CIRCULAR WATER

Report: Water circularity in urban neighbourhoods

M. Sc. Graduation Project: Circular Water

Water circularity and pro-environmental behaviour for urban neighbourhoods

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CONTENTS

RESEARCH INTRODUCTION

In the current context of the developed world and the upper and rising middle classes in many developing countries, the consumption pattern that most people have grown accustomed to includes a limitless access to food, energy, water, clothing and consumer goods. At the end of this supply line are problems of climate change, global resource depletion and environmental damage. This is a result of industrial and agricultural activities that surround and sustain life in cities as well as people's direct consumption of resources from networks of water, food and energy. Discharge of excess and used materials has not only resulted in problems of landfills and ecosystem imbalance but has also led to the loss of material value and its potential for reuse, increasing the entropy of the state of natural resources by making them less and less accessible for human use. This has created an endless demand for fresh resources which are consumed at a rate faster than they can be naturally replenished.

The network of supply and discharge of resources in cities is largely invisible to people, except for those involved in its functioning. An over-dependence on techne (craft) to satisfy the seemingly endless needs of our growing population and an underdevelopment of sophia (wisdom) of how to manage natural resources in an equitable and responsible manner has lulled human beings into a state of comfort and naivety (Timmeren and Henriquez, 2018) Water infrastructure is located underground, energy production systems, farm lands of various kinds and water treatment systems are largely centralized and, hence, located far away from cities. Used water streams of various compositions are discharged in underground networks, excess food from supermarkets is thrown away and synergetic energy-use is only an upcoming strategy, also incorporated through inconspicuous engineering design, leaving people unaware of the systems that make their cities function.

CONTEXT

In developing countries, urban scale problems are often due to the lack of a certain key resource, or the mismanagement of it. However, in developed countries that have achieved more than the required standard of living, long term environmental problems come from the comfort that people have grown accustomed to. In such places, it is also easy to forget the need for effective resource management for human survival (White, 2010). This can also be said of some classes of societies in developing countries with large class hierarchies where the consumption effects of the upper and middle classes are offset by those of the lower class.

Air, water, food, energy, building materials and living organisms are all part of the natural cycle of the world with its shifting patterns of growth and death. Cities are parasitic landscapes; their functioning is inextricably related to their ability to control and draw resources and capital from their hinterlands. Current systems of growing food and supplying water are nearly invisible in the urban fabric, disconnecting us from the resources that we are invariably dependent on, causing a sub-conscious assumption that this comfort is here to stay. A gradual disconnection of cities from the environmental constraints of their hinterlands may have caused societies to collapse in the past since the migration of peoples towards resource-intensive urban centres creates a concentration of both risk and capital (White, 2010). A well-known example from history is that of the Fertile Crescent population which is described as having committed 'ecological suicide' by destroying their own resource base due to overgrazing and converting forests into agricultural land (Diamond, 1997). After centuries of resource use for cultivation, by 1992 most of the original marshland had disappeared, leaving behind a desert in what was the fountainhead of agricultural revolution (History.com Editors, 2018).

While we are substantially aware of problems of the past and have a sense of potential dangers to urban areas in the future, these prospective issues may not be affecting us significantly enough for us to rethink our resource management strategies (White, 2010). In addition, it is not enough that we solve anthropocentric problems, allowing the natural environment to bear the brunt of urban solutions. The issues of vulnerability, risk and resilience are as applicable to the natural environment as to the human population. Concerns related to the natural environment are often addressed after the water needs of people are met.

This broad problem forms the underlying reasoning for this thesis, the focus of which is water systems in the urban context. Environmental damage, following water practices of industrialized and centralized systems, can be described as the result of two main phenomena, the linear flow of resources and consumerist behaviour. While behaviour is a factor pertaining to humans, linear resource flow is a characteristic of the network that humans have been developing. The two parts of the problem are related to each other and described further in the next section.

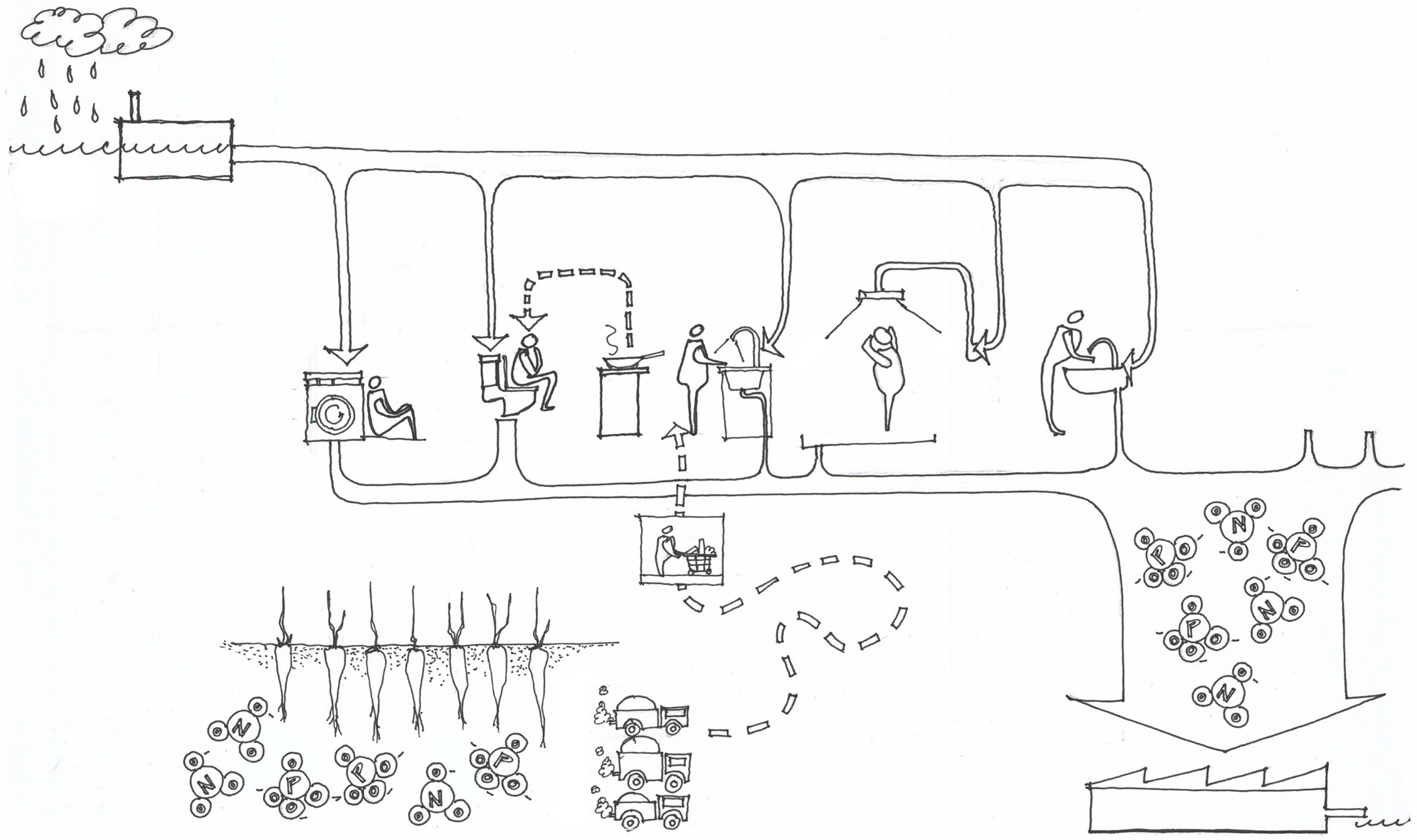
LINEAR RESOURCE FLOW

PROBLEM STATEMENT PART 01

With regard to risks arising from excess water, most developed cities are well-protected from the problem of flooding although coastal cities in many parts are still vulnerable in this respect. From the perspective of water as a key resource, agricultural and industrial water (also termed 'virtual water') for production processes have been indispensable in creating the ubiquitous urban lifestyle of the 21st century. Within the realm of water supply for domestic use, the conventional urban water network has been largely successful in satisfying people's needs of drinking water and protecting public health. However, this urban water network is linear in its transport of nutrients through the medium of water. Streams of greywater, faeces and urine are mixed for ease of plumbing and discharge, but this results in the displacement of nutrients that are present in them from the consumption and digestion of food, which came from soil containing these nutrients.

In the case of a country like The Netherlands which lies in the delta region of three rivers which are fed by the Alps, it may be true that water availability will not be a cause for concern in this century. The central water supply system in The Netherlands is enviable for its quality and cost, but it does not practise the reuse of waste water, treated or not, for domestic purposes. Similar to systems in most other developed countries, it is based on the principal error of using large volumes of drinking water to transport small volumes of faeces and urine (Holgund, 2001) over intercity distances.

In practice, fertilizer from human and animal waste has been replaced by artificial fertilizers, the production of which costs substantial energy and the run-off of which pollutes water bodies. Phosphorous was recycled continuously with minimal losses when human and animal excreta were used as fertilizer (Bartram, 2018). A circular resource management system was indeed practised prior to the modernization of water, regardless of the term used then. In the



central treatment of waste-water, organic matter, nitrogen and phosphorous are removed and discarded. Nitrogen is released into the atmosphere but phosphorous is disposed as sludge into surface water, hence causing the concern of global phosphorous depletion and eutrophication of water bodies. While it is still possible to recover energy from the organic matter, it is less efficient to do so in its highly diluted and mixed state.

This transfer of nutrients from soil to living organisms to water, thus, follows a linear pattern, minimizing the potential of restoring nutrients to the soil. This process is also a rather long one, starting and ending in locations considerably far away from the users it is designed for, making the process seem inconsequential for urban dwellers. There is no such thing as waste in the natural world where a completely closed-loop system recognizes waste as a valuable resource. This is the basis for a circular resource management system (Lucey, Barraclough & Buchanan, 2010).

It generally appears that most urban situations have both their problems and solutions in technological aspects of systems. Humans are not seen as having some potential to improve the situation mainly due to the misconception that people's convenience and comfort need to be sacrificed to produce a result that is truly good for the natural environment. Innovations go far in optimizing and improving the performance of machines and infrastructure but not as much in changing human behaviour which could contribute towards the same goal.

The problem of linear resource flow is addressed, in this thesis, parallel to the problem of human behaviour with respect to resource use. Further, the objective also attempts to relate specific aspects of the two problems with each other such that a coherent solution may be arrived at.

CONSUMERIST BEHAVIOUR

PROBLEM STATEMENT PART 02

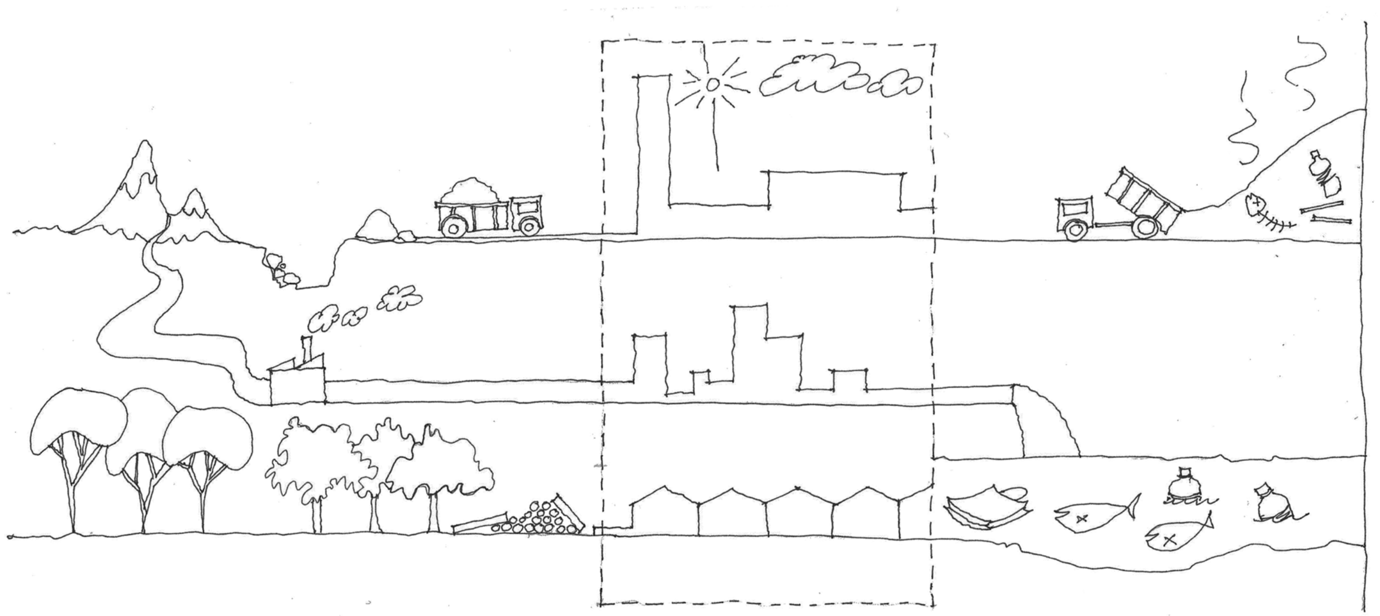
Most technological innovations in the recent past aim to make our lives easier but not necessarily make us more mindful or conscious of our lifestyles. A capitalist-consumerist society is based on material economic activity, each step of which has environmental impacts. Increasing standards of living and affordability give people increasing access to consumer goods, which means economic development of societies continuously escalates the degradation of global environmental commons (Tolbert & Schindel, 2018).

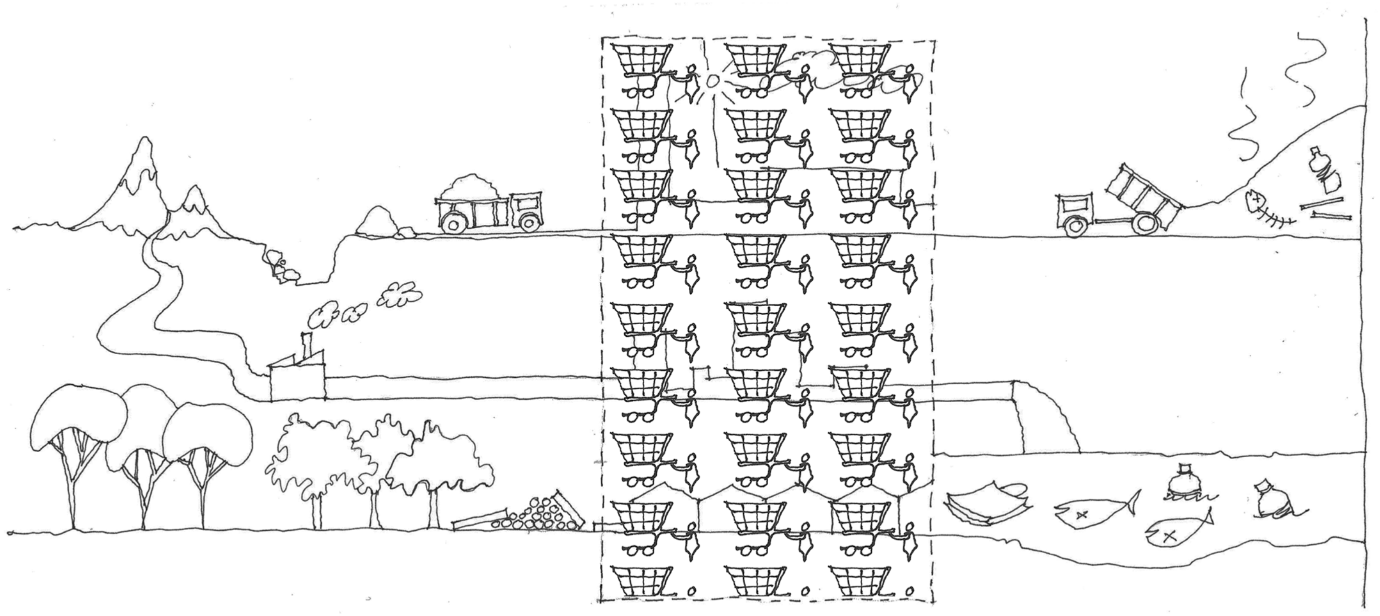
Centralized systems of supply and discharge have led to societies that are completely dependent on governing bodies and corporate companies for food, water and energy. The obvious advantage of being part of such a centralized system is that it allows people more freedom in their choice of work and leisure activities. Like the way agriculture allowed humans to settle down and specialize in various fields without having to worry about feeding their families daily (Diamond, 1997), present day supply networks provide an assured supply of resources without much effort from users apart from being able to afford them.

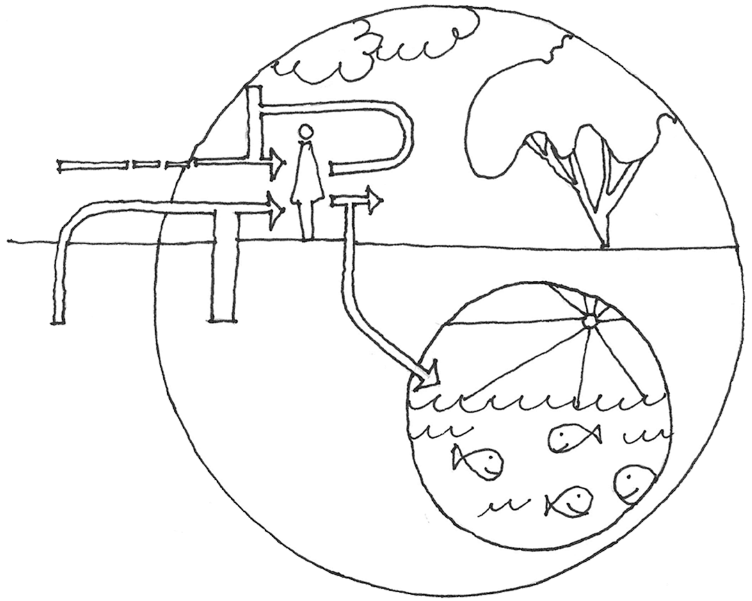
More recent developments related to urbanization and the infrastructure that is needed to support it bear an undercurrent of technocentric methodology. However, this has received criticism with the argument that the power and variability of climate can challenge design parameters. Protection from the risk of resource depletion or our inability to manage them in adverse climatic conditions cannot be absolutely guaranteed with mere hard engineering (White, 2010).

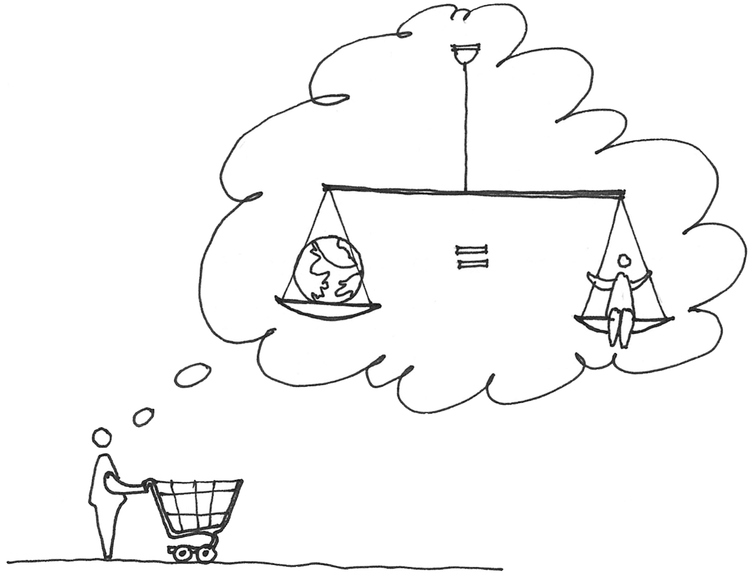
Infrastructure created to transport resources to cities are becoming increasingly invisible, which means they are perceived less and less by people with every change in infrastructure design. In predictive models for human behaviour, a sizable chunk of the influencing factors is one's knowledge of a certain problem and respective action strategies to control it (Stepath, 2006). Perception is a basic requirement for the cognitive reasoning of a problem and the resulting behavioural response. Perception is dependent on the creation of experiences through our senses. Direct visual and aural perception of resource use is far more impactful than merely reading about it (Kollmus & Agyeman, 2002).

There is sufficient research being done with the aim of reducing the environmental impact of urban water systems, but not enough to reduce resistance towards such ideas. This resistance is a result of growing comfort and convenience in the developed world which most societies are motivated towards. Many projects where, for example, new sanitation measures were attempted have failed due to resistance from potential inhabitants. Such resistance arises from a lack of knowledge of the overall picture of human impact on the environment through resource use. In the overlap between principles of water use and human behaviour lie factors of knowledge and attitude which result in certain behaviour, many of which are repeated and established as habits through daily activities involving water. The situational factor for this behaviour is the built environment itself, the design of which is in the control of engineers, architects and policy-makers.









RESEARCH OBJECTIVE

The objective of this thesis is to define technical and behavioural strategies for water circularity in urban residential neighbourhoods. It addresses both parts of the problem statement, that is, the system of linear resource use and the role of users in the system. This objective can be stated in the form the following research questions:

How can a circular water system including pro-environmental behaviour among users effect long-term environmental benefits?

1. How can circularity be defined for water systems in varying contexts of climate and water availability?

2. How does the experience of water infrastructure by users influence their resource consumption habits?

3. What environmental benefits can a circular water system provide and how can these be measured?

This is a small part of the larger vision of including users in the design of technological systems for the urban environment. Such systems need to balance the relationship between technology, people and the natural environment. This is similar to the TBL (Triple Bottom Line) approach to water and urban resource sustainability goals which includes economic, environmental and social aspects of urban problems (Daigger, 2010). In contrast, we are currently in a technocentric time period that tries to rely almost entirely on technological innovation for problem-solving without disrupting people's apparent comfort and without accounting for the limits of the natural environment.

Although there seems to be sufficient awareness of occurrences such as climate change and rising sea levels, attitudes towards such problems tend to be general whereas behaviour is very action-specific. (Kollmus & Agyeman, 2002). People seem to be aware of the larger picture in a rather detached way, that is, we often don't relate our own activities to the global problems we are actually aware of.

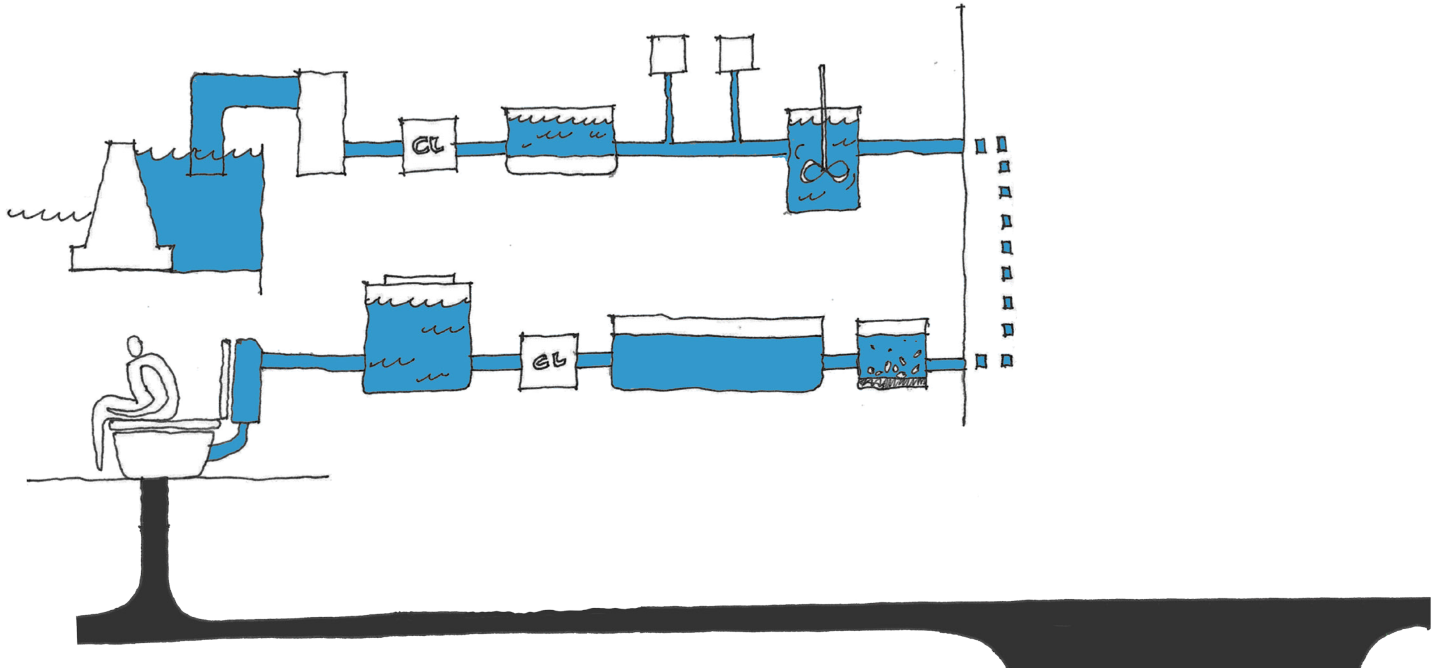
Design tool as thesis result

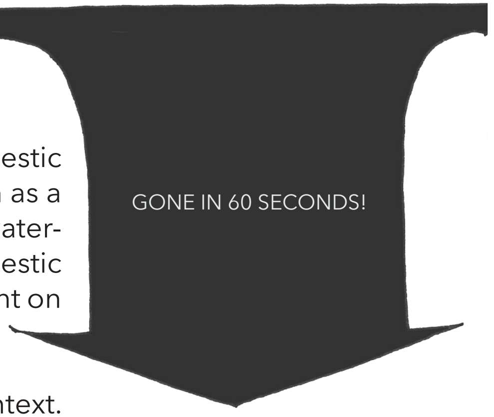
Results of research are incorporated into a digital tool that takes context-related inputs and provides options for circular water and pro-environmental behaviour strategies to incorporate in the design of a residential neighbourhood.

It is partly possible to bridge the awareness-gap in resource availability and consumption through design – of the tool as well as a neighbourhood designed using the tool. This thesis attempts to create a coherent solution involving circularity of water and pro-environmental user behaviour, corresponding to the two-part problem statement. Three broad water-practice objectives drive the functioning of the tool: reduction in the demand for drinking water, increase in the acceptance of treated greywater and increase in the acceptance of non-flush toilets. These are explained in detail in the following pages.

REDUCE DRINKING WATER DEMAND

TOOL
OBJECTIVE 01



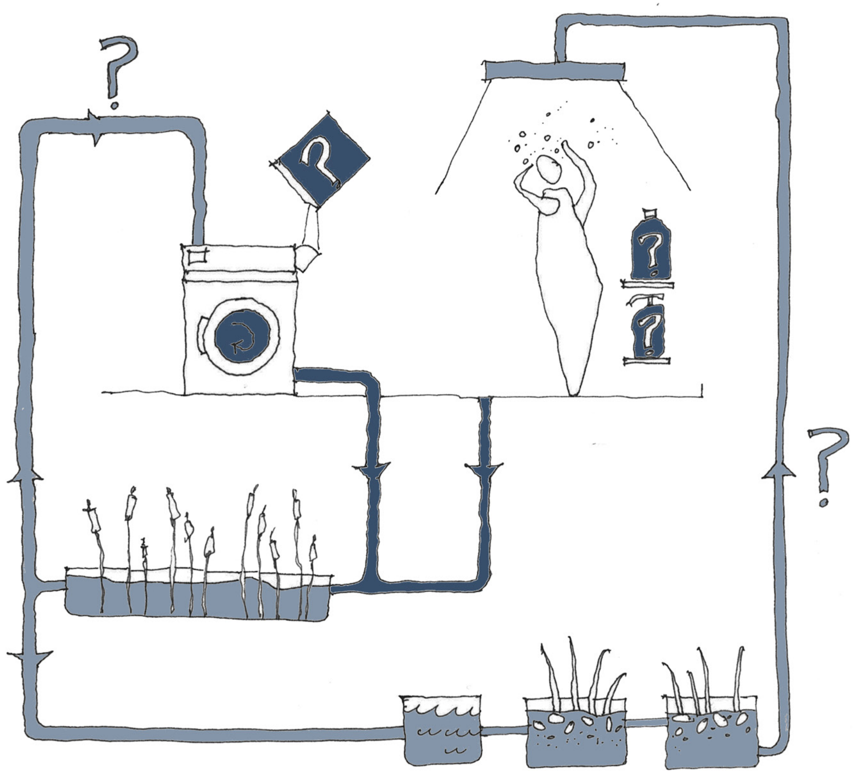


Reduce drinking water demand through conscious consumption of domestic and virtual water , and water reuse within the neighbourhood. This is seen as a combined result of multiple strategies– judicious use of shower water, water-saving fittings, use of rainwater where possible and reusing water for domestic purposes. Some of these are purely technical whereas some are dependent on users' knowledge of and attitude towards the circular water system.

The possibility of rainwater use depends on its availability for a given context. The tool will account for the rainfall level and pattern and provide requirements for catchment, basic treatment and storage.

INCREASE ACCEPTANCE OF GREYWATER REUSE

TOOL
OBJECTIVE 02

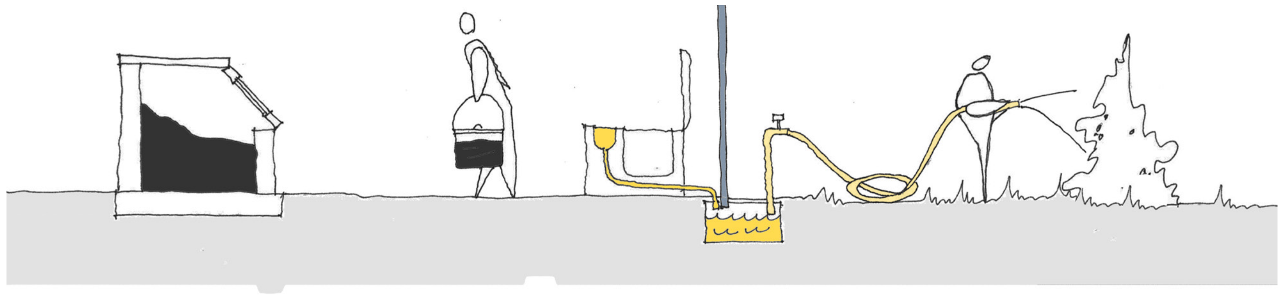


Increase the acceptance of greywater reuse through the integration of neighbourhood strategies for inducing such behaviour, the design of visible treatment systems in the neighbourhood and controlled use of certain household products. It is understood, based on literature study of realised projects, that some kinds of visible resource networks results in users feeling relatively more responsible for the resource and contribute to its management. Hence, the design tool prioritizes such methods of water treatment and supply that are visibly integrated in the neighbourhood, but is not necessarily limited to these.

INCREASE ACCEPTANCE OF NON-FLUSH TOILETS

TOOL
OBJECTIVE 03

Increase the acceptance of non-flush toilets with the aim of recovering nutrients and organic matter within the soil environment as well as the general aim of reducing drinking water demand. This issue seems to face resistance from users mainly due to the relative inconvenience it poses compared to the ubiquitous flush toilet, and some lack of knowledge of how non-flush toilets are used. This non-acceptance of, for example, composting toilets is largely due to the fact that most people in cities have never or are not accustomed to using one. While the design tool could compare and prescribe different types of toilets that allow circular water use, it cannot control the successful implementation of such toilet use since that could require potential inhabitants to make trial uses of such toilets before agreeing to use one in their own household.



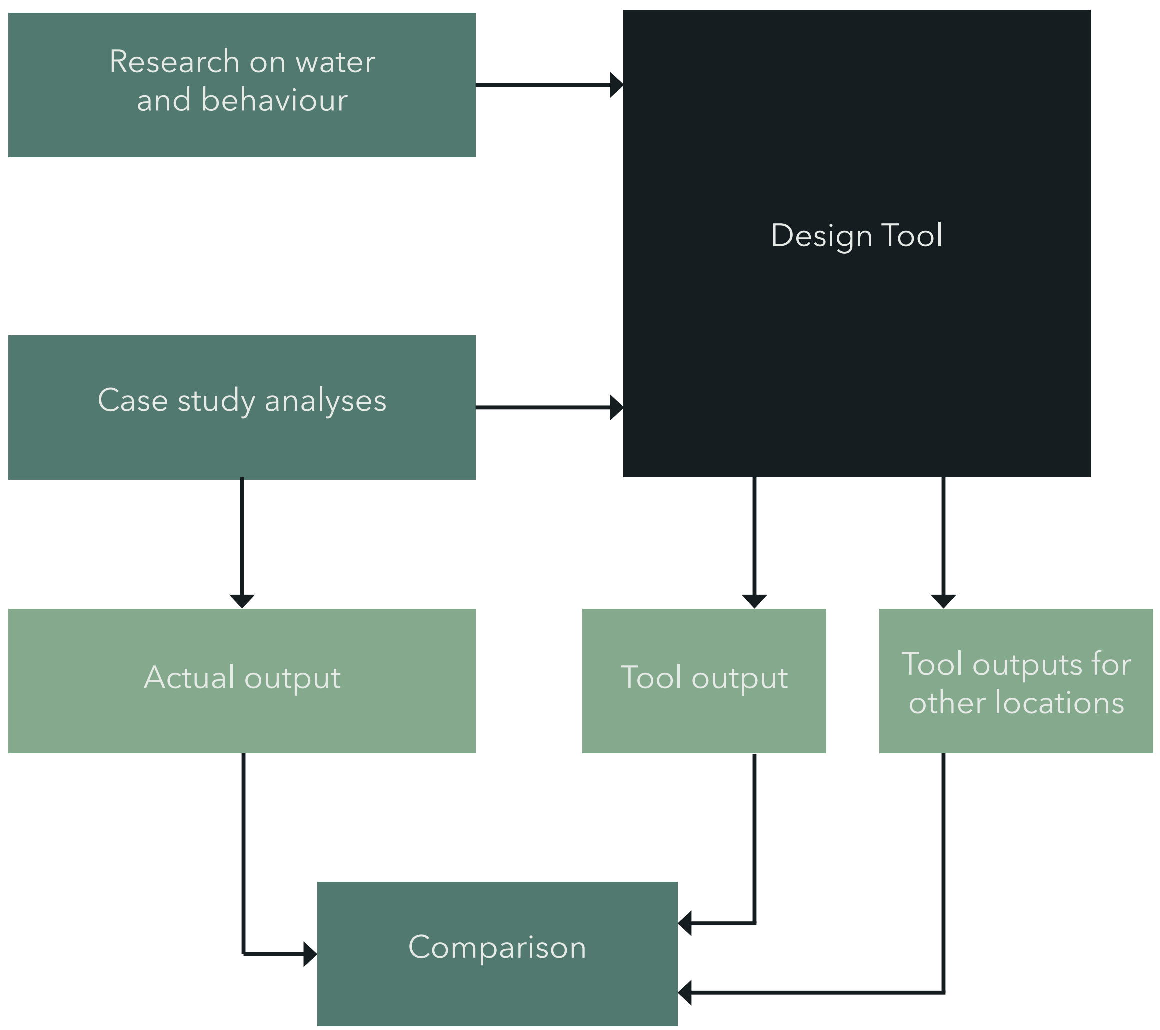
METHODOLOGY

The methodology for this thesis involves two main parts which lead to the tool development. Research on water includes water quality suitable for various domestic needs, rainwater availability, treatment of rainwater and greywater, and decentralised extraction of nutrients and energy from water.

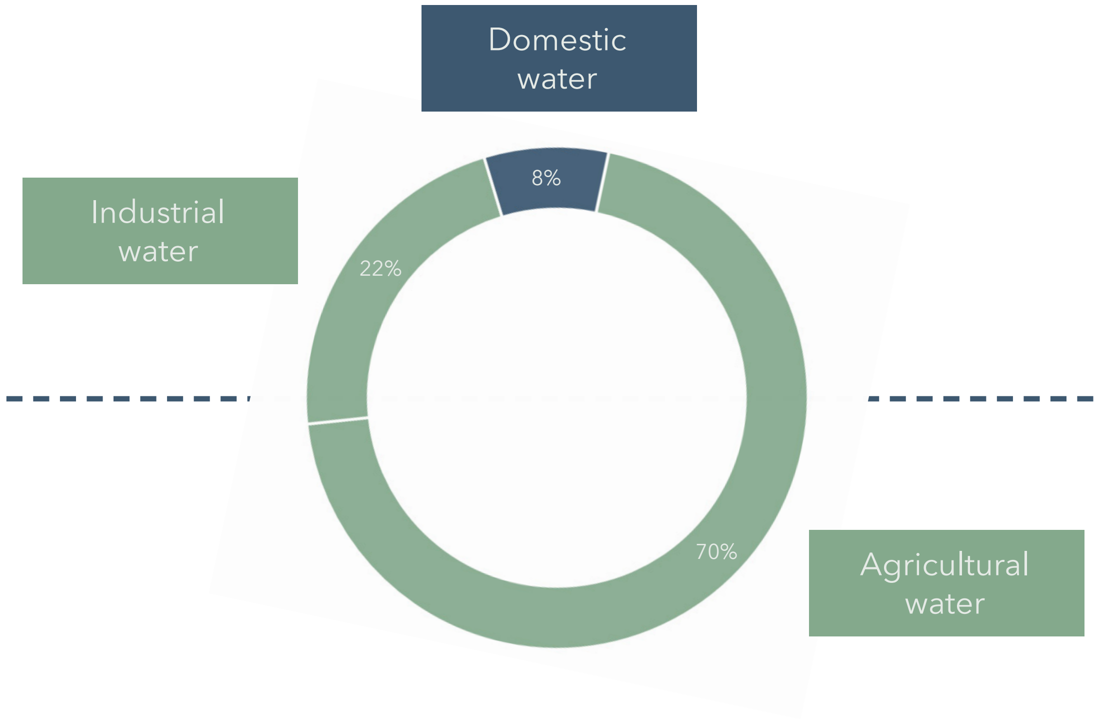
Three Dutch neighbourhoods have been chosen as case studies, each with a non-conventional decentralised water system. Interviews were conducted to determine, to some extent, the relationship between the design of these systems and the residents who depend on it. This would allow future circular water systems to be designed to consider their effect on human behaviour.

Conclusions drawn from literature research and case study analyses lead to the development of a design tool that enables the design of circular water systems for neighbourhoods. It provides both behavioural and technical strategies related to circular water practices.

Finally, the tool is tested for various locations to arrive at a definition of water circularity for various contexts. These may be different in terms of rainwater availability, population density, etc. Final decisions in actual projects are normally made based on space and economic constraints. In this regard, the tool also indicates these requirements for various strategies but only based on rules of thumb. The tool user is expected to make the final decisions based on calculated local cost constraints.



URBAN WATER SYSTEMS



Proportions of freshwater uses in the world (Main Uses of Water: Agriculture, Industry and Humans, n.d.).

Current water systems and practices substantially differ from those that were created at the start of urbanization. Perspectives of water have also changed over time with increasing technological developments and water crises in various forms. While the water cycle is conventionally explained as a hydrological cycle entirely independent of the interference of humans, an alternative model has been developing slowly among several sociologists, anthropologists, geographers and historians. This model of a hydrosocial cycle (Timmeren & Henriquez, 2018) is the process by which water and society function together. The modern scientific view of the water cycle excludes local conditions and the cultural, social, religious and ecological significance of the use of water. From the perspective of the natural environment, a reductionist command-and-control approach does not work well with the natural environment. Resilience and adaptation are as important as conservation, efficiency and equity in a sustainable built environment (Timmeren & Henriquez, 2018).

URBAN WATER SYSTEMS

Within the realm of urban water systems, domestic water constitutes only 8% of the total freshwater consumption in the world (Main Uses of Water: Agriculture, Industry and Humans, n.d.). While this is a very small fraction compared to the 70% that is used for agriculture, global urbanization is rapidly increasing, demanding the need for sustainable domestic water supply systems. Current systems, even in developed countries are not without problems.

General urban water system objectives fall into three broad categories, those are water supply, public health protection and environmental protection (Daigger, 2010). Water supply is planned according to zoning of cities into domestic, commercial and industrial areas. Concerns of public health are related to flooding and the spread of pathogens and toxins. Environmental protection largely deals with the quality of surface water and river water in terms of oxygen demand, nutrients, toxins and micro-pollutants and the effect of these on water ecosystems.

Problems related to water either arise from too much water in the city or too little (White, 2010). The former leads to issues of flooding which could lead to problems of disease, damage to infrastructure and the disruption of everyday life, and needs to be addressed through strategic planning at an urban scale. The lack of sufficient water for drinking and domestic purposes requires strategies at urban, neighbourhood and even household levels such as harvesting rainwater locally instead of being fully grid-dependent, conservation of water by reducing the demand and the reclamation and reuse of water to create local supplies. Concerns related to the natural environment, such as the quality of surface water resulting from urban effluent discharge, are often addressed after the water needs of people are met. In this regard, recent strategies being experimented upon generally involve source-separation of various waste-water streams for recovery of nutrients and energy, which is also the focus of this thesis.

In the developed world, the supply system provides safe drinking water to all inhabited areas. This water is normally supplied by building a water reservoir across a river, upstream of cities. This has the consequence of reduced quantity and unnatural seasonal variation, thus altering the ecology of the river. Waste-water treatment is also a centralized system followed by discharge to a downstream part of the river. However, since the treatment does not remove all pollutants from the waste-water, thus causing adverse long-term effects on the river's ecology. This, in combination with the energy required to pump these water streams across long distances in environmentally degrading (Ho, 2010).

Developed cities are characterised by reliable drinking water supply systems, well-designed sewage systems for waste-water discharge to protect public health, followed by drainage to protect against flooding. These cities are currently in the stage of addressing environmental effects of their established systems, mainly by controlling pollution of natural water bodies.

Most developed cities have well-functioning centralized water supply and treatment systems and also happen to be characterized by cold climates and high population densities, making it inconvenient to break away from such systems. High population density in mostly high-rise buildings means that rainwater can only meet a fraction of the domestic water demand, but it

WATER SUPPLY & DISCHARGE

Prior to designing a circular water-management system, it is necessary to understand that water occurs in different forms within the water cycle due to conditions imposed by the natural environment as well as nutrients present in water streams at various stages of interaction with the man-made environment. Of all the water present on the Earth, freshwater sources only account for 2.5%, out of which ground water makes up 30.1% and surface water and other fresh water make up 1.2% (USGS, 2016). Although desalination plants allow the use of ocean water for consumption, a vast majority of human water needs are met by surface water and other fresh water sources. Ground water is used in some parts of the world by direct pumping but is largely dependent on the local soil quality. Water of various qualities have been described below, from the point of view of human consumption and, to some extent, effect on the natural environment.

Surface water

Non-saline water present on land, that is, in the form of rivers, lakes, wetlands, etc. are called surface water. From the point of view of human consumption needs, the quality of surface water varies heavily and is influenced by microbial presence and industrial wastes.

Ground water

Water present in porous media below the Earth's surface is called ground water and is normally accessed for human use through hand-pumps, wells and springs. In comparison to surface water, ground water has a more consistent quality free of pathogens but could be contaminated by iron, manganese, fluorine and arsenic in some regions. It also tends to be brackish in coastal areas.

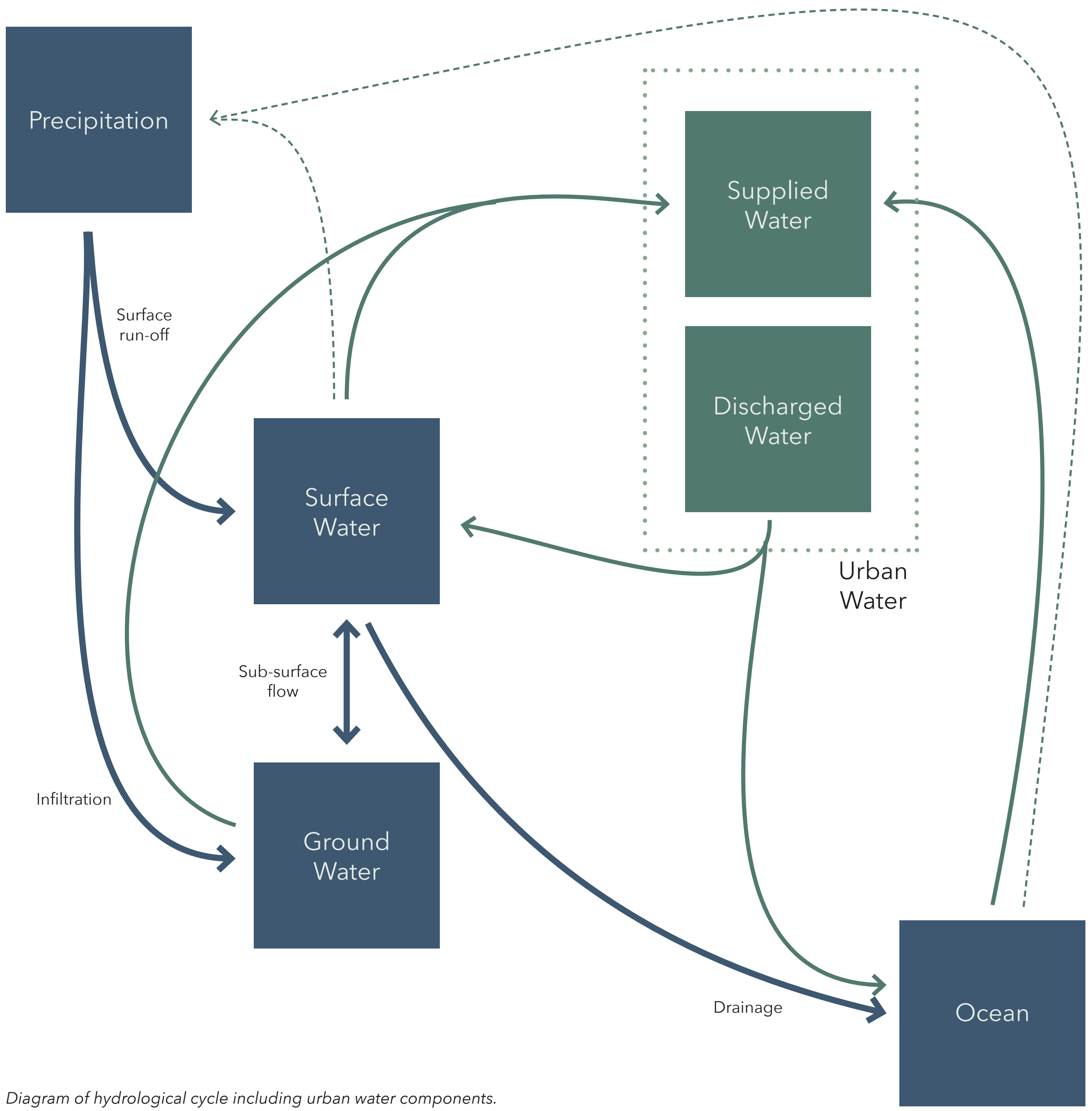


Diagram of hydrological cycle including urban water components.

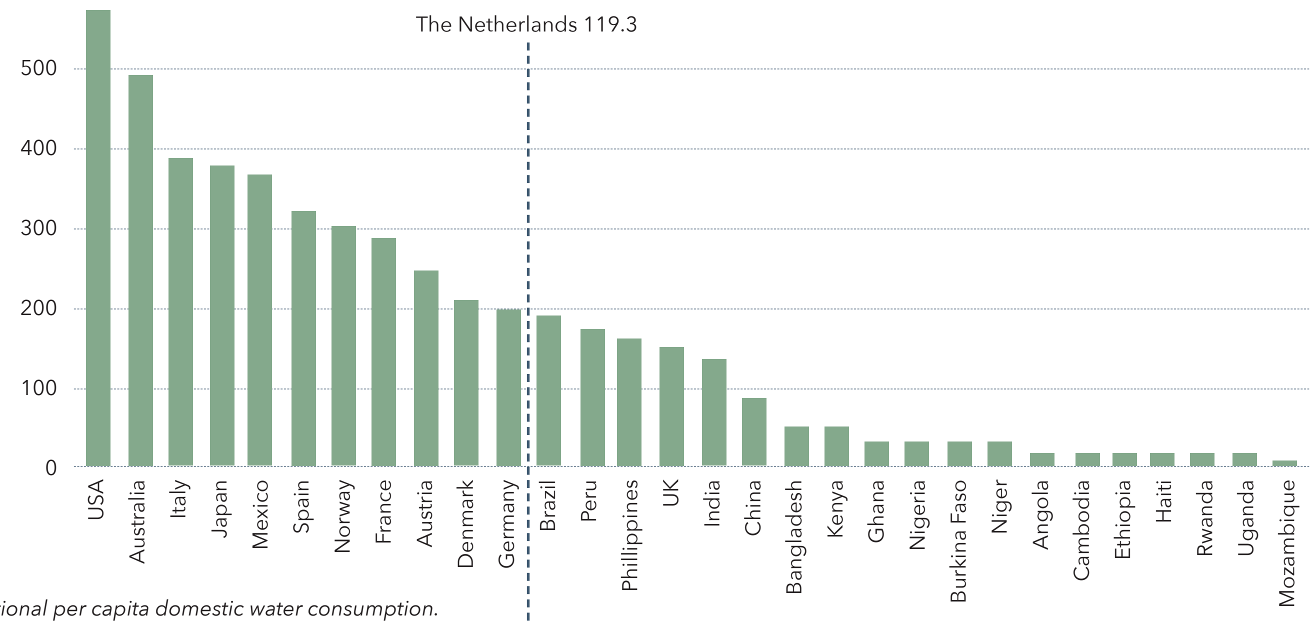
Rainwater/Greenwater

The quality of rainwater always exceeds that of surface water and, in some cases, can be compared to ground water, atleast until it touches a certain surface which could be contaminated. In general, rainwater is the closest natural source to drinking water in terms of its quality, giving it huge potential as a local water source due to relative ease of treatment.

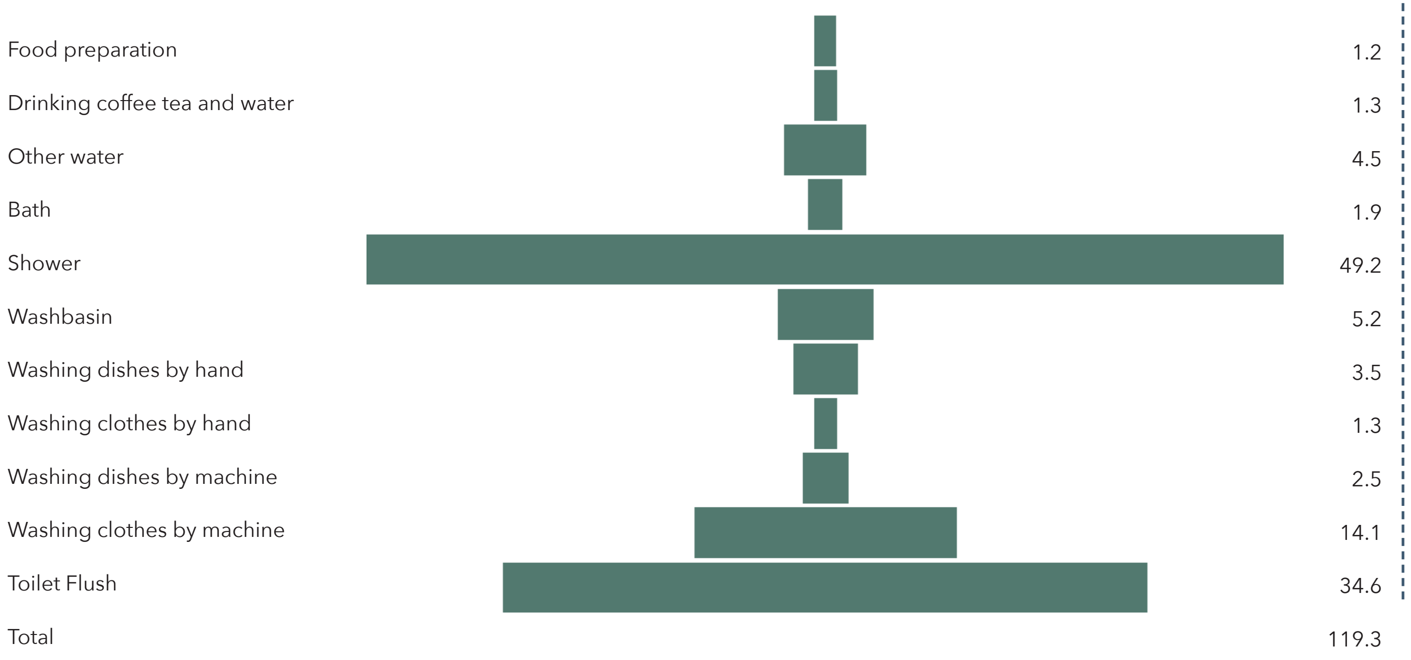
Potable water or drinking water

As defined in the WHO guidelines (2017) for drinking water quality, safe drinking water is that which does not represent any significant risk to health over a lifetime of consumption, including different sensitivities that may occur between life stages. Safe drinking water is required for food preparation, direct consumption and other domestic needs such as personal hygiene. Contamination by microbes and chemicals are the most common risks associated with drinking water.

In general, microbial risks related to drinking water arise from contamination by human or animal (and bird) faeces which are sources of pathogenic bacteria, viruses, protozoa and helminths. Disinfection is an indispensable step in treatment of water for potability. Health concerns related to chemical constituents in water are related to prolonged periods of exposure in most cases, rather than a more immediate effect as in the case of microbial risk. Chemically contaminated water usually becomes undrinkable due to unacceptable taste, odour and appearance.



National per capita domestic water consumption.
(Water Usage and Individual vs Collective Action. (n.d.).



Typical Dutch household water consumption (numbers in litres per person per day) (VEWIN, 2018).

Discharged water

In a conventional centralized waste-water treatment system, all used water streams in a household are collectively discharged. The distribution of organic matter and nutrients in typical European waste-water is stated in Table 01. (Ho, 2010). However, the point of defining streams such as greywater, blackwater, etc. is that the nutritional content of each of these streams varies depending on the activity that produced it. For example, water discharged after showering is in a much more diluted form and contains different nutrients compared to water discharged after flushing a toilet. Typical constituent proportions of greywater, urine and faeces are mentioned in Table 02 (Gulyas, Gajurel & Otterpohl, n.d.).

Greywater

The term greywater is generally collectively used for water discharged from the activities of showering, washing hands and washing clothes. It specifically excludes water discharged from the toilet and, in most cases, from the activity of washing dishes used for food preparation since this may contain food waste in at least small quantities (Akcin, Alp, Gulyas & Bust, n.d.).

It is important to note that greywater is typically generated in large volumes and small nutrient mass flows. However, about 1/3 of the potassium, an important nutrient for plant growth and limited fossil fertilizer component, is contained in greywater (Gulyas, Gajurel & Otterpohl, n.d.). Its highly diluted and high-volume state makes it highly relevant to reuse it without mixing faeces and urine. Where greywater is intended for reuse after decentralized treatment, it is very important that it is not contaminated by blackwater which is almost always contains pathogenic micro-organisms. This can be controlled by avoiding urinating while showering, rinsing reusable baby-diapers in sinks, etc. Such habits vary widely across the world.

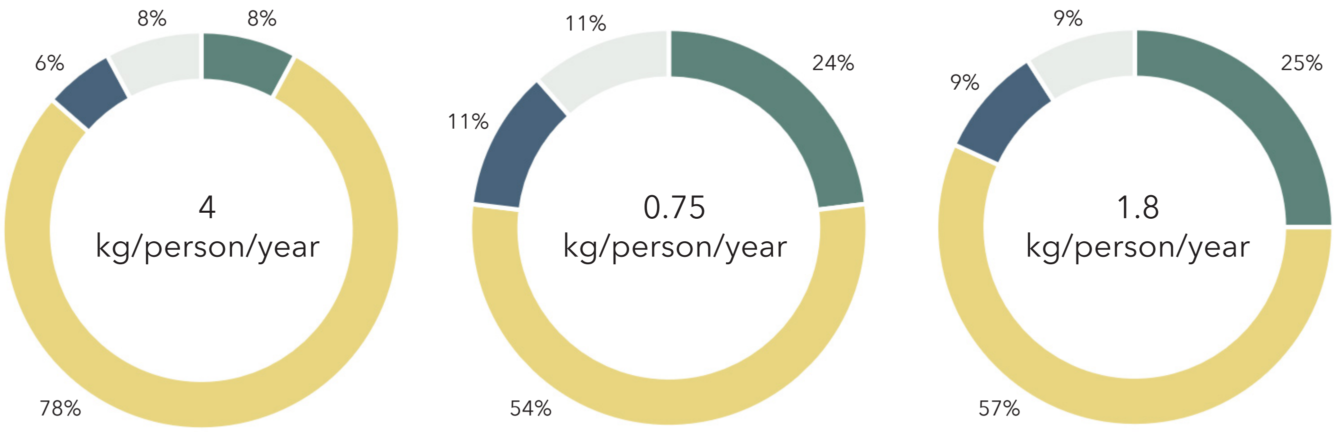
Where the greywater is strictly discharged from showering, washing clothes and hand-washing, it is available for reuse in a dilute pathogen-free form. After ensuring non-contamination of discharged greywater, the next step is to control the type of soaps and detergents used for the respective activities, such that its treatment requires relatively simpler techniques which consume the least amount of energy and chemicals, if any.

Blackwater

The term blackwater generally refers to water discharged from toilets and, thus, is a mix of faeces (brown water) and urine (yellow water). In a conventional wastewater system where the various streams are not separated, the resulting water (including greywater) is blackwater.

Domestic blackwater (including faeces and urine) contains 38% of the COD, 82% of nitrogen and 68% phosphorous present in wastewater (De Graff, 2010). Urine and faeces typically only make up 1% of the total volume of household waste-water and, thus, represent a highly concentrated stream with high resource recovery potential.

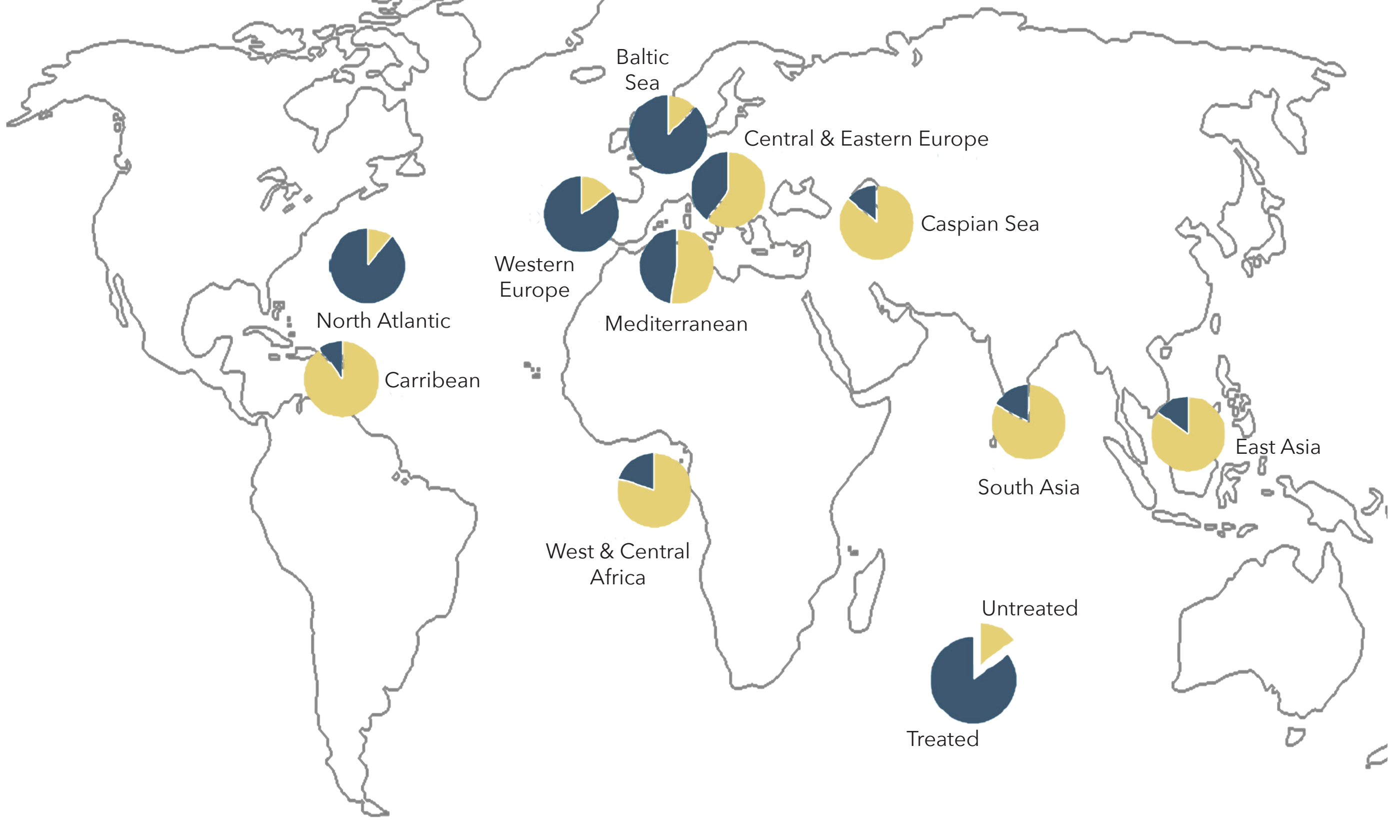
Transport systems that use minimal water are required in order to retain this high concentration. Urine-diversion with composting, urine-diversion and vacuum flushing for faeces or vacuum flushing for blackwater are the least water-consuming toilets and have the potential to enable resource recovery. Where urine-diversion and composting of faeces is not an option, vacuum toilets enable resource recovery while still functioning similar to flush toilets apart from creating a higher sound level while being flushed (De Graff, 2010).



	Source	Total-Nitrogen	Total-Phosphorous	Potassium
Blackwater	Faeces	1.1	0.6	1.1
	Urine	11	1.4	2.5
	Kitchen	0.8	0.3	0.4
Greywater	Bath/ laundry	1.1	0.3	0.4
	Total	14	2.6	4.4

Values of N, P and K in typical waste-water streams (numbers in table are in g/person/day) (Ho, 2010 & Gulyas, Gajurel & Otterpohl, n.d.).

CENTRALIZED WATER SYSTEMS



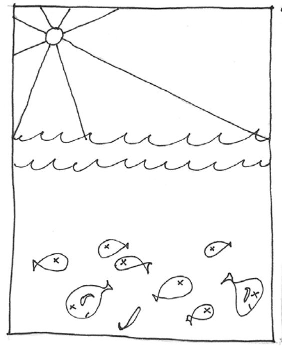
Proportion of centralized and decentralised waste-water treatment in different parts of the world (UNEP, 2010).

The beginning of the 20th century saw the development of piped water infrastructure in many urban centres in the world, breaking the faecal-oral cycle in the transmission of water-borne diseases and, thus, separating people from their wastes (Ho, 2010). The habit of flushing away faeces and urine instantly after using a toilet and showering with clean water on a daily basis regardless of one's cultural background are strongly associated with a sense of hygiene and this comfort has been made possible in all but the most water-scarce regions of the world mainly due to the construction of piped water infrastructure for supply and discharge.

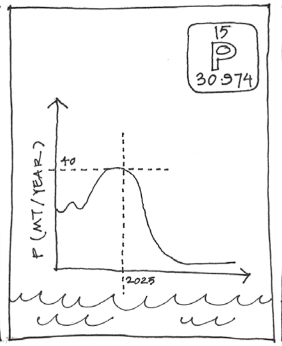
As was exemplified during the Cape Town water crisis of 2018, designed from the point of view of urban hygiene and individual comfort, this system has resulted in various water-related problems across the world, in some places by increasing the vulnerability of societies due to unpredictable weather patterns, rising sea levels and increasing urbanization, and in others by continuously displacing nutrient levels in the soil and land environment effecting consequences for ecosystems and resource accessibility for people.

Although developed countries and many regions in developing countries have established central waste-water treatment systems and appear to be convenient and well-functioning, modern waste-water treatment plants are hardly affordable for developing countries and cause eutrophication in water bodies (Gulyas, Gajurel & Otterpohl, n.d.). In general, centralized sewerage systems can be very expensive for places with low population density since the costs of such an extensive system have to be borne by a small number of inhabitants. Such costs may be unaffordable for people living in developing countries (Gulyas, Gajurel & Otterpohl, n.d.). Factors of population density, geography, climate, economy and the environment may demand that a non-conventional sewage system be designed for it.

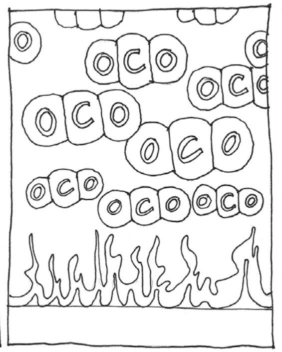
ENVIRONMENTAL IMPACT



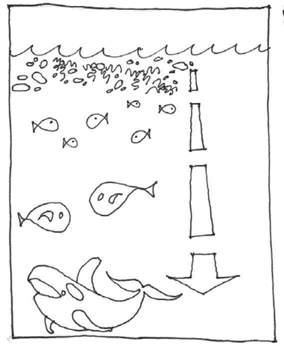
Eutrophication



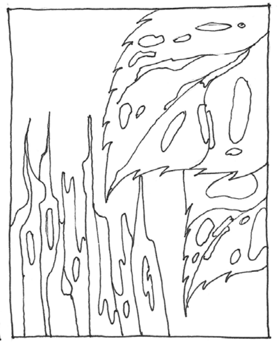
Displacement of phosphorous from accessible reserves



Increasing carbon emissions



Bioaccumulation



Increase in soil phytotoxicity

Contamination of surface water is one of the adverse effects of a centralized waste-water treatment system where multiple nutrient streams are mixed with each other and transported in large diluted volumes, making it more difficult to extract specific chemicals and nutrients from them. Domestic waste-water contains valuable plant nutrients and organic matter and has the potential to be used as fertiliser and soil conditioner for agriculture. As a result, this would reduce the production of chemical fertilisers which uses fossil-fuel based energy and causes environmental pollution (Gulyas & Otterpohl, n.d.).

The problem of contaminated agricultural run-off is due to the use of chemical-based fertilizers. The presence of medicines and other pharmaceuticals in waste-water from cities is due to the large-scale disposal of partially-treated waste-water into surface water. Both problems adversely affect water ecosystems but the potential for a solution could lie in local and source-separated waste-water treatment including local food production.

Conventional centralized water supply and treatment systems utilize considerable amounts of energy for pumping, the source of which may not always be non-fossil-fuel based. Energy recovered, say in the form of biogas from blackwater, in a decentralised system can be used locally, perhaps to run the treatment system itself.

The environmental impact of urban water systems is only a fraction of the impact induced by agricultural and industrial water-dependent processes. The relevance of domestic circular water goals can be justified by the increasing urbanization and the advent of new neighbourhoods every passing decade. The following chapter explains the environmental goals of domestic circular water systems, not with the aim of providing complete solutions, but to suggest a direction for circularity of resources in neighbourhoods.

ENVIRONMENTAL GOALS

ASPECT OF SUSTAINABILITY	GOAL
Economic	Financially stable utilities with the ability to maintain their infrastructure
Environmental	Locally sustainable water supply (recharge exceeds net withdrawal) Energy neutral or positive with minimal chemical consumption Responsible nutrient management that minimizes dispersal to the aquatic environment
Social	Provide access to clean water and appropriate sanitation for all

Triple Bottom Line approach to resource management (Daigger, 2010).

In response to future risks related to centralized water systems and environmental goals of water practices, attempts are being made to develop new systems of water supply and sanitation, many of have their underlying principles in ancient methods and naturally occurring phenomena. The TBL (Triple Bottom Line) approach to water practices (Daigger, 2010) accounts for the benefits for people in terms of economy and social fairness as well as benefits for the natural environment in terms of sustaining a water source, using low-energy, low-chemical methods for drawing and treating it and managing waste-water nutrients rather than displacing them through the water medium.

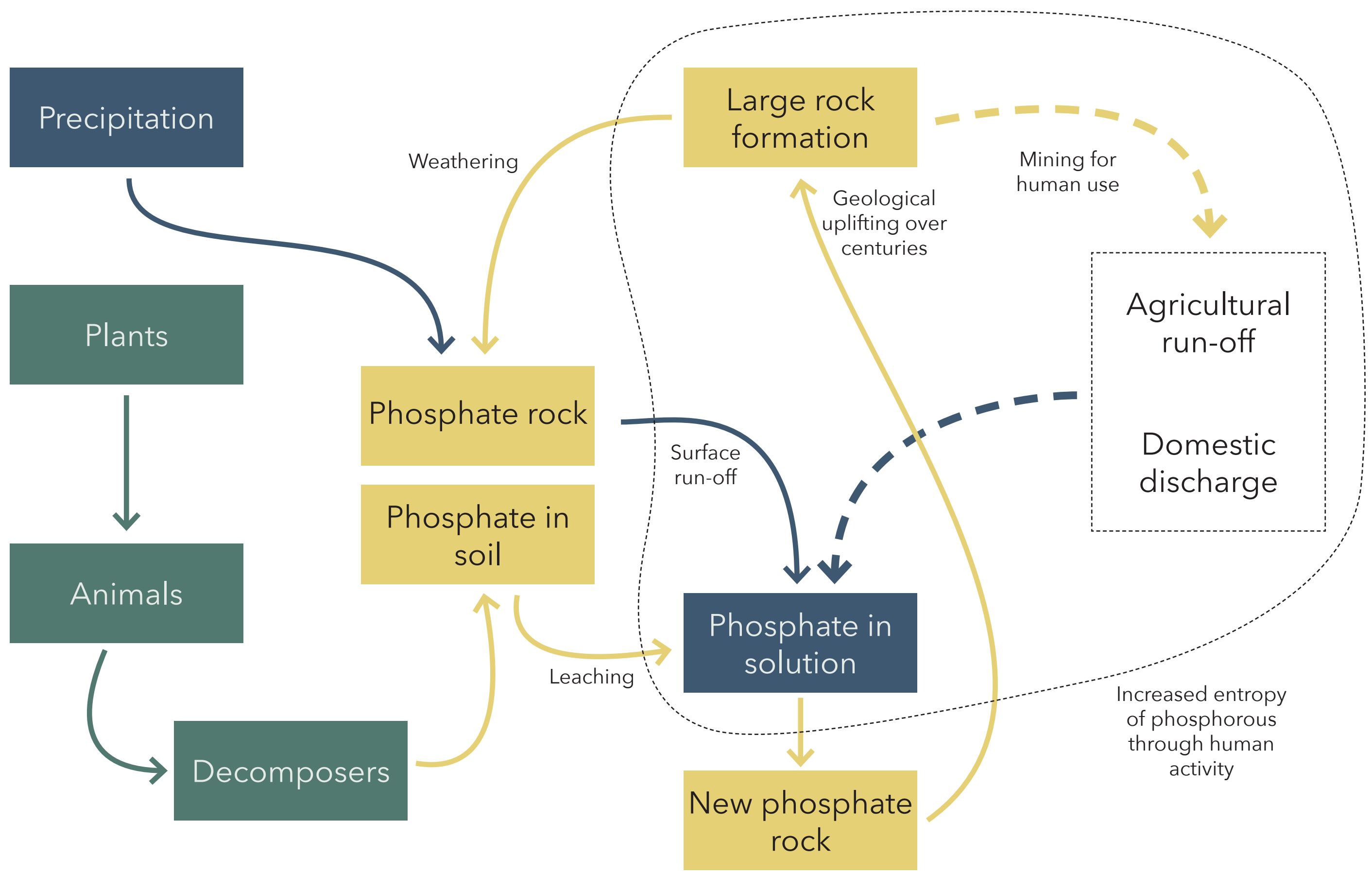
In the natural environment, each component of an ecosystem is multi-functional, maximising the efficiency of the system, while a number of overlapping niches create resiliency in the system. The same principle of multi-functionality applies to infrastructure and urban design thus creating the idea of an integrated urban water and resource management system (Lucey, Barraclough & Buchanan, 2010). Such systems rely on local water resources, thus reducing the city's dependency on water imported to the city from a central facility.

ENVIRONMENTAL GOALS

These systems have the potential to produce energy locally and restore significant quantities of nutrients back to the land environment (Daigger, 2010). After several attempts to define environmental goals of domestic circular water systems, three have been described in this chapter: phosphorous recovery, surface water quality and local energy generation. They are mutually related to each other and also related to local fertilizer generation potential. This is not explicitly mentioned as goal since it would be a repetition of atleast the first two goals.

The design tool developed based on this research expresses local fertilizer generation potential rather than surface water quality maintenance since the latter is dependent on a more complicated network of factors which go beyond the domestic water realm.

PHOSPHOROUS RECOVERY & SURFACE WATER QUALITY



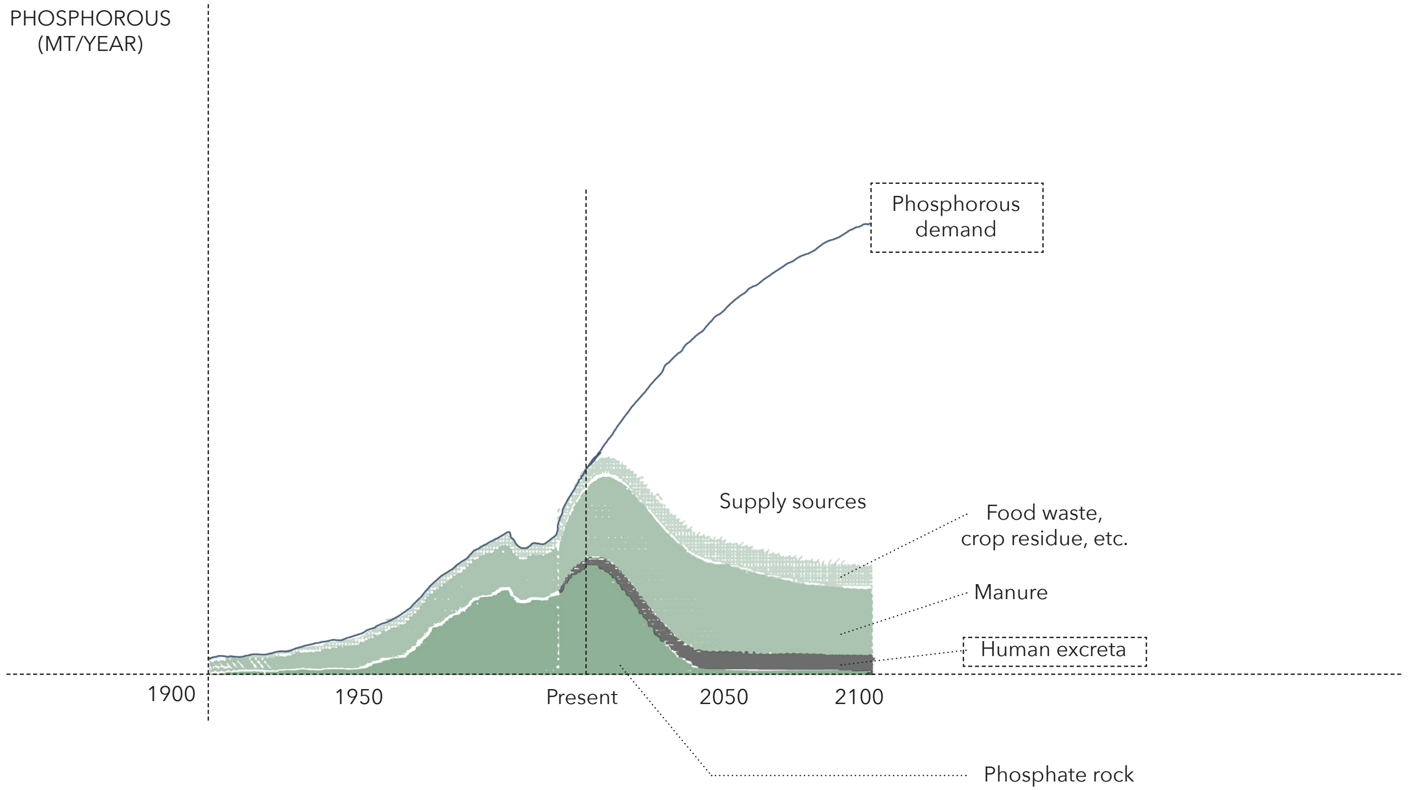
The conventional centralized waste-water treatment system is based on the principle error of using large volumes of clean water to dilute and transport small volumes of human waste. Environmental problems resulting from centrally treated waste-water effluents are often second or third priority concerns in the development of water infrastructure, the first being safe and convenient sanitation for users.

Over centuries, this paradigm has resulted in the transport of some nutrients and organic matter from soil to surface water through the system of consumption of food and excretion. Similar to the deposition of nutrient by-products in the land environment in the natural world, the nutrient cycle that humans are included in should also be closed within the land environment, rather than extending it to the water environment (Daigger, 2010). Domestic waste-water contains valuable plant nutrients and organic matter and has the potential to be used as fertilizer and soil conditioner for agriculture. As a result, this would reduce the production of chemical fertilizers which uses fossil-fuel based energy and causes environmental pollution (Gulyas & Otterpohl, n.d.).

Among the nutrients displaced to the water environment through a centralized water system, a potential future shortage of phosphorous has increased the concern for its existing reserves. Fertilizers derived from phosphate rock have been integral in sufficient food production and reduction of malnourishment since mid-1900s.

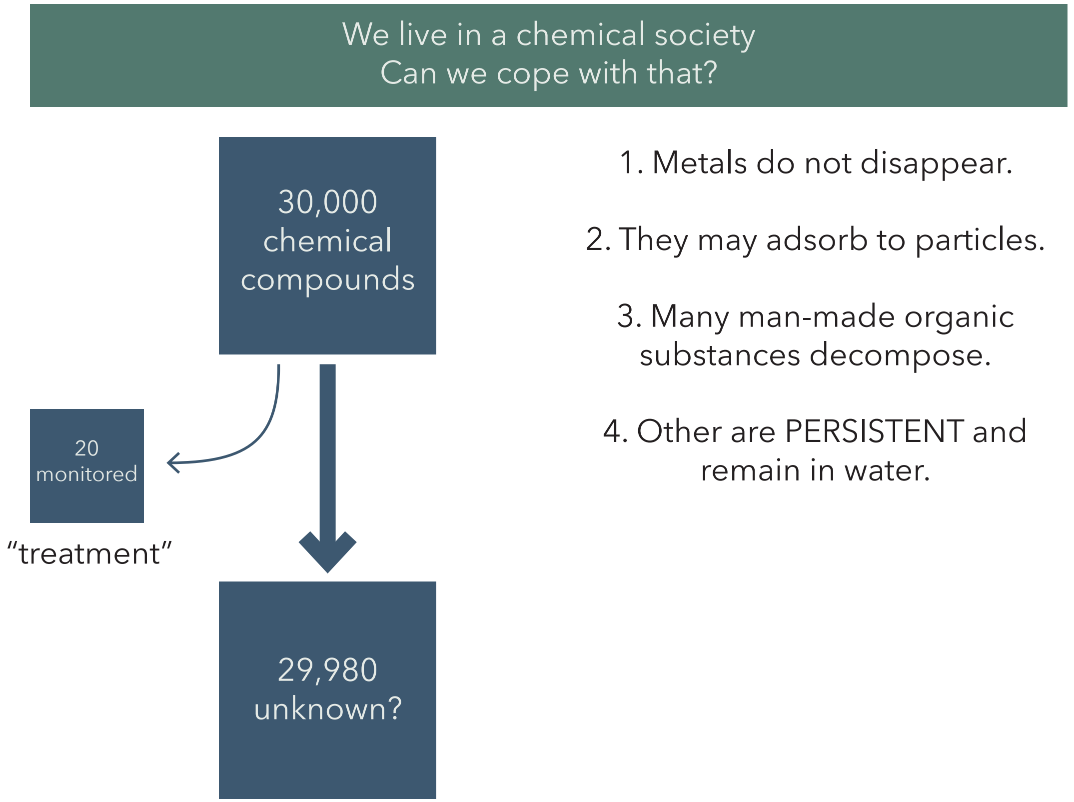
Although the agricultural sector is the largest culprit in global phosphorous mismanagement, the water and organic waste sectors have to control the discharge and, hence, wastage of phosphorous, nitrogen and energy. Drangert (2012) states the following possibilities for recycling urban phosphorous:

1. Replace phosphorous in detergents with alternative compounds.
2. Reuse phosphorous (and other nutrients) directly by applying human urine as fertilizer.
3. Reuse organic waste generated from restaurants and household kitchens as fertilizer (compost).



The second strategy could save around 20% of the amount of phosphorous needed as fertilizer for food production. Most research phosphorous recovery has focused on waste-water sludge management. With current phosphate rock availability, sludge-recycling processes are not economically competitive with phosphate rock mining, but this gap is reducing (Drangert, 2012).

A circular water system has the potential to return excreta (which contains phosphorous consumed as food) back to a farm where it re-enters the food cycle, reducing the need for mining phosphate rock. This is possible through the separation of waste streams at source, that is, at the point of generation of a waste-water stream. The main goal of source-separation is the keep nutrients in their respective streams without mixing or dilution and recover them to restore soil fertility (Gao & Zhang, 2010). This strategy will be explained in detail in the next chapter of this report.



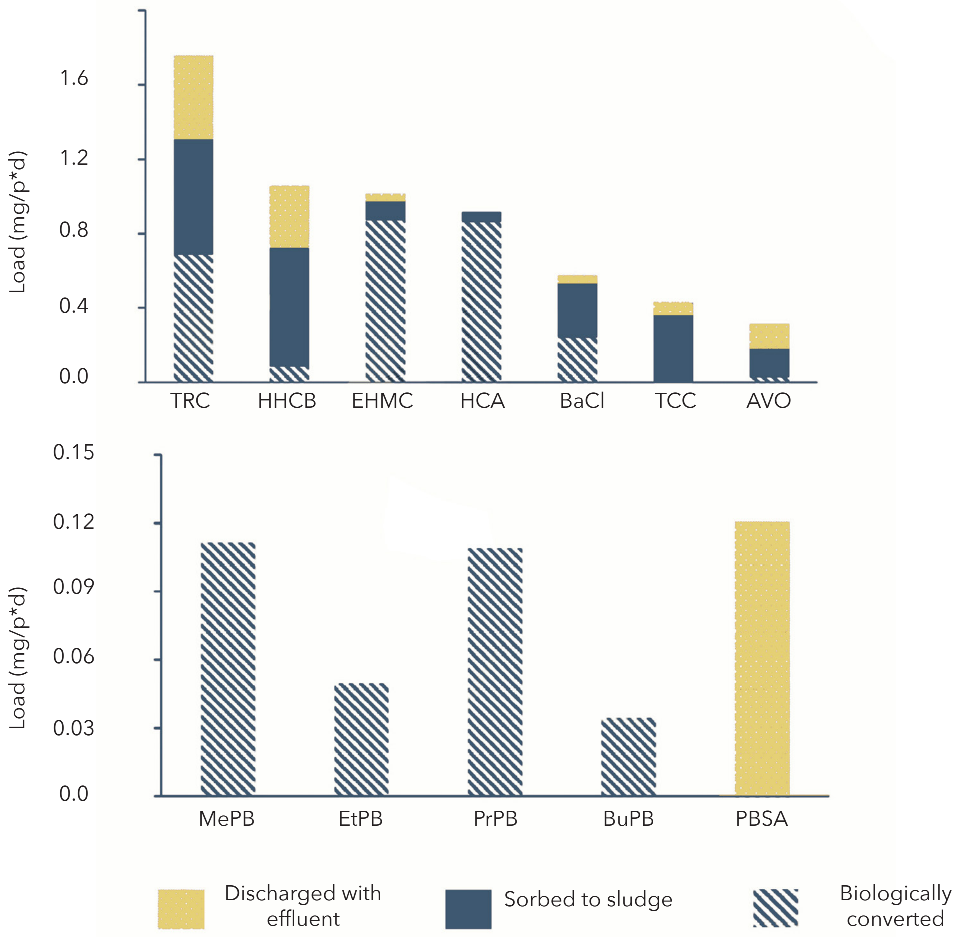
One of the major goals of the Dutch Water Plan for 2021 is to improve the quality of surface water. The Netherlands Environmental Assessment Agency and the Office of Economic Cooperation and Development (OECD) indicate that additional effort is required to counter new substances that impact chemical water quality, such as medicines and microplastics (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2014). The goals for nitrogen, phosphorous and pesticide levels in surface water are yet to be met. The National Water Plan has set a 90% reduction target for the overruns of surface water standard by the year 2023 (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2014).

The described goal of phosphorus recovery is partly related to sustaining ecosystems in surface water bodies. Although comparatively smaller in volume than agricultural run-off, centralized waste-water treatment systems cause ecosystem disruption in water environments through eutrophication (due to nitrogen, phosphorous, potassium and organic matter) and bio-accumulation (due to heavy metals). Water extracted from the same surface water bodies for agricultural supply can cause soil-phytotoxicity since these heavy metals are not extracted nor degraded. A typical waste-water treatment plant is not designed to extract the 30,000 chemicals used by a typical urban household in this century (Drangert, 2012).

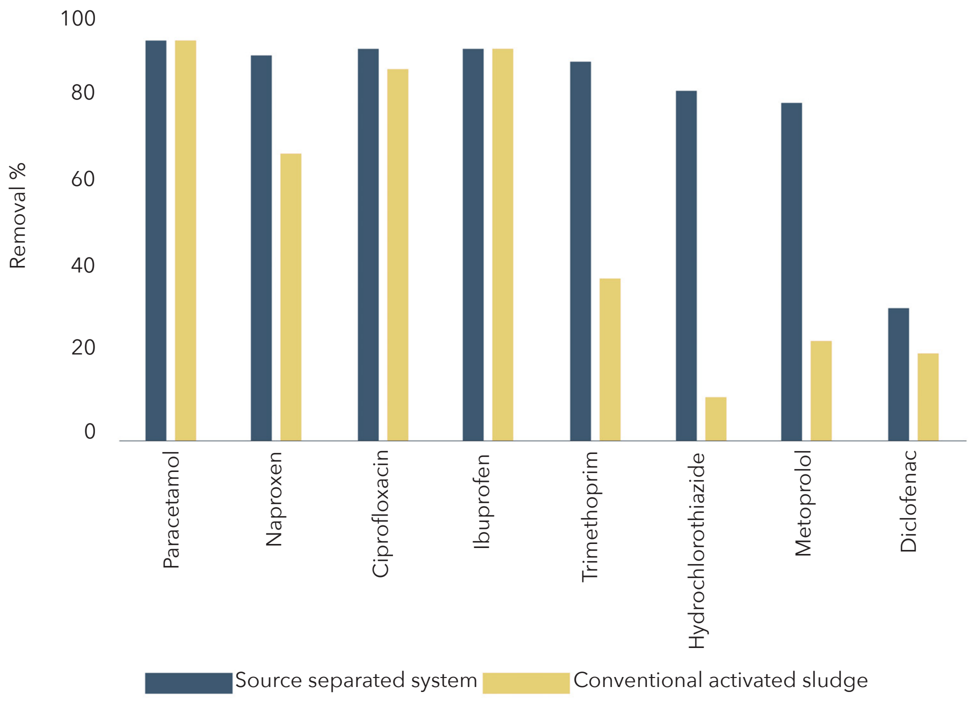
Eutrophication is the enrichment of surface waters with plant nutrients. While eutrophication occurs naturally, it is normally associated with anthropogenic sources of nutrients. Agriculture is a major factor in eutrophication of surface waters due to run-off of phosphorus-rich water. Although both nitrogen and phosphorus contribute to eutrophication, classification of trophic status usually focuses on that nutrient which is limiting. In most cases, phosphorus is the limiting nutrient. A water body is said to be eutrophic if its phosphorous level is 84.4 mg/cu.m. and hypertrophic if it is above 750 mg/cu.m. (FAO, 1996). While the effects of eutrophication such as algal blooms are readily visible, the process of eutrophication is complex and its measurement difficult.

The presence of pharmaceuticals and personal care products in waste-water from cities is due to the large-scale disposal of partially-treated waste-water into surface water. Pharmaceuticals form a major group of persistent organic pollutants and are present in blackwater since they are excreted from the human body. Existing waste-water discharge requirements do not account for pharmaceutical concentrations. Several of these compounds affect the natural environment by increasing carcinogenicity, bio-accumulation and inhibition of organism growth. Pharmaceuticals are present in conventional wastewater in the range of nanograms/litre to micrograms/litre and many are not extracted in conventional activated sludge treatment systems (Butkovskyi et. al., 2015).

Similarly, a large number of organic micropollutants could be present in typical domestic greywater due to the use of personal-care products. Apart from polyaromatic hydrocarbons (PAHs), phthalates, organotin compounds, etc. which are sometimes measured in waste-water, constituents of detergents, soaps, shampoos, preservatives, etc. are typically ignored. An important



Butkovskyi, A., Rijnaarts, H. H. M., Zeeman, G., & Leal, L. H. (2016).



Butkovskyi, A., Leal, L. H., Rijnaarts, H. H. M., & Zeeman, G. (2015).

difference between pharmaceuticals and personal-care products is that the latter are designed to prevent their degradation and washing-off from surfaces, making them non-biodegradable (Butkovskyi et. al., 2016).

A source-separated waste-water treatment would keep the water volumes low and possibly more concentrated, making it easier to extract pollutants. However, technological research in the extraction of pharmaceuticals and micro-pollutants from source-separated waste-water could be done parallel to a change in resident behavior with respect to water. Before the 1950s, people used far fewer types of soaps and detergents which were also mostly biodegradable (Drangert, 2012). In contrast, we now live in a full-scale chemical society without full knowledge of the implications of such water practices. Therefore, in addition to technological research into extraction of specific waste-water constituents, the solution demands a change in people's perspective of their water-related habits.

BIOMASS-ENERGY GENERATION

Considering the current human population and growing urbanization, fossil fuel utilization poses a threat to global ecosystems by contributing to global warming emissions. Fossil fuel reserves are, in any case, finite which means that a transition to renewable and clean energy sources is required. The 'trias energetica' principle outlined three points for sustainable energy use, those are to reduce the demand, use renewable resources and generate excess demand using clean and efficient sources (Lysen, 1996). However, a more reliable strategy to ensure sustainable energy flow could be to apply the cradle-to-cradle idea in this aspect. Among other flows, energy can be generated from 'waste' material and 'waste' water (Dobbelsteen, 2008).

In the realm of urban domestic water systems, biomass in the form of blackwater and household organic waste are potential renewable energy sources. Biomass in these forms is abundantly and consistently available, unlike solar and wind energy for which storage methods are still under development. The impact of biomass energy installations on the natural environment is usually much less adverse compared to, for example, hydro-power installations. Biomass energy generation does not require rare elements, unlike solar PV cells and wind turbines (De Jong & Van Ommen, 2015). However, the conversion of solar energy into biomass is generally low, which implies that relatively large surfaces are needed to generate the material mass required to generate energy. It has limited effective availability and may only partially contribute the energy demand (De Jong & Van Ommen, 2015).

The argument against centralized water systems is strengthened by the vast amounts of energy consumed for pumping and the produce the materials and chemicals used in the operation and maintenance of central water utilities. In the US, water and waste-water treatment account for 30 to 40% of the energy that is used by municipal facilities (Venkatesh et. al., 2014). With water discharge standards becoming more stringent, cleaner water bodies could result in increased energy consumption to meet them. This bolsters the argument made previously that the treatment of waste-water is easier if not polluted with chemicals in the first place. Source-separation and controlled use of household products is, hence, aligned with the goal of reducing the energy demand for water and generating energy from water and related flows.

Thus, apart from the recovery of nutrients and soil-conditioning solids as by-products, more recent goals of urban water systems include the recovery of energy in the form of heat and electricity for heating and the reduction of GHG emissions (Novotny, 2010). Energy recovered, say in the form of biogas from blackwater, in a decentralized system can be used locally, perhaps to run the treatment system itself. Heat recovery from greywater is also possible in a decentralized system for local use.

CIRCULAR WATER

The ideals of water-self-sufficiency, source separation and purpose-based water supply can be applied at the scale of a house, a cluster of houses, a high-rise building, a neighbourhood or a city, with varying technological and spatial requirements and economic impacts. Overall, it appears that the optimum size for achieving and water system that is justified by the Triple Bottom Line rule is a cluster of dwellings or a neighbourhood (Ho, 2010). This allows the use of open urban space for incorporating, say, wetlands and provides economy of scale in using a common treatment plant for a certain waste-water stream. A large highly-populated urban area, however, might be deterred by the lack of land available for water catchment or treatment, thus requiring relatively longer piping and more energy for pumping.

The idea of reclaiming used water within a neighbourhood is based on the idea of Cradle-to-Cradle proposed by William McDonough and Michael Braungart in 2002. Although their proposal was first applied to the manufacture and use of consumer products, it has potential in the management of resource systems as well (Dobbelsteen, 2008).

CIRCULAR WATER
THE RATIONALE

There is no such thing as waste in the natural world where a completely closed-loop system recognizes waste as a valuable resource. The recovery of energy and nutrients is essential to sustain successive generations of living organisms (Lucey, Barraclough & Buchanan, 2010). With regard to water practices, this could start by reducing the demand for drinking water, treatment of used water within the land environment at relevant scales and reusing the treated water according to the purpose of the activity where water is needed.

For example, a different water quality is needed for washing clothes compared to irrigation of plants. Within the realm of water for plants, it is more suitable to use greywater containing even traces of potassium for a neighbourhood farm rather than extracting these nutrients and later adding manufactured fertilizers.

The underlying principle of water circularity is fit-for-purpose treatment, that is, treatment of a certain water stream based on the purpose it is needed for. Following this, four clear strategies follow: (i) Source-separation of nutrients (ii) Reduction of shower water consumption (iii) Use of rainwater and (iv) Reuse of greywater.

Source-separation addresses one of the largest domestic water consuming activities, i.e., toilet flushing, while also enabling the recovery of energy and nutrients. This is followed by reducing the other major water consumer, i.e., showering. Following this major reduction in water demand, it is attempted to meet the remaining demand using rainwater, a local relatively clean water source, if available sufficiently. The demand not met by rainwater can potentially be met by treating greywater which is generated on a daily basis from domestic actvities.

FIT-FOR-PURPOSE REUSE

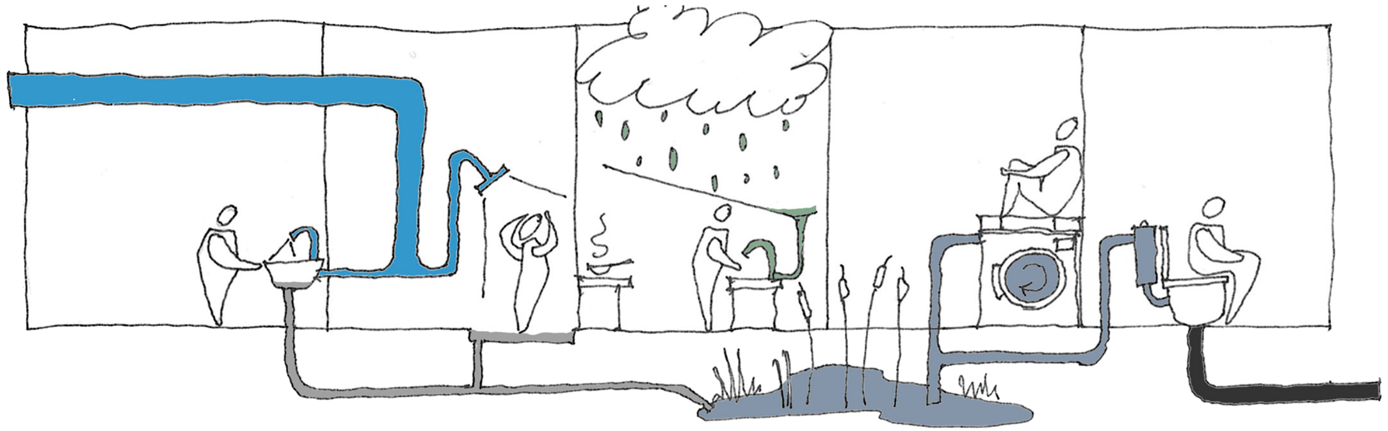
The idea of self-sufficiency reflects the need to be secure in terms of water-availability within the boundaries of a certain property. The application of this concept depends on the availability of a water source and the technology to impart a quality-level to the water depending on its purpose. A water-self-sufficient system is usually designed along the principle of 'fit for purpose' (Ho, 2010). For example, rainwater from the roof could be used for drinking and domestic uses since it is a relatively clean source compared to surface water and greywater, while greywater resulting from domestic use can be used for irrigation of plants.

However, the need for complete or partial self-sufficiency depends very much on the context. If the availability of a central drinking water source is assured now and for the next many decades to come, it may not be as important to have an off-grid supply system as it is to treat waste-water locally and recover nutrients for local use as fertilizers. A place with a long dry period may need to rely on treated greywater for most activities since it may not be possible to provide the required storage space for rainwater to tide over the dry period. It is important to understand primary and secondary resource related problems in a place and apply context-specific solutions rather than attempt a universal solution.

This underlying principle is applied in the remaining strategies in different ways in the 'Circular Water' design tool. Source-separation starts by understanding the quantities of potential nutrients and energy recoverable from a certain number of residents and water-related activities. Treatment of rainwater and greywater depends on the the cleanest purpose they will be reused for. These are explained in detail in the respective sections.

In principle, it is impractical to provide a different water quality for each domestic water activity. 'Circular Water' considers food preparation, showering, washing dishes, washing clothes and toilet flushing as the five reference activities for choosing the water quality required. The implications of this rationale are seen in the strategies for rainwater use and greywater reuse.

One limitation in such a rationale, however, is that the combined water requirement of shower, wash basin, bath and 'other water' typically constitute the highest proportion of water demand. This could limit the possibility of using rainwater or greywater for this set of activities since the water demand of this set might only partially be met by a certain water stream.



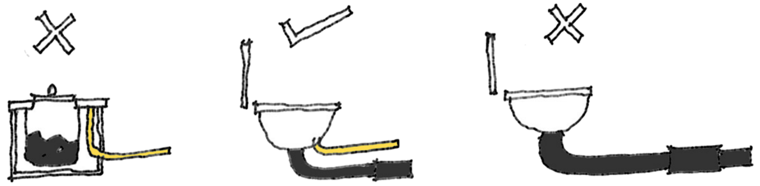
NUTRIENT SOURCE-SEPARATION

Various waste-water streams are suited to different methods of treatment and reuse. The idea of source separation is based on the fact that waste-water streams differ in quality depending on the activity it is discharged from. Toilet waste-water consists of urine and faeces, both concentrated-nutrient streams. Shower and sink water are relatively very dilute nutrient streams. A large part of the organic matter and nitrogen and phosphorous in municipal waste-water come from human excreta (Gao & Zhang, 2010).

In general, dual plumbing is sufficient for transporting greywater and blackwater in two different streams. However, to further separate blackwater into faeces and urine, it is necessary to use a toilet designed differently from that of a flush toilet. A non-flush toilet may or may not keep the two streams separate, but only reduce the water needed for flushing (eg. Vacuum toilets commonly seen in long-distance buses). A composting toilet is a form of dry toilet which does not use water for transporting faeces (thus, least water consumption and most effective separation system), but might involve manual handling of the collecting box at regular intervals.

The potential for reuse of biomass and urine in various forms is explained below. An understanding of this potential and its relevance for a specific project can help select the toilet type for the project. Two goals can be met using the right type of toilet - reduced water use for flushing and recovery of nutrients from faeces and urine.

Typical flush toilet
34.6
litres/person/day

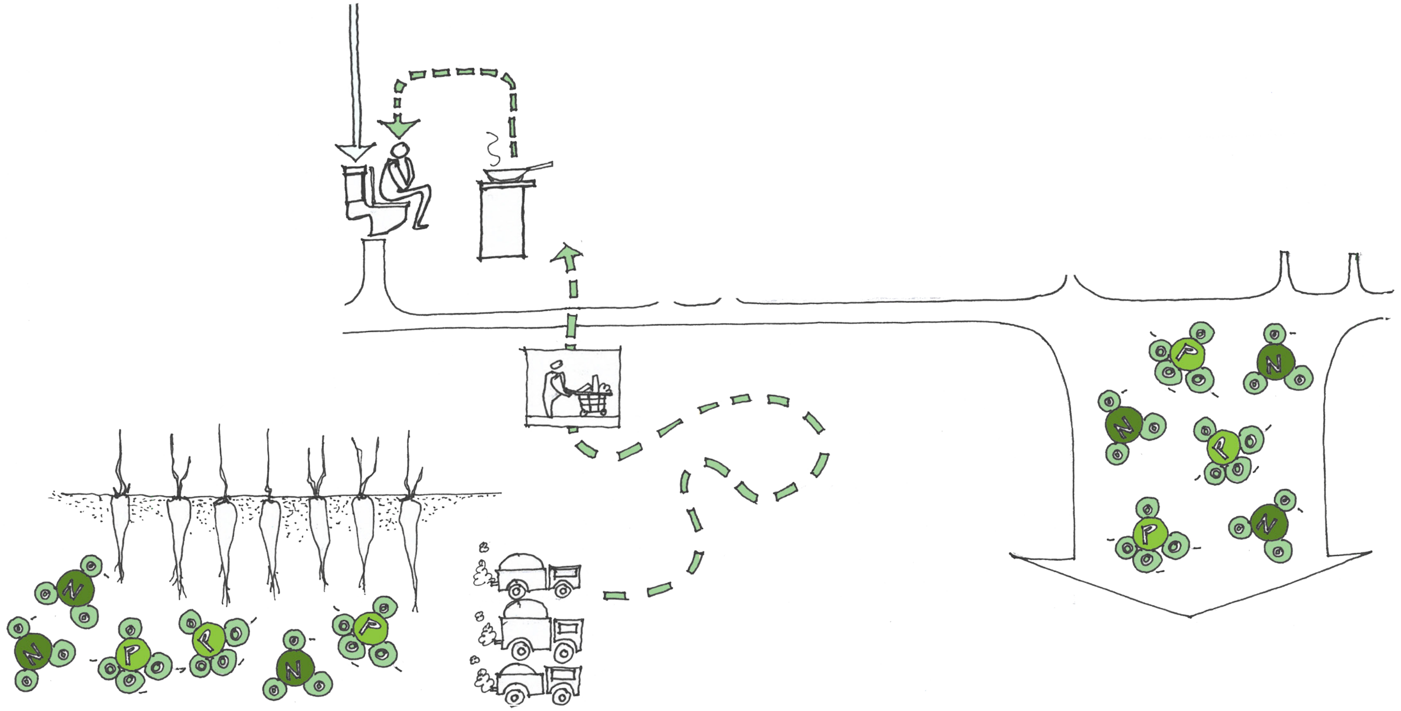


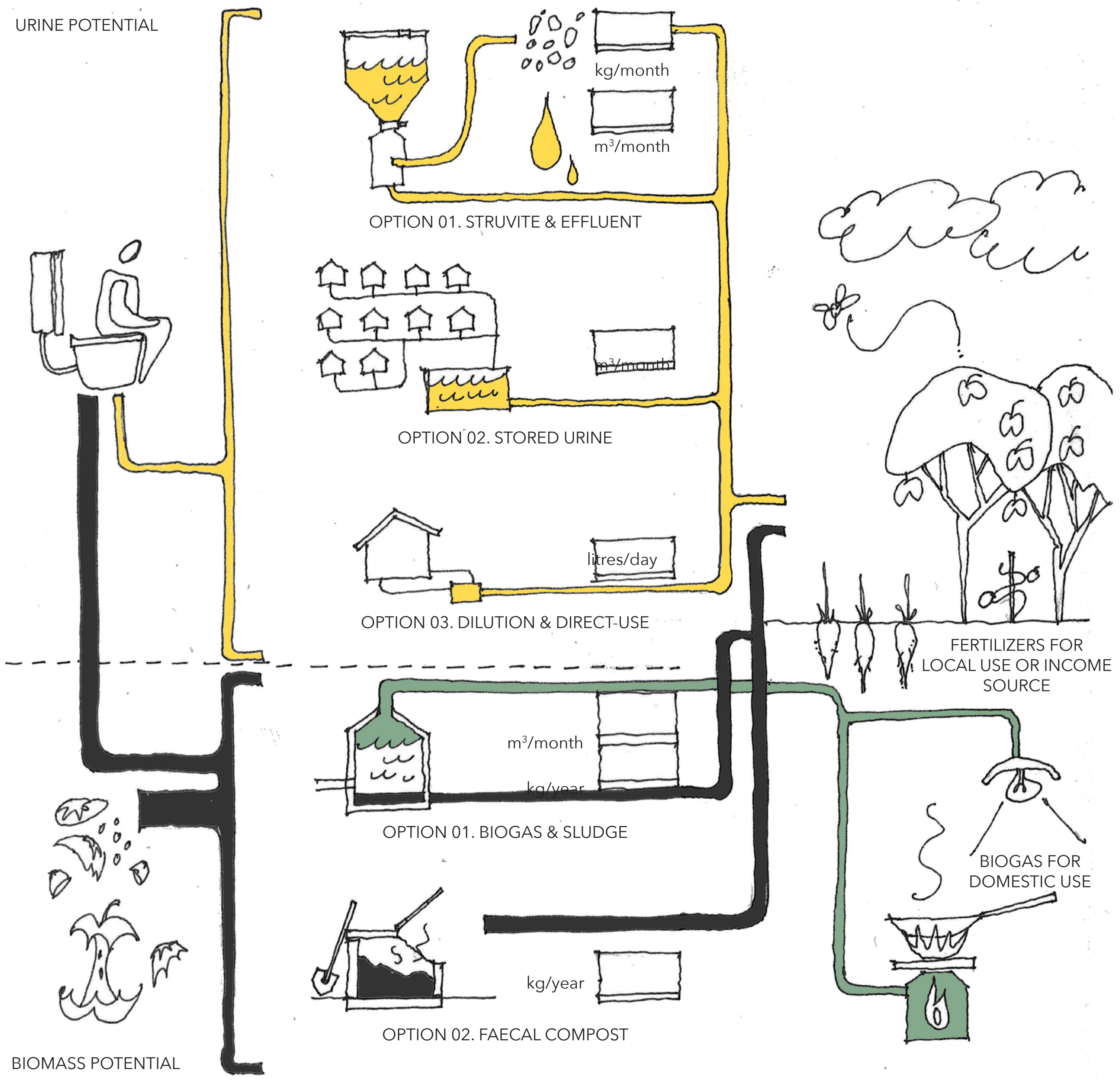
Urine-diverting composting toilet	Urine-diverting vacuum toilet	Vacuum toilet
1.5 litres/person/day	2.2 litres/person/day	3.2 litres/person/day

>90% reduction in domestic water demand

+

Decentralised recovery of energy and nutrients




URINE POTENTIAL
kg/month
m³/month
OPTION 01. STRUVITE & EFFLUENT
m³/month
OPTION 02. STORED URINE
litres/day
OPTION 03. DILUTION & DIRECT-USE
FERTILIZERS FOR LOCAL USE OR INCOME SOURCE
m³/month
kg/year
OPTION 01. BIOGAS & SLUDGE
BIOGAS FOR DOMESTIC USE
kg/year
OPTION 02. FAECAL COMPOST
BIOMASS POTENTIAL

BIOMASS POTENTIAL

Within the realm of domestic activities, biomass is typically generated in two forms - organic waste from food preparation and faeces from food consumption. Both are potential renewable energy sources as well as soil fertilizer sources; the choice of use depends on the need of each case and the availability of resources to extract what is required from them. Methods of processing them are explained below.

Since this thesis addresses only domestic sources of biomass, other forms of biomass for the same purpose are not discussed even though they might have much more potential for biogas energy or nutritional value as fertilizers. The purpose of the following strategies is decentralised management of domestic blackwater streams and reduction in water demand for their respective activities. For each option, calculation methods of establishing quantities are stated followed by a brief explanation of processing and storage methods. In a later chapter of the report, specific examples are shown with actual quantities generated.

Option 01:
Biogas from organic waste and faeces & sludge as fertilizer

Since both faeces and organic matter are typically generated on a daily basis from domestic activities, the 'Circular Water' design tool considers both forms of biomass in the calculation of local energy generation potential. The biogas production unit volume from each varies; it is considered as 20 litres/kg for faeces and 169 litres/kg for organic waste (De Jong & Van Ommen, 2015). In comparison to other forms of biomass typically used for energy, organic waste is comparable to grass (151 litres/kg) and second to maize silage (231 litres/kg) (De Jong & Van Ommen, 2015).

In the 'Circular Water' design tool, monthly generation of biogas in the neighbourhood is calculated as follows:

Biogas unit volume (blackwater) = 20 litres/kg
Water used per day for flushing faeces = 0.7 litres (considering urine-diverting vacuum toilet)

Biogas unit volume (organic waste) = 169 litres/kg
(De Jong & Van Ommen, 2015)

Mass of human faeces = 0.035 kg/person/day (Rose et al., 2019)

Mass of organic waste = 0.14 kg/person/day

No. of residents = R

Biogas from faeces flushed using urine-diverting vacuum toilet

+ Biogas from organic waste

= Monthly mass of blackwater in neighbourhood x biogas unit volume

+ Monthly mass of organic waste in neighbourhood x biogas unit volume

= [{(0.035 + 0.7) x 30 x R} x 20] + [(0.14 x 30 x R) x 169] (litres)

The tool further calculates the electricity and heat that can be generated from this volume of biogas using a CHP of 85% efficiency and electric efficiency of 40% (EPA, 2017).

Calorific value of biogas = 39.8 MJ/ m^3 = 11.06 kWh / m^3 (Jorgensen, 2009)

Annual electricity generated from biogas

= (Monthly biogas in litres)/1000 x 12 x 0.4 x 11.06 (kWh/year)

Annual heat generated from biogas

= (Monthly biogas in litres)/1000 x 12 x (0.85-0.4) x 11.06 (kWh/year)

A feasible method of energy generation from blackwater conveyed using a type of vacuum toilets would include anaerobic digestion. If urine-diversion is not included in the toilets, this could be followed by struvite precipitation and autotrophic nitrogen removal, which would totally produce 56 MJ/person/year of electricity. This represents 40% of the energy used by conventional waste-water treatment plants (De Graff, 2010).

Recent developments in decentralised waste-water management usually include a UASB (Upflow Anaerobic Sludge Blanket) reactor to convert most of the organic matter in blackwater to biogas. Sludge produced as a by-product of biogas generation consists of substantial organic matter and, if urine diversion is not incoporated, phosphorous. Conventional waste-water treatment facilities utilize chemical and physical processes for sludge stabilization. Micropollutants from pharmaceuticals and personal-care products are not extracted in central facilities and are discharged into soil or water ecosystems. An alternative to such processes in decentralised waste-water management is local composting of anaerobic sludge with organic waste. The organic waste (bulking agent) provides a biodegradable carbon source. A study conducted by Wageningen University and Wetsus showed that composting of UASB sludge with wood waste for 92 days resulted in the degradation of pharmaceuticals by 87 to 99% (Butkovskyi, 2016). Control of some other micropollutants which were not sufficiently degraded might have to be controlled at the source.

Anaerobically digested blackwater, however, produces much lesser sludge compared to aerobic digestion. For 100 kg of COD, anaerobic digestion produces 5 kg of sludge, in addition to biogas, while aerobic digestion produces 30 to 60 kg of sludge, and both methods produce similar amounts of effluent in terms of COD. This makes anaerobic digestion the preferred method of blackwater management.

The method of quantifying anaerobic sludge in the 'Circular Water' design tool is as follows:

Total COD generated by a person = 30 kg/year

Faecal COD proportion = 47% (Gulyas, Gajurel & Otterpohl, n.d.).

Organic waste COD = 0.15 kg/litre

Organic waste per person = 0.14 kg/day

Assuming 1 litre of organic waste = 1 kg

Total influent COD = (0.47 x 30) + (0.14 x 365 x 0.15) = 21.77 kg/person/year

20 kg of influent COD = 1 kg of sludge (Henze et. al., 2008)

No. of residents = R

Total sludge = (1/20) x 21.77 x R (kg/year)

The nutritional value of composted sludge would further allow one to comapre its value to commerically produced fertilizer. Although this aspect is yet to be integrated in the tool, the intention is to convey the value of potential local fertilizers produced in terms of the industrial products they could replace, potentially benefitting the consumer economically in a future where industrial mining and production could be ecologically non-feasible.

Option 02:
Compost from faeces
& compost from organic waste
& compost effluent

Human faeces, along with animal faeces and other organic waste, were managed by composting for centuries before the establishment of centralized waste-water management infrastructure. Through the process of composting, organic matter is aerobically converted to carbon dioxide, water and stabilized sludge. If composted correctly, organic matter turns into a humus-like material and can be applied in agriculture, although it is not as nutritious as human urine in terms of nitrogen, phosphorous and potassium. In the case of residential neighbourhoods, it provides a relatively low-tech, affordable option of safe-management of faeces where compost can be used or sold as locally generated fertilizer, especially where the setting-up of bioreactors for faecal biogas energy production is not feasible.

The success of composting depends on proper installation and maintenance of composting toilets. While there is a general non-acceptance of such toilets, especially in cities where people have grown accustomed to the comfort and convenience of flush toilets, there are also many composting toilets designed and marketed to serve such an urban population. Among these are incineration and freezer toilets, both meant for situations where piping is not possible or the aim is to reduce water consumption. However, in this thesis, faecal composting has been addressed through the use of urine-diverting composting toilets which are relatively low-energy-consuming (if not zero-energy) toilets. Primitive designs typically implemented in rural, suburban and experimental settlements are usually self-built and require neither energy nor water. Such types usually require space on the ground and are harder to maintain indoors and on higher floors due to the inconvenience of material removal.

The 'Circular Water' design tool considers toilet capacities based on a modern urine-diverting composting toilet which is developed by a Swedish company and available in the market. The following calculation method is included in the tool to understand the annual quantity and quality (in terms of N, P, K and organic matter) of compost generation from a residential neighbourhood, such that it can be a potential replacement for industrially produced commerical fertilizer.

Average household size = r

Total toilet container capacity = 0.023 m^3 (Separett, 2019)

Filled toilet container capacity = 0.9 x 0.023 = 0.0207 m^3

Total composting unit capacity = 0.5 m^3 (Separett, 2019)

Filled composting unit capacity = 0.9 x 0.5 = 0.45 m^3

Toilet filling time = 16 weeks / r

Composting time = 12 months

No. of toilet container changes in 12 months

= (Toilet filling time/4)/12 (round-up to whole number)

= n

No. of toilet containers emptied into 1 composting unit

= 0.45 / 0.0207 = 21 (after rounding down to whole number)

No. of composting units required at a time

= n / 21

The resulting number provides the tool user an indication of the amount of space to allot (say, in the garden or basement) for each house to enable composting of faeces in the neighbourhood.

Total nitrogen = 1.1 g/person/day

Total phosphorous = 0.6 g/person/day

Potassium = 1.1 g/person/day

The tool indicates the amounts of these nutrients generated in the neighbourhood by simple multiplication of these values over a period of 365 days for the number of residents (R).

Fertilizer equivalent of faecal compost = C kg/year

Density of compost = 600 kg/m^3 (Khater, 2012).

Annual compost generated in neighbourhood

= n x 0.0207 x 600 x R (kg/year)

The potential of generating compost and compost effluent from household organic waste can be generated by the tool, but in a later version.

URINE POTENTIAL

Urine contains the highest concentration of nitrogen, phosphorous and potassium among domestic waste-water streams. Three possible options of using urine as fertilizer are considered here - converting it to struvite through precipitation using magnesium, using it in liquid form after storage for 6 months and using it directly on a daily basis as it is generated, with dilution with greywater or drinking water. The first two options are relevant for the scale of a neighbourhood and the third is suitable for individual homes or small apartment blocks with gardens or farms.

Option 01: Struvite as fertilizer & effluent as fertilizer

Struvite (or Magnesium Ammonium Phosphate Hexahydrate) is a naturally occuring precipitate from urine. It has the potential to be used as fertilizer for agriculture since it contains most of the phosphorous that is ejected from the human body through defecation. From about 500 litres of urine, 1 kg of struvite can be precipitated (Seecon, 2018). A soluble form of magnesium is required for the process, a potential source of which could be 'bittern', a by-product of salt extraction from sea water. With regard to the environmental goal of phosphorous recovery, struvite precipitation from human urine would reduce the industrial production of phosphorous by upto 21% (De Graff, 2010).

The biggest advantage of using urine as fertilizer in the form of struvite is that its volume is greatly reduced from its liquid form. Struvite can be stored without changing its properties for much longer periods of time than urine and can be handled with relatively more safety. Nutrients in struvite can be readily absorbed by plants. It guarantees a slow but steady nutrient supply due to low solubility. During the precipitation process, pharmaceuticals and heavy metals are excluded from the struvite, making it a highly pure fertilizer for agriculture.

However, after the struvite is removed, the same volume of urine remains, which can be used as fertilizer through drip irrigation. This effluent contains a substantial amount of nitrogen from the urine, hence struvite alone may not be enough to provide sufficient soil fertility.

The 'Circular Water' design tool indicates the amount of struvite that can be potentially generated in the neighbourhood and also compares it to industrially produced fertilizer in mass. Depending on the context, this can be multiplied by the local price of fertilizer to check the economic benefits of local struvite production.

Urine production = 1.4 litres/person/day (Rose et. al., 2019)

Urine production in neighbourhood = R x 1.4 x 30

Struvite yield = 1 kg per 500 L of urine

Struvite production potential = (1 / 500) x (R x 1.4 x 30) (kg/month)

Struvite precipitator capacity = 0.4 m^3

Daily urine production in neighbourhood = (1.4 x R)/1000 (m^3)

No. of precipitators required = ((1.4 x R)/1000) / 0.4

This number indication allows the tool user to allocate the right amount of space to generate struvite from urine at the neighbourhood scale. Further, this is quantified into the amount of phosphorous recovered annually through this process:

Total phosphorous = 1.4 g/person/day

Assuming a 90% precipitation efficiency (Seecon, 2018)

Phosphorous recovered = (0.9 x 1.4 x 365 x R) (kg/year)

Option 02:
Stored urine as fertilizer

According to Hoglund (2001) guidelines for storage and reuse of urine are based on the time and temperature needed for pathogen inactivation. Lower temperatures require longer inactivation time for the same pathogens. The design tool 'Circular Water' considers a storage temperature of 4°C and 6 month storage time to calculate the storage volume required.

Urine production = 1.4 (litres/person/day) (Rose et. al., 2019)

No. of residents = R

Storage volume required in neighbourhood

= (R x 1.4 x 30 x 6)/1000 (m^3)

Option 03:
Direct-use urine as fertilizer

Urine-diverting composting toilets made for typical urban households are installed with a tank for urine storage. Considering a household tank capacity of 50 litres (Separett, 2019), the number of such tanks is calculated by the tool as follows:

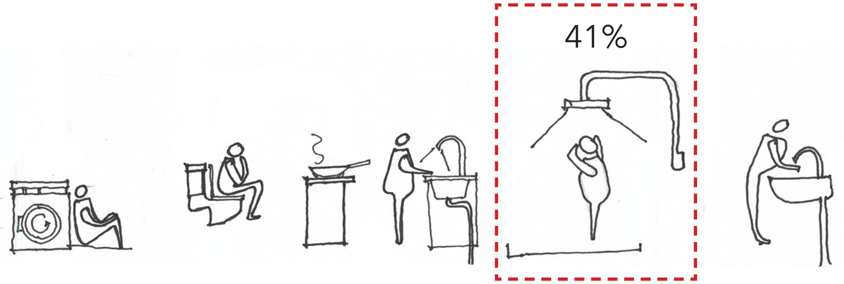
Water consumption per toilet use = 0.5 L
Assumed number of toilet uses in a day = 5 Average household size = r
Urine production = r x 1.4 (litres)

Daily storage volume = ((r x 1.4) + (r x 5 x 0.5))/50

Assuming that the urine will be used once in 3 days and an additional buffer of 10 litres,

Number of 50 litre tanks required
= ((Daily storage volume x 3) + 10)/50
(rounded up to nearest whole number)

SHOWER WATER



Typical Dutch water consumption for showering is 49.2 litres (VEWIN, 2018). A popular trend which aims to reduce this water quantity is the use of water-saving shower-heads, the best ones using around 4 to 6 litres per minute. However, the reduction of shower water consumption depends on two more factors which are dependent on behaviour - showering time period and frequency of showers. While the water required for toilet flushing is much more dependent on the toilet flush system itself, showering is much more behaviour-dependent.

Shower-head water consumption = s (litres/minute)

Number of showers per week = w

Showering time = L (minutes)

Daily shower water consumption per person

= (s x L x w)/7 (litres)

The tool 'Circular Water' allows the user to change the three variables to arrive at a value less than half the typical Dutch consumption, atleast to enable some reflection on one's showering time and frequency. The resulting numbers are indications of required habit-change, if not judicious already. The habit of showering daily can be reconsidered during colder seasons and less-active days. Water-saving shower-heads without any control over the number or time period of showering can result in a higher-than-typical water consumption, precluding the purpose of such technology.

RAINWATER USE

Rainwater is a clean renewable water source that is ideal for domestic use if available in sufficient quantity to meet the domestic demand. Typically, harvested rainwater is used for non-potable purposes such as toilet flushing, laundry, car washing and garden watering. Rainwater for potable use requires filtration and disinfection whereas non-potable uses do not require disinfection. (Che-Ani et. al., 2009). The treatment of rainwater typically involves a pre-storage step called first-flush diversion. First-flush diversion is a simple method used to divert the first rainfall of the season which might be contaminated with bird faeces and dust. Microbial populations in stored rainwater depends on climatic conditions (eg. wind speed and direction), use of first-flush mechanism and the possibility of animals coming in contact with the catchment surface.

'Circular Water' provides the tool user the option of selecting the pollution level of the catchment areas in consideration. In principle, higher the pollution level, higher the volume of first-rain water required to "clean" the roof. First-flush diversion is usually sufficient to use rainwater even for showering.

Pollution level	Pollution factor (litres/m2)
Low	0.53
Average	1.31
High	2.10

First-flush volume = Pollution factor x catchment area (litres)
(First Flush Diverter Volume Calculations, 2019).

Sand-filters are used to improve water turbidity. Rainwater for drinking and food preparation requires further post-storage treatment. Post-storage treatment typically requires two steps – particle filtration and disinfection. Slow-sand filtration is a common rainwater filtration method to remove particulates and heavy metals and remove turbidity. (Campisano et. al., 2017).

Disinfection is done to improve the microbiological quality of rainwater and can be done using bleaching powder, heat, chlorine, potassium permanganate, iodine, UV light or ozonation. A combination of filtration, UV and ozonation developed into a point-of-use device was successfully tested in the UK to treat harvested rainwater for potability. Some low-cost disinfection methods have been developed in water scarce parts of developing countries such as the combination of the Moringa stenopetala seed, sand filter and boiling for potable water use in Ethiopia (Campisano et al., 2017).

Catchment and storage

Rooftops of buildings and streets are typically used as rainwater catchments surfaces if they are impermeable. Catchment area and storage volume can be limiting factors to the size of the rainwater harvesting system. Both depend on the rainfall pattern of the location. In general, places with evenly distributed rainfall require smaller catchment area and storage volume than those with a long dry season.

The 'Circular Water' design tool provides the volume needed for storage of rainwater in the neighbourhood based on the following data entered by the user: the monthly rainfall of the location, rooftop area of each house available for catchment and the activities for which rainwater can be potentially used. The process is explained in detail with examples and results later in the report. Below is the method of calculation for rainwater storage:

Annual rainfall = Sum of monthly rainfall (mm)

Total catchment area
= (No. of houses or blocks x rooftop area of each house or block)
+ 60% additional area for streets

Total annual harvestable rainwater
= (Total catchment area x annual rainfall) (m^3)

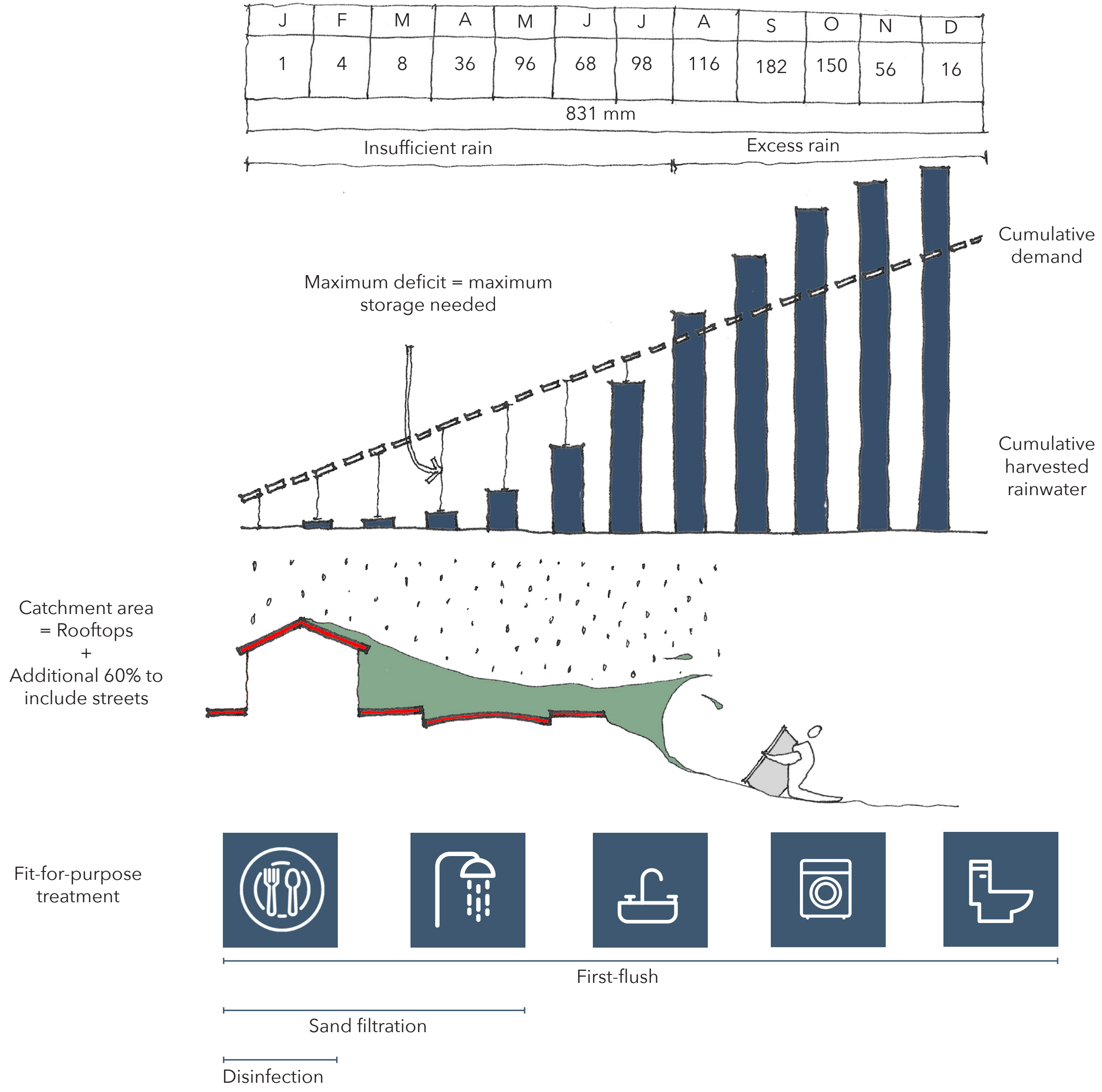


Diagram of rainwater catchment, storage and treatment parameters.

Average daily rainwater available per capita
= Total annual harvestable rainwater / (365 x R)

This value is compared to the daily per capita water demand to determine how much of it can be met by rainwater. The user is prompted to try changing the water sources for activities to treated rainwater, starting from the cleanest requirement (i.e. for food preparation) such that the per capita rainwater demand falls within the average available daily rainwater per capita.

Harvested rainwater for each month

= Respective monthly rainfall x total catchment area x 0.9

Monthly rainwater demand of neighbourhood

= Daily rainwater demand per capita x R x 30

The monthly harvested rainwater is compared with monthly rainwater demand. The latter is assumed to be constant although domestic water use does change with seasons in some countries. Starting with the month where least rainwater is harvested, the cumulative monthly rainwater harvested and cumulative monthly rainwater demand are compared. The largest negative difference represents the largest deficit in rainwater required during the year and is considered as the resulting storage requirement.

Excess rainwater available in the neighbourhood

= Total annual harvestable rainwater - Total annual rainwater required

This excess rainwater, if not used for any specific purpose such as agriculture, should be recharged into the ground through wells or infiltration ponds since most water-scarce parts of the world face the problem of depleting groundwater levels.

The storage tank is especially a critical point in the design and depends, to some extent, on the purpose of rainwater harvested. Storage tanks can be above-ground barrels placed in the garden of each household or above-ground or below-ground concrete tanks to store and treat rainwater collected from the neighbourhood (Campisano et. al., 2017).

GREYWATER REUSE

Broadly speaking, a good water treatment system should be designed for the required output water quality, be simple in operation and maintenance and have relatively low energy requirement. In principle, greywater can be effectively pre-treated in an anaerobic unit, followed by an aerobic process. The anaerobic step reduces the COD of greywater by 40 to 63% and the aerobic step treats the anaerobic effluent for reducing BOD and conversion of ammonia to nitrate. This should be followed by disinfection although the need for this step depends on the required quality of reuse and the effluent quality after the aerobic step (Abu Ghunmi, 2009).

Since the purpose of research related to principles of circular water use are incorporated in a design tool rather than for a single context-specific case, it was necessary to first establish a hierarchy of domestic water sources rather than include every single one and attempt to find quality requirements for each one.

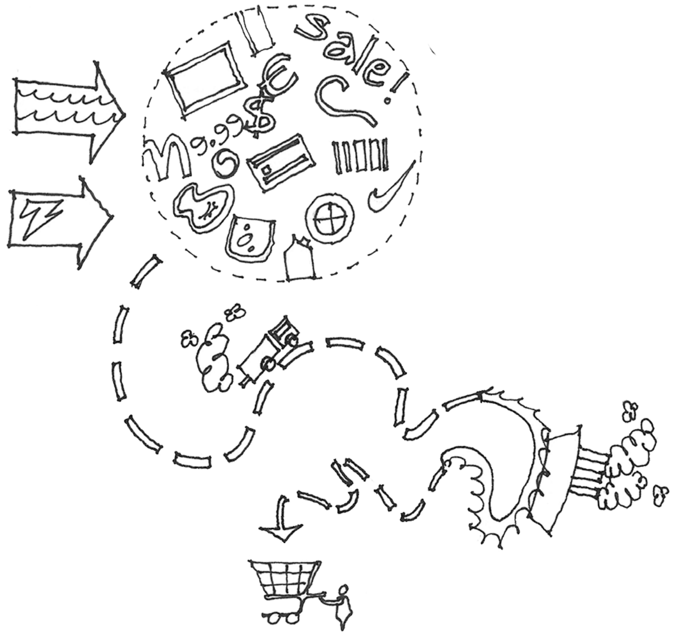
Water quality for various uses is measured using different sets of parameters by different organisations and governing bodies. Standards are not easily available for each activity. The table on the right shows the underlying principle of how ‘Circular Water’ provides treatment steps for greywater according to the cleanest purpose of reuse. Not all values for the quality parameters are available, nor are all treatment systems guaranteed to provide the quality required in terms of these parameters. Some systems are suggested based on their successful implementation in pilot projects. The final choices of systems should be made after consulting a local engineer and contractor since this can be very context specific. ‘Circular Water’ does provide the area requirements (current version) and cost and energy requirements (subsequent version), but these are only indicative and thumb-rule based.

	BOD_5 (mg/l)	COD (mg/l)	Total-N (mg/l)	Total-P (mg/l)	TDS (mg/l)	TSS (mg/l)	Turbidity (NTU)	Total coliforms (MPN /100 ml)	Faecal coliforms (MPN /100 ml)	Space-intensive treatment system	Space-efficient treatment system
Shower[a]	10	10	-	-	-	10	30	50	1.8		Membrane bioreactor Disinfection
Washing dishes										Septic tank Constructed wetland Ozonation pond Disinfection	Living machine
Washing clothes[b]	10	-	-	-	2000	10	2	-	25	Septic tank Constructed wetland Ozonation pond Disinfection	Living machine
Toilet flush[b]	30	-	-	-	1000	30	No limit	-	800	Septic tank Constructed wetland	Bioflocculation
Discharge[c]	25	125	15	2	-	-	-	-	-	Septic tank Constructed wetland	Bioflocculation
Farm or garden[b]	100	200	-	-	-	100	50	-	400	Mulch pit & garden	Septic tank Slow sand filter

a. Ministry of Environment, Forest and Climate Change, Government of India (2015).
b. Lade & Gbagba (2018)
c. European Union (1991)

Defining greywater treatment methods according to water quality needed for different domestic activities.

CONSUMERIST BEHAVIOUR



CONSUMERIST BEHAVIOUR

In a typical 21st century urban setting, there is an abundance of ‘signals’ of various forms, constantly urging people to buy consumer products of all kinds. There is no lack of advertisement for consumer goods, with business districts of most cities shining bright with brand names and pop-culture figures pushing the limits of people’s tendency to want things to satisfy themselves. The accumulation of material wealth has most often been considered a sign of a successful and comfortable life and, while there are exceptions to the norm, the aspiration for increasing comfort can be said of people in general.

Consumption is simply the process of using up a resource, such that it cannot be used again for the same purpose immediately. The word is commonly used for key resources, but it is also used for commodities such as household items, the manufacture of which probably ‘consumed’ substantial amounts of energy, land and water in a typical industrial process. When most people ‘consume’ a certain commodity, they are hardly conscious of the amount of key resources consumed to manufacture it. It involves what is commonly termed as the ‘market’ which is defined as the place where those wishing to purchase goods and services and those wishing to sell them come together (Migone, 2006). Thus, as long as the demand for a commodity is set up, the market often provides a seller for it. Consumption has been pin-pointed as one of the major hindrances to sustainable development.

Consumerism is a formal word for the economic and social order that encourages this pattern of incessant accumulation of material goods by people. It is the cumulative result of the behaviour of a sizable proportion of Earth’s human population, substantial enough to effect adverse changes in the natural environment from where most of the resources needed to manufacture these consumer goods are extracted. In a slow awakening process, some awareness of the effects of consumerism is being spread among people to impress upon them the unsustainability of their lifestyles and habits.

Hedonistic consumerism is the latest result of modern capitalism and is a highly wasteful and discriminatory consumption pattern (Migone, 2006). The nature of modern capitalism distinguishes itself materially by providing mass-produced goods rather than luxury goods. This concurred with technological advances of the Industrial Revolution, creating a synergy of industrial production and sustained, large-scale consumption. The enormously productive economy that has resulted from this synergy of capitalism and mass-production demands that consumption is the way of life and that the measure of social acceptance lies in our consumption patterns (Lebow, 1955).

The need for validation and social acceptance *(Brookman-Byrne, 2018).*

Human motivation in consumerism

The phenomenon of consumerism as a cumulative result of individual behaviour is better explained when seen from the perspective of the need to feel accepted by society. The attainment of goods may have been a way of surviving amid competition at a certain time in the past, but today they may be needed to achieve a state of acceptability among one's social groups (Michaelis, 2000). Familiarity is established by the similarities between people's material possessions, thus pushing the individuals closer to the fulfilment of their esteem need.

It is important to note that the dominating goal, or the goal that is yet to be fulfilled in the hierarchy stated by Maslow, not only determines a person's current outlook but also their perspective of their future. With regard to consumption allowing the fulfilment of the esteem need, this could imply that the habit of accumulating material wealth could lead the individual in a vicious loop of consumption for a major part of their life, since the next pre-potent need is self-actualization, a far less-easily defined need.

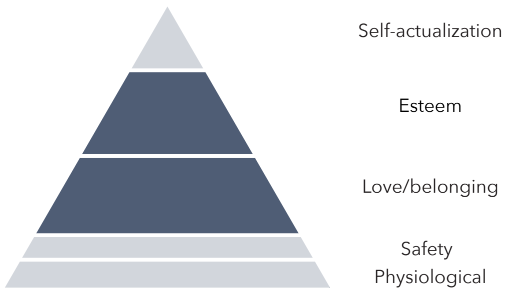


Diagram 01. Adapted from Maslow (1943).

In long-term perspective, research has confirmed that people do not necessarily get more satisfied when they get richer, beyond the point where their basic needs for nutrition, health and shelter are met (Michaelis, 2000). This can be used to strengthen the argument against consumption since it not only has adverse effects on the natural environment, but it is also not as beneficial for the human population as originally assumed. The basis of world-scale decisions often lies in economic benefits, but apparently has long-term detrimental effects on citizens, resulting in a lose-lose situation for the world.

HUMAN BEHAVIOUR IN THE BUILT ENVIRONMENT

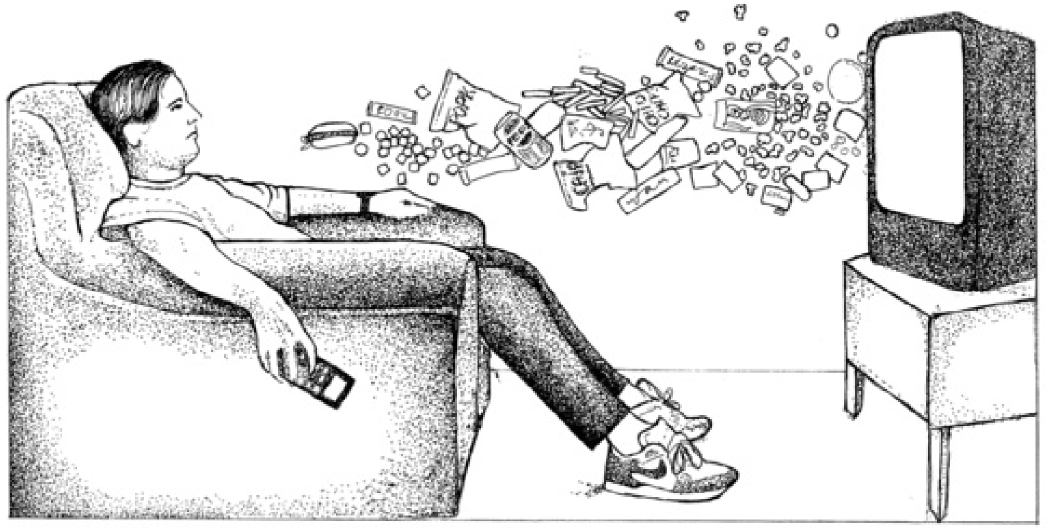


Image 02. What do we perceive? (Eksioglu, 2017).

The built environment can be described as having three categories of functions for people, those are physiological support, activity support and psychological support (Lang, Burnette, Moleski & Vachon, 1974). The general perception is that the built environment is basically a manifestation of the human need for shelter and safety. However, such a simplistic definition fulfils only one function of the built environment, that is the provision of physiological support. While this function might be of primary importance, the next two functions should follow closely since all three functions play a role in spatial perception.

Human behaviour involves three important steps – perception, cognition and spatial behaviour (Lang, Burnette, Moleski & Vachon, 1974). Perception involves receiving input from the environment through one's senses, cognition is the internal process of thinking, remembering and feeling, and spatial behaviour is the output or response of the person to the environment.

Perception in the built environment

Humans are adept at recognising patterns and using them to plan ahead to increase their chances of survival or, in the modern-day context, well-being or a specific achievement (Ricci, 2018). Our ability to match new patterns to ones from memories allow us to discern consistency as opposed to chaos. When the built environment is perceived as being consistent to a familiar pattern, it evokes a sense of security in the human mind because it knows what to expect. While this skill of pattern-recognition seemed far more useful in the age of hunting and gathering, it continues to affect the way we perceive, process and behave in built space.

A very relatable example is the use of branding to evoke familiarity in people's minds. In the process of globalisation, an increasing number of metropolitan cities have nearly the same brands of restaurants, retail stores, etc. in their business districts, encouraging people to buy from 'well-known' stores. Although corporate supermarket companies are many, most have the same array of products and similar internal ambience in their stores, all designed to make the consumer perceive a picture of abundance, freshness and variety. This is done regardless of the fact that supermarkets only need to provide for man's basic physiological need of hunger and thirst and, instead, now influence their need of esteem by assuring that they are consuming what everyone else is consuming.

Similarly, the familiarity of a flush toilet and the idea of hygiene and comfort that we associate with it is available in almost all cities of the world today, making it almost an aspirational model for hygiene standards. The design of such a sanitation system fails in impressing upon its users their impact on, say, surface water quality and depletion of soil nutrients, through its use. The realised possibility of receiving safe drinking water in all taps all over most countries of the Global North creates a perception of limitless availability of water among its people, lulling us into a state of naivety and lack of concern, leaving us powerless to deal with a potential unfamiliar situation.

Cities such as Los Angeles and Cape Town are technologically developed but in water-scarce regions of the world and very good examples for the phenomenon of insufficient resource-conscious human behaviour in a technocratic built environment. Cape Town faced a near-zero water availability in 2017 due to drought, with the situation made worse due to constantly increasing population in cities, agricultural output and lack of restrictions on water use (Wikipedia contributors, 2018). Following the crisis, although there are now restrictions on per capita daily water use, there are other impending problems resulting from solutions for managing water. Residents are being urged to use rainwater and greywater for flushing toilets, but without the necessary infrastructure for doing so. Some restaurants have switched to using disposable plates and cutlery to save water, but this is a waste-generating "solution." Such a situation is the result of generic urban planning of a metropolitan city without allowing its citizens to perceive the availability of key resources in their built environment.

"NORMALLY WET NETHERLANDS NOW FORCED TO INVEST IN FIGHTING DROUGHTS."

The above statement (Newman, 2019) is from an article that says the government meteorological institute KNMI predicts that the country will become increasingly drought-prone. While the effects of the 2018 summer was only felt by the agricultural sector, it is only a matter of time until domestic water use is also affected by such extreme climatic conditions. However, since the water-management system in the country is atleast sufficiently engineered, the population is hardly aware of the risks involved in living with such water conditions (Ministry of Infrastructure and the Environment & Ministry of Economic Affairs, 2014). This applies to risks related to flooding as well as supply for domestic consumption and industrial processes. Infrastructure for resource management is integrated into the urban fabric, the result of which is that it is not perceived (consciously or otherwise) by general public, lulling them into a state of *naivete* over decades of being surrounded by such a mask of a built environment.

This leads to the question of how the supply and discharge of resources is perceived in the built environment and what effect it has on human behaviour. Perception, in general and of the built environment, occurs through the senses of (human) beings. Sensory stimuli or sight, smell, hearing, touch and maybe even taste collectively allow a person to perceive space and impact their consequent behaviour. The subsequent pairs of images compare visible and less visible components of water infrastucture from various time periods.

Water flowing down a railing at Generalife Palace (Storyblocks.com editors (2019).

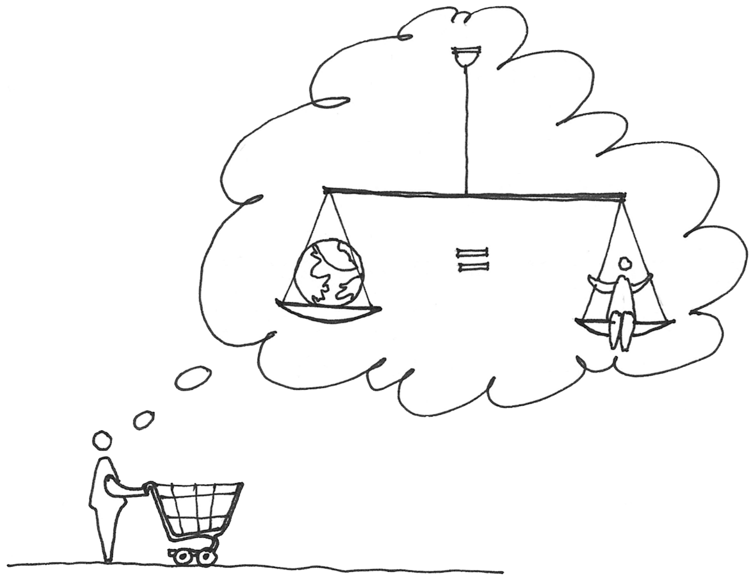
Typical 21st century central waste-water treatment facility.

An open-well water source in India. (India New England News, 2018).

Typical bathing practice in 21st century. (Kowart, 2016).

Night-soil carrier in Singapore. (Thimbuktu, 2014).

PRO-ENVIRONMENTAL BEHAVIOUR



Behaviour that seeks to minimize the negative impact of one's actions on the natural and built environment is called pro-environmental behaviour (Kollmuss & Agyeman, 2002). For example, this could include minimizing one's daily energy consumption, using household soaps and detergents that are not toxic to water ecosystems and reducing the production of household waste by reducing one's shopping quantities.

Many theories have been formulated since the 1950s in the field of social psychology among which the most influential has been the Theory of Reasoned Action proposed by Icek Ajzen and Martin Fishbein in 1980 (Kollmuss & Agyeman, 2002). This theory accounts for personal tendencies as well as the opinion of other people, as opposed to the linear assumption from the 1970s that knowledge and attitude are sufficient to result in a certain behaviour.

PRO-ENVIRONMENTAL BEHAVIOUR

In the last 40 years or so, psychologists and sociologists have tried to understand why people act pro-environmentally and what the barriers are to pro-environmental behaviour. Some explanations are given here, based on causes defined by Rajecki in 1982 (Kollmus & Agyeman, 2002). Direct experiences tend to have bigger impacts than indirect ones, such as walking past a landfill every day and merely reading about it in the newspaper. If cultural, social and familial norms propagate a certain lifestyle habit, such as regular meat-eating, awareness of its adverse effects might not be sufficient to lead to a vegetarian diet.

The relationship between the occurrence of an incident and people's opinion of it reduces with increase in time gap between the two. More recent news tends to

Smell.

I don't know.

Diarrhoea.

Sewage beverage.

The water authorities.

have more impact on behaviour, even if the attitude towards the topic remains unchanged. In addition to this discrepancy which affects researchmethodology in the field, attitude and behaviour tend to vary inherently. Attitudes tend to be general and whereas behaviour is very action-specific. Concern for the environment is an attitude but it encompasses a range of actions, not all of which may be adhered to by an individual. A person might care about the environment and, thus, reduce plastic consumption but follow a daily-meat-eating diet.

Problem-solving by technological innovation can be largely limited by public acceptance of solutions. In spite of technological advancements in reuse of treated waste-water and the gravity of the world's water crisis, there is considerable resistance among people to the idea of waste-water reuse. This attitude is influenced by trust in the technical process of waste-water treatment, trust in the water-reuse organisation and trust in the final quality of the treated water (KWR, 2015). Several variables influence trust of the users in these parameters:

1. Sensorial information from the treated water, that is, how it looks, smells and tastes.
2. Knowledge of the process of water treatment and supply.
3. Personal experiences with water and health.
4. General information about water reuse.
5. Perception of water reuse organisations and regulatory authorities.

Each of the above factors can be categorized as a knowledge factor or a personality factor. The former is often influenced by one's knowledge of a situation (very simply put, one cannot want to change without being aware that change is needed). The built environment is the situational factor or context in which behaviour occurs. It can or cannot allow for a set of behaviours, the intention for which is decided by factors of personality and knowledge.

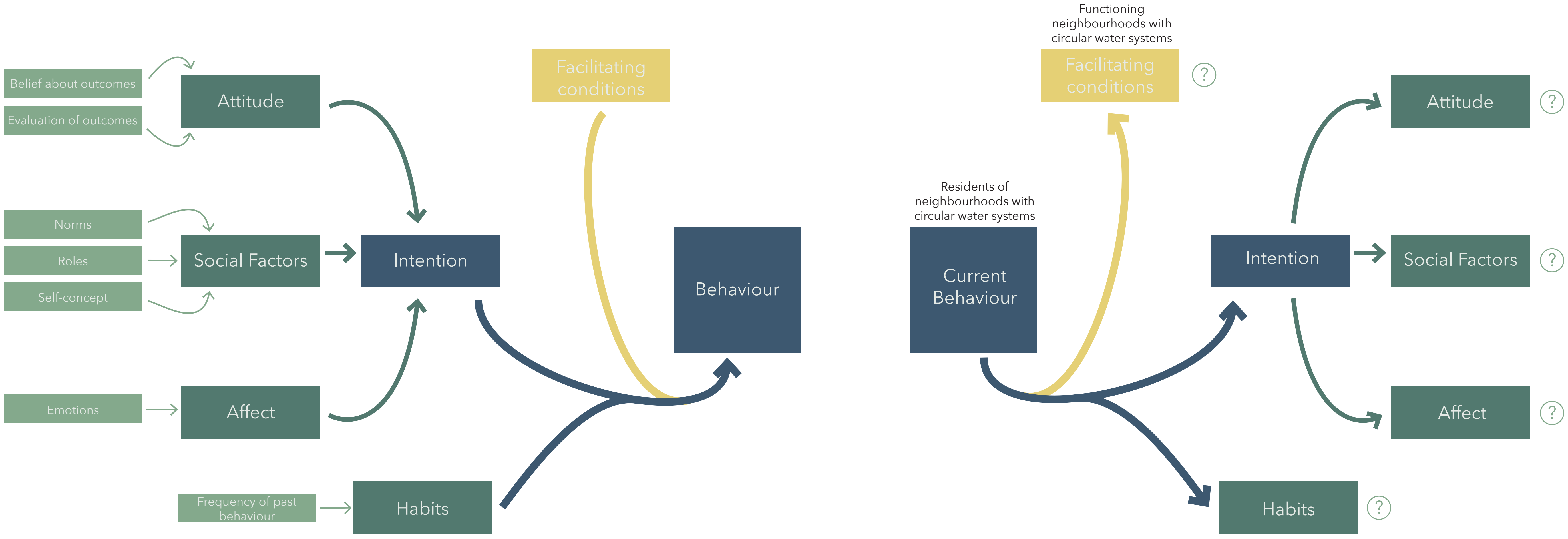
THEORY OF INTERPERSONAL BEHAVIOUR

A framework for designing interventions for sustainable behaviour involve the following steps: understanding the user's actions in context, selecting a behavioural target, selecting an intervention strategy to change behaviour and evaluating the intervention in terms of resulting behaviour (Niedderer, Clune & Ludden, 2017).

A set of factors influence the occurrence or non-occurrence of a certain behaviour. The Theory of Interpersonal Behaviour formulated by Harry Triandis states that the individual is central to rational decision-making, and behavioural action is a result of one's attitude, emotions, social factors (leading to behavioural intention), habits that one is accustomed to and conditions of the physical environment that facilitate the behaviour (Niedderer et al., 2017). In this model, habits are key factors interceding with the intention to perform a behaviour.

In my thesis, each case study involves a set of behaviours (together forming a lifestyle) created by the interaction of inhabitants with the neighbourhood. Here, the neighbourhood, as designed and built, is the facilitating condition for an inhabitant's behaviours.

The inhabitant has certain attitudes and emotions (personal factors) and they influence each other through daily interaction (social factors), all of which lead to a certain intention to act. This action is further influenced by current habits of the inhabitant. The theory can be used to predict a certain desired behaviour or analyse an existing behaviour by breaking it down to its influencing factors. In my thesis, I have three specific behavioural targets (see table) as the foci of my design tool. This makes it necessary to extract behaviour related information from the case studies to analyse how these behavioural targets are addressed, if at all, in built projects.



Theory of Interpersonal Behaviour. Adapted from Triandis (1977).

User's actions in context	Behavioural target (Same as the objectives underlying this thesis research)	Relationship with circular water system
Direct and virtual consumption of water.	Reduction in consumption of drinking water.	Reduced reliance on centralized network (supply).
Expectation of linear water use for domestic convenience.	Increased acceptance of treated greywater, indirectly inducing the use of specific non-chemical household products.	Reduced reliance on centralized network (supply and discharge). Discharge clean effluents.
Comfortable and convenient use of flush toilets.	Increased acceptance of non-flush toilets, indirectly inducing reduced use of pharmaceuticals.	Reduced reliance on centralized network (supply and discharge). Local nutrient recovery. Discharge clean effluents.

BEHAVIOUR ANALYSIS BY QUESTIONNAIRE

The behavioural targets defined in relation to water circularity correspond to the three objectives underlying this thesis. Factors affecting these behavioural targets can be quite personal and subjective. Such data, which is also difficult to measure, needs to be collected from the residents themselves since it might not be credible enough if taken from existing research sources.

One of the points mentioned in the problem statement of this thesis is that there is sufficient on-going research to reduce the environmental impact of urban water systems but not enough to reduce resistance from typical urban societies towards such ideas. There seems to be incomplete awareness of the impact of specific behaviours on the natural environment because the realm of impact is physically invisible (eg. sewage outlets to water bodies may be hidden) or located much further away from the place where the behaviour occurs (eg. Industrial effluent outlets to rivers and oceans are often not located within cities where the final step of consumption occurs). One's awareness of a situation influences their attitude and emotions about it and also affects how and what they communicate about the problem to their social circles.

To put it simply, one's established habits and awareness with regard to a certain resource lead to a specific behavioural intent. This behavioural intent of a whole population then causes a butterfly effect on the natural environment, despite appearing insignificant in an individual's intent. Among all the factors mentioned by Triandis in his Theory of Interpersonal Behaviour, designers and engineers have the most control over the facilitating conditions which is the built environment itself. Established habits are hardest to influence, whereas social factors and attitude are results of one's knowledge of the situation and this can be influenced to some extent through feedback mechanisms, control through monetary regulations, etc., not all of which is in the hands of the designer.

The table on the right shows the relationship between the three behavioural targets and circular water systems. Interventions for each target are categorized based on the Behaviour Intervention Selection Axis (BISA) tool, (developed by Hanratty in 2015). The table provides a larger picture of the scope of influencing these behaviours, within which the design tool being developed in this thesis is part of the feedback system and uses a question-answer interaction method with the user. Not all of these interventions are within the scope of this thesis but provide hints for further research in this topic.

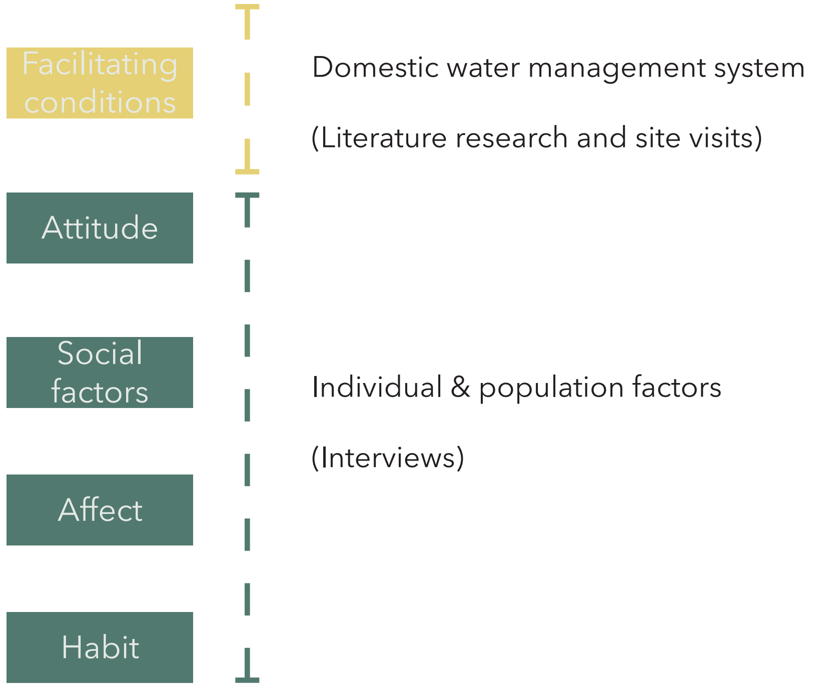
Role of questionnaire in 'Circular Water' design tool:

Data collection regarding resident behaviour was done for two out of three case studies through a list of questions that was posed to each individual personally in face-to-face interviews. The questions are in the following page but the responses and their analyses are included in the next chapter.

Answers to the questionnaire from residents of the case study neighbourhoods have provided a good idea of their awareness and the influence of their neighbourhood on atleast one of the three desired behavioural targets. An analyses of the responses has influenced the definition of behavioural influence strategies towards water circularity. Such strategies will be incorporated as suggestions in the design tool along with example projects where similar strategies have been used. The examples are intended to inspire similar ideas in architects, planners and designers to effect behaviour change through the design of the built environment.

These strategies are suggested to the tool user after entering responses to the same list of questions that was posed to the residents of the case studies. It is included in the tool as an introduction to circular water systems for the tool user before going directly to technical guidelines for the water system. They may not influence the final tool guidelines directly, but instead provide the tool user a sense of resident tendencies in terms of pro-environmental behaviour. It could also influence the interface of the tool since the tool is meant to be educational and provocative, apart from providing circular water guidelines.

Axis of influence.
(Hanratty, 2015)



The following pages contain the list of questions posed to the residents of EVA-Lanxmeer and Polderdrift. Detailed explanation of the neighbourhoods and responses from their residents are explained in the next chapter. Each question attempts to one of the four broad factors in the Theory of Interpersonal Behaviour - Attitude, Affect, Social Factors and Habit. A more accurate set of questions would come from the more specific causes that lead to these factors (belief about outcomes, norms, self-concept, etc.). A more accurate set of questions and response choices based on more specific causes may have resulted in difficult interview sessions and a rather confused audience.

Circularity of water is a complex topic to begin with, an idea still in its incipient stage especially in cities that have enjoyed assured water management without having to pay substantial attention to their involvement in the system. Although the three neighbourhoods chosen as case studies in this thesis are occupied by residents who are relatively more ecologically-concerned than those in typical neighbourhoods, only a fraction of the topic is clearly understood by most of them. This led to a fairly simple and clear set of questions that could be posed to residents even without a background in the technical aspects of water.

	1	What is your name?			
	2	What is your age?			
			A	Less than 25 years	
			B	Between 25 and 35 years	
			C	Between 35 and 50 years	
			D	Between 50 and 65 years	
			E	Above 65 years	
	3	What is your gender?			
			A	Female	
			B	Male	
			C	Other	
			D	I do not want to reveal my gender	
	4	How long have you been living in this neighbourhood?			
			A	Since the neighbourhood was built	
			B	For less than five years	
			C	Five to ten years	
			D	More than ten years	
ATTITUDE	5	Are you aware of how greywater is treated in your neighbourhood?			Code
			A	Yes, but I am not sure why it is treated here	1
			B	Yes, and I know why it is treated here	1
			C	No, I do not know	0
AFFECT	6	How do you feel about your neighbourhood's greywater treatment system?			
			A	I feel proud of it because I know it is better for the natural environment	1
			B	I feel proud of it because it makes the neighbourhood beautiful	1
			C	I do not feel anything specific about it	0
			D	I would prefer living in a neighbourhood without a greywater treatment system	0
AFFECT	7	Considering that hygiene standards are met, how would you feel about using treated greywater for washing your clothes in a washing machine?			
			A	I would happily accept it	1
			B	I would happily accept it if my clothes do not smell unnatural after washing	1
			C	I would accept it after trying it a few times	1
			D	I would be unhappy about using it, I will only use drinking water	0
HABIT	8	Do you check the ingredients of soaps and detergents when you buy them?			
			A	No, I don't check the ingredients	0
			B	Yes, I sometimes check them	0
			C	Yes, I always avoid using soaps and detergents with certain ingredients	1
ATTITUDE	9	Do you think it would affect the greywater treatment system in a negative way if you urinate in the shower every day?			
			A	Yes	1
			B	No	0
			C	I am not sure	0

SOCIAL FACTOR	10	Do you think your neighbours consume less, more or the same amount of drinking water as you do?			
			A	Less than me	0
			B	More than me	1
			C	Around the same	0
			D	I do not know	0
SOCIAL FACTOR	11	Would you be willing to share a laundry room in the neighbourhood instead of having a private washing machine in your house?			
			A	Yes	1
			B	No	0
			C	Maybe	0
SOCIAL FACTOR	12	Do you ever talk to your neighbours about the greywater treatment system?			
			A	Yes, all the time	1
			B	No	0
			C	Yes, sometimes	1
ATTITUDE	13	Why do you think drinking water is used even for non-drinking purposes such as toilet flushing and laundry?			
			A	It is not safe to use any water other than drinking water for these activities	0
			B	It is easier to supply one type of water for all activities	1
			C	There is an unlimited supply of drinking water in The Netherlands	0
			D	I do not know	0
AFFECT	14	Considering that hygiene standards are met, how would you feel about using treated rainwater/greywater for showering and washing hands?			
			A	I would happily accept it	1
			B	I would happily accept it if my hands do not smell unnatural after washing	1
			C	I would accept it after trying it a few times	1
			D	I would be unhappy about using it, I will only use drinking water	0

ATTITUDE	15	Where does the water from your toilet go when you flush it?			
			A	To a large waste-water treatment facility far from the neighbourhood	1
			B	To a small waste-water treatment unit in the neighbourhood	1
			C	Directly to a river, lake or the sea	0
			D	I do not know	0
ATTITUDE	16	What are some constituents of human waste (faeces and urine)?			
			A	Organic matter from our food	0
			B	Some elements from the soil	0
			C	Medication I consume	0
			D	All of the above	1
			E	I am not sure	0
AFFECT	17	How do you feel when you use drinking water to flush toilets, in general?			
			A	I feel clean and safe	0
			B	I feel nothing specific	0
			C	I feel guilty because it is a waste of water	1
			D	I am not sure	0
HABIT	18	Have you ever used a toilet that uses lesser water than your household one? (Apart from toilets on trains, buses and flights).			
			A	Never	0
			B	One or two times	1
			C	For a few years	1
			D	For many years	1
HABIT	19	Would you be willing to use a composting toilet on a daily basis?			
			A	No, I like the comfort of a flush toilet	0
			B	Yes, I can use a composting toilet if it does not smell too much	1
			C	I am not sure	0
HABIT	20	How many times in your life have you had to use non-drinking water in your house?			
			A	Never	0
			B	One or two times	0
			C	For a few years	1
			D	For many years	1
HABIT	21	Have you ever lived in a neighbourhood or house that did not have continuous water supply?			
			A	Never	0
			B	For a few months	1
			C	For a few years	1
HABIT	22	Was your previous neighbourhood different from your current one in terms of water use? If yes, how?			
			A	No	0
			B	Yes:	1

Direct consumption of water, expectation of linear water use for domestic convenience and the comfortable and convenient use of flush toilets are the user's current behavioural influences which need to shift towards circular water behaviour. The indications of behavioural intent (meant to be hidden from the survey/interview participant) are meant to assign a certain tendency towards the desired pro-environmental behaviour according to the question. Each question also falls under one of the three objectives of this thesis - reduction in drinking water demand, increased acceptance of greywater reuse and increased acceptance of non-flush toilets.

NEIGHBOURHOOD CASE STUDIES

NEIGHBOURHOOD CASE STUDIES

Three neighbourhoods were chosen for behavioural analyses and design of water systems. All of them have been occupied and functioning for atleast 10 years assuring a steady state of use. Being a relatively non-water stressed country, The Netherlands makes a great testing ground for non-conventional technology. Some direct involvement with the residents seemed necessary to do justice to the behaviour-related exploration in this thesis. Hence, neighbourhoods within the country seemed relevant and convenient to use as case studies.

EVA-LANXMEER

CASE STUDY 01

Location: Culemborg, The Netherlands

Year of realisation: 2003

No. of households: 300

No. of residents: 720

EVA-Lanxmeer was designed and built on an area of land which originally belonged to Vitens, the regional drinking water company. The company still owns a part of the land within the neighbourhood where they extract drinking water from the ground for domestic use. This resulted in houses that were built on foundations made of aero-concrete and with wooden super-structures to prevent the disruption of the sand and clay layers below ground through which ground water infiltrates over time. A condition was also imposed by Vitens that the neighbourhood be designed along ecological principles.

The image below is a map of the neighbourhood with the helophyte filters marked in red and rainwater ponds in blue.

Water system

The water system in EVA-Lanxmeer includes non-conventional methods of managing rainwater, greywater and drinking water. The extraction of drinking water is done locally, as described above. Rainwater is channelled into two streams, that collected from rooftops and from streets, the former assumed to be relatively cleaner. Rainwater from rooftops is absorbed in ponds within the neighbourhood while the remaining rainwater is directed from the streets to the periphery through 'wadis' or open drains to restored riverbeds.

Greywater (from sinks, showers and washing machines) is separated from black water (from toilets) using dual-plumbing and treated in five helophyte filters in the neighbourhood. The neighbourhood has two helophyte filters of 1500 m^2 each and three smaller ones of 300 m^2 each. However, the treated water is discharged into a neighbouring canal instead of being reused for domestic purposes. In some of the households, plumbing is designed to supply the toilets with treated greywater but this has not been realised. Currently, blackwater is discharged to the main sewer system, although the initial plan was to generate biogas in the neighbourhood.

POLDERDRIFT

CASE STUDY 02

Location: Polderdrift, Arnhem

Year of realisation: 1997

No. of households: 40

No. of residents: 96

Polderdrift is a small neighbourhood of 40 households in the south of Arnhem. The residents are a mixed group of people but most of them have been residing there since its inception in 1997. New members are accepted through interviews and after a tour of the neighbourhood. In general, the residents at Polderdrift seem to be more ecologically conscious than a typical Dutch neighbourhood.

Apart from their unique decentralised water system (described below), there are responsibilities shared by the residents and managed by specific long-term residents such as maintaining the gardens and orchards, organising social activities and events for the neighbourhood, celebrations etc.

Water system

Greywater and blackwater are conveyed in separate streams and the greywater is treated in a vertical subsurface flow helophyte filter. The treated greywater is used for flushing the toilets. Rainwater from rooftops is used for laundry but an optional drinking water connection is also provided for this purpose.

Effluent from the helophyte filter flows into an open pond and then a storage tank. It is not discharged into the neighbouring canals. Although only a few of the residents are involved in maintaining the helophyte filter, all of them are aware of its presence and purpose since it is located in the middle of the neighbourhood adjacent to the pond and the common room.

WATERSCHOON

CASE STUDY 03

Location: Noorderhoek, Sneek

Year of realisation: 2011

No. of households: 286

No. of residents: 600

Waterschoon is actually the name of the new sanitation system implemented at Noorderhoek in Sneek. A total of 286 households are connected to the system (Meulman, 2018). The project was brought into realisation by the following groups - Woningstichting de Wieren (Project developer), Wageningen University (Water research), DeSaH BV (Wastewater company), Sudwest-Fryslan (Municipality), Wetterskip Fryslan (Construction supervisor).

Water system

Waterschoon includes decentralised treatment for both blackwater and greywater. Household organic waste is shred in a grinder in each kitchen and mixed with blackwater. Both are conveyed through a vacuum system. Blackwater and greywater are conveyed separately and treated in an on-site facility housed in one of the open spaces in the neighbourhood.

Waterschoon consists of the following components (De Graff & Van Hell, 2014):

1. Generation of biogas from blackwater and organic waste

2. Purification of blackwater and greywater with the aim of meeting discharge standards

3. Processing of household organic waste with blackwater

4. Heat recovery from greywater for house-heating.

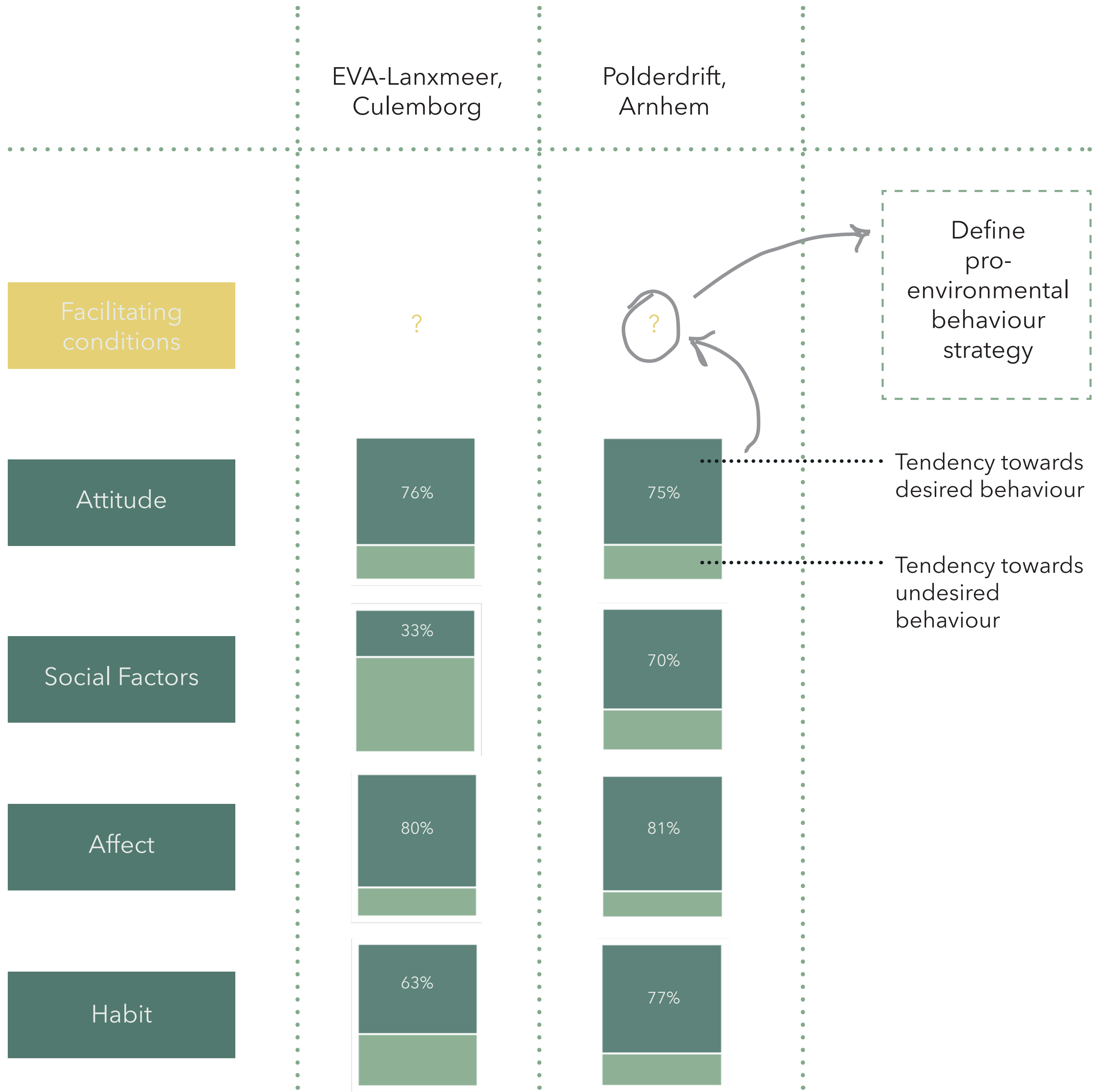
	Drinking water	Rainwater	Greywater	Blackwater	Behavioural influence
EVA-Lanxmeer Realised in 2003 300 households 720 residents	Neighbourhood demand: 86 m^3/day Per capita demand: 119.3 litres/day Source: On-site (Vitens drinking water company)	Drainage: Open drains (*wadis*) Infiltration ponds	Generation: 60 m^3/day Treatment: Helophyte filters Total filter area: 2400 m^2	Generation: 25 m^3/day Discharged to main sewer without treatment	Visible rainwater management system. Visible, plant-based greywater treatment system. Information conveyed to residents about type of detergents to use.
Polderdrift Year of realisation: 1997 No. of households: 40 No. of residents: 96	Neighbourhood demand: 6.8 m^3/day Per capita demand: 70.6 litres/day Source: Municipal drinking water	Drainage: Used for washing clothes & excess is discharged into canal	Generation: 7 m^3/day Treatment: Helophyte filters Total filter area: 230 m^2	Generation: 3.3 m^3/day Discharged to main sewer without treatment	Use of rainwater for laundry. Visible, plant-based greywater treatment system. Substantial involvement of residents in neighbourhood management
Waterschoon Year of realisation: 2011 No. of households: 286 No. of residents: 600	Neighbourhood demand: 52 m^3/day Per capita demand: 86 litres/day Source: Municipal drinking water	Drainage: Discharged into canal	Generation: 45 m^3/day Treatment: Bio-flocculation	Generation: 5.5 m^3/day Treatment: Upflow Anaerobic Sludge Blanket reactor (UASB) OLAND for nitrogen removal Stuvite precipitation for phosphorous recovery	Blackwater and greywater system located in the middle of the neighbourhood, but as an indoor facility. Vacuum toilets in all households.

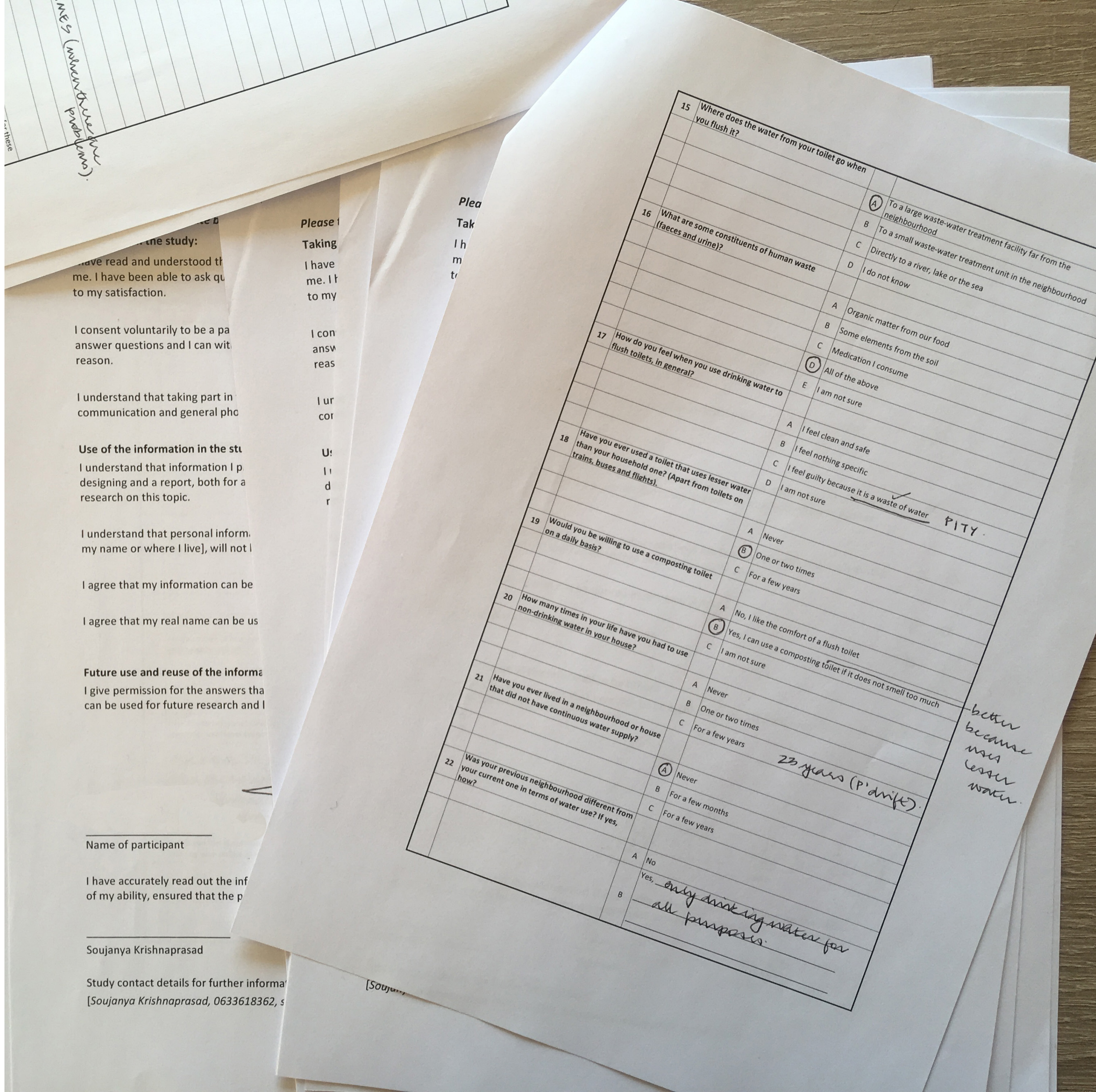
BEHAVIOURAL ANALYSIS

Interviews were conducted at Arnhem and Culemborg on 16.03.2019 and 23.03.2019 respectively. Interviews could not be conducted at Sneek due to insufficient and late responses from the neighbourhood. However, a brief description is provided in the following page as a conclusion of a survey regarding the water system conducted at Sneek by the neighbourhood resident association in 2017.

Eight persons were interviewed at Arnhem and five at Culemborg. Since the purpose of the interviews was to initiate some connection between the behavioural tendencies of residents with regard to their neighbourhood water system and the design of the system itself, and not to arrive at certain statistical data about the topic, it was decided that a small number of participants would be sufficient. Given the nature of questions and potential complexity underlying the topic, the printed survey with specific questions and options was used in face-to-face oral interviews. This allowed participants to ask questions if a certain question or response choice was unclear. Rather than forcing participants to choose strictly from the options, the pre-defined survey acted more as a facilitator for the a semi-structured interview.

After the interviews, responses for each question were counted and categorized into being a potentially pro-environmental tendency or not. The percentage of desired and undesired tendencies was calculated for each factor from the Theory of Interpersonal Behaviour. Since the questions were based on specific factors of the theory and the responses were pre-assigned a score, the process of analysis was relatively simple. Such data collection and analyses could be much more accurate and definite, but the intention in these case studies was merely to establish a general idea of the relationship between behaviour and water in the neighbourhoods.


EVA-Lanxmeer, Culemborg
Polderdrift, Arnhem
Facilitating conditions
?
?
Define pro-environmental behaviour strategy
Attitude
76%
75%
Tendency towards desired behaviour
Tendency towards undesired behaviour
Social Factors
33%
70%
Affect
80%
81%
Habit
63%
77%


15 Where does the water from your toilet go when you flush it?
A To a large waste-water treatment facility far from the neighbourhood
B To a small waste-water treatment unit in the neighbourhood
C Directly to a river, lake or the sea
D I do not know
16 What are some constituents of human waste (faeces and urine)?
A Organic matter from our food
B Some elements from the soil
C Medication I consume
D All of the above
E I am not sure
17 How do you feel when you use drinking water to flush toilets, in general?
A I feel clean and safe
B I feel nothing specific
C I feel guilty because it is a waste of water
D I am not sure
PITY
18 Have you ever used a toilet that uses lesser water than your household one? (Apart from toilets on trains, buses and flights).
A Never
B One or two times
C For a few years
19 Would you be willing to use a composting toilet on a daily basis?
A No, I like the comfort of a flush toilet
B Yes, I can use a composting toilet if it does not smell too much
C I am not sure
better because uses lesser water.
20 How many times in your life have you had to use non-drinking water in your house?
A Never
B One or two times
C For a few years
23 years (P'drift)
21 Have you ever lived in a neighbourhood or house that did not have continuous water supply?
A Never
B For a few months
C For a few years
22 Was your previous neighbourhood different from your current one in terms of water use? If yes, how?
A No
B Yes, only drinking water for all purposes.
I have read and understood the
me. I have been able to ask qu
to my satisfaction.
I consent voluntarily to be a pa
answer questions and I can wit
reason.
I understand that taking part in
communication and general pho
Use of the information in the stu
I understand that information I p
designing and a report, both for a
research on this topic.
I understand that personal inform
my name or where I live], will not
I agree that my information can be
I agree that my real name can be us
Future use and reuse of the informa
I give permission for the answers tha
can be used for future research and
Name of participant
I have accurately read out the inf
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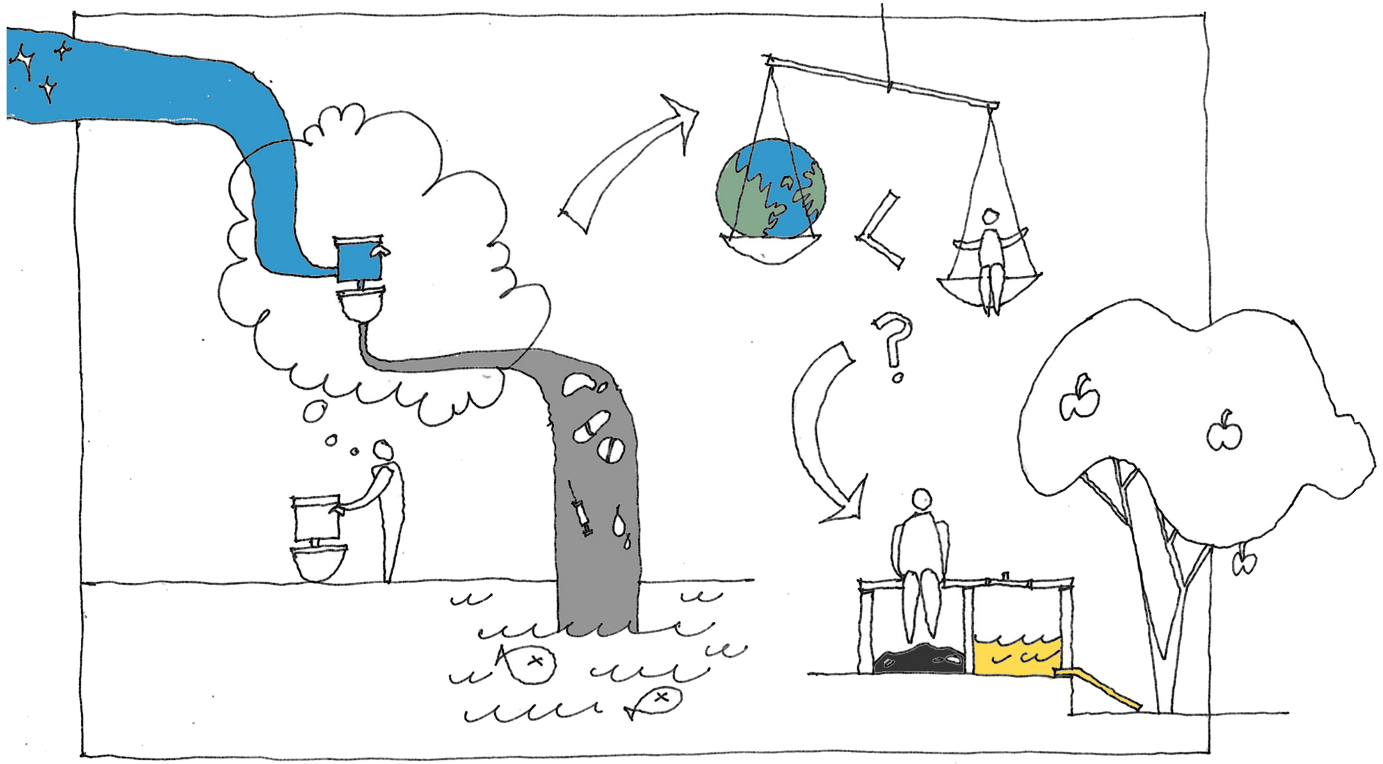


The neighbourhoods at both EVA-Lanxmeer and Polderdrift include helophyte filters (or constructed wetlands) for their greywater treatment. In addition, Polderdrift also uses rainwater for laundry and reuses the treated greywater for toilet flushing. In terms of water treatment systems, Waterschoon is the most different one compared to the other two. It treats both greywater and blackwater in partly connected systems, both of which are advanced and used in experiments by researchers. They are located in the centre of one of the central open spaces, in a structure that looks like one of the houses but with a large glass window to allow people to look at the systems. The households have vacuum toilets, while EVA-Lanxmeer and Culemborg have regular flush toilets.

Most of the questions in the external survey at Sneek are about the comfort and convenience of the vacuum toilets, and not necessarily the residents' awareness of the purpose of such toilets. In some emails exchanged with the neighbourhood 'manager' to establish interviewing possibilities, some points stood out as being indicative of the general neighbourhood dynamic. The manager seemed convinced that the interview questions framed in this thesis were too complicated for the residents to understand and that they would not know the specifics of greywater and blackwater. This response stood out in stark contrast with the willingness of the other two neighbourhoods to participate in the water-related interviews as well as their understanding of atleast a few technical water terms.

	OBJECTIVES:	Reduction in drinking water demand	Increased acceptance of greywater reuse	Increased acceptance of non-flush toilets
FEEDBACK	Guideline	Establish relative ranking of residents (Target factor: Social)	Establish relative ranking of residents (Target factor: Social)	Establish relative ranking of residents (Target factor: Social)
	Example	Rank users by their drinking water consumption.	Rank users by their greywater to drinking water consumption ratio.	Rank users based on their ability to maintain a composting system.
STEERING	Guideline	Provide visible real-time feedback (Target factor: Attitude, Habit)	Stimulate conversation about greywater (Target factor: Social)	Stimulate conversation about toilet-use (Target factor: Social) Allow step-wise habit change (Target factor: Habit)
	Example	Publicly rank users by their drinking water consumption.	Create social environments that encourage conversation about water.	Create social environments that encourage conversation about toilets. Create a trial period for the use of such toilets in homes instead of a sudden shift.
PERSUASION	Guideline	Create functional friction (Target factor: Attitude, Habit)	Allow step-wise habit change (Target factor: Habit)	Create functional friction (Target factor: Attitude, Habit)
	Example	Non-continuous supply of drinking water.	Allow some contact with treated greywater in an outdoor pool with treated greywater fit for that purpose.	Provide an inconvenient flush toilet in the neighbourhood and a beautiful and convenient source-separating toilet in each house.

Below are points to be noted for these aspects and some other ones related to the management of the neighbourhood rather than the design itself.

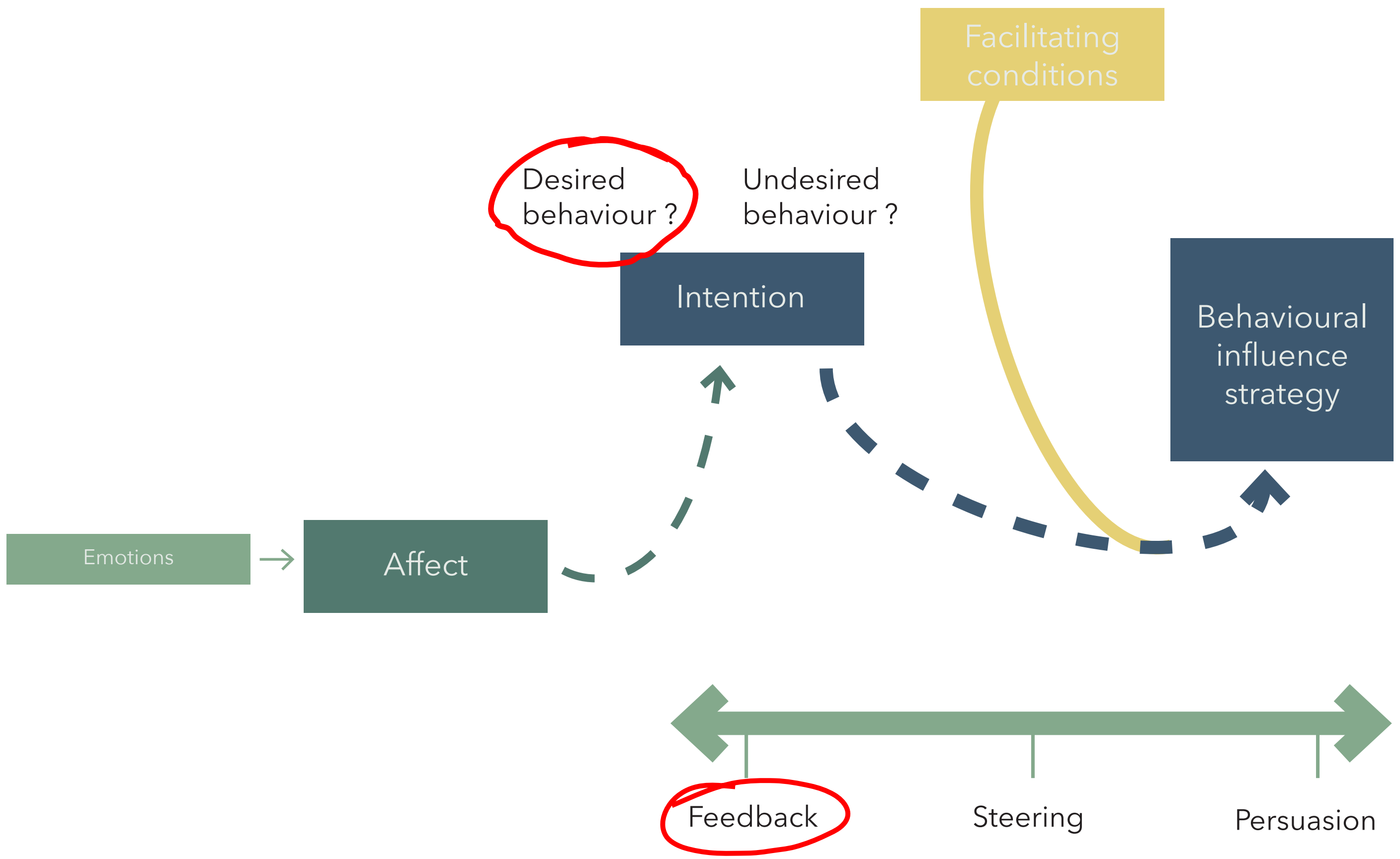
1. A significant point regarding EVA-Lanxmeer is that most residents said they do *not* talk to each other about the helophyte filters. Residents at Polderdrift are far more interactive and actively involved in maintaining the filters themselves. A guess is that Polderdrift being a relatively smaller neighbourhood with the helophyte filter (and pond) in the centre of the site makes it much more visible on a daily basis. The helophyte filters at EVA-Lanxmeer, though much bigger, are located in residual site spaces and do not necessarily become the point of common conversation. Hence, encouraging conversations by managing the neighbourhood dynamic is essential in bringing resource-related issues to the forefront of social interaction.

2. The residents at Polderdrift seemed to feel much more responsible for their neighbourhood common properties (the orchard, helophyte filters, compost heap, common room, garden) in general. Creating a sense of ownership through internal organisation and shared activities directly related to neighbourhood resource management could increase willingness to accept a non-conventional system.

3. While both sets of residents seemed sufficiently aware about greywater, there was not as much understanding of blackwater or the impact of using pharmaceuticals or eating certain foods which would eventually constitute blackwater. This could be because both neighbourhoods discharge blackwater into the sewer without any circular strategy. The mere presence of helophyte filters and the information conveyed to residents, hence, already has a significant impact on their awareness of water types and reusability. Most residents in both neighbourhoods showed considerable willingness to try to use treated greywater even for laundry and showering.

Q. Considering that hygiene standards are met, how would they feel about using treated rainwater/greywater for showering and washing hands?

A. They would happily accept it	(1)
B. They would happily accept it if the clothes do not smell unnatural after washing	(1)
C. They would accept it after trying it a few times	(1)
D. They would be unhappy about using it	(0)

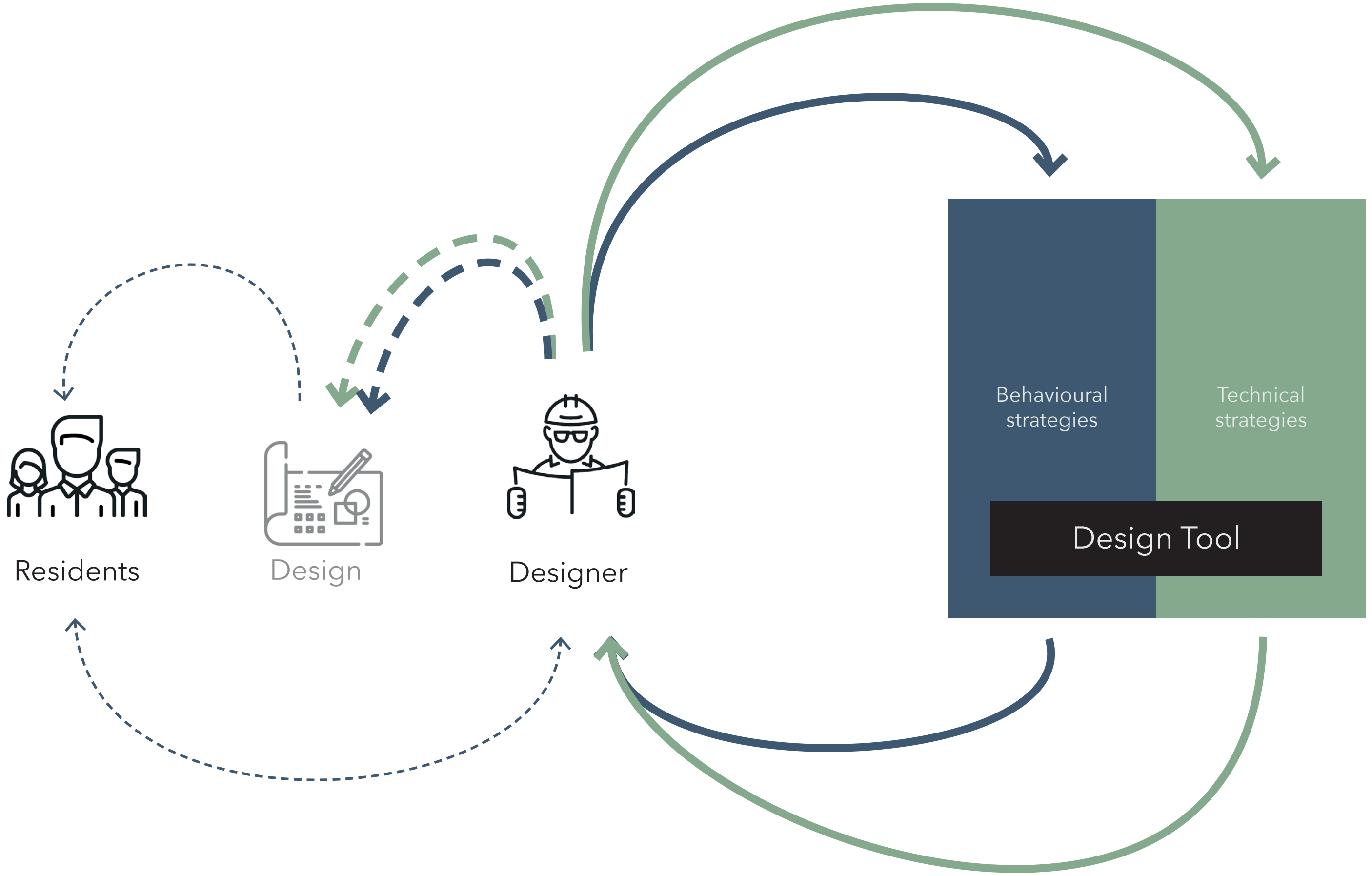


4. In comparison to the other two, Waterschoon has relatively high-tech systems and for both greywater and blackwater. Both are located in a built structure in the centre of an open space where it is visible from the houses and streets around it. Although visible, the system itself is (understandably) inaccessible to the residents, even in terms of sufficient visual access. The lack of an ecological intention for the residents seems to have resulted in a relatively less concerned group compared to the other two neighbourhoods.

5. While Waterschoon has the most advanced of all three treatment systems, the rest of the neighbourhood appears to be like any other neighbourhood of similar size and density in the country. A visual connection between the resource network and residents plays a significant role in resident awareness by being an object of perception on a daily basis, be it conscious or not.

These conclusions have contributed to defining behaviour intervention strategies for circular water systems. The table on the left sums up possible strategies but is in no way comprehensive. The important point to note from the table are the parameters to consider - extent of the influence and target goal of the desired behaviour. The same framework is used in the design tool to provide strategies to effect circular water behaviour.

DESIGN TOOL



The literature research and case studies described hitherto culminate in a design tool 'Circular Water.' This chapter of the thesis attempts to convey the functioning of the tool by stating the inputs and outputs at each step, perhaps as a starting point for a manual on how to use the it. The tool is based on the principles of circular water use and behavioural research and analysis described in previous chapters of this report.

The diagram on the left shows the relevance of the 'Circular Water' design tool in a design process. The meaning of various information flows is explained below:

Communication between designer and residents about non-conventional resource network design (among other design aspects).

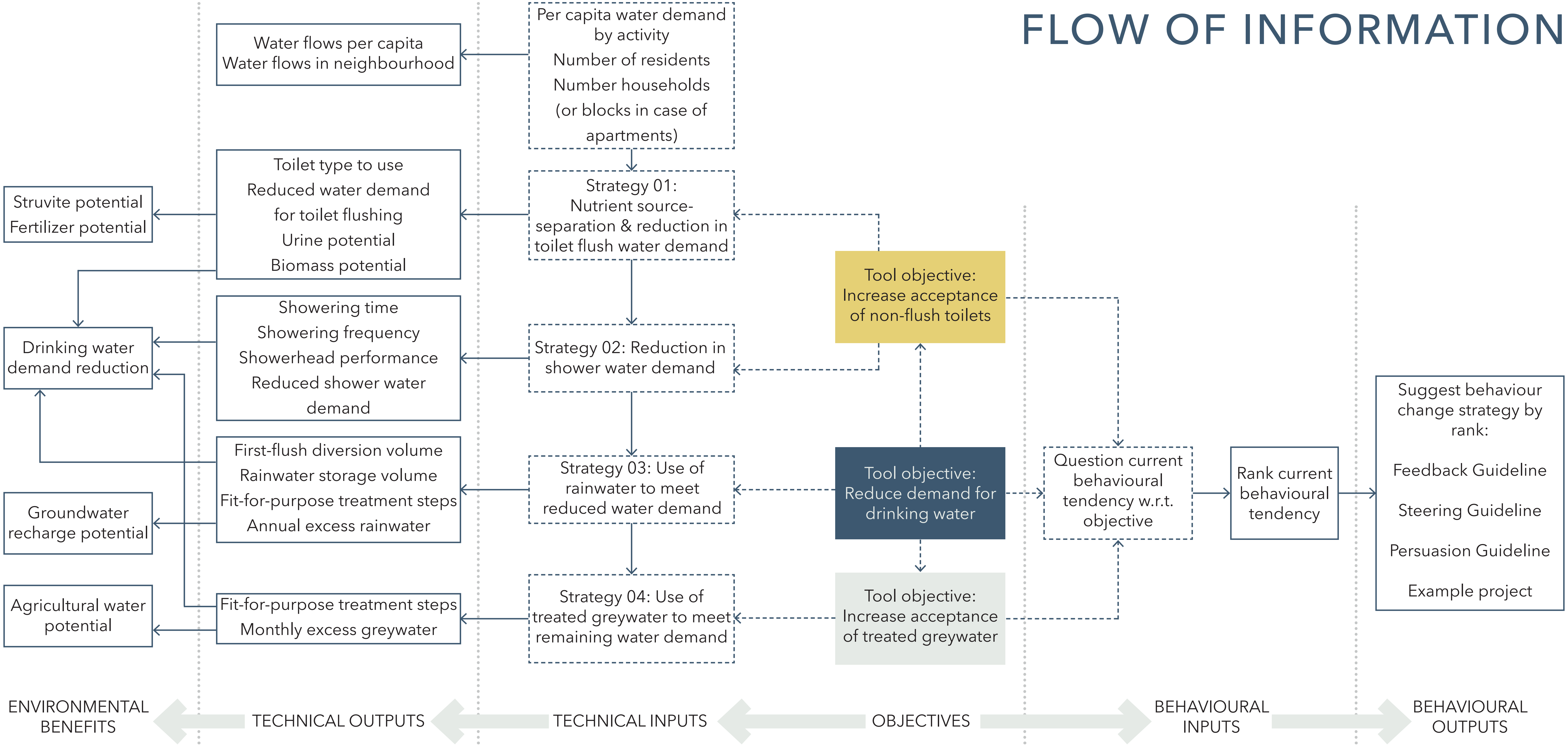
Communication between the designer and tool in the form of simple inputs regarding a specific project, and outputs as circular strategies to be incorporated in the design

Application of technical and behavioural water strategies by the designer

Influence of design on resident behaviour

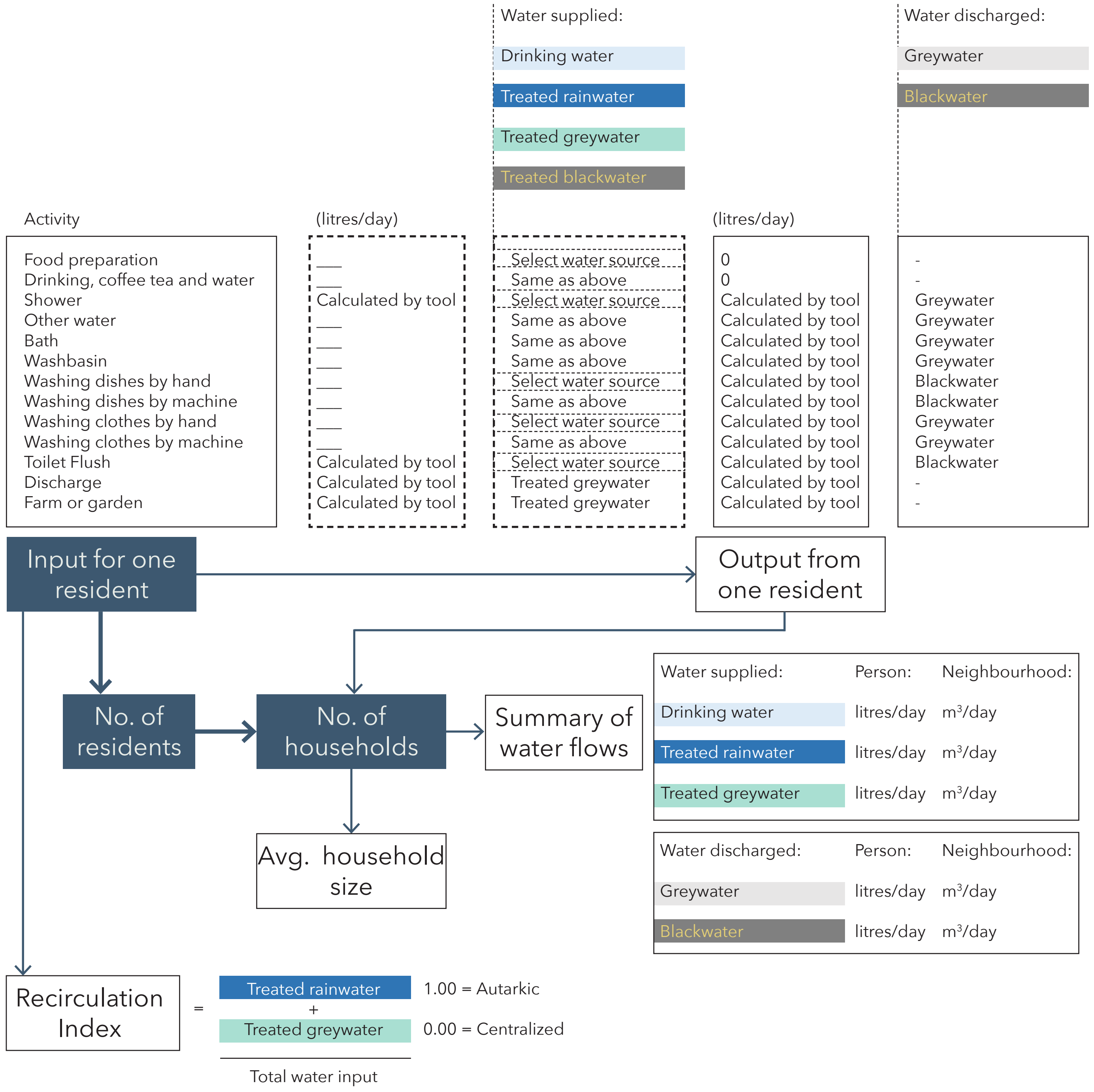
RELEVANCE

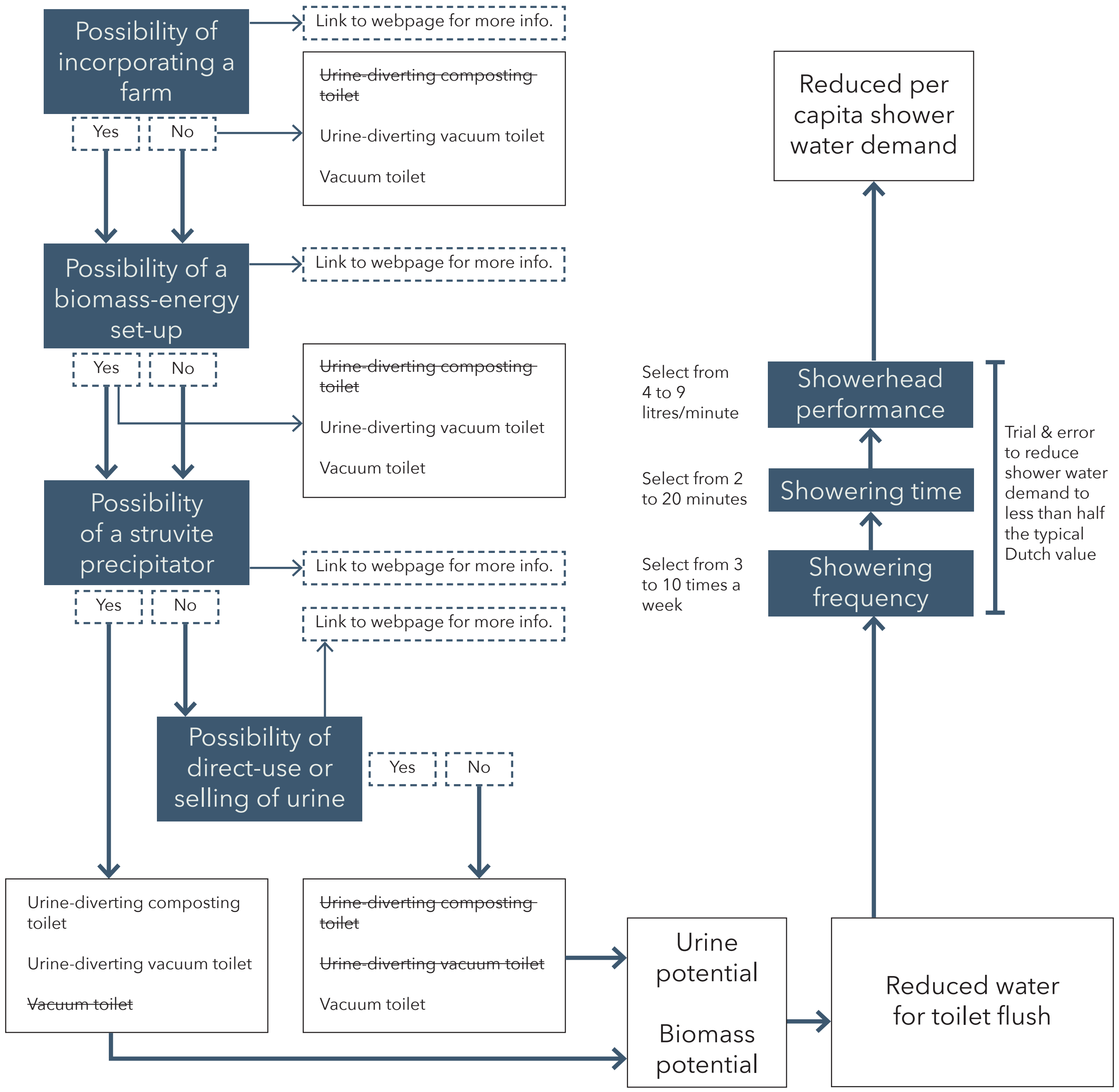
FLOW OF INFORMATION



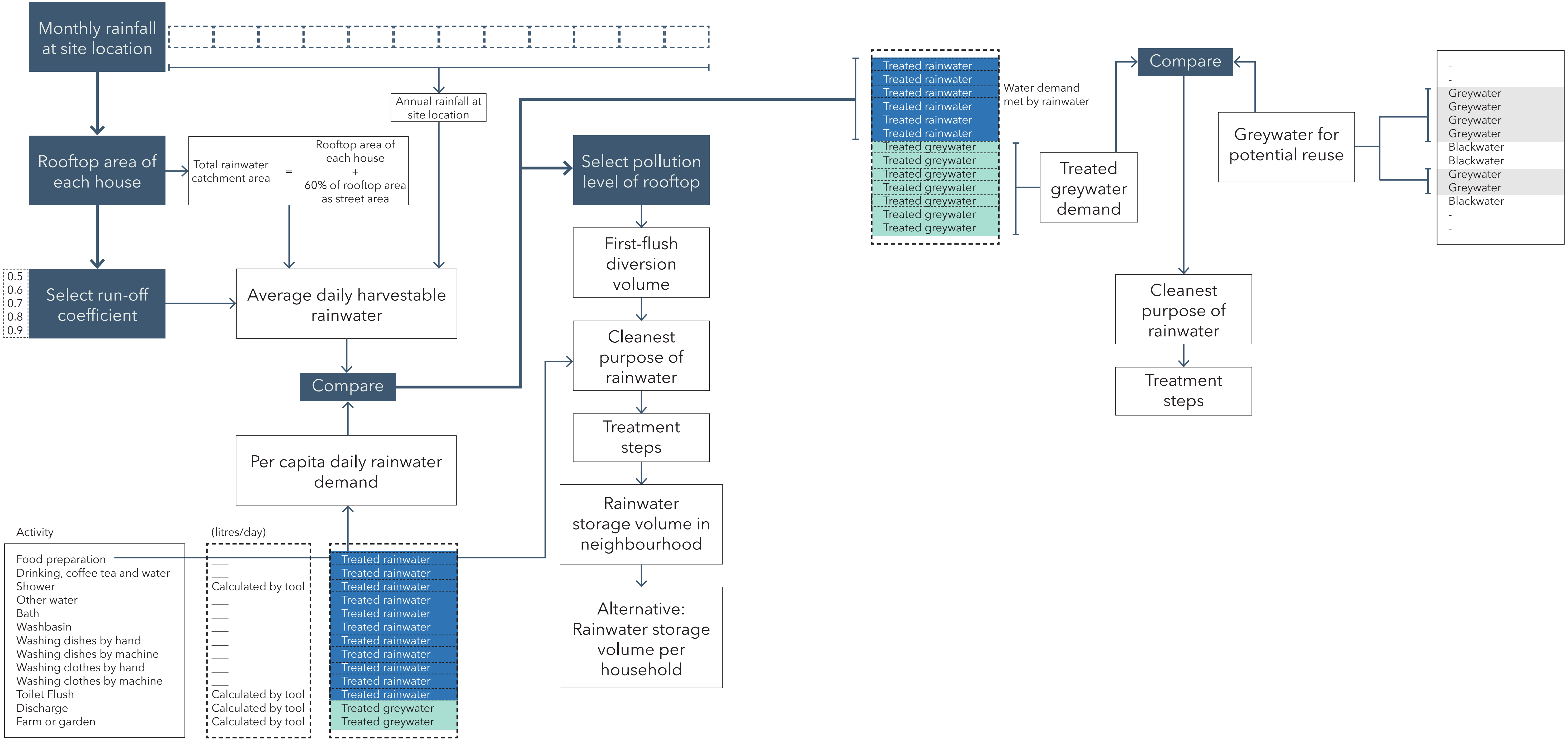
Technical Inputs & Outputs

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum

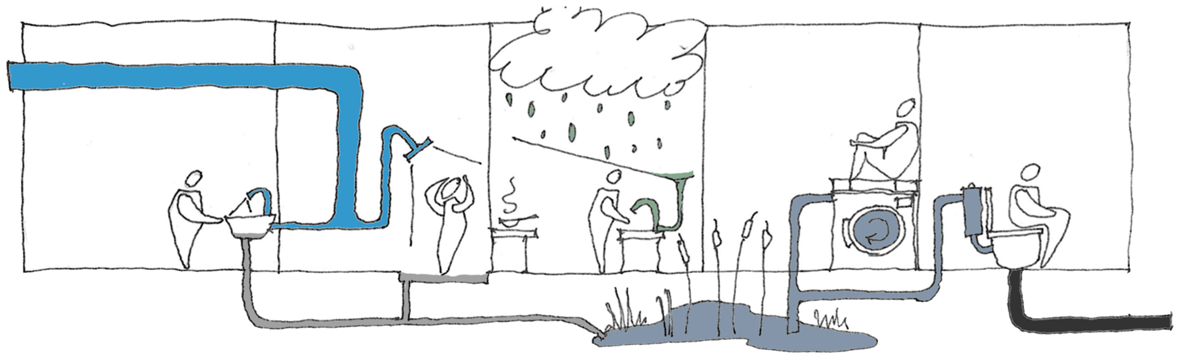




Farm	Energy	Struvite	Direct fertilizer	Storage type	Toilet type	Urine potential		Biomass potential	
Yes	Yes	No	Yes	Neighbourhood tank for 6-month storage	Urine-diverting vacuum toilet	Stored urine as fertilizer	-	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
Yes	No	No	Yes	Neighbourhood tank for 6-month storage	Urine-diverting composting toilet	Stored urine as fertilizer	-	Compost from faeces	-
No	Yes	No	Yes	Neighbourhood tank for 6-month storage	Urine-diverting vacuum toilet	Stored urine as fertilizer	-	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
No	No	No	Yes	Neighbourhood tank for 6-month storage	Urine-diverting vacuum toilet	Stored urine as fertilizer	-	Blackwater discharged	-
Yes	Yes	No	Yes	Household tank for daily use	Urine-diverting vacuum toilet	Urine as direct use fertilizer	-	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
Yes	No	No	Yes	Household tank for daily use	Urine-diverting composting toilet	Urine as direct use fertilizer	-	Compost from faeces	-
No	Yes	No	Yes	Household tank for daily use	Urine-diverting vacuum toilet	Urine as direct use fertilizer	-	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
No	No	No	Yes	Household tank for daily use	Urine-diverting vacuum toilet	Urine as direct use fertilizer	-	Blackwater discharged	-
Yes	No	No	No	-	Vacuum toilet	-	-	Blackwater discharged	-
Yes	Yes	Yes	-	-	Urine-diverting vacuum toilet	Struvite from urine	Effluent from struvite precipitation	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
Yes	No	Yes	-	-	Urine-diverting composting toilet	Struvite from urine	Effluent from struvite precipitation	Compost from faeces	-
No	Yes	Yes	-	-	Urine-diverting vacuum toilet	Struvite from urine	Effluent from struvite precipitation	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
No	No	Yes	-	-	Urine-diverting vacuum toilet	Struvite from urine	Effluent from struvite precipitation	-	Blackwater discharged
Yes	No	No	No	-	Vacuum toilet	-	-	Blackwater discharged	-
No	Yes	No	No	-	Vacuum toilet	-	-	Biogas from blackwater + organic waste	Sludge from bioreactor as fertilizer
No	No	No	No	-	Vacuum toilet	-	-	Blackwater discharged	-


Monthly rainfall at site location
Annual rainfall at site location
Rooftop area of each house
Total rainwater catchment area = Rooftop area of each house + 60% of rooftop area as street area
0.5
0.6
0.7
0.8
0.9
Select run-off coefficient
Average daily harvestable rainwater
Compare
Per capita daily rainwater demand
Activity
(litres/day)
Food preparation
Drinking, coffee tea and water
Shower
Other water
Bath
Washbasin
Washing dishes by hand
Washing dishes by machine
Washing clothes by hand
Washing clothes by machine
Toilet Flush
Discharge
Farm or garden
Calculated by tool
Calculated by tool
Calculated by tool
Calculated by tool
Treated rainwater
Treated greywater
Select pollution level of rooftop
First-flush diversion volume
Cleanest purpose of rainwater
Treatment steps
Rainwater storage volume in neighbourhood
Alternative: Rainwater storage volume per household
Water demand met by rainwater
Treated greywater demand
Compare
Greywater for potential reuse
Greywater
Blackwater
Cleanest purpose of rainwater
Treatment steps

TOOL INTERFACE



WELCOME TO CIRCULAR WATER!

Circular Water can be used to define a domestic water use plan for a residential neighbourhood. It has been developed with the vision of defining strategies for circular water systems for future urban neighbourhoods. These strategies are a part of the larger vision of circular resource management in the built environment.

You are among the first group to try using Circular Water. The intended users of this tool are architects, planners and engineers with some idea of terms related to domestic water consumption.

Following this page, there are three sheets. Please start at the top left of each sheet and go through it in order till the bottom without skipping any question or information. It is important that all the information is filled in. You may enter data related to an existing project or an imaginary one. It is ideal to use the tool at 75% zoom.

How the tool is organised:		
The goal of sheet #01 is to determine technical strategies for water circularity. It involves providing numeric inputs such as the number of residents the neighbourhood will house, the rooftop area of each house, water use per person for showering, cooking, etc. There are default values for some of these already entered in the tool. You may change them if you think they are different for your project. Technical strategies for water circularity include four parts: (i) Source-separation of nutrients (ii) Reduction of shower water consumption (iii) Use of rainwater and (iv) Reuse of greywater. Each part has its own technical outputs.	Sheet #02 requires no numeric inputs. It has a set of questions about resident behaviour. The goal here is to define strategies to influence residents' behaviour towards being more pro-environmental with regard to water. If you are testing the tool with no specific project and resident group in mind, you can be imaginative with the answers. After answering all 15 questions, outputs are provided in the form of descriptive strategies to influence behaviour.	No input is required from you in part #03. It provides an overview of the environmental benefits of the technical strategies determined as a result of your inputs in part #01. Although not comprehensive, this part of the tool provides a starting point to see the environmental results of our choices as designers or engineers.

There are different types of information the tool will provide or ask for.
These are differentiated so:

Type 01	Enter data in cells with this dashed black outline. The colour may vary (you will see why). Some cells require typed-in data, others have drop-down lists to select data from. Click on the cell to see if it is a drop down list (an arrow shows up next to the cell).
Type 02	Read the information in this type of cell. It could be a question or an output based on some previous answer.
Type 03	This is additional information if you are curious (or confused).
	These cells will contain information which is incomplete in this version of Circular Water.

Step 01.
Establishing water quantities for one resident

You may change these water quantities but not the activities

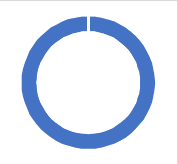
Activity	Input for one resident (litres/day)	Source	Output from one resident (litres/day)	Discharge
Food preparation	1.2	Treated rainwater	0.0	-
Drinking, coffee tea and water	1.3	Treated rainwater	0.0	-
Shower	13.7	Treated rainwater	13.7	Greywater
Other water	4.5	Treated rainwater	4.5	Greywater
Bath	1.9	Treated rainwater	1.9	Greywater
Washbasin	5.2	Treated rainwater	5.2	Greywater
Washing dishes by hand	3.5	Treated greywater	3.5	Blackwater
Washing dishes by machine	1.3	Treated greywater	1.3	Blackwater
Washing clothes by hand	2.5	Treated greywater	2.5	Greywater
Washing clothes by machine	14.1	Treated greywater	14.1	Greywater
Toilet Flush	2.2	Treated greywater	2.2	Blackwater
Discharge		Treated greywater		
Farm or garden		Treated greywater	0.0	

Step 02.
Establishing water quantities for neighbourhood

No. of residents:	1410
No. of houses: (or blocks in case of apartments)	300

Avg. floor height (m)	3.0	
No. of floors	3	
Household/block size	4.7	Average

Recirculation Index (you should aim to make this = 1.00)



1.00

SUMMARY OF WATER FLOWS

Input	Person (litres/day)	Neighbourhood (m^3/month)	Output	Person (litres/day)	Neighbourhood (m^3/month)
Total	51.4	2,174.8	Total	48.9	2,069.1
Drinking water	0.0	0.0	Greywater	41.9	1,773.0
Treated rainwater	27.8	1,176.5	Blackwater	7.0	296.1
Treated greywater	23.6	998.3			

Step 03.
Strategy: nutrient source-separation

Water circularity starts with reducing the largest water demanding activities - toilet use and showering. Here we start with toilet use since it is closely linked to the biomass cycle.

This part of the tool will provide the type of toilet to use in the households and the potential nutrients and/or energy that can be recovered from household blackwater. Please answer the questions in order as they appear. If a question does not appear, leave the respective answer box blank.

Default toilet choice: **Flush toilet**

Nutrient-recovery for soil fertilization works ideally with a farm in or near the neighbourhood.

Is there a possibility of incorporating a farm in or near the neighbourhood? No

Click here to see how to generate energy using faeces and organic waste.

Is it possible to incorporate such a biomass-energy set-up in the neighbourhood? Yes

You may need a struvite precipitator. Click here to find out how it works.

Is it possible to install a struvite precipitator in the neighbourhood? No

You may be able to sell the urine as fertilizer.

Click here to see how this could work.

Is it possible to sell or use the urine? Yes

Toilet type to be used: **Urine-diverting vacuum toilet**

Urine Outputs:

1. **Stored urine as fertilizer**
2. **-**

Biomass Outputs:

1. **Biogas from blackwater + organic waste**
2. **Sludge from bioreactor as fertilizer**

These outputs are based on your responses above. Find these outputs in the table below to see their respective quantities, space requirements and quantities of energy and nutrients recovered.

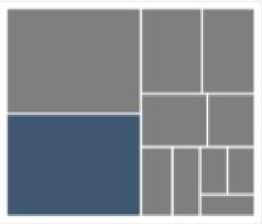
If you would like to change your responses, please delete each one and restart from question A.

		POTENTIAL NUTRIENTS & ENERGY	Scale of application	Production		Storage/processing volume		Total-N (kg/year)	Total-P (kg/year)	K (kg/year)	Compost (kg/year)	Fertilizer equivalent (kg/year)	Electricity from biogas (kWh/year)	Heat from biogas (kWh/year)
FROM BIOMASS	Option 1	Biogas from blackwater + organic waste	Neighbourhood	1,622	m^3/month								86,120	96,885
		Sludge from bioreactor as fertilizer	Neighbourhood	128	kg/month									
	Option 2	Compost from faeces	Household	186	kg/year	1	500L boxes	2	1	2	186			
		Compost from organic waste	Household											
		Effluent from compost	Household	71	litres/year									
FROM URINE	Option 1	Struvite from urine	Neighbourhood	118	kg/month	5	500L tanks	-	648	-	-	15,863		
		Effluent from struvite precipitation	Neighbourhood	59	m^3/month			4,529		1,029	-			
	Option 2	Stored urine as fertilizer	Neighbourhood	59	m^3/month	355	m^3	5,661	721	1,287	-	17,625		
	Option 3	Urine as direct use fertilizer	Household	18	litres/day	2	50L tanks	19	2	4	-	59		

Step 04.
Reduction in shower water demand

Shower water consumption is a result of multiple parameters. Here, three parameters are addressed - frequency of showering, length of showering time and rate of water flow in the showerhead. Although not a universal method of bathing, the tool assumes that the activity of showering is done using a showerhead. The graph on the right indicates shower water proportion w.r.t. other domestic water demand.

How many times a week do you shower?	4	
How many minutes do you shower each time?	4	minutes
Showerhead water use per minute	6	litres/minute
Shower water use per person per day	13.7	litres



If the cell above is red, the shower water demand is more than half the typical Dutch shower water consumption.
The goal is to keep the cell white ;)

Step 05.
Rainwater use

Following the reduction in water demand for toilet use and showering, you need to check if the remaining water demand of the neighbourhood can be met by a local water source. This tool considers rainwater and greywater as local sources and starts with rainwater since it is relatively easier to treat rainwater for domestic use.

In the cells below, please enter the monthly rainfall of the neighbourhood location (in millimteres). Click here to find this information for the nearest city.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	4	8	36	96	68	98	116	182	150	56	16

Annual rainfall of neighbourhood's location	831	mm

Rooftop area of each house (m^2) 45

Area of streets (% of residential area footprint)	0.60	
Total catchment area (m^2)	21,600	m^2

What is the run-off coefficient of the catchment surface? Set it as 0.9 if you do not know. 0.9

Total annual harvestable rainwater in neighbourhood	16,155	m^3
Total daily water demand per capita	51	litres

In Column D, change all water sources for activities to treated rainwater, starting with food preparation.

Total daily rainwater available per capita	31	litres
Total daily rainwater demand per capita	28	litres

If the above cell is red, it means your rainwater demand is more than the rainwater available. Try changing the following:

1. Increase the catchment area (Rooftop area of each house or any additional rooftop/impermeable space available on site)

2. Reduce shower water demand (ii)

3. If neither works, change water sources for activities to treated greywater, starting with toilet flushing, until the cell is white.

Total monthly rainwater required for neighbourhood	1,177	m^3
Total annual rainwater required for neighbourhood	14,119	m^3
Cleanest purpose of treated rainwater	Food preparation	

Select pollution level for rooftops: High

Pollution factor 2.1

First flush diversion volume: 94.6 litres/household

Treatment method required for	Food preparation

Treatment steps:		Volume (litres)	Operation Energy	Installation Cost	Operation Cost	Renewal Cost	Maintenance Cost
Filtration	Sand filter (household scale)	72.0					
Disinfection	Activated carbon filter (POU)	-					

Rainwater storage volume required in neighbourhood: 3,754 m^3

Rainwater storage volume per household: 12,512 litres

OR

No. of barrels needed: 26 500 litre barrels OR 13 1000 litre barrels

Excess annual rainwater available in neighbourhood 2,036 m^3

If these storage options are unrealistically large or small, some of the water demand could be met by treated greywater (see below for the next strategy).

This excess rainwater is best used to recharge groundwater using wells or infiltration ponds, especially in places where groundwater level is depleting.

Step 06.
Greywater reuse

In Column D, change some sources (in order) to treated greywater, starting with toilet flushing.

Greywater generated	1,773.0	m^3/month
Average daily flow (neighbourhood)	59.1	m^3
Total daily per capita greywater generation	41.9	litres
Total daily per capita treated greywater demand	23.6	litres

If the above cell is red, it means the treated greywater demand is more than the greywater available. The remaining water demand may have to be met by another local or central source.
Change water sources for activities to drinking water, starting with food preparation, until the cell is white.

Cleanest purpose of treated greywater	Washing dishes by hai	998.3	m^3/month
Treatment method required for	Washing dishes by hand		

		Applicable to:	Land Area per unit flow (m^2/m^3)	Land Area (m^2)	Operation Energy	Installation Cost	Operation Cost	Renewal Cost	Maintenance Cost
Stage 1	Septic tank	Household		0.6					
Stage 2	Constructed wetland	Neighbourhood	30	1,773					
Stage 3	Ozonation pond	Neighbourhood	0.5	30					
Stage 4	Disinfection	Point-of-use	-	-					

		Applicable to:	Land Area per unit flow (m^2/m^3)	Land Area (m^2)	Operation Energy	Installation Cost	Operation Cost	Renewal Cost	Maintenance Cost
Stage 1	-	-	-	-					
Stage 2	Living machine svstem	Neighbourhood	4	168					
Stage 3	-	-	-	-					
Stage 4	-	-	-	-					

Excess monthly greywater available in neighbourhood: 775 m^3/month

This excess greywater can be used as a potential local source of agriculture, especially since urban farming is gaining relevance in many parts of the world. Depending on local regulations, greywater could be used for farming with little or no treatment.

Step 07.
Behavioural analysis

	Below is a list of questions about the potential residents of the neighbourhood you are designing	Select your answer from the drop-down list for each question	Rank 3	Rank 2	Rank 1
1	How aware are they of the relevance of decentralised greywater treatment systems?	Very aware		-	-
2	How do they feel about decentralised greywater systems?	They understand the necessity for such systems but are slightly sceptical about how they work			-
3	Considering that hygiene standards are met, how would the residents feel about using treated greywater for washing clothes in a washing machine?	They would happily accept it if my clothes do not smell unnatural after washing		-	-
4	Do they already check the ingredients of soaps and detergents when they buy them?	Yes, they are vaguely aware of the relevance of specific ingredients			
5	Are they convinced about not urinating in the shower?	No			
6	Are they relatively more conscious of water consumption than other typical groups of people?	No they tend to consume more than what they really need			
7	Would they be willing to share a laundry room in the neighbourhood instead of having a private washing machine in each house?	Maybe			-
8	Would they be inclined to talk about greywater and rainwater treatment?	No, they will probably not discuss it unless the system malfunctions badly			

Step 07.
Behavioural analysis

9	Considering that hygiene standards are met, how would they feel about using treated rainwater/greywater for showering and washing hands?	They would happily accept it if the water does not smell unnatural	-	-
10	How do they feel about the use of drinking water for flushing toilets?	They think it's a waste of water	-	-
11	Have they used toilets that consume lesser water than typical flush toilets?	One or two times		
12	Would they be willing to use composting toilets on a daily basis?	Yes, they are willing to use composting toilets if the smell is not too bad	-	-
13	Are they accustomed to using non-drinking water for domestic purposes?	For a few years	-	-
14	Are they accustomed to not receiving continuous domestic water supply?	For a few months	-	-
15	Are most of them accustomed to water use/management similar to your intended circular design?	No		

Step 08.
Behavioural influence strategies

Based on your responses, a rank is provided for each target of behaviour change. Rank 1 indicates more pro-environmental behaviour and requires relatively less persuasive behaviour change interventions. In contrast, rank 3 requires more persuasive behaviour change interventions in the design. Based on the rank for each target, a set of strategies is described, each with a guideline, an example and a link to an example project.

1 Reduce demand for drinking water — Rank: 2

	Guideline	Example
Strategy Part 01: Feedback	Establish relative ranking of residents Target factor: Social	Publicly rank users by their drinking water consumption.
Strategy Part 02: Steering	Provide visible real-time feedback Target factor: Attitude, Habit	Reduce shower water use by filling a visible tank before showerhead.
Strategy Part 03: Persuasion	-	-

2 Increase acceptance of treated greywater — Rank: 2

	Guideline	Example
Strategy Part 01: Feedback	0	(Incomplete in this version of the tool)
Strategy Part 02: Steering	Stimulate conversation about greywater Target factor: Social	Create social environments that encourage conversation about water.
Strategy Part 03: Persuasion	-	-

3 Increase acceptance of source-separation toilets — Rank: 2

Strategy Part 01: Feedback	Establish relative ranking of residents Target factor: Social	(Incomplete in this version of the tool)
Strategy Part 02: Steering	Stimulate conversation about toilet-use Target factor: Social Allow step-wise habit change Target factor: Habit	Create social environments that encourage conversation about toilets. Create a trial period for the use of such toilets in homes instead of a sudden shift.
Strategy Part 03: Persuasion	-	-

Step 09.
Potential environmental benefits

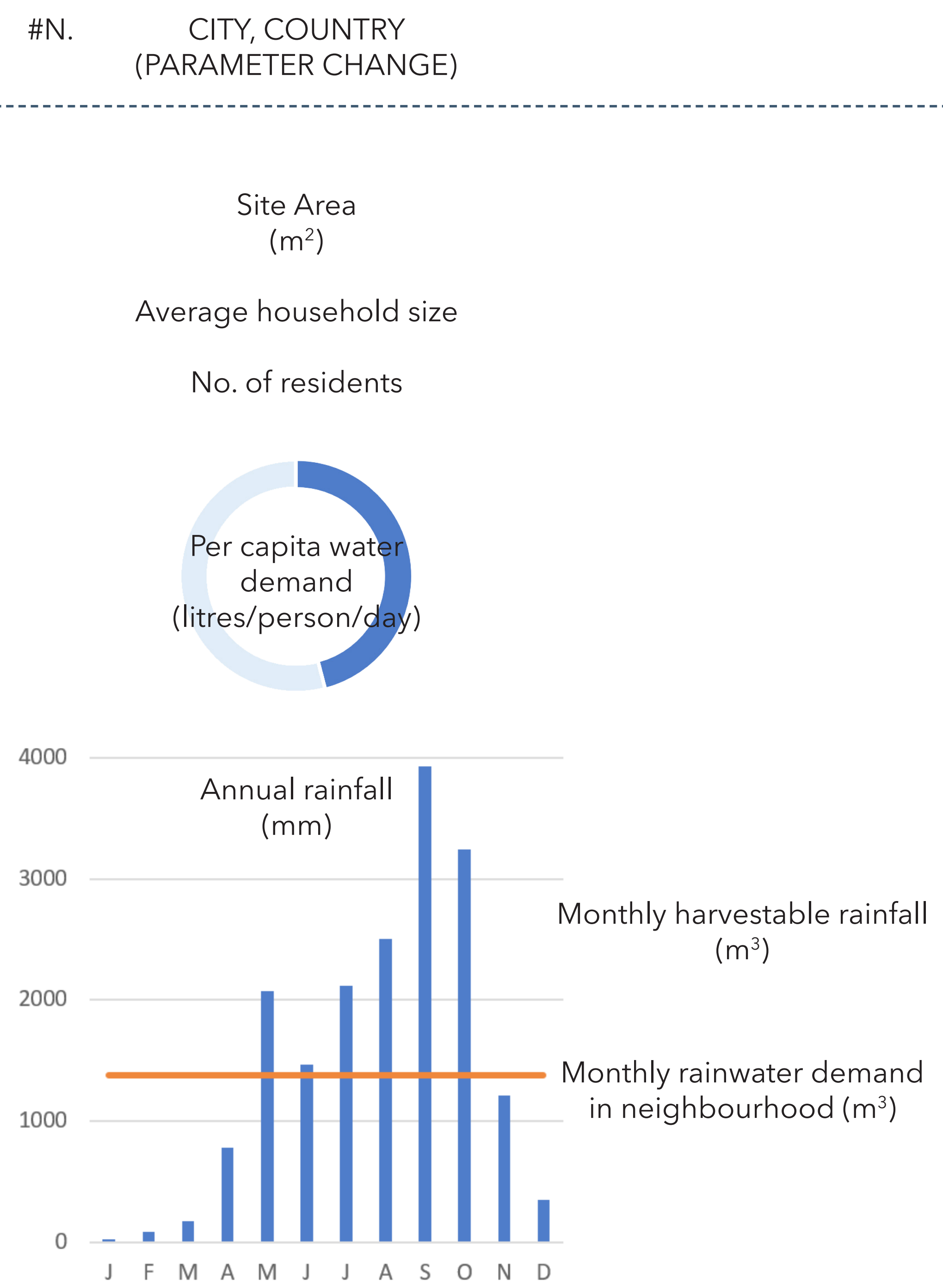
PROJECT NAME:	Enter a project name so you can keep track of potential multiple files for comparison

Recirculation Index	0.46			
Drinking water demand reduction	77 %	(compared to typical Dutch drinking water consumption)		
Groundwater recharge potential using rainwater	11 m^3/person/year			
Agricultural water potential using greywater	7 m^3/person/year			
Struvite produced	1.0 kg/person/year		Potential income	0.77 €/year
Local fertilizer produced	- kg/person/year		Potential income	€/year

TEST CASES

Complete development of the tool is possible only through trials and, as a start, four cases are compared here. The main purpose of these test cases is to arrive at an idea of the definition of water circularity for varying contexts, instead of basing it only on literature review. The tool allows the designer to change several parameters in each case and not necessarily in a strictly defined order.

Hence, the test cases described here along with subsequent ones help validate and refine the tool, apart from answering the core question in this thesis speculation. For all test cases, only technical strategies are compared. Behavioural strategies from the tool are independent of the technical strategies and have not been included. Subsequent tests should be done using actual projects so that actual resident groups can be considered in arriving at corresponding behaviour influence strategies.



Template of diagrammatic representations of simulations done using the tool (see next page).

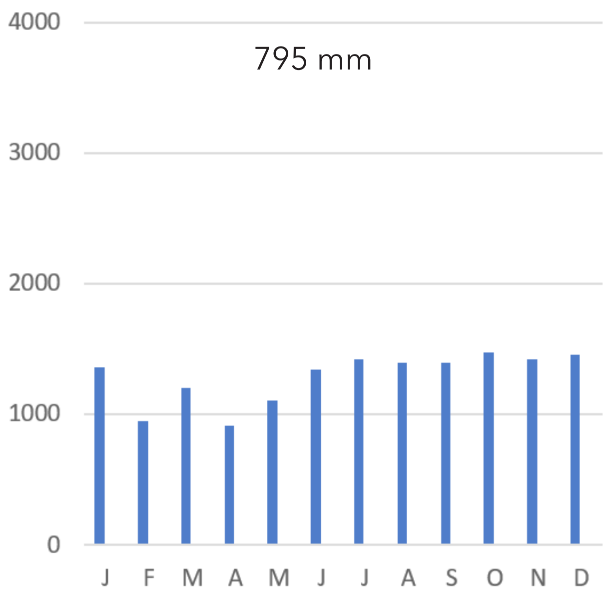
#1 CULEMBORG, NL (BUILT)

4,60,000 m^2
Site Area

2.4
household size

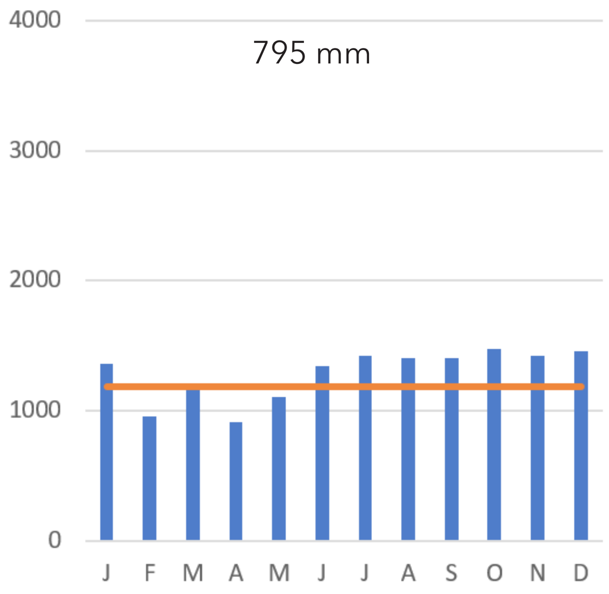
720 residents

-54%



#2 CULEMBORG, NL (CIRCULAR ALTERNATIVE)

4,60,000 m^2
Site Area



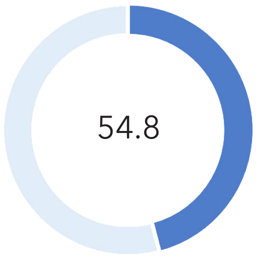
#3 BANGALORE, INDIA (INCREASE POPULATION DENSITY)

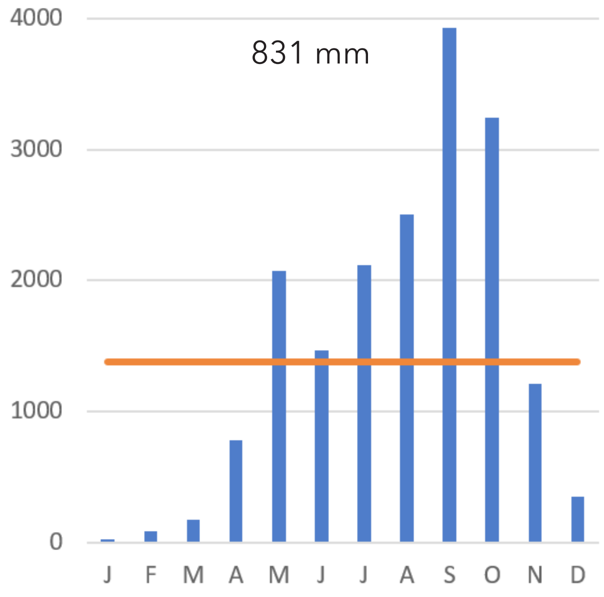
4,60,000 m^2
Site Area

+104%

4.9
household size

1470 residents





#1: One of the three neighbourhoods chosen as case studies in this thesis was chosen to start using the tool. This is a reference line as well as a way to check the functioning of the tool itself.

#2: The same site area, number of residents, rooftop catchment area and household size were taken as Test 01. Farming space was added (since the actual site also has a farm but is not in synergy with the neighbourhood water system) along with biomass-energy generation.

Shower water quantity is simulated to be relatively lesser, considering shorter shower time, frequency and water-saving showerheads. This, along with a urine-diverting vacuum toilet, resulted in a substantial reduction in overall water demand.

#3: For the third test, the same site area was considered but in a different climatic zone (Tropical Wet & Dry (Aw)). The local population density and household size was considered to arrive at the total number of residents and households.

The same shower water quantity is considered as the previous test. Farming space is considered to be available as a destination for recovered nutrients but biomass-energy generation and struvite precipitation are not included. The low-tech alternative of stored urine as fertilizer is included as a method of nutrient recovery.

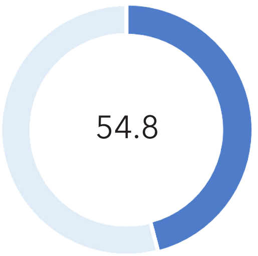
#4 BANGALORE, INDIA (DECREASE SITE AREA)

-99%

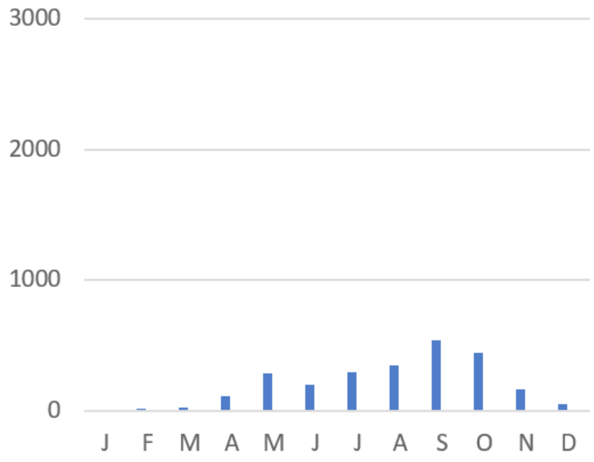
3,288 m²
Site Area

4.9
household size

1470 residents



831 mm



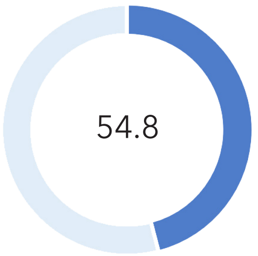
#5 WINDHOEK, NAMIBIA (DECREASE ANNUAL RAINFALL)

+99%

4,60,000 m²
Site Area

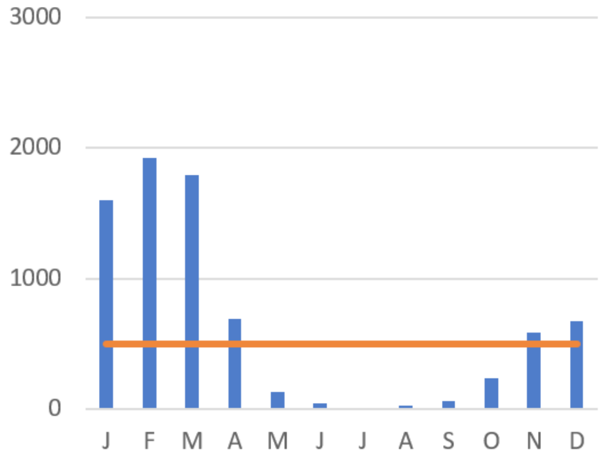
4.7
household size

1470 residents



-57%

359 mm



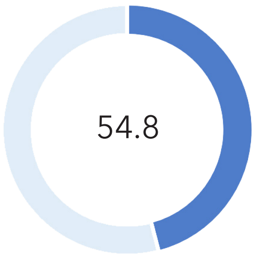
#6 WINDHOEK, NAMIBIA (DECREASE SITE AREA)

-99%

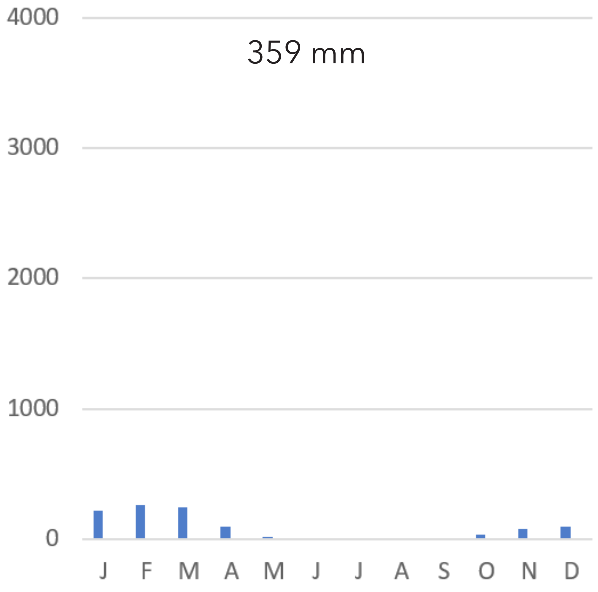
3,288 m²
Site Area

4.7
household size

1470 residents



359 mm



#4: The fourth test considered the same number of residents as test three but in a high-rise apartment of a single block instead of individual households. The number of residents per unit area of ground (and rooftop) is, therefore, much higher than the previous cases.

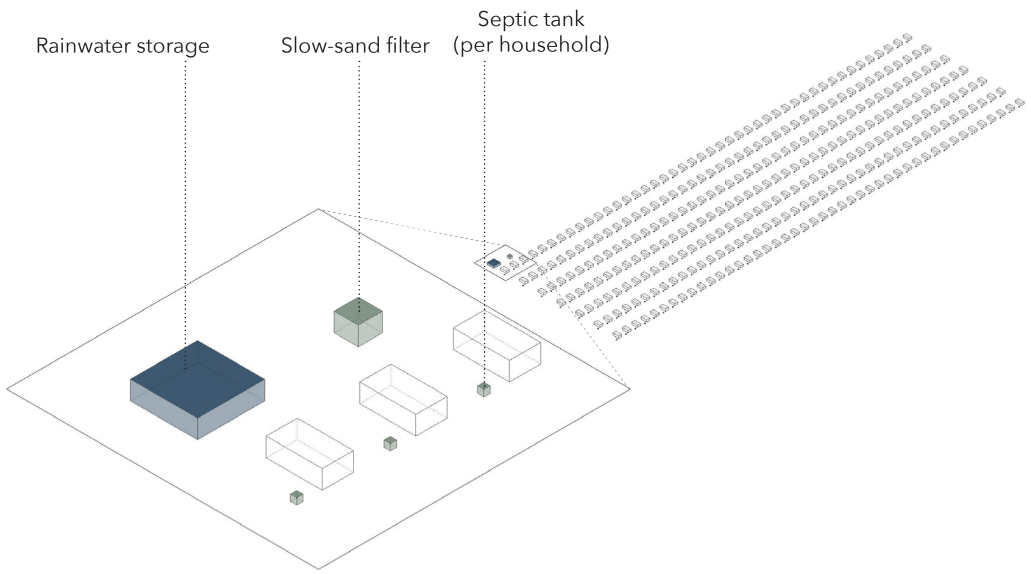
Farming space is not considered to be available since this is a simulation of a dense urban context. The absence of urine-diversion reflects in the absence of nutrient recovery apart from compost from anaerobic sludge.

#5: The same site area is considered as tests 1, 2 and 3, but in Windhoek, Namibia, which has an annual rainfall of 359 mm (Dry Semi-arid climate (BS)).

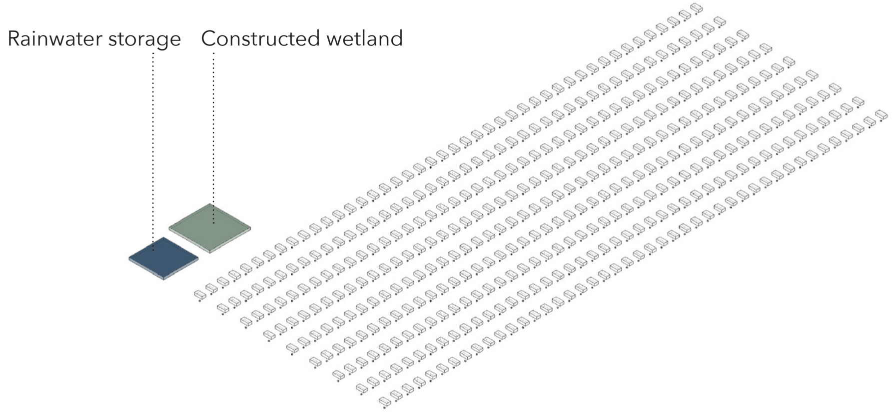
#6: The same site area is considered as test 4 but located in Windhoek. This simulation, hence, considers relatively extreme situations of high population density as well as low annual rainfall.

The next page shows a comparison of these test cases based on significant parameters that the tool can provide. Beyond the numbers of potential nutrient recovery, the tool also compares them to equivalents of industrial fertilizers, quantities of nitrogen, phosphorous and potassium recovered and, in case of energy, how many hours of a lightbulb can be lit with the stated biogas volume. Since these tests cases are only a start, only the significant parameters are compared.

TRIAL LOCATION	SITE POPULATION DENSITY (persons/km²)	SHOWER WATER DEMAND REDUCTION (l/person/day)	TOILET TYPE	FLUSH WATER DEMAND REDUCTION (l/person/day)	RECIRCULATION INDEX	GROUNDWATER RECHARGE POTENTIAL (m3/person/year)	AGRICULTURAL WATER SUPPLY POTENTIAL (m3/person/year)	STRUVITE POTENTIAL (kg/year)
#1 CULEMBORG, NL (BUILT)	1,565	49.2	Flush toilet	34.6	0.00	21.5	27.8	-
#2 CULEMBORG, NL (CIRCULAR ALTERNATIVE)	1,565	17.1	Urine-diverting vacuum toilet	2.2	1.00	1.7	16.3	725
#3 BANGALORE, INDIA (INCREASE POPULATION DENSITY)	4,381	17.1	Urine-diverting composting toilet	1.5	1.00	1.3	8.1	1485
#4 BANGALORE, INDIA (DECREASE SITE AREA)	4,47,080	17.1	Vacuum toilet	3.2	0.44	1.7	7.3	Struvite precipitation not considered possible
#5 WINDHOEK, NAMIBIA (DECREASE ANNUAL RAINFALL)	3,065	17.1	Urine-diverting composting toilet	1.5	1.00	1.8	1.1	1420
#6 WINDHOEK, NAMIBIA (DECREASE SITE AREA)	3,27,907	17.1	Vacuum toilet	3.2	0.44	0.8	7.5	Struvite precipitation not considered possible



Test 02: Relative sizes of rainwater storage, slow-sand filter, septic tanks and houses

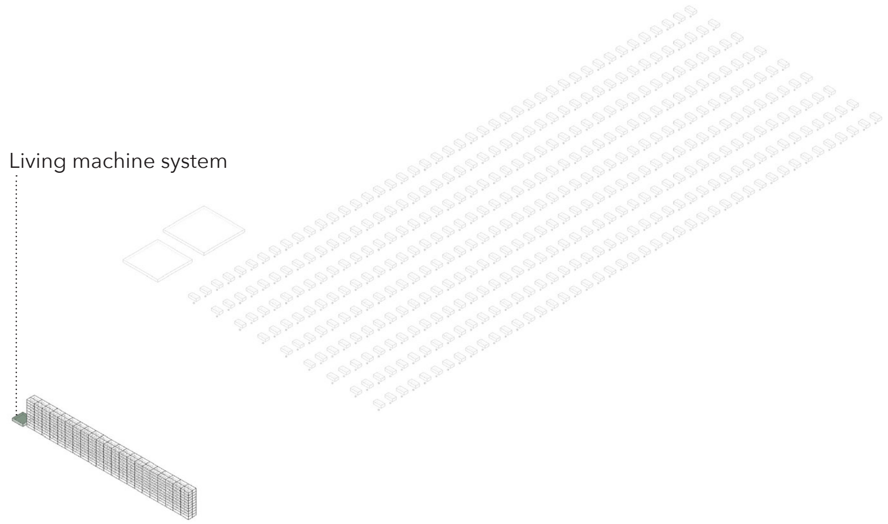


Test 03: Relative sizes of rainwater storage, constructed wetland and houses

Although not a primary function of the tool, these are schematic diagrams generated from the volumes calculated by the tool for each case of rainwater and greywater use. The purpose is to provide the designer an idea of the additional space needed for the required water infrastructure by comparing them to the footprint of the houses.

Although the tool generates two options for treating greywater - a space-efficient one and a space-intensive one, actual space requirements are indicated for both, along with cost implications. Regardless of the two terms, the designer has to determine if an otherwise tight site could still house a relatively larger system for its simplicity.

Cost parameters are included in the tool but the tool is limited in generating sufficiently indicative values since these systems are context specific themselves. Existing cost analyses of the systems are typically according to local labour and material availability, not to mention the vast differences in currency values. An attempt has been made to indicate the cost of one system (in test 3) as a percentage of the annual rent of a person, a parameter that can make costing comparable.



Test 04: Relative size of apartment block and living machine system for greywater treatment.
Test 03 is shown in grey for comparison of site area used to house the same number of residents.

RESEARCH RESULTS

1. How can circularity be defined for water systems in varying contexts of climate and water availability?

Circularity of water starts with identifying water sources available in the given site. Next, it is essential to define each domestic water need and the quality of water it demands, which depends on the nature of human contact with the water. A list of sources (with their availability) alongside a list of quality and quantity demands is then bridged by treatment methods. Treatment of a certain water type to meet a required demand quality, or for the cleanest purpose it is needed for to avoid complicated or impractical plumbing.

This thesis considers the availability of rainwater as a natural source on site. Since rainwater is a relatively clean water source and requires relatively lesser energy if collected at the highest possible point (compared to surface water and ground water), supplying domestic water should first be checked with rainfall availability. It is interesting to note that in one of the tests done using the developed tool, the entire neighbourhood, which currently uses only central drinking water, could be autarkic by relying only on rainwater.

Non-water related parameters play a significant role in determining the ratio of water demand and supply. Rainwater harvestability, in some cases regardless of the annual availability, can be highly limited by the area available for its catchment in comparison to the number of residents relying on it. Places in arid and semi-arid climatic zones may not include infrastructure for rainwater since its supply could only meet a very small fraction of the demand. In places where only a certain amount of the demand can be met by rainwater, the next local source is greywater. Although it requires more sophisticated treatment compared to rainwater for the same purpose, it is a source that occurs in constant quantity throughout the year, unlike rainfall in most places.

It may seem that greywater is an assured source, at least in terms of quantity to begin with. However, it is possible that with drastically reduced shower water use, a part of the treated greywater could turn into blackwater (through kitchen and toilet use), requiring another source to meet this resulting deficit. At this point, it can be said that the circular-water-limit for the population of the site has been crossed and needs to be reconsidered.

2. How does the experience of water infrastructure by users influence their resource consumption habits?

The term ‘water infrastructure’ is, in fact, much more than the physical built environment. It has as much to do with technical functioning of the systems as the network of people who rely on it. Visibility of a system is not necessarily literal visibility but also how much attention it gets during social interaction of residents. A specific intention from the project developer could lead to specific behaviour of the residents through an internal organisation system. This forces residents to talk about the neighbourhood resource network rather than ignoring it to be ‘not their responsibility’.

Although ensuring desired behaviour towards resource consumption is a multi-layered process, the mere visible presence of elements becomes a point of subconscious confrontation. Perception leads to cognition and cognition leads to behaviour, but what people perceive is often not very obvious and can also be subjective. The ‘ambience’ of the built environment establishes a certain idea of the place over a period of time. All that is intentionally hidden from sight and other senses, hence, is a void in what is otherwise a complex network of resources sustaining daily urban lives. Shared responsibilities in the neighbourhood related to resources have a significant impact on the sense of ownership for it. Responsibility forces understanding, which then leads to improved attitude, affect and, eventually, habits.

Aspects of human behaviour in various topics are not mutually exclusive. If a person tends to be conscious of their energy use, they also tend to be less wasteful of food, clothing, etc. it is more likely than not that they would extend such behaviour to other resources as well. Although the behavioural intervention strategies arrived at in this thesis are categorized into three specific aspects of domestic water systems, the process of behaviour change may not be so clear-cut and linear. One intervention could influence another aspect as well, and mostly be aligned with rather than contradict it.

3. What environmental benefits can a circular water system provide and how can these be measured?

Prior even to establishing the environmental goals of water systems, it is necessary to understand that this responsibility is equally that of implemented technology as it of the people who use it. This means that circularity of water is not only about water sources and treatment methods, but also about circular behaviour of people who rely on the technically circular system.

As described in earlier chapters, environmental goals of circular resource networks are defined in response to continuous environmental impact of linear resource networks. If surface water quality is degraded by discharge of nutrients into it, the environmental goal would be to recover the nutrient before it enters the water environment. The growing entropy of phosphorous is one of the more incumbent global issues in this century and domestic waste-water management shows considerable potential in creating local and renewable phosphorous sources.

The goal of maintaining surface water quality is expressed, in the tool and as a research conclusion, in terms of local fertilizer generation, since this is a much more relatable parameter for a project developer or designer or even the residents. Nutrient recovery in this form is directly related to maintaining water quality and, in any case, the agricultural and insutrial impact on surface water is far more than domestic waste-water. Circular water systems including behavioural influence strategies are more likely to successfully control the use of personal-care and household products since closed loops brings micro-nutrients back to the user, causing them to be necessarily concerned about what they use. The same logic can be applied to the use of pharmaceuticals but this is slightly more complicated since the use of allopathic medication is now ubiquitous and strongly related to public health. Still, decentralised waste-water managment has shown a higher possibility of extracting these micro-nutrients than centralized systems.

Local energy generation from biomass can contribute to a fraction of the renewable energy demand but, more importantly, it provides a way of managing domestic biomass waste in places where discharge through piping is not an option. Hence, although this is termed and compared as an energy aspect, it has its roots in preventing discharge of pathogens and nutrients into water ecosystems. Both local energy generation and local fertilizer production have the potential to contribute to the local economy, which could also have potential social benefits where self-sustenance through local employment can be enabled.

Reduction in the demand for central drinking water is not a solution to be imposed on places where infrastructure for its supply is well-established and provides affordable drinking water, which is the case in most of the Global North. However, it is necessary to impress upon other parts of the world and necessarily autarkic situations that central drinking water need not be the most-aspired-for solution where local supplies exist. Specific details of the environmental impact of central drinking water are strongly related to the energy required for large-scale pumping and treatment and perhaps the water needed for that energy generation. This thesis does not go into such specific details, due to which specific benefits of local water supply are expressed only in terms of the drinking water not required for a neighbourhood's sustenance.

Hence, a more comprehensive list of environmental benefits would require more specific data about embodied water and energy for the sustenance of a neighbourhood. The ones described in this thesis are only a start. Therefore, the goals are also stated individually rather than attempting to combine them into a single factor for ease of comparison.

CONCLUSION

The aim of environmental benefits through technical and behavioural circular strategies was defined as the start of this thesis: How can a circular water system including pro-environmental behaviour among users effect long-term environmental benefits?

To sum up and provide a short answer to this question, each aspect of water circularity is a combined result of the interaction between the resource and the user. In this range of interaction, the success of some solutions relies largely on technical functioning of the system, and some others lie in the behaviour of the user with the resource. For each solution, the first potential factor for failure should be understood. Such a factor could tend closer to either end of the spectrum. Both ends of the spectrum and their relationship with each other needs to be defined, within which potential circular water solutions are present. Extending this approach to the design of other resource networks would enable increasingly significant benefits for the environment and create a population that is sufficiently-informed of and involved in the network that sustains it.

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