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Adapting to drought in the Waikato

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Executive Summary

Our climate is changing. Climate projections suggest that parts of the Waikato Region, traditionally a 'water rich' region, will become drier and experience a higher incidence of drought. Changing conditions mean we need to focus attention and resources now on understanding how our region can adapt to the realities of a more drought prone future.

This report introduces a conceptual diagram of the water cycle to better understand the interdependence of human activity and water availability in the region. The system dynamics approach used to explore the drivers of water flow and use complements other analytical tools used by WRC by synthesising diverse sources of knowledge and information.

What follows is as a solution-oriented socio ecological study of drought that integrates disciplines and operating contexts, with the aim of identifying localised opportunities for adaptation and associated policy levers. This approach: 1) focuses attention on largely unconscious and accepted ways of negotiating the relations between economic production and water resources; 2) utilises system dynamics to better understand the opportunities and barriers to adapting to drought in the Waikato.

The conceptual diagram of the water cycle is based on structured interviews with Waikato Regional Council staff who are specialists in various areas of science and/or operational focus. A range of challenges and potential opportunities were identified. The characteristics, influences and pressures of the wider system identified from these interviews were then synthesised into a system diagram by an external specialist in systems thinking (drawing specifically on the discipline of System Dynamics). Such diagrams are developed to articulate the 'system structure', or the interconnected influences that are operating in the system. How these influences interact can explain the trends over time observed in variables of interest within the system – for example declining or increasing levels of something when the opposite may have been expected.

Two versions of this system diagram are shown below. The first is a conceptual articulation of how water flows through (the arrows) and accumulates in (the boxes) the water cycle, including modifications for human extraction and use. In the second, this same conceptual 'plumbing' has been overlaid with a series of feedback loops indicating the nature of various influences and pressures on the flow/use of the water. These influences and the behaviours they encourage are explained in detail in the report.

These diagrams by themselves provide certain insights that can be useful for consideration in drought adaptation. For example, the stock and flow diagram (Figure 1) highlights a range of areas that should be the focus of discussions around drought adaptation. These are shown in Table 1.

Figure 1. All water cycle stocks and flows identified

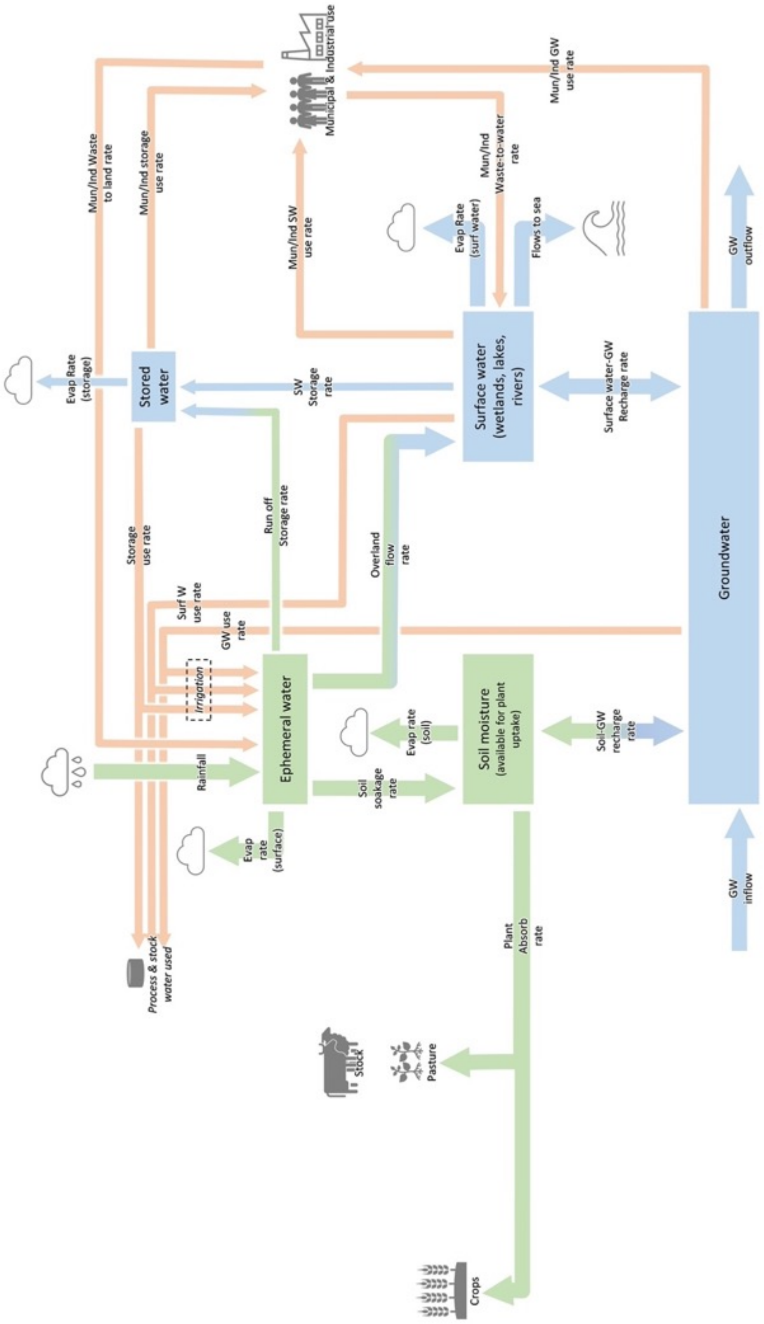

Figure 2. Overview of causal loop diagram

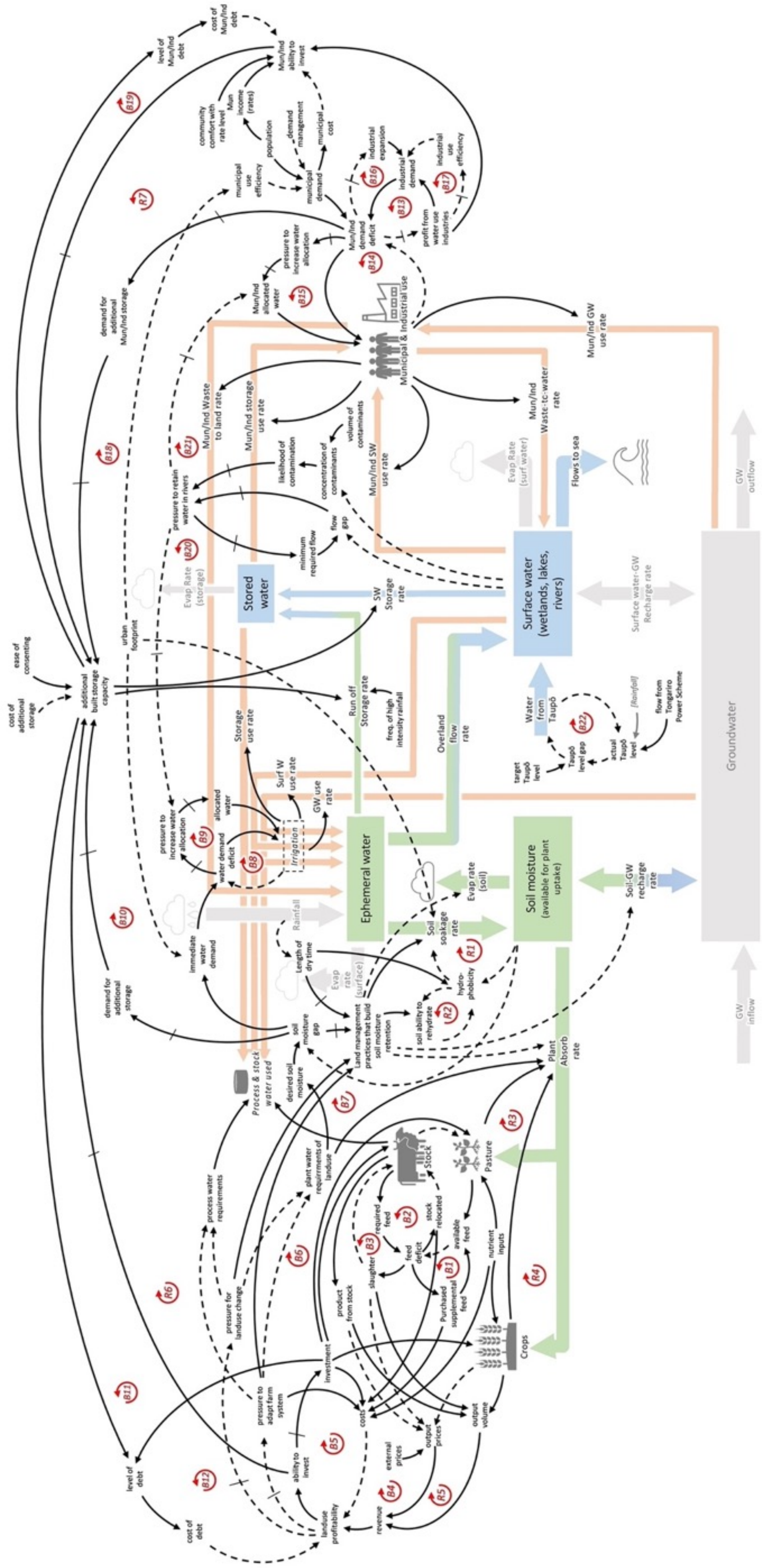

Table 1. Areas of the water cycle that the diagram highlights as important for drought adaptation

Part of diagram	Type of insight/discussion this may support
Soil soakage rate	How can farm management practices enhance the soil soakage rate, from surface water into soil moisture? What types of soil characteristics may need to be enhanced and how might this be done? e.g. maintaining or increasing organic matter.
Evaporation rate (soil)	How can the soil evaporation rate be influenced/reduced? How can ground cover be maintained/established to ensure less evapo-transpiration?
Soil-groundwater recharge rate	What soil characteristics may enable the retention of moisture in soils as opposed to water drainage to groundwater? How might those soil characteristics be retained or encouraged?
Plant absorption rate	What types of plants/crops can provide the same nutritional benefit for less water? What plants/crops are more drought resistant? What plants/crops may still be productive in sustained low soil moisture environments?
Overland flow rate	How might land use practices view the relationship between overland flow and soil soakage rate? Can land management practices encourage soakage rather than run-off?
Groundwater irrigation rate Surface water irrigation rate Storage irrigation rate	How might the demand for irrigation rates be reduced through technology or pasture/crop selection?
Built storage	What examples of built water storage might be possible, useful, or necessary? What types might not?

In addition, an analysis of the feedback loops (Figure 2) and the type of behaviour they generate highlights an additional set of insights that are useful for inclusion in drought adaptation discussions:

- The four key flows of water into and out of soil moisture should be at the core of adaptation to drought resilience.
- The soil moisture gap drives demand for irrigation and additional storage and use but does not immediately drive a change in underlying soil characteristics.
- Hydrophobicity is associated with reinforcing feedback loops that can operate in an undesirable way. These may reach a tipping point where soils hardly absorb moisture.
- The desired feed, based on stock numbers, will eventually rise or fall to meet the available feed, although this may be buffered by additional feed or relocating stock in the interim.
- Increases in allocated water may impact minimum flows and increase the concentration of contaminants.
- Water allocation limits are driven by conflicting feedback loops – one seeking to extract water; the other seeking to retain it.
- Extraction from groundwater may alleviate fluctuations in surface water bodies to a degree.
- Investment is self-reinforcing and is constrained by debt.
- Over time, the paradox of water use efficiency actually encourages greater total water demand.

Some examples of how the diagram can be used to qualitatively explore different potential futures is provided. This is by way of an articulation of broad anticipated trends in the future based on the causal relationships described in the diagram. This approach can be used to explore business as usual scenarios as well as other potential scenarios, as a pragmatic way of gaining insight into the potential behaviour of the wider system in response to potential changes.

As noted, this is the first step of this research. Anticipated future steps include:

1. Assess adaptation options for regional resilience by identifying and providing benefit cost analysis of options identified through a WRC in house analysis for reducing exposure to drought impacts and building adaptive capacity in the Waikato.
2. Investigate private adaptation behaviour changes that can be enabled for implementing pathways towards regional resilience to drought/water shortage.

1 Introduction

Climate change undermines the idea that the Waikato is a 'water safe' region. Rising temperatures and less consistent rainfall are expected to increase the incidence and intensity of drought in the Waikato region with broad implications for the availability of water and water quality, land use and productivity, farm profitability, ecosystem, human and animal health, employment, social values, the risk profile of pests and diseases, erosion, and wildfires.

The broad economic and social costs of drought include human and animal health impacts, restricted recreation and loss of social and cultural values, productivity loss, business failure, unemployment, damage to public and private infrastructure, damage to ecosystems including loss of ecosystem services.

The current management of water and the primary production systems that predominate in the Waikato are built on assumptions about climatic patterns that are changing (Milly, P. C. D., 2008). Continuing to conceive of drought as an interruption of normal climatic conditions, to be managed until 'normal' conditions return, undermines efforts to build adaptive capacity. There is a risk that Waikato Regional Council (WRC) strategic risk reduction plans, measures and stakeholder engagement is caught in an outdated paradigm based on lower levels of variability in climate. According to Stafford Smith et al. 2010,

> *"Climate change in the foreseeable future will not be some new stable 'equilibrium climate', but rather an ongoing 'transient' process, requiring 'an ongoing adaptation process'" (Stafford Smith et al. 2010, p. 197).*

Historically, adaptation to drought has largely been an intuitive and experience-based response to changing conditions and climate variability has always driven reactive adaptations. However, anthropogenic climate change impacts on natural and managed systems have been modelled, and under all IPCC scenarios, adaptation responses that go beyond reacting to impacts are now unavoidable. For these reasons, and the extent of expected change, a new focus on planned adaptation is required.

Climate change will have a larger effect on the duration and magnitude of droughts, representing increased risk to hydrological systems and water resources (Jenkins and Warren, 2014; Harrington et al., 2014; Salinger et al. 2019; Salinger et al. 2020). Even in a best-case scenario, an increase in the frequency and intensity of drought in eastern regions of the Waikato will still challenge management systems in the primary sector with broad implications for New Zealand's economy and society (Stroombergen et al, 2006; Kenny, 2011). Managing a distinct shift toward a more drought prone climate will require more than marginal adjustments to farm practices; transformational adaptation in primary production and water management would likely be necessary. Fundamentally, adapting to drought is about supporting new approaches to water management, new production systems and land uses that are resilient to more frequent and intense droughts alongside other climate change impacts such as heavy rainfall events (Grainger et al. 2021).

Results obtained in previous studies of climate scenarios and drought resilience point to the need for research into future drought adaptation (NIWA, 2011, Cradock-Henry et al. 2019, Hagenlocher et al. 2019). According to Cradock Henry et al. 2019, while much is known about climate change impacts there is less understanding of how these impacts might challenge existing practices and how to adapt. Resilience based research to improve understanding of how to adapt to drought is required to support planning and decision making. This report represents the first phase of the project 'Adapting to drought in the Waikato', which seeks to provide research-based advice to contribute to investment and policy decisions that build resilience to the impacts of more frequent and intense droughts in the region.

This report is structured in two parts.

Part I covers background and methodology. Here, section 1 provides some context and the objectives of this research. Section 2 discusses policy drivers and the socio-ecological context of the work including a discussion of different perspectives and definitions of drought. Section 3 outlines the methodology followed.

Part II describes results and insights. Here, section 4 describes WRC activities and insights for adapting to drought gathered from the interviews. Section 5 describes the conceptual water cycle flows used in the system diagram and insights for drought adaptation. Section 6 describes more detailed articulations of the complex interconnected influences on these flows – these are the core elements and insights of the system diagram. Section 7 presents a large-scale version of the complete water cycle system diagram, while section 8 describes a qualitative way of exploring alternative possible futures, using the diagram as a guide. Section 9 provides a conclusion and outlines next steps.

PART I

2 Context of this research

The impacts of drought on the Waikato region are increasing. In line with this, demand for adaptations that enhance drought resilience and reduce vulnerability and risk are also increasing. This report (and the water cycle system diagram it contains) is Part One of a programme of work *Adapting to drought in the Waikato*. The report and water cycle system diagram are intended as a precursor to a regional assessment of adaptation options and builds understanding of the system-level implications of increasing incidence and intensity of drought for the Waikato.

The report explores regional drought adaptation from a socio-ecological perspective and develops a conceptual diagram of the water system that can, among other things, support benefit-cost analyses of adaptation options, including behaviour change, which are intended to be the focus of the second phase of the project.

2.1 Objective of this research

The report introduces a diagram of the water cycle that enables an overview of the drivers of water flow and use. This is used to explore different forms of policy-relevant knowledge to understand linked vulnerabilities under drought situations.

> *As the effects of climate change unfold, understanding social-ecological system linkages will be important for guiding future adaptations and enhancing resilience in ways that appropriately integrate localised ecosystem capacity and human needs (Welsh et al. 2013, p.1).*

The water cycle system diagram (Figure 2) is a conceptual representation of the water cycle that synthesises direct influences on water flow and use; feedback loops that these influences may be part of and in turn are influenced by; and trends relating to these influences and feedback loops. The diagram is useful for initially and conceptually exploring adaptation options in a way that integrates, and gives appropriate weight to, different issues in considering adaptation priorities including hazard management, soil health and conservation, surface water ecology, land use, consenting and compliance and water allocation.

The diagram of the water cycle is a tool to help facilitate assessment of the technical feasibility of achieving specified goals in drought adaptation and avoid leaps of faith, knee jerk fixes and unintended consequences, eliminating options that will exacerbate undesirable feedback loops.

This report and system diagram aims to integrate policy issues and communicate relevant technical matters, at an aggregate and synthesised level. The tool is part of a broader project that seeks to go beyond seeing drought as a hazard event to be managed until normal rainfall patterns return, to a perspective that integrates current knowledge about how drought under changing climate conditions will impact current ways of managing agricultural production and water management in the region.

The following section discusses some policy drivers and social and economic issues that shape adaptation opportunities in the region.

3 Policy drivers and socio-economic context

Inaia tonu nei: A low emissions future for Aotearoa was released by the Climate Change Commission on June 9, 2021b, after an extensive consultation. The report contains advice to the Government on its first three emissions budgets and outlines the direction for the 2022-2025 emissions reduction plan. In addition to pricing mechanisms to incentivise emissions reductions, and support farmers and growers to identify and implement changes to reduce emissions, the recommendations for agriculture hinge on actions to reduce barriers and enable land use change.

The Commission's emissions reduction plan recommends shifting to farming systems that are less intensive with fewer animals and inputs-including synthetic nitrogen and recognises the potential for soil management to maintain and/or improve soil carbon. Barriers to diversifying land use and to accessing advisory services are prominent in the report which recommends scaling up services that can advise farmers and growers in diverse circumstances about management approaches and farming systems that reduce emissions and are adaptive to climate change (Climate Change Commission, 2021b, p.305-307).

There is increasing recognition from a policy perspective of the need to coordinate public and private investments and to facilitate collaboration and social learning through for example, designing and scaling up extension programmes. The direction of change outlined in the Climate Change Commission report implies heavier investment in information services for councils to support shifting land use towards climate adapted farming systems and products.

Climate adapted production systems and practices will become increasingly relevant to Waikato primary producers for multiple reasons. These include profitability; maintaining socially and economically viable rural communities; and anticipated regulatory changes and requirements associated with the NPSFM 2020 and Te mana o te Wai[1], climate change/adaptation legislation, and particularly the outcomes of the He Waka Eke Noa programme[2]. Some of these points are expanded on below.

Increased incidence of drought will increase on-farm costs associated with bringing in supplemental feed, irrigation costs (including pumping), lowering stocking rates and reduced profitability. These costs to farming operations and the environment will provide their own impetus for change. Some Waikato farmers are already seeking advice on planning for climate change adaptation. These farmers see compliance with existing rules in the context of their own business planning and are seeking support/tools for investment in adaptation planning. There is an important opportunity for WRC to articulate compliance with broader benefits associated with land use change, work-life balance, profitability, and environmental performance.

Te Mana o te Wai must inform council's implementation of the NPS-FM 2020. Te Mana o te Wai refers to the vital significance of water and prioritises the health of water and essential human needs over commercial users. This concept responds to the degradation of water as well as

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[1] Te Mana o te Wai, "the mana of the water" refers to the fundamental value of water for life itself and is expressed in the overarching objective of the NPSFM: to ensure that resources are managed in a way that prioritises:

(a) first, the health and wellbeing of waterbodies and freshwater ecosystems,
(b) second, the essential health needs of people, and
(c) third, the ability of people and communities to provide for their social, economic, and cultural wellbeing, now and in the future.

[2] He Waka Eka Noa Primary Sector Climate Action Partnership is in its second year of a five-year programme to support farmers capacity to mitigate GHG emissions and develop an appropriate pricing mechanism for farm emissions by 2025.

tensions between municipal and industrial/agricultural users. Research evidence on the impacts of climate change on water availability raises the significance of this issue alongside public concern over levels of nitrate and other contaminants in water. Te Mana o te Wai introduces a conceptual 'space of coexistence' that invites consideration of water management systems in the context of our fundamental existential dependence on the water cycle including the broad ramifications of 'adaptive' responses that intensify the commodification of water in the context of climate change impacts.

According to Linda Te Aho, 2018, while there is some uncertainty about how Te Mana o te Wai will be implemented and enforced, *tangata whenua* will be actively involved in shaping new frameworks for allocating water (Linda Te Aho, 2018, p.1620).

3.1 The economics of drought

The economic effects of drought can be thought of as the impacts of a special kind of natural hazard: it comes from a change in natural conditions that impact on the human systems (economy, society, community) that depend on them. They affect a range of values, such as the ecological health of water bodies, incomes from water dependent uses and other uses of water such as for recreation or amenity. Unlike hazards such as floods, fires, storms or earthquakes, droughts tend to be slow-moving, and do relatively little damage to capital assets (Freire-González et al, 2017).

However, as Wittwer and Waschik (2021) note, severe, recurrent or long-term droughts can impact on capital in two ways. First, drying out can have direct effects, such as loss of desiccated soils to wind erosion, or the destablisation of buildings or other infrastructure as their foundations are affected. In the case of soil-based infrastructure, such as flood stopbanks, this damage may occur directly to the capital asset. Secondly, lower farm incomes that result from droughts may have a depressing effect on farmers' investment, and hence, the overall level of capital may be lower than it otherwise would have been.

The Waikato region's potential vulnerability to drought is largely a function of the relative importance of water-dependent land uses. The economic implications of drought are likely to vary across the region, and across industries, depending on the current institutions that determine supply and demand, but agriculture and primary manufacturing are likely to be most affected by drought (Kamber et al, 2013). In the Waikato region, water has historically been plentiful and cheap, and water-dependent land-based (particularly agriculture) industries have become – and remain – an important part of the regional economy.

Recent experience has highlighted the potential significance of drought on the economy. The Ministry of Agriculture and Forestry estimated the 2007/08 drought cost the New Zealand economy $2.8 billion, with Waikato the worst affected region (Ministry of Agriculture and Fisheries, 2009). Frame et al (2020) estimate the cost of the 2007/08 drought in 2017 dollars as $3.2 billion. Continuing dry spells are estimated to have cost dairy farmers an average of $100,000 to $150,000 of income over the three years to 2010 (Ibid). At the same time, electricity production fell by 10 percent from the Waikato River hydro scheme due to low water levels.[3] It is generally considered that the lessons learned from the 2007/08 experience have meant that farmers are much better prepared to manage drought conditions. Levente and Apatov (2020) estimate the effects of a drought of this magnitude on an average dairy farm to be a reduction in annual profit per hectare of $466, an increase in current borrowing of $13,400, and a reduction in intermediate expenditure of $5,600[4]. Yet the Treasury estimated that the next significant drought, in 2013, reduced gross domestic product for New Zealand by $1.5 billion

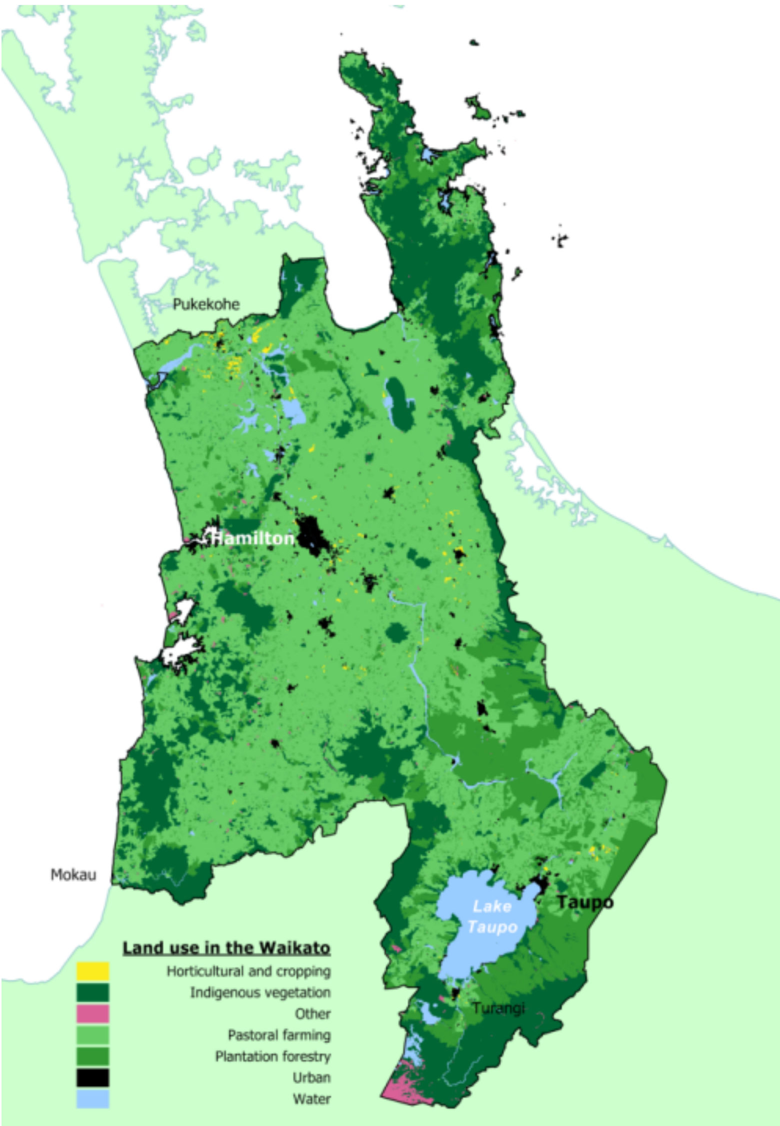
[3] Droughts | Waikato Regional Council

[4] Intermediate expenditures represent farm businesses' spending on inputs (which, in turn, represent incomes for suppliers). Levente and Apatow (2020) note that the reduction was contrary to their *a priori* expectations for an increase in spending due to requirements to buy in additional feed for stock.

(Treasury, 2013). Frame et al (2020) estimate that $800 million (17 percent) of the costs of the 2007/08 and the 2012/13 droughts can be attributed to climate change (Harrington et al. 2014; Salinger et al. 2020).

More than half of the region is used for pastoral farming. Agriculture contributes nine percent of regional gross domestic product (twice as much as the share nationally), ranging from 0.1 percent for Hamilton City to 38 percent for the Ōtorohanga District (Ibid). Across the region, dairy cattle farming provides around half of the agriculture sector's gross domestic product (Ibid). Sheep and beef farms, while producing less value add, cover large parts of the region. While land management systems can be adapted to deal with dryer conditions, such options need to be weighed up according to their benefits and costs. The question of how far to go with making changes to existing systems before the costs outweigh the benefits is an empirical one.

Figure 3. Overview of the Waikato Region



Source: Waikato Regional Council

A drought that affects the cost and/or accessibility of water represents a supply-side 'shock' to water-dependent activities. Such a shock will increase costs for activities that use water as an input, including electricity.

These increased costs may, for example, be the result of a requirement to buy in additional feed for stock to compensate for lack of pasture growth. In response to the scarcity of supplementary feed relative to demand in 2008, some feed prices rose by as much as 400 percent (Ministry of Agriculture and Forestry, 2009).

As well as increasing costs, revenues will also be affected: the quantity of output that can be sold is lower, but this may be offset to some degree by an increase in output prices, with relative scarcity resulting in the market clearing at a higher price. This may be the case for industries that have a significant focus on domestic markets (such as commercial vegetable production), but for others such as most dairy, meat and wool products, product prices are set on international markets, and drought-driven changes in domestic supply may have little effect on farmgate prices. In any case, the effect on total revenues for land use activities will depend on whether the price or volume effect is larger. Levente and Apatov (2020, pp4-6) summarise typical impacts and responses of dairy and drystock farmers to a drought.

Because New Zealand has a significant share in the global trade of dairy products, a large reduction in supply from a major dairy region like the Waikato may have some impact on international prices in the short term. Kamber et al (2013) estimated that the average response to a drought such as that in New Zealand in 2013 would be a 10 percent increase in world dairy prices. Moreover, since agricultural exports make up such a large proportion of New Zealand's export earnings, a drought of this magnitude may also see a fall in the New Zealand dollar exchange rate (further increasing international prices in New Zealand dollar terms).

When considering the economic implications of drought, it is useful to distinguish between 'green water' drought and 'blue water' drought. Following Friere-González et al, (2017), green water can be defined as,

> *"…precipitation stored in the soil or is temporarily stored on top of the soil and vegetation". Blue water is defined as "…fresh surface and groundwater…in freshwater lakes, rivers and aquifers…and captured and stored in artificial dams and reservoirs" (Ibid).*

A green water drought is where dry conditions and lack of rainfall result in low soil moisture levels, affecting the ability to grow pasture and crops. A blue water drought is where stored water levels are insufficient to meet demand.

In dry conditions, irrigation from blue water sources can substitute for a lack of green water, limiting the potential losses of lost primary sector production. The degree to which such substitution is optimal depends on the relative net benefits of the various potential uses.

The capacity to substitute blue water during a green water drought will provide water-dependent land users with a degree of resilience to drought. The potentially limiting factors here are the cost of blue water (the cost of infrastructure, pumping etc. *and* the opportunity cost of the alternative uses of the blue water – such as for ecological flows, industrial or municipal purposes) and the finite supply of blue water in storage. The latter constraint could possibly by overcome by building additional blue water storage capacity. That is, building storage may be an adaptative strategy *up to a point*; the associated costs of adding storage will limit the extent to which this approach is viable: when the costs of adding storage exceed the benefits, this will reduce, rather than improve resilience.

The availability of blue water to substitute for green water in drought conditions can be supplemented by investment in built infrastructure, such as dams, pipes and pumps[5]. The costs associated with such infrastructure mean that, under a given set of conditions, there is an optimal level of investment. Freire-González et al (2017, pp200-201) provide a conceptual model for determining this level based on marginal social costs and benefits and the set of socio-cultural, institutional, and technological factors that affect the water needs of a region at a particular time.

The key point here is that, at some point, the cost of investing in additional blue water infrastructure will exceed the benefits of doing so. One of the fundamental aims of this research is to understand how the various factors in the water resource system fit together – an important precursor to specific questions about resource allocation under changing conditions (including, for example, whether specific investments in blue water infrastructure are economically desirable).

[5] Referred to by Freire-González et al (2017) as 'hydraulic capital'.

For this reason, green and blue have been used in the conceptual diagram of the water cycle described later in this report, to highlight which of these categories flows and stocks of water fall into.

McKinsey (2009, p69) notes that increasing supply is not the only option for closing the gap between supply and demand for water resources. Increasing the productivity of water use and demand management (including the potential for changing to less water-intensive activities) are also potential methods for adapting to changing water availability.

A socio ecological approach to adapting to drought focuses attention on largely unconscious and accepted ways of negotiating the relations between economic production and water use. This suggests the need to explore adapting to drought in the Waikato as a solution oriented systematic study of drought that can integrate operating contexts with the aim of identifying localised adaptation potential and policy levers.

This will involve integrating climate and agronomic science with social and economic data in ways that recognise how social and economic dynamics shape adaptive capacity. This is because some adaptation options may progress only under certain social and economic conditions.

An enabling environment for successful adaptation to drought would align social capacity with local government action and national priorities and targets. Adger, 2003, p.400 suggests adapting to climate change impacts requires recognition of the interdependency between intervention and planning by regulators and the ability of individuals and communities to act collectively. Following Knothe, successful adaptation is influenced more by the quality of the negotiations on the use of common pool resources than by the choice of regulatory instruments (Knothe, 2011).

How we respond to climate change will create opportunities and impose constraints. The capacity of individuals, groups, and communities to accept constraints, perceive opportunities and make necessary changes to their practices is an important feature of climate adaptation and needs to be well integrated with the policy mix and measures supporting adaptation to drought.

The factors that influence private adaptive behaviour need to be well understood to design successful public drought-risk management strategies that will enhance farmers' adaptive capacity (VanDuinen, 2015, 1082).

Melyukhina, 2011, argues that farmers capacity to see risks as opportunities depends in large part on clarity over actions to manage the risk: "New Zealand farmers distinguish risks that generate threats and those that generate opportunities, with the dividing line between the two likely being the ability of the farmer to manage the risk" p.20.

Cradock Henry's 2021 study of Bay of Plenty dairy farms identified key social attributes that support private adaptation. They are critical awareness of potential risks, positive outcome expectancy, and self-efficacy. Cradock Henry's research demonstrates that raising levels of awareness of regional climate change impacts and adaptation options may support farmer resilience if it increases understanding of how their farm is exposed to climate change, what the impacts are likely to be and, by providing benefit cost analyses of available solutions, can support land managers belief in their ability to take necessary steps to adapt.

The next section discusses concepts increasingly applied in policy and practice related to adaptation. It specifically discusses the ways adaptation is understood in relation to resilience, vulnerability and risk and considers the implications for WRC policy and practice.

3.2 Adaptation

Smit et al, 1999, defines adaptation as "adjustments in ecological-social-economic systems in response to actual or expected climatic stimuli, their effects or impacts" (p.200).

In the Waikato region higher temperatures and less reliable and useful rainfall will challenge existing practices. Adapting to drought in the Waikato will include adjustments to agricultural systems, land uses and water management to reduce the impacts of both the long-term change in the frequency of drought and associated recovery time *and* more severe drought events.

Climate extremes and variability along with expected shifts in mean conditions will impact on ecological and human systems. The need for what the Stern report called 'major non-marginal change' (Stern, 2007) will challenge existing planning and management protocols wedded to operational norms. Business as usual is a barrier to successful adaptation.

Resilience strategies associated with emergency response or maintenance of business-as-usual more closely align with operational norms and are seen as politically safer than more adaptive or transformative measures (Adams-Hutcheson, et al. 2019, p.3).

Given the degree and accelerating pace of climate change, adaptation is both a necessity and an opportunity. Successful adaptation, according to Smit and Wandel's (2006, p.289) review of adaptation literature, has involved modifying existing resource management strategies such as water allocation, land management or income diversification and is most likely to occur when measures that address climate change risks are incorporated into existing decision structures relating to risk management, land use planning, livelihood enhancements, water and other resource management systems and development initiatives.

Reactive changes in the short term may be maladaptive if not evaluated in relation to long term goals. The system diagram can be used as part of adaptation planning process, understanding the system, identifying opportunities to intervene in ways that create resilience over the long term. The conceptual diagram of the water cycle focuses on the ways in which the system experiences changing conditions enabling leverage points to be identified that can facilitate the evaluation of adaptation options while accounting for causal relationships, non-linear feedback, counter-intuitive dynamics and unintended consequences.

The irrigation efficiency paradox is an example of fixes that can backfire:

This paradox, that an increase in IE (irrigation efficiency) at a farm scale fails to increase the water availability at a watershed and basin scale, is explained by the fact that previously non-consumed water "losses" at a farm scale (for example, runoff) are frequently recovered and reused at a watershed and basin scale (Grafton et al, 2018).

This is like the economic concept of 'Jevon's Paradox'. The 19th century economist, William Stanley Jevons, observed that, while more efficient technology may reduce the amount of resources needed to produce a unit of something, it may in fact lead to an increase in the total demand for the resource. In this case this would result in more water being exported in products and less water being returned for use downstream (Keenan, 2018). Water allocation policy that fails to take account of such responses can lead to unintended consequences that are counter to the policy intent – i.e. policies designed to reduce water use by improving efficiency can result in an aggregate increase in use. Careful design of regulations, taking into account aggregate effects, is necessary to avoid this.

When considering opportunities for adaptation, resilience, vulnerability and adaptive capacity are useful characteristics. Following Cradock-Henry (2021, p.1) ***Resilience*** is used here to refer to characteristics of a system that enable it "to cope with adverse events and potentially transform to take advantage of opportunities or minimise exposure to risks". Different land uses and water management systems will have different levels of resilience to increased drought incidence and intensity.

Building adaptive capacity involves taking preventative action to avoid adverse impacts of drought across the whole system. ***Adaptive capacity*** is a prerequisite for adaptation. It is the social capital and technical skills directed toward responding to ecological, social and economic impacts of climate change. The ability to shift land uses can be considered a type of adaptive capacity, as can soil management that increases water holding capacity. Both examples increase the capacity to be resilient to drought.

Vulnerability is the opposite of adaptive capacity but is considered in relation to it and encompasses attributes that make people, ecosystems and livelihoods susceptible to harm from climate change impacts. The goal in assessing vulnerability is to ascertain the determinants of vulnerability in the system to identify ways adaptive capacity can be increased.

Vulnerabilities often reflect incapacity to make changes. For example, high levels of debt reduce farmers' capacity to invest in necessary changes and may lock them into intensive systems of production that require a narrow set of conditions to succeed.

The region's vulnerability to drought responds to the dynamics between climate change impacts and a range of factors including the regions water availability and quality; soil quality particularly as it relates to water holding capacity; the dependency of the local economy on water intensive land use; population growth that increases municipal demand; risk perceptions and behaviour change; local geomorphology etc.

According to Adger,

> *the effectiveness of strategies for adapting to climate change depend on the social acceptability of options for adaptation, the institutional constraints on adaptation, and the place of adaptation in the wider landscape of economic development and social evolution. The effectiveness of adaptation also depends on the compounding factors of economic globalization and other trends (2003, p.388)*

Adaptations can be tactical (reactive), strategic or transformational and generally include changes in management, capital investment, and processes to reduce risks and realise opportunities.

3.2.1 Transformative and incremental adaptation

Stafford Smith et al. 2010, considers differences between incremental changes and transformative adaptation. The authors argue that transformative change is a change in the set of variables that determine the systems functioning whereas incremental change is adjustments that enable current objectives to be met under changed conditions.

According to Rickards and Howden, 2012, p.241

The aim of such transformational change is to maintain sets of activities, products (sensu lato), values and processes in the sector or region. In particular, transformative adaptors either seek to: (1) proactively avoid, uncertain and severe challenges in order to avoid transformational change of a more involuntary, uncontrolled and negative character; or (2) be 'first movers' so as to take full advantage of what they see as emerging opportunities

Rather than a narrow defensive task to protect core assets or functions, adaptation should be assessed as both a response to multiple drivers and a source of social and economic change that seeks alignment with changing climate conditions. Climate adaptation can create new and better systems for living well within environmental limits and this is consistent with a move towards 'low regrets' strategies where benefits accrue regardless of whether expected impacts occur.

Before considering WRC adaptation planning it is important to acknowledge that regulation can be counter-active or pro-active. Counter-active regulation builds resilience by 'countering' activities that increase vulnerability such as contamination of water or over allocation. All forms of regulation include policies, procedures and rules. Here, a distinction is made between regulation that simply 'counters' an existing set of problems, and regulation that seeks, 'proactively', to deliberately facilitate a particular set of outcomes. The key shift needed is to move beyond just qualifying (counteracting) an existing situation, to deliberately promoting (pro-activating) a particular project with clearly stated goals and practices. Pro-active regulation pro-actively facilitates resilience and/or encourages resilient behaviour, by for example, providing information and tools, incentives and funding. An approach to building resilience to climate change that creates alignment between counter-active and pro-active regulation will have the greatest impact.

3.2.2 What WRC adaptation planning needs to consider

As the impacts of climate change unfold, reduction in water availability will occur alongside increasing demand for water. Current agricultural production practices in the region are limited in their capacity to adapt to reduced water availability. Competition over water resources will intensify as the supply of water declines. We currently do not have an integrated adaptive management system for managing these anticipated impacts and dynamics.

Decreasing water availability associated with drought exacerbates the need to balance the needs of different constituencies and functions and implies the need to dampen current and anticipated levels of competition between human water needs and the ecological needs of the water bodies.

Adaptation to drought is about adapting water use and production systems to new climatic conditions and involves shifting water allocation and production systems towards alignment with changing climate conditions. Given the climate projections for the Waikato region it makes sense to start preparing a support basis for approaches to adaptation including comparing feasible options using benefit cost analysis (BCA) or other suitable methods[6].

[6] Benefit cost analysis is an established methodology that weighs estimated costs against estimated benefits, with both usually measured in monetary terms. There are other potential approaches that may be suitable or preferred in some circumstances. For example, multi-criteria analysis aims to evaluate costs and benefits, but does not require the consistent use of metrics. This avoids the problem of measuring everything in monetary terms, but it comes with its own difficulties of comparing across qualitatively different types of costs and benefits. Cost-effectiveness analysis attempts to identify the least-cost option for achieving a particular objective or, the most that can achieved for a given budget.

Adapting to drought includes: (1) Interventions to save and hold water available during wet periods and increasing the buffering capacity of the soil and water system; and (2) Accepting the limitations of the new climate system and adapt water allocation and use to increased drought risk. The limits of 1 imply the need for 2.

Adapting production systems to drought conditions is expected to require a range of actions, including but not limited to (in no particular order):

1. New water storage (taking and storing water during winter high flows);
2. Irrigation schemes;
3. Water reticulation (fencing off waterways and replacing with water tanks, pumps, pipes and troughs) approx. 60% of Waikato farms currently have reticulated water systems, mostly dairy farms;
4. Reducing demand;
5. New cultivars, such as deep rooting plants and alternatives to rye grass which is drought sensitive;
6. Increasing soil moisture holding capacity (by for example adding biochar[7] to soil and the use of organic waste material to build soil moisture holding capacity);
7. Rotational grazing to increase macroporosity of soil and improve water holding capacity;
8. Minimum (or no) tillage[8], direct seeding, continuous cropping, crop diversity;
9. Establishing/better utilisation of shelter belts and riparian planting (animal and soil health, carbon offsetting, water temperature reduction);
10. Restoration of wetlands for water storage and denitrification;
11. Use of trees (agroforestry)[9] to provide microclimate, increase rainfall, reduce wind and cool soil as well as protect against erosion.

New or modified production systems and land uses may also feature, including:

1. Changing production systems (shifting to lower emissions and/or less water intensive production)
2. Diversifying: Contracting of operations in existing areas and expanding in others (Agroforestry e.g. planting marginal land in manuka for honey, dry tolerant trees)

Information and support for adaptation to drought should be integrated with the current advice on drought mitigation strategies and other activities WRC currently undertakes to reduce vulnerability and support community resilience as well as to achieve the implementation of WRC climate action road map.

[7] Biochar was recently included as a promising negative emissions technology (NET) in the Special Report on Global Warming of 1.5 °C (IPCC 2018, Chapters 2 and 4) produced by the Intergovernmental Panel on Climate Change (IPCC).

[8] Vegetation protects soil against erosion and water loss by covering it and adding organic matter cements increasing its bulk and fertility.

[9] Agroforestry where woody perennials are used on the same land management units as agricultural crops or animals was popular in New Zealand about 20 years ago as an alternative land use and investment income for poor productive pasture land. There is renewed interest globally because of its capacity to reduce vulnerability to climate impacts.

3.3 Perspectives on drought

Understanding drought based on patterns of incidence has drawn attention to the increasing frequency and severity of drought that is already occurring (Statistics New Zealand, 2021). As the impacts of climate change unfold, the Waikato region is likely to experience unprecedented hydrological extremes. Droughts, storms, and floods are predicted to become more frequent and more severe with the northern and eastern parts of the region becoming drier and the southern and western areas becoming wetter (MfE, 2020b). The Waikato has experienced six out of seven of the driest summers on record alongside dryer than average annual rainfall since 2008.

Defining and quantifying drought is a highly contested field of research. The standard definition of drought is limited availability of water, relative to normal conditions with negative consequences for humans and ecosystems. This definition is used primarily because lack of rainfall is a key driver of drought but also because of the ready availability of precipitation data[10]. In the context of climate change, and according to *Our Atmosphere and Climate 2020,*

> *A drought is a prolonged and marked shortage of moisture compared to what is expected. Drought is caused by a lack of rain, but high temperatures can contribute because they accelerate evaporation and water loss from soil, vegetation, and waterways. Therefore, high temperatures, low rainfall, and more of the rain falling heavily (with consequently longer dry intervals) can quickly lead to drought conditions (MfE, 2020b, p. 40).*

Unlike fires, storms and floods, drought does not have clear entry and exit criteria and impacts can continue well after drought is 'broken' by rainfall. In addition, the impacts are context specific and can vary even between neighbouring farms.

Approaches based on departures from 'average' conditions lend themselves to perceptions of drought as hazardous 'events' with associated drought relief and management strategies. As the impacts of climate change unfold the idea of departures from average climatic conditions will need to be replaced with tools for recognising climate disequilibrium requiring on-going adaptation. In this context, defining drought as a manageable risk provides a broader focus on vulnerability and resilience (NIWA, 2011, p.44).

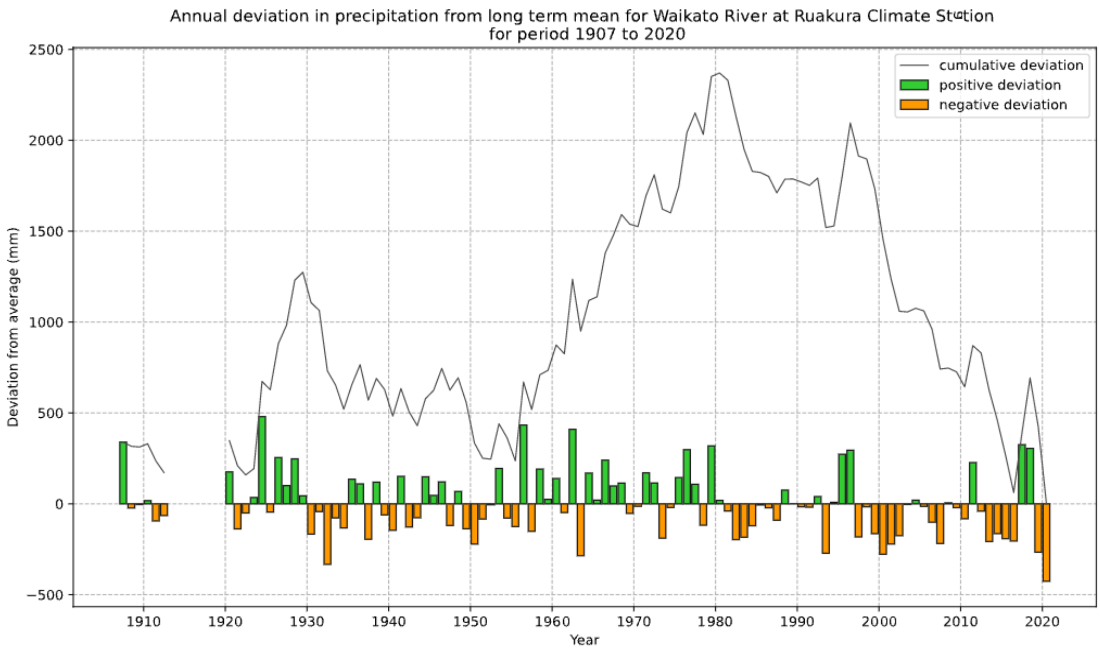
Definitions and indicators of drought based in the perspective of drought as a natural hazard include Meteorological, Hydrological, Agricultural/Soil moisture and Socio-economic. Each of these are explained below.

3.3.1 Meteorological approaches

Meteorological approaches use monthly precipitation data to provide a long-term quantitative analysis of precipitation in an area and are useful for identifying statistically anomalous conditions. 2020 was the driest year on record, as demonstrated in Figure 4.

[10] Integrated data sets that include temperature, evaporation and soil moisture are necessary because the interactions between these can generate distinct impacts. For example, rainfall may not be effective if soil is hydrophobic.

Figure 4. Annual deviation in precipitation from long term mean – Waikato River



3.3.2 Hydrological approaches

The movement from anomalous meteorological conditions to hydrological drought is called drought propagation and focuses on the relationship between precipitation, soil moisture, runoff, and groundwater recharge. It is the relationship between these factors that the system diagram focuses on.

Hydrological approaches define drought by departure from the long term normal in a region based on surface and subsurface water, including lakes, reservoirs, stream flows, wetlands, groundwater, and soil moisture. This approach, and the data used considers a larger spatial area and longer time frames as ground water may have a lag time in response to precipitation. Hydrological approaches consider human systems indirectly in terms of land use, water takes or prolonged over-allocation of ground water and surface water, which affect the severity of drought. The most common indicator of hydrological drought is stream flow (Van Loon, 2015). WRC has a network of water level gauges that measure stream flow.

Multi-year droughts, sometimes described as 'mega droughts' such as the 'millennium drought' in Australia that ran from 1996-2010, can result in hydrological changes. According to Peterson, hydrological drought may persist indefinitely and can cause a permanent reduction in water supply (Peterson et al., 2021).

3.3.3 Agricultural/soil moisture drought

Agricultural drought focuses on deviations from long term conditions in soil moisture to support crops/pasture and is sometimes referred to as soil moisture drought because of its link to crop failure (Van Loon, 2015). Agricultural drought is not measured as a function of precipitation or hydrological availability of water because soil types vary in their uptake and holding capacity. Crops also have different moisture needs. For example, what is considered an agricultural drought in the Waikato may be normal conditions in parts of Otago. Drought, according to this definition, is relative to the production system/land use and sensitivity to drought varies depending on production systems.

3.3.4 Socio economic

The way people experience drought reflects the socio-economic context. The functioning of social life and economic production is always linked to the functioning of natural processes. A socio-economic approach to drought considers the relations between society and water management. Ways of managing water are socio-economic practices. Human relationships to natural processes are routinised and reproduced in everyday practices and mostly happen without much conscious reflection through the exercise of experiential know how (Knothe, 2011). The dynamics and interdependencies between human systems and the water system are an important driver of drought and it is necessary to understand these dynamics to effectively design and plan drought adaptation. Changes in land use can, for example, create faster run off to stream and therefore lower groundwater recharge. Or increased efficiency in irrigation can also reduce groundwater recharge.

The space time interactions between meteorological, hydrological, soil moisture/agricultural and socio-economic drought are also important for a full understanding drought impacts and how drought risk management can reduce negative consequences.

4 Methodology

As previously noted (section 2.1), the objective of this research is to develop insights for adapting to drought using a system approach. In this section system diagrams are introduced (and elaborated on in Appendix 1), and the methodology for developing the conceptual diagram of the water cycle is summarised.

4.1 What is a causal loop diagram/system diagram and systems thinking?

The world that we live in is a dynamic interconnected place of cause and effect. The work of policy development often seeks to respond to undesirable behaviour and its cumulative impacts on our natural environment and therefore seeks to influence these causes, to restrict undesirable behaviour and/or enable desired behaviour.

'Systems Thinking' is a name often applied to a range of approaches to thinking about policy issues holistically. One of these approaches is the academic discipline of 'System Dynamics'. System Dynamics originated from the Sloan School of Management at the Massachusetts Institute of Technology, Cambridge, Massachusetts in the late 1960s.

Systems thinking, as articulated by the discipline of System Dynamics, is a conceptual framework and set of tools that have been developed to help clarify patterns of interconnectedness (Senge, 2006)[11]. They help us understand the structure of various interacting factors that generate the behaviour that we are trying to understand. Once these interconnections are articulated, we can better understand which parts of a system are having the most influence on behaviour, allowing us to identify levers of influence.

Where the term systems thinking has been used here, it refers to the qualitative concepts articulated by the discipline of System Dynamics (Sterman, 2000). The main qualitative tool that this discipline uses to understanding systems is called a causal loop diagram (CLD) or a system diagram. Throughout this report the term 'system diagram' has been used.

A description of the fundamentals relating to how CLDs operate is provided in Appendix 1. This explains the key features of systems thinking and causal loop diagrams – namely the concept of circular causality instead of linear causality. This is shown diagrammatically as either reinforcing or balancing feedback loops. Feedback loops are the basic building blocks of system diagrams.

It is noted that, to fully understand the system diagram presented in the remainder of this report, it will be important for the unfamiliar reader to acquaint themselves with the contents of Appendix 1.

4.2 The process used in this report

The insights in this report were developed from interviewing subject matter experts within WRC. Interview data was used to develop the system diagram and insights described in following sections.

4.2.1 Interviews of subject matter specialists

The findings and drought system diagram are based on semi structured in-depth interviews with 12 key managers, team leaders, scientists and operational staff undertaken during April, May, and June 2021. Participants were selected based on their expertise and experience and for their

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[11] For a detailed introduction to the concepts of Systems Thinking, the reader is referred to *The Fifth Discipline – the art and practice of the learning organisation* (2nd ed.) by Peter Senge (2006) as an accessible introduction.

capacity to represent organisational operational focus areas. This small but purposive sample uniquely offered a multi lens perspective on drought adaptation within a shared framework for understanding issues related to regional resource management.

The 12 participants represented specialist expertise and operational experience in water allocation and consenting, environmental monitoring, hazard management, soil science, hydrology, freshwater science, strategy, and land management advisory services. The interviews followed the same format and lasted for one to two hours. The interviews were semi structured open dialogue in which the research team participated.

Participants were asked to discuss current and anticipated impacts and implications of increased drought, to explore current ways of managing risks and regional sensitivities and sources of adaptive capacity. They were prompted for insight on trends or tensions that they were aware of or anticipated being an issue in the future.

This approach to data collection was designed to investigate how increased frequency and intensity of drought and related impacts around rainfall and temperature will impact on largely accepted ways of negotiating the relations between regional economic development, water resources and drought. This approach is appropriate given managing the risks associated with climate change impacts related to drought is a complex problem where no one person or team knows 'the' answer, or when is not likely that there is a single 'correct' answer.

4.2.2 Synthesising interview insights into a system diagram

The verbal discussions were synthesised and translated into a system diagram by the systems specialist on the research team. This was an iterative and reflective process that drew heavily on the experience with system diagrams brought by Deliberate to develop initial drafts; then reflected these to the WRC authors for feedback, insights and confirmation.

The findings and diagram resulted from the sharing and overlaying of different perspectives on the same issue and the analysis involved integrating different modes of interrogating the problem of regional drought into a coherent diagram.

The interviews were followed by a review workshop, which offered participants an opportunity for participatory reflection on the drafted diagram. This resulted in some refinements of the diagram.

4.2.3 Peer review process

This report was externally reviewed by a New Zealand based social scientist, specialising in resilience and adaptation and a United States of America based specialist in system dynamics, with a focus on participatory approaches and applied experience in natural resource management (especially water). The report was also reviewed internally by a WRC Principal Strategic Advisor.

4.3 Benefits of the system diagram approach

The conceptual system diagram described in this report is informed by the discipline of Systems Dynamics. This approach can interrupt a narrow focus on sectoral interests or specific planning issues, by revealing trends and tensions, feedbacks, delays, and unintended consequences. This provides an integrated picture of how changing drought incidence and intensity will intersect with ecological-social-economic dynamics, land use and water allocation.

Like any tool, the approach has its limitations – its use does not provide rigorous quantitative analysis. Yet whether this is required will depend on the decision-context. In some instances, more rigorous quantitative simulation modelling may be possible and useful for some decision-making. In such instances this tool will be complimentary to such analyses and is intended to help inform what needs to be included in them.

Yet rigorous quantitative analysis will not always be possible or necessary. In these situations, this diagram will be useful as an independent decision-support tool.

The system diagram that is described in this report is useful for:

- providing resource users and stakeholders with a synthesised overview of the complex relationships between land use, water management, ecosystem services and the broader socio-ecological context needed for decision making for adaptation particularly collaborative responses;
- facilitating the perception of the broad system dynamics which can benefit anticipatory thinking and innovation and provide the basis for effective collaboration between differently affected users;
- assisting in creating a common language to enable experts from a range of disciplines to contribute effectively to solutions based research;
- facilitating explicit consideration of multiple interacting factors and trends that resource managers typically evaluate separately and in so doing can help create synergies and avoid trading off objectives (e.g. between drought and flood management);
- bringing understanding to user groups of the changing nature of water reliability so they can plan for operating in periods of low flow and reduced water availability;
- highlighting the type of information, including any gaps that is likely to be required for assessing adaptation options and developing adaptive pathways; and
- enabling effective policy and decision-making that anticipates and prepares for likely future changes, avoids unintended consequences and achieves multiple benefits.

PART II

5 WRC activities and adapting to drought

Increasing drought incidence and intensity in the Waikato and adjacent regions will mean, other things being equal, less water will be available for allocation. Water demand management measures in the context of reduced availability will become increasingly relevant as the frequency and severity of drought increases. It is therefore important to prepare a support basis for such measures and develop ideas on their implementation as well as clearly communicate the full suite of issues. A drought-adapted, integrated system of land and water management in the region that can increase businesses and community resilience to drought will need to consider a range of things as outlined in the following sub-sections. These have been informed by the internal interviews with WRC subject matter experts.

How WRC undertakes its functions can facilitate adaptation but can also inhibit it. For example, WRC can seek minimal compliance with the rules pursuing counter-active regulation to restrict environmental harm or can add to that a pro-active regulatory framework that clarifies compliance goals and seeks alignment with building resilience and adaptive capacity. The following section outlines a range of issues that need to be considered in developing a response to building resilience that recognises that regulation can be both counter-active and pro-active[12].

This section outlines a range of issues that need to be considered in developing an approach to building regional resilience to drought. These issues are summarised in Table 2.

Table 2. Issues to be considered in developing a Waikato Regional Council approach to building resilience

Issue	Summary description
Soil	A greater range of soil quality attributes are relevant in a drier climate – in particular, those that enhance the capacity of soils to hold moisture available for plants.
Hydrophobicity	The impact of poor microbial activity on hydrophobicity and moisture holding capacity will become more important in the coming decades as drought severity increases.
A greater role for groundwater	There could be a greater role for groundwater in the region as a buffer against reduced rainfall to increase allocable capacity and better manage the risks and effects of water use.
Water storage	Water storage can act as a buffer against lower and/or less frequent rainfall although larger scale storage options are costly and can drive intensification and consequent external effects.
Irrigation	The capacity of irrigation to contribute to drought resilience in the region is limited
Restrictions on contaminants	Increased drought incidence and intensity will create further impetus to restrict contaminants because more frequent low flows and reduced ground water recharge reduce the capacity of water to dilute contaminants.
Spatial planning considerations	Climate change is expected to shift agro-ecological zones with consequences for the location of production systems.

[12] See earlier discussion in section 3.2.1.

Issue	Summary description
Hazard risk	The dynamics between flood and drought risk may increase the relevance of an integrated approach to drought and flood risk.
Restoration or building of new wetlands	Wetlands operate to enhance denitrification and provide storage and buffering in cases of intense rainfall events.
The way data is used	Setting allocations should be frequently (five-yearly) reviewed as historical averages on which management decisions are taken may be insufficient to reflect increasingly extreme events, such as frequent or intense dry spells. What are currently considered extreme events may become more frequent *without necessarily affecting average measures*.
Water allocation methods	Rules may need to adapt to improve the flexibility of water allocation, to reduce the use of allocations as insurance (which is usually not used, and which has an opportunity cost). A practical alternative to the 'first-in, first-served' approach may be needed to encourage dynamic efficiency in allocation.
Land use change	High water use production models will face increasing risks as climate change unfolds

5.1 Soil

The social and economic consequences of drought are felt at soil moisture. Dynamic aspects of soil quality contribute to drought resilience and a greater range of soil quality attributes are relevant in a drier climate – in particular, the capacity of soils to hold moisture available for plants. Measures to increase soil moisture holding capacity by increasing microbial activity and macroporosity can increase the effectiveness of rainfall important for adapting to drought.

5.2 Hydrophobicity

In dry conditions water repellency, an issue particularly in the upper Waikato, is caused by hydrophobic compounds forming a water repelling crust on the soil. Rainwater cannot be absorbed by hydrophobic soils, reducing water available for plant growth. Hydrophobic soils also contribute to conditions for flooding.

"In permanent pasture the important cause of soil hydrophobicity is the presence of low-quality carbon caused in part by slow decomposition of organic matter, hard to decompose vegetation such as brown top and poor soil microbial activity" (WRC, 2021).

Microbial activity in soil restricts hydrophobicity and increases soil moisture holding capacity. The impact of poor microbial activity on hydrophobicity and moisture holding capacity will become more important in the coming decades as drought severity increases. Soil management for increased microbial activity involves adding organic matter. The practice of adding organic matter to soil builds resilience to drought by increasing carbon, microbial activity and moisture holding capacity. Minimum or no tillage also builds resilience to drought because unlike ploughing, it maintains the soil structure needed for moisture holding capacity and reduces carbon loss.

Soil compaction also restricts water infiltration and is relevant for drought adaptation. Soil compaction from animals and farm equipment reduces the macroporsity of soils and restricts the infiltration of water. Plant uptake of nitrogen and phosphorus tend to be lower in compacted soils, while sediment, pathogens and contaminants in overland flow also tend to increase (Taylor, 2021, 38).

While in New Zealand and in the region, soil carbon is comparatively high and there is less capacity for increasing soil carbon sequestration than in some other countries where soil is extremely degraded, soil carbon is declining in the arable sector. This is likely due to practices such as power harrowing.

Water repellency is understood to be an issue for the region but there are gaps in understanding of its impacts.

The benefits of soil quality are multiple and are generally at risk in the region with only 11% of soil quality sampling sites in 2019 meeting target values down from 18% in 2006. The main soil quality issues for productive land in the region occur on pastoral land. Pastoral sites represent 58% of the land area and only 3% are in a satisfactory range for all seven indicators (Taylor, 2021, 15). The soil monitoring programme indicates that there is significant room for improvement of soil quality in the region.

Management approaches that can enhance the effectiveness of rainfall by reducing the impact of wind and temperature such as planting trees and practices that improve soil macroporosity such as minimising compaction and adding organic matter have local adaptation potential. Some practices that can enrich soil carbon such as adding biochar are currently uneconomic.

Land management advisory services provide a key function in translating relevant science into recommended on farm practices. The WRC land management advisory services team (LaMas)[13] currently assists farmers and key stakeholders within the agricultural sector with information on farming practices that can support drought resilience[14].

LaMaS extension programmes involve technical information transfer, disseminating guidelines and reports. There is an opportunity for WRC extension programmes to nest compliance within a broader suite of benefits to support localised adaptation, investment and innovation.

5.3 A greater role for groundwater

There could be a greater role for groundwater in the region as a buffer against reduced rainfall to increase allocable capacity and manage risk effectively. A greater role for groundwater in allocation would increase the degree to which surface and groundwater would need to be managed as one resource. Because groundwater effectively moves through the system more slowly than surface water, it is less affected by peaks and troughs related to climate or weather events. This means groundwater may be able to be allocated with lower ecological impacts relative to surface water. Further, it suggests water allocation may be less prone to drought-induced restrictions. However, accessing groundwater can be expensive, and this needs to be weighed against these other benefits (both at the farm and wider scale).

Ground water use in the Waikato is comparatively low and the recharge rate is generally high. There are pockets of ground water contamination particularly in areas where intensive land use has a long history.

Groundwater levels are currently not directly monitored, and rainfall is used as a proxy for groundwater recharge (half of total rainfall is the recharge rate). The allocable flow of groundwater is considered to be half the estimated recharge.

[13] WRC LaMaS team has seven professional staff with expertise in agricultural and environmental science and are responsible for promotion and implementation of sustainable agricultural practices, including the implementation of Healthy Rivers plan change-1, NPS, NESF and s360 regulations.

[14] https://www.waikatoregion.govt.nz/services/regional-services/regional-hazards-and-emergency-management/droughts/

Anticipated climate changes will impact rainfall patterns with less frequent and heavier rainfall expected. Cumulative daily rainfall should correspond with ground water approximately, however there is a big difference between a gently recharging rain and heavy rain events in terms of impact on groundwater recharge because heavy rain events increase water flows off land and into waterways reducing groundwater recharge. Reduced recharge increases the risk of groundwater contamination as contaminants are less diluted.

5.4 Water storage

Water storage acts as a buffer against lower and/or less frequent rainfall. There is some scope for high flow allocation in the Waikato dependent on capacity to store water in winter for use in summer months.

LaMas encourages water harvesting farm ponds using natural gullies not connected to streams. This type of small-scale storage is particularly useful in undulating hill country where water flow can be fast and there is minimal percolation. Farm ponds can recharge water in the ground for up to 3-4 weeks and increase resilience by creating a buffer zone for vegetation (WRC, 2021). Yet the ability of such small-scale water storage to provide adaptive capacity is limited, and the costs of this adaptive approach will need to be considered.

Larger scale storage options face a number of roadblocks. Large scale storage is costly and the economic returns accrue over the long term. This tends to drive intensification of land use to pay for the cost which increases contamination of waterways.

5.5 Irrigation

Water in the Waikato region is close to being fully allocated with some catchments over-allocated. This, and the National Policy Statement for Freshwater Management 2020, means that the capacity of irrigation to contribute to drought resilience in the region is restricted. To the limited extent that irrigation can support production during drought in the region its effectiveness can be increased by soil management practices that increase soil moisture holding capacity.

5.6 Restrictions on contaminants

Restrictions on contaminants and the use of water ways to transport and assimilate waste are important. Low flows impact water quality, ecology and geomorphology. During periods of low flow, higher temperatures and longer residence time create conditions for algae blooms which have negative consequences for ecology, recreation and tourism. Low flows can also create the need for extra treatment of potable water due to the higher concentrations of contaminants during periods of low flow.

The current approach to this situation is to restrict water takes to maintain specified flows. The changes to the Waikato Regional Plan currently in process aim to deal with discharges to water itself. For example, it introduces input controls where nitrogenous fertiliser cannot be applied at rates greater than 30kgN/ha per dressing and not at all during June and July when plant uptake is lower raising the risk of leaching.

Increased drought incidence and intensity will create further impetus to restrict contaminants because more frequent low flows and reduced ground water recharge reduce the capacity of water to dilute contaminants.

5.7 Spatial planning considerations

Climate change is expected to shift agro-ecological zones with consequences for the location of production systems. For example, moving some production to areas that will experience increased rainfall.

5.8 Hazard risk

Hazard risk associated with increased drought in the region includes river-bank stability which can be impacted when low flows occur in conjunction with a king tide cycle because this creates high highs and low lows.

As climate change unfolds the dynamics between flood and drought risk may increase the relevance of an integrated approach to drought and flood risk.

Drought-flood abrupt alternation events, or rapid shifts from drought to flood, may occur more often as precipitation variability increases and temperatures rise[15]. These events can be problematic for reservoir management.

Droughts can increase the likelihood of stop bank failure because the drying effect of drought on stopbanks reduces their weight and thereby lowers their effectiveness against the force of water during flood. Drought induced fires if followed by floods can create problems for reservoirs by increasing the amount of sedimented solids behind the dam. The confinement of river paths within stopbanks can lead to lower infiltration and ground water recharge (Ward et al. 2020, p.3-5).

Planned regional risk assessments can identify key risks and associated impacts and identify pinch points, risk thresholds and management options.

5.9 Restoration or building of new wetlands

Denitrification[16] of water requires slow moving water, carbon, and anoxic conditions. Wetlands provide these conditions and operate to enhance denitrification. This process is enhanced when wetlands are located where the water table is high. The restoration or building of new wetlands also provides storage and buffering in cases of intense rainfall events, as well as denitrification services.

5.10 The way data is used

It is important to consider how historical data records are used to inform decision making about future water allocation. Long term records reflect historical averages. The use of historical averages in resource management is intended to avoid responding to naturally 'noisy' systems with high volatility in their data. However, using *too* long an average period runs the risk that resource management decisions (such as imposing restrictions on water use in a dry period) will occur too slowly. In non-linear systems this runs the risk of overshooting thresholds, with potentially irreversible effects.

Baseline data for identifying low flows used for managing water takes is currently averaged over 30 years. In a rapidly changing environment, the historical averages on which management decisions are taken may be insufficient to reflect increasingly frequent or intense dry spells. Setting allocations should therefore be frequently (five-yearly) reviewed as historical averages on which management decisions are taken may be insufficient to reflect increasingly extreme events, such as frequent or intense dry spells. What are currently considered extreme events may become more frequent *without necessarily affecting average measures*.

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[15] Australia's Millenium drought (1997-2009), which impacted the environment and economy of a large region ended in destructive floods that included the failure of stopbanks along the Murray Riverbank after which the region returned to drought (Ward et al. 2020 p.2).

[16] Denitrification reduces N-pollution to waterways by converting soluble nitrate to nitrogen gas that is emitted to air.

5.11 Water allocation methods

The full volume of consented water takes is often not *actually* taken. For consent holders, the difference between their allowed and actual take in most years represents a type of insurance against dryer year when they *will* need the additional water. In a dry year, they will exercise their consent more fully and the actual use may be expected to more or less equal allocated use (since the consented amount will be based on their needs in a dry year). In other years, actual use may be expected to be *less* than the allocated amount. In a constrained catchment, where the demand for allocable water exceeds supply, there will be opportunity costs in this approach. In particular, in a normal year, consent holders may not utilise their full allocation. This water is not necessarily available to anyone else to take, and hence there is no *ex situ* use value[17].

One approach to realising this value in normal years is to allow the trading of the unused proportion of a consent. The Waikato Regional Plan does indeed to enable the transfer of water under certain circumstances, although it is unclear the extent to which this occurs compared to an efficient outcome (it would only be expected to occur if the transfer provides a consideration to the consent holder that exceeds the insurance value of the allocation). Private arrangements to share consented water while not common are happening and may happen with greater frequency in the future.

There may be some opportunity to build resilience through facilitating transfers. For example, water user groups could water 'bank', sharing allocation by collaborating and negotiating timing and respective shares. Neighbouring farmers/growers may cooperate in this way, for example, through the use of planting on different schedules, so that water needs do not overlap. Scheduling water use is less relevant for adaptive management in catchment areas with more homogenous farm operations such as dairying where water needs overlap.

Alternatively, there may be ways in which the needs of consent applicants can be weighed up differently to more efficiently allocate the resource. For example, the current system offers a high degree of reliability to consent holders. It may be possible to re-weight consenting decisions, trading off lower reliability to consent holders (and matching their needs with a 'normal' year) against increased access to users who may otherwise be unable to secure an allocation. Of course, this would leave consent holders exposed to additional costs in dry years – which may become a larger issue in a climate with increasing dry spells.

Social and economic development pathways are inherent in water entitlements. First-in-first-served allocation may have negative impacts on innovation and economic development because the allocation process arguably creates a bias towards the status quo. Shorter consenting periods may reduce this bias, but also reduce the certainty on which a consent holder will base investment decisions. The Resource Management review panel, 2020, recommends shifting away from first-in-first-served allocation to a yet to be determined approach that recognises scarcity through the inclusion of bottom lines and targets and through greater recognition of the Treaty of Waitangi and Te mana o te Wai - the guiding principle of the NPSFM.

5.12 Land use change

High water use production models will face increasing risks as climate change unfolds and high levels of indebtedness may keep farmers locked into high production model.

LaMas currently provide specific advice to Waikato farmers on drought mitigation strategies. These strategies include feed budgeting, destocking, on-farm cropping, planting particular species of poplars and willows for shelter and stock fodder, improving soil moisture holding capacity, avoiding soil compaction, and water harvesting structures.

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[17] It may, of course, have additional *in situ* values for ecological health, or recreational or amenity purposes.

This advice could be supplemented with advice on adaptation once adaptation options are more fully explored.

Motivations for land use change can include economic incentives, risk management strategies, increasing the farm income as part of a succession plan and reducing environmental impacts and these dimensions will be explored in part 3 of the research project which focuses on the social dimensions of resilience and adaptive capacity.

5.13 Summary

The findings of the participatory process and the development of the system diagram provides key insights into the levers of influence that are important for adapting to drought in the region including:

- There is currently an emphasis on regulating allocation when effective restrictions on contaminants could secure water supplies and increase regional water availability. The Waikato Regional Council's Freshwater Strategy[18] recognises that water quality and quantity are two sides of the same coin (or, at least, not independent of each other), and therefore that policies about the two aspects need to work as an integrated whole.

- Managing groundwater and surface water as an integrated system can smooth out inter-seasonal variations in supply and make water available when it is needed.

- Soil moisture holding capacity plays a key role in regional adaptive capacity.

Land use change better matched with reduced water availability would be expected to lead to a more resilient water use system overall.

Opportunities identified for building resilience to drought in the region could include:

- Localised small-scale storage could play a role particularly if the scale of uptake was large, but as well as possibly requiring regulatory decisions, this would be subject to economic decisions for the respective users. That is, do the expected benefits outweigh the costs?

A number of actions that could be taken to develop WRC's organisational capacity for supporting regional resilience include:

- Behavioural responses such as providing additional support to Waikato producers to adapt by including a broader set of compliance options ranging from minimal compliance actions through to viewing compliance within a broader business and resilience strategy to increase adaptive capacity, environmental performance, and profits.
- Consider updating Farm Environment Plan (FEP) templates with prioritised pre-populated actions that also provide the biggest co-benefits to climate and biodiversity and create resilience to drought.
- Increase the number of soil sites monitored by WRC's soil quality monitoring programme to improve representativeness and monitor a small sample annually to mitigate risk. Consider supporting research on regional hydrophobicity as there are gaps in understanding about what type of organic compounds contribute to hydrophobicity.
- Increase investment in the restoration and establishing new wetlands especially in locations where the water table is high to enhance water quality and slow the water cycle increasing adaptive capacity

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[18] Document Overview: Waikato Freshwater Strategy - a strategy to deliver the best use of fresh water through time.pdf (wairc.govt.nz)

6 Focusing on the water cycle

A socio-ecological systems approach has provided a wide lens on the issue of adapting to drought in the Waikato. This has identified a range of issues to be considered by WRC in developing a regulatory approach to building resilience, recognising that 'regulation' can be both counter-active and pro-active[19]. Spontaneous adaptation[20] will also occur and will impact on WRC activities.

The previous section outlined the links between hydrological and ecological impacts, and water and farm management practices, and draws attention to the interdependencies that need to be considered. The issues identified are all linked to the flow of water through the water cycle. This section describes the basic water cycle stocks and flows at the heart of the conceptual diagram. To provide further insight into where action should be directed, the conceptual diagram of the water cycle and the flow of water through it is overlaid with the complex of interactions and inter-dependencies in the region's water system.

How the system diagram works is explained in Appendix 1. It is recommended that before progressing, readers first read Appendix 1 so that they are familiar with the basic concepts of stocks and flows, feedback loops and the direction of causal influences (same and opposite). This will help them to understand the images in this section.

This section firstly describes the basic water cycle stocks and flows at the heart of the conceptual diagram. It then articulates those areas of lower influence that have been excluded from analysis and those areas of higher influence that have been included. This covers two broad perspectives – one the productive land use and the other municipal and industrial use of water.

The system diagram described in this report has been designed with multiple audiences in mind. Two important ones are farmers and those using large amounts of water in municipal and industrial processes, whether the latter is connected to municipal water supplies or not.

6.1 The natural water cycle

The concept of 'green' and 'blue' water was introduced earlier. Both green water (contained in soils and in/on plants) and blue water (contained in surface water, groundwater and human-made water storage) are of interest in drought situations. Therefore, the diagram focuses on the conceptual representation of the water cycle, which includes all of these. Here, the squares represent **stocks** of water – where it accumulates – and the arrows represent **flows** of water – how it moves – between each stock[21].

There are four main places where water naturally accumulates in the water cycle[22]:

- **Ephemeral water (green water):** Rain falls onto the land, from there it either soaks into the soil or runs off into surface water bodies. The residence time here is usually fleeting or temporary (hence 'ephemeral'). This box represents the accumulation of water on

[19] See section 3.2.1 for a fuller discussion of counter-active and pro-active regulation.

[20] Spontaneous adaptation is adaptation that does not involve a deliberate policy response but rather is response by private actors triggered by ecological, market or social changes.

[21] See the discussion on 'stock and flow notation' in Appendix 1.

[22] According to the green and blue water definition outlined earlier, water can also be retained in vegetation (green water). This has not been shown as a square stock like these other four places have been shown in this diagram. This is because the vegetation that has been represented in the diagram is representative of productive landuse (pasture or crops). As this is harvested or ingested (by animals as pasture) for productive use, this has not been shown as a separate square box or stock, per se. Rather these accumulations of water in plants are shown with images of plants, rather than boxes.

the surface of the land – however temporary – before it either soaks in, evaporates or runs off.

- **Soil moisture (available for plant uptake) (green water):** The water that soaks into the ground, but remains above the water table, is defined here as soil moisture. This is a critical element for productive soils. The term 'available for plant uptake' implies that not all soil moisture is available for absorption by plants.
- **Surface water (wetlands, lakes, rivers) (blue water):** Water that flows off, or all the way through the land, ends up in either surface water or groundwater. This 'surface water' box represents the accumulation of water in *all types* of surface water bodies – wetlands, lakes, rivers etc. It is acknowledged that some of these bodies are themselves flowing, but this is not relevant for the purpose of this exercise. This conceptual tool is *not* intended to diagram out the entire 'plumbing' of the region – i.e. how water flows through a catchment, from upper catchment to the sea. Other hydrological models may have that capability and this tool can be used to compliment those.
- **Groundwater (blue water):** Water that soaks through the land that does not evaporate or get absorbed by plants, ends up in the water table and is considered 'groundwater'. This can remain in situ, or it may also make its way back into surface water bodies through upflow (or the ocean directly, but that is not represented in these diagrams). The residence time in any of these states may vary enormously – again this tool does not seek to replicate the 'plumbing' of those flows, but rather represent the conceptual reality.

The above types of water accumulation are shown as boxes in [Figure 4]. How water flows between these are shown by the arrows. The stocks and flows have been coloured according to the water type: 'green' or 'blue'.

Rain falls on the land and may pool there as ephemeral water, from here it can evaporate directly. It can also soak into the ground where it becomes soil moisture, from where it can also be lost back to the atmosphere through evaporation. It can also be taken up into plants from the soil where it may be consumed by animals or again be returned to the atmosphere through evapo-transpiration. (Evapo-transpiration has not been shown to aid with simplicity, as more notations will be made to this diagram).

Alternatively, ephemeral water can flow via overland flow to surface water bodies. Here it can also be evaporated back into the atmosphere directly or continue to flow out to sea.

There are also water flows between groundwater and both soil moisture and surface water bodies. Sometimes water moves down into groundwater and sometimes it moves up from groundwater. These two flows are the only flows in the diagram that are shown to move in either direction. Groundwater itself is also a complex system of aquifers that may be static or moving.

For the Waikato River specifically, one additional flow is added – that is the flow into surface water from Lake Taupō. It should also be noted that there is a significant diversion of surface water from the Whanganui catchment into Taupo at Tokaanu, known as the Tongariro Power Scheme, so the level of Lake Taupō is dependent on that. (This has not been shown as its own specific flow but is noted as a variable in later additions to the diagram).

The flow between Lake Taupō and the Waikato River is highly (human) modified and there are statutory requirements for the level of Lake Taupō to remain within certain boundaries. Therefore, for the Waikato River specific water cycle, this flow represents the flow from Taupō into the Waikato River. This does not account for the various hydro-electric dams along the Waikato River – again, this is captured by other models. As this is only one of the conceptual inputs into the surface water box, it is not intended to suggest that Lake Taupō can input to all wetlands, lakes, and rivers. This is shown to the left of the surface water box in Figure 6.

Figure 5. The basic water cycle

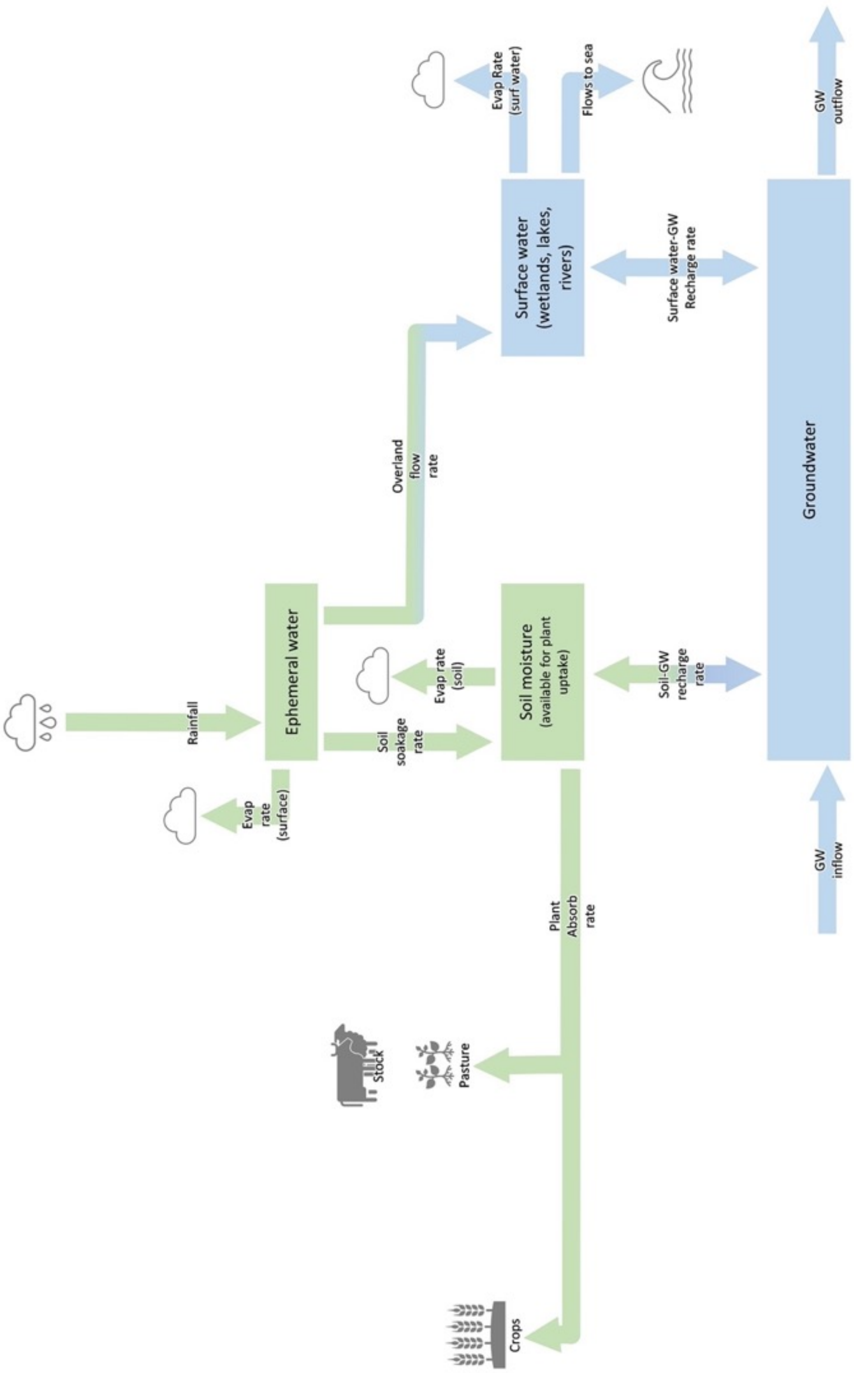
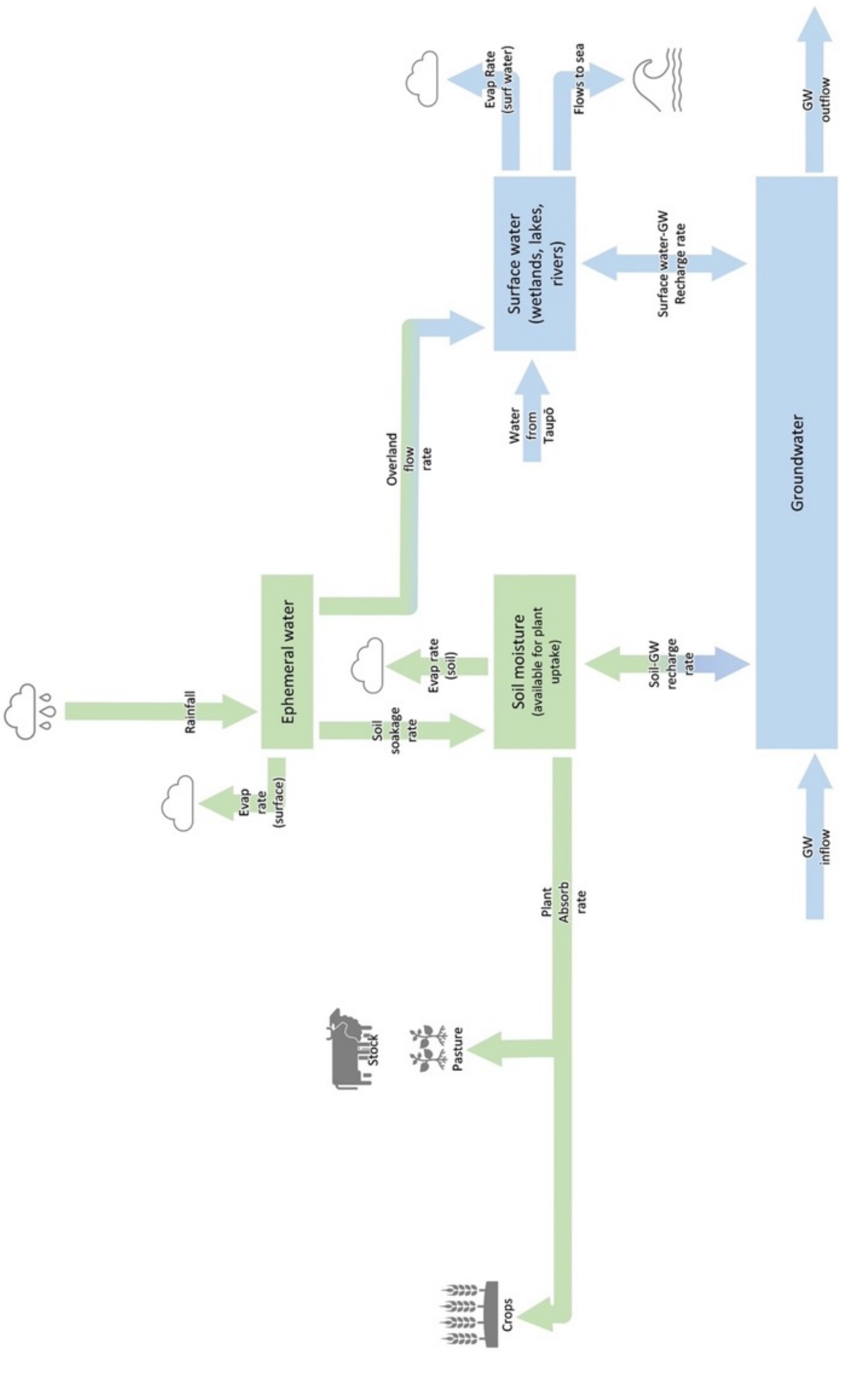


Figure 6. The Waikato River water cycle – The basic water cycle influenced but Lake Taupō



6.2 The human modified water cycle

To this core representation of the water cycle we add human activities that alter water flow through the water cycle. This will be discussed here from two perspectives – productive land use (process/stock water and irrigation) and the municipal/industrial use of water. Both will then be discussed from the point of view of adding additional water storage capacity.

6.2.1 Rural productive land use (process/stock water and irrigation)

Where soil moisture (green water) is relatively lacking, the productivity of land use can be augmented through the addition of (blue) water via irrigation. This is effectively diverting water from surface water or groundwater to replicate rainfall, so it is adding water to the stock of ephemeral water, where it is intended to soak into the soil and increase soil moisture. Depending on the irrigation efficiency, some water may be lost to surface water bodies through overland flow or evaporation.

Process/stock and irrigation water is drawn from either surface water bodies (the predominant source in the Waikato region at present) or groundwater. These two pathways are shown as orange flows in 6.2.2.

6.2.2 Municipal and Industrial use

The other main way that water is extracted for human use is municipal and industrial use. These are represented together here as their main conceptual characteristics are similar.

Both uses extract water from surface water or groundwater for human consumption or use in commercial and industrial processes. Once used, there is usually a flow of water back into the environment as wastewater or trade waste. This usually goes through significant treatment (this is *not* shown as a step in the flow) and either flows back to surface water bodies, or in some instances is disposed of on land.

These flows are represented by the orange flows in Figure 8. The rural productive flows have been greyed out for clarity.

6.2.3 The effect of additional storage on rural productive and municipal/industrial use

The final major human modification to the water cycle is the addition of additional water storage capacity. Some water storage exists in the region – either at an individual landowner level, a collective landowner level or at a municipal/industrial level (e.g. for a city or a major factory in a rural area). However, its use is currently not as widespread as in other regions.

The creation of storage capacity enables an additional source of flow for both irrigation and municipal/industrial use, as shown in Figure 9. This is recharged from either surface water bodies or run-off of ephemeral water (usually during heavy rainfall). Evaporation will occur where stored water is pooled in the open. Again, the original rural productive and municipal/industrial flows have been greyed out for clarity.

Figure 7. Irrigation for rural productive land use (process/stock water and irrigation)

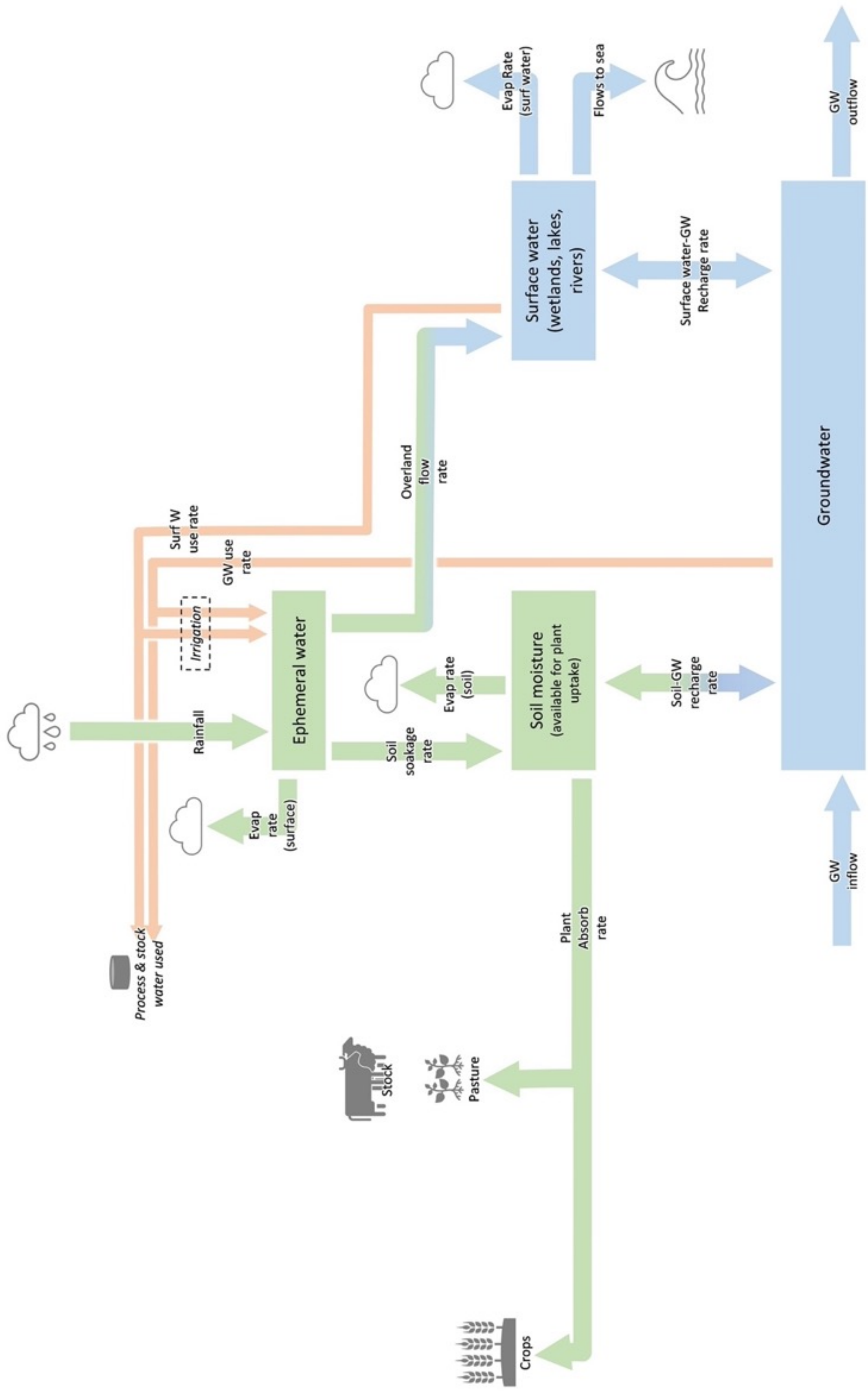


Figure 8. Municipal and industrial use

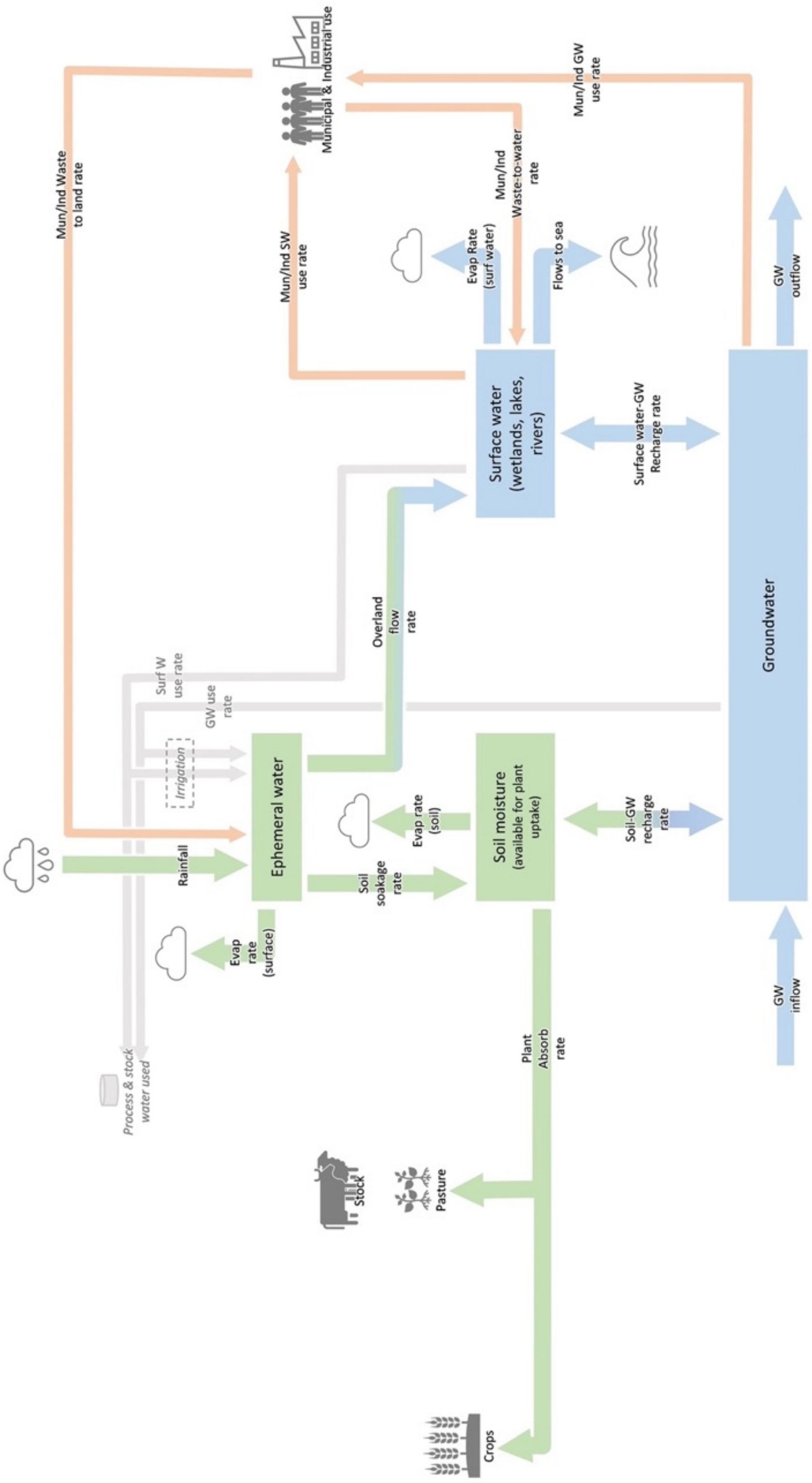
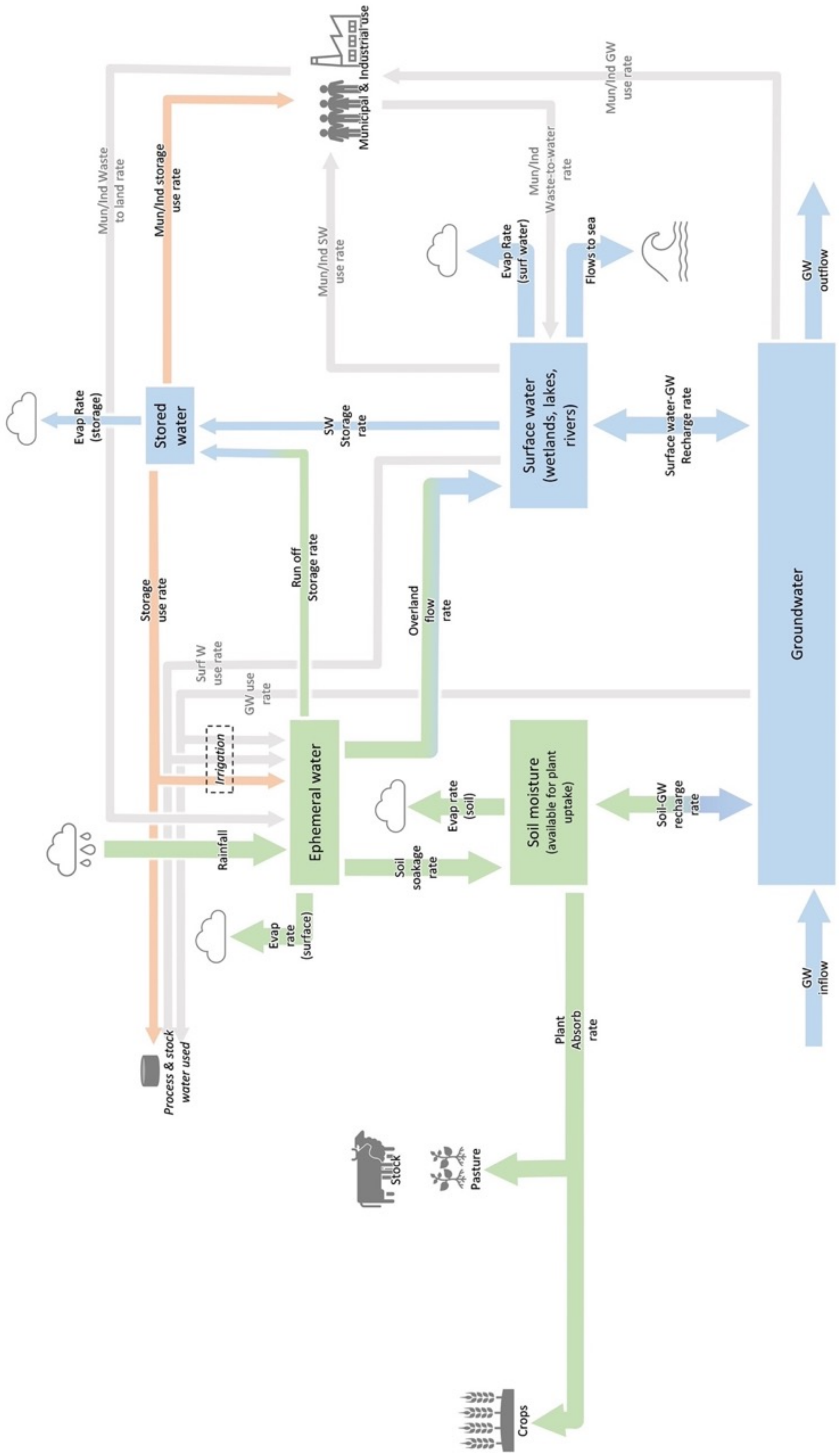


Figure 9. The impact of storage on irrigation and municipal/industrial use



6.2.4 Final components of the water cycle used in this diagram

The previous section outlined the core conceptual stocks and flows in the water cycle. This section highlights those that are retained for focus as the base of the diagram. In these figures the influence of Lake Taupō has been excluded because it impacts the Waikato River catchment only and this tool is for use across all catchments within the Waikato Region. Lake Taupō is however, extremely important in the Waikato River catchment and is discussed in later sections of this report (see section 7.13).

Firstly, the total collection of stocks and flows outlined in the previous section are shown in ⍰.

Some stocks and flows on this diagram are unlikely to be influenced directly. They may be physically inaccessible (for example groundwater); or an area that (even if technically possible) may be unlikely to be an area of intervention, at least initially. For example, covering a hydro-lake to reduce evaporation.

To help make a systemic analysis more focused and useful, these inaccessible or unlikely areas of intervention have been removed – these are highlighted in Figure 11. **This does not preclude them from ever being an area of intervention**. They may still be impacted by interventions in other parts of the system, as described in this reportbecause impacts *elsewhere* in the system may cascade through the flow structure.

Of note here is the removal of *rainfall* as a likely area of intervention. Obviously, it is difficult to intervene with rainfall patterns as an *adaptation to drought*. Yet changes in rainfall patterns are a *key driver of drought*. The removal of rainfall as an area of intervention is not intended to suggest that this does not have a critical impact on the conditions which create drought.

This leaves us with a diagram of the natural and human modified water cycle that highlights the areas that will be explored further with systemic feedback loops of influence. These areas are summarised in the following bullet points and shown in Figure 12.

- Water that is deposited on the land (ephemeral water stock), its soakage pathway (flow) into the soil where it becomes soil moisture (stock) and its subsequent interaction with groundwater as a recharge rate (flow).
- Water that flows overland (a flow) into surface water bodies (stock).
- Water that evaporates from soil into the air (flow).
- Water that is absorbed into plants (either pasture of crops) (flow).
- Surface water bodies (wetlands, lakes and rivers) (a stock) and where these flow to the sea (flow).
- Water that flows into stored water (a stock) from either the ephemeral water stock or the surface water stock.
- Flows from groundwater, surface water or stored water to agricultural use (irrigation or process/stock water).
- Flows from groundwater, surface water or stored water to municipal/industrial use.

Figure 10. All water cycle stocks and flows identified (excluding influence of Lake Taupō)

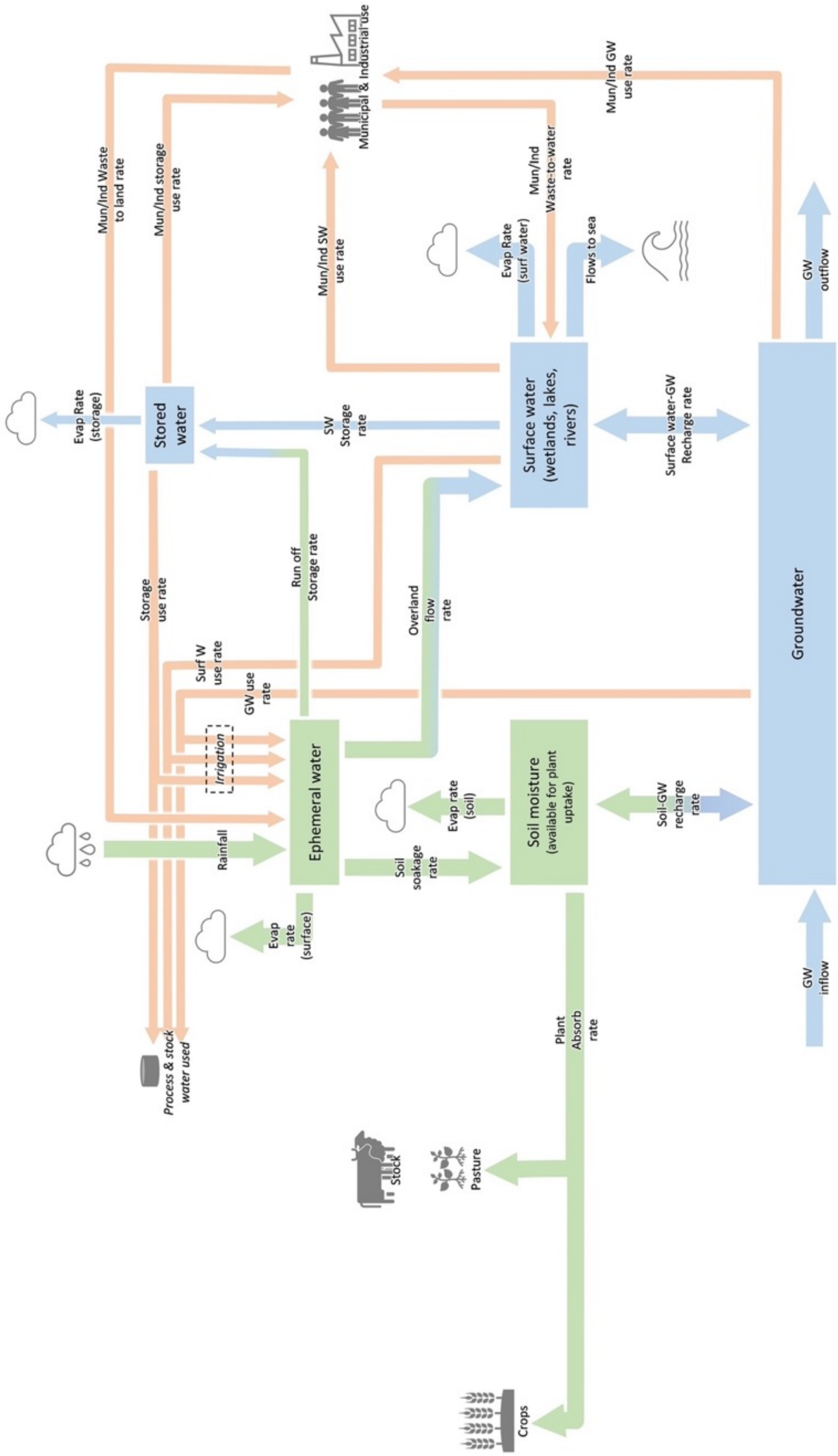


Figure 11. Inaccessible or low-leverage areas of intervention removed from analysis (excluding influence of Lake Taupō)

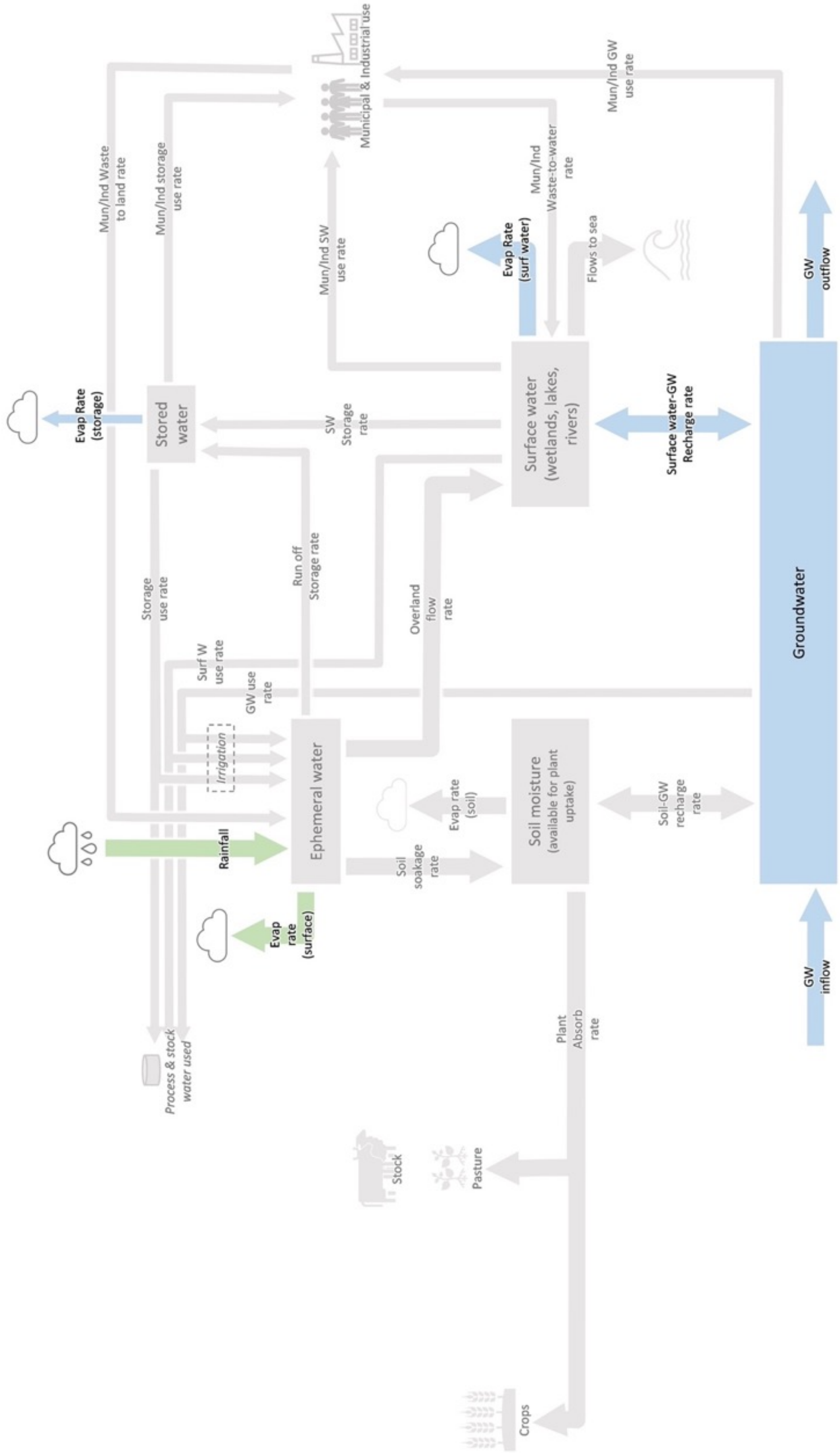
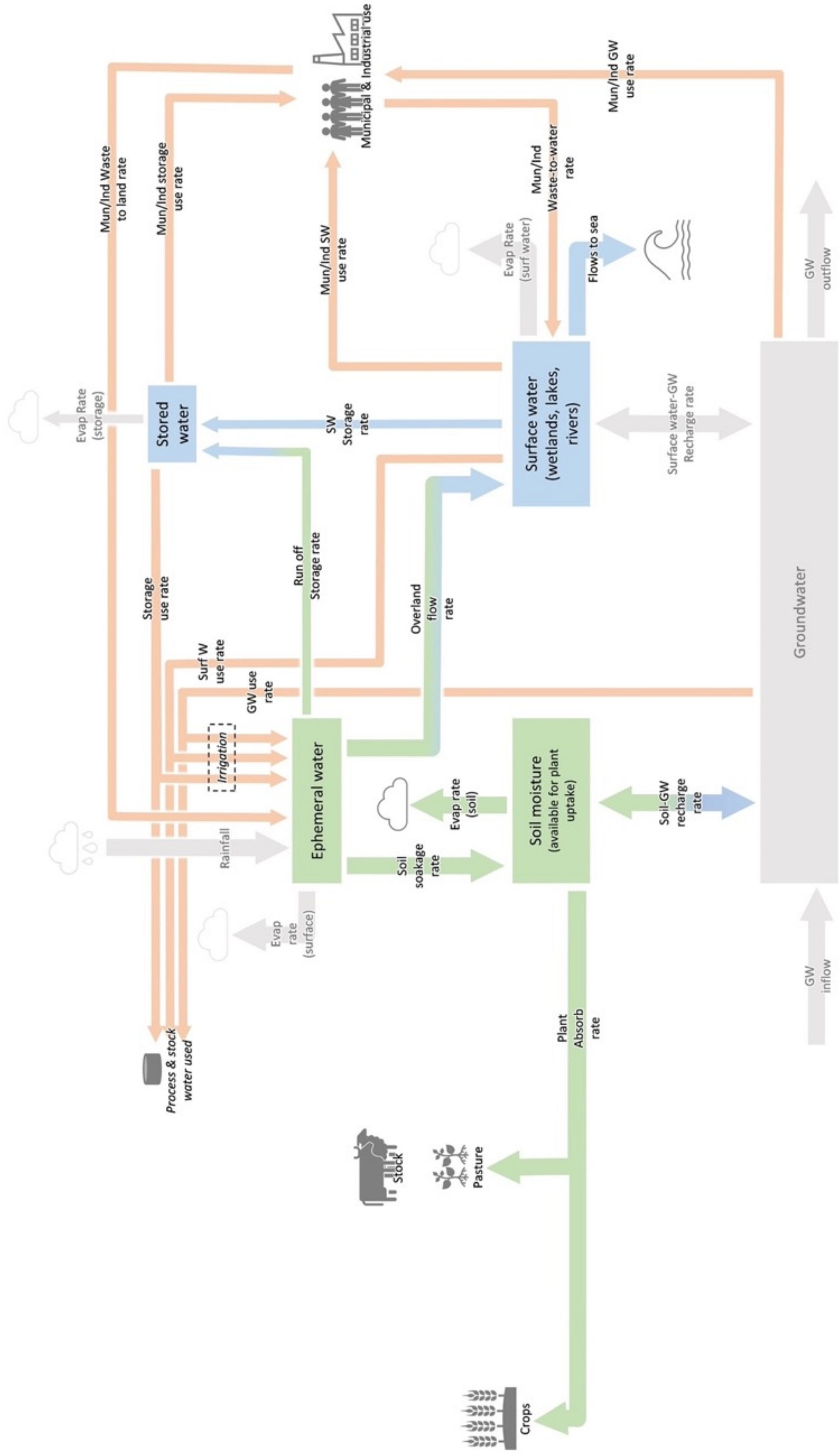


Figure 12. Areas of the water cycle identified for systemic analysis (excluding influence of Lake Taupō)



7 Describing internal (endogenous) causality in the system

This section builds on the stock and flow structure of the water cycle described in the previous section by adding feedback loops of influence. These are a synthesis of the complex inter-relationships within many different parts of the system (including farming and growing, and municipal/industrial uses). This approach highlights the circular nature of causality (feedback loops) within the system, drawing attention to the many *endogenous (internal)* influences on for example, soil moisture (e.g. soil health and structure, plant selection), in addition to the *exogenous (external)* influences on soil moisture (i.e. the climate).

An overview of the system diagram is shown in Figure 14 and a full-sized version of it is provided later in Figure 28 (section 8). The different sections of this system diagram are discussed in turn in the sub-sections that follow. Feedback loops that have been identified and are discussed have been numbered (e.g. B1 or R1) for identification purposes only.

The key for the arrows in the system diagram are shown both in the corner of Figure 14, as well as in Figure 13, below.. Here, the two types of influence are summarised:

- A **same relationship** is when change in variable A results in a change in variable B *in the same direction* – i.e. if **A goes up B goes up and vice versa**. This is shown as a solid arrow.
- An **opposite relationship** is when change in variable A results in change in variable B *in the opposite direction* – i.e. if A goes up B goes down and vice versa. This is shown as a dashed arrow.

Delays between a change and its effect are indicated with a small line crossing the arrow. This indicates that the time taken for this cause to present as an effect is relatively longer than the others.

Figure 13. The direction of influences and conceptual time delays

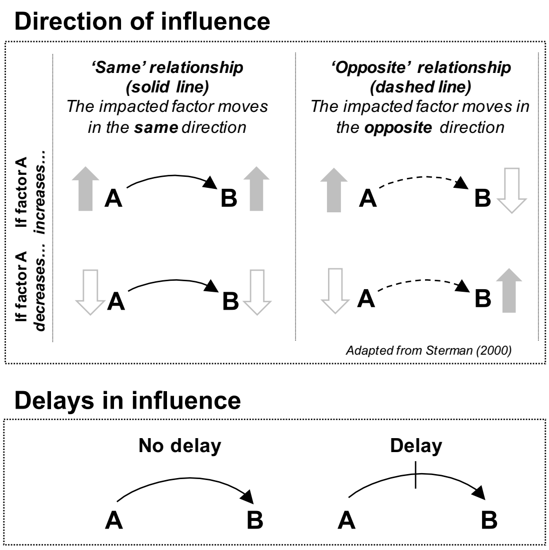
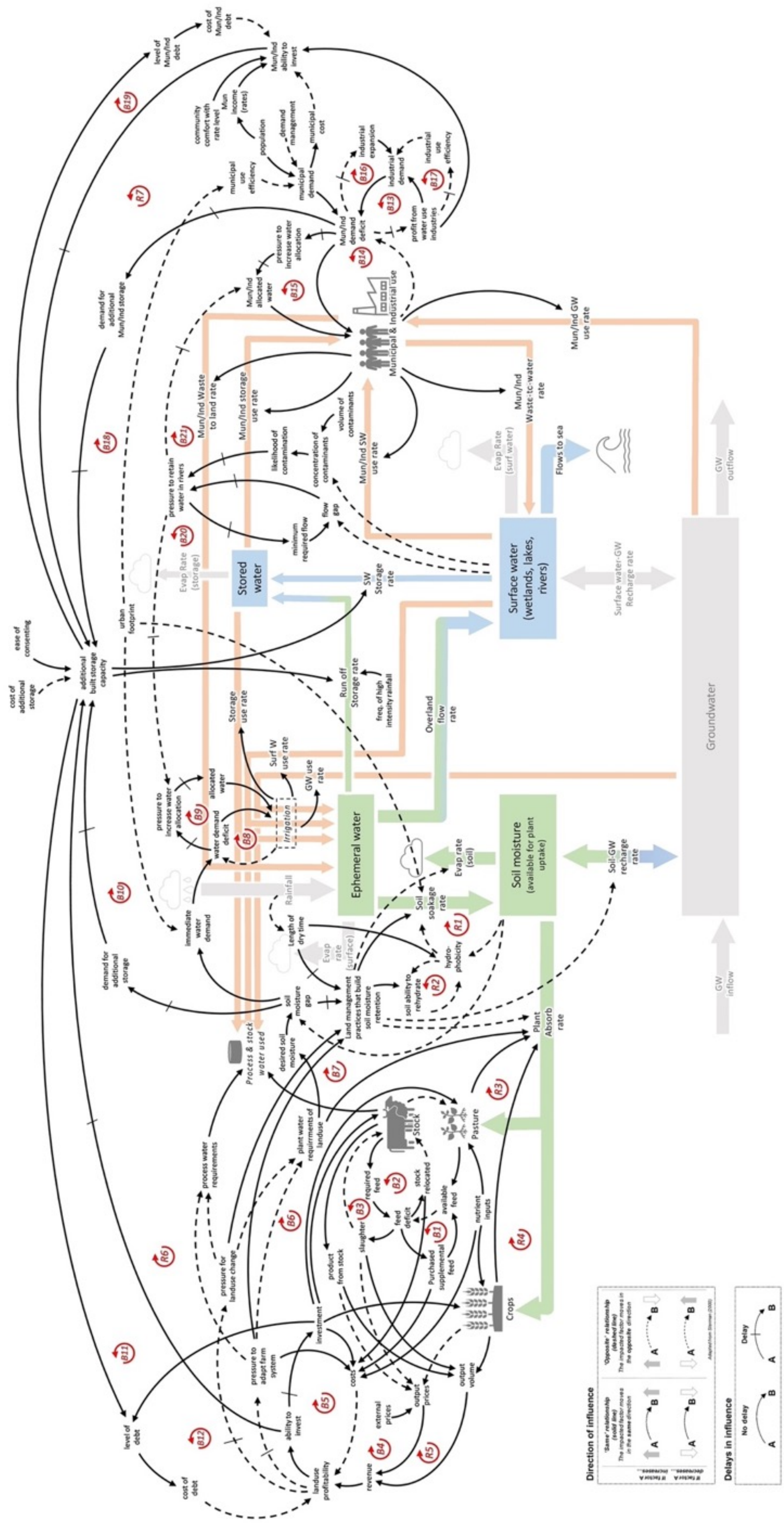


Figure 14. Overview of system diagram (excluding the influence of Lake Taupō on the Waikato)



7.1 Highlighting internal (endogenous) influence over external (exogenous) influence

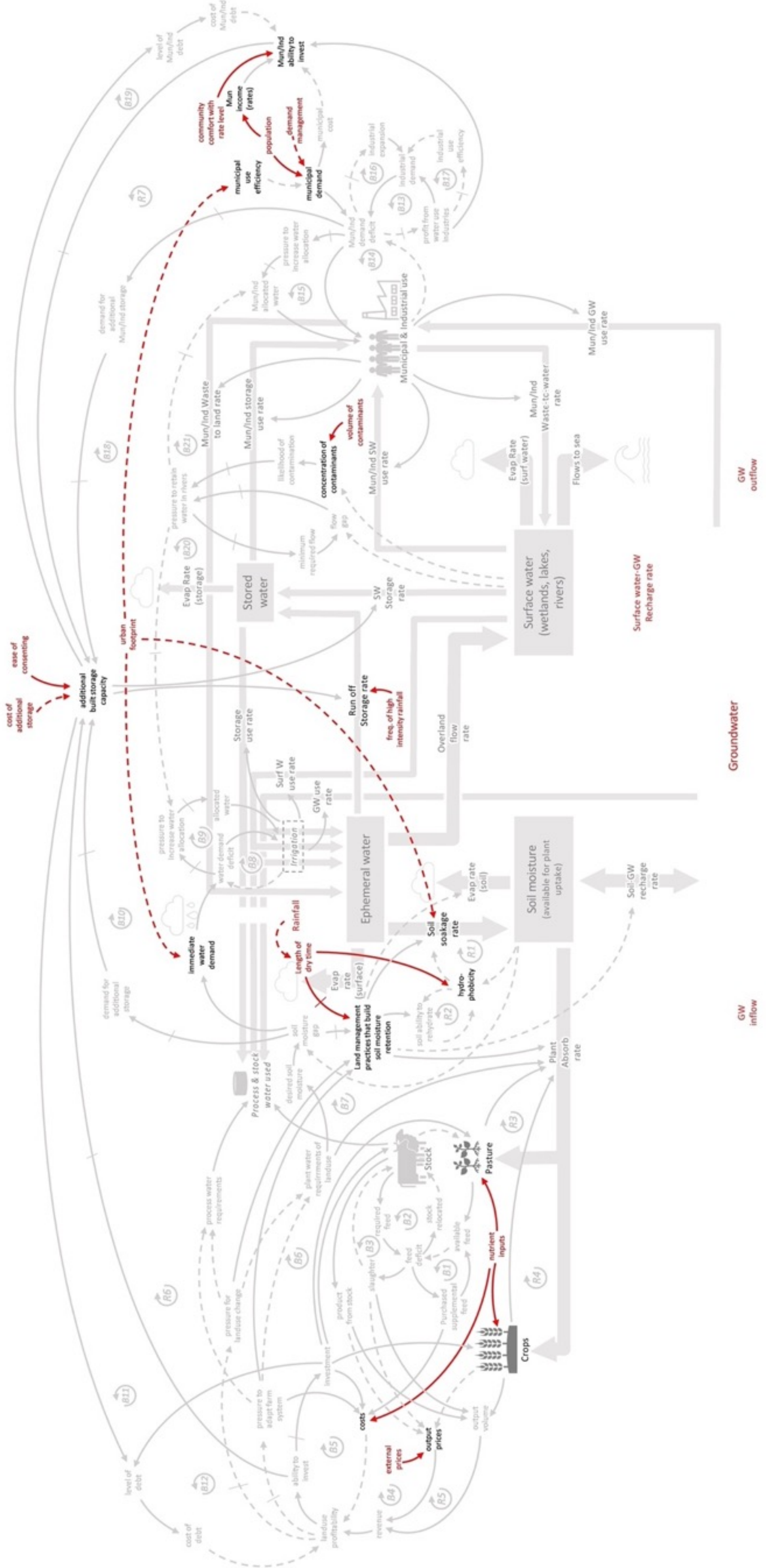
As described in Appendix 1, the concept of circular causality, or reinforcing or balancing feedback loops of influence, is at the heart of system diagrams and systems thinking. This means that we can move from viewing influences as 'external' (exogenous) and something that happens ***to the system***, to something that is 'internal' (endogenous) and a result of the influences ***within the system***.

Only a small number of influences described in the system diagram are external – these are the variables/nodes that only have arrows of influence ***coming from them, not going to them***. These have been summarised below in Table 3 and shown visually in Figure 1. They highlight how most influences represented are internal.

Table 3. Exogenous factors in the diagram

'External' factor	Description
External prices	The prices for commodities from competitors (primarily overseas markets).
Nutrient inputs	The level of nutrient inputs onto/into rural productive systems (e.g. fertiliser).
Length of dry time	Length of time of dry periods, however this is defined and measured.
Frequency of high rainfall events	The frequency of high rainfall events, however this is defined and measured.
Cost of additional storage	The costs associated with planning for, consenting, constructing and running additional water storage.
Ease of consenting	The ease of consenting for additional water storage (excluding the cost of consenting, which is included in *cost of additional storage*).
Urban footprint	The physical size of the urban footprint. Not the environmental footprint of an urban area – ie. resources consumption per Hectare or per person.
Concentration of contaminants	The concentration of contaminants in surface water bodies.
Community comfort with rate level	The aggregate level of comfort that a community has with the level of local authority rates that they have to pay for the services they receive.
Population	The size of the population
Industrial expansion	The level of industrial expansion that occurs, in addition to existing levels of industrial activity/demand.
Rainfall	The quantity and frequency of rainfall.
Groundwater	Stocks and flows of groundwater. Part of the water cycle but treated as 'exogenous' because it is not influenced directly, only via the flows of water in/out of it.
Surface water – Groundwater recharge rate	The recharge rate between groundwater and surface water bodies.

Figure 15. Exogenous factors in the diagram (red) and what they influence within it (black)

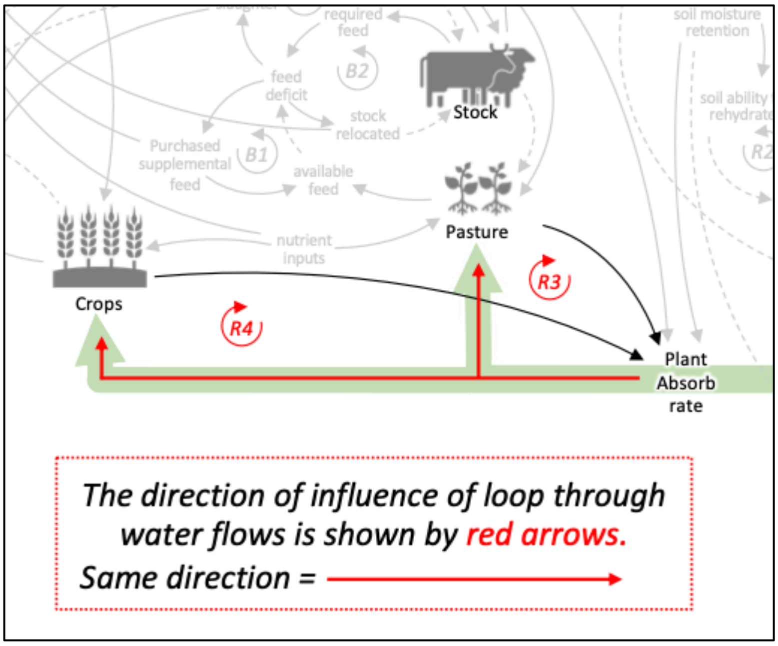


7.2 Plants and water absorption

The loops relating to plant water absorption demonstrate the fundamental relationship between **crops** and **pasture** and their absorption of water (shown here as the flow **plant absorption rate**). The crop or pasture itself has an influence on the amount of water it absorbs. The more **pasture** and **crops** there are, the greater the **plant absorption rate**, the greater the flow of water out of the stock of **soil moisture**. These two reinforcing loops (R3 and R4) represent the fundamental relationship of plant growth supported by available water.

While the exact rate of absorption will depend on things like the plant cultivar, the point is to highlight this relationship as a fundamental one in our system diagram (Figure 16).

Figure 16. Plants and water absorption



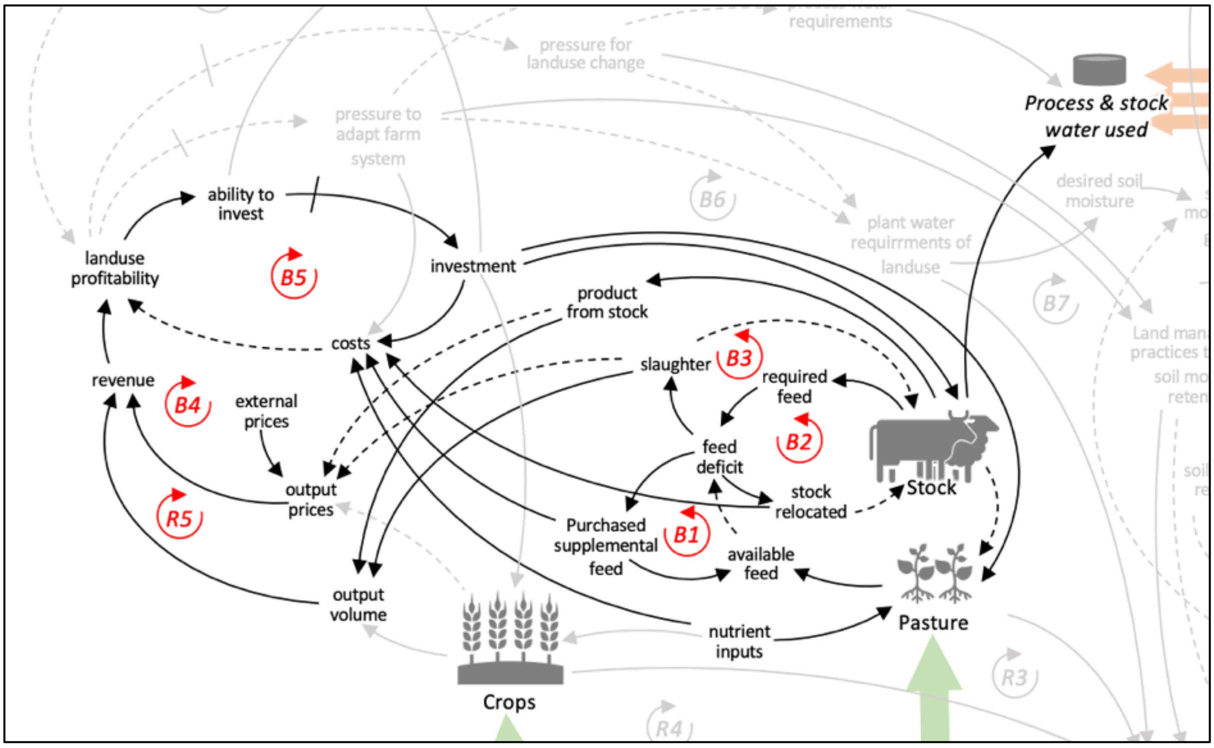
*Note: In Figure 16 (above), the influence of the feedback loops travel with the flows of water. They are **same** relationships (shown as solid red arrows going with the flows of water). For example, if the **Plant absorption rate** was to **increase**, this would increase the flow of water to both **Crops** and **Pasture** (the direction of the flow). Because the flow increases and the factors influenced then increase, this is a **same relationship***. See Figure 26 for an explanation of an opposite relationship.

7.3 Productive land use – pasture, stock and product from stock

Next is a discussion of pasture, livestock and product from livestock (e.g. milk or wool). Here the primary relationship with the water cycle is the quantity of **stock** that can be grazed on **pasture** and the **product from stock**.

The more **stock** there are, the more **pasture** is consumed and thus the less there will be – hence this is an *opposite* relationship (dashed line). The greater the level of **pasture**, the greater the **available feed** – which will fluctuate over a short time scale in response to changes in **soil moisture** and **pasture**. At the same time, the more **stock** the more **process & stock water used**, so this is a *same* relationship (solid line).

Figure 17. Productive land use – pasture, stock and product from stock



The actual number of **stock** have a *same relationship* with a **required feed** amount. Both the **available feed** and the **required feed** form part of a *'goal/gap' structure*. This is where an aspirational target or available amount of something (**required feed**) sets a goal that an actual amount of something seeks to meet (**available feed**), thus forming part of a loop (or series of loops) where the influence generated by this gap self-regulates. Here, **required feed** and **available feed** both connect to **feed deficit**, which is the 'gap' between the two.

If that gap or difference is low or non-existent – i.e. the **available feed** is enough to meet the **required feed** needs, then there is no need to compensate for the shortfall. In this case there is no influence from this 'gap' to the other balancing loops connected to it (B1, B2 and B3) and flow on influence remains dormant. Hence these balancing loops are in relative equilibrium.

However, if the gap is large there is a **feed deficit**, this drives action in one or more of the other loops. Initially, **purchased supplemental feed** (B1) is used to supplement pasture, thus maintaining stock numbers for as long as financially possible. A second option is to have **stock relocated** (B2) to another farm/region for support grazing (thus reducing stock numbers locally). The third and final option is to have stock **slaughtered** (B3) prematurely, reducing overall **stock** numbers.

Purchased supplemental feed and having **stock relocated** will incur **costs**, while (generally) sending stock to **slaughter** will result in income, hence the connection to **output prices** and **output volume**. The production of any product (either meat via **slaughter** or wool/milk etc via **product from stock**) has a same relationship with **output volume** (more product = more volume) and an opposite relationship with **output prices** (more output = lower prices)[23]. **Output prices** is also influenced by **external prices** (e.g. international competitors).

[23] Although it is noted that the relationship with output prices is dependent on the elasticity of prices (the amount the change in response to volume). The volume produced by one farm or region may be insufficient to impact prices, or the price may be more heavily influenced by other factors.

The different relationships between product and both **output prices** (opposite) and **output volume** (same), demonstrate the forces contributing to prices and supply finding their equilibrium.

The combination of **output prices**, **output volume** and **costs** determines **landuse profitability**. The greater **landuse profitability** the greater the **ability to invest**, and over time (as there is a delay) the greater the **investment** that occurs. When **investment** does occur this increases **costs** which then reduces **landuse profitability**, so this loop (B5) balances itself out.

The two final loops in this area (R5 and B4) represent the flow on impact from **investment** activity in **stock** or **pasture**. Here, investment will promote greater production (assuming this is not constrained by the **feed deficit**) and the reinforcing forces of greater **output volume** will be countered by the balancing forces of the downward pressure on **output prices** from that volume. Operating together, these loops (R5, B4 and B5) highlight that **investment** from a profitable land use will occur untils it reaches a balance or equilibrium and the potential returns do not justify any further investment.

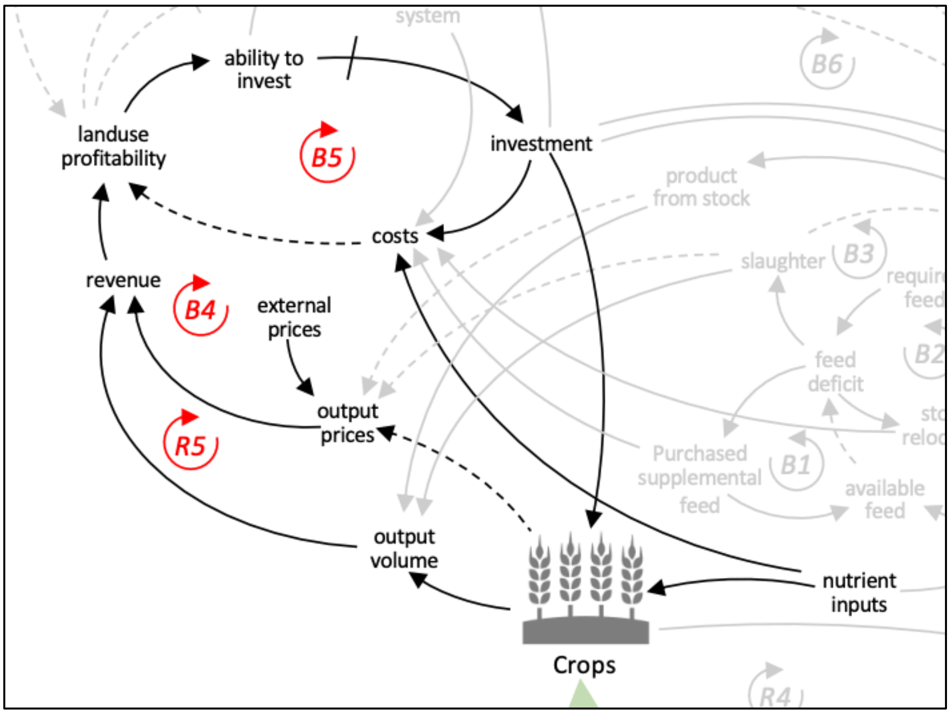
Nutrient inputs are also shown to have a same relationship with **pasture** and **costs**. Their use will encourage pasture growth and incur costs.

7.4 Productive land use – crops

Productive land use for **crops** has a similar relationship with **output volume** and **output prices** as stock in the previous section. The greater the number of **crops** the greater the **output volume** and the lower the **output prices** (see also footnote 21). Like pasture based landuses, there is a reinforcing loop and a balancing loop operating – the reinforcing (R5) encourages more **output volume**, while the balancing (B4) will ensure that downward **output prices** discourage further investment.

Both factors then have same relationships with **revenue** – that is, if **volume** or price increases (all other things being equal) then **revenue** increases. As for pasture based landuse, **revenue** and **costs** both determine **land use profitability**.

Figure 18. Crops, revenue/cost and land use change loops



The ability to invest loop (B5) and the two loops mentioned above (R5 and B4) will again operate together up until a point when the cumulative **investment** increases **crops** and **revenue** to the point where further investment will provide no margin return.

7.5 Pressure to change farm system or landuse

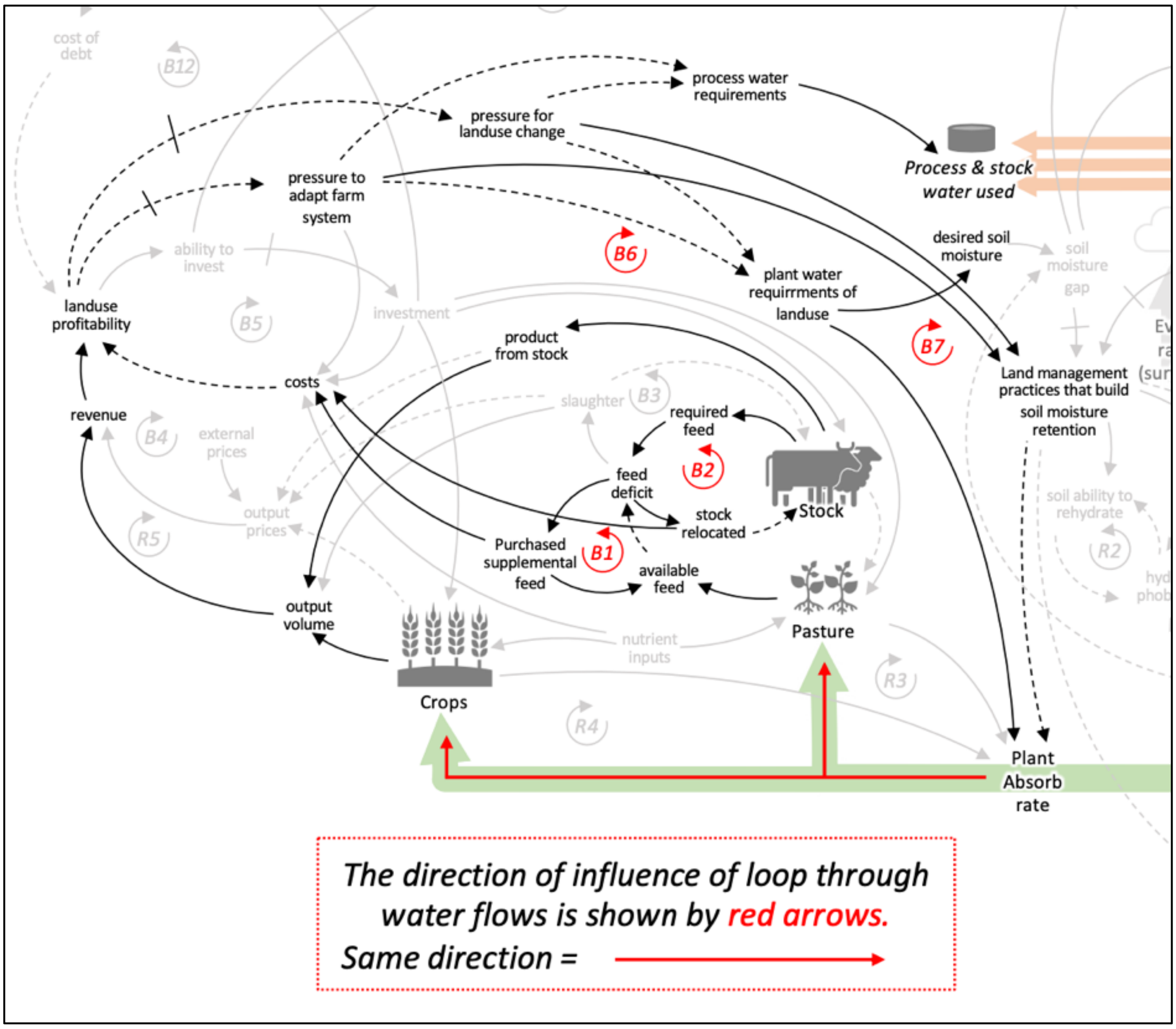
Important links have been made in the system diagram from **landuse profitability** to **pressure to adapt farm system** and **pressure for landuse change** (both with delays). With so many variables affecting productive landuse, there is a regular tension around whether a farm system should be adapted or a change in landuse to keep in line with the conditions (in this case water security/soil moisture) and remain profitable is called for.

If landuse profitability is consistently low, then the delayed influences will build to increase pressure to, initially, adapt farm systems and, in the longer term, change landuse more dramatically. Both present in similar ways via similar factors.

Firstly, balancing loop B6 will determine that the **plant water requirements of [that particular] landuse** will be reduced, most likely through changing plants, crops or cultivars. This will reduce the **plant absorption rate** and allow a similar amount of pasture or crop to be sustained for less water. While the exact combination of changes will vary depending on the farm, this change will then flow on through the feeding loops (B1 & B2), output volume and costs, until **landuse profitability** is restored. Whether this is farm system adaptation or landuse change will depend on the extent of change. While they are two distinct pathways in loop B6 here, they are different ends of a spectrum of adaptation.

These two loops also show the influence of path dependency whereby farmers may seek to pursue adaptation of the existing farm system rather than change landuse (Abel et. al, 2016).

Figure 19. Pressure to change farm system or landuse



Secondly, balancing loop B7 will determine that the **land management practices that build soil moisture retention** are increased. As above, this could be via a pathway of farm system adaptation or more transformative change in landuse.

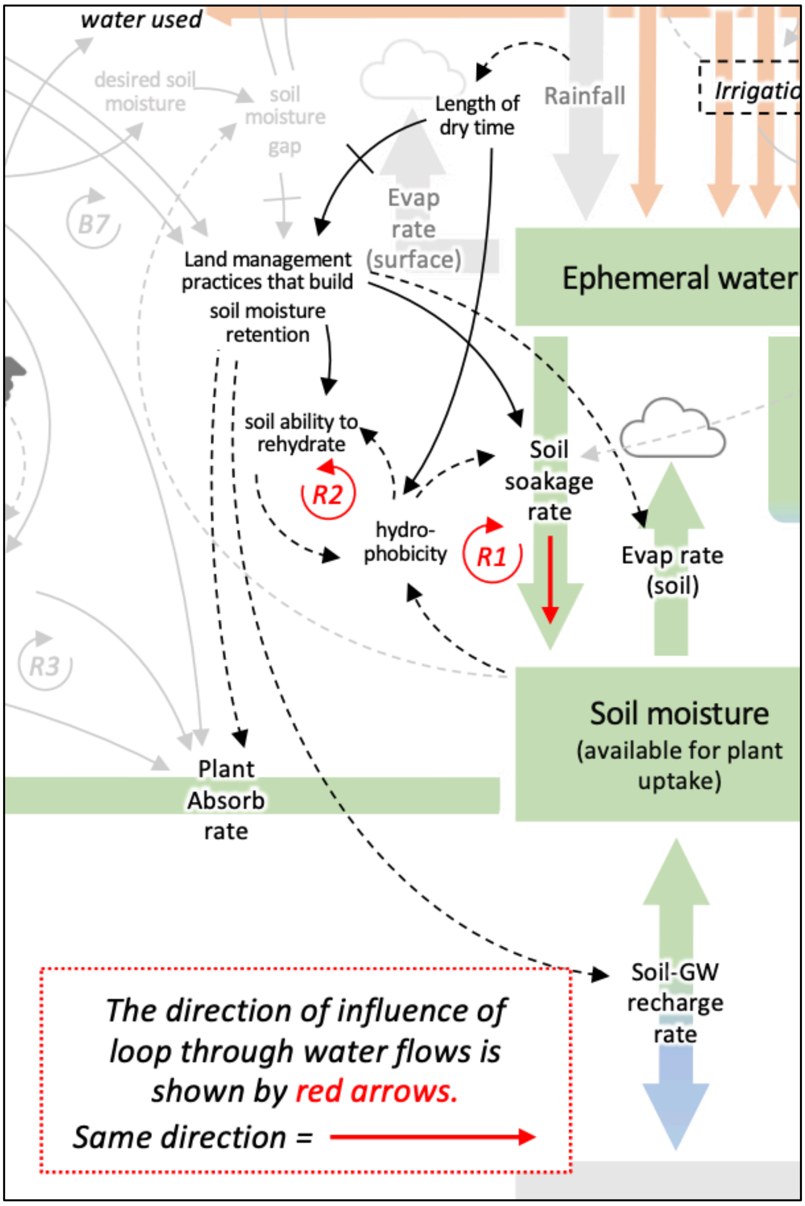
The more of these practices that are adopted, the more likely changes in plant, crop or cultivar use will result in a lower **plant absorption rate**. Note that this node also influences the soil soakage recharge rate but this is discussed later.

As with B6, the impacts of land management practice changes will flow through the **pasture/stock** and **crop** pathways, **output volume** and **costs**, until **landuse profitability** finds some kind of equilibrium again. Only then will these pressures reduce, but because they all have the ability to self-correct, or come 'back into balance', these are balancing loops.

7.6 The relationship between soil moisture and the soil soakage rate

Soil moisture above the water table is at the core of the system diagram and productive land uses. The influences on this are very important for adaptation to drought and a number are represented in the diagram. The greater the **soil soakage rate** and the lower the **evaporation rate (soil)** and the **plant absorption rate**, then the greater the level of **soil moisture (available for plant uptake)**.

Figure 20. Influences on the soil soakage rate



There are two key influences on the **soil soakage rate**, one natural and one human management. Firstly, the natural **hydrophobicity** of soils (which varies according to the type of soil) will reduce the **soil soakage rate**, thus reducing the ability of **temporary surface water** to soak into the soil and become **soil moisture**. **Hydrophobicity** is increased by the **length of dry time** (i.e. lack of rainfall), so the longer the dry period the more hydrophobic soils naturally become.

Hydrophobicity has a reinforcing influence (R1) on the soil soakage rate and soil moisture, where hydrophobicity reduces soil moisture, which further increases hydrophobicity. It also has a reinforcing relationship (R2) with **soil ability to rehydrate** naturally. Here, the greater the **hydrophobicity** the lower a **soils ability to rehydrate**, which produces even greater **hydrophobicity**. Both these loops interact to further reinforce each other in either vicious or virtuous cycles.

That is, when soil moisture is in a desirable state, the tendency of the loops to reinforce soil moisture dominate – a virtuous cycle. However, if there is a sustained reduction in soil moisture then these loops may 'flip' – encouraging and then reinforcing **hydrophobicity** which may come to be the dominant pattern – a vicious cycle. This would reduce soil's ability to naturally return to levels of **soil moisture** that support **plant absorption** and productive use. This is unlikely to be a permanent change, however it may be significant enough to cause issues when times of dry are broken by rainfall – especially if broken by sudden downpours as that will likely result in low **soil soakage rates** and high **overland flow rates**. To break this cycle sustained periods of light rain will be required to allow the dominance of hydrophobicity in soils to be broken naturally – and these are the types of weather events predicted to be less prevalent in the future under climate change.

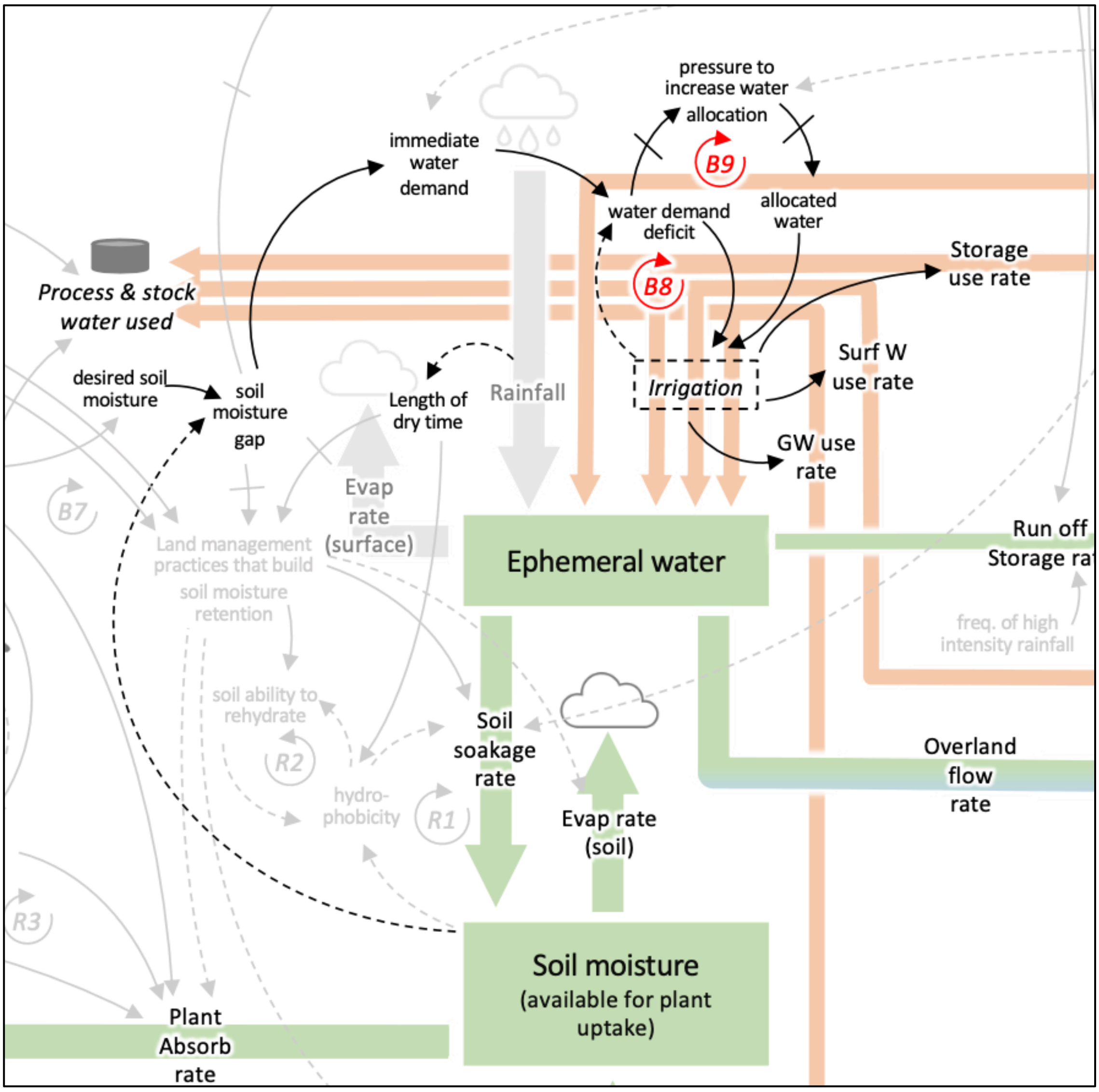
Secondly, land management practices can also have an influence on these factors. Soils can become more hydrophobic when there are low levels of organic matter and low microbial activity, which can be an unintended consequence of certain types of soil management practices. They can also be the intended outcome of other types of soil management practices. Therefore, **Land management practices that build soil moisture retention** have a *same* relationship with **soils ability to rehydrate** and the **soil soakage rate**. That is, if these practices were not present and organic matter and microbial activity *decreased*, then so would these other factors. Conversely, if these practices were present and organic matter and microbial activity *increased*, then so would all these other factors.

Land management practices that build soil moisture retention also have an opposite relationship with three of the influences on soil moisture, these are the **evaporation rate (soil)**, the **plant absorption rate** and the **soil-groundwater recharge rate**. Starting with the **evaporation rate (soil)**, Land management practices can help retain vegetative cover over land and ensure that direct evaporation, as well as evapotranspiration (through additional shading), is reduced. The **plant absorption rate** and **soil-groundwater recharge rate** can both be influenced through plant selection and the type of roots that plants have, as well as potentially through the impact of soil carbon and microbial activity.

7.7 The soil moisture gap and irrigation

As previously noted, soil moisture is of critical importance to productive land use and irrigation is one way of maintaining soil moisture in the absence of rainfall. When irrigation is used as an intervention in the absence of rainfall, its use is moderated by a feedback control relating to the desired level of soil moisture. This is another example of the goal/gap structure.

Figure 21. The soil moisture gap and irrigation



Here, the actual **soil moisture** (the green box) and the **desired soil moisture** level are both connected to a **soil moisture gap** node. When this **gap** is large this increases **immediate water demand**, leading to a **water demand deficit** (where water demand is greater than available supply) which then prompts the use of **irrigation** to reduce that **deficit**[24]. This means that there is an immediate balancing feedback loop (B8) between **water demand deficit** and **irrigation**, the latter satiating the former; as well as one via a longer more complex (but also short in temporal terms) feedback loop where irrigation will result in more water flowing into **ephemeral water**, encouraging a greater **soil soakage rate** and increasing **soil moisture**, which then reduces the **immediate water demand** and the **water demand deficit**.

The amount of **irrigation** will always be the result of the interaction of two factors – the **water demand deficit** and the **allocated water** amount. The former is always constrained by the latter, yet the former can also *influence* the latter. How it does this is as follows: if the **water demand deficit** remains high due to the perceived insufficiency of the **allocated water**, then in the longer term this adds **pressure to increase water allocation**, which in turn can lead to an increase in **allocated water** (B9).

[24] In times of surplus water there is water excess. In these times the gap would go the other way and then the demand won't be for irrigation but for drainage. The feedback loops and influences that relate to drainage have not been shown in this diagram as the focus is on drought. But it should be borne in mind that this is a surplus/deficit equation that *can* go both ways.

This difference between these loops are that B9 influences the amount of irrigation that *can* be undertaken, by increasing the allocated water; whereas B8 influences the actual act of irrigation on a day by day basis.

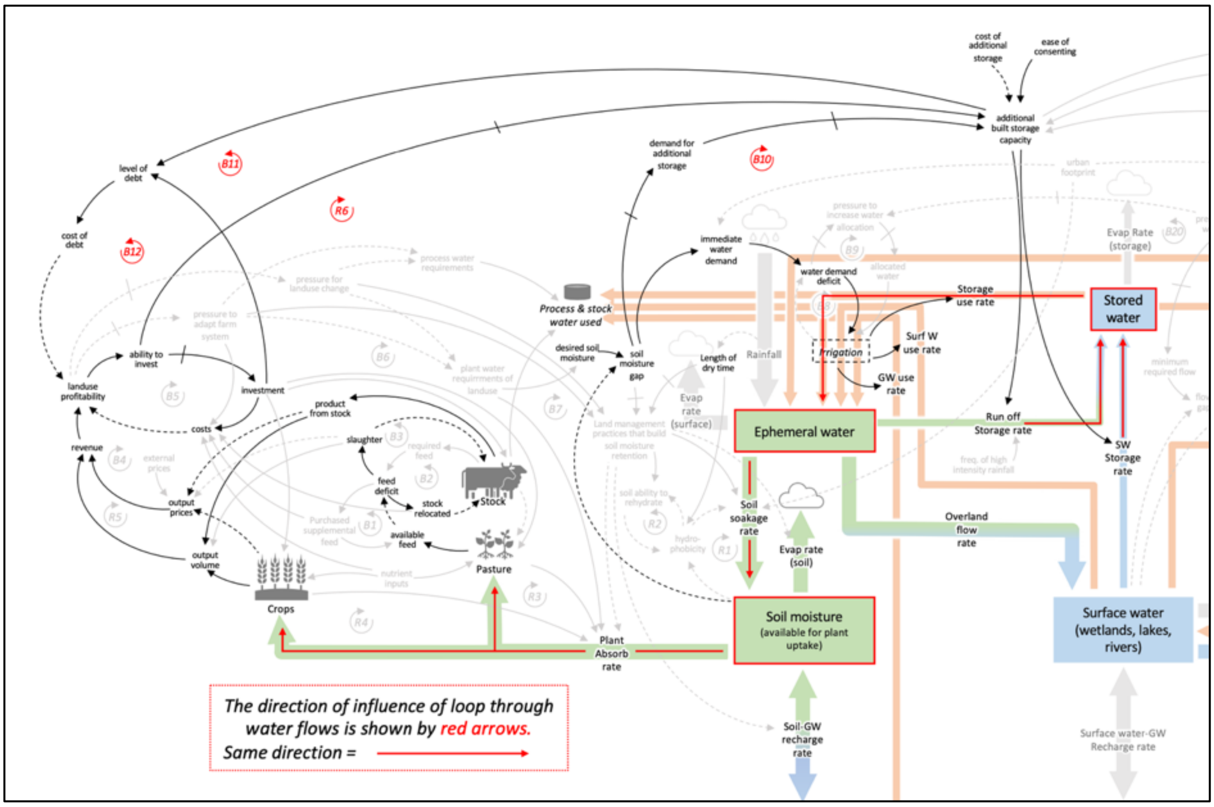
The arrows from the **irrigation** node to the different **irrigation rates** (**surface water**, **groundwater**, and **storage**) simply indicate the pathways from which this irrigation water may come.

7.8 Productive land use and water storage

Productive land use has an important driving relationship with the development of additional **built storage capacity** via a couple of different pathways – **demand for additional storage** and the **ability to invest** in it.

The **demand for additional storage** comes from the **soil moisture gap** described in the previous section. If this gap is persistent and unable to be closed, then over time this will increase the **demand for additional storage,** which in turn, over time, will lead to **additional built storage capacity** (all other things being equal), which enables the amount of **stored water** to increase. In the longer term, the additional capacity provided by **stored water** allows more **irrigation**, greater **soil moisture**, a reduced **soil moisture gap** and therefore a reduction in **demand for additional storage**. Thus, this loop (B10) balances itself out.

Figure 22. Productive land use and water storage



Yet demand is only part of the equation as to whether **additional built storage capacity** is achieved, any storage built will depend on the **ability to invest** in it as well. Here, the ability to invest will depend on the **land use profitability,** which, if buoyant, will enable additional capacity to be built (R6). Yet as noted in earlier descriptions, the ability to invest is likely to be lower when productivity is lower, which is when the soil moisture is reduced and the soil moisture gap (i.e. demand) is high. So, these two influences are likely to be working at slightly different times and at odds with each other.

The other external influences on whether additional storage is built are the **cost of additional storage** and the **ease of consenting**. These are located at the top of the diagram.

In addition, there is a burden of debt loop that operates with any investment in **additional built storage capacity**. Any investment in storage will (generally) lead to an increased **level of debt**, which increases the **cost of debt** on the business. This will drive down **landuse profitability** which in turn decreases any further **ability to invest**, creating a balancing loop (B12). Over time the cost of debt loop (B12) will constrain the ability to invest loop (R6).

Having described most influences on the productive land use side of the diagram, some influences on the levels of municipal and industrial water use will now be described.

7.9 Drivers of Municipal and Industrial use

Municipal and industrial use have been described as the same node here for ease of diagramming recognising that both water uses may be independent of each other. Municipal predominantly describes the extraction and treatment of water for human use in reticulated towns and cities. This includes human consumption, commercial and environmental[25] use (e.g. watering gardens). Industrial use describes the extraction[26] (and where necessary, treatment) of water for large scale industrial use. Sometimes this occurs as part of municipal reticulated networks, sometimes this occurs as stand-alone water extraction consents and infrastructure – for example a processing plant or factory in a rural area.

The arrows from **municipal & industrial use** to the various **use rates** (**stormwater**, **groundwater**, and **storage**) indicate the sources from which the use may come. Similarly, the arrows to the **waste-to-water rate** and **waste-to-land rate** indicate that these are dependent on the amount of water used. That is, the amount of wastewater (which is usually treated) is a direct derivative of the amount extracted for use.

Similar basic influences that drive the irrigation of productive land also apply here. The greater both **municipal demand** and **industrial demand**, the greater the **municipal/industrial demand deficit** (which is where demand exceeds supply), which drives greater **municipal/industrial use** (i.e. supply). Greater use therefore balances out the deficit (B14).

However municipal/industrial use is constrained by the **mun/ind allocated water** amount, so if there is a sustained **mun/ind demand deficit**, then this will (over time) increase **pressure to increase water allocation** which in turn (over time) will lead to an increase in **mun/ind allocated water**. Thus, over a longer time, greater use will tend to increase the amount of **mun/ind allocated water** (B15). (This is not the only influence on allocated water, how various loops affecting allocated water interact will actually determine the amount allocated – see also section 9.2.2.)

Municipal demand is influenced by the size of the **population** in the *same* direction (more population, more demand) and by the **municipal use efficiency** in the *opposite* direction (greater efficiency, less demand). The municipal use efficiency is in part influenced by the **urban footprint**, which recognises the efficiencies of scale gained from more compact urban form and less overall length of water infrastructure (this is shown in a later sub-section).

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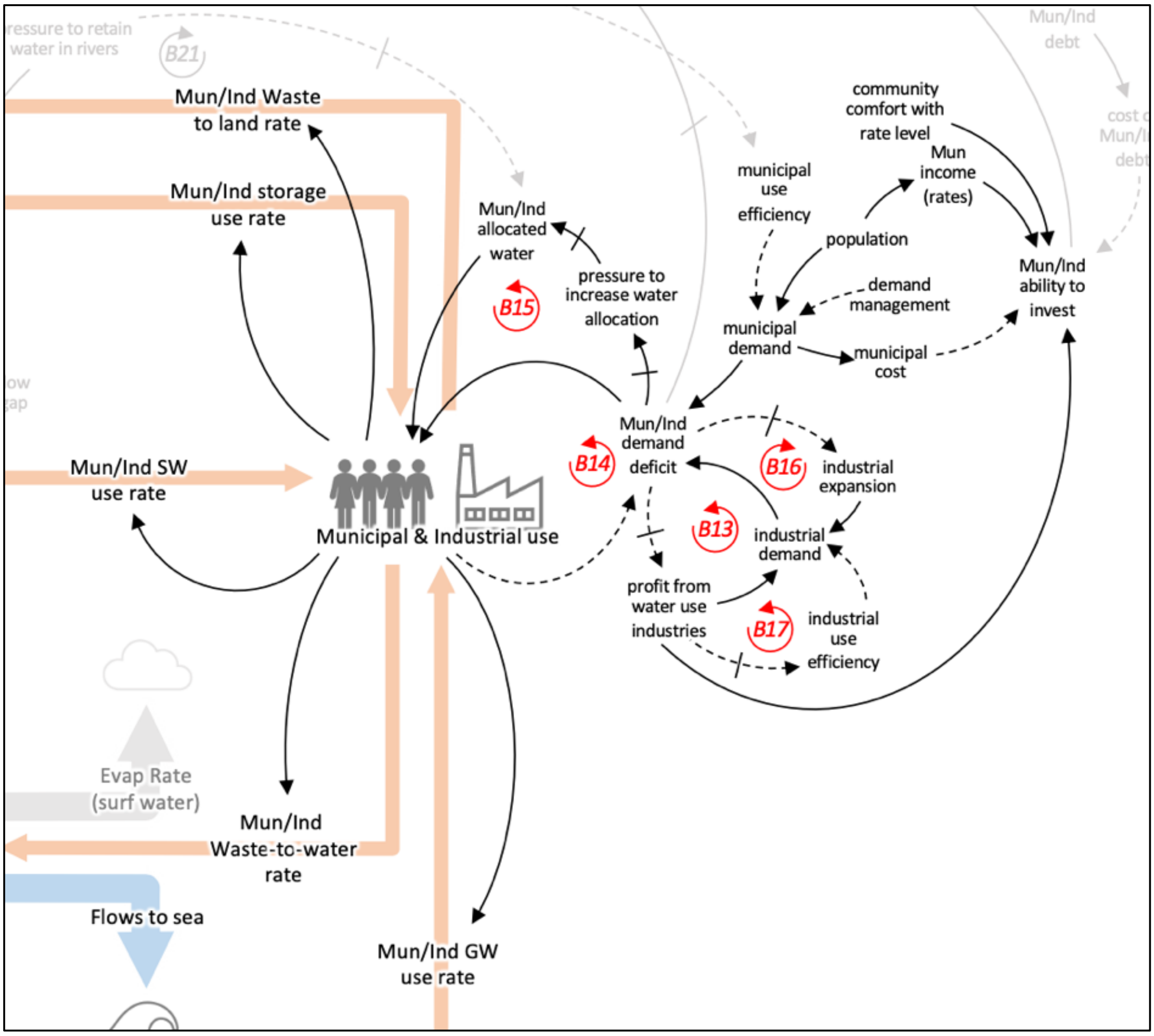
[25] 'Environmental' use here does not refere to water flows in rivers and instream ecological use.

[26] The exception here is hydroelectricity production, where water is retained in surface water bodies for the purpose of electricity generation. This is a non-consumptive use of the water, so the water is not extracted and consumed. However, it is likely to be held in the water body which may impact the ability of other extractive (and likely consumptive) uses to occur further downstream.

Figure 23. Drivers of municipal and industrial use



Industrial demand is involved in several feedback loops. Firstly, greater profit from the use of water in industry (**profit from water use industries**) increases **industrial demand** which increases the **mun/ind demand deficit**, in turn (over time) this maximises **profit from water use industries** unless water amounts can increase, so it is a balancing loop (B13). Yet, at the same time, if the **profit from water use industries** remains low, then this can drive greater **industrial use efficiency** which reduces **demand** and the **demand deficit**, freeing up water for use by industry, reducing or removing the water constraint, and enabling industries to again operate at a state where the amount of available water allows them to operate profitably (B17).

Finally, If the **mun/ind demand deficit** remains persistent, this is also likely to limit **industrial expansion**, which will balance out **industrial demand** and any further pressure on the **demand deficit**, bringing this loop into balance also (B16).

Finally, both municipal and industrial factors influence the **mun/ind ability to invest** in further infrastructure. On the industrial side, the greater the **profit from water use industries**, the greater industry's ability to invest. On the municipal side there are various influences. The greater the **municipal cost** of providing water and the greater the **level** and **cost of debt**, the less the **ability to invest**. At the same time, the greater the population the greater the potential **municipal income (rates)** which, along with any increase in the **community comfort with rate level**, can increase the **mun/ind ability to invest**.

7.10 Municipal & Industrial use and water storage

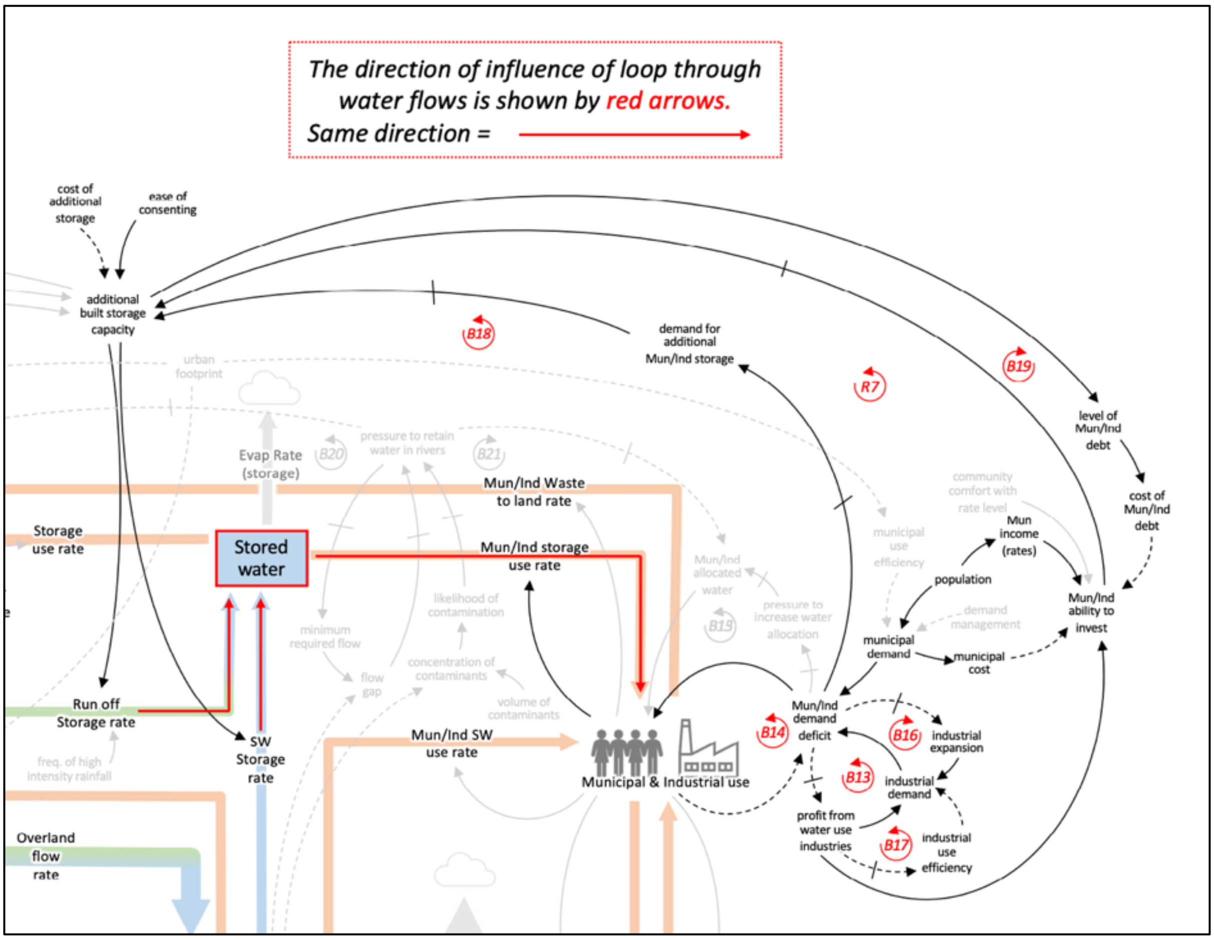
Municipal and industrial water use has balancing relationships with **stored water** that follows the same pattern as water use for productive land use – the demand for, ability to invest in, and actual investment.

On the demand side (B18), a sustained **mun/ind demand deficit** will (over time) increase the **demand for additional mun/ind storage** which, in turn, will increase the **additional built storage capacity** in the longer term. The more **additional built storage capacity** there is the greater the flows to fill that storage, from both **run off** and **surface water**. This will eventually enable more use, thus reducing the **mun/ind demand deficit**.

On the invest/ability to invest side, **increased municipal** is likely driven by increased **population** which man increase **municipal income from rates**, increasing the **ability to invest**. This may also be increased by greater **profit from water use industries** (through paying rates/charges). There will be an opposite influence from increased **municipal cost**, but this may not dominate. A healthy **ability to invest** will (over time) increase **additional built storage capacity** which will enable greater flows and further profit from **water use industries**, thus reinforcing on itself (R7).

At the same time, as with productive land use, the relationship between **additional built storage capacity** and **mun/ind ability to invest** is a balancing one (B19). The greater the **ability to invest** the greater the investment, the greater the **level of debt**, the greater the **cost of debt**, the lower the **ability to invest**. This means that actual investment tends to find balance with the ability to invest.

Figure 24. Municipal & Industrial use and water storage



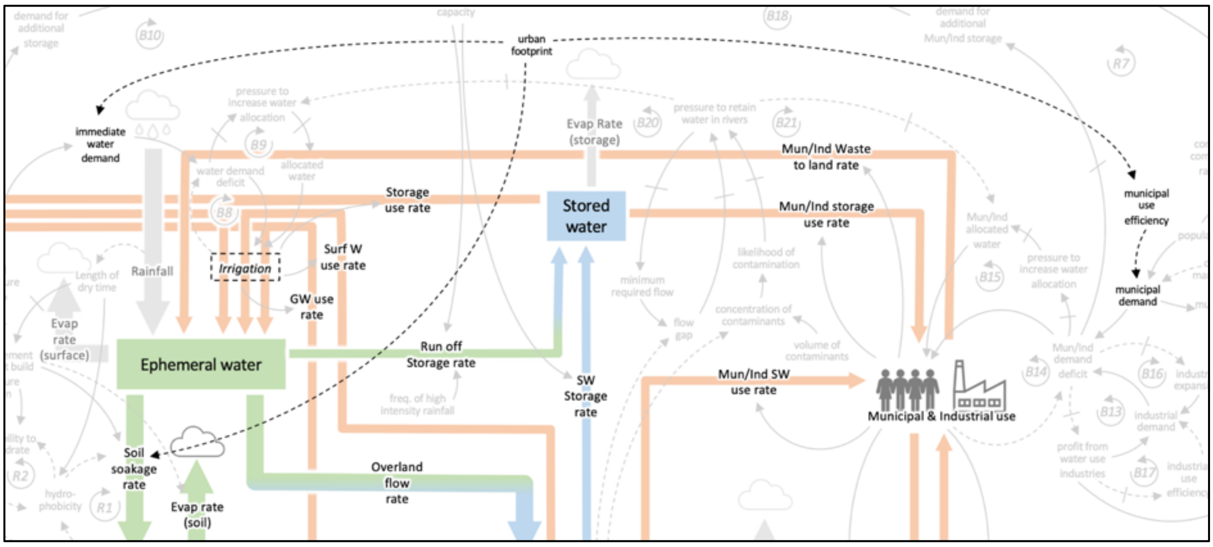
7.11 The impact of urban footprint

This section describes the influence of **urban footprint** on both broad sections of the system diagram – productive rural landuse and municipal demand. **Urban footprint** influences these areas in a number of interesting ways.

Firstly, the larger the **urban footprint** the lower the **municipal use efficiency** of water and the higher the **municipal demand**. This is because when the **urban footprint** is large, water services tend to be spread over a wider (usually lower density) area, which requires larger numbers of smaller pipes to service. Not only does this increase the latent water in the system but it also increases the opportunity for leaks and breaks. The use efficiency is increased when urban form is compact and dense.

Secondly, the larger the **urban footprint**, then the less productive rural land there is, which reduces the **immediate water demand** (the water required to reduce the soil moisture gap, see Figure 21). At the same time, urban areas reduce the ability of water to soak into soils, due to the increase in non-permeable surfaces. Therefore, there is an opposite relationship between **urban footprint** and **soil soakage rate**. While this may not have an immediate impact on plant and crop productivity – because that land tends not to be used for productive rural use – this can have flow on impacts on the amount of water that recharges to **groundwater** (via soil moisture), effectively reducing the store of **groundwater** and diverting more water (via overland flow) to surface water bodies and out to sea.

Figure 25. The impact of urban footprint on productive rural landuse and municipal demand



While all the descriptions so far have focused on the various human uses of water and its extraction, the following section addresses the important link between water extraction and water quality in surface water bodies.

7.12 The impact of water extraction on surface water quality

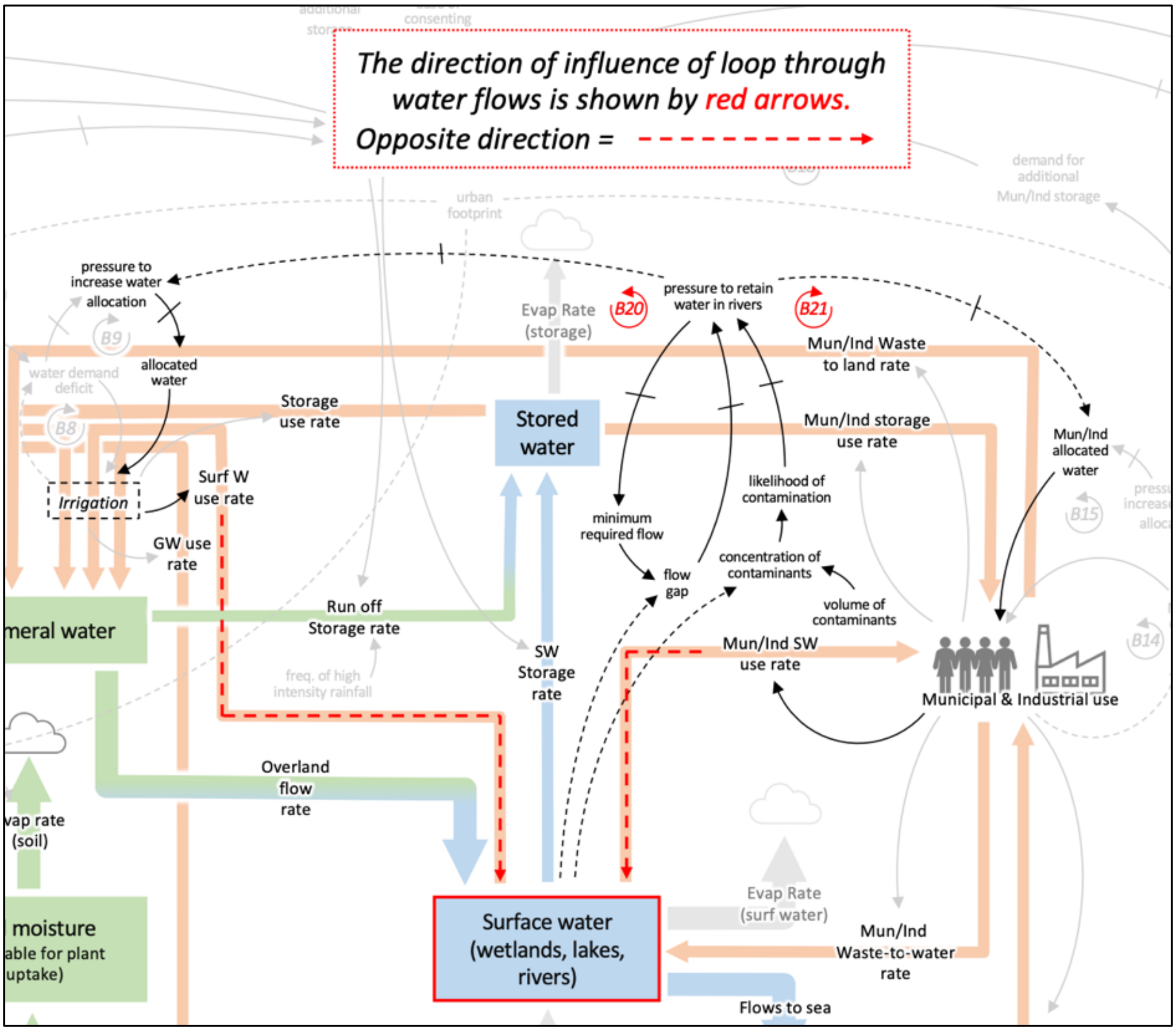
The quality of New Zealand's water bodies has been a particular focus of public debate and government reform over the last decade. The extraction and human use of water and the quality of surface water bodies are intimately linked. The loops in this section describe how this links with both the use of water in productive land uses, and municipal & industrial use.

The volume of water in the **Surface water (wetlands, lakes, rivers)** stock is reduced when water is extracted or evaporates from it (the flows out of this stock). It is also impacted by flows that avoid water reaching this stock (e.g. diversion to storage from run off). When the **Surface water** stock is reduced this impacts the capacity of water bodies to absorb and dilute contaminants. Therefore, the key relationship here is the *opposite* relationship between **Surface water** levels and the **concentration of contaminants**. That is, the lower the **Surface water** levels, the higher the **concentration of contaminants**, assuming the **volume of contaminants remains the same**.

Over the longer term, the greater the **concentration of contaminants**, the greater the **pressure to retain water in rivers**, which helps to dilute the contaminants. This is part of the debate that has played out in New Zealand in recent years. A sustained level of **pressure to retain water in rivers** will over time lead to a maintained or reduced level of **allocated water** for extractive use. As discussed earlier the levels of **allocated water** are a critical factor in the amount of water that is extracted for use. This feeds back to influence the flows of water themselves and ultimately the levels of **Surface water (wetlands, lakes, rivers)**, thus forming two balancing loops (B20 & B21).

These two loops (B20 & B21) will interact with those loops driving extractive use (B9 & B15). Those loops that are more dominant will, over time, influence the direction of the level of **allocated water** for either rural or municipal/industrial use.

Figure 26. The impact of water extraction of surface water quality



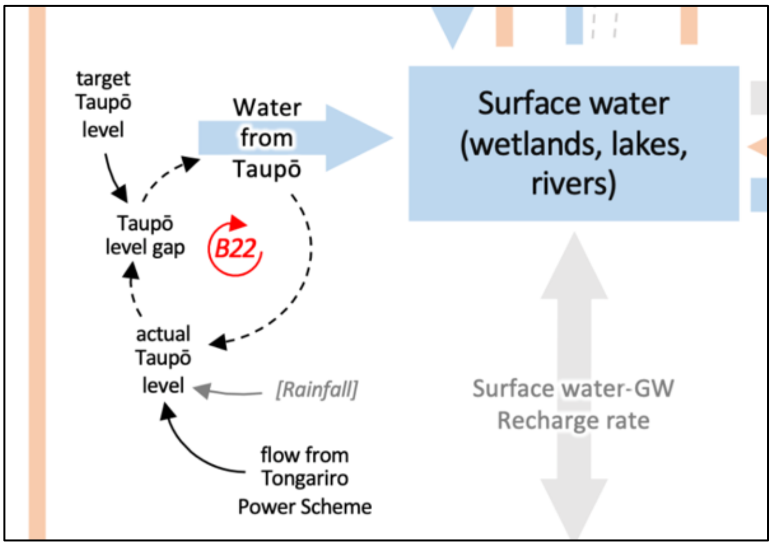
Note: In Figure 26 (above), the influence of the feedback loops travel upstream along the flows of water. Therefore they are ***opposite*** *relationships (shown as dashed red arrows going up the flows of water). For example, if the* ***Municipal/Industrial surface water use rate*** *was to* ***increase****, this would increase the flow of water to* ***Municipal & Industrial use*** *(the direction of the flow), yet it would* ***decrease*** *the stock of water from where this flow originated –* ***Surface water (wetlands, lakes rivers)****. Because the flow increases and the originating stock decreases this is an* ***opposite influence*** *of the flow on the stock. (See Figure 16 for an explanation of a same influence).*

7.13 The impact of Lake Taupō on the Waikato River

This final section outlines the specific and yet impactful relationship that the level of Lake Taupō has on the Waikato River.

Mercury Energy is required to manage the level of Lake Taupō within a certain level range. The level of Lake Taupō is naturally impacted by **rainfall** in its catchment area and is humanly impacted by the diversion of water from the Whanganui River into Lake Taupō known as the Tongariro Power Scheme (this diversion is not shown as a flow on the diagram but is shown as variable that influences the **actual Taupō level**).

Figure 27. The impact of Lake Taupō on the Waikato River



The actual and target level of Lake Taupō form an important goal/gap relationship. When the actual level is within a certain range of the target level (i.e. the gap is *low*) the **water from Taupō** flows with minimal restrictions. However, if the actual level gets too far away from the target level (i.e. the gap is *high*) then the flow of **water from Taupō** into the Waikato River is restricted. This is an important way in which the flow into the **surface water** body of the Waikato River can be impacted.

As **rainfall** is an influential driver here, extended dry periods are likely to result in reduced flows down the Waikato River. This will likely be at roughly the same time that similar sustained low rainfall is driving greater water use deficits in the human use loops described in earlier sections. Therefore, this relationship is one that is of particular importance in the Waikato River catchment.

7.14 A complete list of feedback loops (endogenous or internal influence) identified in the system diagram

This section provides a summary table (0) of all the feedback loops identified in the above description of the system diagram. In the table below, each loop is only described in one direction only, however the may also operate in the other direction.

Table 4. A complete list of the feedback loops identified in the system diagram

Feedback loop number	Label/Description For brevity, loops are described in one direction only but also operate in the other direction
Reinforcing feedback loops	
R1	**Hydrophobicity and soil soakage loop** Increased Hydrophobicity of soils decreases the Soil soakage rate, which decreases the Soil moisture which in turn further increases (or reinforces) Hydrophobicity.
R2	**Hydrophobicity and soils ability to rehydrate** Increase hydrophobicity reduces the soils ability to rehydrate in wet weather events, thus further reinforcing hydrophobicity.
R3	**Pasture growth loop** The greater the plant absorption rate the more pasture, which results in more pastures drawing on water absorption through the plant absorption rate, thus more water continues to be absorbed.
R4	**Crop growth loop** The greater the plant absorption rate the more crops, which results in more crops drawing on water absorption through the plant absorption rate, thus more water continues to be absorbed.
R5	**Output volume (of crops or pasture) and investment loop** The greater the volume of stock or crops, the greater the output volume of product from stock or crops. This increases revenue, the profitability of that landuse, the ability to invest and therefore further investment, resulting in more stock or crops.
R6	**Additional built water storage capacity and output volume loop** The greater the output volume, the greater the revenue, profitability, and ability to invest. This encourages more investment in built water storage, increasing irrigation capacity and further reinforcing soil moisture and output volume.
R7	**Additional built water storage capacity and Municipal/Industrial ability to invest loop** The greater the built water storage, the more Municipal and Industrial users can use water. Particularly in relation to industrial users, this reduces any demand deficit, enabling profitability and rate paying, this further enables municipalities to invest in built water storage, encouraging further built water storage.
Balancing feedback loops	
B1	**Purchased supplemental feed loop** The lower the available feed (for stock), the larger the feed deficit, the more supplemental feed is bought, thus providing more available feed. *Loops B1, B2 and B3 are all ways of dealing with an imbalance of feed available for stock on a farm. Loops B1 and B2 are likely to be initiated before loop B3.*
B2	**Stock relocation loop** The numbers of stock on a farm determines the level of feed required for those stock. If this is out of balance with the available feed, this will increase the feed deficit. One way of dealing with this is to temporarily relocate stock to other farms, which reduces the number of stock and their required level of feed.

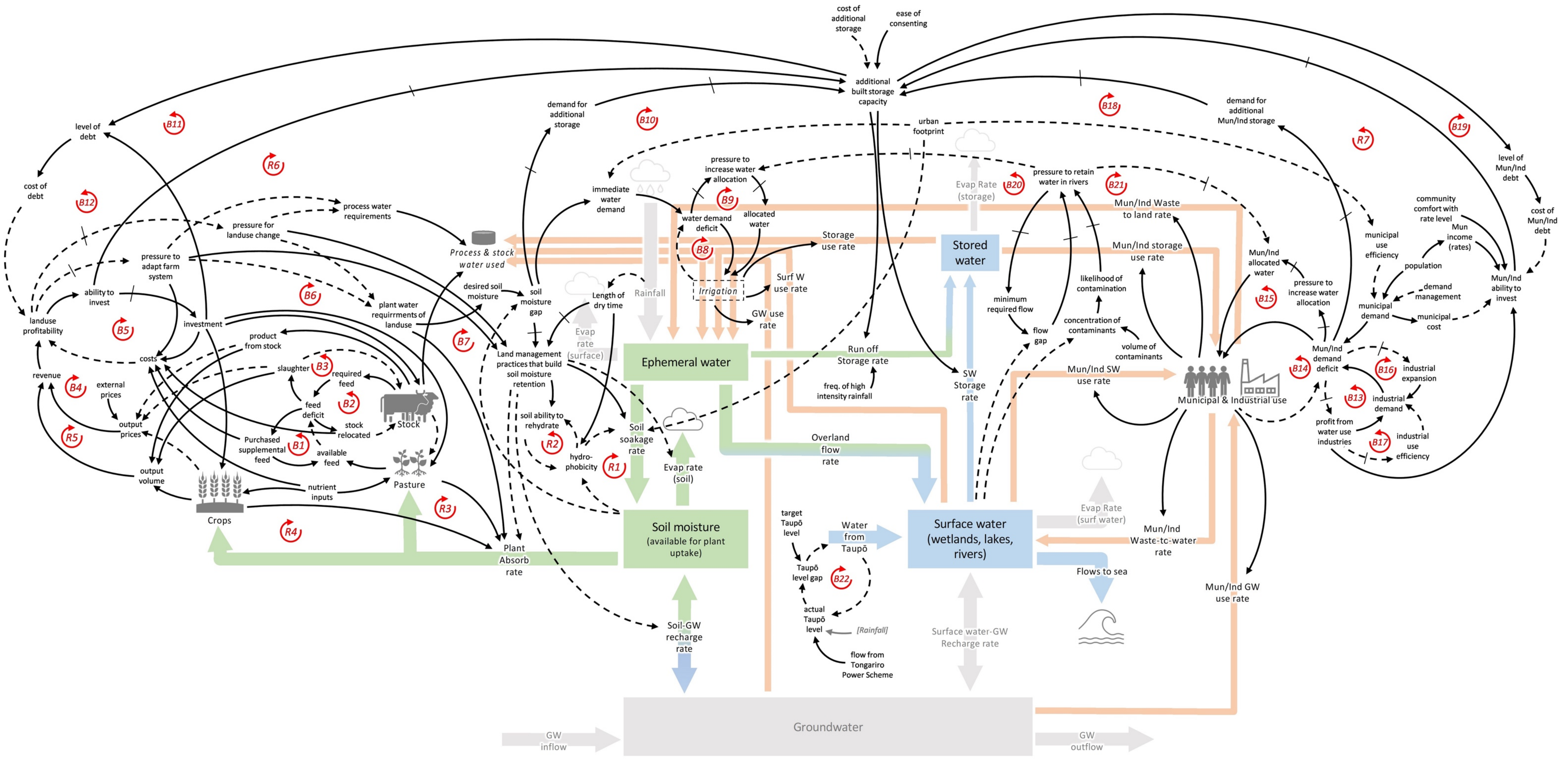
Feedback loop number	Label/Description For brevity, loops are described in one direction only but also operate in the other direction
	Loops B1, B2 and B3 are all ways of dealing with an imbalance of feed available for stock on a farm. Loops B1 and B2 are likely to be initiated before loop B3.
B3	**Stock slaughter loop** The amount of stock on the farm determines the level of feed required for those stock. If this is out of balance with the available feed, this will increase the feed deficit. One way of dealing with this is to send some of the stock for slaughter. This can bring the amount of stock back into balance with the amount of available feed, thus reducing the feed deficit. *Loops B1, B2 and B3 are all ways of dealing with an imbalance of feed available for stock on a farm. Loops B1 and B2 are likely to be initiated before loop B3.*
B4	**Output prices response to volume loop** The greater the product from stock or crops, the lower the output price, due to potential oversupply. This decreases revenue, the profitability of that landuse, the ability to invest and therefore further investment, resulting in less product from stock or crops. While this is represented as a general relationship, the actual relationship will also be influenced by the elasticity of prices in relation to supply, which will vary per industry.
B5	**Investment increasing costs loop** The greater landuse profitability the greater the ability to invest. Over time, this is likely to lead to greater investment, which means that more costs are incurred at that time, this will then impact the profitability of that landuse.
B6	**Pressure to adapt or change plant water requirements loops** These loops relate to the pressure to adapt plant selection within a farm system or for a landuse in a more wholesale way, in response to low soil moisture affecting the absorption rate of plants. If the plant water requirements of a particular landuse are high and soil moisture is low, then this will affect the volume of pasture and crops. This reduces revenue and profitability, increasing pressure to adapt farm systems or change landuse, or both - two pathways exist in these loops. Adaptations are then made to reduce the plant water requirements (for example through crop/cultivar selection), which reduces the plant absorption rate in line with available soil moisture. This brings production and therefore profitability back into balance with each other.
B7	**Pressure to adapt or change land management practices loops** These loops relate to the pressure to adapt land management practices to retain soil moisture within a farm system or for a landuse in a more wholesale way, in response to low soil moisture affecting the absorption rate of plants. If current land management practices do not encourage soil moisture retention, then less water will be absorbed into the soil, meaning soil moisture is low which affects the volume of pasture and crops. This reduces revenue and profitability, increasing pressure to adapt farm systems or change landuse, or both - two pathways exist in these loops. Adaptations are then made to increase land management practices that encourage soil moisture retention (for example through low/no tillage), which increases the soil soakage rate and soil moisture. This brings crop/pasture production and therefore profitability back into balance with each other.
B8	**Irrigation use loop** Low soil moisture results in a sustained soil moisture gap, which increases immediate water demand. This results in a water demand deficit (there is not enough water to meet the demand). When this occurs, irrigation can be used to supplement the water from rainfall. Irrigating meets the water demand deficit, thus balancing out the need for irrigation.

Feedback loop number	Label/Description For brevity, loops are described in one direction only but also operate in the other direction
B9	**Pressure to increase productive water allocation loop** A sustained water demand deficit will, over time, mean there is pressure to increase the amount of allocated water available for irrigation. This enables more irrigation which meets the water demand deficit. This takes away pressure to increase the allocation of additional water.
B10	**Demand for additional agricultural water storage loop** Sustained low soil moisture and a high soil moisture gap will, over time, increase the demand for additional water storage, which will, over time, lead to more additional built storage. This results in more stored water and irrigation, ensuring that soil moisture is maintained, thus balancing out further demand for additional water storage.
B11	**Agricultural water storage investment loop** The greater the ability to invest, the more likely that additional water storage will be built. When built, additional water storage increases debt and the cost of servicing debt, which balances out any further ability to invest.
B12	**Investment debt loop** This loop assumes that most major investments are funded via debt, this increases the cost of servicing debt and decreases profitability, reducing the ability to invest further.
B13	**Industrial profit and demand loop** The greater profit derived from water use industries, the greater the industrial demand for water, this increases the industrial demand deficit which will constrain further growth in profits derived from water use industries.
B14	**Municipal & Industrial use loop** The greater both municipal and industrial demand, the greater the municipal and industrial demand deficit. That is, demand is greater than supply. This will increase the use of water to meet this demand (providing that water is available), which in turn reduces the demand deficit. In effect, water use will rise or fall to the level of demand, so long as there is water available to do so.
B15	**Pressure to increase municipal & industrial water allocation loop** A sustained municipal & industrial water demand deficit will, over time, mean there is pressure to increase the amount of allocated water available for municipal and industrial use. This enables more use which meets the water demand deficit. This takes away pressure to increase the allocation of additional water.
B16	**Industrial expansion loop** When industrial demand is being met (that is, the industrial demand deficit is low), then industrial expansion is likely to occur. Eventually, this will mean that industrial demand increases, also increasing the demand deficit. A sustained demand deficit (demand not being met) will constrain further industrial expansion.
B17	**Industrial use efficiency loop** This loop describes the low revenue driven innovation to increase water use efficiency. If profits are low, over time this will drive innovation to increase water use efficiency, which will reduce overall industrial demand, reducing the demand deficit. This reduces the scarcity of water and enables further profitable use of water at lower cost.

Feedback loop number	Label/Description For brevity, loops are described in one direction only but also operate in the other direction
B18	**Demand for additional municipal/industrial water storage loop** A sustained municipal & industrial demand deficit will increase the demand for additional water storage, which will, over time, lead to more additional built storage. This results in more stored water and municipal/industrial use, thus meeting the demand deficit and balancing out further demand for additional water storage.
B19	**Municipal/Industrial water storage investment loop** The greater the ability to invest, the more likely that additional water storage will be built. When built, additional water storage increases debt and the cost of servicing debt, which balances out any further ability to invest.
B20	**Environmental pressure to retain water in rivers – agricultural** The less surface water there is in wetlands, lakes and rivers, the greater the flow gap (difference between desired and actual flow) and the higher the concentration of contaminants. These increase pressure to retain water in rivers, which over time will counteract pressure to increase agricultural water allocation. If dominant, this loop will reduce the actual amount of water allocated to irrigation, which reduces irrigation take, which retains water in surface water bodies.
B21	**Environmental pressure to retain water in rivers – municipal & industrial** The less surface water there is in wetlands, lakes and rivers, the greater the flow gap (difference between desired and actual flow) and the higher the concentration of contaminants. These increase pressure to retain water in rivers, which over time will counteract pressure to increase municipal and industrial water allocation. If dominant, this loop will reduce the actual amount of water allocated to municipal and industrial uses, which reduces water take, which retains water in surface water bodies.
B22	**Flow from Lake Taupō loop** According to legislation, the level of Lake Taupō must be managed between certain levels. The greater the gap between the desired level and the actual level, the greater that water flowing from Taupō is constrained. When the Taupō outflow is constrained, the actual level of Lake Taupō will rise, thus reducing the level gap.

8 The complete system diagram

Figure 28. Complete system diagram (including the influence of Lake Taupō on the Waikato)



9 So what? Using the diagram to explore possible future adaptations to drought

The *process* of developing a system diagram has many benefits including building shared appreciation of issues and articulating how causal factors are understood to operate. The resulting diagram is only part of the output, additional insights can be achieved ***when the diagram is used as a basis to explore potential impacts on key area(s) of interest, over time in response to change,*** such as landuses, geographic locations or climatic patterns. This section describes the ways that the system diagram can be used to gain such insight.

9.1 Different ways of gaining insight from a system diagram

Qualitative insights about the structure and likely behaviour (dynamics) of the system can be achieved in a variety of ways. The stock & flow and feedback loop approach recognises that nothing is static and that things are constantly changing – moving into, or out of, balance. Using the diagram to support discussion around the stocks & flows and feedback loops associated with the water cycle can explain how the behaviour of variables of interest may change over time. Or in other words, what the future may look like in response to changes. Insights possible from system diagrams are summarised in Table 5 below.

Table 5. Different ways of gaining insight from a system diagram

Way of gaining insight	Description
1. Highlighting interconnectivity	The system diagram visually demonstrates the interconnected nature of the factors being diagrammed. This is the type of insight described in the following sections: • Insights from stock and flow structure only • Insights from an overview of feedback loops
2. Highlighting internal (endogenous) influence versus external (exogenous) influence	System diagrams also highlight the circular nature of causality. This enables differentiation between endogenous and exogenous influences This can help reframe participants perceptions of how much influence is from 'external' sources and how much is from 'within'. This is the type of insight described in the following sections: • Insights from stock and flow structure only • Insights from an overview of feedback loops

Way of gaining insight	Description
3. Exploring potential futures and changes in the system	Using the system diagram as a tool to guide discussion, the anticipated dynamic behaviour of some elements in the diagram can be discussed and explored as a group. Picking up on this important point, the discussion that follows is anchored around how important variables in the diagram may behave or change in the future, based on the dynamics of the feedback loops that have been articulated. This is a type of scenario analysis. The system diagram approach provides an opportunity to gain a variety of insights relating to different scenarios in a participative and low-cost way. This is the type of insight described in the following sections: • Using the tool to gain insights about a particular landuse, geographic location or climatic patterns

The approaches outlined above are described in the remainder of this section.

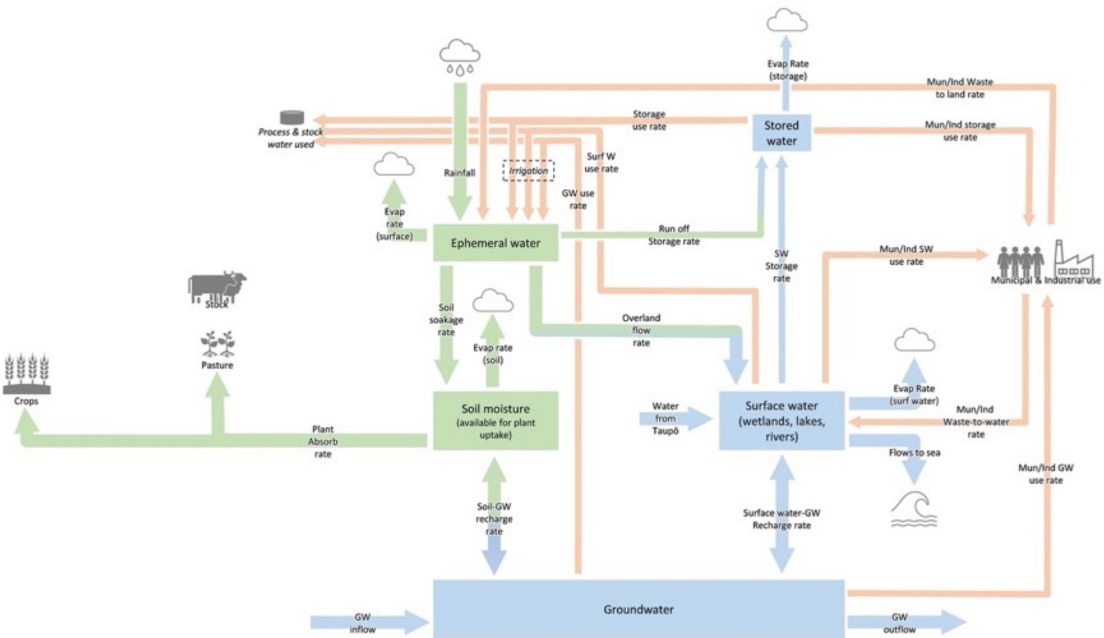
9.2 Using the diagram to support qualitative discussions about alternative futures

Five types of insights are described below. Beginning with insight based on the stock and flow structure progressing towards insight gained once feedback loops are added. Finally, alternative futures can be explored based on a particular land use, geographic area, or climate pattern.

9.2.1 Insights from stock and flow structure only

This stock and flow structure is useful by itself as it highlights the interconnectivity of the various stocks and flows of water in the water cycle. Further, it highlights a range of areas where action may be taken to adapt to a drought prone future.

Figure 29. All stocks and flows identified



A key focus for the Waikato is to enable productive land use. Therefore, the core focus of drought adaptation is enabling and retaining an appropriate level of ***soil moisture*** to continue supporting productive landuse. However, this is not just about adding more water, but also potentially extracting less water, which may be achieved through alternative landuses, as explained in earlier detailed explanations of the diagram.

This most basic form of the diagram could be used to aid discussion about ***how*** adaptation activity might help enable water flows ***into*** the stock of soil moisture; or constrict flows of water ***from*** it, to maintain soil moisture at appropriate levels. Areas of the water cycle that the above diagram highlights as important are listed in Table 6 below. The selection of these was informed by the specialist interviews undertaken within Council and insights from the literature.

Table 6. Areas of the water cycle that the diagram highlights as important for drought adaptation

Part of diagram	Type of insight/discussion this may support
Soil soakage rate	How might farm management practices enhance the soil soakage rate, from surface water into soil moisture? What types of soil characteristics may need to be enhanced and how might this be done? e.g. maintaining or increasing organic matter.
Evaporation rate (soil)	How can the soil evaporation rate be influenced/reduced? How can ground cover be used to ensure less evapo-transpiration?
Soil-groundwater recharge rate	What soil characteristics may enable the retention of moisture in soils as opposed to water drainage to groundwater? How might those soil characteristics be retained or encouraged?
Plant absorption rate	What types of plants/crops can provide the same nutritional benefit for less water? What plants/crops are more drought resistant? What plants/crops may still be productive in sustained low soil moisture environments?
Overland flow rate	How might land use practices view the relationship between overland flow and soil soakage rate? Can land management practices encourage soakage rather than run-off?
Groundwater irrigation rate Surface water irrigation rate Storage irrigation rate	How might the demand for irrigation rates be reduced through technology or pasture/crop selection?
Built storage	What examples of built water storage might be possible, useful, or necessary? What types might not?

9.2.2 Insights from an overview of feedback loops

While the stock and flow diagram of the water cycle is the base of the system diagram, adding feedback loops of influence to this provides insight into how the behaviour of the water cycle is mostly influenced by internal (endogenous) factors within the wider water and land use system.

Reflecting on the system diagram Figure 28 draws attention to how feedback loops and stocks and flows interact with one another, creating internal (endogenous) influence on the water cycle. The authors, reflecting on the insights from the specialist interviews and the pathways of water into and out of key stocks in the water cycle, identified a range of important feedback loops which are summarised in Table 7 below. This list is mostly a subset of (or in some cases a combination of) the feedback loops described in section 7 and 0. Some insights are primarily descriptions of stocks and flows.

Table 7. Insights from feedback loop and stock and flow analysis

Insight summary	Description
1. Hydrophobicity is associated with reinforcing feedback loops that can operate in an undesirable way. These may reach a tipping point where soils hardly absorb moisture.	Natural hydrophobicity (or water-repellency) tends to occur in soils that dry out. This occurs to varying degrees in different types of soils. It is understood that this is more likely in allophanic soils, which occur in the Waipa, the middle Waikato and the upper Waihou/Piako catchments. There are two reinforcing feedback loops that are important here: • Hydrophobicity reduces the soil's ability to absorb moisture and thus rehydrate, which reduces the soil moisture, which further increases hydrophobicity (**R1**). • Hydrophobicity also reduces the soil's ability to rehydrate, which further increases hydrophobicity (**R2**). In combination, these two reinforcing loops may create a tipping point where soils may not rehydrate, outside of long periods of sustained light rainfall. ***This implies that land managers should be aware of the extent that their soils are prone to hydrophobicity and should actively seek ways to manage this.***
2. The required feed, based on stock numbers, will eventually rise or fall to meet the available feed. Although this may be buffered by additional feed or relocating stock in the interim.	The required feed and the available feed are in a series of interlinked balancing feedback loops. The required feed is the human induced factor that farmers will try to maintain. Feed deficits can be compensated for via purchased supplemental feed (**B1**) or relocated stock (**B2**). In the longer term though, if sustained low levels of available feed dominate, it is likely that stock will be sent for slaughter (**B3**). Thus, these compensating feedbacks will eventually reduce the desired feed to come into line with the available feed. ***This highlights the opportunity to better manage land to maintain as consistent a level of available feed as possible without supplementary inputs. How can this be influenced by stock types that have less of a moisture/feed requirement? Or pastures that require less moisture?***
3. Increases in allocated water may impact minimum flows and increase the concentration of contaminants.	Increases in allocated water (**B9 & B15**) will reduce water in surface water bodies, either through direct extraction or through extraction into temporary storage. In general terms this extraction is likely to reduce the amount of water left in surface water bodies, increasing the potential conflict with minimum flow requirements. Also, decreased volumes of water in surface water bodies increases the concentration of contaminants in the remaining water. ***This highlights the cascading impacts of increases in water allocation.***

Insight summary	Description
4. Water allocation limits are driven by conflicting feedback loops – one seeking to extract water; the other seeking to retain it.	Conflicting balancing feedback loops drive water allocation levels. On the one hand, appropriate levels of soil moisture support productive land use. Yet the greater the productive land use the greater the water absorbed by plants and animals through those activities. This results in an increasing soil moisture gap (even with consistent climatic conditions) which increases the demand for water, putting ***upward pressure*** on allocation limits (**B9 & B15**). On the other hand, increasing water allocation contributes to greater water extraction, generally decreasing water levels in surface water bodies. This can increase the risk of there being a gap between the actual water levels and the desired minimum flows. This increases the likelihood of contamination in surface water bodies due to the decreased assimilative capacity of water bodies. Both the water gap and the increased likelihood of contamination over time, will increase the pressure from communities to retain water in rivers/streams. This puts ***downward pressure*** on the amount of water that can be allocated (**B20 & B21**). ***This highlights that the allocated water amount will be more strongly influenced by the more dominant of these two loops.***
5. Extraction from groundwater may alleviate fluctuations in surface water bodies to a degree	As a part of the water cycle, groundwater is intimately linked with surface water body levels through recharge rates provision of water for surface flow. Yet most of the delays associated with groundwater are longer than surface water. Soakage rates are more likely to be slower than overland flow rates; and the residence time of water in the ground is usually much longer than the residence time of water in surface water bodies. Because of these delays, the system diagram highlights that extracting water from groundwater (**B8 & B14** – where they are drawing from groundwater) may provide a 'buffer' effect on the level of surface water bodies. As groundwater has a longer residence time it provides storage capacity from which water can be extracted. This leaves more water for surface water bodies and is likely to relieve some of the pressure on the minimum flows and contamination. ***However, there is still only the same amount of water in the water cycle. The system diagram also highlights that extractions from groundwater may have a delayed influence on soil moisture and surface water bodies, through the groundwater interface with these.***

Insight summary	Description
6. The four key flows of water into and out of soil moisture should be at the core of adaptation to drought resilience.	The **evaporation rate (soil)** & the **plant absorption rate**: These two factors highlight the influence that plant selection and plant cover have on soil moisture retention (**R3, R4 & B6**). The more that soils can be covered in plants of some kind, the less direct evaporation of water from the soil (although some will still occur through transpiration). Also, crop, pasture and plant selection will have a large impact on the rate at which plants absorb water. What kind of plant selection will be appropriate for the local condition? The **soil soakage rate**: The rate at which water soaks into the ground has a huge impact on the ability to increase soil moisture. This highlights the importance of land management practices that retain or encourage soil characteristics (**B7, R2 & R1**) that enable an appropriate soakage rate. The **soil-GW recharge rate**: This flow is the least likely to be influenced directly by human activity, since the characteristics of the sub-soil are difficult to access and influence. However, this should focus discussion on the potential impact of secondary impacts of land management practices. For example. what impact might inputs have on soil characteristics deeper in the ground? Might groundwater extraction impact the soil-GW recharge rate? etc.
7. Investment is self-reinforcing and is constrained by debt.	Investment activity tends to operate in a reinforcing feedback loop. Investment activity increases output volume which ***increases profitability which encourages further investment (R6 & R7)***. At the same time, investment tends to increase debt levels which increases the cost of debt, ***decreasing profitability and at some stage constraining further investment*** **(B11, B5 & B19).** ***Therefore, overall investment levels are usually highly linked to, and importantly constrained by levels of debt.***
8. The paradox of industrial use efficiency encouraging greater water use.	Water is an important input to many industries and industrial processes. Therefore, industrial demand for water is an important influence on water use. Increasing industrial use efficiency will reduce industrial demand in the short term and reduce the water demand deficit (**B17**). However, in the longer term, this reduced demand deficit is likely to ensure that industries continue to profit from water use (because their needs are met) (**B13**), which has the counter intuitive impact of increasing demand for water again. This is an example of Jevon's Paradox – the more efficient use of a resource doesn't necessarily mean that more of it is conserved, in fact the demand for it usually goes up. ***This means that increasing industrial use efficiency will, in the longer term, tend to lead to continued or greater demand for water. This means that water efficiency (and the natural limits of being able to use water efficiently) will continue to have a large impact on water demand.***

Insight summary	Description
9. The soil moisture gap drives demand for irrigation and additional storage and use but does not immediately drive a change in underlying soil characteristics.	The soil moisture gap is the difference between the desired level of soil moisture and the actual level of soil moisture. This gap drives the immediate water demand which drives the use of irrigation to supplement the natural water cycle (**B8**). The soil moisture gap does not have an immediate impact on the underlying soil characteristics. However, it can influence this over the longer term, where a sustained soil moisture gap can lead to greater land management practices that build soil moisture retention. ***Consideration should be given to whether additional irrigation would result in a sustained reduction in the soil moisture gap. If not, then this should raise questions about the efficacy, efficiency and cost effectiveness of this approach. As it does not change the underlying soil characteristics it is likely that even with irrigation, in the future there may be a need to move to land management practices that retain soil moisture.***

9.2.3 Using the tool to explore possible futures of particular landuses, geographic locations or climatic patterns

The feedback loop approach recognises that nothing is static rather, things are constantly changing as they move in, or out of balance. Describing feedback loops seeks to articulate circular cause and effect that can help to explain how variables of interest present as patterns of behaviour over time. The system diagram can be used to explore insights relating to landuses, geographic locations or climatic patterns. This is via a qualitative process of plotting possible futures in relation to anticipated dynamics of changes in factors identified within the system diagram and sketching graphs over time of the results. This is sometimes referred to as *analogue simulation*.

Analogue simulation is a qualitative, pragmatic and applied method to explore what changes might occur in the system in response to interventions (or lack of them) over time. Thus, analogue simulation is a tool that supports dialogue about the possible impacts of changes over time and produces a participant developed, visual articulation of a plausible possible future.

The approach can be used as simply as articulating potential changes over time as a sketch; or a more formal scale might be used with some form of tokens/counters. Some simple examples of the former are described here to *demonstrate* the potential use of the tool.

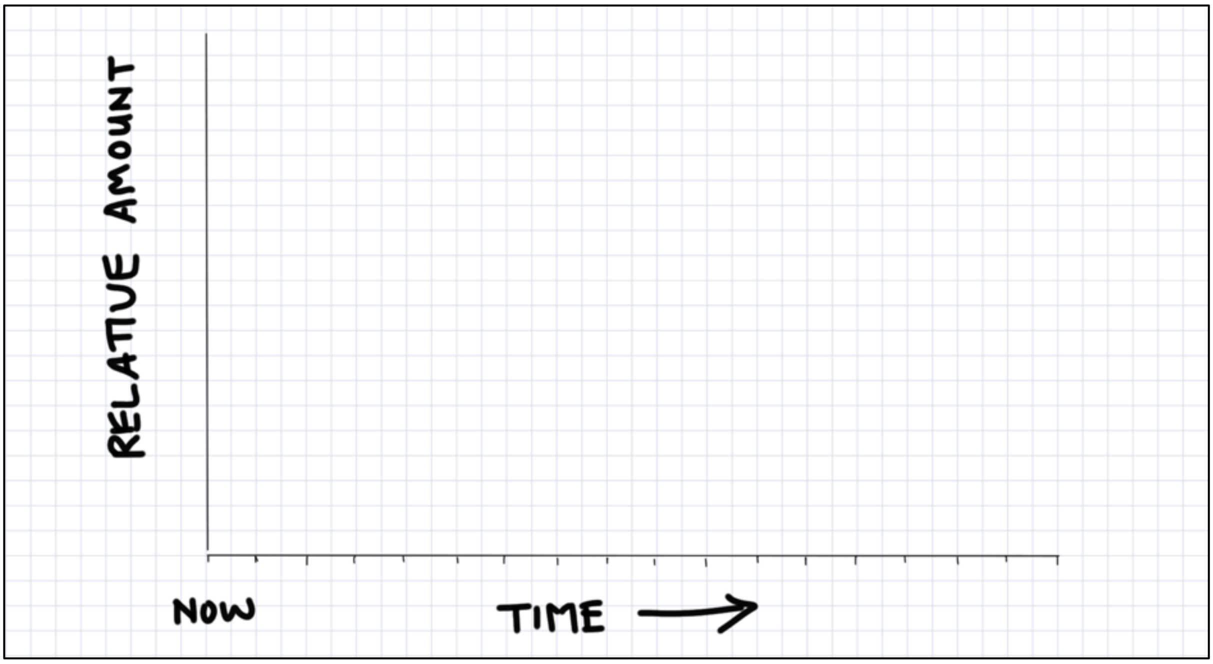
The approach described here is a pragmatic way of increasing our understanding of the impact of the causal factors articulated, in a short timeframe at low cost. The outcome being an increased understanding of broad patterns of behaviour and the possible outcomes of tensions between different influences in the system..

An analogue simulation process may proceed as follows:

- A selection of variables within the system diagram are identified along with an anticipated intervention (or series of interventions) to explore. A selection of variables is identified as it is likely too difficult to track change through ALL of the variables identified in the system diagram. Variables are selected based on their likely dominance in the system. Their selection should be based on how impactful they are perceived to be on the dynamics of interest, either directly or indirectly via pathways articulated in the diagram. This may be based on institutional knowledge and/or empirical knowledge where available, as well as the perceptions and lived experiences of participants in the process. This is necessarily a qualitative process and care should be taken to consider as wide a range of pathways and variables as possible, so as to explore as many dynamics within the system as possible.

- For each set of variables, a blank graph template was drawn up, with the Y axis being the relative change of variables and the X axis being time. Where the X and Y axis intersected was the present. A series of relevant timesteps were marked out on the X axis – e.g. 5 years, 10 years, 15 years etc.
- Sketch out a baseline. Talk through the anticipated behaviours of variables under a 'business as usual' (BAU) scenario. That is, all current issues and influences remain unchanged. This is discussed with those involved in the process. This could be a participatory group or your own team – whatever is appropriate. Sketch out the resulting trend of the variables of interest as this forms your 'baseline'.
- Sketch out the interventions. Working through each intervention (or combination of interventions) in turn, and using the system diagram as a guide, the flow on effect of relative changes from the intervention are plotted for the selected variables. For instance, variable X might start low but over time, due to the additional inputs of variable Y, this might trend upwards. This process is carried out over a reasonable timeframe to explore the potential impacts of change.

Figure 30. Exploring possible futures – qualitative graphing template



The tool could be used to explore how different feedback loops might dominate or not, for different landuses and management scenarios, geographic areas, or likely climatic profiles.

To do this, identify any characteristics for a particular land use that exist in the diagram. For example, is it stock or crop dominated, or both? What is its current level of debt and ability to invest? What are the current soil and soil moisture characteristics? How do the flows of water into and out of soil moisture perform?

Beginning with these initial conditions, the future behaviours and impacts of variables of interest could be qualitatively explored, guided by the feedback loops in the diagram. Alternative possible futures could then be explored based on changes in key variables.

The two hypothetical examples that follow are provided to demonstrate the potential use of this tool:

1. A pasture fed stock farm operating under a business as usual (BAU) approach. No major change is implemented, and drought conditions begin then worsen;
2. A pasture fed stock farm where an active investment is made move to land management conditions that retain soil moisture. Drought conditions begin then worsen;

Drought conditions (described by average rainfall) are assumed to be the same across both examples – there is an initial drought in years c.2-3 which worsens steadily from year c.6-11 then conditions stabilise but at a much lower average rainfall.

Changes occur over a hypothetical 10-15year timeframe.

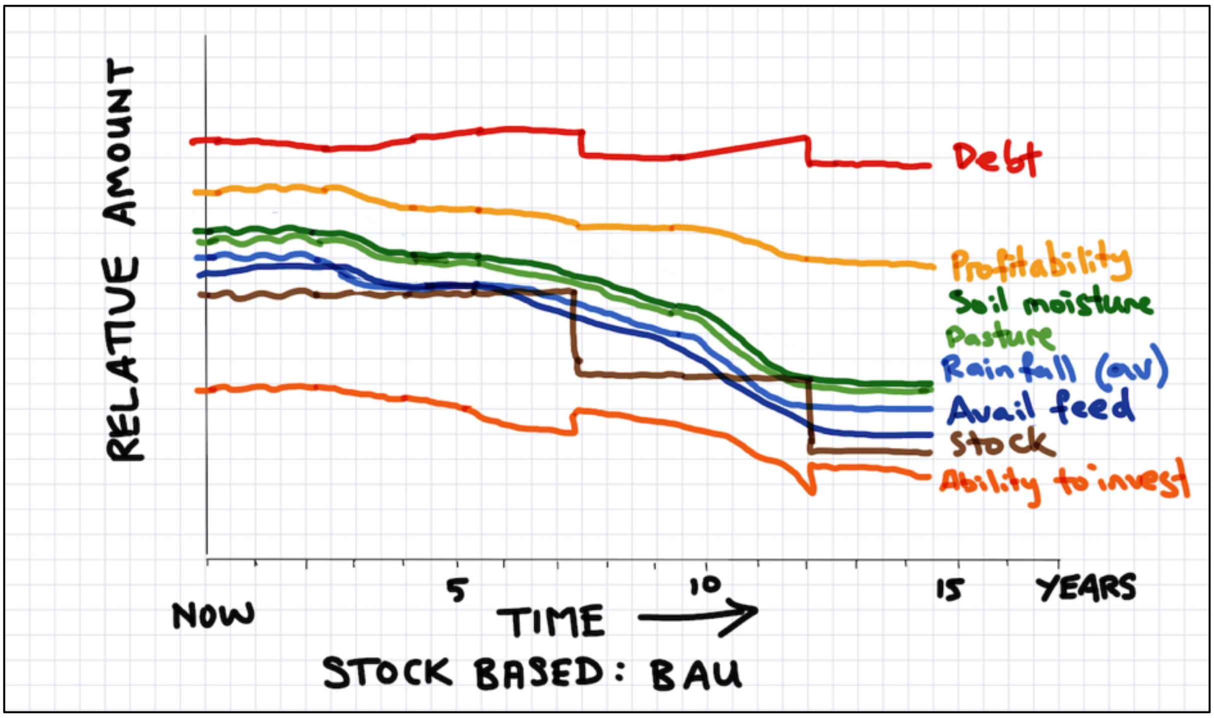
9.2.3.1 Exploring possible futures –stock farm (BAU) approach

This exploration begins with relative amounts of some of the important variables in productive landuse marked on the Y (vertical) axis.

Average rainfall is marked in light blue (there are a range of ways this could both present environmentally and be measured over different time steps, but it is assumed that the total amount of effective rainfall is reduced). The three other environmental factors are soil moisture (dark green), pasture (light green) and the available feed (dark blue) that this provides. Farm system/farmer related factors are the amount of stock (brown), profitability (yellow), the ability to invest (orange) and debt (red).

In this hypothetical situation, the first several years are 'normal' or consistent conditions, where there is a reasonable level of debt but also profitability, and a reasonable ability to invest. Average rainfall, soil moisture, pasture and available feed are all relatively in balance and this is sustaining a steady amount of stock. In this first 2-3 three years debt is slowly reducing due to profitability being able to service the debt.

Figure 31. Exploring possible futures –stock farm (BAU) approach



After 3 years the average rainfall reduces then remains consistent, but at a lower effective level, until around year 6. During this period there is a relative impact on soil moisture, pasture and available feed, but not enough to warrant reducing stock numbers. Some additional costs may be incurred through temporary management costs related to reduced rainfall, possibly even a little additional feed, thus profitability also reduces slightly in this time, with corresponding increase in debt (through reduced ability to service the debt), resulting in a lower ability to invest.

From year 6 to year 10 there is a further and steady decline in average rainfall per year, then a further, more significant reduction in years 11-12, before average rainfall then plateaus and remains consistent but at a much lower level. Through this time there is a corresponding decline in soil moisture, pasture and available feed, with all of these tracking alongside each other fairly closely.

Profitability continues to decline from year 6 to 7 as the same management practices tend to be followed, likely incurring additional costs. Around year 7 a decision is made to cull some animals to a level sustainable with the available feed. This brings profitability back into balance reduces debt with a step down due to the income generated from the animals. This also results in a corresponding increase in the ability to invest.

Profitability remains steady for a few years but the rainfall, soil moisture, pasture and available feed continue to decline. Eventually the stock numbers come under pressure again around year 10 and this is when additional costs are likely to be incurred again, profitability will come under pressure and debt is likely to again begin to trend upwards. Ability to invest begins to decline again.

This trend carries on for a couple of years then another major cull decision is made around year 12. As before this results in profitability coming back into balance, a drop in debt (from sales) and a corresponding increase in the ability to invest.

Coincidentally, this is around when the climatic and environmental conditions begin coming into a new equilibrium, so from here the farm system returns to a relatively stable pattern. Yet it now maintains a much lower level of stock, achieves lower profitability, has a much lower ability to invest but is carrying a relatively similar level of debt.

9.2.3.2 Exploring possible futures – stock farm with management practice change to retain soil moisture

This second example begins with the same variables beginning at the same relative amounts on the Y axis. In addition, one variable is added which is the variable described in the diagram as Land management practices that build soil moisture retention. This is shown as a purple line and begins at a relatively low level. In this example, there is a conscious decision to build the practices before they are required – this may include crop or cultivar selection, or land management practices such as low or no tillage. That is, investment in them begins while climatic conditions are relatively ‘normal’ and consistent (the first few years of this exploration), as a means of proactively adapting to an anticipated drier future.

In this example the first three years remain fairly stable from a climatic point of view. During this time there is a slowly increasing level of implementation of land management practices that build soil moisture retention. Correspondingly, there is a minor increase in soil moisture, pasture and available feed, from the same effective rainfall. There is also a slight decrease in profitability as this investment is made and on-farm changes are made. As a result, debt levels and the ability to invest remain fairly flat, due to debt not being paid down as actively.

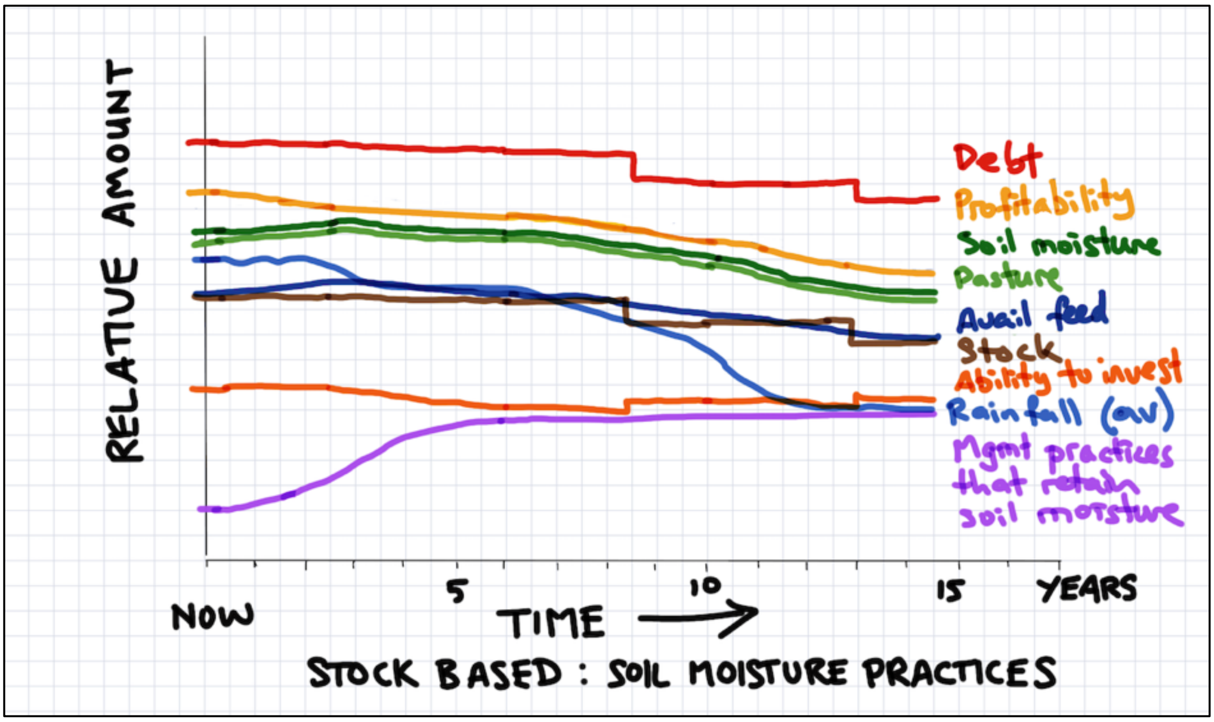
As before, in year 3 the average rainfall declines and them remains consistent until around year 6. At this point a key difference between this graph and the previous graph begins to present – while soil moisture, pasture and available feed remain closely correlated to each other, they no longer track average rainfall quite so closely.

In this hypothetical example the actual relationship here would depend on many factors including farm practices and the soil profile of the area. The intent of this exercise is to plot the possible impacts of the causal loops identified in the system diagram. In this case, increasing land management practices that build soil moisture retention do not disconnect soil moisture and available feed from rainfall, but they are likely to reduce the extent to which changes in rainfall present as in changes in available feed within a short period of time.

Therefore, from year 3-6 soil moisture, pasture and available feed remain constant under the new reduced but constant average rainfall conditions. The important difference here to the previous example is that a slightly higher level of soil moisture and pasture is the result. This helps to keep profitability, debt and ability to invest relatively stable.

From years 6 to 10 rainfall then declines again, and then even more so through years 11 and 12, before becoming consistent again at a much lower level.

Figure 32. Exploring possible futures – stock farm with management practice change to retain soil moisture



It is here that the benefit of the change of land management practices begins to become more evident. The soil moisture, pasture and available feed continue to decline, but not at the same rate that the average rainfall does. Therefore, providing the capacity to maintain a more consistent level of stock.

This does not mean there is no culling of stock, but this tends to occur a little later than in the previous BAU example, and is not as dramatic. This also means that while overall profitability may still be impacted, the total levels of debt and the ability to invest are not impacted as much, as by now the farm system is accommodating the previously additional costs of the change in land management practices.

While this is a hypothetical example, the plausible impact of the feedback loops that drove land management practice change (within broadly the same landuse) can be appreciated. They resulted in a significant dampening effect on the impacts of the drought that was experienced and have enabled the landuse to continue with necessary, but managed impacts on profitability and debt.

10 Conclusion

As climate change unfolds the interacting dynamics between temperature, rainfall and evaporation will increase the frequency and intensity of drought. This will alter how much water is flowing through the system and when. This implies the need to explore opportunities and options for changing practices/investments that can both proceed towards adaptation yet, importantly, safeguard against maladaptive responses. The water cycle system diagram developed in this report brings a systemic awareness to this undertaking.

Its development through a participant research process has enabled the consideration of interactions and interdependencies between ways in which water is used in the region and the implications of those for drought adaptation in the Waikato. The methodological approach offered a way of understanding the core ways that different elements within the wider system have an impact on each other. As a conceptual tool, it makes explicit the pressures that exist and determines the ways they often oppose each other

It provides a useful tool to begin investigating opportunities for adapting to drought from a vantage point at the interface of different disciplines and areas of operating practice. This perspective clarifies the multifunctional character of the demands on the water cycle and can assist decision makers to gain insight into the different levers of influence that are important for adapting to drought, as well as those that are less so.

The diagram is useful for promoting understanding with different audiences. It helps make explicit shared risks and adaptive opportunities and how these may develop over time and between different sectors at different scales.

Adaptation is essentially a local activity. The water cycle system diagram is a useful tool that can be used to explore potential futures under different adaptive management options at local and regional scales. It can also be used to explore specific issues in ways that can clarify the inter-relational dynamics of adaptive responses and facilitate recognition of regional adaptation opportunties and potential policy levers. It is also a synthesis tool that can provide a wide lens to complement other detailed analyses or models.

Further phases of Adapting to drought in the Waikato project are planned. It is anticipated that the next phase will:

1. Assess adaptation options for regional resilience by providing benefit cost analysis of options identified through an internal process for reducing exposure to drought impacts and building adaptive capacity in the Waikato
2. Investigate private adaptation behaviour changes that can be enabled for implementing an adaptive pathway for regional resilience to drought/water shortage.

11 References

Adams-Hutcheson G, White I, Glavovic B, Lawrence J 2019. Fit-for-purpose resilience in Aotearoa New Zealand: Challenges and recommendations. Report for the National Science Challenge: Resilience to Nature's Challenges, University of Waikato, New Zealand. Hamilton, University of Waikato.

Adger WN 2003. Social capital, collective action, and adaptation to climate change. Economic Geography 79(4): 387-404.

Alston, M, Clark, J, Whittenbury K. 2018. Limits to adaptation: Reducing irrigation water in the Murray -Darling Basin dairy communities. Journal of Rural Studies 58: 93-101.

Blomkamp E 2021. Systemic design practice for participatory policymaking. Policy Design and Practice, DOI: 10.1080/25741292.2021.1887576

Burton R, Peoples S 2008. Learning from past adaptations to extreme climatic events: A case study of drought, Part A Summary Report, Ag research, MAF – Climate Change. https://www.biosecurity.govt.nz/dmsdocument/6997/direct [accessed 24/06/20].

Cameron M, Barrett P, Cochrane B, McNeil K 2008. Implications of agricultural change in the Waikato region: Current trends and future scenarios. Environment Waikato Technical Report 2009/28. Hamilton, Waikato Regional Council (Environment Waikato).

Clark A, Mullan B, Porteous A 2011. Scenarios of regional drought under climate change. Prepared for the Ministry of Agriculture and Forestry by the National Institute of Water and Atmospheric Research. Wellington, NIWA.

Climate Change Commission 2021a. He Pou a Rangi: Draft advice for consultation. Wellington, New Zealand Government.

Climate Change Commission 2021b. Inaia tonu nei: A low emissions future for Aotearoa. Wellington, New Zealand Government.

Cradock-Henry NA, Buelow F, Fountain J 2019. Social-ecological inventory in a postdisaster context: The 2016 Kaikoura earthquake, Aotearoa-New Zealand. Ecology and Society 24(3).

Cradock-Henry NA, Flood S, Buelow F, Blackett P 2019. Adaptation knowledge for New Zealand primary industries: Known, not known and needed. Climate Risk Management 25: 100190

Cradock-Henry NA, Blackett P, Hall M, Johnstone P, Teixeira E, Wreford A 2020. Climate adaptation pathways for agriculture: Insights from a participatory process. Environmental Science and Policy 107: 66-79.

Cradock-Henry NA 2021. Linking the social, economic, and agroecological: A resilience framework for dairy farming. Ecology and Society. 26(1):3.

Cradock-Henry NA, Frame B 2021a. Balancing scales: Enhancing local applications of adaptation pathways. Environmental Science and Policy 121: 42-48.

Cradock-Henry NA, Frame B 2021b. Advancing relevance, credibility, legitimacy and effectiveness as a heuristic for local-parallel scenarios. Frontiers in Climate, 02 July 2021. https://doi.org/10.3389/fclim.2021.705229.

Cullen R, Hughey KFD, Kerr GN 2006. New Zealand freshwater management and agricultural impacts. Australian Journal of Agricultural and Resource Economics. 50: 327-346.

Diaz H, Hurlbert M, Warren J. 2016. Vulnerability and adaptation to drought on the Canadian Prairies. Calgary, University of Calgary Press.

Frame DJ, Rosier SM, Noy I, Harrington LJ, Carey-Smith T, Sparrow SN, Stone DA, Dean SM 2020. Climate change attribution and the economic costs of extreme weather events: A study on damages from extreme rainfall and drought. Climate Change 162: 781-797.

Freire-González J, Decker C, Hall JW 2017. The economic impacts of droughts: A framework for Analysis. Ecological Economics 132: 196-203.

Grafton R, Williams J, Perry C, Molle F, Ringler C, Steduto P, Udall B, Wheeler S, Wang Y, Garrick D, Allen R 2018. The paradox of irrigation efficiency. Science, 24, 361(6404): 748-750.

Grainger S, Murphy C, Vicente-Serrano SM 2021. Barriers and opportunities for actionable knowledge production in drought risk management: Embracing the frontiers of co-production. Frontiers in Environmental Science 9. https://doi.org/10.3389/fenvs.2021.602128

Hagenlocher MMI, Andersen C, Min A, Renaud F, Walz Y, Siebert S, Sebesvari Z 2019. Drought vulnerability and risk assessments: State of the art, persistent gaps and research agenda, Environmental Research Letters, Letter 14, 083002 (uni-goettingen.de). [accessed 16/06/21].

Harrington lJ Rosier S, Dean SM, Stuart S, Scahill A 2014. The role of anthropogenic climate change in the 2013 drought over North Island, New Zealand: Explaining extremes of 2013 from a climate perspective. Special supplement of the American Meterological Society 95: S45-S48.

Kamber G, McDonald C, Price G 2013. Drying out: Investigating the economic effects of drought in New Zealand. Reserve Bank of New Zealand Analytical Note series AN2013/02. Wellington, Reserve Bank of New Zealand.

Keenan B 2018. A freshwater strategy of the Waikato region, Making sense of the Waikato economy. Making Sense of the Waikato Economy | Campaign Monitor (createsend.com) [accessed 28/04/21].

Kenny G. 2001. Climate change: Likely impacts on New Zealand agriculture: A report prepared for the Ministry of the Environment as part of the New Zealand Climate Change Programme. Ministry of the Environment, Wellington, New Zealand.

Knight C. 2020. Nature and wellbeing in Aotearoa New Zealand: Exploring the connection. Ashurst, New Zealand, Totara Press.

Knothe B. 2011. Searching for meaning: Intersubjective dimensions in environmental policies. In: Altvater E. Brunnengräber A. (eds) After Cancún. VS Verlag für Sozialwissenschaften. https://doi.org/10.1007/978-3-531-94018-2_9.

Levente T, Apatov E 2020. A growing problem: Exploring livestock farm resilience to droughts in unit record data. Motu Working Paper 20-14. Wellington, Motu.

Manaaki Whenua 2021. Soils portal. The state of New Zealand soils » New Zealand Soils Portal (landcareresearch.co.nz) [accessed 26/02/21].

McKinsey & Company 2009. Charting our water future: Economic frameworks to inform decision-making. IWMI Research Reports H042499. Columbo, Sri Lanka, International Water Management Institute.

Meinke H, Howden SM, Struik PC, Nelson R, Rodriguez D, Chapman SC. 2009. Adaptation science for agriculture and natural resource management – urgency and theoretical basis. Science Direct, 1:69-76.

Melyukhina O 2011. Risk management in agriculture in New Zealand. OECD Food, Agriculture and Fisheries Papers No. 42. Paris, OECD Publishing. http://dx.doi.org/10.1787/5kgj0d3vzcth-en

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz ZW, Lettenmaier DP, Stouffer RJ 2008. Stationarity Is dead: Whither water management? Science 319: 573–574. https://doi.org/10.1126/science.1151915

Ministry of Agriculture and Fisheries. 2009. Regional and national impacts of the 2007–2008 drought. Wellington, Ministry of Agriculture and Fisheries.

Ministry for Business, Innovation and Employment 2021. Regional economic activity web tool. Wellington, MBIE. Regional economic activity report (mbie.govt.nz) [accessed 16 July 2021].

Ministry for the Environment 2020a. National climate change risk assessment for Aotearoa New Zealand: Main report – Arotakenga Tūraru mō te Huringa Āhuarangi o Āotearoa: Pūrongo whakatōpū. Wellington: Ministry for the Environment.

Ministry for the Environment 2020b. Our atmosphere and climate 2020. Our atmosphere and climate 2020 | Ministry for the Environment [accessed 13/05/21].

Ministry of Primary Industries n.d. Climate change: The impact of drier conditions on primary sector production. https://www.mpi.govt.nz/dmsdocument/40953-Dry-conditions-and-primary-production-70-year-view [accessed 27/08/21].

Ministry of Primary Industries 2013. The 2012-13 drought: An assessment and historical perspective. Technical Paper No: 2012/18. Prepared by NIWA. https://www.mpi.govt.nz/dmsdocument/135-The-2012-13-drought-an-assessment-and-historical-perspective [accessed 9/09/20].

Ministry of Primary Industries Sustainable Land Management and Climate Change Fund 2017. Adapting to climate change: Information for the New Zealand food system https://www.mpi.govt.nz/dmsdocument/28164/direct [accessed 10/09/20].

Ministry of Primary Industries 2020. Climate change research for agriculture. Climate Cloud. Climate Cloud | Climate change research for agriculture [accessed 23/10/20].

Moser S, Ekstrom J. 2010 A framework to diagnose barriers to climate change adaptation. Proceedings of the National Academy of Sciences, Dec 21, 107 (51) A framework to diagnose barriers to climate change adaptation | PNAS. [accessed 03/04/20].

New Zealand Productivity Commission 2012. Local government regulatory performance: Issue paper. Issues-paper-Towards-better-regulation.pdf (productivity.govt.nz) [accessed 12/07/20]

National Institute for Water and Atmospheric Research n.d. Drought in a changing climate. https://niwa.co.nz/sites/niwa.co.nz/files/sites/default/files/drought_in_a_changing_climate.pdf [accessed 23/07/20].

Ostrom E. 2009. A general framework for analysing sustainability of social-ecological systems. Science, 325: 419-422. https://doi.org/10.1126/science.1172133.

Petersen T, Saft M, Peel M, John A 2021. Watersheds may not recover from drought. Science 372: 745-749.

Pittock, A, Jones R. 2000. Adaptation to what and why. Environmental Monitoring and Assessment 61: 9-35.

Resource Management Review Panel 2020. New directions for resource management in New Zealand. New directions for resource management in New Zealand | Ministry for the Environment [accessed 5/03/21].

Russell S, Frame B, 2011. From old problems to new solutions. In: Russel S, Frame B, Lennox J. eds. Old problems, new solutions: Integrative research supporting natural resource governance. Lincoln NZ. Manaaki Whenua Press.

Salinger MJ, Renwick J, Behrens E, Mullan AB, Diamond HJ, Sirguey P, Smith RO, Trought MCT, Alexander L, Cullen NJ, Fitzharris BB, Hephurn CD, Parker AK, Sutton PJ 2019. The unprecedented coupled ocean-atmosphere summer heatwave in the New Zealand region 2017/18: Drivers, mechanisms and impacts. Environmental Research Letters 14(4), 004023. https://doi.org/10.1088/1748-9326/ab012a

Salinger MJ, Diamond HJ, Behrens E, Fernandez D, Fitzharris BB, Herold N, Johnstone P, Kerckhoffs H, Mullan AB, Parker AK, Renwick J, Scofield C, Siano A, Smith RO, South PM, Sutton PJ, Teixeira E, Thomsen MS, Trought MCT 2020. Unparalleled coupled ocean-atmosphere summer heatwaves in the New Zealand region: drivers, mechanisms and impacts. Climatic Change 162: 485-506 https://doi.org/10.1007/s10584-020-02730-5

Senge PM 2006. The fifth discipline: The art and practice of the learning organization. 2nd ed. London, Random House.

Schullehner J, Hansen B, Thygesen M, Pedersen CB, Sigsgaard T 2018. Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. International Journal of Cancer 2018 143(1):73-79. doi: 10.1002/ijc.31306. Epub 2018 Feb 23. PMID: 29435982.

Sivapalan M, Savenije HHG, Bloschl G 2012. Socio-hydrology: A new science of people and water. Hydrological Processes 26:1270–1276. doi:10.1002/hyp.8426.

Smit B, Burton I, Klein RJT, Street R 1999. The science of adaptation: A framework for assessment. Mitigation and Adaptation Strategies for Global Change 4: 199–213.

Smit B, Wandel J 2006 Adaptation, adaptive capacity and vulnerability. Global Environmental Change. 16: 282-292.

Stafford Smith M, Horrocks L, Harvey A, Hamilton C 2011. Rethinking adaptation for a 4C World. In: Philosophical transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 369: 196-216.

Statistics New Zealand 2021. New Zealand is getting drier. New Zealand is getting drier | Stats NZ [accessed 19/05/21].

Sterman JD 2000. Business dynamics: Systems thinking and modelling for a complex world. New York, NY, McGraw-Hill.

Stern NH 2007 The economics of climate change: The Stern review. Cambridge, UK, Cambridge University Press.

Stroombergen A, Tait A, Patterson K, Renwick J 2006. The relationship between New Zealand's climate, energy, and the economy to 2025. Kōtuitui: New Zealand Journal of Social Sciences Online, Vol. 1: 139–160.

Swarbrick N 2015. Waikato places – Waikato River, Te Ara. The Encyclopedia of New Zealand. http://www.TeAra.govt.nz/en/waikato-places/page-1. [accessed 18/03/21].

Te Aho, L 2018. Te Mana o te Wai: An indigenous perspective on rivers and river management. River and Research Applications. Special Issue. **https://doi.org/10.1002/rra.3365**

Treasury 2013. Budget economic and fiscal update. Wellington, New Zealand Treasury. 17-18.

Van Duinen R, Filatova T, Geurts P, Van der Veen A 2015. Coping with drought risk: Empirical analysis of farmers drought adaptation in the south-west Netherlands. Regional Environmental Change 15: 1081-1093.

Van Loon A 2015. Hydrological drought explained. WIREs Water, 14 April 2015. doi: 10.1002/wat2.1085.

Waikato Regional Council (Environment Waikato) 2008. The condition of rural water and soil in the Waikato region: Risks and opportunities. Hamilton, Waikato Regional Council (Environment Waikato).

Waikato Regional Council 2012. Waikato Regional Plan: Variation 6 - Water allocation, operative (10 April 2012). Hamilton, Waikato Regional Council. 82.

Waikato Regional Council 2020. Climate action roadmap: A discussion. Waikato Regional Council Policy Series 2020/19. Hamilton, Waikato Regional Council.

Waikato Regional Council 2021. Drought resource for Waikato farmers. Waikato Regional Council Policy Series 2021/05. Hamilton, Waikato Regional Council.

Ward P, de Ruiter MC, Mard J, Schroter K, Van Loon A, Veldkamp T, von Uexkull N, Wanders N, AghaKouchak A, Arnbjerg-Nielsen K, Capewell L, Llasat MC, Day R, Dewals B, Di Baldassarre G, Huning LS, Kreibich H, Mazzoleni M, Savelli E, Teutschbein C, van den Berg H, van der Heijden A, Vincken JMR, Waterloo MJ, Wens M 2020, The need to integrate flood and drought disaster risk reduction strategies. Water Security, 11: 10070.

Welsh L, Endter-Wada J, Downard R, Kettenring K 2013. Developing adaptive capacity to droughts: The rationality of locality. Ecology and Society 18(2).

Wittwer G, Waschik R 2021. Estimating the economic impacts of the 2017-2019 drought and 2019-2020 bushfires on regional NSW and the rest of Australia. The Australian Journal of Agricultural and Resource Economics. https://doi.org/10.1111/1467-8489.12441

Yezdani O, Sanzogni L, Poropat A 2015. Theory of emergence: Introducing a model-centred approach to applied social science research. Prometheus, 33(3): 305-322.

Young R, Smart G, Harding J 2004. Impacts of hydro dams, irrigation schemes and river control works. In: Harding J, Mosley P, Pearson C, Sorrell B eds. Freshwaters of New Zealand. Christchurch, New Zealand Hydrological Society.

Appendix 1: The fundamentals of system diagrams – articulating system structure

At the core of a system diagram is the desire to visually articulate the relationships between causal variables that best explain the behaviour of the system that you are trying to understand. This visual articulation of relationship is known as 'system structure'.

This section outlines important fundamental elements of system structure. These are:

- feedback loops;
- how feedback loops are correctly annotated; and
- the use of the 'goal/gap' structure (as this can explain how different loops dominant in a system at different times).

It is recommended that the reader familiarise themselves with these concepts, as an understanding of them is required to read the system diagrams in this report and gain insight from them.

A1 Feedback loops – the basic building blocks of a system diagram

Systems thinking focuses on moving away from thinking of causality as *linear* to *circular*. That is, a linear way of thinking about causality might be that A influences B, whereas a circular way of thinking about causality might be that A influences B, and then B influences A. This means the causality 'feeds back', so where this is identified it is known as *feedback loops*. There are two types of feedback loops, *reinforcing* and *balancing* (Senge, 1990).

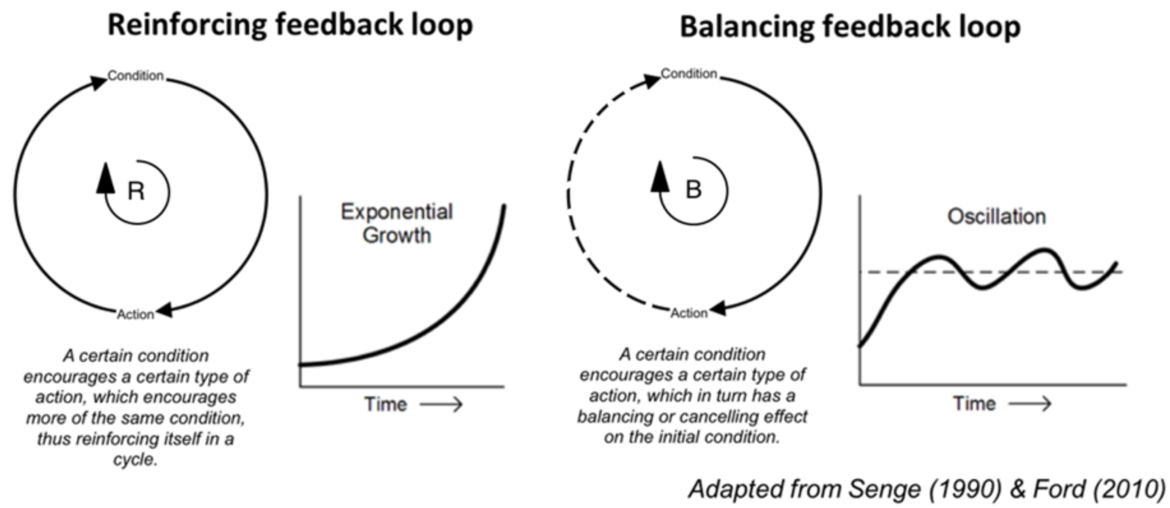
Figure 33. Moving from linear to circular causality

In a *reinforcing feedback loop*, the direction of influence provided by one factor to another will transfer around the loop and influence back on the originating factor in the *same* direction. This has the effect of *reinforcing* the direction of the original influence, and any change will build on itself and amplify. ***Reinforcing loops are what drive growth or decline within a system.***

In a *balancing feedback loop*, the direction of influence provided by one factor to another will transfer around the loop through that one factor (or series of factors) and influence back on the originating factor in the *opposite* direction. This has the effect of *balancing out* the direction of the original influence. **Balancing loops are what create *control, restraint or resistance* within a system**.

The two types of feedback loop are described in Figure 34.

Figure 34. The two types of feedback loops



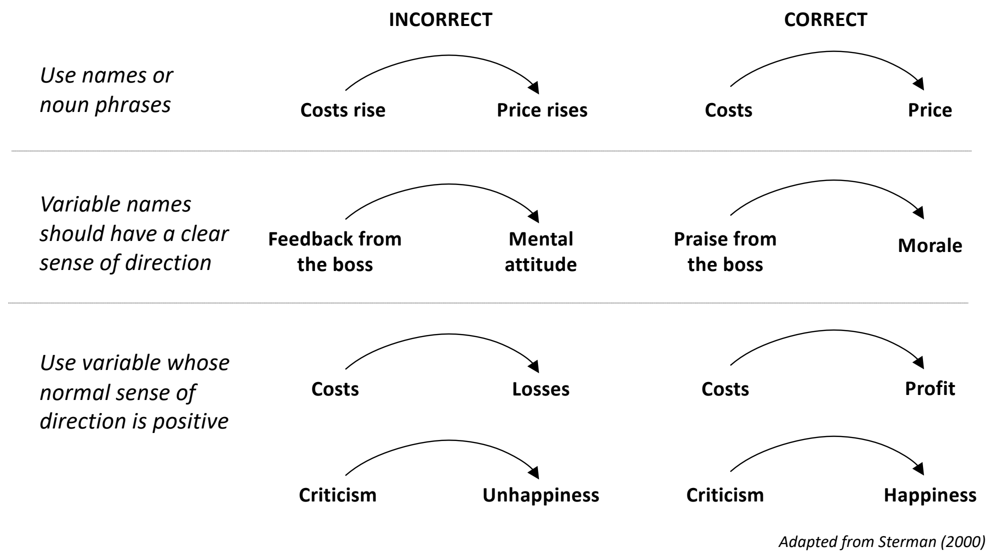
Feedback loops can be made up of more than two variables and can be mapped together to form a system diagram). How these interact provide insight into how a wider system operates.

A2 Labelling variables

An important concept within system diagrams is the concept of accumulation (or decumulation) – where do things build-up (or decrease) in your system? The simple analogy of a bathtub is often used to describe this (for more on this see *'Stock and flow notation'* in this appendix).

In system diagrams, this concept of accumulation is captured by describing variables in such a way that their name implies that they can *increase or decrease*. This means that they should be described as *nouns*; have a clear sense of *direction*; and have a normal sense of direction that is *positive*. Examples to demonstrate this are shown in Figure 35.

Figure 35. Labelling variables



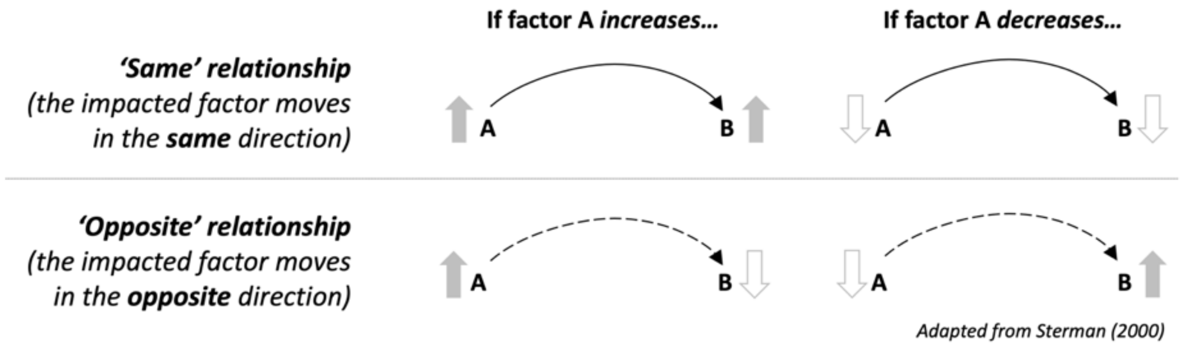
A3 Annotating loops

Variables within system diagrams are connected (and made into feedback loops) by arrows, which indicate that one factor has a causal relationship with the next. **'Same'** arrows are drawn with a **solid**

line, while **'opposite'** arrows are drawn with a **dashed line**. These terms correspond to the direction of change that any change in the first variable will have on the second variable.

For example, if a directional change in one variable leads to a directional change in the next variable in the *same direction*, it is a *same relationship*. Likewise, if the second variable changes in the *opposite direction*, it is an *opposite relationship*. See Figure 36 for a visual description.

Figure 36. How arrows are labelled in system diagrams



If there is a notable *delay* in this influence presenting in the second variable, when compared to the other influences described in the system diagram, this is annotated as a *double line crossing the arrow*. An example of this is shown in Figure 37.

Figure 37. How delays are annotated on arrows

A4 Goals and gaps – driving individual loop dominance.

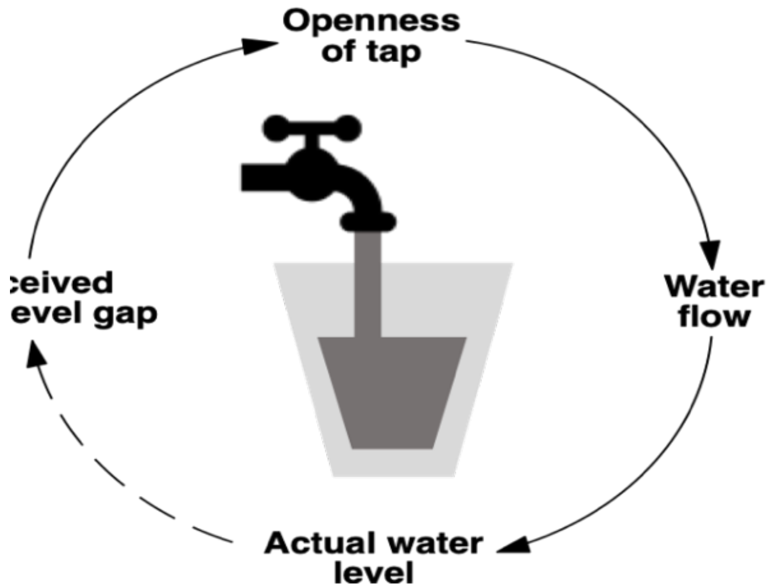
Realising that multiple loops are operating within a system is the first useful insight of systems thinking. A further useful insight is understanding that not all loops operate at the same strength all of the time. Different loops can dominate the dynamics of a system at different times. For example, a system might be dominated by a period of growth (a reinforcing loop), but when a physical limit is approached (e.g. the available space in a pond for algae to grow) a balancing loop will start to dominate, therefore slowing the rate of growth.

One useful mechanism for gaining insight into the strength of a balancing loop is the *'goal/gap' structure*. This is a structure that combines both a *desired level* of something (a 'goal'), with an *actual level* of something. This *difference between these variables* is the 'gap' between the desired and actual levels.

The higher the desired level and the lower the actual level, **the greater the 'gap' or difference and the stronger the operation** of the loops that this gap influences. The lower the desired level and the higher the actual level, **the lower the 'gap' or difference, and therefore the weaker the operation** of the loops that this gap influences.

The 'goal/gap' mechanism can be seen within the system diagram in this report. A conceptual example is shown in Figure 38 which shows the act of filling a glass of water.

Figure 38. Example of a 'goal/gap' structure in a system diagram – pouring a glass of water



Initially, while the *gap/difference* between the desired and actual water level is *high*, the tap will be opened more and the strength of the water flow is higher.

As the desired level of water is approached the *gap/difference reduces*, so the tap is closed further, weakening the flow of water (you don't want the water to overflow the glass), until it is fully closed when the water level reaches the desired amount (Senge, 1990).

A5 Stock and flow notation

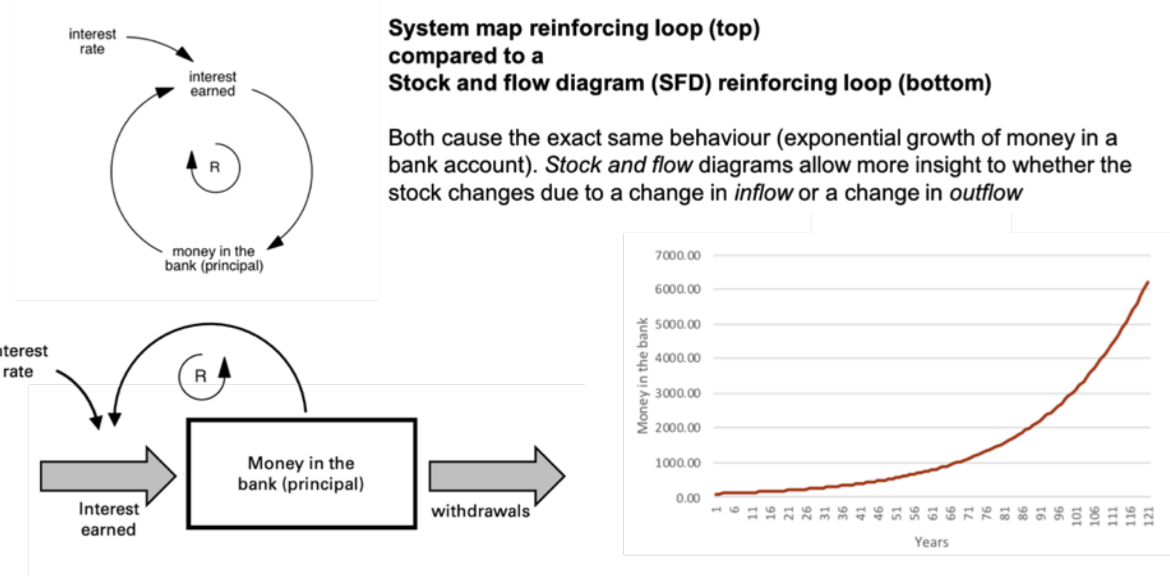
The system diagrams described in this report are made up of both variables and influence arrows as described above as well as *stock and flow notation*. While variables and influence arrows are at the core of system diagrams, because of the complexity of the flow of water through the water cycle, these are described in a more involved way. This is *stock and flow notation*, which allows a more nuanced level of insight to the behaviour of the system.

Using a stock and flow notation is like a metaphorical *bathtub* (as mentioned earlier). A stock might be anything that we are interested in – number of people, quality of water, level of morale, etc. **Stocks can ONLY increase through more inflow** (the tap over the metaphorical bathtub), **and ONLY decrease through more outflow** (the drain in the metaphorical bathtub). This applies to whatever you are interested in – just like the level of water in a bathtub. This is reflected in the diagrammatic description of a stock and flow (Figure 39**Error! Reference source not found.**).

Figure 39. Stocks and flows – the more advanced notations used in System Dynamics

Both basic system diagrams and more complicated stocks and flow diagrams explain the same type of behaviour. Yet the inclusion of stock and flow notation within a system diagram allows a greater level of insight to understand whether a change in a key variable (stock) is due to a change in *inflow* or a change in *outflow* (see Figure 40 for an example).

Figure 40. Comparison of reinforcing loops: System diagrams (causal-loop diagrams) vs. Stock and flow diagrams



Stocks and flows are the language of simulation modelling in System Dynamics. If any of these diagrams were to be developed into quantitative simulation modelling (in potential future research), then full stock and flow formulation would need to be used. This spectrum of quantitative rigour within the tools of System Dynamics is explained in the next section.

A6 How influence operates differently upstream and downstream of a change in flow

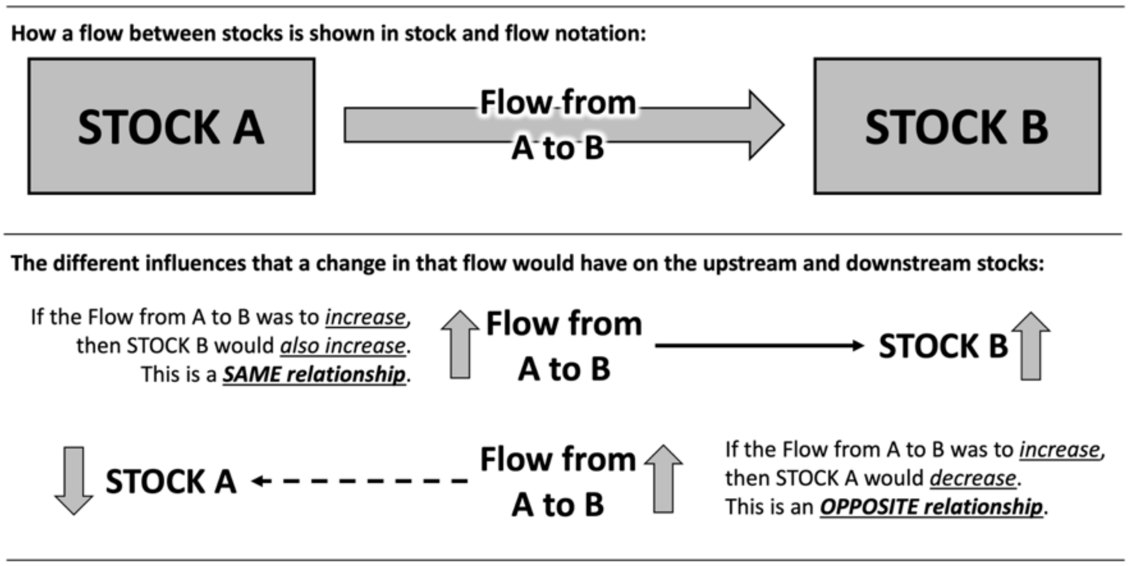
When a diagram is made up partly of variables and arrows of influence, as well as stock and flow notation (as the system diagram in this report is), then the flows themselves often form pathways of influence within feedback loops. When this occurs, the influence can be either same or opposite, depending on which way along the flow the influence is travelling.

When a flow forms part of a feedback loop and the influence is travelling ***with the flow*** (i.e. downstream), then that is a ***same influence***. That is, if the flow was to increase (or decrease), then the stock ***to which it is flowing*** would also increase (or decrease), all other things being equal.

When a flow forms part of a feedback loop and the influence is travelling ***against the flow*** (i.e. upstream), then that is an ***opposite influence***. That is, if the flow was to increase (or decrease), then the stock ***from which it is flowing*** would decrease (or increase), all other things being equal.

The flow structure and the variable/arrow influence structure are compared below in Figure 41Figure 41. Where flow form part of notable feedback loops that are discussed in this report, the influence direction has also been noted.

Figure 41. How influence operates differently upstream and downstream of a change in flow



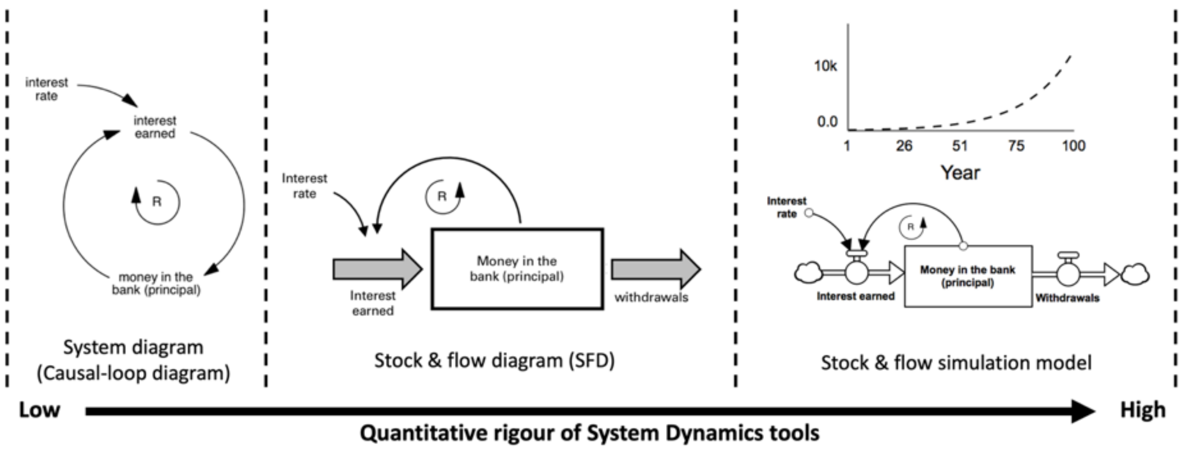
A7 How system diagrams can be used

This section briefly outlines how system diagrams themselves fit within a spectrum of complexity in the discipline of System Dynamics, and how they may be used in conjunction with other methodological approaches.

A7.1. System diagrams on the spectrum of complexity within System Dynamics

The tools of System Dynamics themselves exist on a spectrum of quantitative rigour. These are shown in Figure 42**Error! Reference source not found.** which highlights how these varying tools can d emonstrate the same system, each being able to demonstrate the complexity if that system, yet to differing levels of quantitative rigour, or robustness. This spectrum is also intended to highlight that system diagrams are not the only possible output from the use of SD tools.

Figure 42. System Dynamics tools exist on a spectrum - System diagrams (or Causal loop diagrams), Stock and flow diagrams, and Simulation modelling.



System diagrams as developed here, exist at the conceptual (low quantitative rigour) end of this spectrum. These can range from using the simple dynamics of a single feedback loop to demonstrate a type of behaviour, to multiple loop systems (as in this report) – which can demonstrate the high level of complexity of a system.

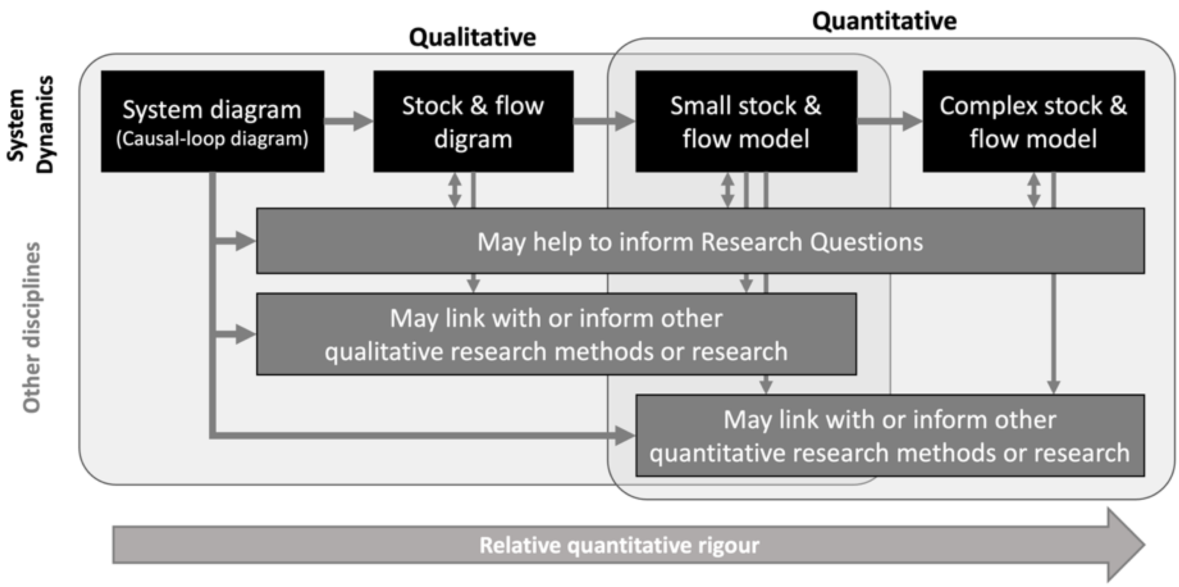
The next step up in quantitative rigour are Stock and Flow Diagrams (SFD). While *water flows and stocks* are represented in the diagrams within this report using stock and flow notation, these diagrams are not considered complete of 'full' SFD. This is because SFD usually contain multiple stocks of interest, not just the focal variables. Although not all factors need to be stocks, their architecture tends to represent a greater level of mathematical functionality (although this may not actually be computed). This is because SFD tend to be qualitative representations of the actual functions and equations that would be represented in a stock and flow model. This level of detail has not been achieved in this report.

Computer simulation modelling (based on the stock and flow formulation) is the next step in quantitative rigour – that is, turning stock and flow diagrams into simulation models. There is huge variability in the types of simulation models that can be developed, with some people advocating that large system insights can be gained from using small scale models (Meadows, 2008), to others demonstrating the utility of large scale and highly complex simulation models (Sterman, 2000).

A7.2. How system diagrams may link with other methodological approaches

While system diagramming may result in complex stock and flow diagrams and/or simulation modelling within System Dynamics, it may also link with or inform other methodological approaches within a wider research project. A diagram outlining how this can work is shown below in Figure 43.

Figure 43. How system diagramming can link with other research methodologies



Note: There is an overlap of the qualitative and quantitative areas of application because they are not mutually exclusive. For example, some quantitative relationships in models and their calculations may be informed by research or data, while others may be informed or assumed via some form of participatory process.

The series of *black boxes* across the top of the diagram in Figure 43 represent the increasing quantitative rigour of the System Dynamics tools. The *grey boxes* in the lower part of the diagram represent the research questions that may be generated during research, as well as the different qualitative and quantitative methods that may be employed within the research. All of these may be informed by the system diagramming process, or a more rigorous evolution of a system diagram (for example a small stock & flow model).

For example, a system diagram may provide insight to the nature of relationships within the system that may inform how a research question is framed. It may also inform the types of people who might be involved (as researchers or as research subjects). Further, the nature of the relationships elicited throughout the system diagramming process could also inform other research methods – either qualitative or quantitative – that may be used.

Please note that our position here is that more precise numerical measures tend to give systems theorists the opportunity to specify more precise relationships and thus add layers of quantitative rigour to their models. Yet highly complex systems need not only be represented with tools of high quantitative rigour – these can be articulated with the qualitative tools also, as in this report. In fact, in complex worlds, qualitative methods are more likely to capture complexity and make it available for analysis. In complex worlds, systems thinking and causal mapping may be used as a decision-support tool that enables a more holistic view of inter-relationships that may otherwise be missed or excluded from reductionist analyses (Senge, 2006).