Parliamentary Commissioner for the Environment

Conceptualising environmental risks associated with the extraction, processing, use, and disposal of natural resources

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Report by:

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Acknowledgements:

This work would not have been possible without a range of selected experts agreeing to be involved in the process. They represented a range of specialties with knowledge in nutrient losses, habitat loss, GHG emissions, plastic pollution, chemical releases, particulate matter and solid waste. Some experts were able to attend all sessions while some were only able to attend some sessions. All their contributions informed the thinking that is captured in this report and the contribution of their time is gratefully acknowledged. The report is, however, the authors interpretation of the expert's knowledge and therefore any potential shortcomings, omissions or errors lie with the report authors.

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Executive summary

The Parliamentary Commissioner for the Environment (PCE) has a programme of work underway on natural resource use and waste generation in the New Zealand economy.

The PCE's wider work programme includes a major focus on improving the understanding of natural resource flows in economic production and consumption. However, establishing the size of individual resource flows and associated waste generation is not necessarily an end in and of itself. What also matters are the environmental risks associated with ever-increasing levels of resource extraction and use: a deterioration in the availability or quality of remaining resource stocks, the generation (and accumulation) of a wide range of potentially harmful pollutants, and deterioration of local ecosystems where the resources are.

This report has the specific aim of helping to improve the PCE's understanding of the second issue: the key environmental risks associated with the extraction, processing, use, and disposal of natural resources (and the products that contain them). It seeks to conceptualise and articulate the impacts that can be reasonably anticipated from the continued and increased flow of resources through the economic value chain and the subsequent accumulations of pollution and waste in the environment. It does not seek to quantify specific details, volumes, or risks. It provides a framework for thinking about these potential risks and helps guide future precautionary studies focused on potential areas of concern.

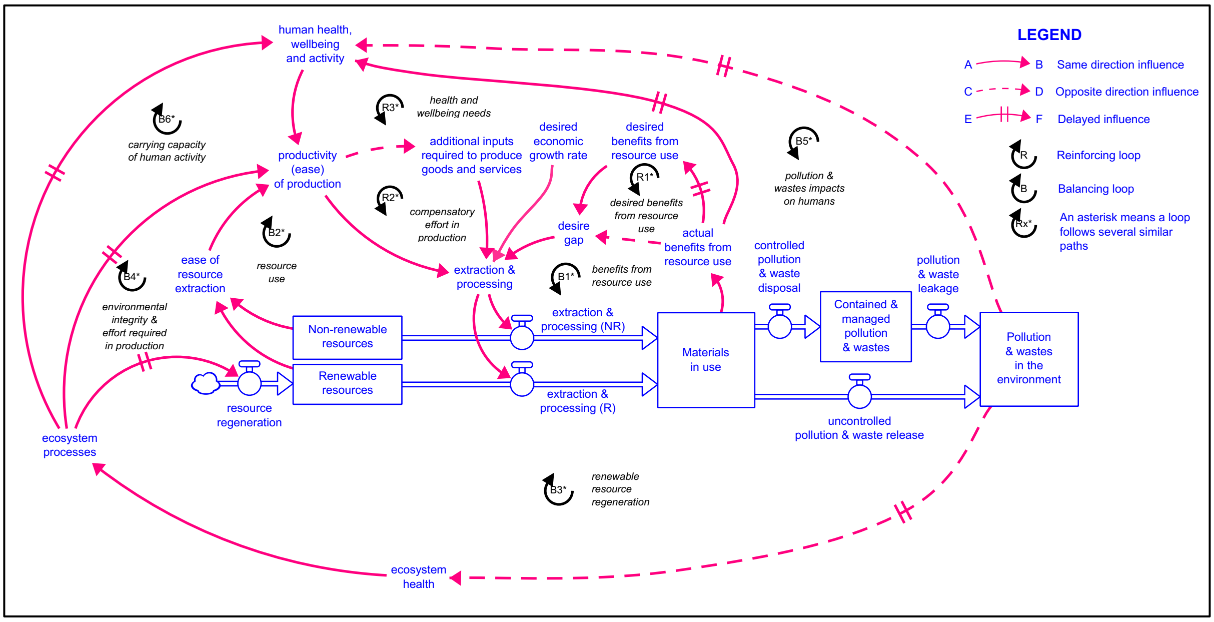
A qualitative participatory systems thinking process (drawing from the methodology of system dynamics) was used. This work was informed by expert opinion on the topic areas and synthesised by the authors. The identification of feedback loops of influence or articulating circular causality as a means of understanding behaviour dynamics, is a fundamental concept of systems thinking. This underpins the approach used in this report and is a key feature of the output diagrams.

The following diagrams were produced from this work:

- A conceptual overview diagram that articulates the main feedback pathways that influence environmental pressures and their broader impacts.
- A range of common causal structures and associated anticipated dynamics that occur across the three subject matter areas. These will also apply to many other subject matter areas so have a wider use.
- Three detailed (yet still aggregated) diagrams of resource flows and the various pathways that influence environmental pressures. These cover the following subject matter areas:
  - Plastics and the chemicals associated with them;
  - Pharmaceutical use in humans and animals; and
  - Water availability.

The overarching conceptual diagram is shown below. The three subject matter diagrams are shown in the report body.

ES Figure 1. **How resource flows create environmental pressures**



The report finds a range of generalisable insights across the three subject matter areas, some specific insights within the subject matter areas, and provides suggestions to consider moving forward.

Generalisable insights:

1. The stock/flow and feedback framing is useful for conceptualising potential and/or reasonably anticipatable environmental pressures as a result of continued resource flows through the economy.
2. Many accumulations and flows are underappreciated and not widely understood. Once they occur, many will have a limited ability to reduce or dissipate.
3. The assimilative capacity of the environment (on various scales) to absorb our pollution and waste streams will likely become a limiting factor of human activity in the longer-term. This may result in the eventual decline of human health, and/or a reduction in the size of our population that can be supported.
4. A range of common causal structures and dynamics were identified:
    a. The continued accumulations (sinks) of pollutants and wastes in the environment will negatively impact the ability of renewable resources to regenerate.
    b. Significant delays are involved in most environmental systems (likely decades or more). So, once impacts are detected, this will likely only be the start of a much larger flow-on impact that is already underway.
    c. There are limits to efficiency gains, and in some cases, these gains may induce a rebound effect and result in *more* of the resource being used. Efficiency gains can help reduce resource use (flows), but only to a point. Technical efficiency gains often result in changes in social expectations of what is possible from the more efficiently used resource, perversely resulting in *more* of the resource being used.
    d. Substituting a problematic resource for a different one could potentially have unknown and delayed impacts. While current problems may be avoided, future ones could be generated, leading to potential cumulative impacts.
    e. Human innovation may improve the capture and containment of pollution or wastes. Yet, due to potential leakages (despite best practice), these are likely to be sources of future environmental pressures in the longer term.

5. Discussions with the subject matter experts highlighted that the pollutant accumulations (sinks), and the pathways by which they may cause harm, are largely unquantified. Alternatively, these bodies of research are only beginning to be developed. The methodology used here plays an important role in conceptualising and anticipating potential issues and how they may interact. These insights can help inform where research may be focused in the future.

Insights to the specific subjects explored:

6. As chemicals from plastics and pharmaceuticals/metabolites continue to accumulate in the environment, there is an increasing risk that these may interact in novel ways that may have unexpected and undesirable effects. What these will be is difficult to anticipate and research in this area is perceived to be lacking. Environmental monitoring is always retrospective – i.e. once environmental harm can be measured, it has already occurred. This conceptual work highlights that effects can (and should) be reasonably anticipated and prompts the question as to what research may help better understand these effects.
    a. Further research may be required to assess what is known about chemicals in the environment and how they may interact with each other.
    b. Research should also be extended to help fill any of the identified knowledge gaps to ensure environmental and human harm is minimised.
7. Anecdotally, the limits of efficiency gains associated with water use and increasing demands on water through the growth of population and agricultural use, suggest that water availability will likely be an increasingly constrained resource in the future.

Suggestions for things moving forward:

This work provides a framework for thinking about potential risks from continued resource flows through Aotearoa-New Zealand. The identification of feedback loops, as a means of understanding behaviour dynamics, underpins the methodology used and has proven valuable. **Future work should build on the feedback dynamics identified**. In particular:

8. Attempts should be made to incorporate important feedback loops described in this work into future research or modelling commissioned by PCE in the wider programme of work. This may also apply to other programmes of work in the future if feedback loops are found to be relevant.
9. Consider further high-level modelling of some of the feedback loops and dynamics described in these diagrams, particularly in relation to the impact that exponential growth of resource flows will have and the likely limited impact of efficiency measures.
10. Avoid emphasising efficiency gains as a means of reducing resource use and environmental pressures. This may be informed by potential modelling as recommended above but is not dependent on it. Significant evidence to support this may also be available from a combination of this report, existing literature and expert opinion.
11. Advocate for a precautionary approach to the substitution of resources or products that are the source of current issues. This should not delay the reduction in use of such harmful resources or products, but should caution against the promotion of substitutes of which little is known, without careful consideration of how else to reduce the harmful product. The risk is that such resources or products may cause future environmental issues.
12. Consider commissioning work based on expert opinion to make informed estimates of which contaminant sinks and pathways of influence identified in this work should be better monitored. This will help build a corpus of data quantifying the conceptualised issues identified in this report.

1. Background

The Parliamentary Commissioner for the Environment (PCE) has a programme of work underway on natural resource use and waste generation in the New Zealand economy.

This work includes a major focus on improving their understanding of the quantity of natural resources that are mobilised each year in support of economic production and consumption. However, establishing the size of individual resource flows and associated waste generation is not necessarily an end in and of itself. What also matters are the environmental risks associated with ever-increasing levels of resource extraction and use: a deterioration in the availability or quality of remaining resource stocks, the generation (and accumulation) of a wide range of potentially harmful pollutants, and deterioration of local ecosystems where the resources are.

The purpose of this work and this report is to help improve the PCE's understanding of the second issue: the key environmental risks associated with the extraction, processing, use, and disposal of natural resources (and the products that contain them).

2. Introduction

In April 2024 Deliberate was contracted by the PCE to undertake the work described in this report. This work seeks to help improve the PCE's understanding of key environmental risks associated with the extraction, processing, use, and disposal of natural resources (and the products that contain them).

This work uses a participatory modelling process and is informed by expert opinion. It takes a systems thinking approach (based on the qualitative tools of the systems dynamics methodology) to create a series of diagrams that clearly illustrate the key relationships, pathways of influence and important feedback loops. While the socioeconomic influences of resource extraction and use (e.g., population and economic growth) are central to PCE's broader work programme, they are not the main focus of this contract. Having said that, factors representing both population and economic growth have been included in the diagrams developed here to help provide a useful link or gateway to/from PCE's other pieces of research across their wider work programme.

This work has developed the following diagrams. Firstly, a high-level overview diagram is intended to help frame the context of resource flows and where they accumulate (in pollution & waste sinks). Secondly, a range of conceptual diagrams that identify important dynamics and common structures that appear across multiple areas of concern. And finally, three detailed diagrams of specific subject matter areas, although still highly aggregated. These are based on the broad structure of the overview diagram and examine the following subject areas: plastics and their chemical additives; pharmaceutical use in humans and animals; and water availability for use in human activity.

The description of the diagrams in this report are supported with various examples to help illustrate the points. These are examples that were mentioned in the interviews or during the workshop with subject matter experts (see the methodology in section 3). These examples are from candid conversations with experts and represent areas of concern that may require further research – rather than definitive statements that these things occur and are current issues. Such examples are either represented within the text of the causal diagram description or are shown in green break out boxes throughout the report (see below for an example).

Descriptive examples illustrating some of the influences described are sometimes shown in green break out boxes throughout the report. These are drawn from comments by and discussions with subject matter experts during the interviews or workshops undertaken in this work. They are not cited and should be considered illustrative. Although they may suggest areas for further future research.

This report is structured as follows:

- Section 3 outlines the methodology, providing an overview of systems thinking based on the system dynamics approach, and the process following to solicit expert opinion and develop the causal diagrams.
- Section 4 provides guidance on how to read a causal diagram. This is an important section to read before reading any of the causal diagrams described in this report.
- Section 5 provides a high-level conceptual overview diagram of resource flows through Aotearoa-New Zealand. This is intended to help frame the high-level context of resource flows and the environmental pressures that result, particularly within the frame of macro feedback loops – that is, how environmental pressures influence back on resource flows.
- Section 6 outlines important structures and dynamics that are common across the detailed diagrams.
- Section 7 describes the causal diagram of plastics and associated chemical flows, as well as their potential environmental pressures and constraints.
- Section 8 describes the causal diagram of pharmaceutical flows through the environment due to use in humans and animals, as well as their potential environmental pressures and constraints.
- Section 9 describes the causal diagram of water and its flows, as well as the associated potential environmental pressures and constraints.
- The report finishes with a summary of key findings and insights (section 10) and appendices containing extra information.

3. Methodology

This section describes the systems thinking methodology and the process used to develop the diagrams.

3.1. What is systems thinking?

The world that we live in is a highly interconnected place of causality and effect. The work of governments and the public sector seeks to respond to undesirable behaviours or patterns that present in our natural environment. They seek to influence the causes of these to alter or improve the behaviours or patterns into a desirable direction.

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

Systems thinking, as articulated by system dynamics, is a conceptual framework and set of tools that have been developed to help make these patterns of interconnectedness clearer (Senge, 2006). They help us understand the structure of a set of various interacting factors that create a 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 the behaviour, allowing us to identify areas of leverage in order to influence this.

Where the term systems thinking is used in this report, it refers to the qualitative concepts articulated by the methodology of system dynamics (Sterman, 2000). The main qualitative tool that this discipline uses to understand systems is called a causal loop diagram (CLD) or a causal diagram. Throughout this report the term 'causal diagram' has been used. Further detail on how to read causal diagrams is provided in section 4 with further information about how to use causal diagrams in Appendix 2

3.2. The process of developing causal diagrams

The insights in this report were developed from a series of discussions and workshops with a selection of experts with knowledge about environmental pressures that were of interest to the PCE. A systems thinking approach was used (see previous sections) and, in particular, a participatory model-building approach based on the work of Vennix (1996) and Hovmand et al. (2013).

The participatory approach meant that workshop participants took a lead role in determining what future environmental pressures were of concern, what factors were contributing to them, and how those factors influenced each other. These deliberations resulted in the causal diagrams that are described in this report.

The process was as follows:

1. PCE identified experts who might contribute to this process and invited them to be involved. These represented a range of specialties with knowledge in nutrient losses, habitat loss, GHG emissions, plastic pollution, chemical releases, particulate matter and solid waste.
2. The authors worked with the experts on three occasions:
    a. Firstly, over an initial virtual discussion about what they thought the future pressing environmental pressures were.

b. Secondly, at an all-day workshop in Wellington, some causal diagram work by Deliberate was shared with the experts, discussed, and refined.

c. Thirdly, over a final virtual meeting to check in on some of the adjustments made since the in-person workshop.

Many pressures and interactions were discussed in the all-day workshop. From this, three areas of focus were developed. These were informed by the discussion with experts at the workshop and decided by PCE. These are the three detailed diagrams that are described in this report.

Some experts were able to attend all sessions while some were only able to attend some sessions. All their contributions informed the thinking that is captured in this report and the contribution of their time is gratefully acknowledged. The report is, however, the authors interpretation of the expert's knowledge and therefore any potential shortcomings, omissions or errors lie with the report authors.

The experts that took part are listed below:

- Dr Anne-Gaelle Ausseil, Ministry for the Environment (MfE)
- Roderick Boys, Ministry for the Environment (MfE)
- Dr Peter Dawson, Environmental Protection Authority (EPA)
- Dr Marie Doole, Mātaki Environmental
- Prof Melanie Kah, University of Auckland
- Harry Livesey, Ministry for the Environment (MfE)
- Dr Ian Longley, National Institute of Water and Atmospheric Research (NIWA)
- Dr Catherine Moore, GNS Science
- Dr Olga Pantos, Institute of Environmental Science and Research (ESR)
- Matthew Paterson, Parliamentary Commissioner for the Environment (PCE)
- Helen Sharpe, Ministry for the Environment (MfE)
- Briar Wyatt, Ministry for the Environment (MfE)

4. How to read a causal diagram

4.1. The fundamentals of causal diagrams – articulating system structure

At the core of a causal diagram is the desire to visually articulate the relationships between factors that best explain the behaviour over time (or trend) of the system that you are trying to understand. This visual articulation of relationships or influences is known as ‘system structure’.

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

- feedback loops.
- how feedback loops are correctly annotated.
- the use of the ‘goal/gap’ structure (as this can explain how different loops dominate in a system at different times).
- stock and flow notation.

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

4.1.1. Feedback loops – the basic building blocks of a causal diagram

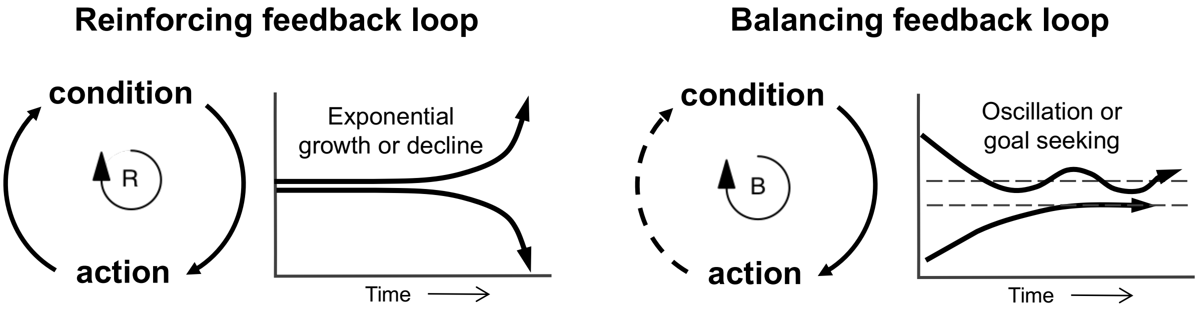
Systems thinking is especially interested in systems where loops of causality are identified – these are called feedback loops. There are two types of feedback loops: reinforcing and balancing (Senge, 2006).

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 *or spiralling* the direction of the original influence, and any change will build on itself and amplify. Reinforcing or spiralling 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 loops are described in Figure 1.

Figure 1. The two types of feedback loops



Adapted from Senge (1990) & Ford (2010)

Feedback loops can be made up of more than two factors and can be mapped together to form a causal diagram. How these loops interact provides insights into how a wider system operates and why certain behaviours or trends occur.

When a loop label includes an asterisk, this indicates that the loop incorporates several pathways that are similar enough to be labelled as one, for ease of reading the diagram. For example, see loops B1* and R1* in the Overview diagram section (section 5).

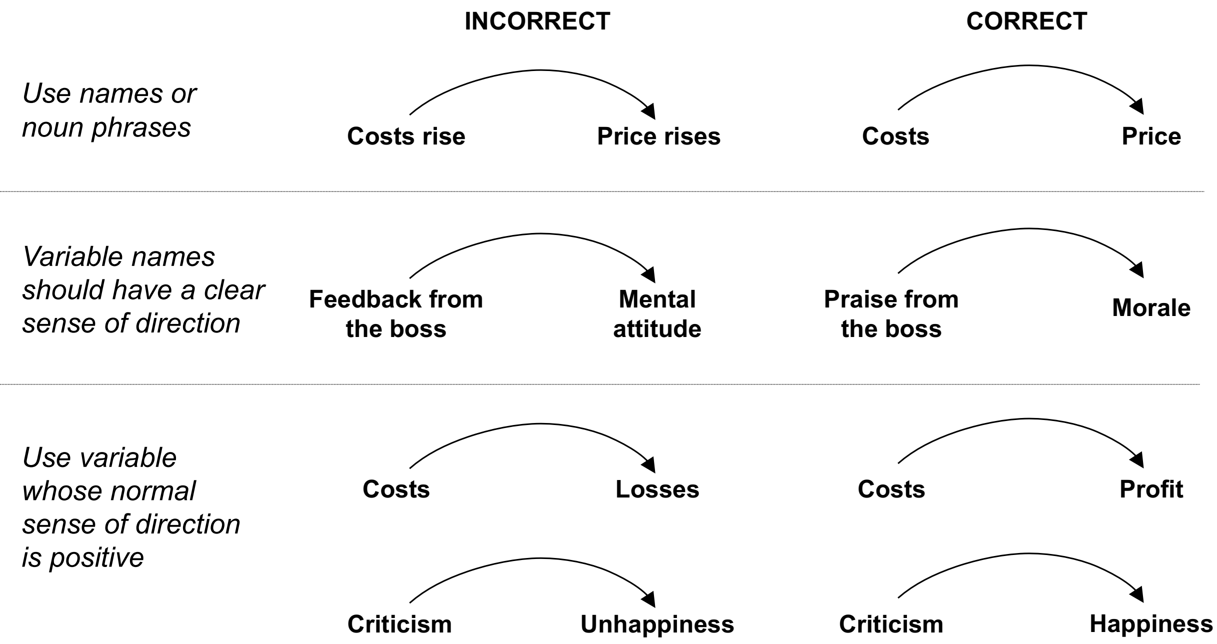
When feedback loops are described in this report, they describe the feedback loop operating by itself only. In other words, this describes their dynamics – all other things being equal. In reality the behaviour over time presented by the systems described in this report will be the result of all the feedback loops operating together.

4.1.2. Labelling factors

An important concept within causal 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 causal diagrams, this concept of accumulation is captured by describing factors 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 2.

Figure 2. Labelling factors



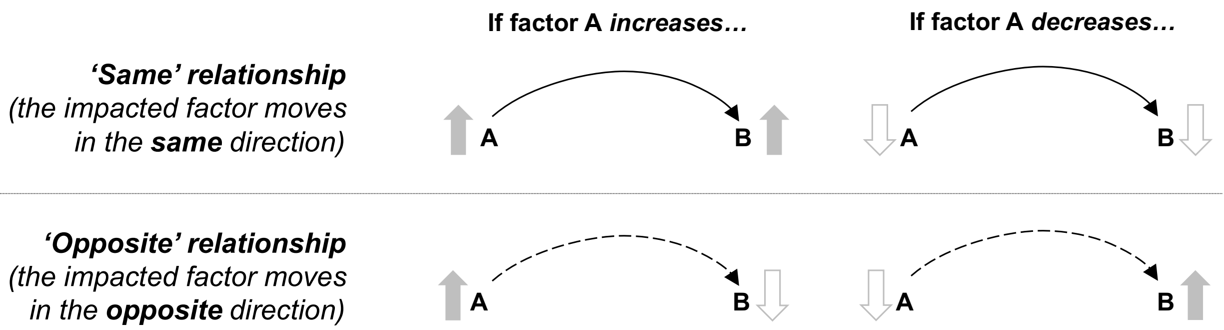
Adapted from Sterman (2000)

4.1.3. Annotating loops

Factors within causal diagrams are connected (and made into feedback loops) by arrows, which indicate that one factor has a causal influence on the next. These arrows are either solid or dashed, indicating 'same' or 'opposite'. These terms correspond to the direction of change that any change in the first factor will have on the second factor.

For example, if a directional change in one factor leads to a directional change in the next factor in the *same* direction, it is a *same* influence. Likewise, if the second factor changes in the *opposite* direction, it is an *opposite* relationship. See Figure 3 for a visual description.

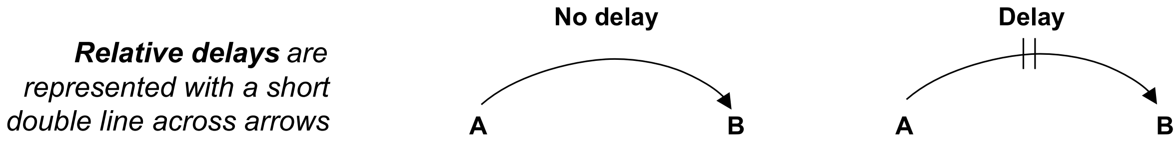
Figure 3. How arrows are labelled in causal diagrams



Adapted from Sterman (2000)

If there is a notable relative delay in an influence presenting in the second factor when compared to the other influences described in the causal diagram, this is annotated as a short double line crossing the arrow. An example of this is shown in Figure 4.

Figure 4. How delays are annotated on arrows



Adapted from Sterman (2000)

4.1.4. Goals and gaps – driving individual loop dominance

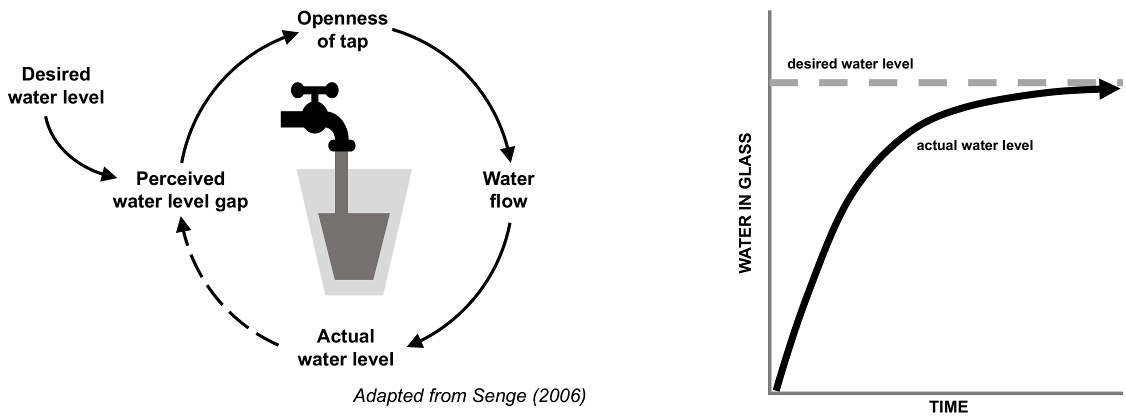
Realising that multiple loops are operating within a system is the first useful insight of systems thinking. A further useful insight is understanding that not all loops operate at the same strength all of the time. Different loops can dominate the dynamics of a system at different times. For example, a system might be dominated by a period of growth (a reinforcing loop), but when some kind of 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 amount 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. The difference between these factors 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 influence that this structure passes on. The lower the desired level and the higher the actual level, the lower the ‘gap’ or difference, and therefore the weaker the influence.

The ‘goal/gap’ mechanism can be seen within the causal diagrams in this report. A conceptual example is shown in Figure 5, which shows the act of filling a glass of water.

Figure 5. Example of a ‘goal/gap’ structure in a causal 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 will be higher.

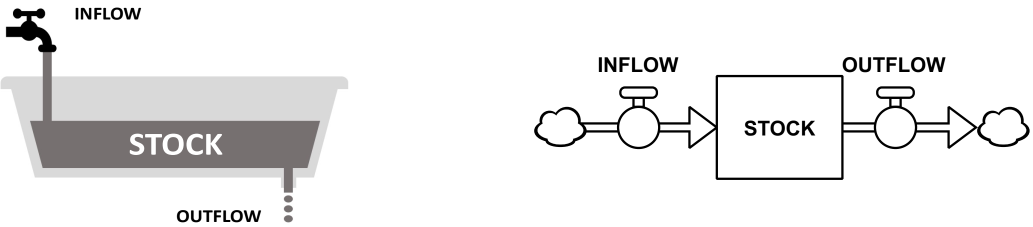
As the desired level of water is approached, the gap/difference reduces, so the tap is closed further, weakening the flow of water (you don’t want the water to overflow the glass), until it is fully closed when the water level reaches the desired amount (Senge, 2006).

4.1.5. Stock and flow notation

The causal diagrams described in this report are made up of both factors and influence arrows as described above, as well as *stock and flow notation*. While factors and influence arrows are at the core of system diagrams, some system elements need greater detail of where things build up or decline and are described in a more involved way. This is stock and flow notation, and it allows a more nuanced level of insight into the behaviour of the system.

Using a stock and flow notation is like a metaphorical *bathtub*. 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 diagram description of a stock and flow (Figure 6).

Figure 6. The bathtub analogy – stocks and flows

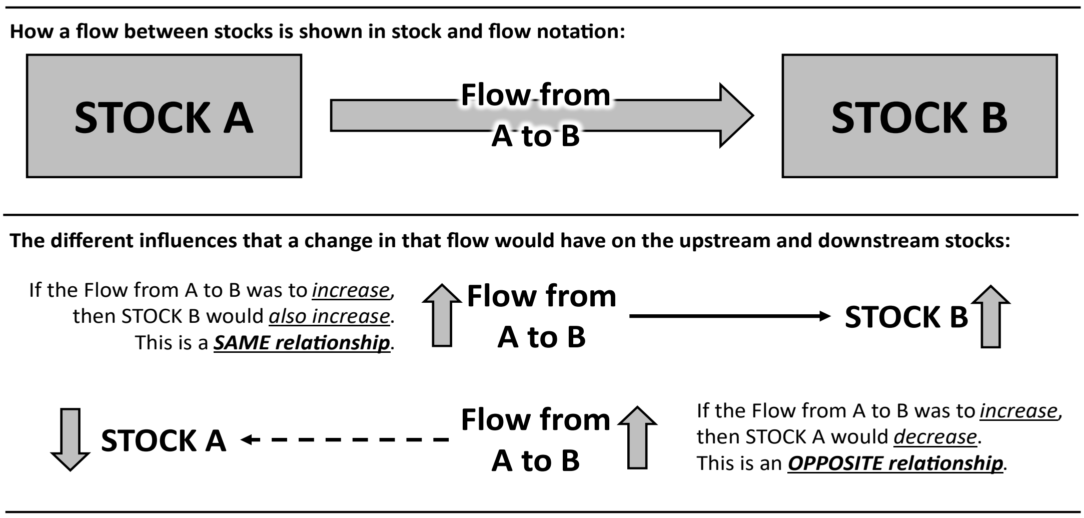


4.1.5.1. How influence operates differently upstream and downstream of a change in flow

When a diagram is partly made up of factors and influence arrows , as well as stock and flow notation (as the causal diagrams in this report are), 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. That is, a flow into a stock has a same relationship, while a flow out of a stock has an opposite relationship.

The flow structure and the factor/arrow influence structure are compared below in Figure 7.

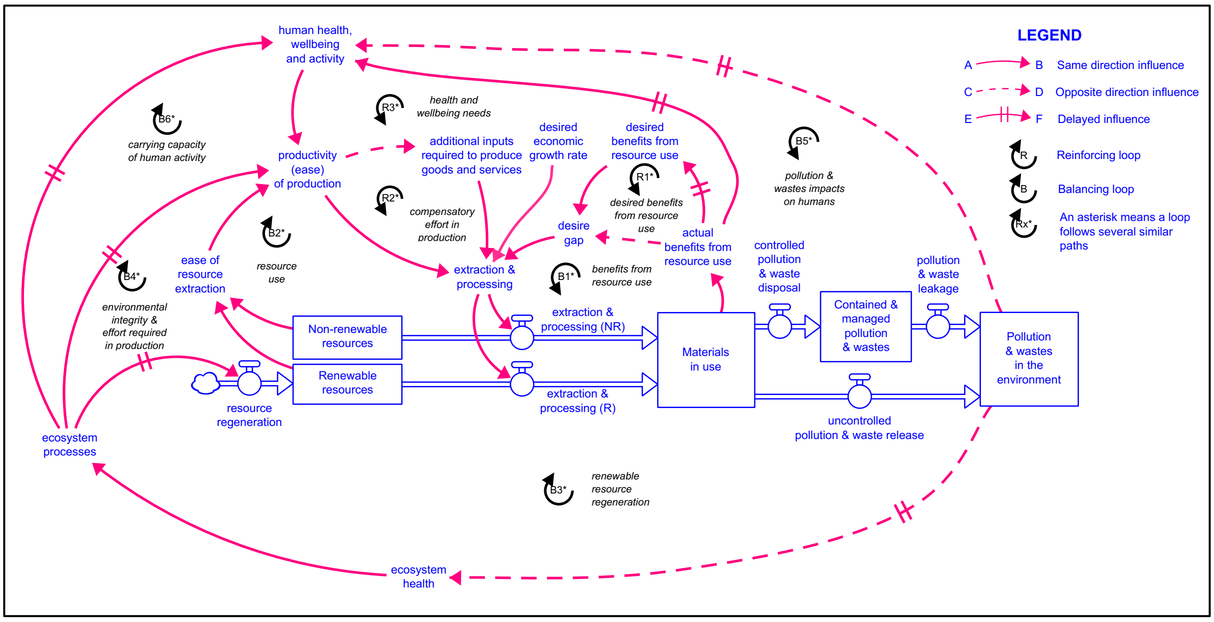
Figure 7. How influence operates differently upstream and downstream of a change in flow



5. Overview diagram

To help explore the insights about future environmental pressures that were sought by PCE, a high-level overview diagram outlining the flow-on impacts of continued resource flow through Aotearoa-New Zealand was developed. This is shown in Figure 8 and described in the following subsections.

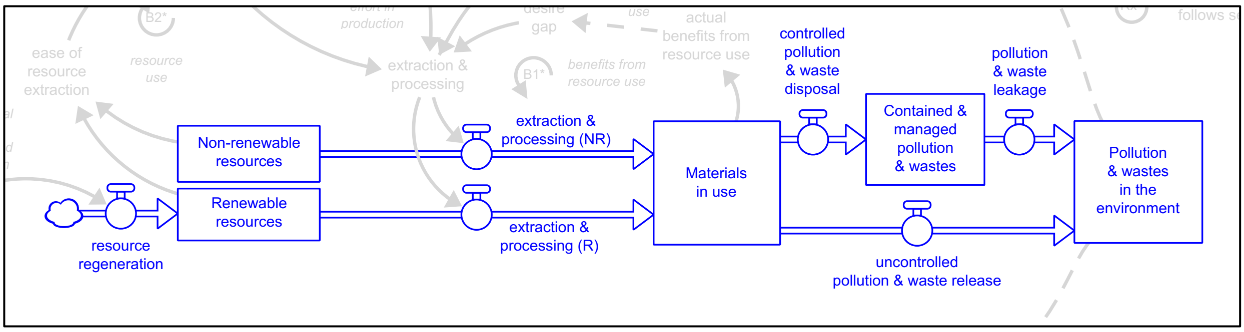
Figure 8. How resource flows create environmental pressures



5.1. Representing resource flows: from resources to pollution & wastes

At the core of this diagram is a representation of resource flows. These are shown as highly aggregated stocks and flows of ‘renewable resources’ and ‘non-renewable resources’ (Figure 9). Non-renewable resources, such as minerals (coal, oil, metals), take millions of years to form, making them effectively non-regenerative on human timescales. Because they are considered non-renewable, this stock ***does not*** have a flow into it. Renewable resources are things like flora and fauna (trees, animals, water) that do regenerate within timescales relevant to humans – therefore, this stock ***does*** have a flow into it to represent this regeneration.

Figure 9. A simple representation of resource flows: from resources to pollution & wastes



Both stocks have *flows out* of them. This demonstrates that they can both be drawn from, yet only one will replenish itself (renewable resources, with the flow in). These flows are labelled ‘extraction & processing (R)’ and ‘extraction & processing (NR)' (R = renewable, NR = non-renewable). Most loops in this diagram have an asterisk because they follow both of these flows. These flows represent all phases of resource extraction and flow through the value chain to end-use. This includes raw materials, refining and processing, development of key inputs or materials, through to finished products, including distribution and all other supply chain logistics along the way.

Both flows go into the stock labelled ‘materials in use’. This represents all material embodied in all built infrastructure across society (e.g. buildings, infrastructure, factories, etc.), machinery and assets currently in use (e.g. manufacturing and industrial plants, transport assets such as vehicles, boats and aeroplanes). It also includes all shorter-lifespan products consumed by society, such as clothing, electronics, food, fuels etc.

‘Materials in use’ can result in byproducts that are pollution or wastes, as well as the actual products also becoming pollution or wastes at the end of their life. This is shown by the two flows labelled ‘controlled pollution & waste disposal’ and ‘uncontrolled pollution and waste release’. Both flow from ‘materials in use’.

‘Controlled pollution & waste disposal’ goes to the stock labelled ‘contained and managed pollution & wastes’. This represents the accumulation of all pollution and wastes that are actively captured and managed, so that they are not deemed to be a risk to human or environmental health. For example, well-managed landfills, or wastewater that is adequately treated in wastewater treatment plants (WWTPs).

‘Uncontrolled pollution & waste release’ goes to the final stock labelled ‘pollution & wastes in the environment’. Importantly, there is also a flow of ‘pollution & waste leakage’ from the ‘contained and managed pollution & wastes’ stock. This represents any intended or unintended direct release of pollution or wastes as a result of ‘materials in use’. For example, rubber that is shed from tyres during use or greenhouse gas (GHG) emissions from cars/chimneys.

Importantly, there is also a flow of ‘pollution & waste leakage’ from the ‘contained and managed pollution & wastes’ stock. This represents any unintended or uncontrollable leakage of pollution or wastes from contained and managed stocks. For example, chemicals that cannot be removed from wastewater during treatment or waste that might spill into the environment from a breached landfill (e.g. as occurred in the Fox River in 2019[1]).

The final stock that these flows go into is critically important for the dynamics this report seeks to understand. It represents the accumulation of all pollution and wastes that make it into the environment – either intentionally or unintentionally. Importantly, no flow out of this stock is shown. This is intended to highlight the fact that there is no ‘away’ where things can be thrown and from where they will eventually dissipate. Waste simply accumulates in another place (at least in terms of time scales that are relevant to humans).

There are some materials that will degrade over the timescale of human interest (such as organic material), and these are less of a concern for this work. However, many of these materials, due to human activity and the resource flows that are associated with them, may contain harmful materials that *do not* degrade over the timescale of human interest. Recognising that such materials exist and remain in the environment is of critical interest to this work. As noted in the introduction, this work seeks to inquire as to what sorts of environmental pressures may be accumulating that will be problematic in the future. This stock represents these environmental pressures.

[1] This example was mentioned by experts in the workshop.
https://www.pmcsa.ac.nz/2019/11/05/compromised-landfills-at-risk-during-extreme-weather/

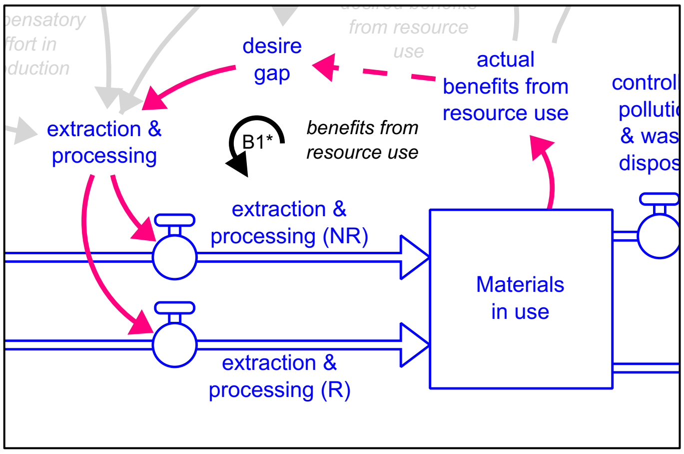
This is represented in various different ways in the three diagrams that follow in this report. Sometimes as stocks and sometimes simply as factors in the diagrams.

It is the flow-on influence and impact of these environmental pressures that we seek to explore in this work.

5.2. Benefit from use drives further use

At its simplest, our collective resource use (from the production of goods and services) is driven by the difference between the 'desired benefits from resource use' that we seek, and our 'actual benefits from resource use' – this is labelled the 'desire gap'. The larger this gap the more effort we put into producing things by extracting and processing resources ('extraction and production') and increasing our stock of 'materials in use'.

Figure 10. Benefits from resource use

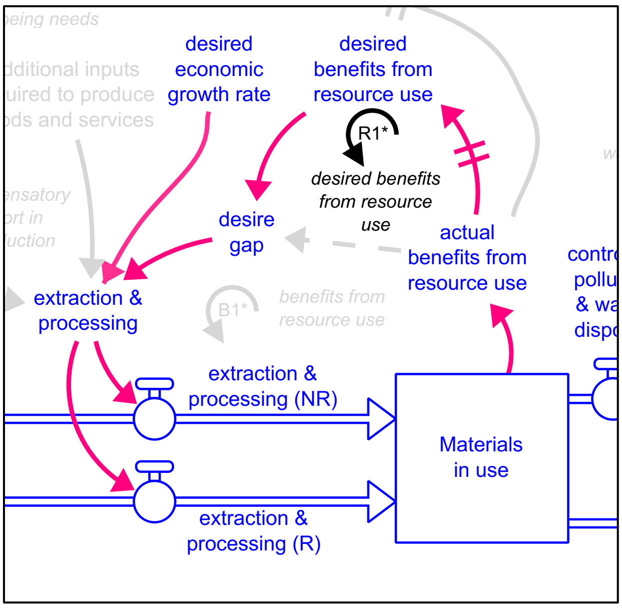


In short, we put in effort to meet the desired level of benefit we want to receive. The more 'materials in use', the more 'actual benefit from resource use' we get, the lower this gap. Simply put, we produce goods that we derive benefits from to meet our desires, to the point where such desires are met. Hence, this is a *balancing loop (B1*)* called *benefits from resource use*. Technically, there are two loops here (one that follows each of the flows from renewable and non-renewable resources), but they are shown as one (B1*) for simplicity.

Loop B1* sits at the core of the diagram and is the primary driver of resource flows through the economic value chain of Aotearoa-New Zealand. See Figure 10.

At the same time, our desired level of benefits is not static. Our 'actual benefits from resource use' have a delayed same influence on our 'desired benefits from resource use' – the more we benefit from 'materials in use', the more our expectations and desires increase. Any increase in desired benefits has a same influence on the 'desire gap', which will increase the gap and increase the effort put into 'extraction and processing'. This creates a *reinforcing loop (R1*)* encouraging further production and 'materials in use' (Figure 11).

Figure 11. Changing desired benefits over time



Loop R1* works in tension with balancing loop B1*, creating the dynamic where continued production and 'materials in use' encourage continued increases in the desired and actual level of consumption in the longer term. This works in both the individual and collective senses.

An individual example is that someone may buy a piece of technology (e.g., a smartphone) that introduces them to a world of technology and convenience that they were not previously aware of. This may have consequential impacts on their expectations, and they may then want other smart devices, such as a tablet or a wearable health monitor. This also has consequential impacts on the technology required to support such devices, like needing to produce charging cables for such devices, as well as an increased demand for electricity to use such devices.

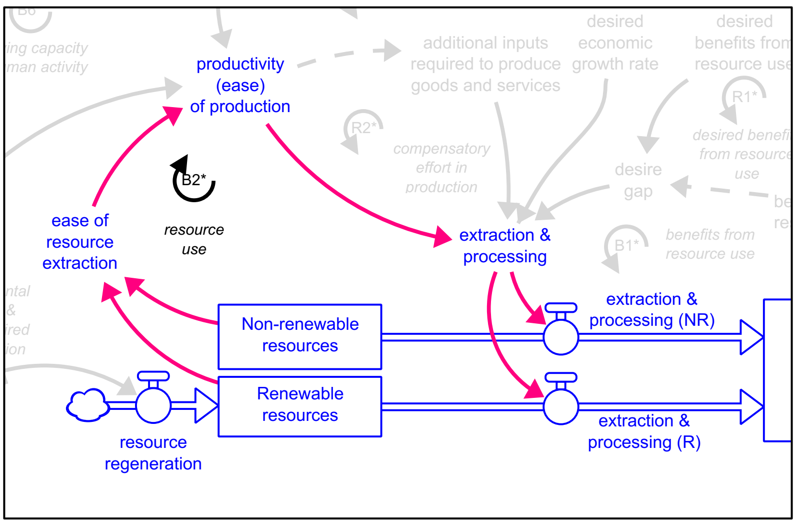
A collective example is that people may be influenced by the actions of those around them. If one person has version 10 of a smartphone and someone else has version 11 or 12, this may encourage the person with version 10 to want a newer version.

The 'desired economic growth rate' of the economy also influences the amount of 'extraction & processing' that occurs. In general terms, the greater the 'desired economic growth rate' the greater the 'extraction & processing' of resources – i.e. these things are still relatively coupled. It is worth noting that any positive rate of economic growth – even a low one – over time will result in an increase in 'extraction & processing' of the resulting 'materials in use' and their eventual 'discarding'.

5.3. How resource availability constrains use

As already noted, the flows of resources through Aotearoa-New Zealand come from sources (stocks) of resources. The availability of these resources is constrained, which will eventually constrain their use. They are either limited in their entirety, such as 'non-renewable resources' that may run out, or they are limited by how much is presently available, such as renewable resources that need to regenerate (Figure 1).

Figure 12. How resource availability constrains use



Generally, the more of a resource there is, the easier it is to extract or harvest (due to its relative abundance). As resource stocks reduce, it becomes more difficult to extract or harvest them. So the level of both resource stocks have a same influence on the factor labelled 'ease of resource extraction'. As resource stocks and their relative ease of extraction *reduce*, this *reduces* (same influence) the relative 'productivity (or ease) of production'.

Or, in other words, how easy it is to extract them. In turn, this *increases* (same influence) the amount of extraction & processing that occurs. In other words, the less of something there is, the harder it is to extract, meaning less is extracted for the same amount of effort. This is shown as *balancing loop B2*,* which has two pathways, one via non-renewable resources and one via renewable resources.

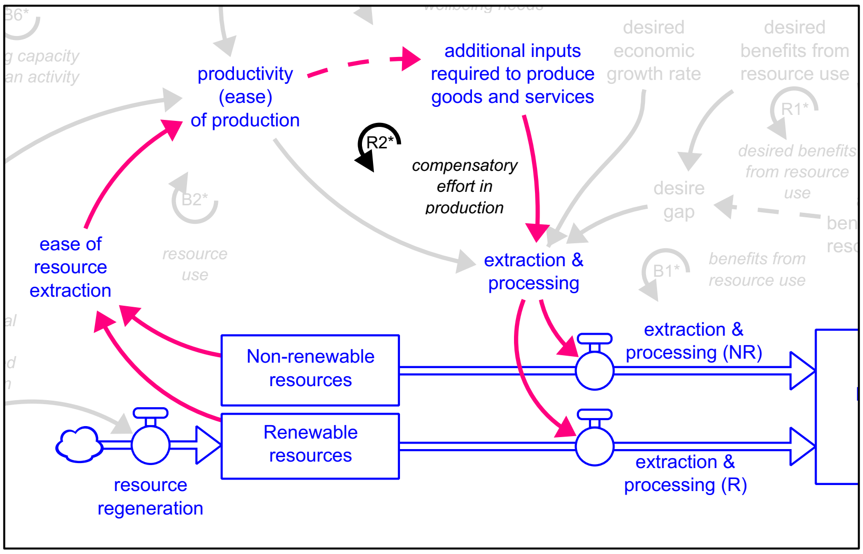
These influences all interact with the 'extraction & processing' factor. This is a function of both the desired level of goods and services and the economic growth rate (both of which are demand drivers) and the ‘productivity (or ease) of production’ – or the amount of effort required to extract resources (a supply constraint).

5.4. Compensatory effort in extraction and processing

As the ease of extraction reduces and ‘extraction & processing’ becomes more difficult, there is an important compensatory effect (Figure 13). A decrease in the ‘productivity (or ease) of production’ has an opposite influence on ‘additional inputs required to produce goods and services’. In other words, when it becomes harder to extract something, we often double down and add additional inputs to help maintain the previous rate of extraction and processing. For example, we may add fertiliser to pasture or crops, or we may add additives to mining operations to help release the resource being mined, or we may add additives to manufactured goods to help lengthen the life of the material or to strengthen it.

All of this has the net result of *increasing* ‘extraction & processing’, further reducing resource stocks. It is, therefore, a *reinforcing loop (R2*)* that goes from more ‘materials in use’, through ‘pollution & wastes’, to reduced ecosystem health and ecosystem processes. This decreases the ‘productivity (ease) of production’, which increases the ‘additional inputs required to produce goods and services’, leading to further ‘extraction & processing’. This *reinforcing loop (R2*)* has been labelled *compensatory effort in production*.

Figure 13. Compensatory effort in extraction and processing



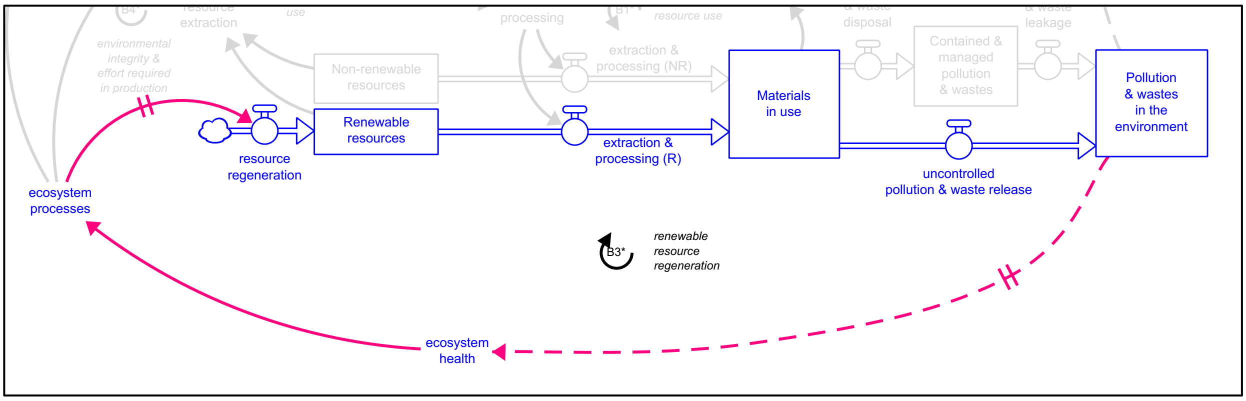
5.5. How continued resource flows impact renewable resources and extraction & processing effort

The influences described in the previous subsections mean that resource flows are likely to continue to grow and persist. This will lead to a persistent flow of ‘discarding’ and a growing accumulation of ‘pollution & wastes’. This section describes two balancing feedback loops that this accumulation influences – its impact on *renewable resource regeneration (balancing loop B3*)* and *environmental integrity & effort required in production (B4*)*.

5.5.1. Renewable resource regeneration

As pollution & wastes accumulate, they will have an increasingly stronger opposite influence on ‘ ecosystem health’ – i.e. over time environmental integrity will decline. This represents the delayed but cumulative impacts that pollution & wastes have on ecosystem health. This single arrow effectively represents all the environmental pressures that impact environmental integrity and ecosystem health – so this is a significant number of pressures! However, the key point of the diagram is to demonstrate how these pressures are linked in feedback loops with the environment and humans, and this pathway does this (see Figure 14).

Figure 14. The impact of continued resource flow on renewable resources

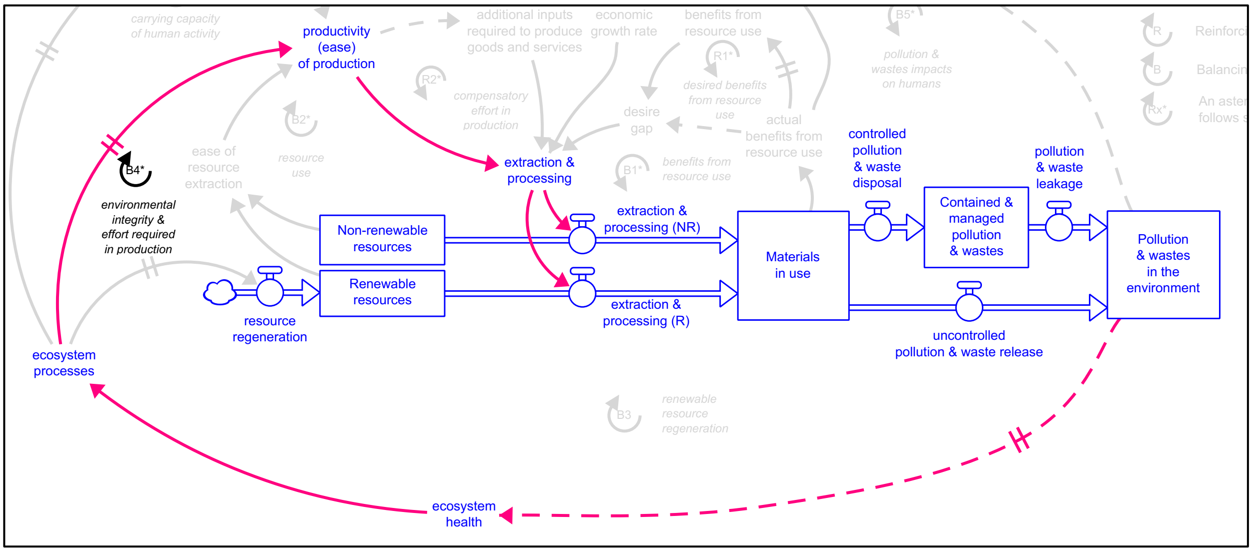


‘Ecosystem health’ has a same influence on the quantity and quality of the ‘ecosystem processes’ that occur. These are the biophysical processes that support, regulate and maintain the environment. If ecosystem health declines, so too do ecosystem processes. In turn, this also reduces (same influence) the ‘resource regeneration’ ability of renewable resources – that is, their ability to regenerate. This reduces the rate at which the stock of renewable resources rebuilds, which constrains the extraction & processing flow from this stock – if they do not or cannot regenerate, there can be no extraction. This completes the *balancing loop B3** (Figure 14). For example, a reduction in water quality in the marine environment may reduce ecosystem health and impact the ability of fish stocks to regenerate. Hence it is a balancing loop as it constrains itself.

5.5.2. Productivity (or ease) of production

The same pathway of influence – ‘pollution & wastes’ *reducing* ecosystem health and processes – then flow on to *reduce* (same influence) the ‘productivity (or ease) of production’ in the longer term (delay). In other words, the lower the quality of the environment associated with the resource required, the harder it is to generate resource flows from it. This describes balancing loop B4*. For example, the resource may be in a reduced state of health or more difficult to access and extract due to other environmental pressures (Figure 15).

Figure 15. The impact of continued resource flow on productivity

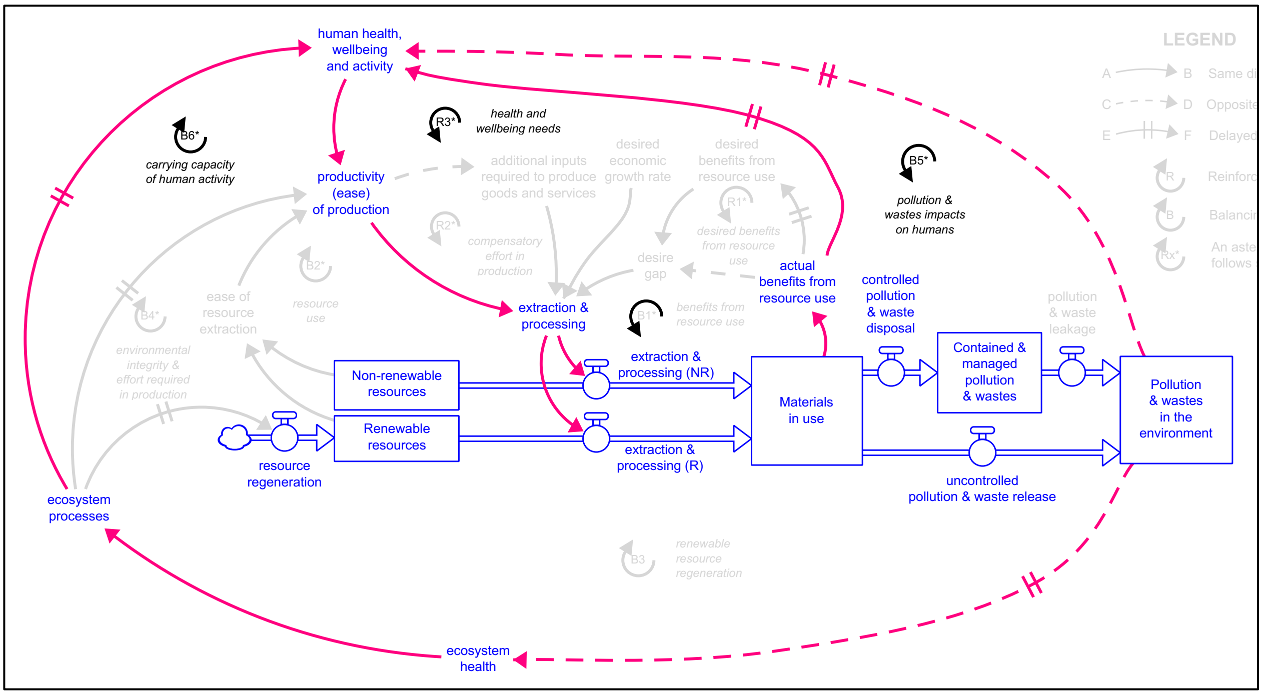


This influence flows on to make ‘extraction & processing’ more challenging (another same influence) and therefore reduces it, reducing overall extraction & processing, which eventually will likely constrain the flow of resources through the Aotearoa-New Zealand. In short, continued pollution and wastes will likely eventually constrain our ability to extract and process renewable resources.

5.6. Feedback loops involving human health & wellbeing

This final section of the overview diagram describes the feedback loops that link resource flows and ‘pollution & wastes’ with ‘human health, wellbeing and activity’. There is one reinforcing loop and two balancing loops (Figure 16).

Figure 16. Feedback loops involving human health & wellbeing



The *reinforcing loop (R3*)* is labelled *health and wellbeing needs*. This is an extension of the *benefits from resource use* loop – increased resource flow and 'materials in use' increases 'actual benefits from resource use', which in part increase 'human health, wellbeing and activity' (this is, after all, one of the reasons why we extract the resources in the first place). The better our health and wellbeing, the greater productivity we can assume in producing goods and services. In other words, the healthier we are, the more things we can produce. The more we produce, encourages further resource flows and material use. In summary, this loop describes how our health and wellbeing are an important input to our extraction and production of resources, which result in goods and services that are strongly linked to our health and wellbeing.

The two balancing feedback loops described here relate to *direct* health impacts from pollution and wastes on humans, as well as the *indirect* impact on human health through the impacts on the carrying capacity of the environment.

The direct impacts are in *balancing loop B5**, labelled *pollution and wastes impacts on humans*. Here, *increases* in 'pollution & wastes' will *decrease* 'human health, wellbeing and activity' (through direct impacts on health) over time, which will *decrease* 'productivity (or ease) of production' (i.e. how much effort we have to put in to extract stuff). This will reduce the total amount of 'extraction & processing', 'materials in use', and eventually 'discarding', as well as the volume of additional pollutants & wastes accumulating in the environment.

The indirect impacts are in *balancing loop B6*, labelled *carrying capacity of human activity*. Here, *increases* in 'pollution & wastes' will *decrease* ecosystem health, 'ecosystem processes' and 'human health, wellbeing and activity' over time. In effect, in the long run, increased 'pollution & wastes' will decrease how many humans can be supported by the environment. This is also known as carrying capacity, which is a term used throughout this report. As human health *decreases*, then the 'productivity (or ease) of production) also *decreases*. This then *decreases* the total amount of 'extraction & processing', 'materials in use' and eventually 'discarding' and the volume of additional pollutants & wastes accumulating in the environment.

Both balancing loops articulate an undesirable pathway where resource flows are eventually reduced as a result of the environmental pressures from the pollution and wastes of resource flows in the first place. In other words, the assimilative capacity of the environment (on various scales) to absorb our pollution and waste streams will likely become a limiting factor of human activity in the long-term. This may result in the eventual decline of human health, or the reduction in the size of our population that can be supported.

Such decreases in the assimilative capacity of the environment and, eventually, human health are likely to be responded to with human innovation. Such innovation may take the form of improvements in efficiency that reduce resource inputs, or pollution and waste outputs. It may be a substitution of materials, where a constrained or damaging material may be swapped for another one that is less constrained or less damaging. It may also be through better capture and containment of pollution or wastes. The risks of leakage from 'controlled and managed pollution & wastes' have already been discussed earlier. Potential limitations relating to both efficiency and substitution are discussed in the following section.

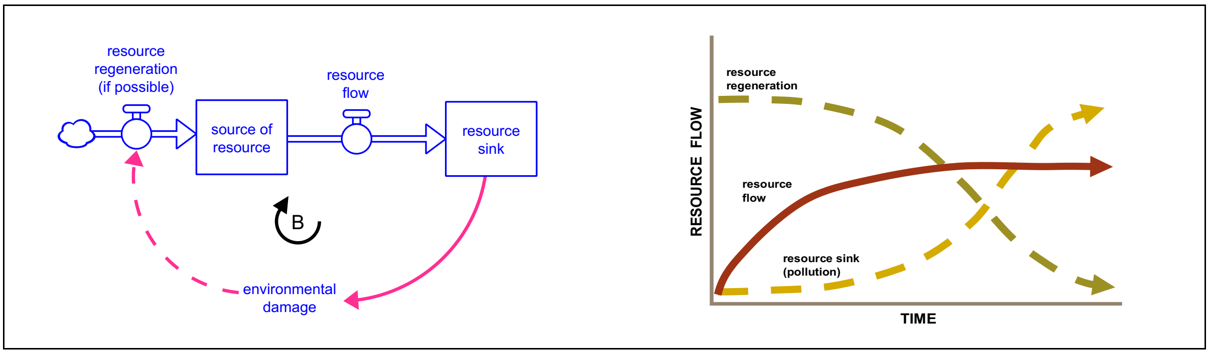
6. Important structure and dynamics common across the detailed diagrams

This section describes a series of important structures that create certain dynamics in all or most of the three detailed diagrams described in this report. These relate to the challenge of continued growth in resource flows in a finite world, how population, primary production and efficiency gains are represented in the diagram. Limitations with efficiency gains and counterintuitive impacts of substitution of one harmful resource for another (potentially) less harmful are also highlighted.

6.1. The challenge of increased resource flows in a finite world

This work is interested in the potential environmental impacts and pressures that may result from continued resource flows through Aotearoa-New Zealand. While the guiding interest is the flow-on impacts of increased resource flows, it is important to recognise this challenge not just as a 'flow' issue, but also as a 'stock' issue. Another way of framing this is as a 'source' and 'sink' issue (Figure 17) – where do resources come from and where do they end up after we have derived benefit from them?

Figure 17. A conceptual representation of 'sources', 'flows' and 'sinks'



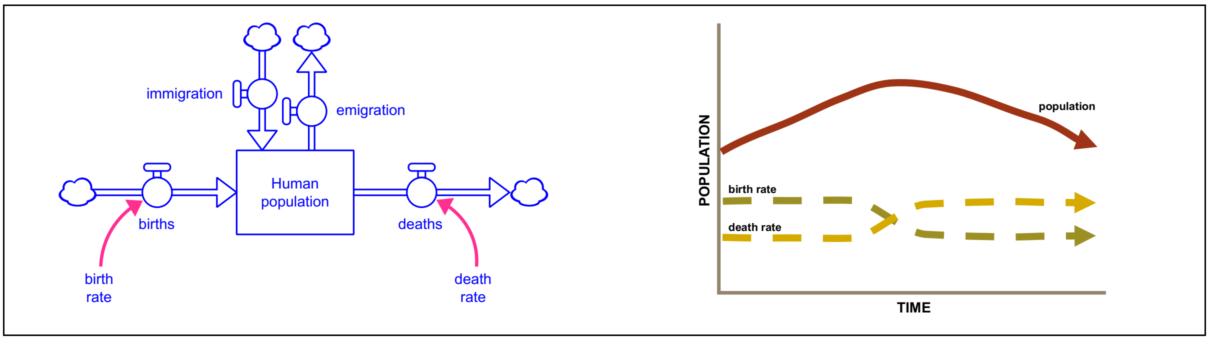
The authors and the PCE are aware that a focus purely on the volume of a flow in any one particular period of time (e.g. a month, a year or a decade) may unhelpfully narrow the focus away from the context of where these flows come from (their 'source') and where they end up (their 'sink'). Therefore, effort has been made to ensure that the diagrams capture the circular nature of influence between these sources and sinks.

This has already been demonstrated in the overview diagram. However, the conceptual diagram in the figure above shows how 'sources', 'flows' and 'sinks' may be represented, as well as the *balancing feedback (B)* influence that 'sinks' may have on 'sources' (especially those that are renewable or self-generate). The graph on the right indicates the likely behaviour over time of resource flows – while they will experience sustained growth initially, the impact of accumulated wastes in the 'resource sink' will constrain the ability of resources to regenerate. This highlights that flows of resources are not able to continue unconstrained *ad infinitum*. Increasing flows of resources would be expected to eventually flatten as a trend, unable to continue to grow due to environmental constraints. For example, the impact of microplastics and chemicals in the environment may impact the growth rate of plants and animals or their ability to regenerate.

6.2. How population is represented

The level of human population is featured in all three detailed diagrams. This has been represented by the stock and flow structure, as shown below (Figure 18.

Figure 18. How human population is shown in the diagrams



The total 'human population' is shown as a stock. This only increases through the flow of 'births' (which is itself impacted by a same influence from the 'birth rate') or the flow of 'immigration'. This stock only decreases through the flow of 'deaths' (itself impacted by a same influence from the death rate') or the flow of 'emigration'. Technically, immigration and emigration are also influenced by rates (i.e. immigration rate and emigration rate), but they are not considered to be relevant to this work and are therefore not shown here. These flows are shown to demonstrate that the population does not *only* increase through births and deaths in Aotearoa-New Zealand.

The graph above demonstrates how the dynamics work. Ignoring the immigration/emigration flows, let us assume the birth rate is higher than the death rate. This means that births are higher than deaths, and therefore, the population increases. If that were to change, and the death rate was to be higher than the birth rate, then there would be more deaths than births, so the population would decline.

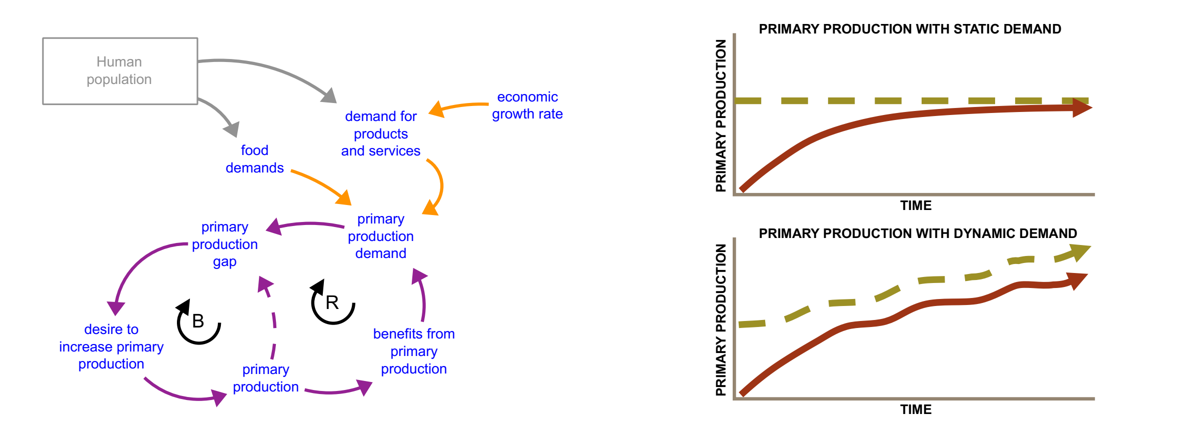
6.3. How primary production is represented

Primary production is also featured in all three diagrams, so this is represented by consistent factors across them (Figure 19.

Firstly, there is a goal/gap structure (as described earlier) that brings together 'primary production demand' and 'primary production' (the actual level of primary production) with the 'primary production gap'. This forms part of a *balancing loop (B)*. If the level of demand is higher than the actual production, then there is a gap. The larger this gap, the greater the 'desire to increase primary production', eventually leading to more 'primary production'. The greater the primary production, the lower the 'primary production gap', meaning the desire is reduced proportionally. In other words, primary production comes into balance with the desired level of production. See the top graph on the right of the figure.

However, a *reinforcing loop (R)* also operates in parallel. The greater the 'primary production, the greater the 'benefits from primary production' which can increase the 'primary production demand'. This means that primary production and the demand for it also operate in a reinforcing loop. This will continue to drive up the primary demand, and production will seek to keep up. This will likely result in dynamics like those of the bottom graph on the right-hand side of the figure.

Figure 19. How primary production is shown in the diagrams

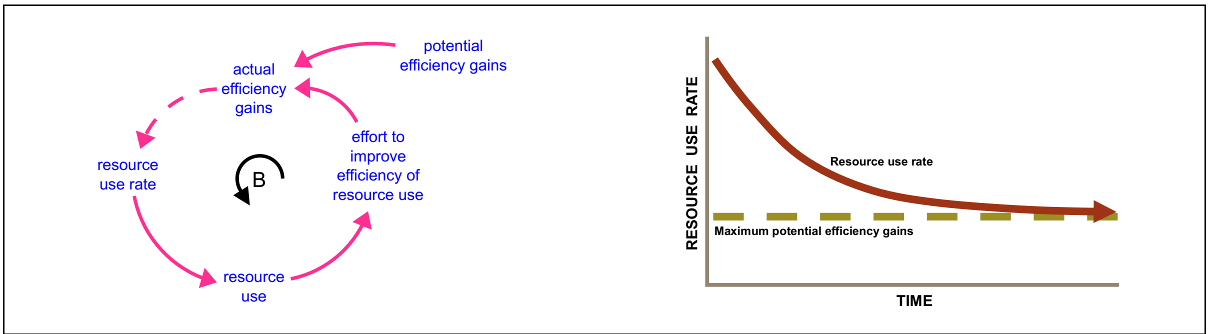


Primary production demand is also influenced by the 'demand for products and services', which is influenced by the 'economic growth rate' (both same influences). 'Food demands' also have a same influence on 'primary production demand'. The volume of the 'human population' stock (see previous section) has a same influence on both 'demand for products and services' and 'food demands'.

6.4. The limits to efficiency gains

Efficiency gains play an important role in reducing resource flows and environmental pressures. This is represented in some of the diagrams as a *balancing loop(s) (B)* (Figure 20).

Figure 20. The limits to efficiency gains.

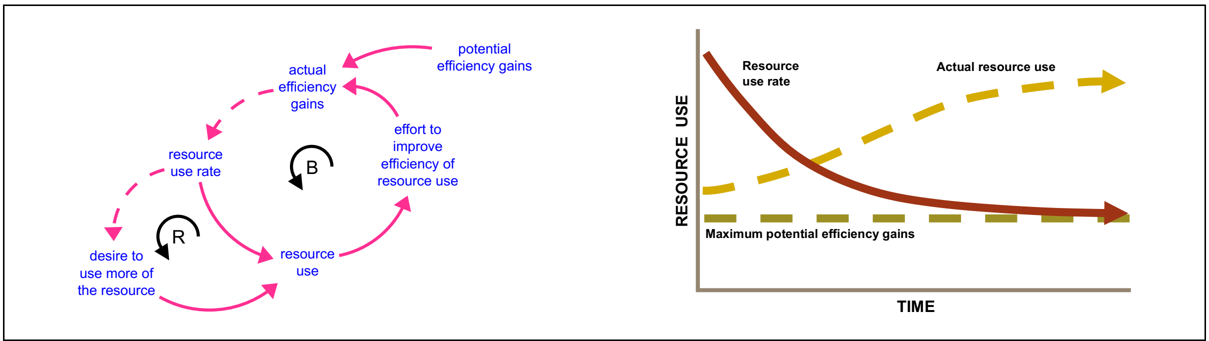


If the 'resource use' is high, this has a same influence on the 'effort to improve efficiency of resource use' – i.e. there is an incentive to achieve efficiency gains. This factor represents the investment in research, development and innovation to reduce the resource use rate, making it more efficient. This has a same influence on the 'actual efficiency gains', which then has an opposite influence on the 'resource use rate' (reducing it), which has a same influence on the actual 'resource use' (reducing this too).

The important thing about this loop is that it is constrained by the 'potential efficiency gains'. The greater this factor, the greater the eventual gains, but they will eventually diminish because 'actual efficiency gains' are a function of the effort invested *and* the 'potential efficiency gains'. Once all the efficiency gains are realised, further effort will no longer yield results. This is a similar concept to the law of diminishing returns. This is because an activity that uses a resource (e.g. plants need water) will always need that resource no matter how efficient they become. These efficiency gains can help reduce resource flows, but only up to a certain point.

At the same time, there is a counterintuitive impact of improved efficiency and a reduced use rate of a resource. This is because we often end up using *more* of a resource when we use it more efficiently. This is because the *technical* solution of reducing the amount of a resource that we use for something has a consequential impact on the *social* expectations around what we can do with that efficiency gain. In short, a compensatory increase in the amount of things produced from a resource is often the result of an increase in the efficiency of using that resource. This is known as a rebound effect (also sometimes called *Jevon's paradox*). This is shown as a *reinforcing loop (R)* in Figure 21.

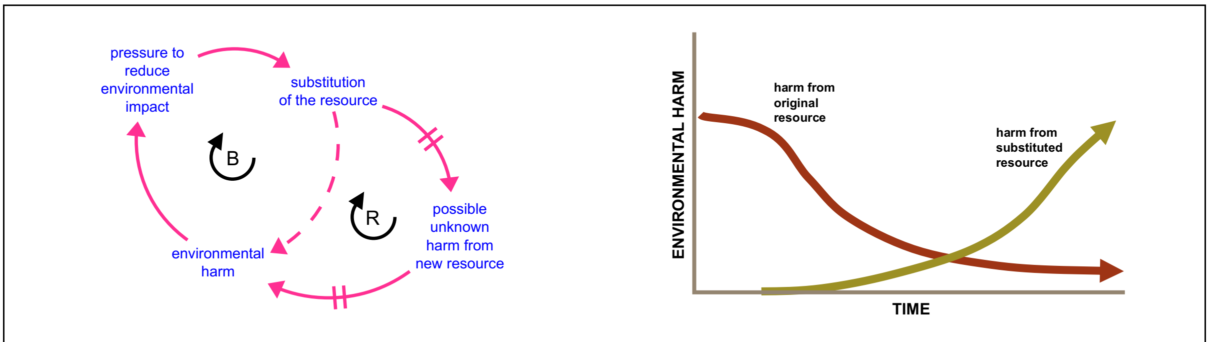
Figure 21. The rebound effect from efficiency gains.



6.5. The challenge of substitution

Like efficiency gains, substitution also has a role to play in reducing either resource flows themselves, or the environmental pressures and harms that may come from them. While this approach may have the desired effect, it may also have unanticipated delayed side effects (Figure 22).

Figure 22. Resource substitution and potential unknown future impacts



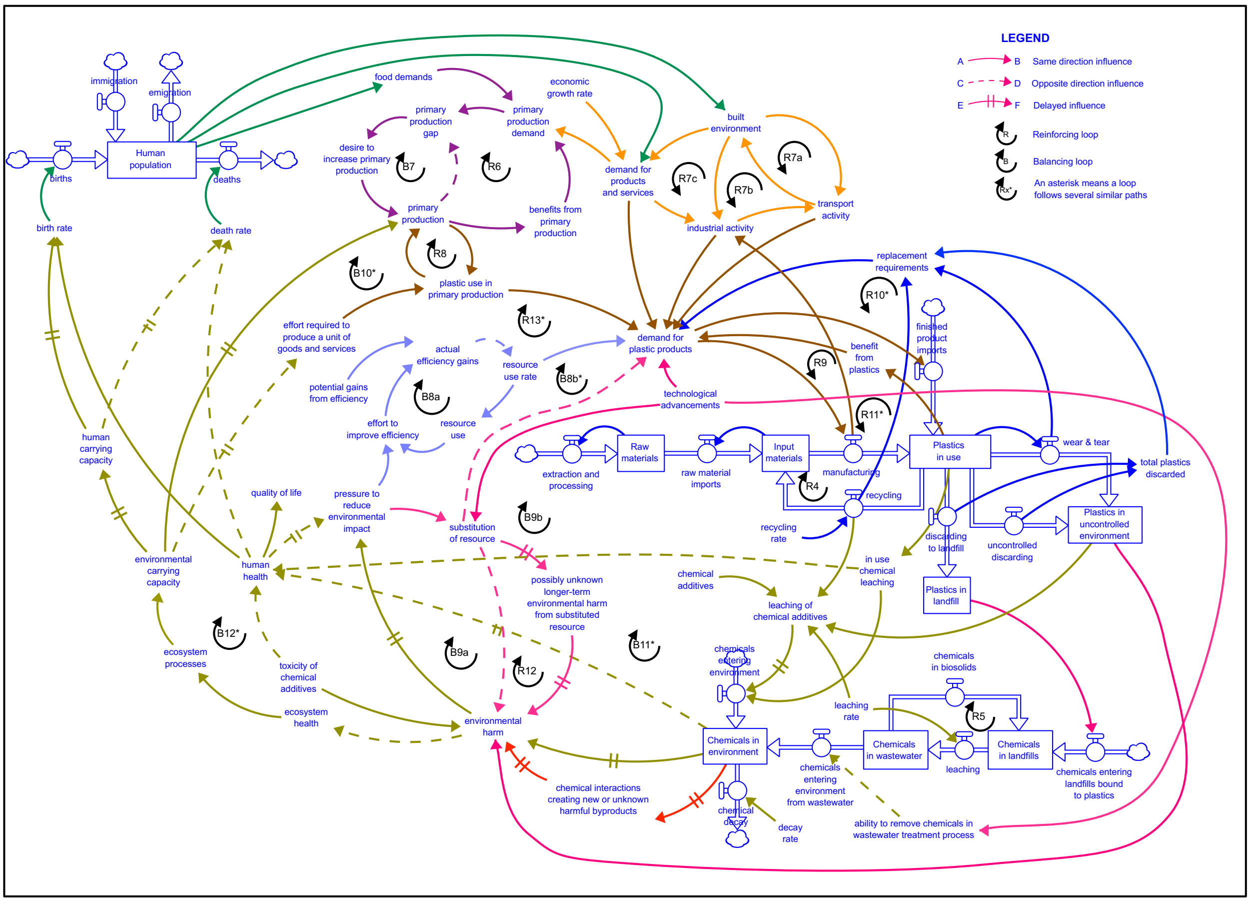
Firstly, the substitution of a resource operates in a *balancing loop (B)*. The *greater* the 'environmental harm' from a resource flow, the *greater* (same influence) the 'pressure to reduce environmental impact'. This may lead to the 'substitution of the resource' (same influence), which then *reduces* environmental harm (an opposite influence). This is shown as the red line on the graph that shows environmental harm reducing.

Secondly, the act of substitution introduces a new resource., In the longer term (delay), this may cause 'possible unknown harm from new resource', which, after further delays, may cause environmental harm (both same influences). This is shown as the green line on the graph. For example, nitrogen fertiliser may be substituted for slow-release nitrogen fertiliser, which may reduce use and lead to less nitrogen leaching. However, the slow-release function is often achieved by encasing the fertiliser in plastic resins, which, over time, results in a build-up of microplastics in the environment. These new or different accumulations of harm will maintain pressure to reduce environmental impacts. This sort of dynamic tends to result in waves of environmental harm of different types over many years – each one may come and go, but they accumulate. There are often unexpected consequences of doing well-intentioned things. Another way of describing this dynamic could be through the saying – "today's problems come from yesterday's solutions".

7. Plastics and chemicals

This section is the first of three separate sections that describe the three detailed causal diagrams that were developed in this project. This causal diagram relates to plastics and their chemical additives as they pertain to the Aotearoa-New Zealand environment. An overview of the diagram is shown in Figure 23. A large version can be found in Appendix 1.

Figure 23. Overview of the plastics and chemicals diagram

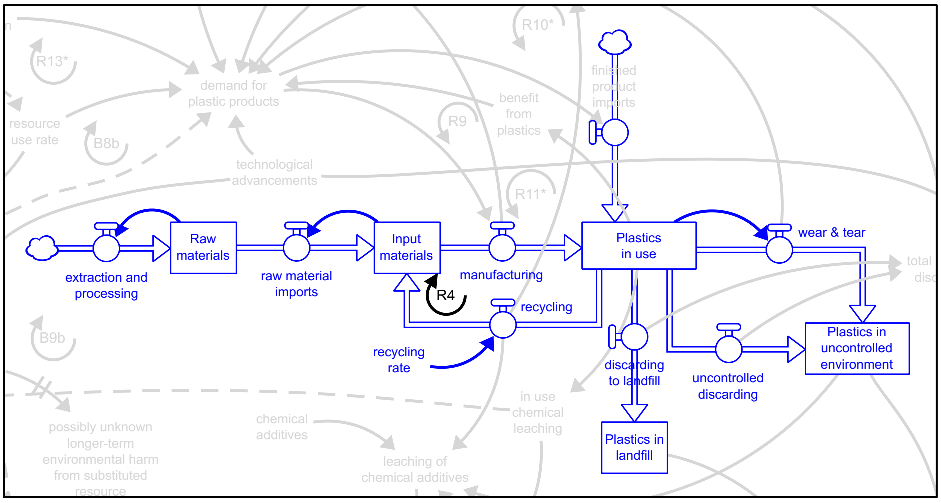


7.1. Representing plastic flows

Stocks and flows are used to capture the flow of plastic materials and their associated chemical additives through the value chain. It is important to note that chemical additives are bound to the plastics and move through the value chain with them (see Figure 24).

Plastics can enter the value chain in two distinct ways: via the ‘extraction and processing’ of virgin materials or through ‘finished product imports’. No virgin plastics are manufactured in New Zealand, so the ‘extraction and processing’ phase that creates the ‘raw materials’ is done offshore. These ‘raw materials’ enter New Zealand through ‘raw material imports’ into a stock of ‘input materials’ that are subsequently turned into ‘plastics in use’ via a ‘manufacturing’ process. ‘Manufacturing’ is influenced by the ‘demand for products’ in the same direction – that is, if demand goes up, manufacturing goes up. ‘Finished product imports’ can also contribute directly to this stock of ‘plastics in use’ and are also influenced by ‘demand for plastic products’. However, the production and manufacturing impacts of ‘finished product imports’ occur offshore.

Figure 24. Value chain of plastics materials and their associated chemical additives



When these materials come to their end of life, they are either sent to landfill, are recycled to create new 'input materials', or end up in the environment through 'wear & tear' or 'uncontrolled discarding'. The 'recycling' process represents a *reinforcing feedback loop (R4)*; everything else considered equal (including assuming the same recycling rate), an increase in plastic use leads to more recycling, which adds to the stock of input materials for manufacturing, and hence plastics in use. This logic can be difficult to comprehend when analysing feedback loops individually, but it is important to note that other feedback loops will also be interacting and potentially counteracting these forces. For example, an increase in 'recycling' leads to more 'input materials', which may reduce the need for 'raw material imports'. It is the combination of interacting feedback loops like these that create the observed behaviour.

Plastics can enter the environment intentionally through acts such as littering, but there are also many unintended pathways for plastics to end up in the environment, including:

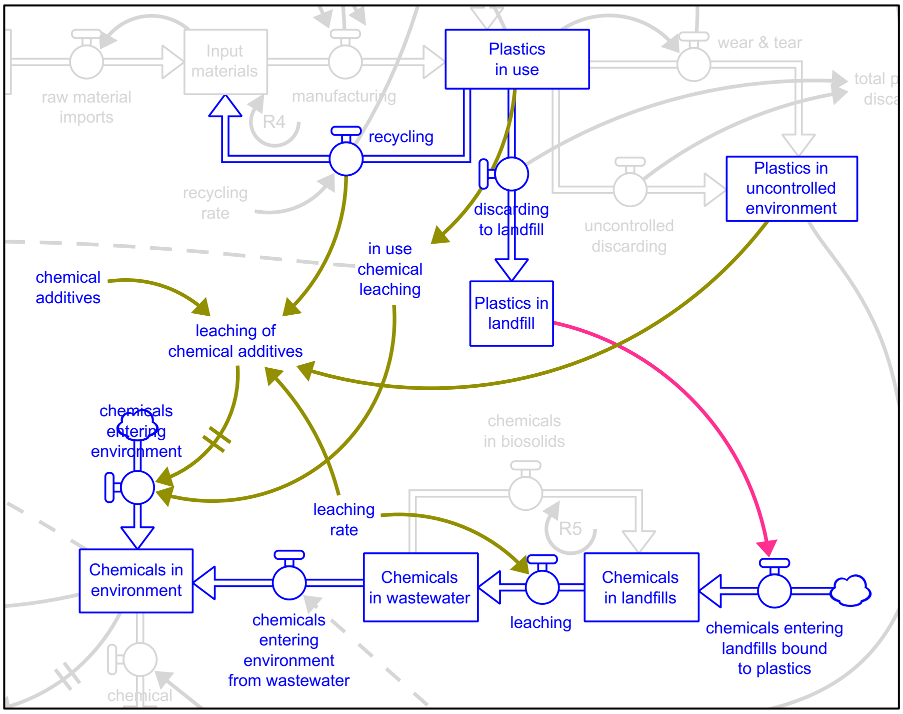
- Synthetic clothes release microplastics into waste wastewater systems every time items are laundered
- Tyre wear is a major source of microplastics
- Stormwater networks can convey plastic debris from streets, parking lots, construction, and industrial sites, into drains that lead directly to water bodies.
- Many countries export their plastic waste to other nations for recycling or disposal. In some cases, these plastics are improperly managed in the receiving country, leading to open dumping or burning, which releases plastics directly into the environment.

7.2. How chemicals enter the environment

This section briefly describes the various leaching processes by which chemical additives can become separated from the plastic polymers and enter into the environment (see Figure 25). This structure is related to the fact that although the chemical additives are bound to the plastics, they can leach out into the environment at various stages throughout the value chain. This is widely observed for certain chemicals (BPA, phthalates, etc.), but there are still thousands of chemical additives that are either classified as hazardous or have no hazardous data available[2].

[2] Several experts referred to the *PlastChem | State of the science on plastic chemicals* report

Figure 25. Chemical leaching pathways



The amount of 'plastics in landfill' directly relates to the amount of 'chemicals entering landfills bound to plastics'. However, chemicals can also leach from plastics during various other phases of the value chain. For example, the 'recycling' process and the amount of 'plastics in uncontrolled environments' can lead to more 'leaching of chemical additives'. Additionally, more 'plastics in use' can also lead to more 'in use chemical leaching' (e.g. chemicals released from products during their use, such as from some plastic containers to their contents). These factors have flow on effects for how chemicals accumulate in the environment, as well as various environmental and human health implications.

Plastic materials are known to release various chemicals into the environment at different stages of their value chain, from production to disposal. For example:

Leaching from plastics in use:

- The endocrine disruptor Bisphenol A (BPA) can leach out when plastic containers are used to store hot foods or liquids, especially if they are microwaved.
- Phthalates from food wraps can leach into fatty foods, especially when the plastic wrap comes into direct contact with the food, or when the wrapped food is heated.

Leaching from the recycling process:

- Stabilisers, plasticisers, and other additives in plastics can potentially leach out during the recycling process.

Chemicals leaching from landfills:

- As plastics degrade in landfills, chemicals like heavy metals, plasticisers, and other additives can leach into the surrounding soil and contaminate groundwater. Modern landfills collect this leachate and pass it through some form of wastewater treatment process. It is uncertain how effective these treatment processes are at removing these substances form wastewater before it is reintroduced into the environment.

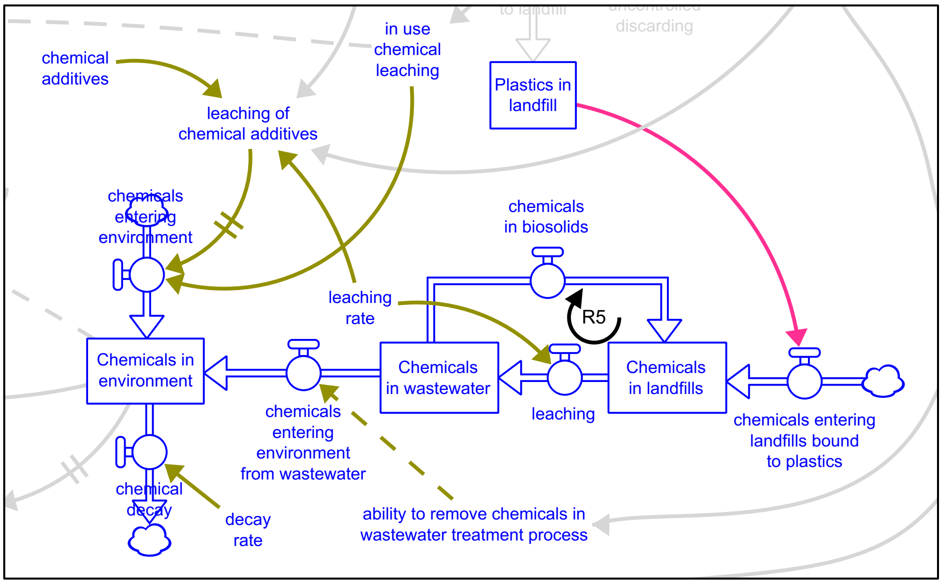
Breakdown of plastics:

- Environmental exposure causes plastics to break down into smaller particles and release additives such as UV stabilizers or antioxidants.
- These microplastics are a known to accumulate persistent organic pollutants (POPs) from the environment (e.g. PFAS, PCBs, DDT), which affecting living organisms if ingested.

7.3. Representing chemical accumulations in the environment

A simple stock and flow structure is used to capture the various pathways that the chemicals from plastics may end up in the environment (Figure 26).

Figure 26. Chemical pathways into the environment



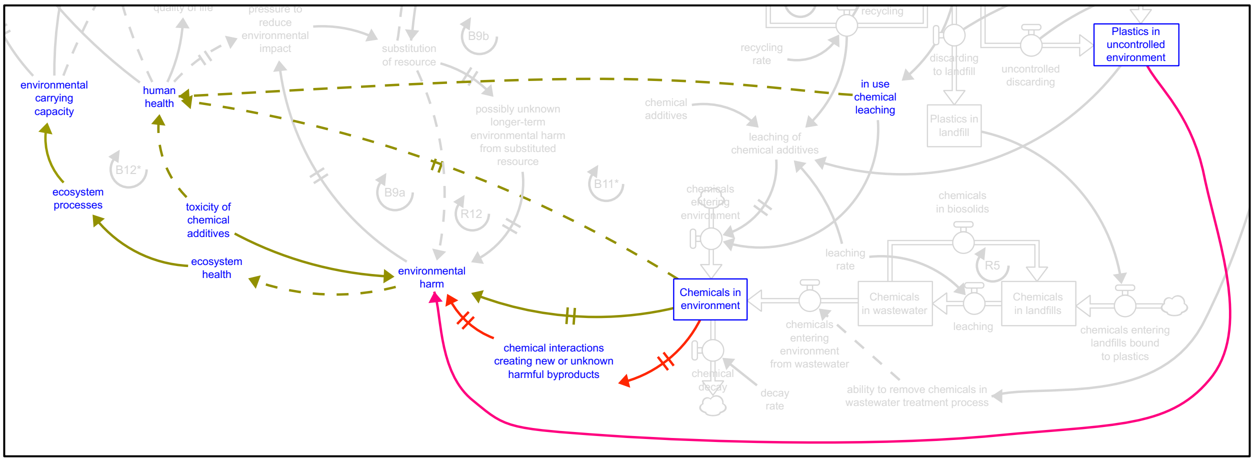
'Chemicals entering landfills bound to plastics' adds to the stock of 'chemicals in landfills', which subsequently undergo 'leaching' processes and end up as 'chemicals in wastewater'. Modern landfills either pump their leachate to municipal wastewater treatment plants or treat it onsite before being discharged to the environment. Historic landfills are potentially leaching these chemicals directly into the environment. Depending on the region within New Zealand and the treatment process, chemicals may be filtered out of the wastewater (depending on the efficacy of the wastewater treatment process) and returned to landfill via the 'chemicals in biosolids' flow. This completes the *reinforcing loop R5*. Alternatively, the 'chemicals in wastewater' could be transferred directly to the environment by the flow of 'chemicals entering environment from wastewater'. This represents the amount of chemicals still in the wastewater (post-treatment) when it is released into the environment or the act of spreading biosolids from the wastewater treatment process (which contain some of the leached chemicals) on land. The flow of 'chemicals entering the environment from wastewater' is a function of the amount of 'chemicals in wastewater' and our 'ability to remove chemicals in wastewater treatment processes'.

Chemicals from plastics can also enter the environment through other non-landfill sources. This primarily occurs through the previously described 'leaching of chemical additives' and 'in use chemical leaching' factors. The amount of 'chemicals in environment' can also be reduced through 'chemical decay' as these substances break down into different molecules depending on their 'decay rate'.

7.4. Representing human and environmental health implications

This section describes how the chemical additives from plastics can influence environmental and human health (Figure 27). The physical implications of plastics in the environment are also represented in this diagram.

Figure 27. Human and environmental health implications



As mentioned, ‘plastics in uncontrolled environment(s)’ can have physical implications on ‘environmental harm’. This is represented by an influence in the same direction, where an increase in the former leads to an increase in the latter. ‘Environmental harm’ is also directly influenced (in the same direction) by the amount of ‘chemicals in the environment’, the ‘toxicity of chemical additives’, and any potential ‘chemical interactions creating new or unknown harmful byproducts’. For example, phthalates and brominated flame retardants (BFRs) can interact to create harmful brominated dioxins and furans. However, interactions between many of the chemical additives (stabilisers, plasticisers, antioxidants, colourants, etc.) may produce harmful byproducts, including potentially toxic compounds that are still not fully understood.

‘Environmental harm’ has an opposite influence on the ‘environmental health’ and ’ecosystem processes’, which subsequently influences the ‘environmental carrying capacity’. That is, an increase in environmental harm, decreases the carrying capacity of the environment.

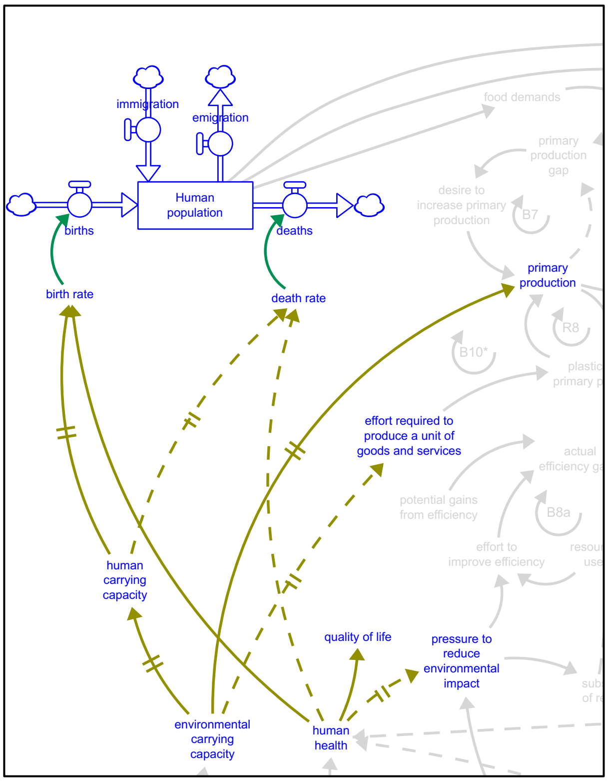
As well as affecting environmental health, many of these factors also directly influence ‘human health’. ‘In use chemical leaching’, ‘chemicals in environment’, and the ‘toxicity of chemical additives’, all have an opposite influence on ‘human health’. An increase in these factors will lead to a decrease in ‘human health’.

7.5. Representing carrying capacity

This section provides a brief contextual overview of how the generic primary production and human population structures are influenced by carrying capacity and health factors. These structures are shown in Figure 1.

The ‘environmental carrying capacity’ has a delayed same influence on the quality and quantity of ‘primary production’ and a delayed opposite influence on the ‘effort required to produce a unit of goods and services’. The ‘environmental carrying capacity’ also affects people through a delayed same influence on ‘human carrying capacity’. These conceptual pathways that influence carrying capacity are often under-appreciated, yet they are very important, long-running and impactful. Making them explicit, even though examples may not yet be fully understood, is an important objective of this work.

Figure 28. Carrying capacity and health implications on primary production and human population

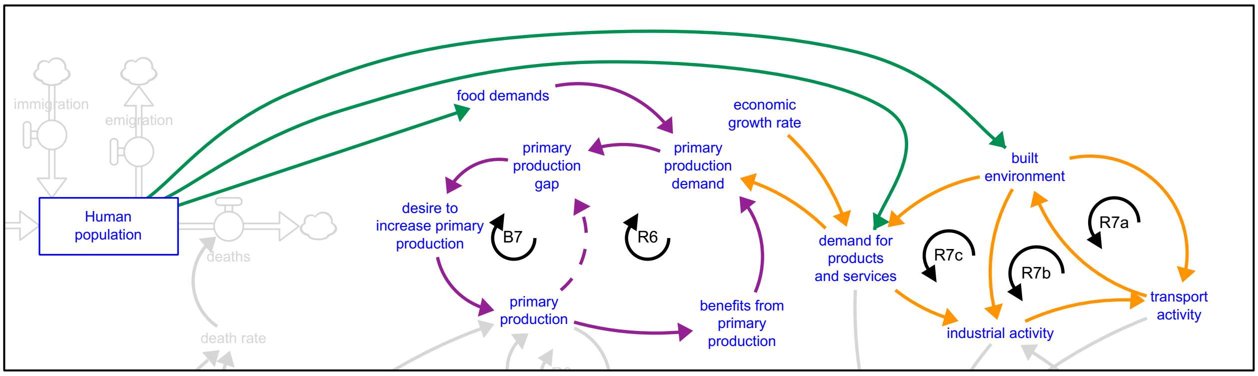


The ‘human carrying capacity’ influences the ‘birth rate’ and ‘death rate’ in the same and opposite directions, respectively. That is, an increase in ‘human carrying capacity’ can increase the ‘birth rate’ and/or decrease the ‘death rate’. The inverse is also true related to any potential decrease in ‘human carrying capacity’. ‘Human health’ impacts also have a same influence on the birth rate, and an opposite influence on the death rate. Changes in these rates go on to have obvious implications for the ‘human population’ (structure described earlier in section 6). ‘Human health’ and ‘human carrying capacity’ can therefore be considered complementary factors that influence the ‘human population’ in similar ways. ‘Human health’ also has a same influence on ‘quality of life’ and an opposite delayed influence ‘pressure to reduce environmental impact’.

7.6. Representing demand for products and services

This section provides a summary of how the population influences primary production and demand for products and services. These structures are shown in Figure 29.

Figure 29. Human population and the demand for products and services



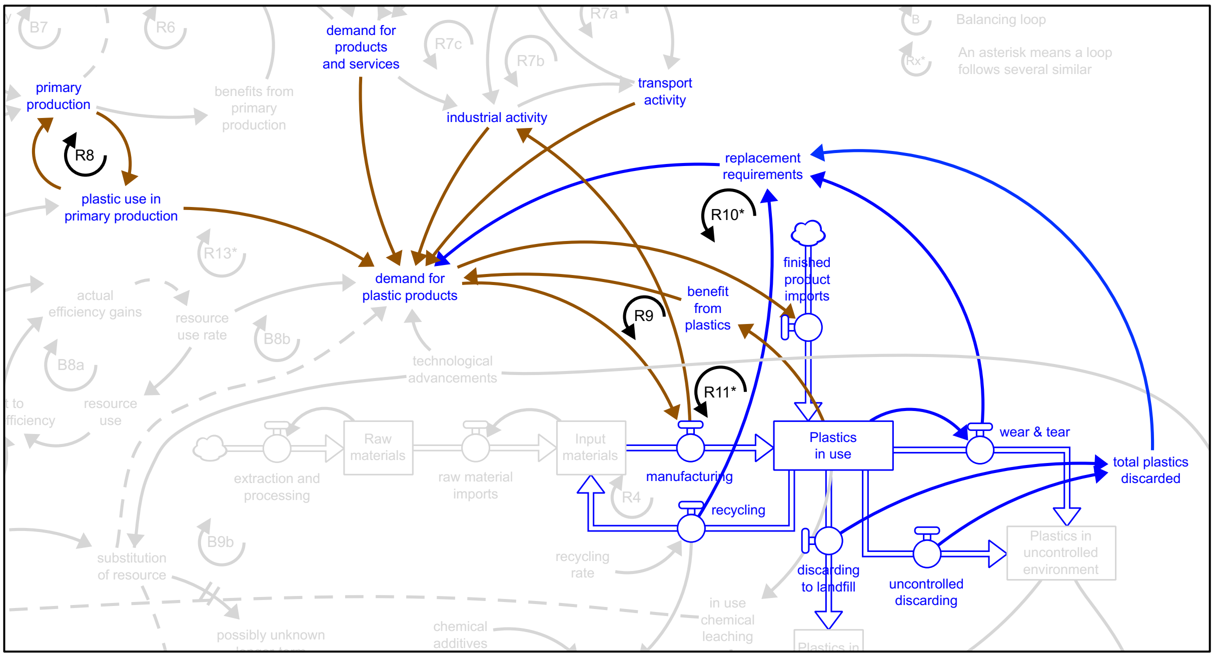
‘Human population’ influences three main factors: ‘food demands’, the ‘built environment’ and ‘demand for products and services’. These influences all occur in the same direction, whereby an increase in population leads to an increase in all of the other factors. An increase in ‘food demands’ leads to an increase in the ‘primary production demand’, which is incorporated into the common primary production structure, shown here as *balancing loop B7* and *reinforcing loop R6* (see section 6). The ‘built environment’ has a same influence on ‘transport activity’, which also has a same influence on the ‘built environment’ – resulting in *reinforcing loop R7a*. The ‘built environment’ also has a same influence on the amount of ‘industrial activity’, which also has a same influence on ‘transport activity’, thereby completing an additional *reinforcing loop R7b*. Finally, the ‘built environment’ also has a same influence on the ‘demand for products and services’. This then also has a same influence on both ‘primary production demand’ (which contributes to the primary production) and ‘industrial activity’, which (via ‘transport activity’ and ‘built environment’) contributes to another *reinforcing loop (R7c)*.

In short, there are a range of inter-connected reinforcing loops relating ‘human population’ to the demands we place on our natural and built environments. These all tend to reinforce each other and have flow-on implications for the ‘demand for products and services’.

7.7. Representing demand for plastic products

This section describes the various influencing factors that contribute to the demand for plastic products and the various outputs from that demand. This dense set of interrelated factors are shown in Figure 30.

Figure 30. Demand for plastic products



‘Demand for plastic products’ is driven by a series of factors that all influence this demand in the same direction. These factors include the amount of ‘plastic use in primary production’ which in turn is related to the amount of ‘primary production’. As plastics are continually being implemented in primary production to increase productivity and decrease costs, this leads to the creation of a *reinforcing feedback loop (R8)*. The amount of ‘plastic used in primary production’ is also influenced by the ‘effort required to produce a unit of goods and services’. This is related to the concept of return on investment, in that as products become harder to produce, more resources are invested to generate the same level of output. Additional drivers of ‘demand for plastic products’ include the following:

- The ‘demand for products and services’ due to many of these products and services being made from or enabled by plastics.
- The amount of ‘industrial activity’ as plastic products are often required for this ‘industrial activity’ to occur, as well as commonly being included in both the inputs to, and outputs of, this activity.

- The amount of 'transport activity' through both the production of vehicles and through their use, with consumables such as tyres being largely made from plastics.

A change in the 'demand for plastic products' produces the same direction of influence on 'manufacturing' and/or 'finished product imports'. The 'manufacturing' process itself is a form of 'industrial activity', which completes the *reinforcing loop R9*.

Assuming plastic products provide some form of beneficial service to their user, then as they wear out or are thrown away, people will want to replace them. The amount of 'discarding to landfill' and 'uncontrolled discarding' both contribute to the 'total plastics discarded' and subsequently influence the 'replacement requirements' of plastics. Additionally, the amount of 'wear & tear' and 'recycling' also both contribute to the 'replacement requirements'. These 'replacement requirements' further add to demand, with all of these factors producing an influence in the same direction – i.e. an increase in any of these factors produces an increase in 'demand for plastic products'. Greater demand leads to more plastics in use, thereby representing the *reinforcing loop R10** (when an asterisk is used on a feedback loop label, this means that there are multiple similar pathways for this loop, but they have all been captured under the same label).

The 'benefit from plastics' is also an important contributor to demand. This is driven by the amount of 'plastics in use' and represents the idea that plastic products provide some beneficial application to people. With greater proliferation of these materials, more new and novel applications are being found for them, further driving demand. These factors, along with the 'demand for plastic products' influencing the amount of 'plastic in use' creates an additional *reinforcing feedback loop (R11*)*.

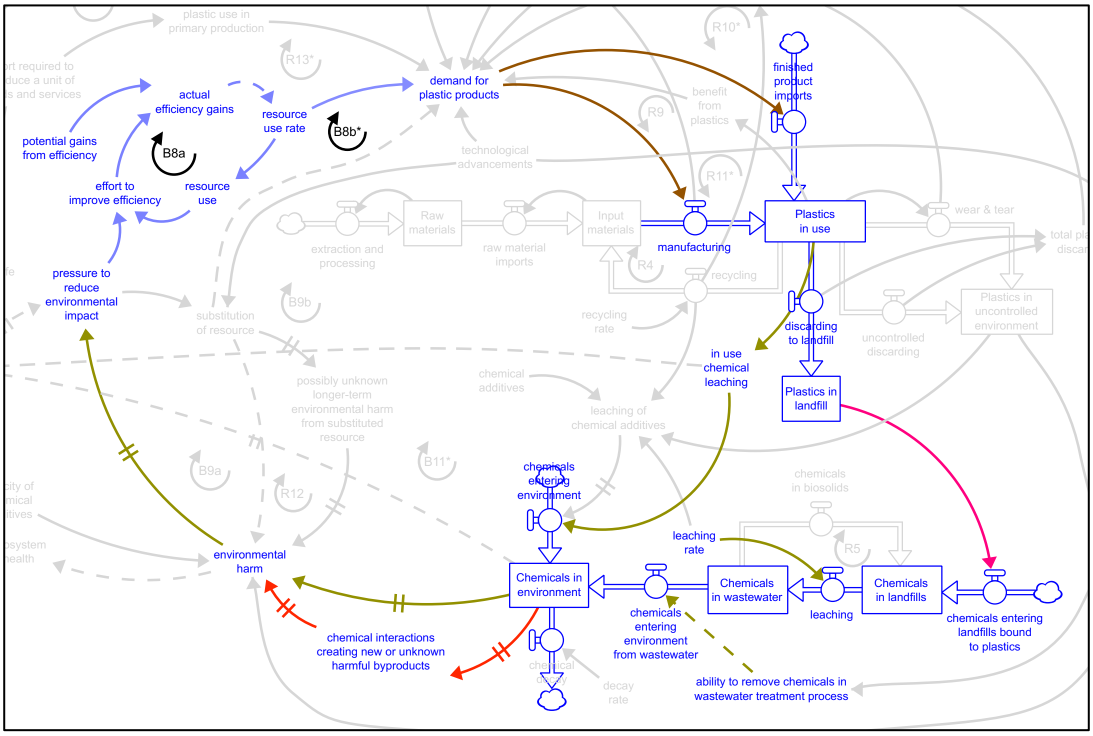
7.8. Representing future advancements

This section describes the various social and technological factors that lead to, or limit, technological advancements related to plastic use and disposal (Figure 31). These factors include areas such as efficiency gains, substitution, and various other advancements that can both mitigate and reinforce the demand for plastics and the potential harm they cause.

Deteriorating 'environmental health' and 'human health' impacts increase the 'pressure to reduce environmental impact'. In turn, this pressure can influence and activate the efficiency gains *balancing loop B8a*. This is a version of the common structure explained in section 6. That is, as 'effort to improve efficiency' increases, this drives up efficiency gains and reduces resource use, which subsequently reduces any additional 'effort to improve the efficiency'. However, these efficiency gains are limited by the 'potential gains from efficiency. For example, the act of "lightweighting" is a common approach to try and use less materials while achieving the same outcomes. This is when slightly less plastic is used to produce the same product, in effect making the components of the product thinner or lighter. This may reduce resource use and ease the pressure for further improvements, but there are obvious limits to such gains. Paradoxically, these gains may also result in other unintended consequences such as increasing litter (as they may break more easily), etc.

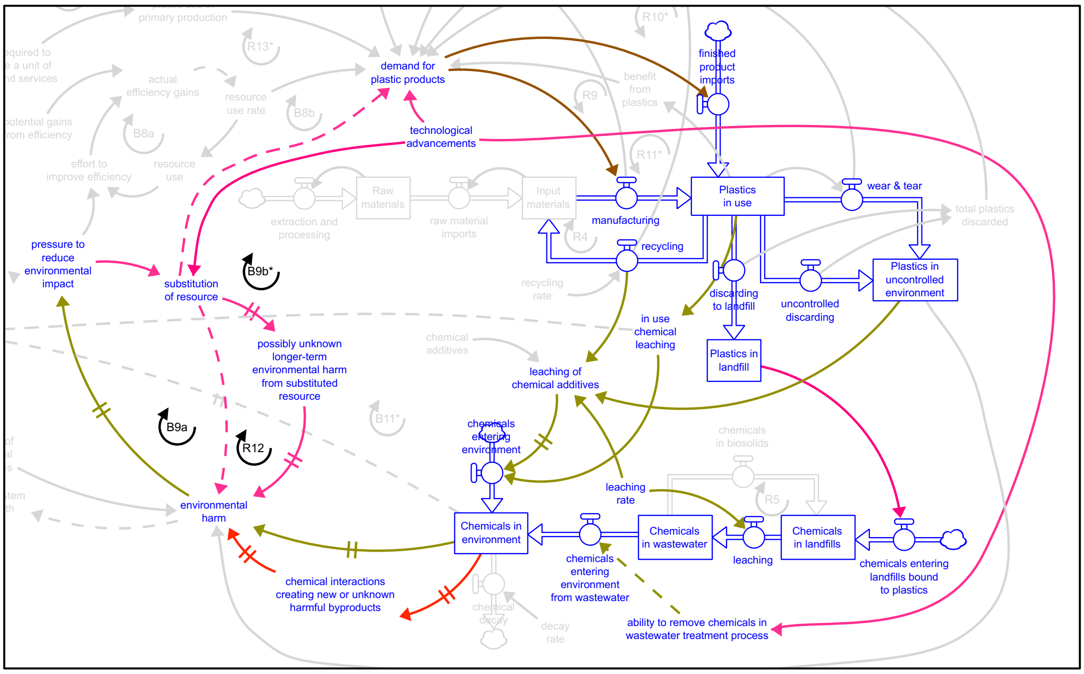
The link between resource use and demand contributes to the *balancing loop B8b**, which is a feedback loop through the wider system. That is, when efficiency gains lead to a reduction in 'resource use rate', this reduces the demand for plastics and leads to less plastics in use. This reduces the amount of chemical additives that eventually leach out and accumulate in the environment, leading to a relative reduction in 'environmental harm'. In the longer term, this reduces the pressure to improve efficiency, thereby reducing the 'effort to improve efficiency' and limiting further efficiency gains.

Figure 31. Efficiency gains in plastic use



A change in the 'pressure to reduce environmental impact' also has a same influence on the 'substitution of resources' (Figure 32). This factor represents where plastics may be substituted for different materials that are not perceived to be as harmful to the environment. Substitution is also influenced in a same direction by changes in 'technological advancements'. This factor represents technological advancements that may produce a more suitable material than plastic. This 'substitution of resources' has multiple different effects. A change in this factor produces an opposite change in both 'demand for plastic products' and the 'environmental harm'. These two influences represent the intended outcomes of the 'pressure to reduce environmental impact' and filter through the system to complete the *balancing feedback loops B9a and B9b,* respectively.

Figure 32. Substitution of plastics for another material



In *B9a*, an increase in environmental harm leads to a delayed increase in the pressure to reduce environmental impacts, which leads to a substitution of resources that decrease environmental harm. In *B9b*, that same harm, pressure and substitution lead to a reduction in plastic demand and, subsequently, less plastics in use. This reduces the amount of chemical additives that eventually leach out and accumulate in the environment, which leads to a relative reduction in 'environmental harm'.

However, increasing the 'substitution of resources' can also lead to more 'possibly unknown longer-term environmental harm from substituted resources'. This is represented by the *reinforcing feedback loop R12,* which works against *balancing loop B9a*. This is an example of the common structure representing the challenges of substitution described earlier in this report.

Substituting plastics with alternative materials can lead to unintended environmental consequences, especially if the substitutes introduce new problems or exacerbate existing ones.

For example, biodegradable plastics may require specific conditions (such as high temperatures in industrial composting facilities) to break down fully. In natural environments, they may only partially degrade, leading to microplastic pollution. Alternatively, if biodegradable plastics are sent to landfills, they can produce methane emissions.

Finally, 'technological advancements' can also have a direct influence in the same direction on both 'demand for plastic products' and the 'ability to remove chemicals from wastewater treatment processes'. This means that technology has the ability to provide substitutes for plastics in an attempt to reduce the harm from these materials and their chemical additives, but these technologies can also create new applications for plastics and drive up their demand.

7.9. Additional feedback structures

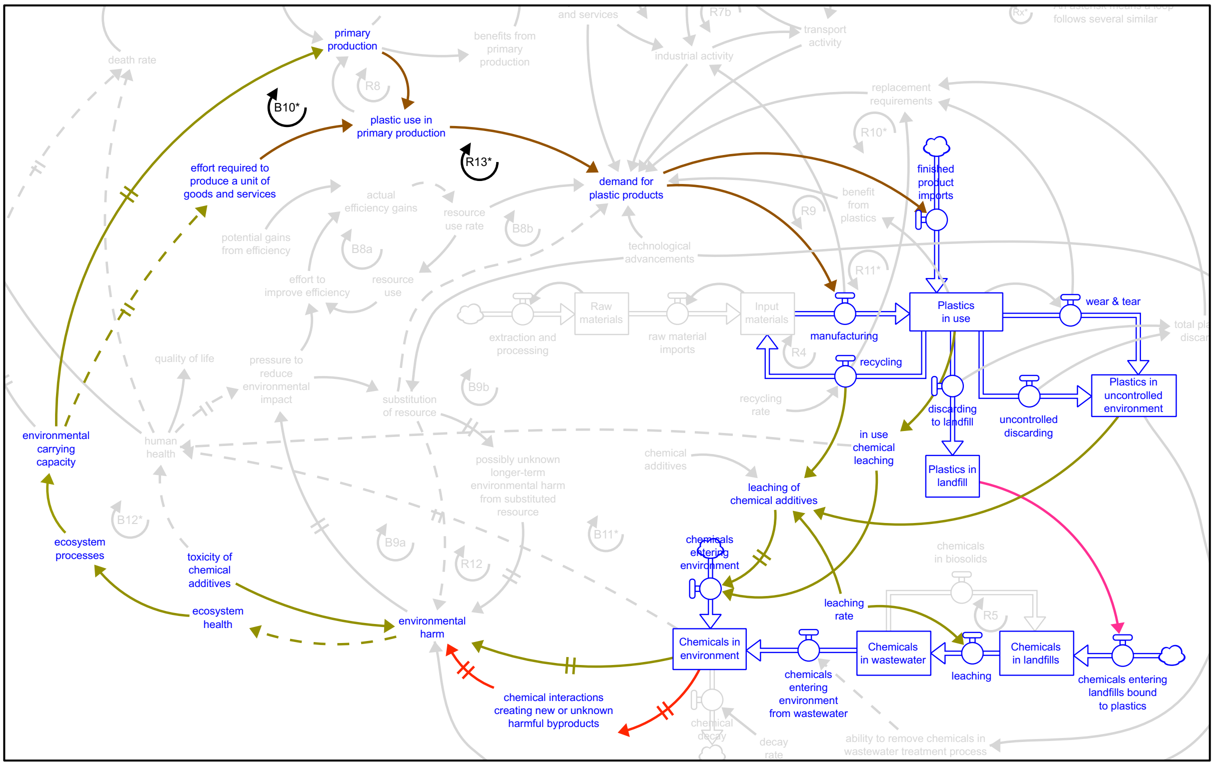
Many of the smaller and more direct feedback mechanisms have been described in the subsections above. However, as shown in the high-level overview, there are also multiple feedback mechanisms that incorporate several different parts of the wider plastics and chemical additives diagram.

7.9.1. Production feedbacks

This section describes the larger feedback mechanisms related to plastics and chemical additives and how they correspond to the carrying capacity of our natural world and its ability to regenerate (Figure 33). This shows two main sets of feedback structures related to the effort required for production (*R13**) and the ability to regenerate that production (*B10**). These are comparable to the high-level *compensatory effort in production (R2*)* reinforcing loop and the *renewable resource regeneration (B3*)* balancing loop in the high-level overview diagram, respectively.

The amount of 'plastics in use' filters through various pathways within the value chain and leads to physical and chemical accumulations in the environment. An increase in these various accumulations leads to increases in 'environmental harm', which decreases 'ecosystem health'. In turn, this leads to a reduction in 'ecosystem processes' and the 'environmental carrying capacity'.

Figure 33. Ability and effort required to maintain production



Microplastics and their associated chemical additives are known to have a multitude of effects on various ecosystems. For example:

- Many of these substances are known endocrine disruptors that affect the fertility of organisms. Some evidence suggests that marine organisms, such as bivalves, exposed to microplastics have lower reproduction rates. Additionally, microplastics can impair their filtering capacity, leading to a smaller and less effective population. Bivalves play a crucial role in water purification, which influences water quality and fish stocks in coastal ecosystems.
- Plastics can be used directly in primary production through items such as water pipes, baleage wraps, weed mats, bird nets, etc. Additionally, the application of biosolids, wastewater, compost, etc., can unintentionally add vast amounts of microplastics and their associated chemicals to land. This can alter the physical properties of soil by affecting its structure, porosity, and water retention capacity. They can also interfere with plant growth by affecting processes like nutrient uptake, photosynthesis, and respiration while also affecting the microorganisms that support these processes.

In the *reinforcing loop R13**, this leads to a greater ‘effort required to produce a unit of goods and services’, resulting in more resources being used. This drives up the ‘demand for plastic products’ and further increases the amount of ‘plastics in use’. These feedback mechanisms are similar to the *compensatory effort in production* reinforcing loop in the overview diagram. An example of this could be a reduction in soil productivity, leading to the application of slow-release fertilisers, which are often coated in a plastic resin, thereby leading to more plastic and chemicals entering the environment.

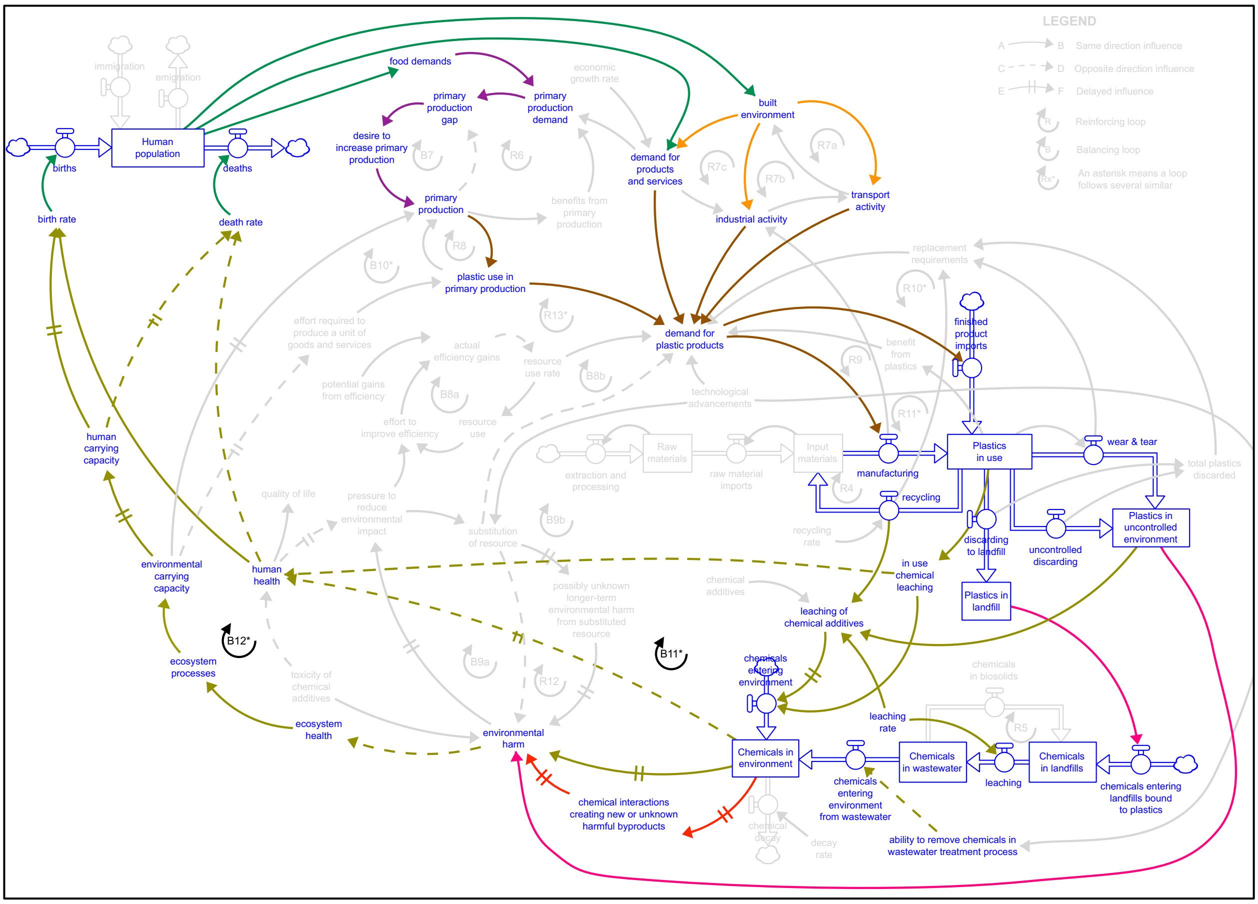
Alternatively, the reduction in the ‘environmental carrying capacity’ also reduces the ability to support ‘primary production’. This leads to less plastics being used in this sector, which reduces demand and results in a relative reduction in the amount of ‘plastics in use’. This completes a set of *balancing feedback loops (B10*)*, which are similar to the *resource regeneration* balancing loop in the overview diagram. This overview diagram uses this balancing structure to show how the depletion of renewable resources creates a limiting structure that reduces further pollution and wastes.

In summary, the contamination of soils and water bodies by plastics and their associated chemicals pose a significant threat to primary production, with potential long-term consequences for ecosystem health and food security. It should be noted that efforts to counteract these undesirable trends may result in additional plastics and chemicals entering the environment, which should be avoided.

7.9.2. Human population feedbacks

This section describes the larger feedback mechanisms related to how plastics and chemical additives impact the human population (Figure 34). This shows two main sets of feedback structures related to human health (*B11**) and human carrying capacity (*B12**). These are comparable to the high-level *pollution & wastes impacts on humans (B5*)* and the *carrying capacity of human activity (B6*)* balancing loops in the overview diagram, respectively.

Figure 34. Human health and carrying capacity impacts



The human population creates multiple demands on the natural and built environment. Plastics are widely used in the built environment, in the creation of products in the provision of services, and in assisting in food production. An increase in the population therefore increases the demand for ‘plastic products’, subsequently leading to more ‘plastics in use’. These plastics can leach various chemical additives and result in negative effects on ‘human health’. Several of these effects are known, such as the carcinogenic nature of some plastics and their additives, their ability to disrupt people’s endocrinology, and a source systemic inflammation. Additionally, there are also several effects of plastic and chemical exposure that are less understood, including any potential cumulative and synergistic effects.

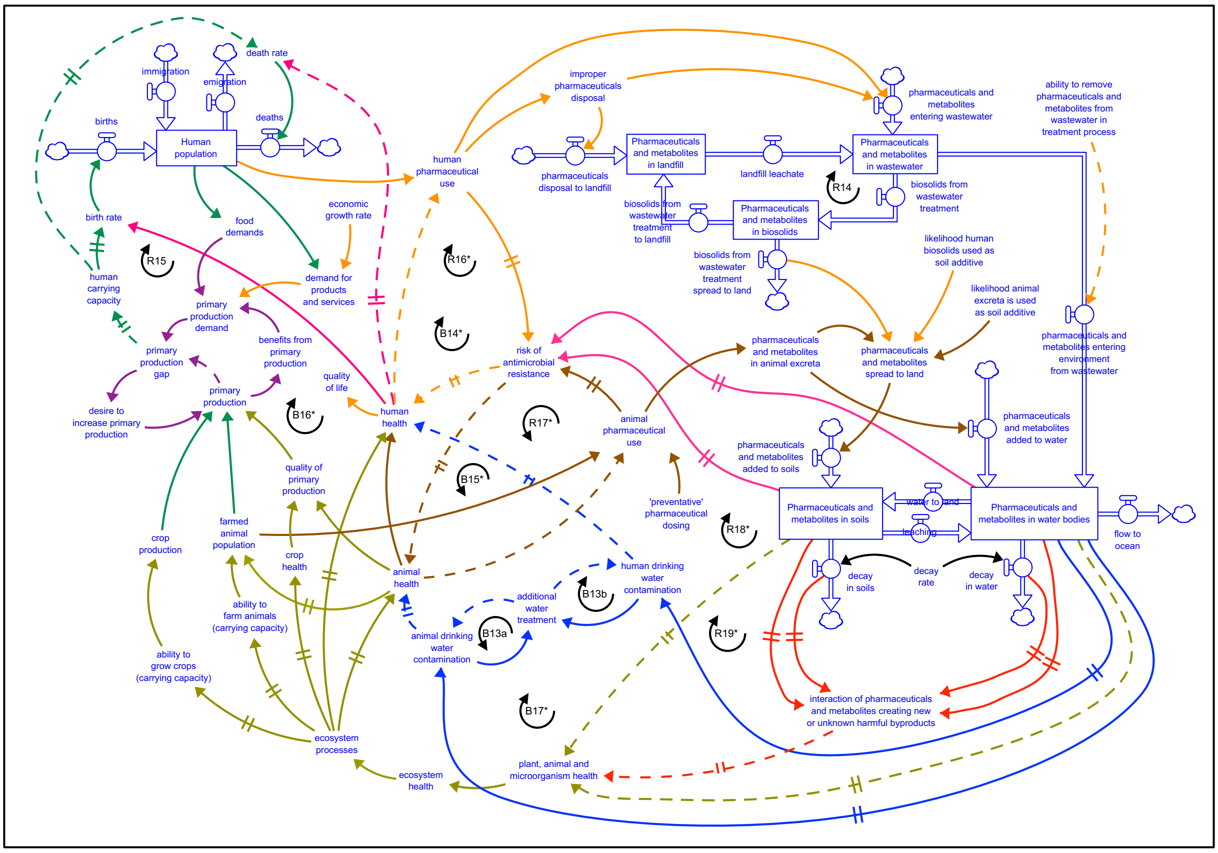
A reduction in ‘human health’ can reduce the ‘birth rate’ and/or increase the ‘death rate’, both of which act to reduce the ‘human population’ and produce a set of *balancing feedback loops (B11*)*. These feedback mechanisms are similar to the *pollution & wastes impacts on humans (B5*)* balancing loop in the overview diagram.

Additionally, plastics and their chemical additives have multiple different pathways to eventually end up in the environment and lead to an increase in ‘environmental harm’. This reduces ‘ecosystem health’ and ‘ecosystem processes’ that all living organisms depend on (see previous example break out box). Subsequently, this reduces the ‘environmental carrying capacity’ and, therefore, the ‘human carrying capacity’. A reduction in these carrying capacities also has the effect of influencing human birth and death rates in a manner that reduces the ‘human population’. This completes another set of *balancing feedback loops (B12*)*, which are similar to the *carrying capacity of human activity (B6*)* balancing loop in the overview diagram.

8. Pharmaceuticals

This section is the second of three separate sections that describe the detailed causal diagrams that were developed in this project. This causal diagram relates to pharmaceutical use in people and animals in Aotearoa-New Zealand. An overview of the diagram is shown in Figure 35. A large version can be found in Appendix 1.

Figure 35. Overview of the pharmaceuticals diagram



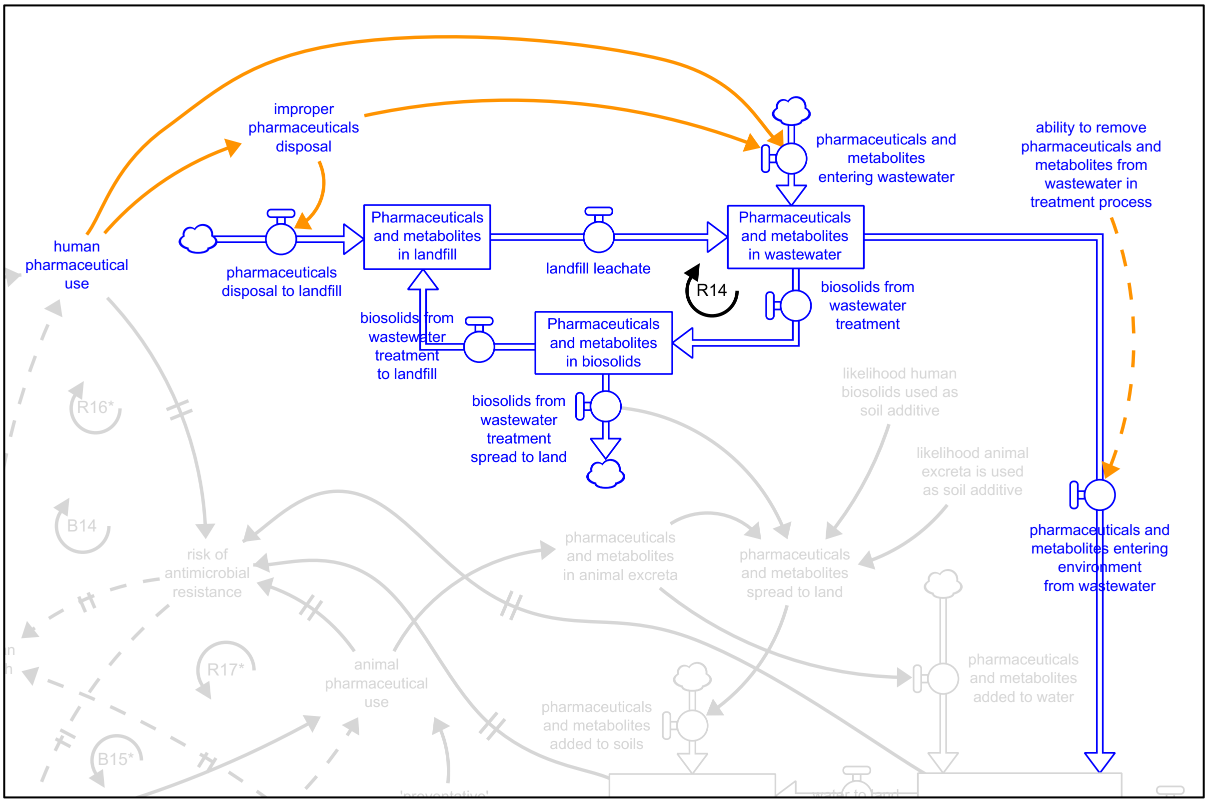
8.1. How pharmaceuticals enter the environment

This section describes the use of pharmaceuticals in both animals and humans, and how these can enter the environment. Stocks and flows are used to capture the flow of these pharmaceuticals and their derivatives through the environment. The following descriptions have been separated based on the source of the pharmaceuticals being from either people or animals.

8.1.1. Pharmaceutical use in people

This subsection highlights the mechanisms by which human pharmaceuticals enter the environment, as shown in Figure 36.

Figure 36. Human pharmaceutical use



Pharmaceuticals used by people can enter into the environment in two distinct ways:

- Pharmaceuticals pass through people in both unmetabolised and metabolised forms. This informs the first pathway, ‘human pharmaceutical use’ has a same influence on ‘pharmaceuticals and metabolites entering wastewater’.
- Unused pharmaceuticals are also often disposed of incorrectly by sending them to landfill (via household waste collections) or adding them to the waste water system (down the sink/toilet). This informs the second pathway, ‘human pharmaceutical use’ has a same direction influence on ‘improper pharmaceuticals disposal’ This subsequently has a same direction influence on both ‘pharmaceutical disposal to landfill’, and ‘pharmaceuticals and metabolites entering wastewater’.

All of these pathways eventually lead to the accumulation of ‘pharmaceuticals and metabolites in wastewater’. However, the ‘pharmaceuticals disposal to landfill’ initially flows into the stock of ‘pharmaceuticals and metabolites in landfill’, which are eventually transported out via the ‘landfill leachate’ to end up in the stock of ‘pharmaceuticals and metabolites in wastewater’.

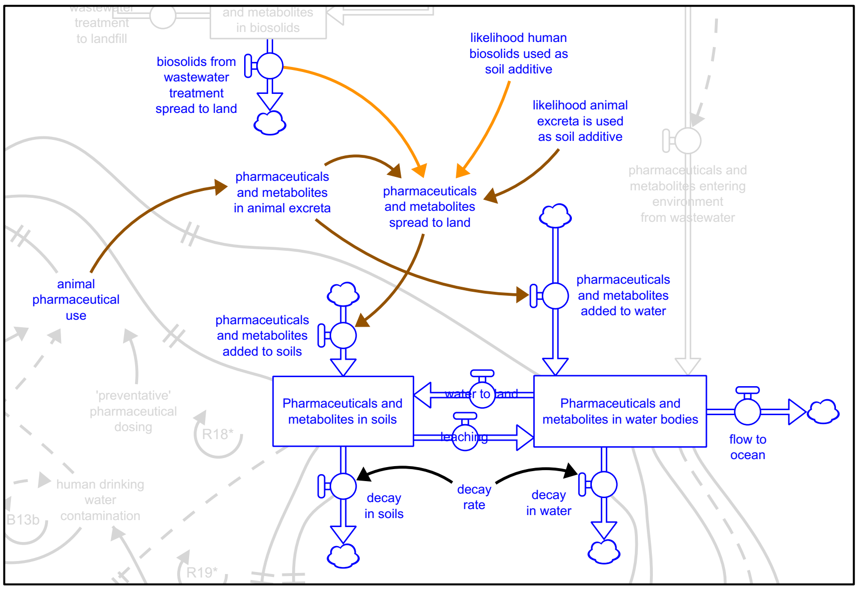
The stock of ‘pharmaceuticals and metabolites in wastewater’ has two distinct paths in which they can be transported out of the wastewater system. They could enter the environment directly via the flow of ‘pharmaceuticals and metabolites entering environment from wastewater’, which is oppositely influenced by our ‘ability to remove pharmaceuticals and metabolites from wastewater in treatment process’ (the better the treatment, the less enters the environment). Alternatively, they could be removed in the ‘biosolids from wastewater treatment’, which leads to an accumulation of ‘pharmaceuticals and metabolites in biosolids’. These biosolids can either be spread to land or returned to landfill, which completes the *reinforcing loop R14*.

The potential for human excreta to be spread to land is covered in the following section, with the same pathway for animal excreta.

8.1.2. Pharmaceutical use in animals

This subsection highlights the mechanisms by which animal pharmaceuticals enter the environment, as shown in Figure 37.

Figure 37. Animal pharmaceutical use



'Animal pharmaceutical use' leads to 'pharmaceuticals and metabolites in animal excreta' via a same direction influence. This excreta can be directly spread to land, along with human biosolids, depending on the likelihood of both of these factors being used as soil additives. For example, most livestock in Aotearoa-New Zealand will deposit their excreta directly onto the soils while they graze, while effluent collected from dairy sheds is often irrigated back onto the land. It was also noted that there are examples of human waste being spread to land after treatment. 'Pharmaceuticals and metabolites spread to land' influences the flow of 'pharmaceuticals and metabolites added to soils' in the same direction. Animal excreta can also directly enter water bodies (either by animals defecating directly into waterways, or by excreta being washed into water bodies by rain/overland flow paths) via a same relationship on the flow of 'pharmaceuticals and metabolites added to water'. This flow combines with the human 'pharmaceuticals and metabolites entering the environment from wastewater' to accumulate in the stock of 'pharmaceuticals and metabolites in water bodies'.

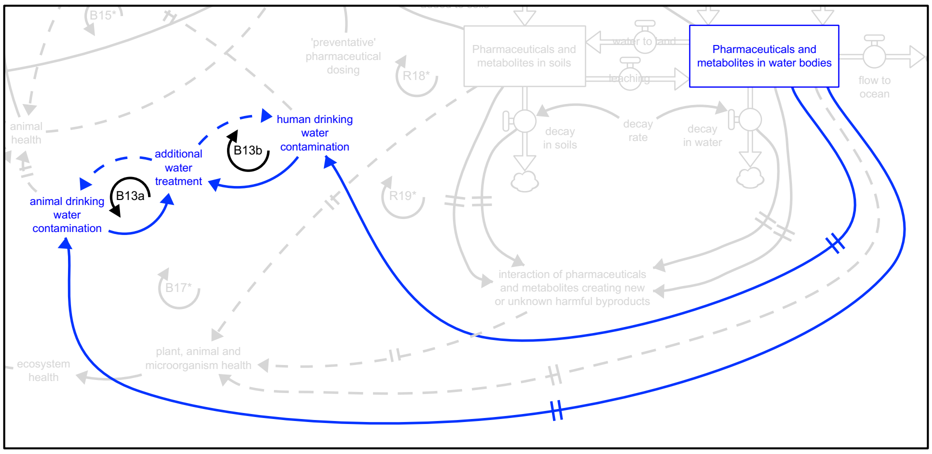
The pharmaceuticals and metabolites in soils and water bodies can readily interact through processes such as the leaching of soil moisture into water bodies and groundwater systems, or in the other direction by water being applied to the land via irrigation. Both these stocks may have 'pharmaceuticals and metabolites being removed through natural decay, while those in water bodies can also be removed through the 'flow to ocean'. A stock representing the ocean has not been incorporated in this diagram; however, it should be noted that this pathway will continue to allow pharmaceuticals to build up in the ocean and may have potential impacts on marine ecosystems.

8.2. Representing drinking water contamination

This section describes how pharmaceuticals and metabolites can lead to the contamination of human and animal drinking water, as shown in Figure 38.

A simple set of causal relationships exist whereby the amount of 'pharmaceuticals and metabolites in water bodies' has a same direction influence on both 'human drinking water contamination' and 'animal drinking water contamination'. For example, Auckland sources a portion of its drinking water from the Waikato River, which contains treated wastewater from multiple towns/cities upstream. Although pharmaceuticals have been found in drinking water around the world, very few regions routinely test for these[3].

Figure 38. Drinking water contamination

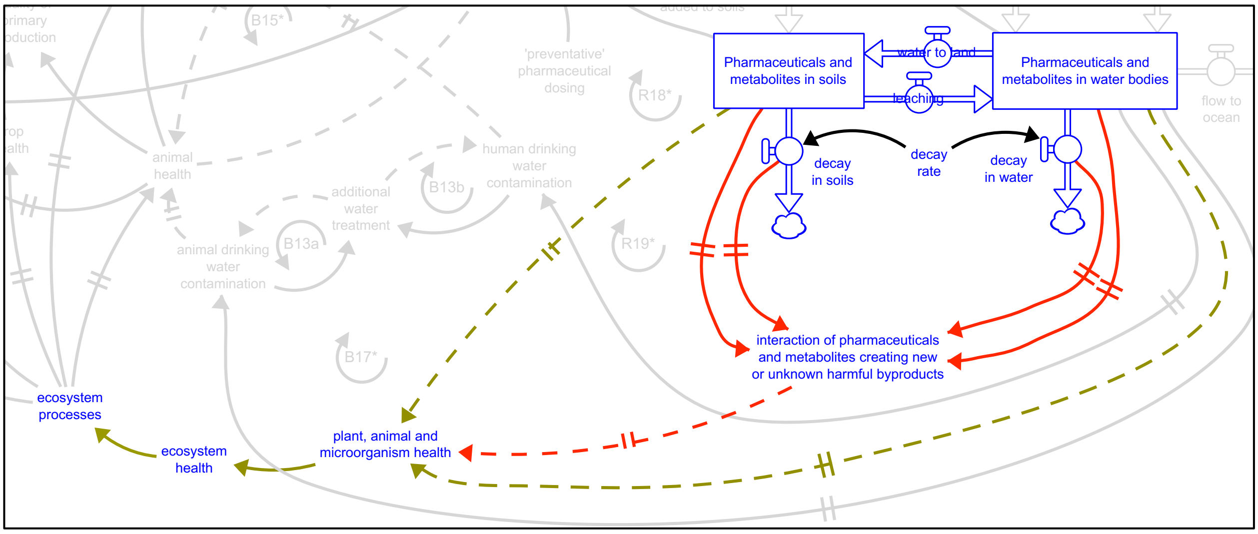


Both of these factors subsequently have a same influence on the need for ‘additional water treatment’, which in turn has an opposite influence on contamination levels. This is represented by the *balancing feedback loops B13a and B13b*, respectively. In other words, if there are more pharmaceuticals and metabolites in natural water bodies, then there is a higher risk of drinking water contamination, which requires additional water treatment to mediate. This additional water treatment, in turn, reduces the contamination levels of both animal and human drinking water supplies.

8.3. Representing ecosystem impacts of pharmaceuticals in the environment

This section also describes a relatively simple set of causal relationships that show how pharmaceuticals and metabolites in the environment can impact ecosystem processes (Figure 39).

Figure 39. Ecosystem impacts from pharmaceuticals and metabolites in the environment



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[3] WHO Report: Pharmaceuticals in drinking-water

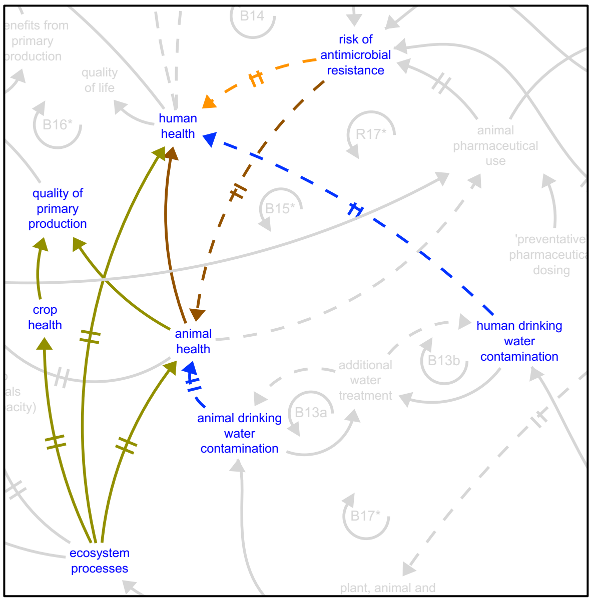
The amount of pharmaceuticals and metabolites in soils and water bodies have an opposite influence on 'plant, animal and microorganism health'. For example, NSAIDs[4] (which can cause renal failure) and oestrogen's from contraceptive pills (which can cause hormonal and reproductive disruptions) have been found to cause issues in aquatic and terrestrial organisms.

Additionally, various different types of pharmaceuticals and metabolites in the soils and water bodies can interact with each other, either directly or as they decay, leading to potential cumulative and synergistic effects. This means that if there are more pharmaceuticals and metabolites in soils and water bodies, then more are decaying into new substances, which increases the likelihood of the 'interaction of pharmaceuticals and metabolites creating new or unknown harmful byproducts'. These potentially new and unknown harmful byproducts may have an opposite influence on 'plant, animal and microorganism health'. The health of these species influences 'ecosystem health' and, therefore, 'ecosystem processes' in the same direction.

8.4. Representing human, animal, and crop health

The section describes the relationships that influence human, animal, and crop health outcomes, as shown in Figure 40.

Figure 40. Human, animal, and crop health



The previously described 'ecosystem processes' have a delayed same direction influence on 'human health', 'crop health', and 'animal health'. The latter two factors ('crop health' and 'animal health') both have a same influence on the 'quality of primary production'. 'Animal health' also has a same influence on 'human health' based on the human consumption of animals and animal products. Additional drivers of both 'human health' and 'animal health' include the following:

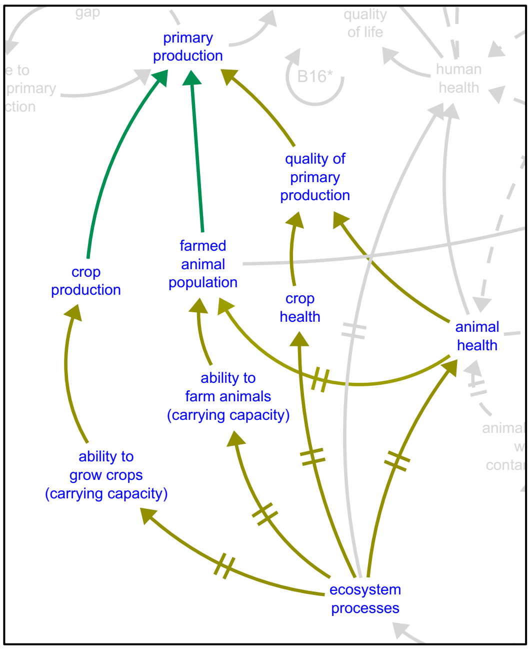
- 'Animal drinking water contamination' and 'human drinking water contamination' both have delayed opposite influences on 'animal health' and 'human health', respectively.
- The risk of antimicrobial resistance (discussed separately below) has a delayed and opposite influence on both factors as new strains of bacteria are more difficult to treat, resulting in negative health outcomes.

[4] Non-Steroidal Anti-Inflammatory Drugs

8.5. Representing primary production

This section describes how ecosystem processes influence primary production (Figure 1).

Figure 41. Primary production



As previously described, ‘crop health’ and ‘animal health’ both influence the ‘quality of primary production’. This has a same influence on ‘primary production’. The flip side of quality is the quantity of primary production. This has been incorporated by ‘ecosystem processes’ having a delayed same direction influence on both the ‘ability to farm animals’ and the ‘ability to grow crops’. These factors represent the carrying capacity of the environment and subsequently have a same influence on both ‘farmed animal population’ and ‘crop production’, respectively. ‘Farmed animal population’ is also influenced in the same direction by ‘animal health’, with all these variables subsequently having a same influence on ‘primary production’.

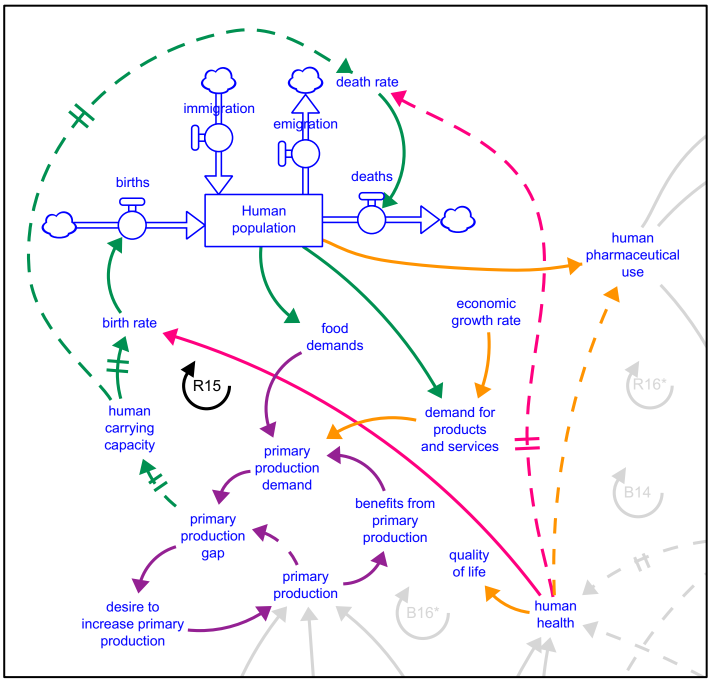
Although little is known about how pharmaceuticals and their metabolites may interact in the environment and disrupt ecosystem services, several examples were raised about the potential risks of these interactions and how they could flow through to affect primary production. For example:

- Antimicrobials can alter the composition and functioning of microbial communities, which are essential for processes like nutrient cycling and organic matter decomposition. This could reduce soil fertility, thereby affecting plant growth and reducing agricultural productivity.
- Pharmaceuticals like anti-inflammatory or endocrine-disrupting compounds can interfere with plant hormones, affecting growth and development. This also impacts the overall productivity of the environment.
- Plant growth and soil microbiome health can also affect soil structure and erosion control, thereby creating additional impacts on primary production

8.6. Representing human population

This section details the various causal factors related to human population, as shown in Figure 1.

Figure 42. Influences factors related to human population



The common primary production structure described earlier (section 6) is used here and shows how the 'primary production gap' has an opposite influence on 'human carrying capacity'. This influences the common human population structure via changes in the 'birth rate' and 'death rate'. As well as the carrying capacity, 'human health' also influences the 'birth rate' and 'death rate'.

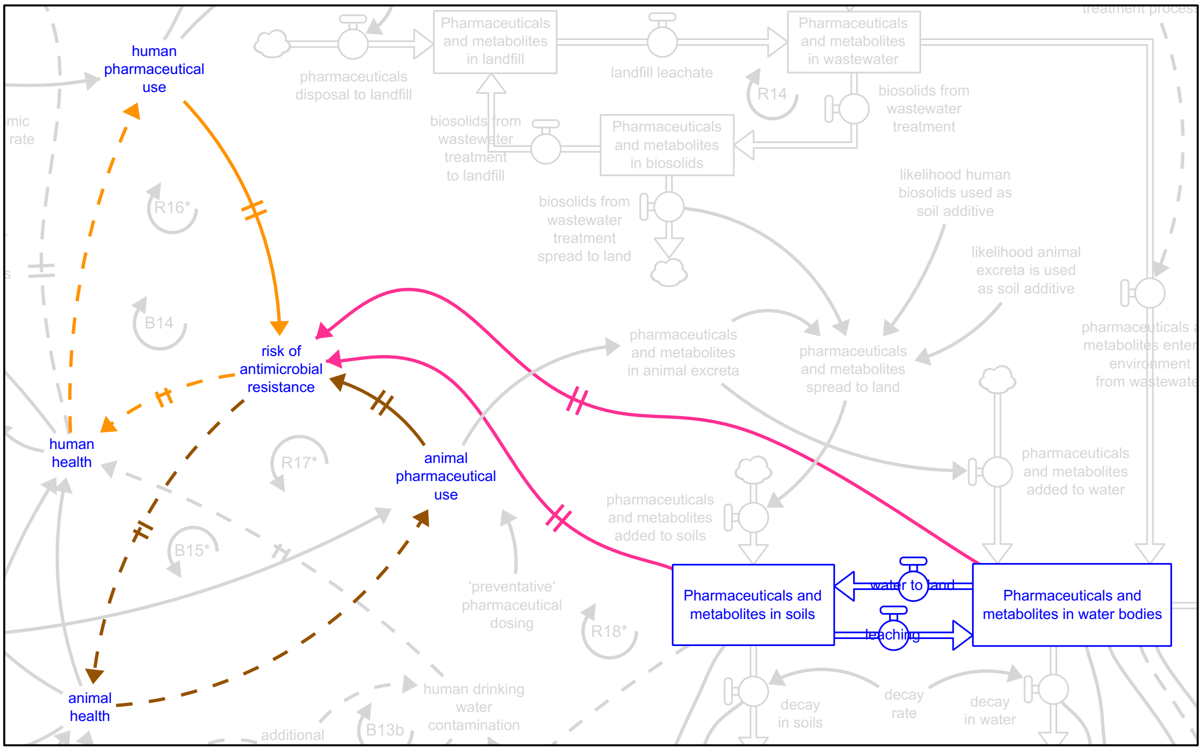
A change in the 'human population' creates a change in the same direction of both 'food demands' and the 'demand for products and services'. These factors also have a same directional influence on 'primary production demand', which completes the *reinforcing feedback loop R15*.

Finally, both 'human population' and 'human health' influence the amount of 'human pharmaceutical use' in different ways. That is, an increase in the 'human population' leads to an increase in 'human pharmaceutical use' as there are more people who require these medications. Alternatively, if the population is healthier, represented by an increase in 'human health', this should lead to a reduction in 'human pharmaceutical use' as there are fewer illnesses that require treatment.

8.7. Representing antimicrobial resistance

This section details the various factors and feedback loops that are related to antimicrobial resistance. Given the widespread use of antimicrobials (a type of pharmaceutical), their use has the potential for undesirable outcomes. This is of particular concern, and it has therefore been represented specifically in the diagram. Antimicrobial resistance occurs when bacteria, viruses, fungi, and parasites no longer respond to antimicrobial medicines (antibiotics, antivirals, antifungals, and antiparasitic) used to prevent and treat infectious diseases in humans and animals. These factors are shown in Figure 43, with the relevant feedback loops related to human and animal antimicrobial resistance detailed in the subsections below.

Figure 43. Antimicrobial resistance



Antimicrobial resistance is a natural process that occurs as pathogens evolve. However, the use (and misuse) of pharmaceuticals increases the exposure of pathogens to antimicrobial compounds, increasing the rate at which they can evolve and become resistant to medications. The effect of pharmaceutical metabolites, as well as any potential cumulative and synergistic effects, remain largely unknown.

The 'risk of antimicrobial resistance' therefore has four delayed drivers, which all have a same direction of influence:

- 'Human pharmaceutical use'
- 'Animal pharmaceutical use'
- 'Pharmaceuticals and metabolites in soils'
- 'Pharmaceuticals and metabolites in water bodies'

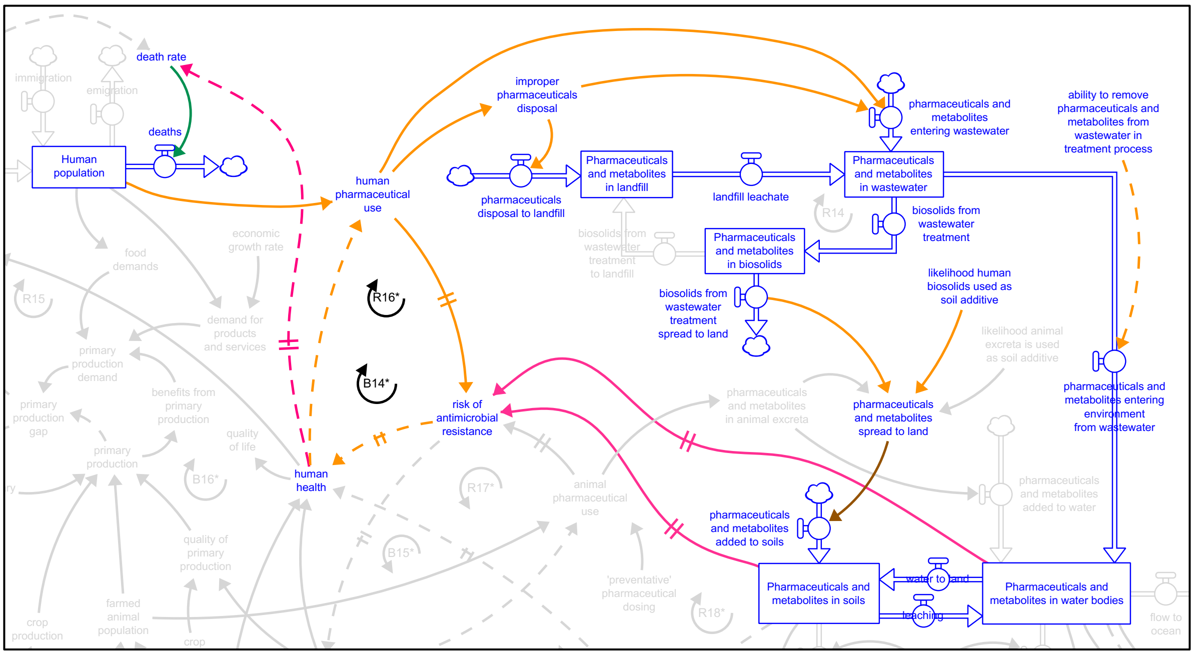
The 'risk of antimicrobial resistance' also has a delayed and opposite effect on both human and animal health outcomes. That is, an increase in the risk of antimicrobial resistance eventually reduces human health outcomes and animal health outcomes. According to the World Health Organization[5], antimicrobial resistance is considered one of the top global public health threats, with antimicrobial medicines such as antibiotics becoming ineffective and infections becoming more difficult or impossible to treat.

[5] https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance

8.7.1. Feedback mechanisms related to antimicrobial resistance in people

This subsection highlights the balancing and reinforcing feedback mechanisms related to antimicrobial resistance in humans, as shown in Figure 44. These feedback mechanisms can be considered as adaptations of the *carrying capacity of human activity (B6*)* and *compensatory effort in production (R2*)* loops from the high-level overview diagram.

Figure 44. Human antimicrobial resistance feedback loops



Changes in ‘human population’ create a change in the same direction for ‘human pharmaceutical use’. This has multiple paths by which pharmaceuticals and metabolites can lead to a delayed same direction influence on the ‘risk of antimicrobial resistance’. This could occur as a result of ‘human pharmaceutical use’ directly increasing the ‘risk of antimicrobial resistance’. Alternatively, pharmaceuticals and their metabolites could flow through the wastewater system to end up in the wider environment, which subsequently increases the ‘risk of antimicrobial resistance’. For example, if biosolids contaminated with antibiotics are spread onto land, microorganisms (specifically bacteria in this case) will be exposed to those antimicrobials, thereby increasing the risk of resistance. Both cases have the same direction of influence on the risk of ‘antimicrobial resistance’, which subsequently has a delayed opposite influence on ‘human health’.

In one set of feedback structures, a change in ‘human health’ has a delayed opposite influence on the ‘death rate’. For example, antimicrobial resistance can make infections harder to treat and makes other medical procedures and treatments much riskier (such as surgery or chemotherapy). The WHO suggests this is already directly responsible for millions of deaths each year globally[6]. This change in the ‘death rate’ influences the ‘human population’ in the opposite direction, which completes the *balancing feedback loops B14**. This set of structures are similar to the *capacity of human activity* balancing feedback loop in the high-level overview diagram. This suggests that an increase in the wastes from human activity (in this case the pharmaceuticals and metabolites in the environment) may threaten human health and our ability to sustain the population in the longer term.

In the other set of feedback structures, a change in ‘human health’ has an opposite influence on the amount of ‘human pharmaceutical use’ as people attempt to use additional pharmaceuticals to

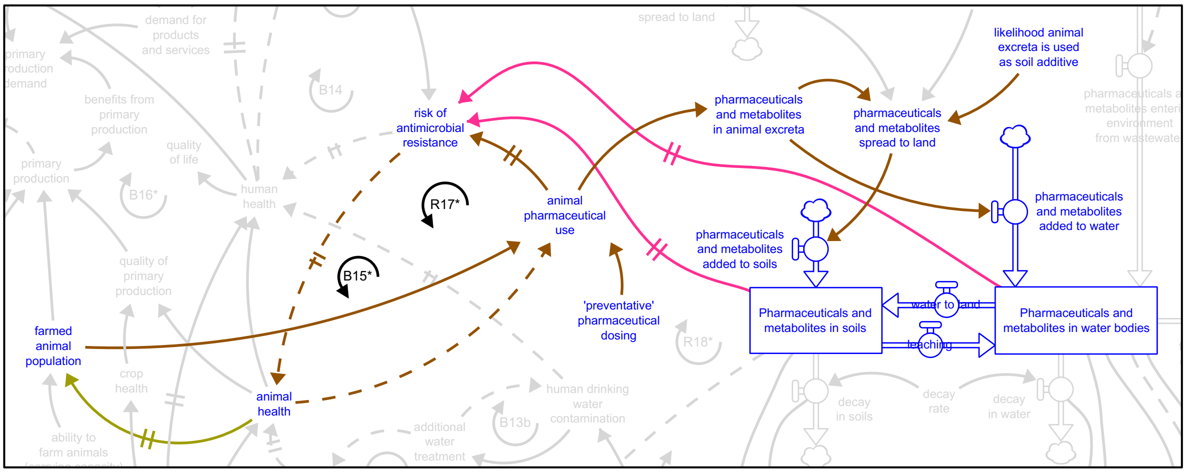
[6] ibid

improve their health. This completes the *reinforcing feedback loops R16**. This set of structures are similar to the *compensatory effort in production* reinforcing feedback loop in the high-level overview diagram. This suggests that an increase in the wastes from human activity (in this case the pharmaceuticals and metabolites in the environment) threatens human health, which requires greater efforts (more pharmaceuticals) to maintain the same level of output (human health). In other words, people may double down on the use of pharmaceuticals to remedy their poor health that results from the overuse (or misuse) of previous pharmaceutical use[7].

8.7.2. Feedback mechanisms related to antimicrobial resistance in animals

This subsection highlights the balancing and reinforcing feedback mechanisms related to antimicrobial resistance in animals, as shown in Figure 45. These are a similar set of structures to those related to antimicrobial resistance in people. The feedback mechanisms shown in this subsection can be considered as adaptations of the *renewable resource regeneration (B3*)* and *compensatory effort in production (R2*)* loops from the high-level overview diagram.

Figure 45. Animal antimicrobial resistance feedback loops



Changes in 'farmed animal population' creates a change in the same direction in 'animal pharmaceutical use'. As with human pharmaceutical use, there are multiple paths by which the chain of influence can lead to a delayed influence on the 'risk of antimicrobial resistance'. Again, as with human pharmaceutical use, this could be represented by a direct influence from 'animal pharmaceutical use' to 'risk of antimicrobial resistance'. Alternatively, 'animal pharmaceutical use' could produce an influence in the same direction on the 'pharmaceuticals and metabolites in animal excreta', which can enter the environment via either soils or waterbodies. Both cases have the same direction of influence on the risk of 'antimicrobial resistance', which subsequently has a delayed opposite influence on 'animal health'.

A set of *reinforcing feedback loops (R17*)* exist, whereby 'animal health' has an opposite influence on 'animal pharmaceutical use' as people attempt to improve 'animal health' outcomes by giving them more pharmaceuticals. Again, this set of structures are similar to the *compensatory effort in production* reinforcing feedback loop in the high-level overview diagram. That is, an increase in the wastes from our activity (in this case the pharmaceuticals and metabolites in the environment)

[7] It was noted in conversation that there may be a lack of pharmaceuticals being developed to keep up with these rapidly evolving pathogens. This would have a significant impact on the dynamics described but this has not been represented directly in the diagram.

threatens animal health and requires greater efforts (which may include more pharmaceuticals) to maintain the same health outcomes.

The identified structures in Figure 45 also reveal a set of *balancing feedback loops (B15*)*. In this case, the ‘animal health’ has a delayed influence in the same direction on ‘farmed animal population’. As an extreme case, the health of the animals can directly influence whether they live or die. This change in population influences the ‘animal pharmaceutical use’ as more animals require more pharmaceuticals. ‘Animal pharmaceutical use’ is also sometimes prescribed on a preventative basis and not necessarily based on need, which further increases the (potentially unnecessary) pharmaceutical use and thereby further increases the risk of developing antimicrobial resistance. This set of structures are similar to the *renewable resource regeneration (B3*)* balancing feedback loop in the high-level overview diagram, whereby the waste products from our agricultural practices (in this case the pharmaceuticals and metabolites in the environment) threaten our ability to sustain those agricultural practices.

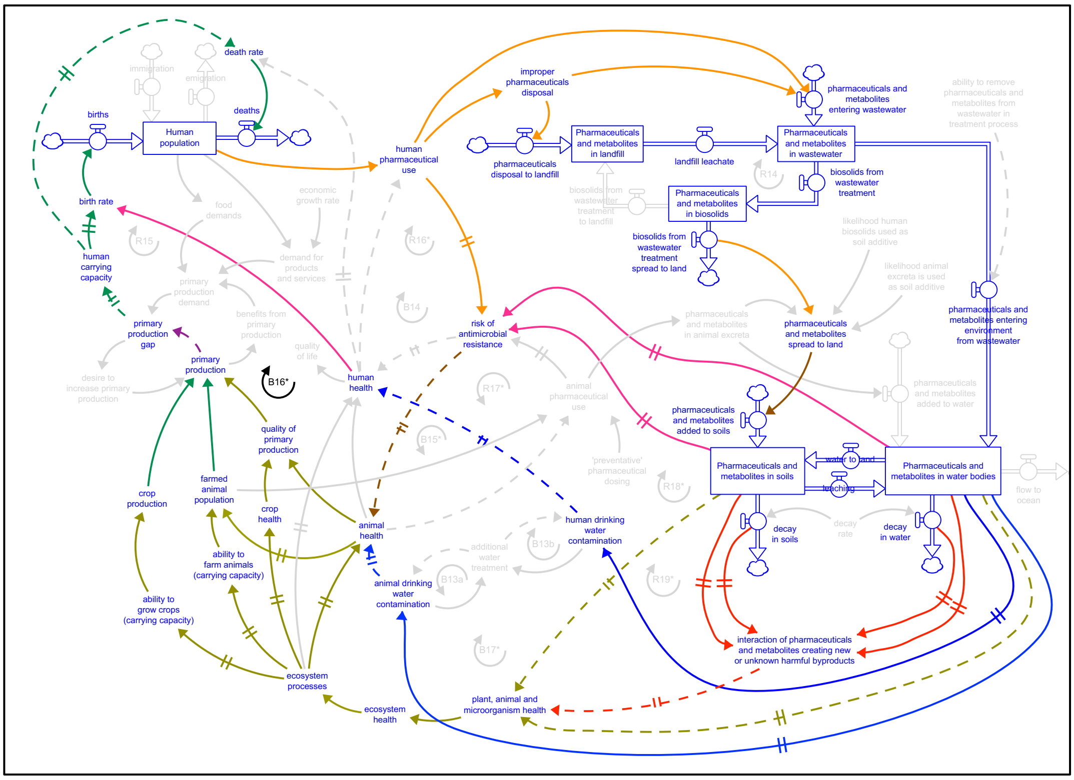
8.8. Additional feedback structures

Many of the smaller and more direct feedback mechanisms have been described in the subsections above. However, as shown in the high-level overview, there are also multiple feedback mechanisms that incorporate several different parts of the wider pharmaceuticals diagram. These have been separated out and are discussed below based on their identified feedback mechanisms.

8.8.1. Human carrying capacity feedbacks

This subsection describes the larger feedback mechanisms related to the use of pharmaceuticals and how they filter through the environment to impact the human carrying capacity (Figure 46).

Figure 46. Impact of pharmaceuticals on human carrying capacity

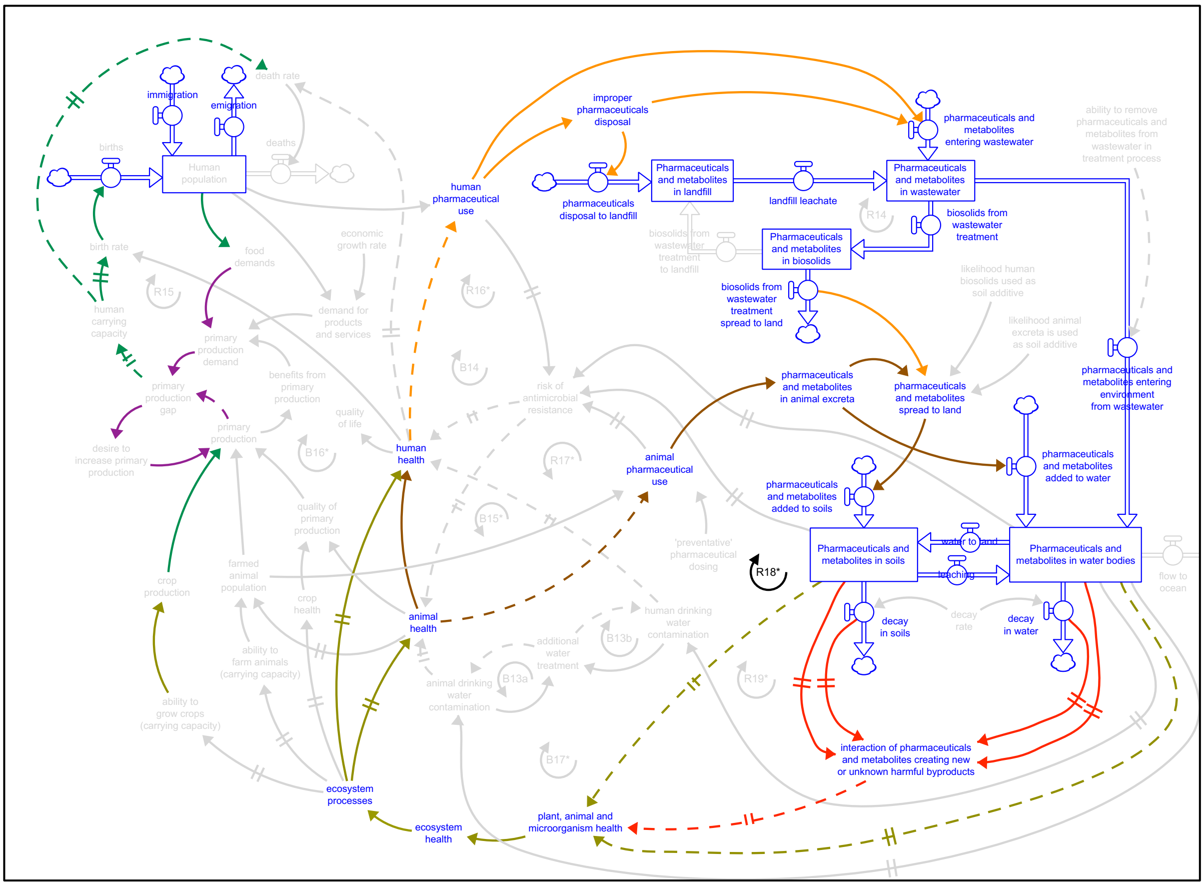


As previously discussed, there are multiple pathways for pharmaceuticals and their metabolites to end up in the environment. This raises two primary areas of concern, in that an increase in the pharmaceuticals and metabolites in the environment can lead to both an increase in the ‘risk of antimicrobial resistance’ and a decrease in ‘plant, animal and microorganism health’. The flow-on effects from these outcomes have previously been discussed but all filter through to result in a reduction in ‘primary production’, which leads to a reduction in ‘human carrying capacity’. This limits the ‘human population’ and thereby restricts the need for further pharmaceutical use, completing the *balancing feedback loop B16**. This set of feedback mechanisms is similar in structure to the *carrying capacity of human activity (B6*)* loop in the high-level overarching diagram.

8.8.2. Human and animal health feedbacks

This subsection describes the larger feedback mechanisms related to how pharmaceuticals indirectly affect human and animal health through various ecosystem impacts (Figure 47).

Figure 47. Effects of pharmaceuticals on human and animal health based on ecosystem impacts

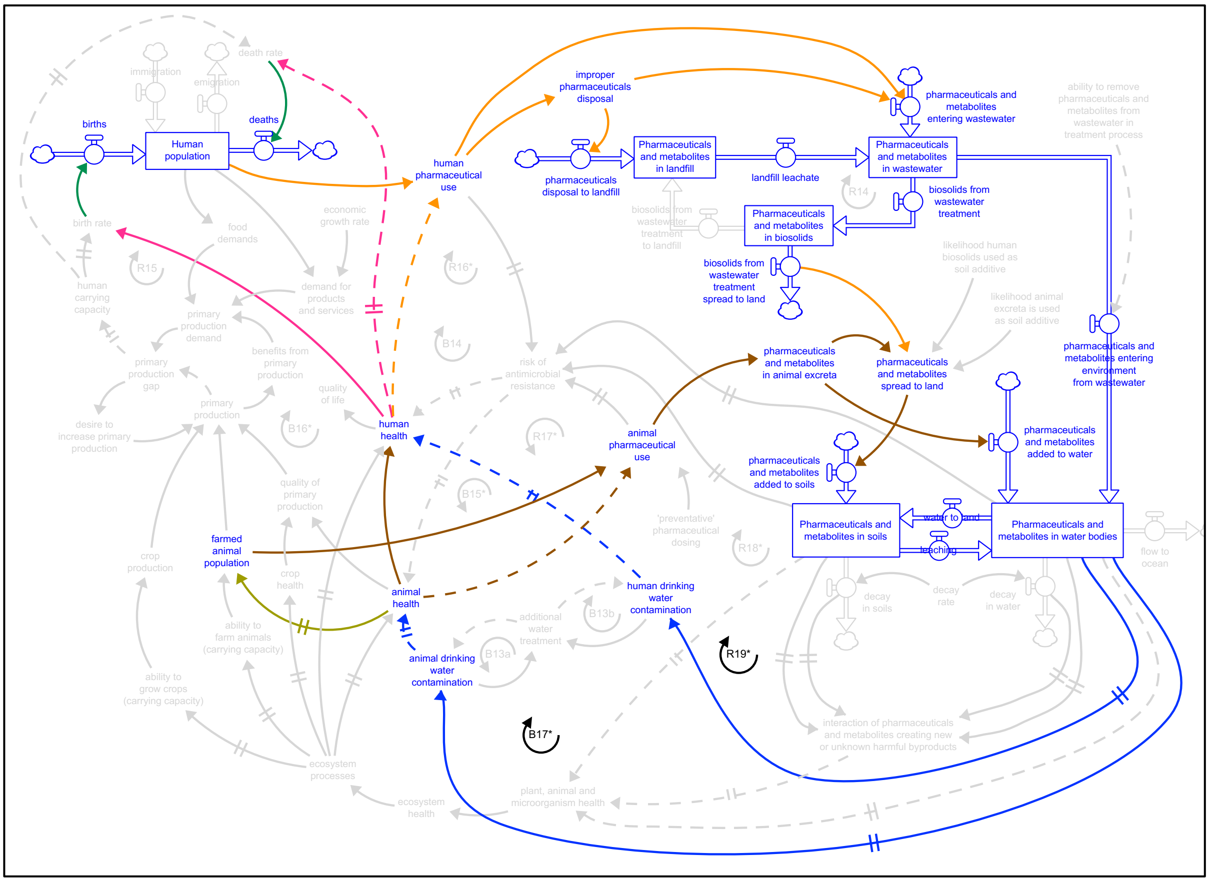


As previously described, human and animal pharmaceutical use have multiple pathways by which they can end up as accumulations of pharmaceuticals and metabolites in the environment. An increase in these environmental accumulations leads to a decrease in ecosystem health, which subsequently reduces animal and human health outcomes. Additional pharmaceuticals may be subsequently used in an attempt to improve these health outcomes. This creates a set of *reinforcing feedback loops (R18*)*, which present as similar structures to the *compensatory effort in production (R2*)* reinforcing loop from the high-level overarching diagram.

8.8.3. Water contamination feedbacks

This subsection describes the larger feedback mechanisms related to how pharmaceuticals can lead to the contamination of drinking water supplies and the effects this has on human and animal health (Figure 48). This shows two main sets of feedback structures related to the reinforcing (*R19**) and balancing (*B17**) feedback mechanisms related to drinking water contamination. These are comparable to the *compensatory effort in production (R2*)* reinforcing loop and the *pollution and waste impacts on humans (B5*)* balancing loop in the high-level overview diagram, respectively.

Figure 48. Drinking water contamination feedbacks



Pharmaceuticals and metabolites in the environment, in particular an increase in 'pharmaceuticals and metabolites in water bodies', can increase the risk of human and animal drinking water contamination, which reduces human and animal health outcomes, respectively. This can lead to greater pharmaceutical use in an attempt to lift those health outcomes, which would complete the *reinforcing feedback loops R19**.

Alternatively, the reduction in human and animal health can also lead to an eventual reduction in the population of both humans and animals, respectively. This reduction means that less pharmaceuticals are required to meet the needs of those populations, thereby completing the *balancing feedback loop B17**.

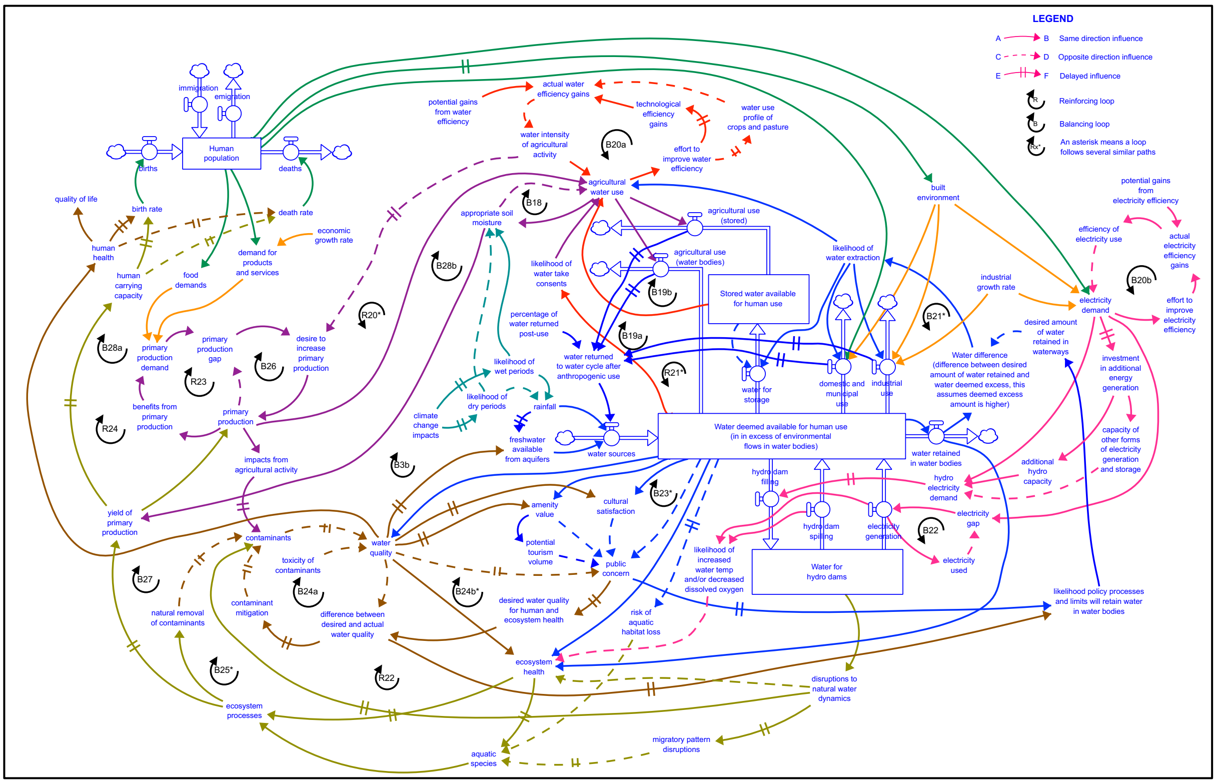
9. Water availability

This section describes the causal diagram related to freshwater (or water) availability. Of the three diagrams described in this report, it has the most connections. In part, this speaks to the complexity of the issues attempting to be captured.

This work is not intended to replicate other work that describes or models the immense detail and complexity of elements of the water cycle or water availability/allocation issues at the local scale. Many of these already exist around New Zealand and often serve a different purpose. This diagram is intended to synthesise the relationships between water availability (broadly defined here as municipal, industrial and agricultural use, as well as hydro dams for electricity generation) and the other areas shown in the diagram (such as water quality, ecosystem health, and human health and wellbeing). This is along the pathways and within the broad feedback loops already described earlier in this report (section 5).

An overview of the complete diagram is shown in Figure 49. A large version can be found in Appendix 1

Figure 49. Overview of the water availability diagram

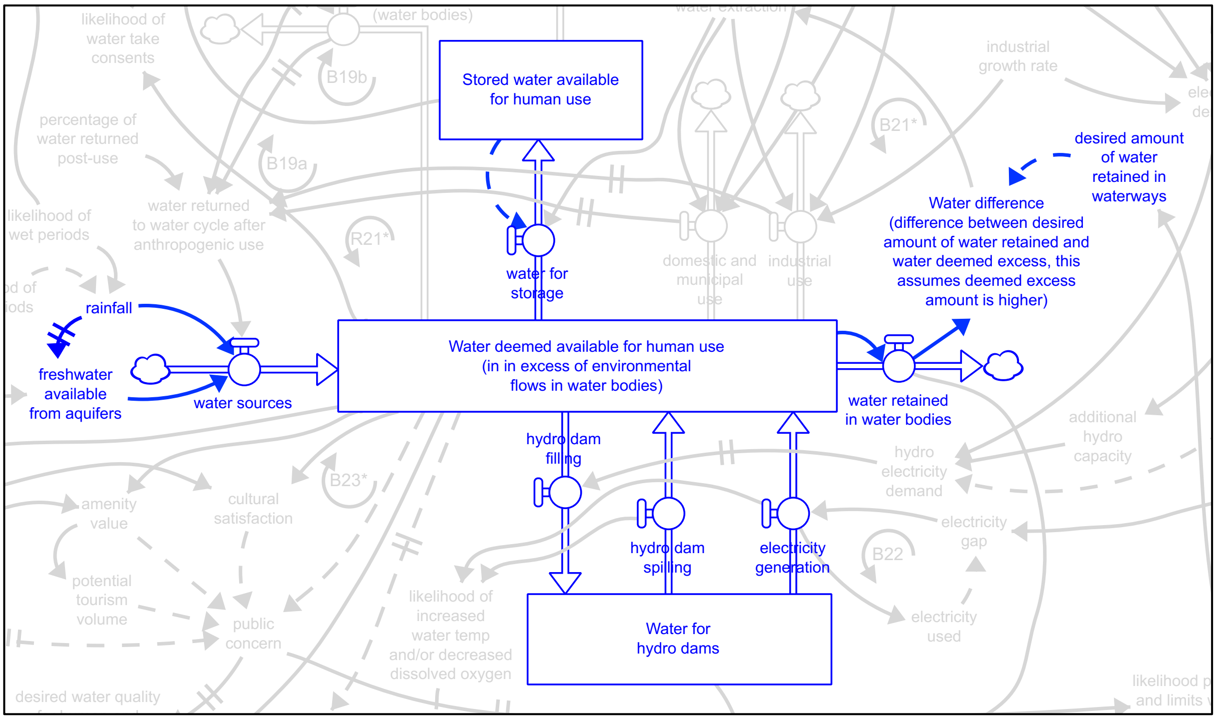


This diagram approaches the challenge of water availability from the perspective of the *water cycle*. It is important to note that this is different from a hydrological flow approach which tends to follow how water flows through a catchment.

9.1. Representing water availability

Stocks and flows seek to capture the different influences and pressures on three main conceptualisations of where water accumulates: ‘water deemed available for human use’; ‘water for hydro dams'; and 'stored water available for human use' (for use in agricultural settings). These are shown as stocks and flows in Figure 50.

Figure 50. Water available for human use, in hydro dams, and stored water



'Water deemed available for human use' describes the water that is in excess of environmental flows or the desired amount to be retained in water bodies. Water bodies describe all surface water bodies – such as rivers, lakes and wetlands. This is added to by water provided by 'water sources' (water sources are deemed to include streams, rivers, lakes and wetlands) and does not include 'water retained in water bodies'. 'Rainfall' and 'freshwater available from aquifers' have a same influence on 'water sources' – if they go up, so too do 'water sources' and, all things being equal, 'water deemed available for human use'.

There is an important goal/gap structure attached to 'water retained in water bodies' that determines whether there is enough water for human use. This is the 'water difference' – the difference between 'water retained in water bodies' and the 'desired amount of water retained in water bodies'. This latter factor is determined by societal processes, such as council planning processes. But this node is not meant to capture the nuance of such planning processes – merely that a desired amount of water is the result.

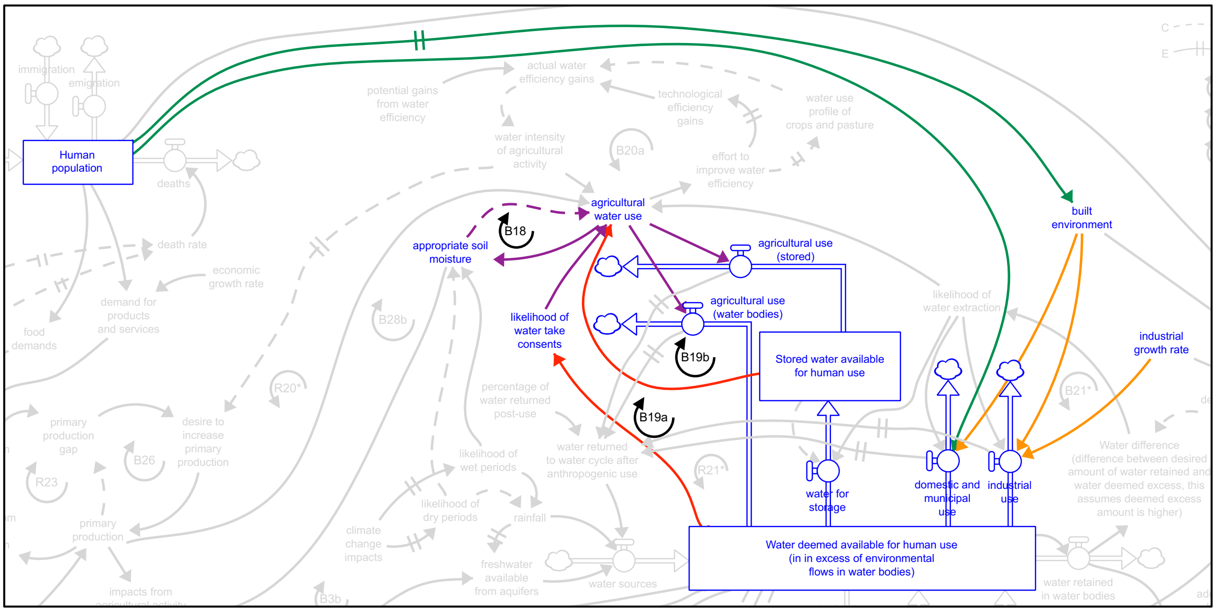
From the 'water deemed available for human use' stock, water can flow (via 'water for storage') to 'stored water available for human use'. This represents any water storage scheme for agricultural use, held either privately or collectively and at any scale. This does not include water stored in reservoirs for the purpose of municipal supply. This is not shown in the diagram, primarily because the residence time is much less than stored water (days or weeks rather than seasonally).

Water can also accumulate in 'water for hydro dams', which represents the amount of water retained behind hydro dams as potential electricity generation. The pathway to this is shown via the flow 'hydro dam filling'. Water in hydro dams is then either used for 'electricity generation' or it is spilled (let through the dam – shown as 'hydro dam spilling') in times of excess. Both of these flows return the water to the stock of 'water deemed available for human use'. Whether or not that water is then available for further hydro dams, storage or use will depend on the physical characteristics of the catchment, which are not captured in this conceptual diagram.

9.2. Representing water extraction

Water extraction is represented via four flows: 'agricultural use (water bodies)' (water extracted from water bodies); 'agriculture use (stored)' (water extracted from stored water stocks); 'domestic and municipal use'; and 'industrial use'. All flow from the 'water deemed available' stock, except the 'agriculture use (stored)', which flows from the 'stored water' stock. These are shown in Figure 51.

Figure 51. Representing water extraction



The two agricultural flows are influenced by a same influence from 'agricultural water use'. The higher this factor, the more water is extracted via the two flows, decreasing the amount of water in the 'water deemed available for human use' and/or 'stored water available for human use' stocks. 'Agricultural water use' is in a *balancing loop (B18)* with 'appropriate soil moisture'. 'Soil moisture' is a factor that represents an appropriate amount of soil moisture to support the type of agricultural activity that a farmer seeks to undertake on their land – for example, pasture of crop production. The lower the 'appropriate soil moisture', the more the 'agricultural water use' (an opposite influence), while the more the 'agricultural water use', the more the 'appropriate soil moisture' (a same influence). In other words, if the soil moisture drops too much, this can be compensated by irrigation from either water bodies or stored water (assuming the water is available).

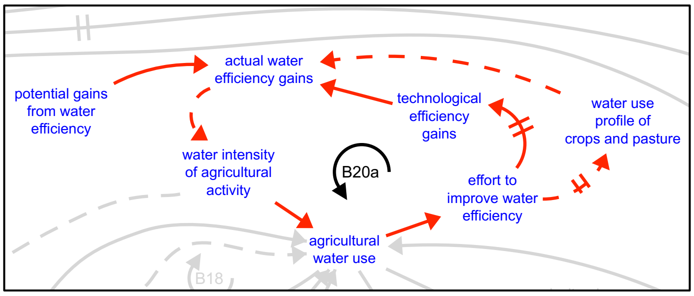
The *balancing loops B19a and B19b* are also linked to 'agricultural water use'. These both describe the way that water use and water availability balance each other out. With *B19a*, the greater the 'water deemed available', the greater the 'likelihood of water take consents' and the greater 'agricultural water use'. The more water used, the less 'water deemed available' in the stock, hence the balancing loop. Loop *B19b* works the same way, but via the stock of 'stored water' and without the factor of a water take consent, as this is already assumed to have been granted for a water storage asset.

'Domestic and municipal use' captures water used in municipal schemes or from non-reticulated residential bores. 'Industrial use' captures water used in industrial processes and does not differentiate whether this is sourced via a municipality or its own water extraction. Both of these are influenced by the level of the 'built environment' (same influence), which captures all built features, not just urban areas, so also includes rural industry. In addition to this, 'domestic and municipal use' is influenced by the level of the 'human population', and industrial use is also influenced by the 'industrial growth rate' (both same influences).

9.3. Potential efficiency gains and the rebound effect in agricultural water use intensity

The important dynamics of potential efficiency gains made in agricultural water use are represented by the *balancing loop (B20a)* (Figure 1). Here, *greater* 'agricultural water use' leads to a *greater* 'effort to improve water efficiency' which, over time (delay), leads to either a *lower* (opposite influence) 'water use profile of crops and pastures' (e.g. through cultivar breeding or selection) or an *increase* in 'technological efficiency gains' (e.g. through investing in more efficient technology). Both then lead to *increased* 'actual water efficiency gains', which *reduces* the water intensity of agricultural activity' and then *reduces* 'agricultural water use.

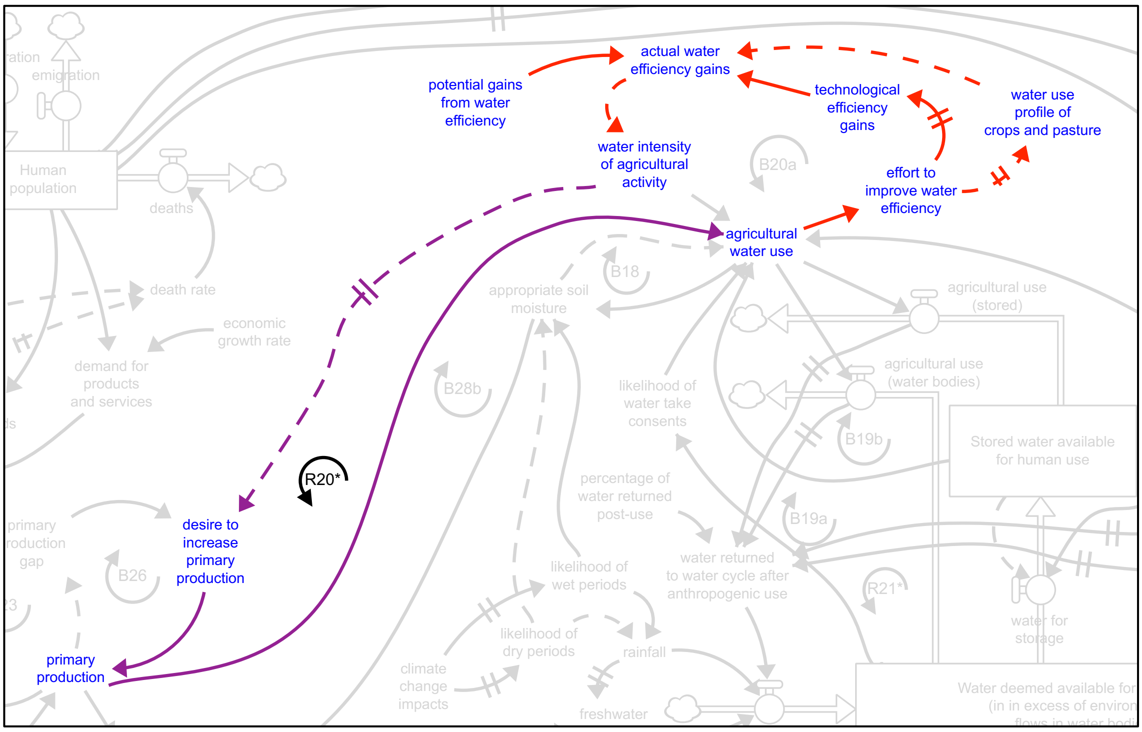
Figure 52. Potential efficiency gains in agricultural water use intensity



This is an example of the common efficiency balancing loop described earlier in the report that is constrained by the *potential gains* that can be made. That is, the 'actual water efficiency gains' are a function of both the 'effort to improve water efficiency' and the '*potential* gains from water efficiency' – efficiency gains have a limit and cannot be made *ad infinitum*. Efficiency gains will only reduce demand *to a point*.

At the same time, all things being equal, a reduced 'water intensity of agricultural activity' tends to increase the 'desire to increase primary production' (assuming the water is available). This can result in a counterintuitive rebound effect as described in the common structure section, where a decrease in water use due to technical improvements can lead to an increase in the social desire to produce more (Figure 53).

Figure 53. The rebound effect

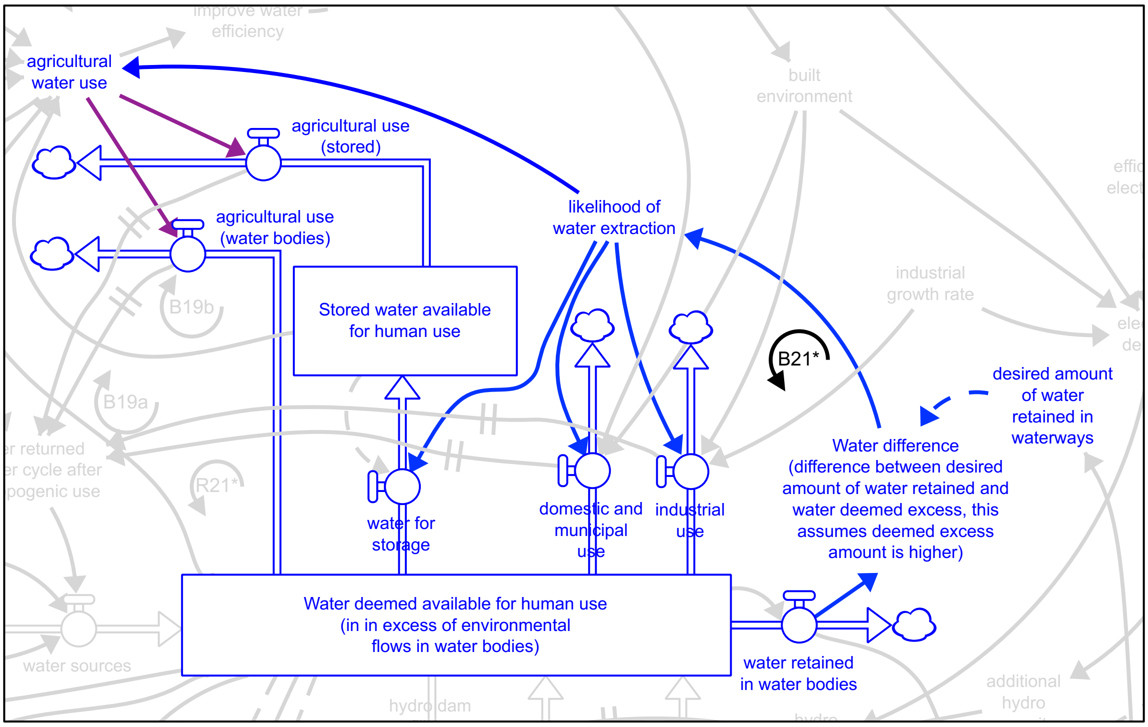


If this desire is pursued, it can cancel out the absolute savings made in water use, and potentially even increase total water use – i.e. via the pathway of increased ‘primary production’ and increased ‘agricultural water use’, which then forms a *reinforcing loop (R20*)* via further increased efforts to reduce water use, which continues to encourage further water use.

9.4. How water extraction is constrained

Water extraction from any source (agriculture, domestic, municipal or industrial) is constrained by the ‘water difference’ – the goal/gap structure mentioned earlier (Figure 54).

Figure 54. How water extraction in constrained

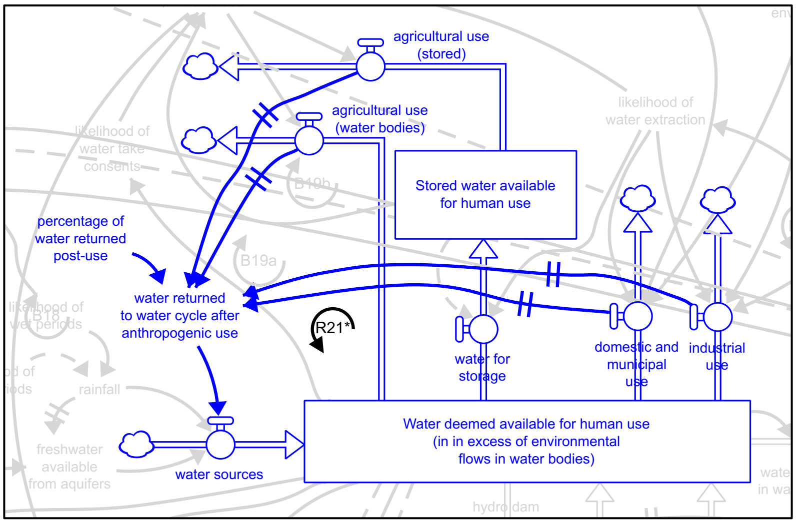


The more water there is in water bodies, the higher this ‘water difference’ is (same influence), the higher the ‘water difference’, the higher the ‘likelihood of water extraction’ (same influence), and the higher any of the extraction flows (same influences). The higher those extractions, the *less* water there then is in the ‘water deemed available’ stock, which in turn reduces the ‘water difference’ and lessens the ‘likelihood of water extraction’. This is a *balancing loop (B21*)* and includes an asterisk as it is actually representing four loops – one via each extraction pathway.

9.5. How water returns to the water cycle over time

The water extractions described in the previous sections are often referred to as *consumptive* uses of water, as it is consumed by or in an activity – e.g. water absorbed into pasture or consumed by humans. Yet it was noted during the development workshops that such water usually returns to the stock of available water – *eventually* (Figure 1). Sometimes fairly quickly, as in treated wastewater returned from municipalities. This is represented via the *reinforcing loop R21** (another loop label representing four similar pathways). Here, all consumptive extraction (agriculture, domestic and municipal, and industrial) are assumed to be at least partially returned to the water cycle. This is captured by the factor ‘water returned to water cycle after anthropogenic use’, which is impacted by delayed same influences from all extraction flows. Eventually, this water returns as ‘water sources’.

Figure 55. How water returns to the water cycle over time

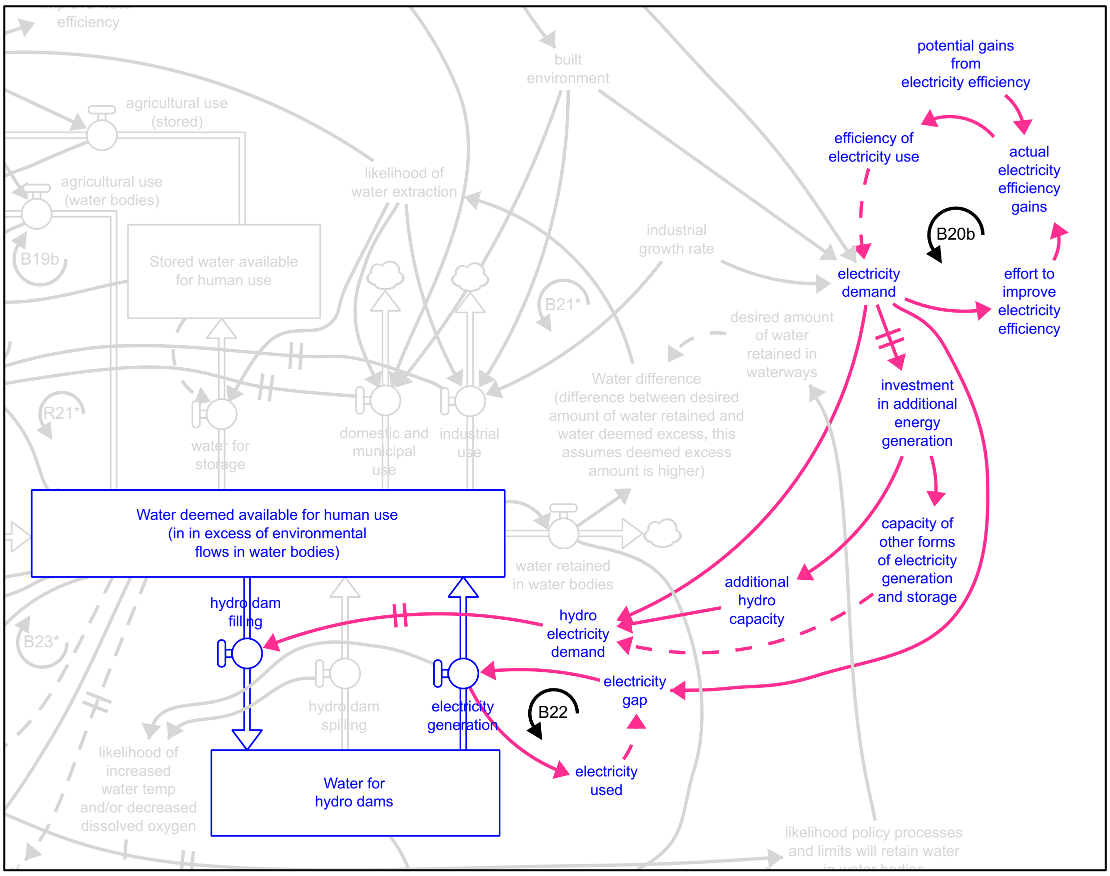


Obviously, not *all* water returns to being available for extraction again. Water is absorbed by humans and animals, as well as embodied in products and produce (e.g. milk or fruit). So the factor 'percentage of water returned post-use' represents the amount of water that is returned. This will vary across different situations but is used to demonstrate that there is an assumed proportion of water that is returned.

9.6. Electricity demand and hydro dams

'Electricity demand' is a key influence on the activities of hydro dams (Figure 56). This represents the demand for electricity from the size of the 'human population', the 'built environment' and the 'industrial growth rate' (all same influences), as well as the level of the 'efficiency of electricity use' (an opposite influence – if efficiency goes up 'electricity demand' goes down).

Figure 56. Electricity demand and water in hydro dams



‘Electricity demand’ influences hydro dams via two pathways. One way is that it influences ‘hydro dam filling’ – or the storing of water in hydro dams for future use. Firstly, this is via ‘hydro electricity demand’, which it influences directly (same influence). Secondly, this is via a delayed pathway of ‘investment in additional energy generation’ which either adds ‘additional hydro capacity’, thus leading to more ‘hydro dam filling’ (same influences); or it increases the ‘capacity of other forms of electricity generation and storage’ which *reduces* the ‘hydro electricity demand’ (opposite relationship).

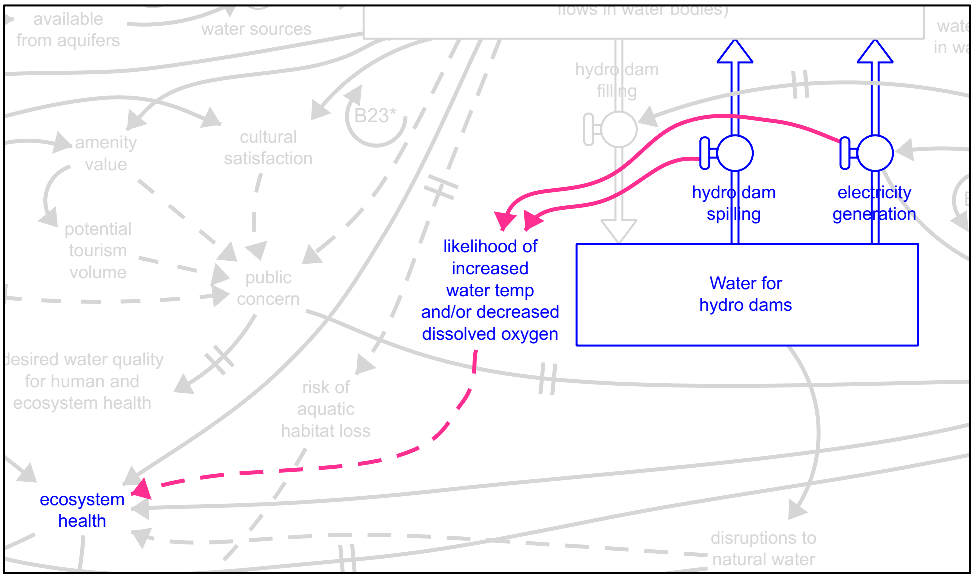
The other way is that it influences hydro ‘electricity generation’ via another goal/gap structure, made up of ‘electricity demand’, ‘electricity used’, and the ‘electricity gap’ between them. The greater the gap – the more electricity generated, while the lower the gap – the less. This forms a balancing *loop B22* with this flow of water.

The other important dynamic that is represented is the impact of energy efficiency gains made on electricity demand, represented by the *balancing loop B20b*. Here, greater ‘electricity demand’ leads to a greater ‘effort to improve efficiency’, greater ‘actual efficiency gains’ and greater ‘efficiency of electricity use’ (all same influences). Greater efficiency then leads to *lower* ‘electricity demand’. This is an example of the efficiency balancing loop described earlier in the report, which is constrained by the *potential gains* that can be made. Therefore, ‘potential gains from efficiency’ also has a same influence on ‘actual efficiency gains’. For example, improved heating technology may use less electricity, or the improved insulation of houses may reduce electricity demand, but only to a point. Heaters will still require electricity and even well-insulated homes will likely still require some form of heating.

9.7. The impact of hydro dam flows

Hydro dam flows, because of either spilling or generating, can have undesired impacts – through either an increase in the temperature of the water or a decrease in the levels of dissolved oxygen (Figure 57). This can result in undesirable impacts such as a reduced population of fish or changes to the ecology of a water body. This is represented by the factor ‘likelihood of increased water temperature and/or decreased dissolved oxygen’, which has a same influence from both dam flows. This factor then has an opposite influence on ‘ecosystem health’ – in other words, increased flows from dams can reduce ecosystem health.

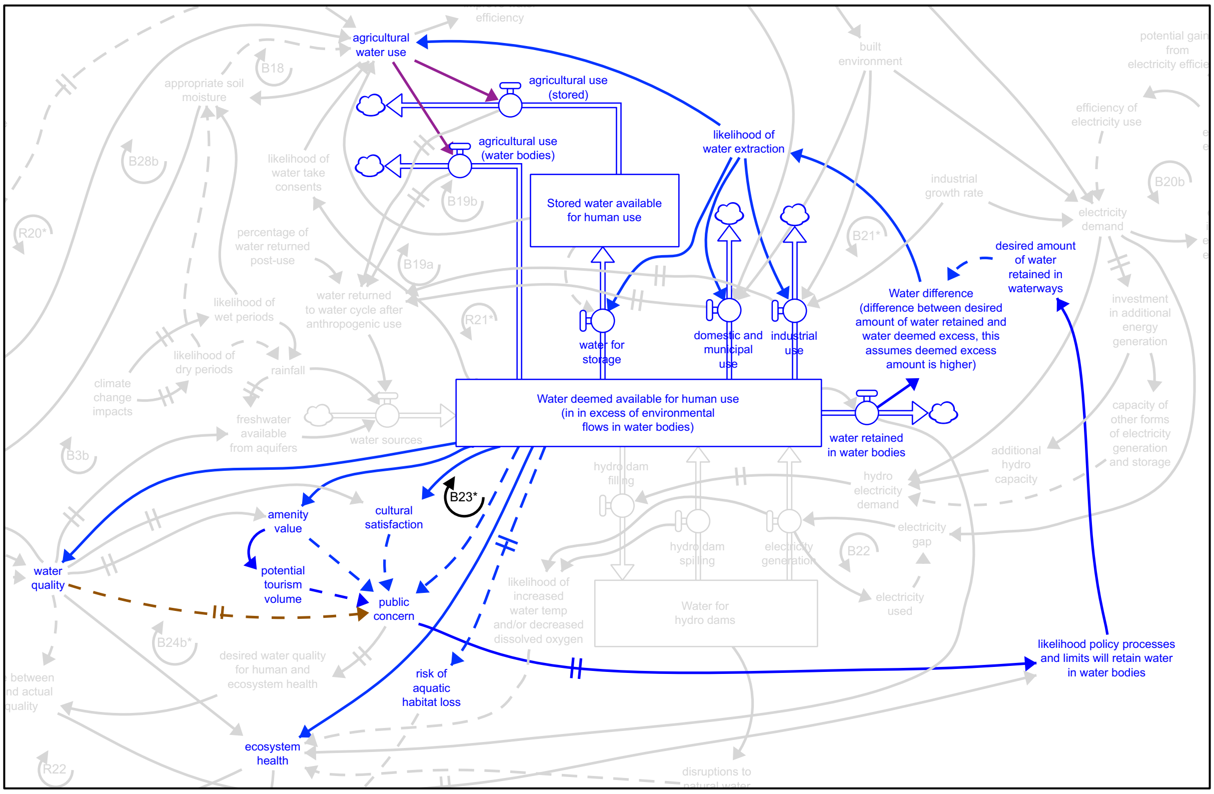
Figure 57. The impact of hydro dam flows



9.8. The influence of water in water bodies

The level of water in water bodies over and above that which is determined as a minimum – i.e. that which has not been extracted – flows on to impact a number of things. It contributes to ecosystem health, amenity value (including the potential tourism that encourages), cultural satisfaction and public concern relating to water bodies. These are shown in Figure 58.

Figure 58. The influence of water retained in water bodies



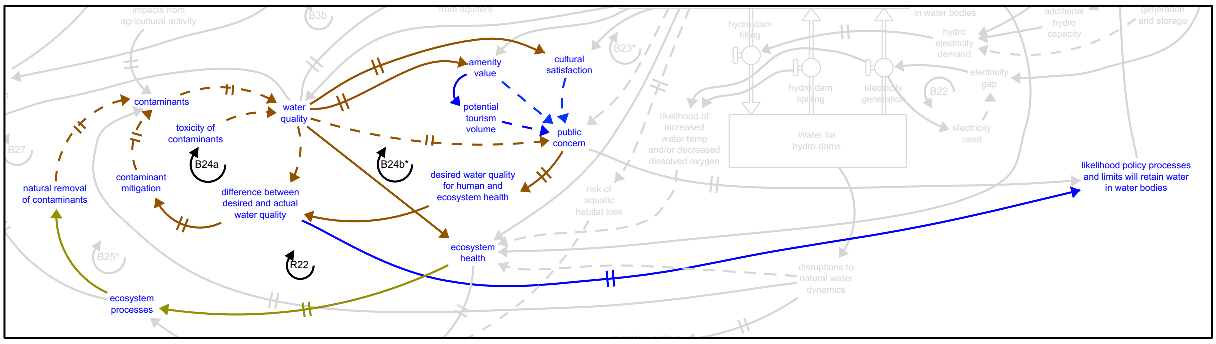
The greater the amount of water not used for human uses, the greater the ‘ecosystem health’ because there is more water in the water bodies. At the same time, the greater the amount of ‘water deemed available for human use’ but not extracted, the greater the water quality (all other things being equal), amenity value of an area (as it is closer to its natural state) and cultural satisfaction. Similarly, if the ‘water deemed available for human use’ was to *decrease* (either through extraction or drought), this would *increase* ‘public concern’ (opposite influence) about the state of the water bodies. In the slightly longer-term, it may also *increase* the ‘risk of habitat loss’ (opposite influence).

Decreased ‘amenity value’ and ‘cultural satisfaction’ can also increase ‘public concern’ (opposite relationship). While changes in ‘amenity value’ also have a same influence on ‘potential tourism volume – if amenity value reduces, so too may tourist numbers, which can then *increase* public concern (opposite influence). Increased ‘public concern’ can, over time (delay), influence the levels of water retained in water bodies. This is shown via the same influence on the ‘likelihood policy processes and limits will retain water in water bodies’, which then has a same influence on the ‘desired amount of water retained in water bodies’. This then creates a goal/gap structure with the amount of ‘water retained in water bodies’ which influences the extractions of water described earlier. These links complete the *balancing loop B23** – effectively the same loop flowing via multiple pathways.

9.9. Water quality

This diagram is focused on water availability, but it is acknowledged that discussions relating to the amount of water should not be divorced from discussions about its quality. So, this has also been represented in the diagram. As it is not the main focus of the diagram, it has been represented in an aggregated way – primarily via balancing loops with a goal/gap structure (Figure 59).

Figure 59. How water quality is represented



In the *balancing loop (B24a)*, the desired water quality is shown ('desired water quality for human and ecosystem health') along with actual 'water quality'. Both influence the 'difference between desired and actual water quality'. The size of the difference influences the level of 'contaminant mitigation' over time, which can have long delays (for example, due to delays in realising issues, deciding to act on them and then mobilising effort). The *greater* the 'contaminant mitigation', the *lower* the 'contaminants' (opposite influence with a delay, again because mitigations can take time to implement, such as planting riparian margins or reducing nutrient inputs), and the likely the *better* the 'water quality' in the long run (opposite influence with a delay), which *reduces* the difference between desired and actual states, bringing the loop closer to balance. This loop is also influenced by the external 'toxicity of contaminants', which has an opposite influence on water quality – more toxic contaminants can have a larger impact.

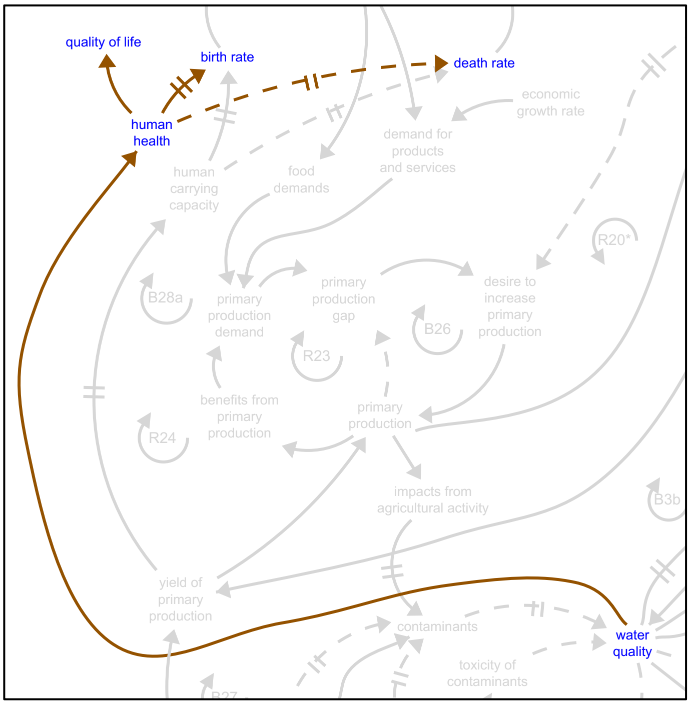
The 'difference between desired and actual water quality' also has a delayed same influence on the 'likelihood policy processes and limits will retain water in water bodies'. In other words, public concern about reduced water availability (described in the previous section) and reduced water quality can lead to advocacy and action that results in policies retaining more water in water bodies.

'Water quality' also influences some of the same factors that water availability influences. It has a delayed same influence on 'amenity value', 'cultural satisfaction', 'ecosystem health' and the 'freshwater available from aquifers' – if water quality reduces, so too do those factors. It also has a delayed opposite influence on public concern – if 'water quality' reduces, 'public concern' increases. These form another *balancing loop (B24b*)* with water quality – the lower 'water quality', the higher 'public concern', the higher the desired water quality, and the greater the difference with the actual. Over time, this promotes more mitigations, leading to fewer contaminants, increasing water quality and balancing out 'public concern'. It is noted that the strength of this feedback loop depends on the extent to which people care about water quality – the less people care about this, the weaker the influence of this loop will be. It is also noted that there are delays on nearly all of these influences, so this loop will take significant time to come into balance.

Decreased 'water quality' also reduces 'ecosystem health', 'ecosystem processes' and the ability for the 'natural removal of contaminants' in water bodies. This can increase 'contaminants' and further decrease 'water quality'. This is shown as the *reinforcing loop R22*.

Additionally, 'water quality' also has an important influence on 'human health'. It has a same influence on 'human health' and 'quality of life'. The lower one, the lower the others. The flow-on influence of human health will be described in a later subsection. This is shown in Figure 60.

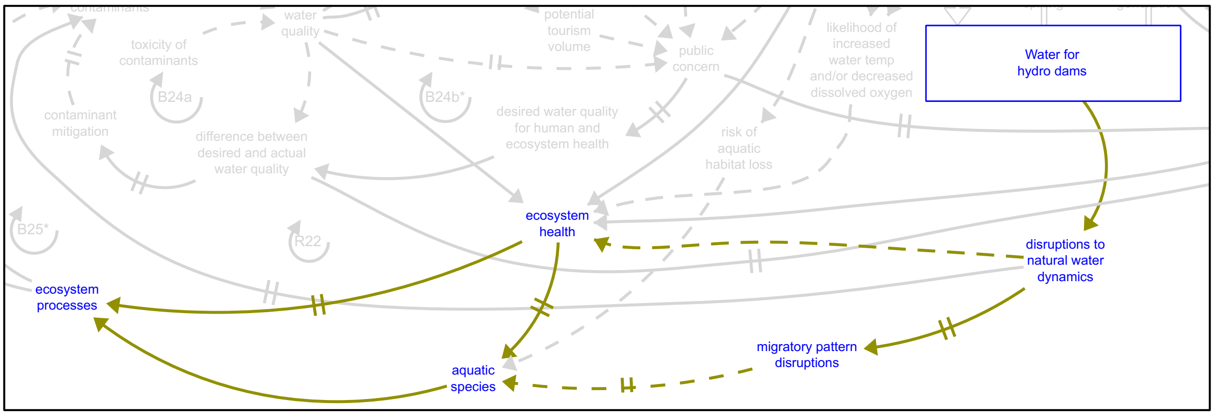
Figure 60. The impact of water quality on human health



9.10. The impact of water retained by hydro dams on ecosystem health and ecosystem processes

The influence of water retained by hydro dams on ‘ecosystem health’ and ‘ecosystem processes’ forms an important pathway of influence in the diagram. This is shown in Figure 61.

Figure 61. The impact of water disruptions on ecosystem health and ecosystem processes



A previous section described the influence of water deemed available on ‘ecosystem health’. Hydro dams also have an impact here. The greater the number or volume of hydro dams (for which the factor ‘water for hydro dams’ is used as a very loose proxy), the greater the ‘disruptions to natural water dynamics’ in water bodies (same influence). These disruptions have an opposite influence on ecosystem health – the more disruptions, the lower the health. For example, while a higher number or volume of hydro dams may increase water in lakes behind the dams, this may have a detrimental impact on the level of water flow in rivers below the dams, which may reduce the ecosystem health in-stream. These disruptions also have a (delayed) same influence on ‘contaminants’ (by potentially contributing more contaminants), and ‘migratory pattern disruptions’ (by impacting the habitat of water plants and animals). Over time, increased ‘migratory pattern disruptions’ can decrease ‘aquatic species’ (opposite influence). This is also influenced by an opposite influence from the ‘risk of aquatic habitat loss’ – the more habitat loss, the less ‘aquatic species’. For example, the more wetland or shallow stream bank habitat loss, the less indigenous biodiversity in those places. A general reduction in ‘ecosystem health’ also reduces ‘aquatic species’ (same influence) – the lower the ecosystem health, the less aquatic species it can support.

Both ‘ecosystem health’ and ‘aquatic species’ have a same influence on ‘ecosystem processes’ – if either reduces, so too do ‘ecosystem processes’. And ‘ecosystem processes’ support the ‘natural removal of contaminants’ (a same influence).

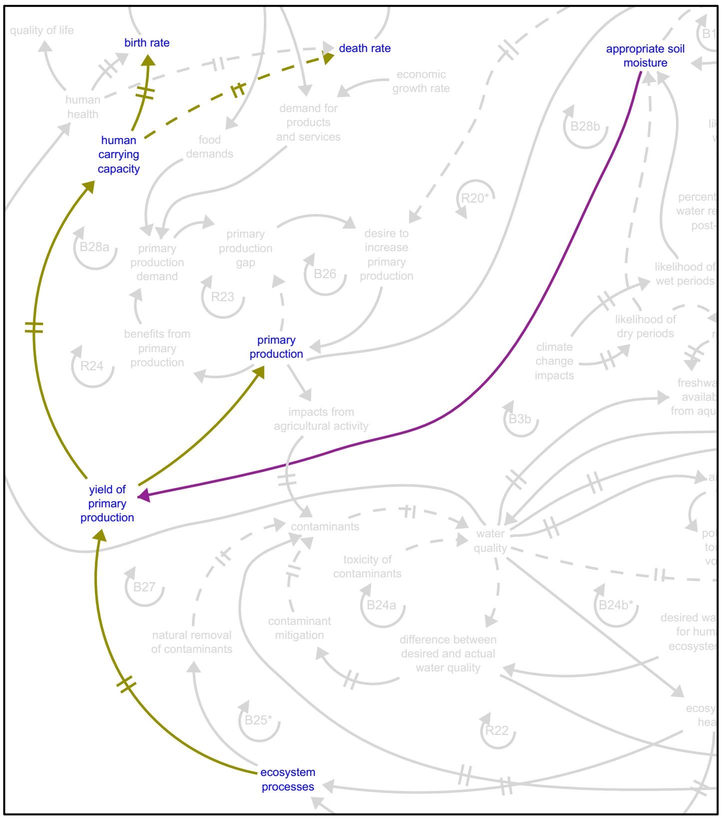
9.11. The circular connection of ecosystem processes and human activity

The previous section described natural ecosystem health and processes and how they were impacted by water availability. This section describes how ecosystem processes influence human activity and extend this into a loop back onto ecosystem services.

9.11.1. The influence of ecosystem processes on human activity

Ecosystem processes underpin the ‘yield of primary production’, which is a factor representing the ability of the natural world to support the healthy production of food and fibre. This is of critical importance because it not only underpins anthropogenic ‘primary production’ (i.e. our ability to farm), but also the number of humans that the environment can sustain (the ‘human carrying capacity’) (see Figure 1).

Figure 62. The influence of ecosystem processes

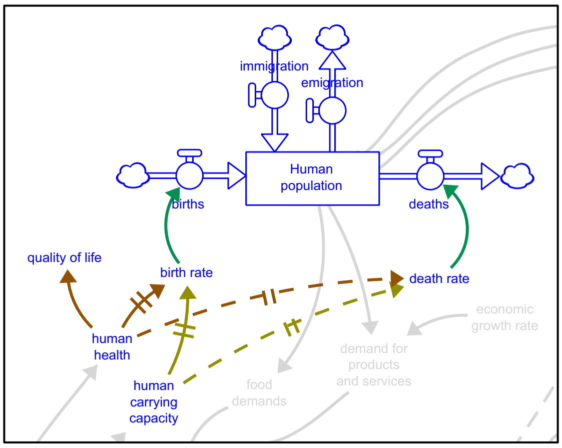


It is important to note that ‘appropriate soil moisture’ (explained earlier) also has a direct pathway of influence on ‘yield of primary production’. The soil moisture level impacts how well primary products can grow.

9.11.2. Representing human population

As in the common structure described at the start of the report, ‘human population’ is represented in stock and flow form (see Figure 1).

Figure 63. Representing human population

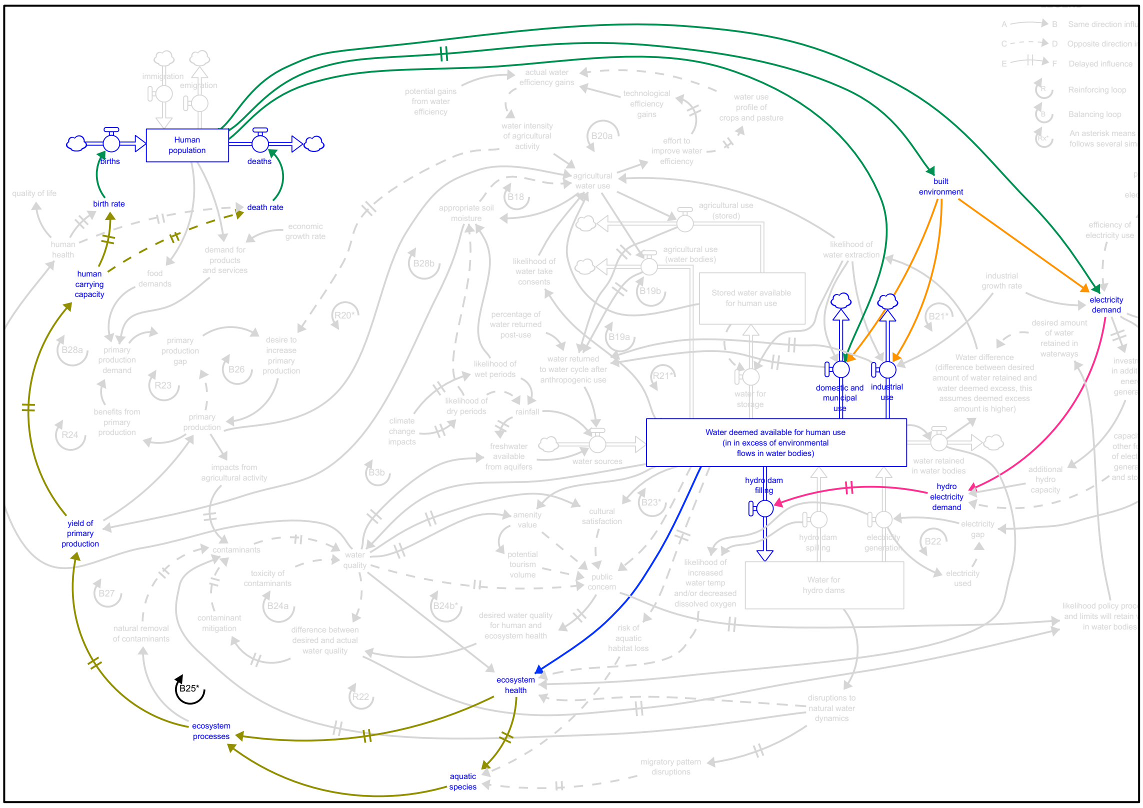


Here the level of water available eventually has an impact on both ‘human health’ and ‘human carrying capacity’, which impact human birth and death rates. The size of the ‘human population’ impacts on the food demands which links into the other common structure relating to food production. If population was to increase this increases the demand for food and the demand on the food production system to produce more.

9.11.3. How population levels impact water availability, ecosystem health and ecosystem processes

Human population influences water availability, ecosystem health and ecosystem processes in a series of feedback loops that cycle back to influence human population (see Figure 64).

Figure 64. Population, water use, and ecosystem health feedback loops



The level of ‘human population’ has a direct influence in the same direction on the amount of water for ‘domestic and municipal use’ and ‘industrial use’ (via the level of the ‘built environment’) which reduces the ‘water deemed available for human use’. ‘Human population’ also has a direct impact in the same direction on ‘electricity demand’, which impacts the amount of water used in hydro dams (the ‘hydro dam filling’ flow). This also reduces the amount of ‘water deemed available for human use’.

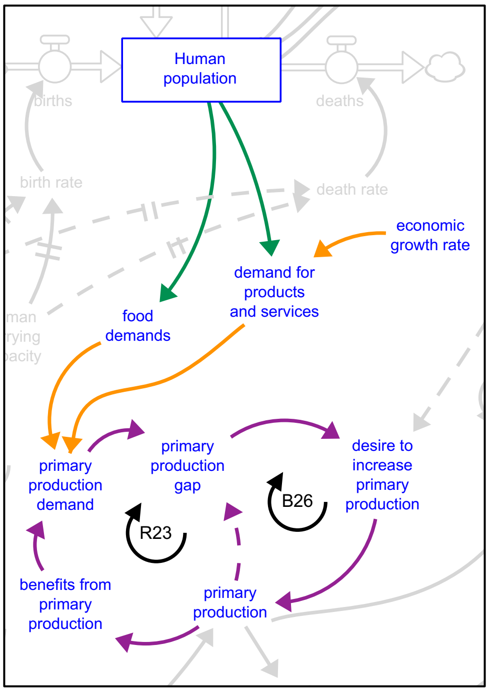
The reduced levels of water in water bodies (‘water deemed available for human use’) and the increased ‘water for hydro dams’ have flow on impacts on ‘ecosystem health’, ‘aquatic species’ and eventually ‘ecosystem processes’, reducing them all. This then impacts the level of ‘human population’ described in the previous section, completing a *balancing loop (B25)*. This links human health and population to non-agricultural water use, to ecosystem health and process and back to human health and population.

9.12. Human agricultural activity

Consistent with the other diagrams, the main human activity represented in this one is primary production. This is via the demand for food generated by the human population, and the demand for products and services generated by economic activity (0).

Both of these influence pathways link to ‘primary production demand’. The higher the ‘human population’ the greater the ‘food demands’ and the ‘primary production demand’. The higher the ‘economic growth rate’ the higher the ‘demand for products and services’ and the ‘primary production demand’. Note that ‘primary production’ is also dependent on the ‘yield of primary production’. All are same influences. Primary production is then captured in two loops, one balancing and one reinforcing.

Figure 65. Human agricultural activity



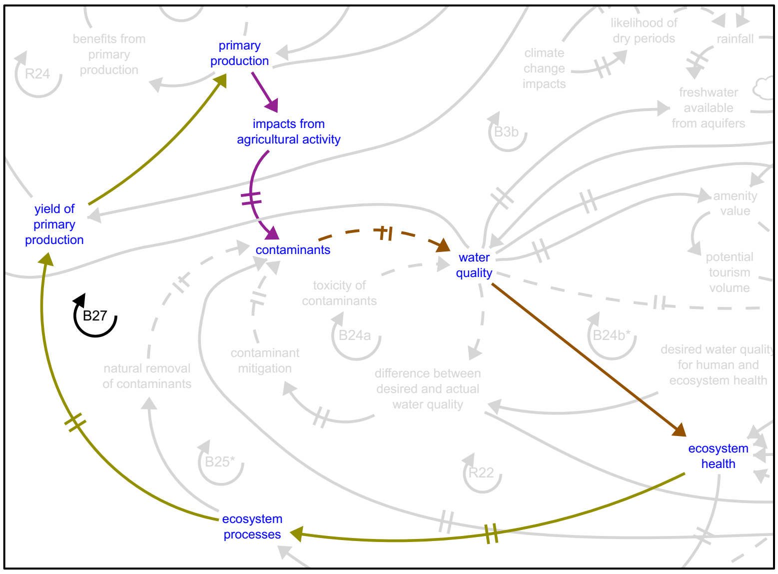
The *balancing loop B26* describes production *meeting* demand. ‘Primary production demand’ and ‘primary production’ for a goal/gap structure, with ‘primary production gap’ – the lower the production, the greater the gap. The size of the gap (e.g. large) influences the ‘desire to increase production’ (more), which influences ‘primary production’ (more) – all same influences. As ‘primary production’ increases, the ‘primary production gap’ decreases – and the loop comes closer to balance.

The *reinforcing loop R23* describes production *increasing* demand. The influences described above still hold, yet when ‘primary production’ increases, so too do the ‘benefits from primary production’ (e.g. through the sustenance provided from food, but also the revenue from farming). This increases ‘primary production demand’ which further increases the ‘primary production gap’. In short, production will tend to increase demand (R23) as well as trying to meet it (B26), so these loops are likely to continually be in tension with each other. This captures the competing influences that tend to operate in markets and describes the efforts to meet demand, as well as the demand dynamics that occur in response to supply.

The ‘intensity of primary production’ also has a same influence on the ‘impacts from agricultural activity’ (such as nutrient runoff), which can then also have a delayed impact on the level of ‘contaminants’ described earlier. Similarly, it has a same influence on the level of ‘agricultural water use’ – the greater the intensity, the greater the water use.

The ‘impacts from agricultural activity’ are linked in a *balancing loop (B27)* that links their impacts to ‘contaminants’ in water, ‘water quality’, ‘ecosystem health’, ‘ecosystem processes’, and the ‘yield of primary production’. This means that the impacts of primary production on the environment are related to the ability of the environment to support primary production (Figure 66).

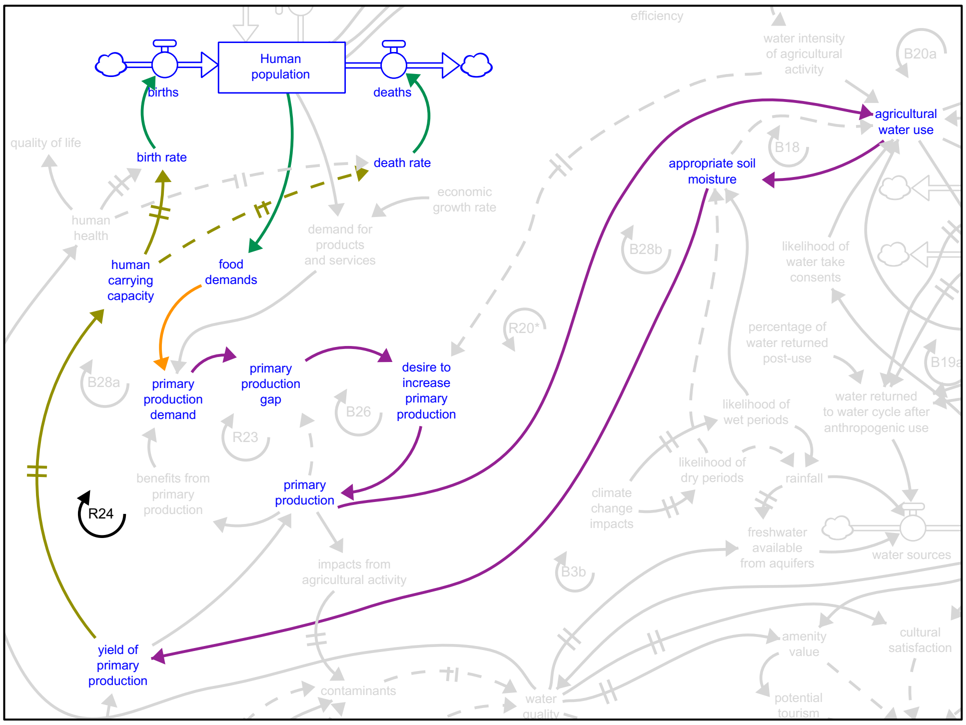
Figure 66. How agricultural impacts limit agricultural production



9.13. Tension between human population, primary production, agricultural water use and primary production yield

This section links the influence of human population, primary production, agricultural water use and primary production yield. It also described the tensions at play between these factors.

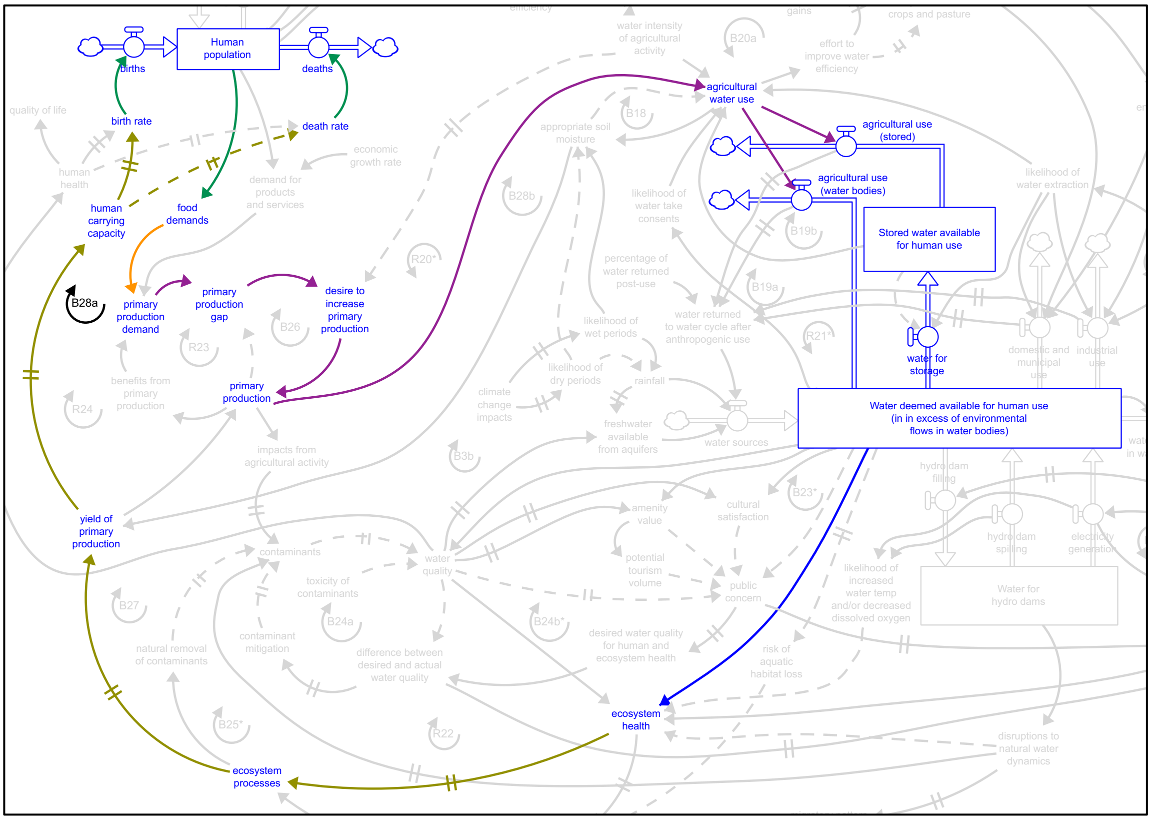
Figure 67. Reinforcing loop R24: Population, primary production, water use and yield



Firstly, all these areas are linked in a *reinforcing loop (R24)*. The greater the population, the more demand for food and primary production; this drives an increase in production, which leads to more water use. More water helps increase the yield of primary production, which improves the carrying capacity and leads to further population growth. This loop reinforces itself and is a simple but useful description of the reinforcing activity that has occurred throughout recent human history (Figure 67).

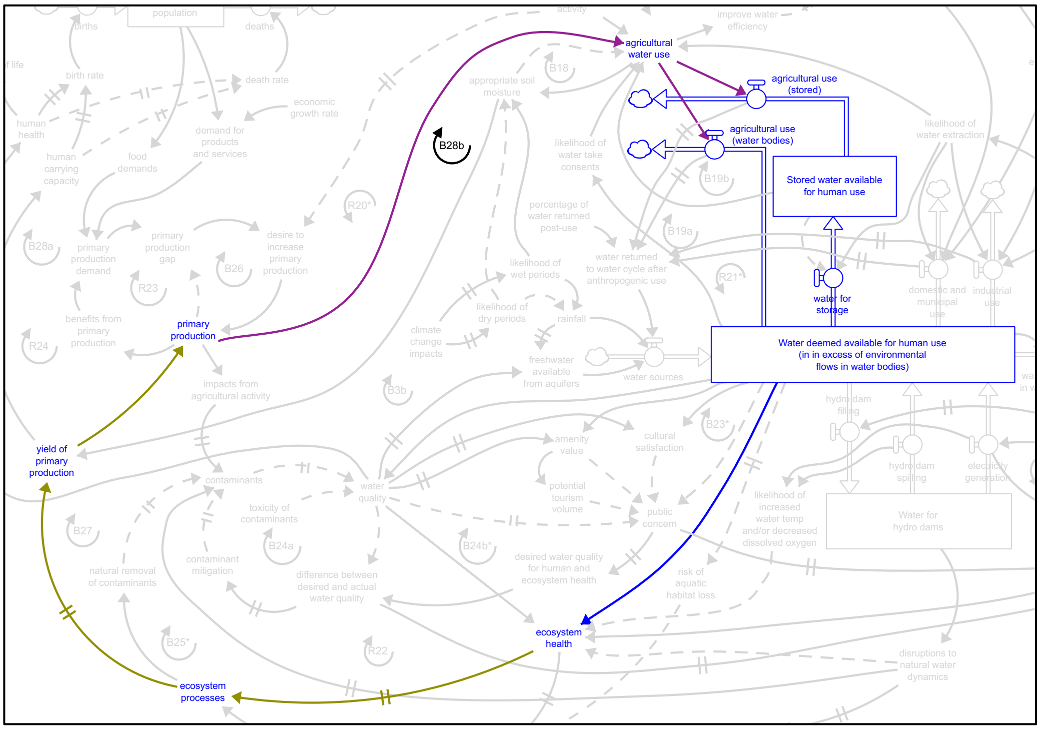
However, all of these areas are also linked through a *balancing loop (B28a)*, but via the pathway of the additional stock of 'water deemed available' (Figure 68). In this loop, the same pathway exists: an increased population leads to more demand for food and primary production, which increases water use. But then the pathway diverges – increased water use *decreases* the stock of 'water deemed available' which *reduces* ecosystem health and ecosystem processes. This *reduces* the 'yield of primary production', which *decreases* human carrying capacity and eventually the population. This loop influences the 'yield of primary production' in the opposite direction, so these two loops (R24 & B28a) are in tension.

Figure 68. Balancing loop B28a: Population, primary production, water use and yield



There is also another *balancing loop (B28b)* that doesn't incorporate the human population (Figure 69). Here, an increase in the 'yield of primary production' increases total 'primary production', which increases 'agricultural water use'. This reduces the stock of water deemed available for human use, which reduces 'ecosystem health' and 'ecosystem processes', and eventually reduces the 'yield of primary production'.

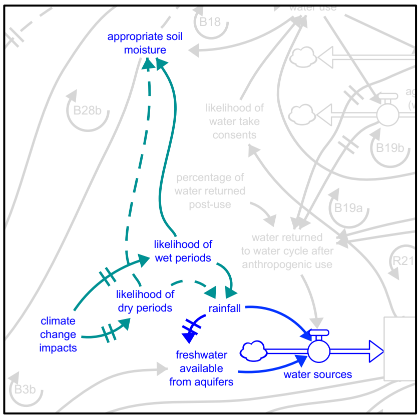
Figure 69. Balancing loop B28b: Primary production, water use and yield



9.14. The impacts of climate change

The impacts of climate change are represented by the factor ‘climate change impacts’. This has a delayed same influence on both the ‘likelihood of wet periods’ and the ‘likelihood of dry periods’ – both are likely to increase. As the ‘likelihood of wet periods’ increases, so too does the ‘rainfall’ and the ‘appropriate soil moisture’. The opposite is true for the ‘likelihood of dry periods’ – if these *increase*, then ‘rainfall’ and ‘appropriate soil moisture’ will *decrease*. See Figure 1.

Figure 70. The impacts of climate change



An increase in dry periods due to ‘climate change impacts’ will reduce potential water sources and put pressure on the stock of ‘water deemed available for human use’. Additionally, the change in wet/dry periods will affect the soil moisture levels. Both of these pathways have flow-on effects, including a potential reduction in agricultural production etc.

It should be noted that the climate change influences described here are general trends and these impacts may actually present as extreme events. For extreme dry events, the impact is likely to be similar to that described above – this will result in extreme pressure on water availability. However, for wet periods, an extreme event may have many other impacts that have not been described here (for example, slips on hillsides, destruction of crops or pasture from flooding, etc).

Their omission does not diminish their impact, but it is noted that wet periods are less likely to be an environmental stressor on water availability, from the point of view of water being an input to agricultural production. The seasonality of such impacts may also be important but are not represented in the diagram. For example, dry periods may be worse in summer, which may compound the flow on impacts or lead to increased water demand at very specific times and not others.

10. Summary

This report describes a series of causal diagrams covering a range of resource flows through Aotearoa-New Zealand and their anticipated environmental pressures and pathways of influence/harm. The causal diagrams are based on the system dynamics methodology and were developed with a range of subject matter experts.

10.1. What this work has developed

This work sought to help PCE increase their understanding of a range of potential future environmental pressures that may result from continued and sustained resource flows through Aotearoa-New Zealand. It has developed the following:

- A conceptual overview diagram, which articulates the main feedback pathways that influence environmental pressures and how they will impact other areas.
- A range of common influence structures and associated anticipated dynamics occur across the three subject matter areas. These will also apply to most other subject matter areas, so are of use to PCEs work in that regard.
- Three detailed (yet still aggregated) diagrams of resource flows and the various pathways that influence environmental pressures. These three diagrams cover the following subject matter areas:
  - Plastics and the chemicals associated with them.
  - Pharmaceutical use in humans and animals.
  - Water availability.

10.2. Key findings

The authors believe that these diagrams help develop PCE's understanding of the high-level feedback loops and potential impacts associated with continued resource flows in the subject areas explored. This work highlights a number of **generalisable insights**:

13. The stock/flow and feedback approach has been useful for conceptualising a large number of potential detrimental pathways of influence associated with the (historic and) ongoing flows of resources through economic value chains in Aotearoa-New Zealand.
14. Many of these flows or accumulations are under-appreciated and many are not widely understood. In particular, representing these accumulations as stocks in the diagrams highlights that some have limited ability to reduce, so they are likely to persist for a significant period of time to come (potentially decades). For example, plastics in the uncontrolled environment (e.g. soils and water), or chemicals in landfills and the leachate from those landfills.
15. The assimilative capacity of the environment (on various scales) to absorb our pollution and waste streams will likely become a limiting factor of human activity in the longer-term. This may result in the eventual decline of human health, or the reduction in the size of our population that can be supported.
16. A range of common causal structures and dynamics have been identified across the subject matter areas. These include:

a. The continued accumulations (sinks) of pollutants and wastes in the environment will negatively impact the ability of renewable resources to regenerate. For example, long-life chemicals from plastics may contaminate soil or water, reducing our ability to produce food, or increased concentrations of pharmaceuticals or metabolites from pharmaceutical use may impact the reproductive cycles of plants or animals.

b. Significant delays are involved in most environmental systems (likely decades or more). So, once impacts are detected, this will likely only be the start of a much larger flow-on impact that is already underway and yet to present.

c. There are limits to efficiency gains, and in some cases, these gains may induce a rebound effect and result in *more* of the resource being used. In other words, efficiency gains can help reduce resource use (flows), but only to a point, as there is a limit to the gains that can be made with efficiency – if a resource is required as an input, it will only be able to be reduced so much. In addition, such efficiency gains often result in changes in social expectations of what is possible from the more efficiently used resource, perversely resulting in *more* of the resource being used (a.k.a. Jevon's paradox).

d. Substituting a problematic resource for a different one could potentially have unknown and delayed impacts. While current problems may be avoided, future ones could be generated, leading to potential cumulative impacts. For example, a build-up of chemicals in the environment, of which little is known, may later be found to be harmful.

e. Human innovation may improve the capture and containment of pollution or wastes. Yet, due to potential leakages (despite best practice), these are likely to be sources of future environmental pressures in the longer term.

17. Discussions with the subject matter experts highlighted that the pollutant accumulations (sinks), and the pathways by which they may cause harm, are largely unquantified. Alternatively, these bodies of research are only beginning to be developed. However, all of their perspectives were able to be conceptualised within this work. The lack of data on these issues highlights how this work can play an important role in conceptualising and anticipating potential issues and how they may interact. These insights can help inform where research may be focused in the future.

This work has also highlighted a range of **insights to the specific subjects explored**:

18. As chemicals from plastics and pharmaceuticals/metabolites continue to accumulate in the environment, there is an increasing risk that these may interact in novel ways that may have unexpected and undesirable effects. For example, chemicals may interact with each other directly, or they may break down over time into other substances that may interact with each other. This could result in unexpected or new chemicals or compounds (a form of novel entities) that may be harmful. In the workshops, it was pointed out that this was difficult to anticipate, and the experts were unaware of research that identified where/how this may occur. This highlights the fact that environmental monitoring of this nature is always retrospective – i.e. once environmental harm can be measured, it has already occurred. The conceptual work in this report highlights that such effects can (and should) be reasonably anticipated and prompts the question as to what research may help better understand these effects.

    a. Further research may be required to assess what is known about chemicals in the environment and how they may interact with each other.

    b. Research should also be extended to help fill any of the identified knowledge gaps to ensure environmental and human harm is minimised.

19. Anecdotally, the limits of efficiency gains associated with water use and increasing demands on water through the growth of population and agricultural use suggest that water availability will likely be an increasingly constrained resource in the future.

This work has sought to conceptualise and articulate the impacts that can be reasonably anticipated from continued and increased resource use through the economic value chain and the subsequent accumulations of pollution and waste in the environment. This qualitative work is based on expert opinion and does not seek to quantify specific details, volumes, or risks. However, it provides a framework for thinking about these potential risks and helps guide future precautionary studies focused on potential areas of concern. Additionally, the identification of feedback loops as a means of understanding behaviour dynamics is a fundamental concept underpinning the methodology used in this report. **Future work should build on the feedback dynamics identified**. In particular:

20. Attempts should be made to incorporate important feedback loops described in this work into future research or modelling commissioned by PCE in the wider programme of work within which this sits. This may also apply to other programmes of work in the future, if feedback loops developed here are found to be relevant.
21. Consider further high-level modelling of some of the feedback loops and dynamics described in these diagrams. Particularly in relation to the impact that exponential growth of resource flows will have, and the likely limited impact of efficiency measures.
22. Avoid emphasising efficiency gains as a means of reducing resource use and environmental pressures. This may be informed by potential modelling as recommended above but is not dependent on it. Significant evidence to support this may also be available from a combination of this report, existing literature and expert opinion.
23. Advocate for a precautionary approach to the substitution of resources or products that are the source of environmental pressure of contamination. This should not delay the reduction in the use of such harmful resources or products, but caution should be sounded against the promotion of substitutes of which little is known, without careful consideration of how else to reduce the harmful product. The risk is that such resources or products may cause future environmental issues.
24. Consider commissioning work based on expert opinion to make informed estimates of which contaminant sinks and pathways of influence identified in this work should be better monitored. This will help build a corpus of data quantifying the conceptualised issues identified in this report.

10.3. Limitations

This work has followed a rigorous and comprehensive methodology. The qualitative nature means the main insights are focused on how different dynamics interact. This approach cannot quantify these dynamics and gives no indication on the strength of different pathways or the size of accumulations.

This project involved 9 experts, over three periods of contact. While engagement was comprehensive, time was limited, which means not all relevant perspectives may have been captured, or there may be limitations or bias in those that were.

11. References

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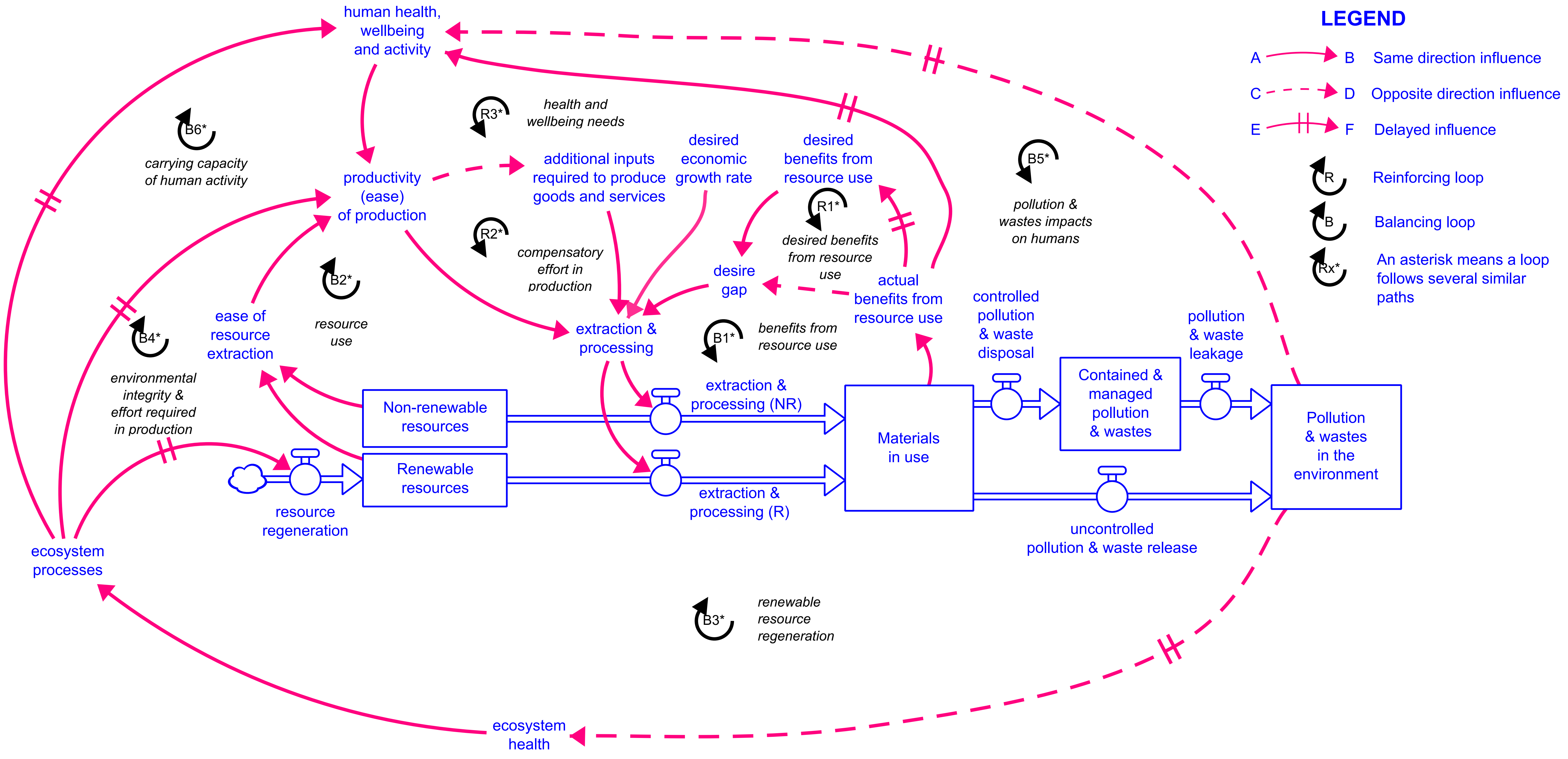
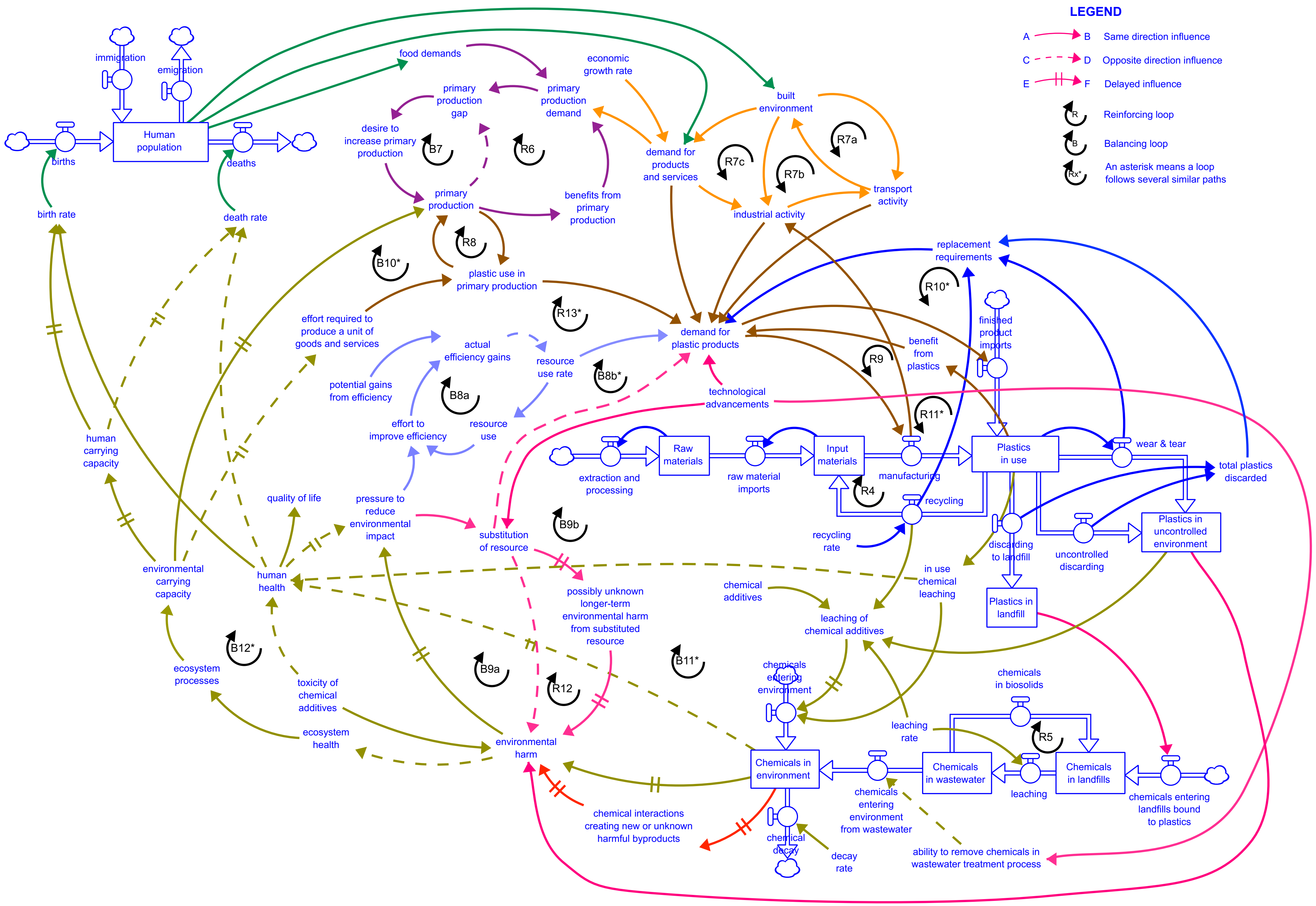
Appendix 1. Large versions of the causal diagrams

This appendix includes large versions of the three detailed causal diagrams. These are: Plastics and chemicals, pharmaceuticals and water availability.

How resource flows create environmental pressures





Plastics & Chemicals

LOOP LABELS

R4 = Recycling

R5 = Wastewater treatment

R7 = Built environment

R8 = Primary production and plastic use

R9 = Plastic demand and industrial activity

R10 = Plastic replacement demand

R11 = Plastic benefits

R13 = Effort to produce plastic

B7 + R6 = Primary production

B8 = Efficiency gains

B9 + R12 = Substitution

B10 = Carrying capacity and production

B11 +B12 = Population and plastic demand

COLOURS

Human population and influences of

Human built environment activity and influences of

Primary production activity and influences of

Plastic use

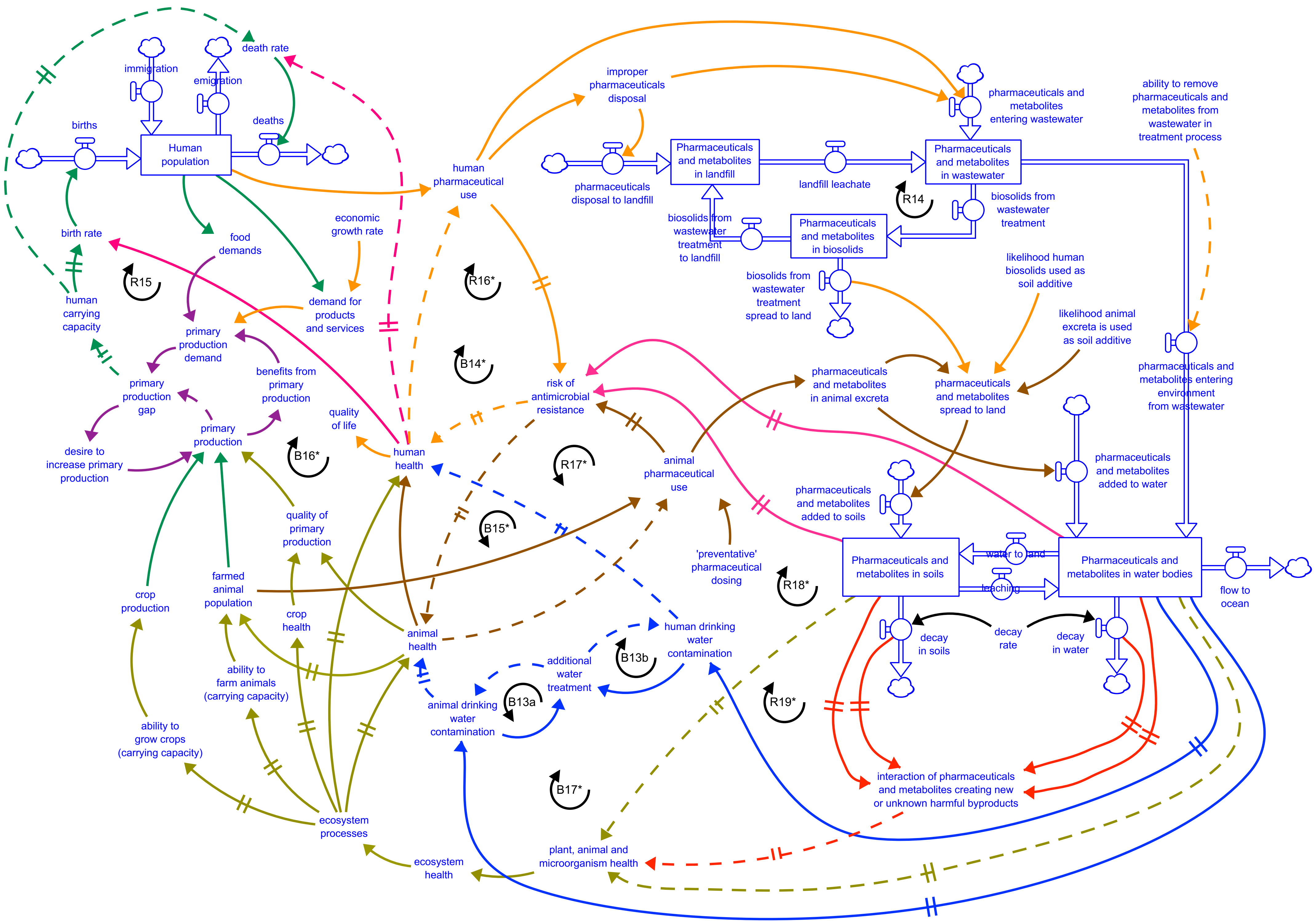
Plastic lifecycle replacement influences

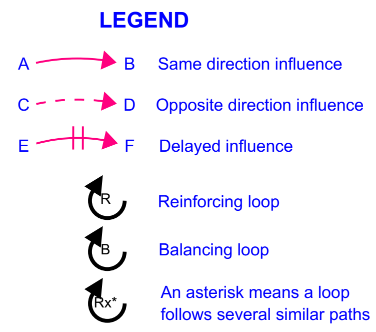
Potential chemical mixing and novel impacts

Impacts pathways on environmental and human carrying capacity

Efficiency gains of resource use

Substitution of plastics for alternative product





Pharmaceuticals

LOOP LABELS

R14 = Landfill leachate

R15 = Human food demands

R16 + B14 = Microbial resistance in humans

R17 + B15 = Microbial resistance in animals

R18 = Effects of pharmaceutical use of ecosystem processes

R19 + B17 = Drinking water contamination

B13 = Water treatment

B16 = Human pharmaceutical demands

COLOURS

Human population and food production

Primary production and influences of

Human activity, pharmaceutical use and disposal

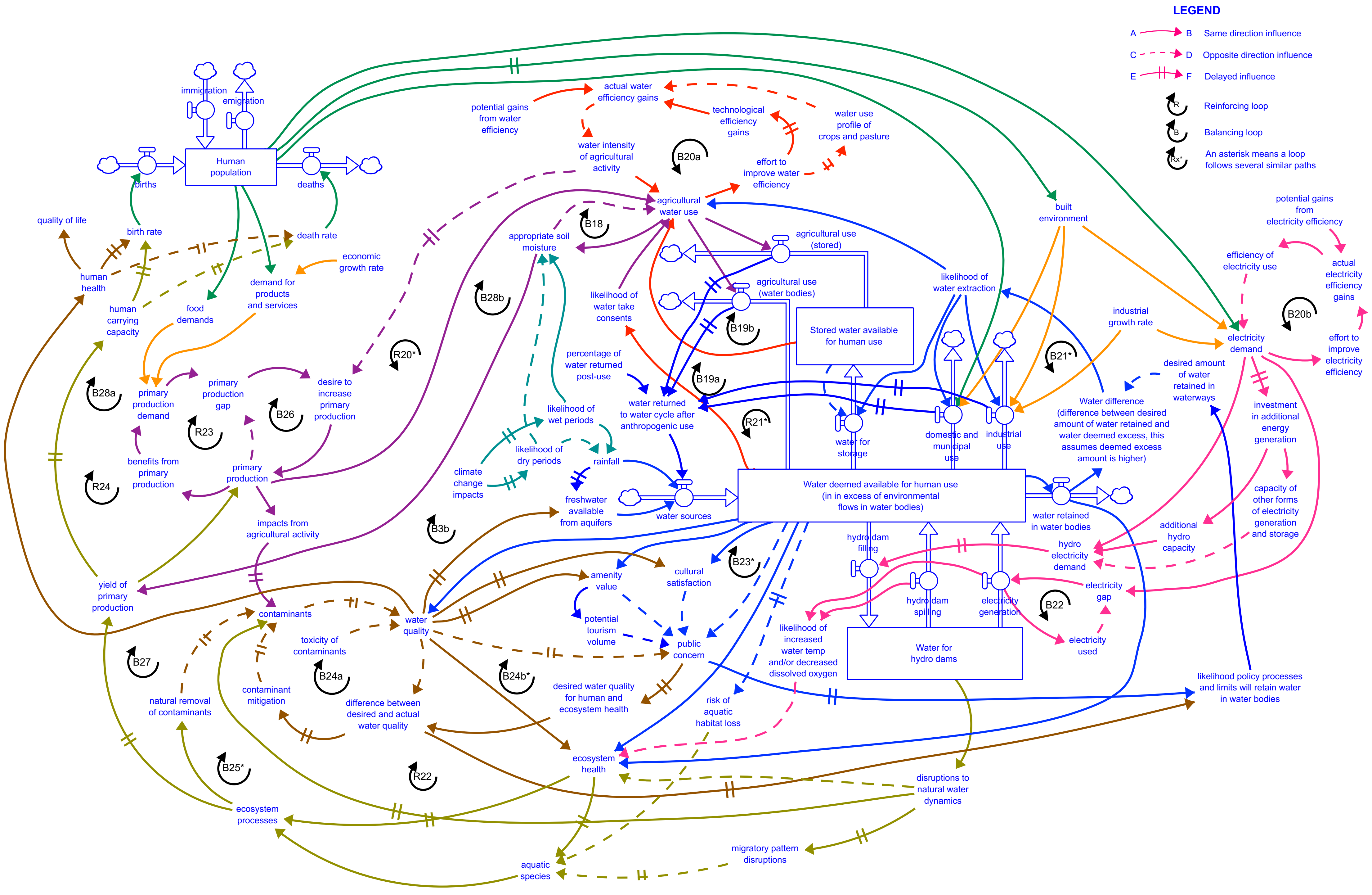
Animal pharmaceutical use

Antimicrobial resistance and human health

Contamination pathways from water

Potential pharmaceutical mixing and novel impacts

Impacts pathways on environmental carrying capacity (animal and human)



Water availability

LOOP LABELS

R20 = Rebound effect

R21 = Ag water use intensity

R22 = contaminant processing

R23 + B26 = Primary production

R24 = Ag value add an intensity

B18 = Agriculture water use and soil moisture

B19 = Ability to irrigate

B20 = Efficiency gains

B21 = Water use control

B22 = Electricity generation

B23 = Water quantity and public concern

B24 = Water quality, contaminant mitigation and public concern

B25 = Human carrying capacity

B27 = Ag activity and water qual

B28 = Ag water use and carrying capacities

COLOURS

Human population and demand implications

Primary production and influences of

Human activity and influences of

Contaminants: impacts, mitigation and public concern

Water quantity: impacts, mitigation and public concern

Hydroelectricity demand, generation and efficiency

Water use and efficiency

Impacts pathways on environmental carrying capacity (animal and human)

Climate change impacts

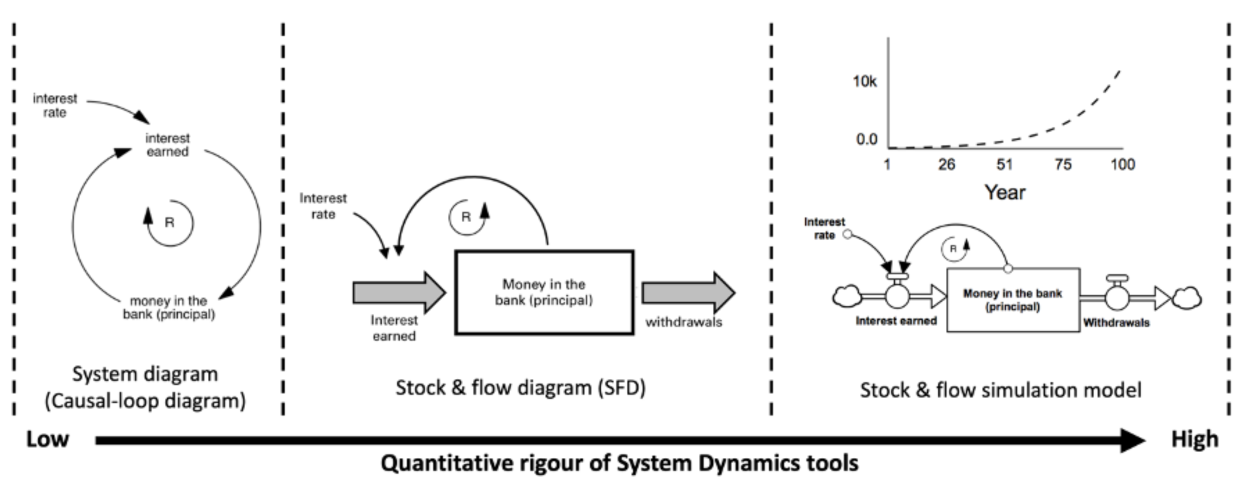
Appendix 2. How system diagrams can be used

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.

A1. Causal 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 A1**.** which highlights how these varying tools can demonstrate 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 A1. 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.

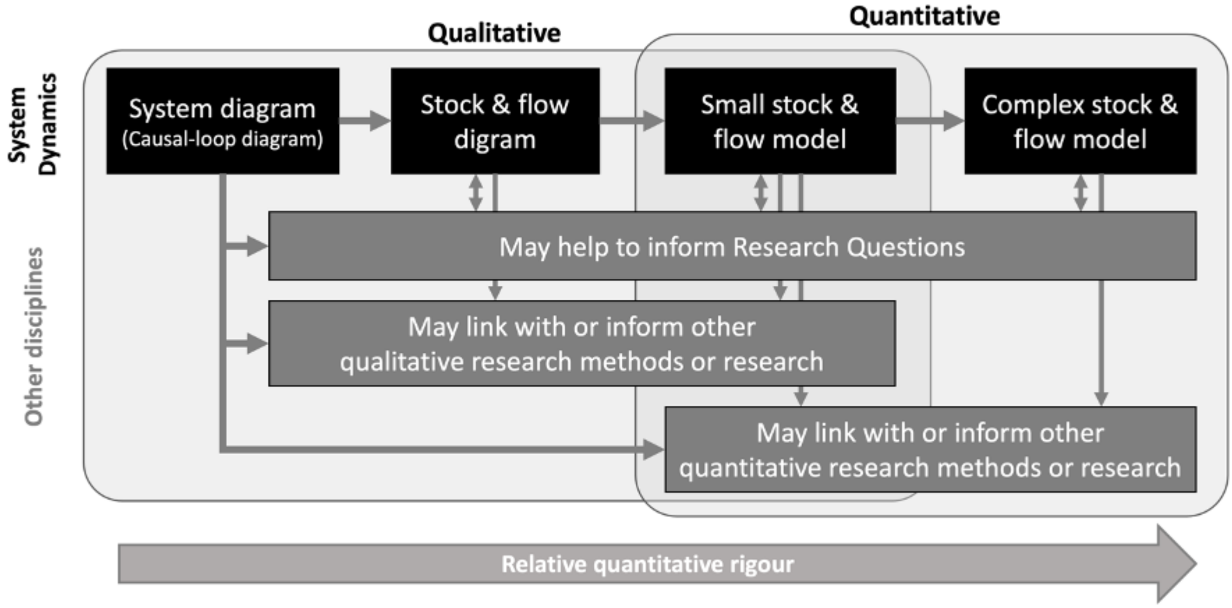
The next step up in quantitative rigour are Stock and Flow Diagrams (SFD). While *water flows and stocks* are represented in the diagrams within this report using stock and flow notation, these diagrams are not considered complete of 'full' SFD. This is because SFD usually contain multiple stocks of interest, not just the focal factors. 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).

A2. 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 A2.

Figure A2. 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 into 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).