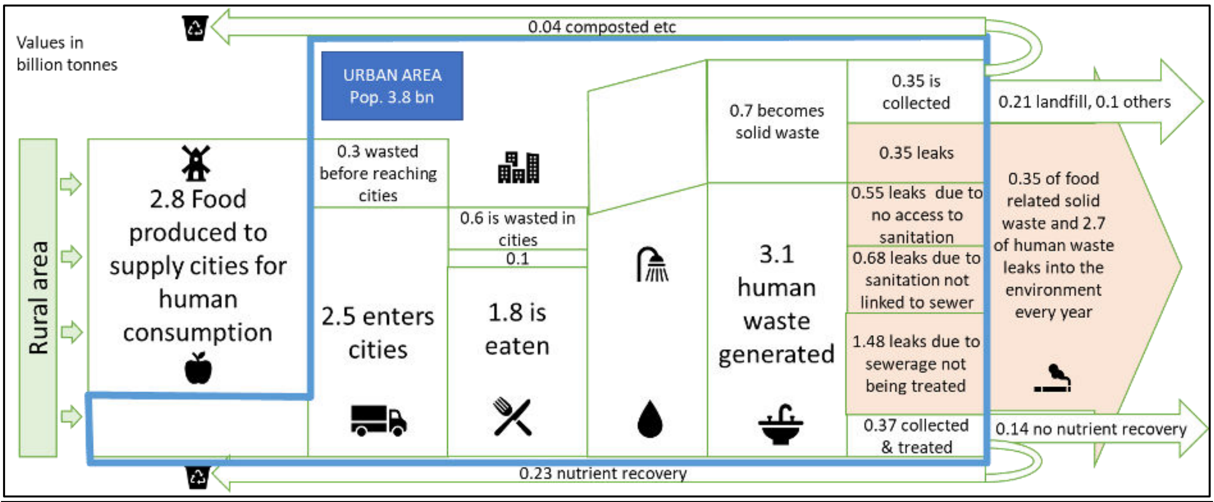
There are alternatives to the standard flush toilet. Many low-flush variants have been developed, and the elimination of flush water can be largely achieved with vacuum toilets. Lubeck-Flintenbreite is an experimental ecological housing estate in Germany which uses vacuum toilets connected to a local anaerobic digestion facility, and Melbourne Water have installed Jets^{TM} vacuum systems at their head office [78-80].

Composting toilets are widely deployed globally. However, they have too large a footprint for urban environments, have incomplete sanitation and require further residuals management. Waterless electric incinerator toilets, which combust the waste to produce an ash, are commercially available. However, the energy demand for these is particularly high.

Unsafe sanitation systems remain problematic in developing world cities. This imperative for affordable and safe sanitation provision motivated the Bill and Melinda Gates Foundation to establish the Reinvent the Toilet Challenge. The challenge has invested extensive research funding into transformative toilet technologies which can treat excreta on-site. A range of next-generation toilets are potentially emerging which achieve treatment for households. Technologies such as wet oxidation (Scion), hydrothermal carbonisation (Loughborough University), smouldering (Toronto University), solar electrochemical (Caltech), microbial fuel cells (University West of England), amongst others, are being developed.

Facilitating circularity in urban resources

Food production and sanitation services are intimately linked. The flow of nutrients and waste generation at a global scale is shown below.



Global food system flows: the bioeconomy's circular challenge (adapted from Stuchtey, 2017 [81]*)*

Urban forests

Partnering urban forestry with eco-technologies can benefit business and provide services critical for human well-being, beyond the capacity of trees [82]. This statement from Endreny aligns well with the rise in technologies that enable this resource connection in the urban environment. Endreny discusses the services and actual, potential and perceived disservices of trees in an urban landscape as well as raising the potential to integrate urban forestry in a way that replaces grey infrastructure with green infrastructure.

Single Cell Protein

Single Cell Protein (SCP) are edible microorganisms with high protein content. The combination of wastewater treatment and SCP production could substantially influence the water-energy-food-climate intersection of the coming decades [42]. A future centralised treatment plant could be configured to recover SCP as food for animals and humans. For context, conversion of fertiliser-nitrogen into edible plant protein has inherent losses, with only 30% being incorporated into plant matter the remainder lost to run-off and volatilisation. Conversion of plant protein into meat protein adds further losses, so that on 17% of the input fertiliser-nitrogen is retained. In contrast, harvesting of microbial protein grown on nitrogenous waste can recover close to 100% [43].

Cape Town (South Africa) has a widely documented water crisis, arising from years of drought and planning difficulties. One of the interesting features that is developing in this region is increased consideration of wastewater for reuse [1]. In efforts to avoid "Day Zero", the date at which "the water taps get turned off", the municipality currently makes effluent available to businesses for industrial and non-potable uses (e.g. industrial cleaning, wash-down water, livestock applications) [3]

Image ID 84939069, courtesy of Dreamstime Stock Photos is licensed under CC0

Current examples of urban agriculture

Urban agriculture is already a familiar concept to many. It is emphasised in times of struggle e.g. Relief Gardens were dug during the Great Depression in America [83], and the Dig for Victory campaign during World War II[84]. In the local context, there are numerous examples of Community Gardens in New Zealand. There is a growing body of research into urban farming. Concepts of vertical farming, also known as sky farming or Zfarming (zero-acreage farming), are becoming theorised. By growing food within population centres, urban agriculture can break down the divide existing between cities and nature.

The benefits of urban agriculture are discussed in Mok et.al. [83], and include reduced food transportation distance, carbon sequestration, potentially reduced urban heat island effect, improved physical and mental health, improved aesthetics, community building, employment opportunities, improved local land prices, shortened supply chains and, thus, reduced price differentials between producers and consumers, provision of habitat for wildlife, and waste recycling. Importantly, urban agriculture can reduce food insecurity for low income households. Aerofarms® intentionally locate their building farms on major distribution routes near population centres.

There are existing examples of cities seeking to locally grow crops. Melbourne has responded to urban sprawl, climate disruption and loss of peri-urban food production through developing urban agriculture projects for localised production [85]. The ParisCulteurs project in Paris is looking to divert 100 hectares of building space in Paris to food production by 2020 [86]. Existing schemes still require the import into cities of nutrients required for growth. Localised reuse of nutrients and water may enable these schemes to become more mainstream.

The option of using decentralised treatment to grow willow as a biofuel in CHP plants has been proposed [87]. A further example can be found in Masdar, an experimental sustainable city in Abu Dhabi looking for more sustainable food production. Researchers there are harvesting the first crop of the biofuel feedstock Salicornia, which is a local halo-tolerant and oil-rich plant. Salicornia also has been evaluated for its ability to treat urine [88]. Biofuel crops present an alternative option which may have a market in some locations.

Challenges for urban agriculture adoption

There will be risks arising from a future city heavily utilising urban agriculture. At some scale, there will be a competition for land between agriculture and residential property. During early stages, risks such as potentially high investment costs, requirements for new cultivation techniques, exclusionary effects, and a lack of acceptance, could limit adoption rates.
Of course, distributed or decentralised treatment may lose some economies of scale enjoyed by the incumbent systems [89]. However, with a high density of decentralised plants (>1 – 1.5 per m^2) strong cost reductions have been modelled [90]. Would a small-scale operation be more or less efficient with respect to water, fertiliser application, harvesting and energy needs? If not managed properly Zfarming, for example, may not be any more sustainable than conventional agribusinesses [91]. The additional infrastructure for households may inflate direct costs for users, whilst the redundant centralised plants would no longer incur operational costs. Questions of governance and maintenance of assets may need radically different solutions.

Risks from contaminated land and impacts of urban air pollution are also not yet widely evaluated in the context of urban farms.

Transitioning to a new system

Transitioning from incumbent systems to new approaches is fraught with challenges. Examples exist throughout the world of sub-optimal outcomes as visions are implemented.

Songdo in South Korea was designed around technology, and promised to be the city of the future. Unfortunately, what started 15 years ago, now stands as an unfinished project.

This project was driven by property developers with government support. Due to the high cost of living in the city, Korean's are leaving the city to foreigners. One of the key problems is that the "city for living in" was developed two-hours away from Seoul, the "city for working in".

This is an example of a vision created without consideration of the people who were meant to live there or of the wetland species that used to live where the "green" city now sits.

http://www.dailymail.co.uk/sciencetech/article-5553001/28-billion-project-dubbed-worlds-Smart-City-turned-Chernobyl-like-ghost-town.html

The complexity of cities, relative inertia of the built environment and large investment costs sunk into urban infrastructure represent a challenge when you seek to manage a transition to more sustainable and resilient cities [25].

Understanding behavioural elements, and user preference, will be particularly important where sanitation solutions are required. Societies have developed taboos around defecation with associated emotions of shame, guilt and disgust [92]. Arguably, ownership of a flush-water toilet has come to symbolise cleanliness and civility and is thus a desirable social signal, and superior to alternative toilet configurations. Trials of dry diversion toilets in South Africa received poor uptake partly because flush toilets were perceived to be more socially desirable [93]. Where waterborne sanitation is seen to be for the wealthy, and dry sanitation for the poor [94], flush toilets will remain more desirable.

In New Zealand, traditional Māori waste management processes have evolved to ensure a high level of compliance of what is disposed of, where and when [95]. Changes in modern wastewater management to bring elements of the spiritual tapu back into contact with people, without going through a process to move from tapu to noa (the antithesis of tapu), would be against the traditional Māori values, and thus not acceptable.

An actor-network theory coevolution framework was used to explore transition pathways from water-flush systems within London to dry sanitation [27]. In this analysis, whilst flush toilets represent stable network configurations, the lack of available freshwater resources was the main driver for developing alternative co-evolved pathways [27].

How risk that is perceived by the public for an alternative system is critical; especially for those technologies in which nutrients may be ultimately recycled into the food chain. Community engagement when encouraging biosolids reuse was found to be helpful [40]. Similarly, Community Led Total Sanitation (CLTS) is a methodology shown to be effective for successfully embedding sanitation solutions in developing countries [96].

Innovation in organisational and regulatory models maybe needed for the successful implementation of decentralised treatment facilities. Sensor and communications technologies are likely required to monitor performance from a highly distributed network of treatment plants by a central operator. This would represent a contracting scheme system of governance [71]. Computational modelling of the urban water cycle and nutrient cycles [97] are likely to be essential in evaluating the impact of decentralised treatment.

A transitions framework was discussed in the paper by Brown et.al. [2]. Cities transition through temporal ideological and technical context regarding urban water supply, overlaid with city specific histories, ecologies, geographies and socio-political dynamics. How to implement institutional change for the ‘hydro-social contract’ is described in the paper with pathway towards the future Water Sensitive City [2].

A more intimate integration of cities with nature leading to more self-sufficiency in energy, food and other resources may require a radical shift in values and behaviours of residents. Bennett et.al. discuss values, processes and features that lead to initiatives that fundamentally change human-environmental relationships [98]. Decentralised wastewater infrastructure could be a means to restore resource abundance in a city and work more aligned with natural ecosystems.

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