Wastewater Reuse in Food Production Systems for New Sustainable Urban Developments

Bohdan Jess Dakota Daw Davies

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Unit Coordinator – Dr. Gareth Lee

Academic Supervisor – Dr. Ralf Cord-Ruwisch

School of Engineering and Information and Technology

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This paper is submitted to the school of Engineering and Technology and IT as the final report, to fulfil the requirements of the ENG470 Engineering Thesis.

I, Bohdan Jess Dakota Daw Davies, formally declare that the work in this paper is that solely of my own, except where the work of others is noted by reference. No part of this work has been submitted elsewhere, or completed for other course work at Murdoch University or any other institution.

Signed

Bohdan Jess Dakota Daw Davies

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Urban housing developments face growing pressure from the public and regulatory bodies to be more sustainable in their built form, energy and water consumption. This is currently achieved through application of better building design and implementation of various technologies to reduce environmental impacts. However, the aspects of food production and wastewater treatment and reuse, are not common aspects of these new developments in Western Australia. Designing these features into new residential developments could bolster resiliency, whilst also decreasing the net ecological footprints of these sites, and urban areas as a whole.

This project's focus is on the fundamental limits of nutrient cycling, derived from wastewater, to produce food in new urban developments. Variables of waste nutrient inflows of phosphorus and nitrogen were the primary focus, but factors of locality, water, energy and community acceptance were developed. The paper presents system metrics appropriate for the case study; Landcorp's White Gum Valley (WGV) a residential urban development in Perth Western Australia.

Key findings of the study showed urine separation offering the most beneficial method for nutrient reuse for food production in new residential urban developments. The modelled case study of a urine reuse system giving a potential food production output satisfying 3.5% of the population's total dietary metabolic energy needs, this being 98% of the recommended vegetable intake for the population. This production potential projected to be achieved with a capture of ~40% of the total populations production of urine and utilising 0.25ha of land area. With a number of assumptions, ~44000MJ/Y and ~935kl/Y of energy and water respectively may be saved from the implementation of such a system. The proposal of closed containment of urine throughout the separation and reuse scheme, alleviates odour issues before application, and reduces human pathogen and virus exposure risks. Payback periods of such a system are projected to be >24 years though are highly dependent on the marketability of food produce grown with human wastewater. The feasibility of such a
project with marketability of produce will require further market investigation; however the value of creating closed loop nutrient cycles goes beyond financial gain, and is suggested as a way forward in creating sustainable urban developments.
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“By agriculture only can commerce be perpetuated; and by Agriculture alone can we live in plenty without intercourse with other nations. This therefore is the great art, which every Government ought to protect, every proprietor to practice, and every inquirer into nature improve.”

- Dr Samuel Johnson 1709-1784
Abbreviations

EFWW - Energy Food Water Waste nexus

EPA – Environmental Protection Authority

GHG – Green House Gas

MFA – Mass Flow Analysis

N – Nitrogen

NIMP – Nutrient and Irrigation Management Plan

P – Phosphorus

SCP – Swan Coastal Plain

TP – Total Phosphorus

TN – Total Nitrogen

UDT – Urine diversion Toilet

UDDT – Urine Dry Diversion Toilet

WA - Western Australia

WWTP - Waste Water Treatment Plant

WGV - White Gum Valley Development
1 Introduction

1.1 Background
The traditional industrial approach to energy, food, water and waste systems, globally, is leading to a vast array of resiliency, sustainability and environmental issues. These issues are complex, where the fundamental system techniques which have been developed from a focus on increasing economic outputs are very hard to break away from (Blay-Palmer 2010). Broad system changes, to reduce the linear use of water, nutrients and energy, will allow holistic sustainable systems in many different contexts to be created to sustain the growing global population (Lal 2013).

System stacking (many yields/functions from one system/element) such as that proposed by Mollison (1988), coupled with nexus systems design approaches (refer to Appendix A: The Nexus design approach) and striving for closed loop systems, may alleviate pressures on resource hinterlands and waste disposal sinks. Integrated food, water and waste systems in urban areas, are largely missing in Western Societies. A move to regarding all waste products as resources can only have beneficial outcomes in terms of sustainability when coupled with holistic designed systems.

1.2 Research project context
The global network of urban forms connected through highly developed transportation systems, is termed; the anthroposphere. The anthroposphere is considered to act in the biosphere and is evolving constantly, with functions akin to a living system, similar to that of plants, animals and ecosystems (Baccini and Brunner 2012). The anthroposphere consumes, stores and discharges products, acting as a facilitator for the mass and chemical transfers, between the earth systems of the geosphere, lithosphere, hydrosphere and biosphere (Baccini and Brunner 2012). The studies of these material and energy flows is crucial in understanding, sustainable development, climate change, resource scarcity and urbanisation metrics, with all major global issues having complex relationships to these points (Baccini and Brunner 2012).
The study of the metabolic flows (mass and energy) through urban areas gives the data necessary for sustainability accounting, with aspects of GHG emissions, waste discharges and storage of materials being of key interest (Kennedy, Pincetl and Bunje 2011). Incorporating economic models to studies of the urban metabolism can also lead to the development of better policy design, giving broader improved outcomes, directing design away from “end of pipe” solutions to more holistic solutions and outcomes (Kennedy, Pincetl and Bunje 2011).

Most cities are growing in population and consumption; this is amplified spatially by increasing population densities and the spending power of residents, with over 50% of the global population now living in urban areas (Baccini and Brunner 2012). Higher population density does increase efficiency of use of individual materials, however the supply of goods, energy, and water and the need for treating/disposing of the by-products post-consumption, is a problem most urban environments face (Baccini and Brunner 2012). Due to technological innovation and economic prosperity the growth in goods supply and raw materials redistribution has seen exceptional and constant growth patterns (Baccini and Brunner 2012). Understanding the metrics of the urban metabolism and the capability of creating resources from waste products as feedstock for other processes will greatly increase the sustainability of urban areas.

1.3 Methods

1.3.1 Literature Review Approach

A plethora of studies have been conducted on the reuse of wastewater and/or its decentralised treatment, however the implementation of such projects in urban developments is limited in Australia. To understand why this is the case, an aim of the study was to investigate aspects of urban; food production, water use and wastewater seperation and treatment technologies. This review leading to an understanding of better systems to sustain the urban metabolism.
1.3.2 Modelling

A modelled case study of wastewater reuse in a food system for a new sustainable urban residential development addresses some of this gathered literature review information. This case study of a new residential development in the Perth (WA) Metropolitan area is presented to show the outcomes possible from higher reuse of wastewater for food production in urban areas. Project implementation is often debunked by economic analysis in this realm; therefore the proposal of simple passive systems is utilised in design, with economic analysis as a focus. Assumptions for dynamics of the reuse system are derived largely from literature. Site metrics for the case study and the use of fundamental relationships of mass and energy balance were used to determine the limits of reuse of wastewater in food production.

1.3.3 Prototype Trials

A small scale recirculated wastewater hydroponics system was also simulated to bolster understanding in the limitations and potential of real world wastewater nutrient use in food production systems.

1.3.4 Objectives

The initial investigation of this report was the mass and energy flows through human built systems. This study was predominantly qualitative but gave insight to the broader issues and functions at play in urban areas in a global context. This lead into the following quantifiable objectives to focus this research project;

1. What are the fundamental limits of wastewater reuse in food production systems, using standard soil cropping, relating to the Swan Coastal Plain (SCP) (Perth WA)?

   • Can this system be further improved by the implementation of more efficient growing techniques in terms of water, nutrient and energy usage?
2. What are the destinations of applied nutrient flows (nitrogen and phosphorus) in these systems? Is this sustainable with long term application?

3. What are the potential food production outputs from these systems and does this equate to a potential revenue stream to show an economically feasible case for a wastewater reuse scheme?

4. What are the energy and water usage/savings for a proposed system of wastewater reuse in a food production system for the proposed case study?

2 Literature Review

2.1 Modelling Anthropogenic Systems

Modelling of the systems that make up the energy and mass flows of the earth has been conducted scientifically since the mid 1960’s (Kennedy, Pincetl and Bunje 2011). With the aid of technology advances in computational power, models can now be developed with high complexity, based on the flows in the anthroposphere, hydrosphere, lithosphere, atmosphere and biosphere (Boumans, et al. 2002). Modelling earth systems is a complex task with many different variables from a multi-disciplinary context affecting each facet of the ‘spheres’. The area of modelling anthropogenic footprints, nutrient flows, water flows and energy flows is well documented, however the utilization of this knowledge for designing new technologies seems lacking in many urban developments (Brunner and Rechberger 2004). Before the industrial revolution and even before the move of civilisations relying on agriculture to sustain grouped populations, the anthropogenic metabolism was nearly identical to the requirements of the human physiological metabolism, i.e. living as hunter gatherers (Baccini and Brunner 2012). Now that the consumption and turnover of resources is closely linked to economic growth, where many of these resources are known to be finite, the move away from these systems which promote this high turnover is required in the pursuit of sustainability (Brunner and Rechberger 2004).
'Climax states' can be seen in natural systems when an equilibrium of energy and resource flow is reached (Decker, et al. 2000), in the context of urban development, a look back in history to pre-modern cities gives examples of climax states being reached in the anthroposphere. In pre-modern cities the transport, harvest, and trade of resources was based on renewable practices, man (or animal) power, and sunlight as energy input (converted to food energy). The system limited spatially by transportation of resources by foot, a climax state reached due to the carrying capacity of the local landscape(solar resource conversion limited) (Decker, et al. 2000). With the advent of fossil fuel and technological innovation, the modern city development and resource flow use is now on a global scale. The modelling and portrayal of climax state being an interesting development surrounding sustainability, this climax state being achieved when there is a steady state of maximum utilization of available resources (renewable) and growth has ceased (Decker, et al. 2000). However, this state is hard to imagine in the current climate, though modelling these systems, will give insights into areas of key focus to reach this state or if it is possible at all.

2.2 Water

"Human history is more or less the product of successful water control, through which fundamental human needs could be met, such as everyday household water supply and then requirements of crop irrigation to supply food to the population." (Falkenmark and Rockstrom 2004)

Water flows through the biosphere can be classified as two broad types of flow; blue or green, blue flow being the precipitation that is in visible flowing water form, above or below ground, which makes its way through terrestrial ecosystems to the ocean, this is estimated to be roughly 1/3 of all terrestrial precipitation (Falkenmark and Rockstrom 2004). Green flow is in general the water vapour portion either directly evaporated to the atmosphere or transpired through biomass (Falkenmark and Rockstrom 2004). Generally the anthropogenic management of water for agriculture and sanitation/consumption, views only blue water resources, however, 60-70% of food production is estimated to be derived from rain fed agricultural (Falkenmark and Rockstrom 2004). Therefore
when looking at food security for a growing population the ‘business as usual’ approach to water management; increasing blue water flow, for irrigation to support larger agricultural operations, may not be the secure option, as aquatic ecosystems are increasingly pressured from the current anthropogenic demand (Falkenmark and Rockstrom 2004). A move to increase the efficient reuse of wastewater streams in urban areas in urban food production can reduce the pressures on blue water flow, whilst increasing food and water security.

Rainfall patterns, on a global context, can be used to gauge the importance of broad water management, the origin of rainfall depends on the locality of the region, coastal regions rely heavily on oceanic evaporation, this accounts for about 40% of total global precipitation, whereas 60% is derived from terrestrial (green flow) vapour produced from land surfaces (Falkenmark and Rockstrom 2004). Therefore there is an importance of careful management of broad landscapes, ensuring the landscape function continue to support the biosphere (supported by rainfall) and subsequently the anthroposphere (Falkenmark and Rockstrom 2004, 25-44). Better management will give more productive landscapes, from biosphere reuse of water (the green water cycle loop). With good planning and action regenerating ecological function in vastly disturbed landscapes across the globe maybe possible, where decentralised wastewater treatment and subsequent reuse can play a role in this goal, in greening urban areas.

The global average use of water for food amounts to approximately 1300m³/PE/Y, Falkenmark and Rockstrom (2004) claim this figure as being nearly 10 times that of any other water use. The fresh water supply is currently decreasing in quality and quantity as a global trend, with a growing population, an estimated increase of required water flow presented by Falkenmark and Rockstrom (2004), to feed the globe is approximated to be 3300km³/Y by 2050. This volume is almost as large as the direct current blue water withdrawal globally, therefore the move to increase food production must lie primarily in the increase of efficiency of food production per unit of water input in the current cultivated arable land. The move to virgin agricultural land is another solution but is fraught
with many obvious issues of deforestation, lack of infrastructure/markets, resources, land toxicity etc. due to these issues, it is not considered as a viable option (Falkenmark and Rockstrom 2004). The goal of increasing food production per unit of water can also be achieved by recognising wastewater outputs as a water resource especially in concentrated population urban areas, giving an avenue for agricultural development in these urban environments.

2.3 Energy

Energy and chemical flows are the basis of all ecosystem functions, the conversion of solar energy into biomass with the use of minerals and elements to make these biological structures is what supports this life (Pimentel 1984). Studies performed by anthropologists on ancient people such as the !kung bushmen of Dobe Botswana, have shown the bushmen’s energy conversion in harvesting and shelling a particular nut species, would outlay an energy ratio of 1:4 (Pimentel 1984). As humans moved further away from nomadic ways of living to more stationary lives, different forms of agriculture were developed. With energy ratios of slash and burn techniques: 10.7:1 (corn grain), ox or horse techniques: 3-4:1 (corn grain), fossil fuelled machinery and high embodied energy nutrient, pesticide, and herbicide techniques: 3.5:1 (corn grain)(Pimentel 1984). The utilisation of higher energy input to the food energy output seems like a drastic issue when deliberating on sustainability. The use of energy efficient technologies and designing passive systems for food production (low to no external energy input), will be a pathway to reducing this ratio to a sustainable level (moving towards <1:1). With the increase in locally produced food in urban environments, transportation energy will be drastically reduced, with wastewater nutrients the embodied energy of fertiliser nutrients and water for such production, will also reduce energy input.

2.4 Food

33.1% of the world’s land area is currently used for agricultural purposes, this represents an area of approximately $10^9 \times 4.9$ ha, out of the approximate total land mass of earth $10^9 \times 14.8$ ha, where most of the land not utilized for agriculture is only so because it is marginal or too far from
civilisation (Eswaran, Beinroth and Reich 1999). With the land area utilised for agriculture seemingly near its maximum without further degrading natural ecosystem functions, there is an issue with the projected required food production increase of 70% from 2007 production rates to meet the projected population demand by 2050 (Food and Agriculture Organization of the United Nations 2009). This production increase will be challenging to say the least due to its unprecedented nature, and coupled with other concerning factors such as; climate change, energy security and the unknown effects of food scarcity.

'Food Deserts' (areas with little access to affordable easy access to healthy food) exist in many urban areas globally as discussed in Blay-Palmer (2010). The intensive production of food on a more local community scale will diminish this scarcity of nutritional food at a low energy and economical cost. A barrier to moving forward with this, however, is that economic influence usually prevails as the most important factor of land development (i.e. residential and business space over food production and ecological function). It is speculated in Eswaran, Beinroth and Reich (1999); that the land-soil classified as 1 and 2 (most productive and resilient soils, and where cities are generally built upon) could support approximately 9 billion people, showing that lands of which urban areas are built on, could be utilised much more productively in supporting the population which resides there. This gives two avenues of progression - the development of economically viable systems of food to compete with other land use developments, or, reform in the basis of economic development being the most important aspect of land development. A focus on developing environmentally sound systems, which have economic prosperity as a key focus, maybe the way to intensify the implementation of new food technologies. Though the embodied savings and identification of value of non-monetary outcomes of such systems, is also important to consider to make progress in the development of these projects.
2.5 Agriculture

Agriculture is a resource intensive activity (in the current general practise), with a focus on economic output, with a high proportion of eutrophication of watersheds and greenhouse gas emissions derived from this sector (Risku-Norja and Mäenpää 2007). Reform towards sustainable production will hold potential to reduce strains on the environment; firstly in the supply reduction of input resource, and then the subsequent reduction of negative outputs from their inefficient use such as watershed eutrophication from over fertilisation (Risku-Norja and Mäenpää 2007). Population growth in the new industrial age in the 19th century saw the first recorded decrease in agricultural yields in history, this due to increased harvest rates and a move away from the previously closely managed crop residue and manure application to manage nutrients in agricultural soils (Dawson and Hilton 2011). This decreased yield and the pressure of growing population brought about the advent of commercial phosphate fertiliser in the 1840’s and nitrogen from the Haber Bosch process in 1909, this brought yields back up, but further decreased the organic management of soil nutrients (Dawson and Hilton 2011). The careful management of agricultural soils to increase yields, needs to occur if the demand is to be met for the current population projections. With pressures of climate, transport costs and especially salinity in Australia; intensive urban food production will arguably be a growing industry to meet this need.

2.5.1 Phosphorus

During the past century the use of non-renewable phosphorus inputs to agriculture has steadily grown, the main source being mined rock phosphate. It is speculated that this resource maybe entirely depleted in the next 50-100 years where peak production is expected to be reached in 2030 (Cordell, Drangert and White 2009). It is inferred from data available on mining and general farming application rates of phosphate fertilisers, that 5 times the amount of phosphate is being mined compared to that consumed by humans (Cordell, Drangert and White 2009), with a predicted 90% of all phosphorus mined being used for food production globally (Smil 2000). It would seem more
careful management of a finite resource is required for the sustainable supply of phosphorus into the future is to be guaranteed.

Peak phosphorus is a concerning topic with regards to food security for the global population, crop yields are increasing yet one of the key elemental inputs to agriculture (phosphate) to obtain these higher yields is diminishing, with increasing price for a resource which will become lower in quality as supply diminishes (Cordell, Drangert and White 2009). As Cordell, Drangert and White (2009) stated "There are currently no international organizations or international governance structures to ensure the long-term, equitable use and management of phosphorus resources in the global food system." It is a grave concern that one of the key macro nutrients required for food production is being used inefficiently at rates that some literature foresees will not be possible in the next generation. It is obvious therefore that action needs to be taken on this, be it one of many, agricultural sustainability issues.

Contrary to the above information, however, a recent report on phosphorus reserves reported that the estimated reserve sits at approximately 300,000 million tonnes (U.S. Geological Survey 2015). Considering this far exceeds other recent projections, the pressure for reducing raw material use may be less of an issue. However geopolitical and human rights risks still pose a concern for guaranteed phosphorus supplies. This is particularly true for Australia which heavily relies on phosphorus imports to sustain generally low phosphorus containing soils (Australian Academy of Technological Sciences and Engineering (ATSE) 2015). Therefore, more sustainable use of phosphorus resources is still considered an important aspect feeding into current research, including the reduction of the embodied energy in fertiliser use, with 13.7 million tonnes of phosphorus fertiliser produced globally in 2006 (World Health Organisation 2006). With a projected average energy usage to produce this fertiliser of approximately 15MJ/kg suggested by (Wells 2003), therefore there is a substantial energy saving possible by reusing waste water derived phosphorus in food systems.
2.5.2 Nitrogen

Nitrogen (N) is closely related to nearly all biological reactions in some way, the addition of large amounts of N based fertiliser has been prevalent in agriculture for hundreds of years. Nitrogen is in seemingly unlimited supply in the atmosphere. However, fertiliser production through the Haber-Bosch process is energy intensive, with the best industry practice achieving 34MJ/kg\textsubscript{N}, giving N-based fertiliser production an energy usage of approximately 90% of the total input of all fertiliser production (Dawson and Hilton 2011). Passive gains of nitrogen can occur through microbial fixation of N\textsubscript{2} and by addition of small amounts of ammonia (NH\textsubscript{3}) and nitrate (NO\textsubscript{3}) in rain fall events. Losses occur through cropping, leaching to groundwater and volatilisation (Stevenson and Cole 1999).

Figures of fertilisers sold globally from 2006 show approximately 130 million tonnes in total sales. 78 million tonnes is nitrogen based, 63% of this was sold in the developed world (World Health Organisation 2006). This represents a very large energy sink. A suggested rate of 45MJ/kg\textsubscript{N} (Ledezma, et al. 2015) is required for the processing and transportation of N based fertilisers. Moving to close nutrient cycles where possible has the potential of vastly reducing this artificial fertiliser requirement, and therefore reducing the coupled energy and nutrient loss associated with their current unsustainable use.

2.6 Wastewater Reuse

Wastewater contains the essential macro nutrients to support plant growth (N, P, and K). If wastewater is used as the supply for at least a portion of the water and nutrient requirement, agricultural development could meet future demand with minimal strain, or even increased environmental integrity (Niemczynowicz 1999). The reuse of wastewater in agricultural applications is not a new development. Evidence of reuse of human excrement goes back as far as 3000BC to Mesopotamia and other regions of the ancient Nile and Indus (Ledezma, et al. 2015). The World Health Organisation (2006) also outlines how the reuse of wastewater aligns with the millennium development goals; Goal 1; eliminate extreme poverty, and Goal 7; ensure environmental
sustainability (World Health Organisation 2006). However the reuse of excrement in modern civilisations for the most part has become increasingly difficult; urbanisation has spatially removed populations from the areas of food production; potential pathogen development; and micro-pollutant transfer pathways, poses human health risks, hindering the development of reuse systems (Ledezma, et al. 2015).

The reuse of wastewater involves technical, social, environmental, cultural and political issues (World Health Organisation 2006). The wastewater treatment systems utilized need to be designed for the specific situation and location, the optimal solution will depend on the intended reuse of the treated outputs and the transport distance to the end use (Niemczynowicz 1999).

2.6.1 Wastewater reuse risk

In Australia the current wastewater system is generally by deep sewer removal treatment and ocean outfall discharge, leading to people being dissociated from their waste, and having a negative perception to its reuse. Frameworks such as the World Health Organisation’s Stockholm framework can give an approach to addressing these perceptions and risks, to give input to design for the safe reuse of waste streams. The World Health Organisation refers to the Stockholm Framework to combine risk assessment and management, proposing that if proper research and development of regulation for given situations is undertaken, the benefits of wastewater reuse can outweigh potential risks. For details on the process see Appendix B.

2.9.1.2 Wastewater Reuse in Australia

Water Corporation operates the majority of centralised wastewater services in WA, with only a small number (approximately 30) of council-run regional wastewater treatment operations (Turner 2006). Western Australia has committed to 30% reuse by volume of wastewater by 2030. Meeting this target is associated largely with the progression of a large scale aquifer recharge scheme for the Gnangara Mound, with trials commencing in 2010 at a rate of 1.5GL/Y. This water is treated to a very high standard with ultra-filtration, reverse osmosis and ultra-violet disinfection before injection
The expected peak volume of recharge is expected to be in the range of 70-100GL/Y. This volume is recognised by the Department of water to be a key player in reaching WA’s goal of 30% recycled water by 2030 (Marsden Jacobs Associates 2012). Other wastewater reuse schemes include the Kwinana water recycling plant producing 6GL/Y recycled water for industrial use, and the Subiaco treated wastewater irrigation of McGillvray Oval pilot project, being the main wastewater reuse projects in the Perth metropolitan area (Marsden Jacobs Associates 2012); (Turner 2006). The regional areas of WA however utilise a much higher proportion of wastewater flow in recycling projects. These include; Albany irrigating 575ha of blue gum plantation with ~4.5ML/day, Mt Barker; 140kl/day for vineyard irrigation, Broome; golf course and sports oval irrigation, Northam; parks and trotting track irrigation, Wyalkatchem; Bowls Club irrigation (Marsden Jacobs Associates 2012); (Turner 2006).

The reuse of wastewater nutrients is however far more limited, with the only centralised reuse scheme example being the distribution of biosolids from Subiaco, Beenyup and Woodman Point sewerage treatment plants to broad acre wheat belt farm application (Water Corporation 2015). However in general terms the reuse of centralised wastewater nutrients is difficult due to the mixed nature of the resource, having contaminants and varied quality, additionally there is the transportation cost for a resource that is not of high monetary value at current market prices of fertilisers. With smaller scale decentralised source separated reuse schemes, these issues may be nullified, giving a future progression of wastewater nutrient reuse in urban and regional areas of Australia.

2.7 Literature Issues in Summary

Decentralisation of agriculture systems coupled with reuse of wastewater streams in urban areas could hold potential in vastly reducing energy, water and agricultural issues, whilst also bolstering food security in urban areas. Technology and innovation in agriculture has helped in sustaining the population to its current level. The need now is to harness new innovation and improve on old
models in the reuse of anthropogenic wastewater allowing the closing of concentrated nutrient cycles found in urban areas, for productive benefit. Given the current climate of increasing population growth, world food security, water security and energy security the development of reuse of wastewater for food production seems like a logical path forward to sustaining urban populations, whilst reducing negative effects of the current systems.

2.8 System investigation

2.8.1 Urine Separation

Urine on average contributes 79%, 47% and 71% to the total N, P, and K respectively in household wastewater. In terms of volume this only represent 1% of total wastewater flow (Ledezma, et al. 2015). The use of urine as a fertiliser could replace the need for industrially sourced fertiliser products by 20% for the macronutrients N, P, and K globally, a figure projected by Ledezma, et al. (2015). This reduction in industrial produced fertilizer would represent a large energy saving for these nutrients, in terms of manufacturing energy and for transportation requirements. Nitrogen based fertilisers, have an embodied energy value of approximately 30-60 MJ/kg$_{N}$ (Ledezma, et al. 2015). Where once the subsequent food products are consumed the nitrogen for the most part is either discharged straight to the environment, or is processed through energy intensive wastewater treatment plants to be released back into the atmosphere (at an energy usage of approximately 45MJ/kg$_{N}$) (Ledezma, et al. 2015). With phosphorus fertiliser, the global average energy for fertiliser production is approximated at 15MJ/kg$_{P}$ by Wells (2003), and has an associated average energy usage for P precipitation processes in wastewater treatment projected at 49MJ/kg$_{P}$ as a global average (Maurer, Schwegler and Larsen 2003). With the reuse of urine derived nutrients the energy cost of fertiliser production and wastewater treatment could be greatly reduced, especially if reuse with minimal required treatment processes can occur (i.e. direct land application of urine).

The reuse of urine in western societies is seldom performed, although its use in agriculture can be seen in some parts of the world, such as the market gardens of some Chinese cities (Ledezma, et al.
Due to risks of odour, pathogen exposure, heavy metal contamination and hormonal and pharmaceutical medication transfer, the avoidance of reuse has led to the current general deep sewer discharge that is generally practiced in Australia. This has somewhat hindered the innovation of technologies for the application of urine treatment. However, innovation in technologies is creating some positive outlooks and enthusiasm in the industry in recent years (Maurer, Pronk and Larsen 2006).

The heavy metal concentration in urine has been assessed against other heavy metal sources in agriculture, either present in existing soils, or from inputs (fertilisers), by Maurer, Pronk and Larsen (2006). They show a much greater inflow from other sources in comparison to urine concentrations. Treatment technologies to remove pathogen contamination, such as storage techniques, offer simple solutions to reduce colonies of many pathogens (Maurer, Pronk and Larsen 2006). Micro pollutants (hormones and pharmaceuticals) pose a more complex issue in urine treatment, though techniques such as nano-filtration do offer the potential to highly reduce the micro pollutant loading whilst retaining the nutrient fractions important for fertiliser application (Maurer, Pronk and Larsen 2006). Continued research in the area of micro-pollutant treatment/removal is progressing, with these factors an important aspect for the safe reuse of urine for food production (Maurer, Pronk and Larsen 2006). With research on particular pollutant constituents feeding into frameworks of risk management, safe and resilient systems should be possible in the future.

With sufficient testing facilities and treatment technologies coupled with frameworks of risk management such as the Stockholm framework, the reuse of urine for nutrient input to agriculture could be safely achieved. Urine source separation and reuse offers the benefits of; reduced energy consumption (reduced fertiliser production and wastewater treatment), and reduction of environmental impacts from any nutrient discharges from centralised wastewater treatment plants. A move to decentralised household-community scale urine treatment systems offers a method of wastewater reuse with minimal transport cost and human handling/exposure.
2.7.1.1 Urine separating technologies

A number of methods of urine separation and treatment exist, the separation of urine can be achieved with dual cistern flush or dry diversion toilets, and urinal fixtures. A number of treatment technologies to reduce volume, pathogen contaminants and other micro pollutants whilst retaining the valuable nutrients for fertiliser use have been developed. Struvite precipitation by the addition of Mg salts is considered to be currently the most promising processes for N and P removal and volume reduction for source separated urine (Ledezma, et al. 2015). A review of likely technologies potential applicable for the case study focus of this report have been included below.

2.7.1.2 Struvite Precipitation

Struvite, magnesium ammonia phosphate (MAP), is a precipitate formed by the addition of Mg\(^{2+}\) (i.e. addition of salts such as MgCl\(_2\), MgSO\(_4\), MgO) to urine leading to the general precipitation reaction:

\[
\text{Mg}^{2+} + \text{NH}_4^+ + \text{PO}_4^{3-} + 6\text{H}_2\text{O} \rightarrow \text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O(s)}
\]

Although the stoichiometric values for Mg\(^{2+}\), \text{NH}_4^+, and \text{PO}_4^{3-} are equal in the precipitation reaction, the general proportions of these constituents in urine are 50-100:10:1, therefore the addition of magnesium salt for the effective precipitation of total phosphate is required (Ledezma, et al. 2015). Due to the molar ratios, the effluent urine, after struvite precipitation, still contains approximately 90% of the nitrogen. Therefore the process gives a potentially higher level of management for nutrient application in agriculture, by largely separating the N and P components.

In many urine separation and wastewater struvite precipitation case studies, it is well documented that phosphorus recoveries are generally between 90%-99% (Cordell, et al. 2011). Studies have shown various methods of increasing the N recovery, including the addition of Mg\(^{2+}\) and zeolite together, allowing the production of struvite and zeolite adsorbed ammonia products, giving approximately 90% N removal and 99% P removal efficiencies in lab scale tests (Ban and Dave 2004). Though where transport of urine products is not of concern (reuse of urine near its source), the volume reduction achieved via the addition of zeolite for a N nitrogen product may not be required,
and the associated additional savings of removing zeolite treatment, will give economic advantages to the proposed system.

2.8.1.3 Microbial Electrochemical Technologies (METS)

Microbial electrochemical Technologies (METS) is a method of biological ion transfer in a cell format for energy generation. The technology is a relatively new development for the treatment of urine. It is projected that nutrient recovery could occur for phosphorus from the precipitation of stuvite on the cathode (though it is difficult to remove), and nitrogen by the movement of ammonia and ammonium ions to the cathodic compartment through a cation exchange membrane (Ledezma, et al. 2015). The technology however is expensive and still in early stages of development. Therefore it is not considered further in this report.

2.8.1.4 Urine Storage and Hygienisation

Storage of urine at sufficient temperature, pH and time has been associated with the die off of potential pathogen contamination by Hoglund, et al. (2002). Risks of enteric viruses such as Salmonella typhimurium are considered to have a higher survival rate in stored urine in comparison to bacterial and protozoan pathogens as shown in Hoglund, et al. (2002). With sufficient storage temperature of approximately 20°C and pH ranges ~9 the risk decreases, with bacterial and protozoan pathogens below detection levels with storage in these conditions for 6 month holding times (Hoglund, et al. 2002). Potential issues with the use of storage of urine are mainly surrounding struvite precipitation causing blockages in piping and fittings.

2.8.1.4 Evaporation for Volume reduction

Evaporation techniques have been developed for projects requiring volume reduction for transport of nutrient constituents, and also in the case of NASA international space station, for recovery of water from the urine waste stream (Fewless, Sharvelle and Roesner 2011). Thermal energy wastage and loss of ammonia are the main restraints of this technique for nutrient
However, stabilization by acid addition to lower pH can reduce ammonia volatilisation rates to levels acceptable for its recovery through evaporation (Fewless, Sharvelle and Roesner 2011).

2.8.1.5 Ammonia Striping and subsequent absorption

Oxygenation of urine with optimized pH and temperature to induce ammonia volatilisation and subsequent absorption through sulfuric acid was tested in Kabakci, Ipekoglu and Talinli (2007). The product being an ammonia sulphate solution, maybe applied directly to land as a fertiliser (Fewless, Sharvelle and Roesner 2011). It is estimated this process could produce the nitrogen from urine into a fertiliser form at a rate of lose of approximately 8-10% of the nitrogen found in urine (Fewless, Sharvelle and Roesner 2011).

2.8.1.6 Micro-pollutant removal

There are a number of suggested methods for micro-pollutant removal, such as electrodialysis; the movement of ions contained in urine through selective ion membranes via an electro-potential difference (Fewless, Sharvelle and Roesner 2011). The membranes remove larger constituents such as pharmaceuticals which are left behind in the dilutant (Fewless, Sharvelle and Roesner 2011). Ozonation can be an added treatment to the resulting product for degradation of remaining micro-pollutants (Fewless, Sharvelle and Roesner 2011). Nanofiltration via pressure differential membranes can also remove larger constituents such as pharmaceuticals. However, tests with 001-003 μm pore size membranes were found to also reject phosphate. Therefore nanofiltration is not recommended for full nutrient recovery from urine, though there are prospects when the addition of struvite precipitation is included in the process (Fewless, Sharvelle and Roesner 2011).

2.8.1.7 Pathogens

The World Health Organisation reviewed study on the potential pathogen and bacterial risks associated with the reuse of urine. The main findings are outlined in Table 1: Summary of key pathogens and bacteria of concern from urine separation practices.
### Table 1: Summary of key pathogens and bacteria of concern from urine separation practices (World Health Organisation 2006)

<table>
<thead>
<tr>
<th>Pathogen</th>
<th>Urine as a pathway of infection</th>
<th>Risk Perception</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>E. Coli</em> and other faecal pathogens</td>
<td>Only from faecal contamination</td>
<td>Generally insignificant with adequate storage time</td>
</tr>
<tr>
<td><em>Leptospirainterrogans</em>, <em>Salmonella spp.</em>, <em>schistosomahaemotobium</em></td>
<td>Unusual to insignificant in well-designed systems</td>
<td>Low</td>
</tr>
<tr>
<td>Mycobacteria</td>
<td>Unusual</td>
<td>Low</td>
</tr>
<tr>
<td>Viruses – hepatitis</td>
<td>Hepatitis is of main concern with one reported case of infection through lettuce consumption</td>
<td>Probably low</td>
</tr>
<tr>
<td>Urinary tract infections</td>
<td>Non-transferable in reuse</td>
<td>insignificant</td>
</tr>
<tr>
<td>Sexually transmitted disease</td>
<td>Do not survive outside the body</td>
<td>insignificant</td>
</tr>
</tbody>
</table>

2.8.1.5 Pathogen life cycle in Soils

A study performed by (Nyberg, *et al.* 2014) found that pathogens can remain in soil horizons for a substantial time at small concentrations, after application of human urine and cow slurry. The results of field trials showed that the risk was higher with cow slurries than human urine, with trials showing positive tests to 50cm soil depth. No leaching of the pathogens was recorded even though rainfall events occurred over the testing period. With the addition of hygienisation through storage the effect of pathogens in soils will be further reduced. When coupled with appropriate risk management in application and minimizing soil disturbance after urine application, the pathogen risks to humans should be negligible (Nyberg, *et al.* 2014).

2.9 Striving for sustainability with food production systems

In striving for sustainable systems that incorporate food production, there is a need to understand recommended human nutrient intakes. Table 2 shows the assumed values for dietary needs of an average adult, giving a basis for the dietary requirements assumed for the population of WGV. A focus on the vegetable requirement of 300-375g/day has been taken (Kouris-Blazos 2011), over production of cereal, fruit and animal products, as vegetable production per land area has the fewest constraints in the urban environment.
Table 2: Core food groups recommended daily intakes for adults (19+ years) (Kouris-Blazos 2011)

<table>
<thead>
<tr>
<th>Food Type</th>
<th>Recommended g/day/person</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cereals (bread units)</strong></td>
<td>210g</td>
</tr>
<tr>
<td>Fruit</td>
<td>300g (2 medium pieces)</td>
</tr>
<tr>
<td>Vegetable</td>
<td>300-375g</td>
</tr>
<tr>
<td><strong>Meat and alternatives</strong></td>
<td>85g</td>
</tr>
<tr>
<td>35g cooked meat = 40g fish or one egg or 1/4 cup beans or 1/3 cup seeds/nuts</td>
<td></td>
</tr>
<tr>
<td><strong>Milk (or equivalent)</strong></td>
<td>450ml</td>
</tr>
<tr>
<td>250ml milk = 1/2 cup evaporated milk = 40g cheese = 200g yoghurt</td>
<td></td>
</tr>
<tr>
<td><strong>Total MJ/Person/Day (Adult)</strong></td>
<td>8.75-11.5</td>
</tr>
</tbody>
</table>

3 Case Study; White Gum Valley Development

3.1 Background

Landcorp’s White Gum Valley (WGV) is a residential estate development located in the Perth metropolitan area. The site has been awarded the first Western Australian One Planet Living recognition, for its focus on sustainability (Landcorp 2015). The site incorporates third pipe water connections for garden irrigation from a community bore, sustainable built form in design and application of appropriate technology to reduce energy and water consumption, and various stormwater management design aspects including; improved suburban infiltration basin design collecting stormwater runoff from the surrounding suburb, local street runoff infiltration basins, and recommendation for household collection and storage schemes. However the incorporation of wastewater treatment and reuse, and the provision for intensive food production on site is largely missing. Though a number of street fruit trees are planned for the site.

Nitrogen, phosphorus, potassium and sulphur (N, P, K and S) are the four major macro nutrients inputs required for agricultural production. S and K, however, are deemed to have comparatively unlimited supply, with minimal energy requirement for their effective application to the sector (Dawson and Hilton 2011). Therefore, a focus has been given to nitrogen and phosphorus for this study’s scope. Potassium figures are included in some tables and figures for the ease of future
reference. The Department of Water of WA presents guidelines for wastewater irrigation in the Water Quality Protection Note 22 and 33. For an outline of the key features of these notes affecting this project, refer to Appendix I: Water Quality Protection Notes

3.2 The White Gum Valley development

3.2.1 Site Metrics

3.2.1 Land area availability scenarios for crop production

In order to evaluate the possibility of the WGV development to effectively recycle phosphorus and nitrogen contained in wastewater, the site dimensions and areas by use have been quantified in Table 3.

There is no current household wastewater treatment or reuse provision at the site, though stormwater management with roof top collection systems is proposed. A 0.25ha area, currently appointed to be developed into public open space, has been identified as the most realistic and beneficial site for food production. In Figure 1: The shaded areas represent scenario 1 in red, addition of purple represents scenario 2 the red shaded area represents an area of 0.25ha. The site being a highly developed residential space, the area remaining for potential wastewater treatment and reuse on crop production is small. However, two other land use availability scenarios have been presented; scenario 1; 0.25ha as previously mentioned, scenario 2; 0.53ha being a larger fraction of WGV being released for the purpose of wastewater treatment and crop production, i.e. a portion of road reserves (in purple) and some residential backyard spaces (not depicted), scenario 3; 1.5ha as a much larger land area scenario presuming that nutrients can be transported to the nearby Booyeembara Park.
Table 3: The Metrics of the White Gum Valley Site (assumed from landscaping site plans)

<table>
<thead>
<tr>
<th>Population (Total)</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average solar irradiance (MJ/m²/day)</td>
<td>20</td>
</tr>
<tr>
<td><strong>Areas (ha)</strong></td>
<td><strong>Percentage of Soft Land</strong></td>
</tr>
<tr>
<td>Road reserve</td>
<td>1.1ha</td>
</tr>
<tr>
<td>residential</td>
<td>1.4ha</td>
</tr>
<tr>
<td>public open</td>
<td>&gt;0.25ha</td>
</tr>
<tr>
<td>lots</td>
<td>2.8ha</td>
</tr>
<tr>
<td><strong>Available for crop production</strong></td>
<td>Assumed</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5.55ha</td>
</tr>
</tbody>
</table>

² Soft land refers to land with no built form, i.e. grass or vegetated land, where infiltration of precipitation can occur.

![Figure 1: The shaded areas represent scenario 1 in red, addition of purple represents scenario 2](image)

3.2.1 Geomorphology and Site Soils

The White Gum Valley development lies on the Spearwood dune system soil association of the Swan Coastal Plain. The Spearwood dune system lies on the Tamala limestone formation, capped with a calcite rock layer, and overlain with varying depths of sand (McArthur 1991). The sand portion has
been highly leached. It is assumed to have a calcareous beach sand origin and now contains a high portion of decalcified siliceous sand with a pH varying between 5.82–7.81 (McArthur 1991), (Salama, et al. 2001). These soils are extensively used for market gardening. With additions of key nutrients and use of shallow aquifer irrigation these areas can maintain high vegetable yields (McArthur,1991).

3.2.2 Wastewater Nutrients Projection for WGV

The quantities of P and N are assumed constants for urine nutrient composition and the volumes produced by the average adult is seen in Table 4. These values are used throughout calculations for wastewater reuse and nutrient mass balances. Phosphorus and nitrogen available through the various waste streams at WGV are calculated by mass balance. The below equation shows the amount of phosphorus derived from urine in WGV given the assumed population (150 adults) and P content of urine (100% of urine produced).

\[
P \frac{kg}{Y} = \frac{L_{Urine}}{Person/day} * \frac{kg}{L_{Urine}} * Population * \frac{kg P}{L_{Urine}} * 365 \frac{days}{year} = 47.9 \frac{kg P}{Y}
\]

The same equation is used for the balance of N and is also applied to the faeces stream of wastewater (see Table 4). The results summarised in Table 4 are based on faeces containing 40% of excreted phosphorus, 10% excreted nitrogen and 35% excreted potassium (Heinonen-Tanski and Wijk-Sijbesma 2005).

To give reference to the potential of wastewater derived nutrients for a crop production system a comparison to standard fertiliser rates must be made, the assumed general fertilisation rates for Swan Coastal Plain (SCP) market garden operations and the number of crop cycles per year are seen in Table 5.
Table 4: Assumed Wastewater quantity and quality constants \(^1\) (Karak and Bhattacharyya 2011), \(^2\) based on percentage nutrient flows of wastewater from (Heinonen-Tanski and Wijk-Sijbesma 2005)

<table>
<thead>
<tr>
<th>Nutrient Content of Excreta</th>
<th>WGV Totals/day</th>
<th>WGV Total/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Urine</strong></td>
<td>1.25 L/Person/day</td>
<td>187.5 L</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>.7gP/L(^1)</td>
<td>131.25 g</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>9gN/L(^1)</td>
<td>1687.5 g</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>2gK/L(^1)</td>
<td>375 g</td>
</tr>
<tr>
<td><strong>Faeces</strong></td>
<td>136 g/Person/day(^2)</td>
<td>20.5kg/day</td>
</tr>
<tr>
<td>Phosphorus (P)</td>
<td>4.45 gP/kg(^2)</td>
<td>90.9 g/day</td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td>9.56 gN/kg(^2)</td>
<td>195.1 g/day</td>
</tr>
<tr>
<td>Potassium (K)</td>
<td>10.28 gK/kg(^2)</td>
<td>209.9 g/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Combined Waste Streams Totals WGV</th>
</tr>
</thead>
<tbody>
<tr>
<td>P kg/Y</td>
</tr>
<tr>
<td>N kg/Y</td>
</tr>
<tr>
<td>K kg/Y</td>
</tr>
</tbody>
</table>

Table 5: The assumed crop cycles and standard fertiliser application rates

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crops Per year</td>
<td>2 (6 months summer crop), (6 month winter crop)</td>
<td>Assumed</td>
</tr>
<tr>
<td>Phosphorus Fertiliser Application Rates</td>
<td>126.9 kgP/ha/Y</td>
<td>(Department of Water WA 2015)</td>
</tr>
<tr>
<td>Nitrogen Fertiliser Application Rates</td>
<td>972 kgN/ha/Y, 486kgN/crop</td>
<td>(Lantzke 2015)</td>
</tr>
<tr>
<td>Nutrient Application Rates Suggested maximums</td>
<td>120kgP/ha/Y, 480kgN/ha/Y</td>
<td>(Department of Water WA 2008)</td>
</tr>
</tbody>
</table>

3.3 Soil Based Cropping Nutrient Application

3.3.1 Phosphorus Dynamics

To estimate the potential for WGV to apply wastewater derived phosphorus to crop production, literature has been cited for standard application rates of P in agriculture practise, see Table 6. An assumed rate of 126.9kgP/ha/Y has been taken as a lower end market garden application rate and used as a base for this report.120kgP/ha/Y is suggested as a maximum for application of nutrient rich wastewater irrigation by Department of Water WA (2008), but is not based on market garden
applications. Table 7 shows the summary of initial modelled P flow results, using the assumed application rate with the land use scenario 1; 66% of urine derived P could be applied for crop production.

Comparatively if a higher maximum considered application rate of phosphorus is assumed, 340kg/ha/Y (85kg for .25ha) taken from (Environmental Protection Authority Perth 1992). At this rate application of 100% of the available phosphorus in wastewater flows from the site could occur. However further site investigation and intensive operations would have to be in place to ensure no adverse environmental impacts from rates above 126.9kgP/ha/Y, where the EPA is the authority on the granting of NIMP’s (sufficient evidence that no adverse environmental impact will occur has to be presented for NIMP approval). Fertiliser application rate examples for different land uses on the SCP are shown in Table 6 for reference.

The yield of phosphorus for a number of horticultural crops common on the SCP can be seen in Table 8. Of particular interest are cauliflower and tomato crops for this study. Assuming two cropping cycles per year (cauliflower over winter and tomato over summer), these crops were used for all subsequent modelling. It is suggested in literature that harvest times for both these crops are generally within 60-120 days of seedlings transplant (dependent on transplant age), therefore two crops should easily be achievable per year, whilst also allowing cropping area to go fallow or “rest”. The modelled phosphorus yield in the edible/harvested portion given average SCP yields is 10.8kgP/ha/crop and 8.8kgP/ha/crop for tomatoes and cauliflowers respectively. Edible yield is only accounted for as a phosphorus output, as in the pursuit of a more sustainable agricultural practise it is expected that crop residues would be kept on site to increase the integrity of nutrient management practise.
Table 6: Phosphorus application rates found in literature

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Land Use</th>
<th>kgP/ha/Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dep. Water WA</td>
<td>Swan Coastal Plain</td>
<td>Annual Horticulture</td>
<td>126.9</td>
</tr>
<tr>
<td>Dep. Water WA</td>
<td>Swan Coastal Plain</td>
<td>Urban residential</td>
<td>26.4</td>
</tr>
<tr>
<td>Dep. Water WA</td>
<td>Swan Coastal Plain</td>
<td>Piggery</td>
<td>144.7</td>
</tr>
<tr>
<td>EPA WA 1 Highest rate</td>
<td>Swan Coastal Plain</td>
<td>Market Gardens</td>
<td>600</td>
</tr>
<tr>
<td>EPA WA 1 High Rate</td>
<td>Swan Coastal Plain</td>
<td>Market Gardens</td>
<td>214</td>
</tr>
<tr>
<td>EPA WA 2</td>
<td>Swan Coastal Plain</td>
<td>Market Gardens</td>
<td>530</td>
</tr>
</tbody>
</table>

Table 7: Phosphorus application rates given different land area scenarios based on 126.9kgP/ha/Y

<table>
<thead>
<tr>
<th>Waste Stream</th>
<th>Scenario 1 Area 0.25ha P kg/Y</th>
<th>Scenario 2 Area 0.53ha Acceptable Rate¹ kgP/ha/Y</th>
<th>Scenario 3 Area 1.5ha Acceptable Rate¹ kgP/ha/Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine</td>
<td>47.9</td>
<td>91.25</td>
<td>31.9</td>
</tr>
<tr>
<td>Faeces</td>
<td>31.9</td>
<td>60.83</td>
<td>21.3</td>
</tr>
<tr>
<td>Combined</td>
<td>79.8</td>
<td>152.08</td>
<td>53.2</td>
</tr>
</tbody>
</table>

Table 6: Results of phosphorus balancing through a number of example crops (AusVeg 2015), (Henderson and Dimsey 2009), (Wade 2009)

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>% mass phosphorus ¹ (The United States Department of Agriculture 2011)</th>
<th>Assumed maximum yield T/ha/crop</th>
<th>Phos. yield kg/ha/crop</th>
<th>Phos. yield kg/ha/crop 0.25ha proposed growing area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broccoli</td>
<td>0.00066</td>
<td>7.1²</td>
<td>4.686</td>
<td>1.1715</td>
</tr>
<tr>
<td>Cabbage</td>
<td>0.00026</td>
<td>37³</td>
<td>9.62</td>
<td>2.405</td>
</tr>
<tr>
<td>Potato</td>
<td>0.00056</td>
<td>32³</td>
<td>17.92</td>
<td>4.48</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>0.00024</td>
<td>45³</td>
<td>10.8</td>
<td>2.7</td>
</tr>
<tr>
<td>Swiss chard</td>
<td>0.00046</td>
<td>14⁴</td>
<td>6.44</td>
<td>1.61</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>0.00044</td>
<td>20³</td>
<td>8.8</td>
<td>2.2</td>
</tr>
</tbody>
</table>

3.3.3 Phosphorus Discussion

The destination of applied phosphorus in agriculture practise is of key importance in determining the sustainability of nutrient application practises. The possible flows of phosphorus and destinations post application are;
- Flow through - leaching to groundwater
- In-organic bonding to soil constituents (Fe$^{2+}$, Ca$^{2+}$ and Al$^{3+}$)
- Organic bonding to other soil biota and organics
- Non-edible fraction (not harvested)
- Surface run off
- Harvested Yield

The rate of overall loss of phosphorus from agricultural application is generally assumed, as a global figure, to be around 33% of that applied, this can occur from two broad categories - diffuse source or point source loss (Cordell, Drangert and White 2009). Diffuse loss refers to large area functions with low concentration phosphorus loss, though having a high volume of flow; this refers to large areas of land losing applied phosphorus through aeolian or alluvial mechanisms. Point source loss refers to high concentration of phosphorus being lost in low volumetric flow situations. This rate however does not conform to the results shown by Salama, et al. (2001) for the study performed on phosphorus loss in SCP soils in agricultural application. A figure closer to 75% was found to be lost to leaching to groundwater or bond in insoluble compounds.

The quantities of flows of phosphorus in soils, as stated by Stevenson and Cole (1999), is a function of soil mineral composition, pH, carbon content, particle size, microbial composition and plant-soil minerals and soil-biota relationships. As WGV is located on the Spearwood dune system CaCO$_3$ will be present in the lower soil horizons from deposition of underlying Tamala limestone. With the presence of CaCO$_3$ in the soil, the formation of di or tri-calcium phosphates ((Ca$_2$(HPO$_4$)$_2$) and Ca$_3$(PO$_4$)$_2$) is likely to occur over time. These two species will be gradually converted to carbonate hydroxyapatite 3[Ca$_3$(PO$_4$)$_2$.CaCO$_3$] the latter is a highly insoluble form of phosphorus (Stevenson and Cole 1999). It is therefore suggested that the effect of phosphorus leaching to groundwater at WGV will be lessened due to the insoluble formation of calcium phosphate compounds in the lower soil horizons. The long term effect of this process, however, is questionable, due to the depth of cropping plant roots not reaching these lower soil horizons, to abstract this phosphorus. Therefore an accumulation of these compounds will occur over a longer time scale. This is further outlined in (Salama, et al. 2001) with phosphorus testing on irrigated strawberry and turf farms on Gnangara
Mound suggesting the level of leaching to groundwater or at least leaching below the cropped root zone was up to 75% of phosphate fertiliser applied. To fully understand the dynamics of phosphorus in the soils of WGV, specific soil horizon tests would have to occur to quantify this rate of calcium phosphate compound creation and the subsequent retention of phosphorus in the soils.

The formation of microbial biomass in soils is expected to take up 1-2% of P and a rate of 1-1.2kgP/ha/Y is lost to insoluble soil bonding (di-tri valent cations with calcium containing soils)(Stevenson and Cole 1999). Where the bulk >90% of soil P is assumed to be found as insoluble fixed forms(Stevenson and Cole 1999). However P losses to erosion can have a significant contribution to soil P loss due to P being adsorbed to soil particles and subsequently eroded from the application site. An example shown by Stevenson and Cole (1999) showed typical phosphorus concentrations in soil for the USA as 450-2000kgP/ha to the depth of ploughing. Therefore if 1 tonne of soil is eroded from an agricultural site this will carry .22-1.88kgP with it. View Figure 2 to see the general phosphorus fertiliser fates after application to soil surface. Thorough soil testing is recommended to further develop the Nutrient and Irrigation Management Plan NIMP for WGV. Table 9 shows the predicted quantities of phosphorus flows given a number of assumptions.
3.3.2 Nitrogen Dynamics

The land application rates for the available nitrogen in urine, faeces and combined waste streams has been calculated for the given land use scenarios (Table 10). A maximum application of 486kgN/ha/crop (972kgN/ha/Y) was assumed for SCP soils. Further examples of literature
application rates of N fertiliser are in Table 11. The results show an excess amount of nitrogen is available in urine at WGV for the 0.25ha land use scenario, where there is an excess of ~2.5 times the suggested fertiliser N application rate. If 100% of produced urine was available (urine N 615.9kgN/Y), an intensive cropping application of 0.63ha could be supported.

Table 8: Nitrogen application rates and percentage of chosen maximum application rate for different land use scenarios

<table>
<thead>
<tr>
<th>Nutrient Available</th>
<th>Scenario: 1 0.25ha</th>
<th>Scenario 2:0.53ha</th>
<th>Scenario 3:1.5ha</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N kg/Y</td>
<td>Acceptable Rate</td>
<td>kN/ha/Y Acceptable Rate</td>
</tr>
<tr>
<td>Urine</td>
<td>615.9</td>
<td>No</td>
<td>1162.1</td>
</tr>
<tr>
<td>Faeces</td>
<td>71.2</td>
<td>Yes</td>
<td>134.3</td>
</tr>
<tr>
<td>Combined</td>
<td>687.1</td>
<td>No</td>
<td>1296.4</td>
</tr>
</tbody>
</table>

Table 9: Example of nitrogen accounting for SCP market garden operations taken from (Lantzke 2015)

<table>
<thead>
<tr>
<th>Yield T/ha/crop</th>
<th>Application Rate kgN/ha/crop</th>
<th>Crop Removal kgN/ha/crop</th>
<th>Residual N kgN/ha/crop</th>
<th>% of N applied, removed in harvest yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market Gardens</td>
<td>486</td>
<td>135</td>
<td>351</td>
<td>28</td>
</tr>
<tr>
<td>Carrots</td>
<td>60</td>
<td>320</td>
<td>86</td>
<td>234</td>
</tr>
<tr>
<td>Cauliflower</td>
<td>30</td>
<td>500</td>
<td>109</td>
<td>391</td>
</tr>
<tr>
<td>Celery</td>
<td>100</td>
<td>550</td>
<td>151</td>
<td>399</td>
</tr>
<tr>
<td>Lettuce</td>
<td>50</td>
<td>300</td>
<td>120</td>
<td>180</td>
</tr>
<tr>
<td>Onions</td>
<td>60</td>
<td>400</td>
<td>147</td>
<td>253</td>
</tr>
<tr>
<td>Potatoes</td>
<td>55</td>
<td>550</td>
<td>184</td>
<td>366</td>
</tr>
<tr>
<td>Tomatoes</td>
<td>100</td>
<td>650</td>
<td>148</td>
<td>502</td>
</tr>
</tbody>
</table>

334.2.1 Nitrogen Discussion

A study conducted in 2006 by a group of Perth based researchers (Salama, et al.2001), showed that leaching of nitrogen compounds to groundwater tables in the sandy soils of the SCP is an issue in the market garden regions of Perth, and can be upwards of 20% of total applied nitrogen. These assumptions have been used amongst others to understand the destination of nitrogen applied at WGV. For the projected destinations of applied N see Table 12. With losses of nitrogen equating to approximately 38%, it is suggested that more efficient cropping and fertiliser application techniques
must be employed on sandy soils to reduce this inefficient use of nitrogen and any follow on effects of eutrophication of groundwater and nearby waterways.

Table 10: Nitrogen Flow destination after fertiliser application

<table>
<thead>
<tr>
<th>Flow of Nitrogen</th>
<th>Nitrogen Input/Output</th>
<th>Percentage of inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertiliser Input</td>
<td>486kgN/ha/crop (Lantzke 2015) 972kgN/ha/Y</td>
<td>100%</td>
</tr>
<tr>
<td>Urine to achieve rate</td>
<td>~108000L/ha/Y</td>
<td>NA</td>
</tr>
<tr>
<td>Crop yield¹</td>
<td>109.76kgN/ha/crop cauliflower 148 kgN/ha/crop tomato 257.8 kgN/ha/Y</td>
<td>26.5%</td>
</tr>
<tr>
<td>Erosion/runoff²</td>
<td>13kg/ha/Y inorganic 9.25kg/ha/Y organic Total 22.25kg/ha/Y</td>
<td>2.3%</td>
</tr>
<tr>
<td>Leaching³</td>
<td>0-194.4kg/ha/Y</td>
<td>0-20%</td>
</tr>
<tr>
<td>Volatilisation⁴</td>
<td>~48-107kg/ha/Y</td>
<td>5-11%</td>
</tr>
<tr>
<td>Denitrification⁵</td>
<td>~39kg/ha/Y</td>
<td>4%</td>
</tr>
<tr>
<td>Retained in soil biomass/inorganic</td>
<td>351.9kg/ha/Y</td>
<td>36.2% assumed from balance of other factors</td>
</tr>
</tbody>
</table>

¹ based on uptake of nitrogen in cauliflower and tomatoes crops as an average (Lantzke 2015)

² Erosion and runoff based on figures from the USA (Stevenson and Cole 1999) includes organic and inorganic forms. Figures from grain, potato and cotton farms.

³ Based on leaching rates of NOx and NH₃ to above 80cm in depth (past most annual crop roots) (Salama, et al. 2001) stating in some cases for SCP (swan coastal plain) market gardens leaching loss of nitrogen can be upward of 20%

⁴ Based on rates from wheat field and fallow field fertilised in large cropping application methods (Schwenke 2014)

⁵ Based on Salama et al. (2001) for Spearwood sands, due to generally lower levels of soil organic content and therefore redox potential. In comparison; denitrification can be up to 9% in Bassendean sands due to higher organic carbon in this soil. This is also subject to land use and N application rates (Salama, et al. 2001), with these figures based on 202.4kgN/yr applied in a market garden scenario.

3.4 Conclusion on Nutrient Application at WGV in soil cropping

An important part of the feasibility study of wastewater used for food production systems is the limiting factors of nutrients. In the case for WGV it has been found, for a land use within the
boundaries of WGV (0.25ha), there is an excess of nitrogen in the available urine stream alone, if all household urine is collected. The suggested applications of urine to achieve maximum fertilisation rates of N and P can be seen in Table 13. With the land use scenario 1 (0.25ha), 27000 L/Y of urine would be sufficient to reach fertilisation rates of N and P used in market garden operations on the SCP, this is ~40% of the urine total produced by the population.

The percentage of time spent at home by the population at WGV is a consideration to the waste derived nutrients available for use; i.e. the rates of urinating and defecating occurring on site. It is expected that 40% of total urine production/collection on site should be achievable, assuming average time in the household would be >40% of the year. Some basic assumptions that lead to this conclusions (8 hours of sleep per day average, 4 hours at home each day on average for domestic duties (≥50% of time)), surveys are a suggested method to deliberate further on this point (no literature reference was found for average time that Australians spend at home).

Table 11: Suggested application rates of urine to reach standard fertilisation rates for the SCP

<table>
<thead>
<tr>
<th>Urine Available (L/Y)</th>
<th>68437.5 (100% collection)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land Scenario (ha)</strong></td>
<td>0.25 0.53 1.5 0.63</td>
</tr>
<tr>
<td><strong>Volume of Urine Utilised (L)</strong></td>
<td>27000 57200 68400 68400</td>
</tr>
<tr>
<td><strong>Nitrogen Applied (kg)</strong></td>
<td>243.0 515.2 615.9 615.9</td>
</tr>
<tr>
<td><strong>Nitrogen App rate (kg/ha)</strong></td>
<td>972.1 972.0 410.6 972.0</td>
</tr>
<tr>
<td><strong>Phosphorus Applied (kg)</strong></td>
<td>18.9 40.1 47.9 47.9</td>
</tr>
<tr>
<td><strong>Applied Rate (kgP/ha/Y)</strong></td>
<td>75.6 75.6 31.9 75.6</td>
</tr>
</tbody>
</table>

3.5 System investigation

3.5.1 Introduction

As there is an excess of nitrogen available in urine alone for the WGV site for a land use scenario of 0.25ha, the use of black water treatment and reuse has not been investigated for the system components. This alleviates the social, economic and technical complexity that black water
treatment and reuse may add to the project. For future larger scale developments with a higher level of available cropping land the use of black water stream maybe feasible. Further investigation into this is suggested. The use of urine diversion in crop production is also anticipated to be more socially accepted as more pilot projects come online globally.

3.5.1.1 Source Separation of urine

3.6.1.1.2 Urine separating toilets

Urine diverting toilets are becoming more readily available globally with more manufacturers producing dual cistern toilets, with both dry and wet flushing technologies available. However, these are rare in Australia, with no current WaterMark toilets available (WaterMark is the Australian trademark certification for products which meet the current regulatory requirements). Recognising that producing a system which is socially accepted is of upmost importance, due to stigmas on wastewater handling in Australia, the proposed design should utilize a dual cistern toilet, with dual flush, differing only slightly to the current practise (Figure 3). These systems are known to be less problematic with odour issues due to the capability to flush the urine cistern, a recent design development in the industry. A study performed by Mitchell, Fam and Abeysuriya (2013) analysed two dual cistern toilets at the University of Technology Sydney; Wostman EcoFlush UDT (Urine Diversion Toilet) and Dubbletten UDT. Neither toilet reached the full specification of Australian standards. This shows that further development of toilets for the Australian market is required, which is anticipated to be a function of increased pressure on suppliers to meet the Australian market and standards. For modelling of water flows and costs, the Wostman Ecoflush UDT has been chosen as the UDT for this proposal.
3.5.1.2 Plumbing

With a manufacturer’s specification and instruction it is expected that, a qualified plumber should easily be able to achieve effective installation. The following are some key recommendations in terms of plumbing for urine diversion (Mitchell, Fam and Abeysuriya 2013).

- Keep all piping for urine transfer of at least 1:65 (1.5%) gradient, and closer to 1:25 (4% gradient) is recommended. The highest gradient possible should be utilised, to minimise stagnation and struvite precipitation
- Avoid any metal contact in plumbing of urine to avoid solids build up. Piping should either be stainless or smooth plastic
- Ensure education on the maintenance of urine diversion systems to ensure struvite build-up is avoided or minimised
- Protection against surge or sewer blockage should be in place
- Plumbing and tanks should be configured to minimise atmospheric nitrogen loss
- Sewer diversion of diverted urine in case of system malfunction or oversupply of urine resource should be in place. This also allows for effective chemical flushing provision if required in the maintenance schedule
3.5.1.1.3 Maintenance

The build-up of precipitated struvite in urine diversion systems is of key concern in any diversion system, this can be avoided somewhat by ensuring adequate gradient to all transport pipes of urine and adequate flow (flushing), minimising any stagnation. Sewer bypass valves should be included on all toilet installations. This will ensure limited disruption if clogging does occur, and also allows chemical cleaning and flushing to sewer without implications for cropping land. An appropriate maintenance schedule as specified by the manufacturer should minimise any potential system failures. Sewer diversion of the; urine storage tank, sump tank, fertigation holding tank system, should also be in place to allow for the flushing/chemical cleaning of the individual system sections to remove struvite and any other salt build up over time. It is suggested that after each urine transfer from sump tank to storage tank, plumbing and pump should be flushed with water, to reduce stagnant struvite build-up. The destination of this flush water could be irrigation, dilution of urine in fertigation holding tanks, or diverted to sewer.

Struvite precipitation can be effectively removed with acidic solutions. Light build up in cistern or house plumbing may be removed by household vinegar or citric acid solutions. More intensive chemical formulas are available, and are generally used for wastewater treatment plant descaling.

3.5.2 Recirculating Hydroponics for reuse of urine

3.5.2.1 Introduction

To investigate the processes and configuration of hydroponics food production systems applicability to treat household source separated urine, a pilot scale system was created in the suburb of St James, Perth. Hydroponics systems are the utilisation of a soilless medium, with recirculation of nutrient rich water to produce vegetative growth. Many different system configurations exist, design examples including; deep water culture, nutrient film techniques, and a number of filter media system configurations; horizontal and vertical flow. The use of soilless growing media techniques to treat wastewater is a tried and tested method, with constructed wetlands being used widely for
treatment of waste effluents. The coupling of hydroponics with aquaculture wastes, coined the term Aquaponics is also a technique, with growing commercial interest globally. The potential for hydroponics to treat waste effluent such as urine in new developments is constrained by the factors of human safety concerns (contact with pathogen breeding grounds), and economic constraint.

The pilot system was configured to accompany the future potential to include aquaculture fish production (aquaponics). The system is comprised of a 1000L fish tank, a 650L sump tank and 4 220L media based vegetable production grow beds (~4.2m² growing area) (Figure 5 and Table 14). The system was run with nutrient loading from human urine and vermicompost (worm farm) leachate, though purchased organic fish emulsion and seaweed extract was utilised to initially build the bacteria colony (cycle the system).

Hydroponics media beds have many factors affecting treatment of the various nutrients. These processes are outlined in; Appendix E: Hydroponics Treatment Processes.

3.5.2.2 Design methodology

The design approach taken for the home system was to reuse waste products for nutrient input to reduce input costs. The costs of production are a key concern for any horticulture practise. Figure 4 illustrates the system and basic biomass transfer relationships found in a constructed wetland and hydroponics system using media based bio-filteration.
Figure 4: Basic mass transfers in biomass in wetlands (Kadlec and Wallace 2009)

Figure 5: General configuration and water flows through the hydroponics system Notes on Figure 5; A; solids lift overflow to lift accumulated solids from the base of the fish tank to apply to grow beds, B; a balanced gravity feed to grow beds to remove additional costs of taps to control flow, C; limestone blocks for grow bed support
Table 12: Item list for the backyard system, obtained second hand where possible to reduce costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Cost</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>International Bulk Carrier Containers (IBC’s)</td>
<td>4</td>
<td>$80ea</td>
<td>No net cost as a labour exchange arrangement was made</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Containers are available from various ex-industrial use for transport of bulk liquids</td>
</tr>
<tr>
<td>Limestone Retaining wall Blocks</td>
<td>24</td>
<td>Free</td>
<td>For grow bed supports</td>
</tr>
<tr>
<td>Plumbing</td>
<td>Various</td>
<td>$60</td>
<td>Majority obtained for free</td>
</tr>
<tr>
<td>Pump</td>
<td>1</td>
<td>$235</td>
<td>PondMax 45000</td>
</tr>
<tr>
<td>Media (Blue Metal)</td>
<td>1.5m²</td>
<td>$120</td>
<td>The cheapest clean inert media found</td>
</tr>
<tr>
<td>Nutrients</td>
<td>2.5L Fish Emulsion</td>
<td>~$60/Y</td>
<td>CharlieCarp fish emulsion</td>
</tr>
<tr>
<td></td>
<td>2L Seaweed Extract</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Trace Element</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Usage</td>
<td>120W Pump 6 hours/day</td>
<td>~$75.4/Y</td>
<td>A1 tariff at $0.257029</td>
</tr>
<tr>
<td>Water Usage</td>
<td>250L/week Summer 100L/week Winter</td>
<td>9.1kl/Y $13.81/Y</td>
<td>$1.518/kl Perth Metro. Water charge rate</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>$884.20 First Year $149.21/Y subsequent</td>
<td>First Year = Capex + sundries</td>
</tr>
<tr>
<td>Production</td>
<td>2 peoples vegetable need satisfied</td>
<td>$10 Value/week $520/Y</td>
<td>Based on qualitative interview only</td>
</tr>
</tbody>
</table>

Figure 6: Home system after 4 months of nutrient cycling
3.5.2.3 Hydroponics results observations and outcomes

The system was achieved at a total costs of ~$885 with a growing area of 4.2m². The outputs of food products from the system were estimated qualitatively by interview of household members to the quantity and quality of the produce. The conclusion is that the vegetable requirements of 2 healthy adults could be met, if consumption sacrifices were made (variation on produce, favouring leafy green vegetables). See Table 15 for a summary of nutrient loadings as measured. The sole application of urine was from January 10th-27th. This led to an increase in Ammonia from 0ppm – 0.25ppm, with the growth of plants being sustained, but at a slower rate (from visual inspection) than when compared to the fish emulsion and seaweed extract cycling period. Only a short period of testing of urine occurred, therefore no solid conclusions can be made on the system’s effectiveness.

Table 13: Average nutrient loadings as measured for the pilot scale household hydroponics system

<table>
<thead>
<tr>
<th>Load time</th>
<th>Nutrient Sources</th>
<th>Volume in put</th>
<th>Avg. Ammonia Concentration</th>
<th>Avg. Nitrate Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>September 5th-December 10th</td>
<td>Fish Emulsion, Seaweed Extract, Urine, Vermicompost leachate</td>
<td>2.25L Fish Emulsion, 2L Seaweed Extract, 0.1L/day</td>
<td>0.5ppm</td>
<td>80ppm (range from 0-160ppm)</td>
</tr>
<tr>
<td>December 10th – January 10th</td>
<td>No Input</td>
<td>NA No input occurred over this time</td>
<td>NA (no test results)</td>
<td>NA (no test results)</td>
</tr>
<tr>
<td>January 10th – January 27th</td>
<td>Urine</td>
<td>~0.250L/day</td>
<td>0.25ppm</td>
<td>0ppm</td>
</tr>
</tbody>
</table>

3.5.2.4 Hydroponics at WGV

As the household system was based largely on utilising waste resources recycled for construction to reduce cost, extrapolating on potential scalability to the WGV case study is difficult. From the pilot project experience, a higher input of maintenance and sacrifice of resiliency was found (intensive non-passive hydroponics compared to more passive soil cropping techniques), though this giving a
higher vegetable output yields over standard soil cropping (increased growth rates were found to also rely heavily on the species of vegetable grown, where vascular leaf vegetables showed the highest increase in growth rate). Commercial hydroponics systems are operating in Australia and globally, therefore there is merit for further investigation into the implementation of these systems for wastewater reuse. However due to the economic input ($220/m² cropping area) and therefore economic feasibility, which is based heavily on the market value of produce (where the viability of community acceptance of marketed wastewater grown produce is the key factor to the success of these systems) therefore, lower initial cost systems should be favoured for pilot scale system development. Therefore soil based cropping techniques should be favoured and are developed in the following section.

3.5.3 Soil System Investigation and Design

3.5.3.1 Introduction

In the pursuit of an economically feasible solution for food production utilising wastewater at WGV, soil cropping nutrient application has been investigated. The overall schematic for a urine diversion and reuse system for soil cropping at WGV is seen in Figure 7. The relevant sections of the schematic and their components described in the following chapter sections.
3.5.3.4 Collection and storage

3.5.2.4.1 Sump tank and pump out

To increase the passive design, a gravity fed sump tank collection and subsequent pump out is proposed. With sump collection the need to bury storage tanks in the residential area is minimised. For costs associated see section 3.5.4.4 Economic Analysis.

3.5.3.4.1 Storage tanks

To reduce pathogen risk, a storage time of 6 months for all urine before crop application is proposed. Adequate storage time and temperature is associated with the die off of pathogens in urine. This is suggested in a number of references including Maurer, Pronk and Larsen (2006) and Mitchell, Fam and Abeysuriya (2013). To achieve this storage time of 6 months for 150 residents with varying percentage of urine input to the system, the minimum storage vessels to handle the volume of the site is seen in Table 16.
Table 14: Storage vessels for 6 month retention of urine, at varying percentage of urine inflow

<table>
<thead>
<tr>
<th>Percentage of Urine inflow to system</th>
<th>100%</th>
<th>75%</th>
<th>50%</th>
<th>25%</th>
<th>39%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urine L/yr WGV</td>
<td>68437</td>
<td>51328</td>
<td>34218</td>
<td>17109</td>
<td>27000</td>
</tr>
<tr>
<td>Tank Volume Total</td>
<td>34,218L</td>
<td>25,664L</td>
<td>17,109L</td>
<td>8,554L</td>
<td>13,500L</td>
</tr>
<tr>
<td>Tank Size (4 Separate)</td>
<td>~8600L</td>
<td>~6500L</td>
<td>~4300L</td>
<td>~2200L</td>
<td>~3400L</td>
</tr>
</tbody>
</table>

3.5.4 Soil Based Cropping

To utilise the nutrients derived from separated urine at WGV an intensive soil based market garden is proposed, utilising current proposed public open space at the site. The current planning for use of the public open space area is to be a mix of turfed area and native landscaped gardens. Care must be taken in ensuring aesthetic value is retained in the area as this project should be regarded as a showcase for onsite wastewater reuse in new residential developments. As seen in the nutrient modelling in the above sections, there is adequate nitrogen in urine and to a lesser extent phosphorus for direct application. It is expected that growth of market garden crops should be on par with other operations found on the SCP, though investigation in field experiments is suggested for different crops performance. Expected tools and irrigation line/fittings costs for cropping operations and estimated costs are listed in Table 17 (irrigation line requirement is based on 0.25 ha of cropped land, with plant row spacing of 50cm).

Table 15: Assumptions of tools and irrigation required for soil production at WGV

<table>
<thead>
<tr>
<th>Hand Tools</th>
<th>Power Tools</th>
<th>Transport</th>
<th>Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake</td>
<td>Cultivator</td>
<td>Wheelbarrow, Harvest Containers</td>
<td>~5000m Toro Enviro drip (grey water standard)</td>
</tr>
<tr>
<td>Hoe</td>
<td></td>
<td></td>
<td>Fittings</td>
</tr>
<tr>
<td>Shovel</td>
<td></td>
<td></td>
<td>100M Main Line 32mm PN High Pressure</td>
</tr>
<tr>
<td>Secateurs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pliers</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$250</td>
<td>$850</td>
<td>$200</td>
<td>$6450&lt;sup&gt;1&lt;/sup&gt; Irrigation Line</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~$100 fittings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$160 main line</td>
</tr>
</tbody>
</table>

3.5.4.1 Crop Management

For full crop management to achieve viability at this scale, it is suggested that a trained horticultural consultant be approached to properly develop the site, with an ongoing farm operator to be employed at approximately 35hr/week.

Fremantle Men’s Shed – is a community amenity located at the WGV site, the organisation is designed to encourage the participation of community members in such activities as wood and metal work, socialising and community scale projects. With the development of community gardens a hot topic for city residents in Perth and globally, it is also advised that the Fremantle men’s shed could be involved in the development of the area, giving outcomes of community involvement in maintaining the site, and the output of locally grown vegetables. This involvement may also result in potential markets for the vegetables as the project is developed.

3.5.4.1.2 Fertigation

Fertigation is a method of nutrient delivery to cropping area via soluble nutrient input into irrigation lines. This method of fertilisation has the benefits of;

- Soluble fertiliser application (nutrients generally in plant available form)
- An increase in precision of delivery when coupled with drip irrigation straight to the root zone of plants.
- Better control on nutrient quantity applied

A number of systems are available with the three main configurations; Pressure differential bypass tank, Vacuum injection, Pump injection (International Potash Institute 1999). For the use of urine the recommendation of use of the pressure differential system is given, this allowing good control of rate of application over venturi methods and minimal contact with urine.
3.5.4.2 Energy Savings

The energy savings from the proposed system components for soil cropping have been quantified in Table 19. These figures are related to the embodied energy savings of producing a cropped product to feed the population of WGV by reducing fertiliser use and centralised wastewater treatment for the standard practise. A 0.25ha application of urine diversion and fertigation gives an energy saving of 28087MJ/Y (7802 kWh/Y).

A modelling investigation of decentralised separation of urine, collecting, thermal mass reduction and application to broad acre farm areas has been preformed by Maurer, Schwegler and Larsen (2003)The results show a use of 65MJ/kgN for the reuse scheme, compared to 157MJ/kgN for the atmospheric cycle of N (wastewater denitrification and artificial fertiliser with N fixation and transport). This example included the transportation of decentralised source seperated urine over 60km to an evaporation pan for the thermal mass reduction and a subsequent further 100km to distribution to agricultural land with the calculated transport energy approximately 13MJ/kgN. The outcome shows an embodied energy value of urine to be equivelent to 0.87MJ/PE/day (0.44MJ/PE/d fertiliser value and 0.43MJ/PE/Day for wastewater treatment (Maurer, Schwegler and Larsen 2003)).

Assumptions of Energy used to source separate urine;

- Dual cistern toilets are used with sump collection tanks at the household and community scale where designs permit
- The energy required to transport urine from cistern to sump is assumed to be negligible with gravity drainage
- Sump tanks are pumped out through plumbed main lines, to avoid the use of a tanker for urine transport from household to end crop use
- Head height has been nominated at a maximum of 7m, this has been estimated assumes no more than a maximum of 300m pipe length for transfer of stored urine to the growing area,
using minimum 2 inch irrigation line. The proposed growing area is also topographically advantageous due to it being the low point of the development.

Table 16: Energy usage calculations for WGV proposed urine diversion system

<table>
<thead>
<tr>
<th>Head Height (maximum)</th>
<th>7</th>
</tr>
</thead>
</table>
| **Pump Number**
| **Brand**            | D25A Davey |
| **Pump rate at head**| 5400L/hr |
| **Watts**             | 250w |
| **kwh to pump urine volume**
| **0.25ha (27001L)**  | 12.50kwh |
| **kwh to pump urine volume**
| **0.53ha (57242L)**  | 26.50kwh |
| **kwh to pump urine volume**
| **1.5ha (68437L)**   | 31.68kwh |

Table 17: Embodied energy of Elemental P and N as a global average in Fertiliser

<table>
<thead>
<tr>
<th>Field</th>
<th>Energy Embodied</th>
<th>Energy at WGV application rate .25 ha</th>
<th>Energy at WGV application rate .53 ha</th>
<th>Energy at WGV application rate 1 ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus fertiliser (elemental P)</td>
<td>15 MJ/kg</td>
<td>18.9 kg/Y</td>
<td>40.1 kg/Y</td>
<td>47.9 kg/Y</td>
</tr>
<tr>
<td>Nitrogen fertiliser elemental N</td>
<td>65 MJ/kg</td>
<td>243 kg/Y</td>
<td>515.2 kg/Y</td>
<td>615.9 kg/Y</td>
</tr>
<tr>
<td>Total fertiliser embodied energy</td>
<td>NA</td>
<td>16270.9 MJ/Y</td>
<td>34089.5 MJ/Y</td>
<td>40752 MJ/Y</td>
</tr>
<tr>
<td>Source separated urine</td>
<td>.00166 MJ/L urine</td>
<td>45 MJ/Y</td>
<td>95.02 MJ/Y</td>
<td>113.6 MJ/Y</td>
</tr>
<tr>
<td>Wastewater Treatment</td>
<td>49 MJ/kgP</td>
<td>926 MJ/Y</td>
<td>1965 MJ/Y</td>
<td>2347 MJ/Y</td>
</tr>
<tr>
<td></td>
<td>45 MJ/kgN</td>
<td>10935 MJ/Y</td>
<td>23184 MJ/Y</td>
<td>27715 MJ/Y</td>
</tr>
<tr>
<td>Total Saved</td>
<td>28000 MJ/Y</td>
<td>59100 MJ/Y</td>
<td>70700 MJ/Y</td>
<td></td>
</tr>
</tbody>
</table>

1 (Wells 2003), 2 (Maurer, Schwegler and Larsen 2003)

3.5.4.3 Water Usage

To calculate the water balance changes for WGV the embodied water of vegetable produce with different rates of consumption of produce created on site, are compared to embodied water of vegetables otherwise produced off site and imported for consumption (Figure 8). A decrease in 935kl/Y water usage is calculated if 100% of the suggested yield offsets imported vegetable consumption has been calculated. Note that this figure does not include the water usage of the manufacturing of system components for WGV.
Figure 8: System water usage and embodied water savings for consumption of produce onsite
3.5.4.4 Economic Analysis

System components and their associated assumed maintenance time and initial capital investment is seen in Table 20. The initial estimates do not take into account life cycle costs.

Table 18: The maintenance assumptions for system components

<table>
<thead>
<tr>
<th>System Component</th>
<th>Maintenance Time Allocation</th>
<th>Associated labour/Part Replacement Cost</th>
<th>Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toilets</td>
<td>240 hr/Y .5hr bi-monthly check/clean</td>
<td>-</td>
<td>No labour as expected home owners to maintain home toilets</td>
</tr>
<tr>
<td>Additional Plumbing</td>
<td>-</td>
<td>-</td>
<td>Extra fittings and plumbing for urine diversion</td>
</tr>
<tr>
<td>Storage Tanks</td>
<td>10hr/Y</td>
<td></td>
<td>Descaling and leak/seal checks</td>
</tr>
<tr>
<td>Storage tank Pump</td>
<td>5hr/Y</td>
<td>$70 Labour $30 parts/cleaning agents</td>
<td>2 year warranty Replacement pump if cost of maintenance is above $100/year</td>
</tr>
<tr>
<td>Fertigation injection unit</td>
<td>10hr/Y</td>
<td>$175 Labour $30 parts</td>
<td>(5 year warranty) <a href="http://www.gplawn.com/p-591-ez-flo-main-line-products.aspx">http://www.gplawn.com/p-591-ez-flo-main-line-products.aspx</a></td>
</tr>
<tr>
<td>Pipe descaling/ maintenance</td>
<td>10 hr/Y</td>
<td>$105 Labour $30 Descaling chemicals</td>
<td>Chemical flushing of piping system to remove scale</td>
</tr>
<tr>
<td>Cropping Area</td>
<td>30hr/week 1560 hr/Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1835 hr/Y $25/hr</td>
<td>$440/Y</td>
<td></td>
</tr>
</tbody>
</table>
The payback period analysis was initially performed without use of full LCA to give an idea of the system costs initially. The system payback period is based on the sole income stream of marketable produce. For net energy and water usage increases with system installation at WGV, though embodied savings are had, this does not equate to economic gain.

### 4 Recommendations

Systems for wastewater reuse in food production especially in Western cultures face many issues.

With this in mind the following recommendations have been made regarding this study;

- The implementation of systems as outlined in the study, need further development at pilot scale to ensure human safety from food products containing any transferred pathogens and hormones

---

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>Cost ea($)</th>
<th>Capex ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cisterns</td>
<td>80</td>
<td>1375</td>
<td>110000</td>
</tr>
<tr>
<td>Sump Tank</td>
<td>2</td>
<td>2100</td>
<td>4200</td>
</tr>
<tr>
<td>Pump</td>
<td>2</td>
<td>450</td>
<td>900</td>
</tr>
<tr>
<td>Plumbing 100mm</td>
<td>200</td>
<td>7.5</td>
<td>1500</td>
</tr>
<tr>
<td>Storage tank</td>
<td>4</td>
<td>1456</td>
<td>5824</td>
</tr>
<tr>
<td>Plumbing</td>
<td>50</td>
<td>7.5</td>
<td>375</td>
</tr>
<tr>
<td>Fertigation</td>
<td>1</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Irrigation Drip line m</td>
<td>5000</td>
<td>0.5561</td>
<td>2780.5</td>
</tr>
<tr>
<td>Fittings</td>
<td></td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>Tiller</td>
<td>1</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Tools</td>
<td></td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>Greenfield</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adjustment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contingency</td>
<td>20</td>
<td></td>
<td>26687</td>
</tr>
<tr>
<td>Total Capex</td>
<td></td>
<td></td>
<td>115935</td>
</tr>
<tr>
<td>Labour</td>
<td></td>
<td>-$44375/Y</td>
<td></td>
</tr>
<tr>
<td>Sundries</td>
<td></td>
<td>-$600/Y</td>
<td></td>
</tr>
<tr>
<td>Vegetable Product</td>
<td></td>
<td>+$54825/Y</td>
<td></td>
</tr>
<tr>
<td>Payback Period</td>
<td></td>
<td>&gt;23 Years</td>
<td></td>
</tr>
</tbody>
</table>
• Market investigation of the potential value of such food products, is the main limitation of these projects reaching economic viability. Therefore further analysis in this sector needs to be performed.

• A general movement to more sustainable systems to support urban areas seems logical to an environmental activist. However engineering design needs to provide the solutions which work at scale, having holistic beneficial outcomes. Given the limitations of sustainable systems is most often based around economic feasibility in a market economy, the drive to pursue these systems is often somewhat lacking. Shifting community perceptions of the value of closing nutrient cycles is difficult when a stigma is associated to the use of waste resources, educating the community on the benefits and showcasing what is possible with smaller scale pilot facilities is recommended as a way forward to increasing the pursuit of these systems.

A number of gaps in literature were found in the study area, a list of recommended research questions to address a number of these are outlined below;

• Urine application affects on soil salinity, for specific site contexts (sandy soils at WGV), and how differing applications methods affect this, i.e. concentration of nutrient application in dripper zones when drip line irrigation and fertigation methods are utilized.

• Urine crop irrigation maintenance requirements; how does struvite and other salt build-up affect pressurized irrigation systems, and nutrient injection methods of fertilization (fertigation)

• What are the limitations of reaching sustainable developments through the entire wastewater streams being utilized, so as to close nutrient and to a lesser extent water cycles on site.

• In the pursuit of sustainable anthropogenic systems, what is the effect on regional water cycles from the greening of urban areas, can the multiple conceptual reuse of available water before discharge to the ocean lead to more productive landscapes from prevailing coastal winds leading
to higher inland precipitation from evaporation on coastal plain operations. What are the outcomes for the urban heat island effect and climate change mitigation?

- Pathogen and pharmaceutical contaminant investigation, is a very broad topic of investigation which will be ongoing, for the dynamics and variety of pharmaceuticals and hormones found in differing waste streams and their dynamics through varying treatment processes and life cycle after application in reuse schemes.
5 Conclusion

Wastewater reuse in food production systems can hold keys to solving many global issues surrounding sustainability, food security, and climate change mitigation. The proposal for systems to be put in place for new urban developments does however face constraints due to social perceptions of wastewater reuse and governmental regulation on irrigation approaches to uphold environmental integrity. Another constraint is the cost benefit limits for such systems in the Australian context. This project has outlined the issues by which wastewater reuse can be applied to food production through literature review and desktop modelling, with a system proposed for application at Landcorp’s White Gum Valley residential development in the Perth Metropolitan area. The key findings of this research case study are presented below;

1. The nutrients contained in 40% of the urine produced by the projected population at WGV can support the growth (in terms of nutrient requirements of nitrogen and phosphorus) of an intensive market garden scenario on 0.25ha of land.
   a. Systems can be implemented to improve the efficiency of water use per unit of yield and yields per area with the use of a recirculated hydroponics system, though a large barrier to these systems is the capital expenditure and reduced system resiliency over traditional soil cropping techniques.

2. The destinations of nitrogen and phosphorus after application were explored through literature and modelling with a general finding that approximately 38% of nitrogen and 33% of phosphorus is generally lost from various processes. Only a small fraction is harvested in vegetable products, while the rest is held in various forms in the soil. It is recommended that onsite soil testing and monitoring after any nutrient application be undertaken.

3. The food production output for the WGV was based on the assumption of two crops being produced (tomatoes in summer, and cauliflowers in winter). With these two crops 18.75
tonnes of yield could be produced. This represents approximately 3.5% of the recommended dietary intake, and 98% of the recommended vegetable intake of the WGV population.

4. The proposal of a soil based market garden system to reuse waste nutrients is modelled to have a net water and energy usage increase within the site boundaries. However when the embodied energy and water of the food and wastewater support systems for the site, an embodied energy and water usage decrease of ~44000MJ/Y and ~935kl/Y respectively was calculated.
Bibliography


Lantzke, N. C. *Understanding nitrogen fertilisers for vegetable production on sands*. Perth: Department of Agriculture Western Australia, 2015.


Appendix

Appendix A: The Nexus design approach

The nexus design approach allows for cross sector, scaled management and policy design, in a multidisciplinary context, to ensure fewer negative, economic, environmental and social impacts in system design (Hoff 2011). A number of papers are available in the quantitative area with a portion of these revolving around the methods of modelling such complex systems, and a number of case study models created in specific contexts (generally spatial). The approach of modelling complex system dynamics in the areas of metabolism of the anthroposphere allows the exposure of interactions between sectors, some of which may otherwise be oversights in design.

System thinking approaches are appropriate when trying to understand the concepts of material flows derived from physical and chemical mass and energy balancing. Systems approaches need specific scale and boundary, where the system should be as small as feasible but as large as necessary to aid in reducing complexity as much as possible, where setting useful system boundaries is often difficult, though one of the most important points of creating useful anthropogenic models (Baccini and Brunner 2012). On the Global scale, material flow is essentially a closed system (in thermodynamic theory, neglecting space travel outputs and meteorite inputs) where three processes: the geosphere, biosphere and anthroposphere have flows between their boundaries, with the common energy input; solar energy (Baccini and Brunner 2012). The trend of urban centres, to be 'through put economies' (material flows being linear from the hinterlands through consumption and to subsequent waste disposal) puts large pressures on waste sinks. The hydrosphere and atmosphere are the two critical waste sinks for much of the linear usage waste outputs, these two sinks are therefore of special concern for the sustainable future of the cities which rely on them (Baccini and Brunner 2012).
Appendix B: Stockholm Framework Application

The Stockholm Framework is helpful in assessing health risks before setting targets and policy/regulation to meet these. The integration of disease pathways from other exposures are also included to allow holistic outcomes (World Health Organisation 2006). Figure 9 shows the general Stockholm Framework approach for the integrated assessment of risk, and how to plan around these and manage them effectively.

Figure 9: General Stockholm Framework approach for the integrated assessment of risk

**Landcorp’s White Gum Valley Development**

The close study of the risks associated with the implementation of wastewater reuse is required for any successful development of these technologies in the agricultural industries, especially in Western Societies. The process of the Stockholm Framework for health risks of waste/wastewater reuse in food systems at WGV can be applied as a basis for other urban developments in Perth or further abroad. The following section details some of the considerations when applying the framework, these considerations are derived from the detailed section for the Stockholm
Framework in (World Health Organisation 2006), the close referral to this text is advised for future studies into the impacts of certain wastewater reuse technologies.

**Assessment of health risk**

The process of identifying the health risks for the reuse of wastewater in agricultural practice are through; Epidemiological studies, and Quantifiable Microbial Risk assessment. These are processes to ensure a thorough integrated investigation identifies risk severity and likelihood. The considerations when using these tools, sourced from World Health Organisation (2006);

- Assessment of risk should be reoccurring as data becomes available and environments change.
- Modelled QMRA (quantitative microbial Risk assessment) should be backed up with real world testing and data acquisition.
- This process is highly dependent on quality data, therefore care must be taken in this regard.

**Tolerable Risk based Targets**

Considerations;

- Needs to be realistic and achievable within the constraints of the setting.
- Set based on a risk-benefit approach: should consider cost effectiveness of different available interventions.
- Should take sensitive subpopulations into account.
- Reference pathogens should be selected for relevance to contamination, control challenges and health significance.

**Health risk management**

Considerations;
• Health-based targets should be a basis for selecting risk management strategies; combining exposure prevention through good practices and appropriate water quality objectives is recommended.

• Risk points should be defined and used to anticipate and minimize health risks; parameters for monitoring can be set up around risk points.

• A multiple-barrier approach should be used.

• Monitoring - overall emphasis should be given to periodic inspection/auditing and to simple measurements that can be rapidly and frequently made to inform management.

• Risk management strategies need to address rare to catastrophic events.

• Analytical verifications may include testing wastewater and/or crops for *E.coli* or viable gelminth eggs to confirm that the treatment processes are working to the desired level.

**Public Health Status**

Considerations;

• Needs to evaluate effectiveness of risk management interventions on specific health outcomes (through both investigation of disease outbreaks and evaluation of background disease levels).

• Public health outcome monitoring provides the information needed to fine-tune risk management process through an iterative process; procedures for estimating the burden of disease will facilitate monitoring health outcomes due to specific exposures.
<table>
<thead>
<tr>
<th>Risk</th>
<th>Area</th>
<th>Degree of Risk</th>
<th>Preventative Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pathogen</strong></td>
<td>Farmer, Vegetable consumer, Household owner</td>
<td>Medium</td>
<td>Closed system design, Subsurface drip irrigation, Education for household owners, Urine storage (6 months)</td>
</tr>
<tr>
<td><strong>Exposure Risk</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Virus Risk</strong></td>
<td>Farmer, Vegetable consumer</td>
<td>Low</td>
<td>See above</td>
</tr>
<tr>
<td><strong>Site Risks</strong></td>
<td>Farmer, Public</td>
<td>Low</td>
<td>Proper training and safety equipment provision, Signage for public risks, Exclusion from irrigation equipment</td>
</tr>
<tr>
<td><strong>Odour</strong></td>
<td>Farmer, Public</td>
<td>Medium</td>
<td>Sealed system design, Sub surface irrigation with night time application</td>
</tr>
</tbody>
</table>
Appendix C: MSA

2.1.1 MSA

Using MSA (multi-sectorial analysis), diverse and best practise solutions can be achieved over multiple facets of the anthroposphere (Villarroel Walker, Beck and Hall 2012). MSA modelling allows the patterns of consumption of energy, food and water in urban areas, which have been historically addressed independently, to be now conceptualised in their interconnectedness (Villarroel Walker, et al. 2014). MSA has three key components; Substance flow analysis’s based on conversion of mass and energy theory, the definition of metabolic performance metrics based on material and energy flows, and rationalised sensitivity analysis (Villarroel Walker, et al. 2014).

To explain the conceptual use of MSA, an example is given; In a wastewater management scenario using MSA, the "business as usual" approach will be to assess the main issue of; i.e. direct pollution of water ways from discharge of effluent, and designing solutions of treatment to counter these issues. Using MSA further investigation of other sectors effected by the same situation; i.e. water use efficiency in transportation of liquid waste, energy required to pump and treat water, water scarcity issues feeding into a plethora of implications ecologically and for agriculture. This break down from a multidiciplinary standpoint allows a more holistic potential engineering solution to the original wastewater discharge issue. Decentralisation of wastewater systems to reduce water transport energy, increase water use efficiency (source separation and reuse), and the potential associated positive outcomes in its reuse; increase biodiversity, and agricultural production, are all possible positive outcomes associated with taking a MSA approach to design.

The basis of MSA and the flows of the Nexus are based around simple mass and energy balances in a multidiciplinary context. The fundamental mass flows relating to general anthropogenic metabolisms is shown in a very simplified arrangement in Figure 10.
Figure 10: Simplified overall framework of the MSA in urban areas (Villarroel Walker et al. 2012)
## Appendix D: Crop growth factors

### Table 21: The dietary assumptions of representative primary food groups for N, P with energy and water flows

<table>
<thead>
<tr>
<th>Food Group</th>
<th>TN % of total mass</th>
<th>TP % of total mass</th>
<th>MJ/kg</th>
<th>L water to produce 1kg product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>1.085 3.0 (Hong, et al. 2012)</td>
<td>.055 (Hong, et al. 2012) .057 (The United States Department of Agriculture 2011)</td>
<td>3.22 (The United States Department of Agriculture 2011)</td>
<td></td>
</tr>
<tr>
<td>Fruit</td>
<td>.04 (Hong, et al. 2012)</td>
<td>.007 (Hong, et al. 2012) .011 (The United States Department of Agriculture 2011)</td>
<td>2.17 (The United States Department of Agriculture 2011)</td>
<td></td>
</tr>
<tr>
<td>Leafy Greens</td>
<td>(grasses Approx 2.5 (Hong, et al. 2012)</td>
<td>.04 .049% spinach (40mg/100g) (The United States Department of Agriculture 2011)</td>
<td>.96 spinach (The United States Department of Agriculture 2011)</td>
<td></td>
</tr>
<tr>
<td>Pulses</td>
<td>.14 4.05 (Hong, et al. 2012)</td>
<td>.38 (Hong, et al. 2012) .053 (The United States Department of Agriculture 2011)</td>
<td>1.758 (peas)(The United States Department of Agriculture 2011) 2145L/kg</td>
<td>Soybeans</td>
</tr>
<tr>
<td>Milk</td>
<td>.296 (Chatzimpiros and Barles 2013)</td>
<td>.1 (Klop, et al. 2014) .093 (The United States Department of Agriculture 2011)</td>
<td>2.1 2.67 (The United States Department of Agriculture 2011)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Value</td>
<td>Source</td>
<td>Density (L/kg)</td>
<td></td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
<td>------------------------------------------------------------------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Beef</td>
<td>4.8</td>
<td>(Bongghi, Swaney and Howarth 2011)</td>
<td>8.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.215</td>
<td>(Williams 2007)</td>
<td>7.66</td>
<td></td>
</tr>
<tr>
<td></td>
<td>.21</td>
<td>(The United States Department of Agriculture 2011)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15400</td>
<td></td>
</tr>
<tr>
<td>Cheese (cheddar)</td>
<td>.473</td>
<td>(The United States Department of Agriculture 2011)</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3180</td>
<td></td>
</tr>
</tbody>
</table>
Appendix E: Hydroponics Treatment Processes

Nitrogen

Atmospheric Deposition

The accumulation of nitrogen through passive atmospheric function, such as rainfall deposition with a general range of nitrogen contained in precipitation (as ammonia or nitrate) being 0.5-3mg/L. This is highly variable, dependent on atmospheric conditions (Kadlec and Wallace 2009). Deposition may also occur from snowfall and dryfall, which is reference to organic particles being blown into a system.

Ammonia Sorption

Ammonia can be sorped to organic and inorganic substrate, via the process of cation exchange, this is generally a loose bond and dependent on water conditions will readily be resuspended in solution (Kadlec and Wallace 2009). Oxidised forms of nitrogen (nitrite, nitrate) do not readily bond to substrate (Kadlec and Wallace 2009).

Ammonia Volatilisation

Ammonia in solution is readily volatile, meaning a change of state from solution to gas phase will occur at rates dependent on atmospheric, water and system designs factors (Kadlec and Wallace 2009). Ammonia may only be volatilised if it is not ionised (NH₃), ionised ammonia (ammonium NH₄⁺) will not be volatile. There are a number of equations involved in working out the process of volatilisation of ammonia from a wetland system (or hydroponic media system) as outlined in (Kadlec and Wallace 2009), these are shown below.

Enzyme activity

Urea is a dominant form nitrogen when expelled from the body in urine, urea (NH₂)₂CO is catalysed in soils by the enzyme urease (Stevenson and Cole 1999), shown in the equation below;
Plants and soil microbes are attributed to creating the enzyme Urease, it is generally understood that the Urease enzyme is not the limiting factor for hydrolosis of urea and in most agricultural soils the this process of urea being converted to ammonia being within 0-7 days after application (International Plant Nutrition Institute (IPNI) 2015).

\[(NH_2)_2CO + H_2O \rightarrow CO_2 + 2NH_3\]

Equation 1

\[C_{AL} = \frac{C_{ATL}}{1 + K_d}\]

\[C_{AL} = \text{concentration of ammonia (NH}_3\text{) in the bulk water g/m}^3\]

\[C_{ATL} = \text{concentration of total ammonia in the bulk water, g/m}^3\]

Equation 2

\[J = k(C_{AL} - C_{AL}^*)\]

Equation 3

\[\frac{1}{K_L} = \frac{1}{k_L} + \frac{1}{HK_G}\]

\[C_{AL}^* = \text{water concentration of free ammonia that would be in equilibrium with the free ammonia in the bulk air}\]

H = Henry’s Law coefficient, dimensionless

\[K_L = \text{overall mass transfer coefficient, m/d}\]

\[k_G = \text{air side mass transfer coefficient, m/d}\]

\[k_L = \text{water side mass transfer coefficient, m/d}\]

The value of H is temperature-dependent.
Equation 4

\[ H = \left( \frac{2.395 \times 10^5}{T + 273.16} \right) \exp\left( \frac{-4151}{T + 273.16} \right) \]

Equation 5

\[ J = K_a C_{AL} \]

Equation 6

\[ J = K_a \left( \frac{C_{ATL}}{1 + K_d} \right) = k C_{ATL} \]

k = first order rate constant based on total ammonia, m/d

Two choices present themselves for the justification of ammonia volatilisation from a constructed wetland or hydroponics system, one based on the free ammonia concentration in solution (Equation 5) or one based on the total ammonia concentration in the water (Equation 6) (Kadlec and Wallace 2009).

**Microbial processes**

Heterotrophic and autotrophic microbes are involved in nitrogen processing in constructed wetland/hydroponic systems, heterotrophs consume organic substrate, whilst autotrophs consume inorganic substrates. Denitrification is often performed by heterotrophs whilst nitrification is carried out by autotrophs (Kadlec and Wallace 2009). Some of these microbial process equations are outlined below, taken from (Kadlec and Wallace 2009).

**Urea breakdown**

\[ \text{NH}_2\text{CONH}_2 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 \]

**Amino acid breakdown**

\[ R\text{CH(NH}_2\text{)COOH} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{CO}_2 \]
Nitrification (nitrosomonas)

$$2\text{NH}_4^+ + 3\text{O}_2 \rightarrow 2\text{NO}_2^- + 2\text{H}_2\text{O} + 4\text{H}^+$$

Nitrification (Nitrobacter)

$$2\text{NO}_2^- + \text{O}_2 \rightarrow 2\text{NO}_3^-$$

General dinitrification process

$$2\text{NO}_3^- \rightarrow 2\text{NO}_2^- \rightarrow 2\text{NO} \rightarrow \text{N}_2\text{O} \rightarrow \text{N}_2$$

There are also a number of other processes which may vary the nitrogen form in wetland systems outlined in (Kadlec and Wallace 2009), though these more complex relationships, are not shown here, for future reference on these see Kadlec and Wallace (2009).

**Phosphorus**

Microbial transformations of phosphorus in soils can change the availability of P to plants by the following; taken from Stevenson and Cole (1999). (Stevenson and Cole 1999)

1. By degradation of organic P compounds, with release of available inorganic phosphate
2. By immobilisation of available phosphates into cellular material
3. By promotion of the solubilisation of fixed or insoluble mineral forms of P, such as through the production of chelating agents

The rate of mineralisation of P in soils is determined by the common factors of soil microbiology; temperature, soil moisture, aeration, pH, cultivation, presence of plants, and fertiliser additions (Stevenson and Cole 1999). With inorganic phosphate being the main form plants uptake ($\text{H}_2\text{PO}_4^-$, $\text{HPO}_4^{2-}$). The rate of P immobilisation (inorganic $\rightarrow$ Organic) is found to be lessened in soils containing lower ratio of carbon content to organic P. This means that soils with high organic matter ratio to available inorganic phosphorus, immobilisation of this phosphorus is more likely to occur to
form organic unavailable phosphorus (Stevenson and Cole 1999). In a hydroponics system situation where there is a somewhat controlled carbon to phosphorus ration in the soil/media/solution, the immobilisation of phosphorus to organic form should be somewhat limited. The governing mobilisation of P from organic to plant available inorganic is given by the equation found below:

**Equation 7:** Immobilisation (organic P) and mobilisation (Inorganic P) of P

\[ P \leftrightarrow Inorganic\ P\ (H_2PO_4^-,\ HPO_4^{2-}) \]

The other process of converting organic phosphorus to plant available inorganic phosphorus forms is by the action of phosphatase enzymes. Two types of these enzymes exist; acid phosphatases and alkaline phosphatases, depending on the pH range of the soil.

**Equation 8:** The general equation of enzyme mobilisation of phosphate, R represents an organic carbon change (Stevenson and Cole 1999)

\[ RPhosphate + H_2O \rightarrow ROH + HPO_4^{2-} \]

The fixation of phosphorus in non-microbial processes i.e. forming Al, Fe, Ca compounds as detailed in the section: 3.3.1 Phosphorus, are not considered as important factors in the production and modelling of a hydroponic system. This is assumed due to the use of benign materials present in construction of these systems, and media/biofilter, and control over constituents in solution. The use of these benign materials ensuring the immobilisation of phosphorus to inorganic precipitates of phosphate does not occur.

**Appendix F: Hydroponics System Case Study**

Due to the lack of physical design and construction of a technology in the project direction, it was deemed worthwhile to implement an example of a small scale intensive food production system utilising waste nutrients and products where possible. A plan for a household scale pilot hydroponics system with provision for future aquaculture experimentation was created, allowing the investigation of design constraints and outputs of such a system. The goal; to further understand the design constraints of hydroponics, and the potential vegetable output in comparison to soil based...
cropping, with specific interest in the use of huma wastewater nutrients to feed the system nutrients and its potential to be scaled for application in future urban developments.

The aim; to form as close to closed loop cycling system as possible, processing nutrients derived from human urine, vermiculture leachate and effluent from an aquaculture farm, through bio-filters for the symbiotic production of fresh vegetables, on a small footprint. with construction to utilise recycled materials where possible to reduce cost and overall ecological footprint. Future proposed studies utilising the same system configuration of aquaculture fish food inputs to be tested include; waste derived worms from a vermiculture system or various species of fly larvae produced in a similar fashion from food or animal wastes.

Background

The connection of aquaculture to hydroponic techniques is termed ‘Aquaponics’ and has been around for many years with the technology and processes well developed in literature. The system showcases identification of a number of inefficiencies in the aquaculture industry; waste nutrient resource, water use inefficiency, and marrying these to inefficiencies in the food sector; water use inefficiency by flow through in irrigated soil cropping and the energy intensive production of synthetic nutrient for hydroponic and soil based growing operations. Aquaponics is a more holistically designed intensive food system, allowing the treatment of aquaculture production wastes, closed loop water cycles, and relative lower energy footprint food production (compared to traditional hydroponics).

Benefits;

- Systems generally use 90% less water than conventional growing techniques (http://www.volcanoveggies.com/benefits-of-aquaponics/) due to the closed loop cycling of water through the system, the only loss is through harvested produce and transpiration/evaporation (no flow through losses).
• Small scale intensive food production is beneficial for urban areas. Relatively low energy footprint (when compared to traditional hydroponics).
Appendix G: Nutrient Budgeting Techniques

Nitrogen


1. Take samples of soil to the depth of the root zone or wetting front, to determine the nitrate-N and ammonium-N values and soil water status, close to the time of planting the crop.

2. Use an appropriate (computer) model to determine the likely N availability through the crops life. Such models should include the local soil climatic (seasonal) data that influence mineralisation rates, an estimate of minerals available (organic) carbon or total soil N and growing season rainfall or rainfall probabilities, and have the grower set realistic yield and protein goals based on plant available water content of the soil and local experience.

3. Take plant samples during the growing season to indicate how well the crop is taking up the available N and if necessary and appropriate, suggest some extra N fertiliser to augment the soil’s supply, especially if a higher yield of protein grain is likely to be achieved with the available water.
Appendix I: Water Quality Protection Notes

The Western Australian Government has produced two documents for the guidelines for reusing nutrient rich waste water for irrigation, the main points of these notes applicable to this study have been reproduced here for convenience.

**Note 22; Irrigation with Nutrient Rich Wastewater**

**Purpose:**

To ensure irrigation with chemical/nutrient addition to water (or use of wastewater) does not incur environmental degradation. The note is focussed on fertigation with wastewater derived from agricultural industry, such as; abattoirs, animal holding yards, aquaculture, breweries and food processing.

The proposed use of any irrigation plans for large scale agricultural activity need an effective environmental management plan. The general points are outlined below regarding the safe and appropriate use of fertigation with wastewater, as outlined in note 22.

**Location information**

- 1: Fertigation should be confined to sites with the following attributes
  - Zoned for compatible activities in the local government planning scheme
  - Remote from areas where odours or spray drift may cause local nuisance
  - The minimum water table depth is two metres
  - Sufficient area of arable soil is available
  - Slope of land is less than one in twenty
  - Appropriate buffers are retained to sensitive water resources
  - The irrigated area is not subject to seasonal flooding

Restrictions near sensitive water resources
• 2: Wastewater should not be applied to land that is permanently or seasonally flooded, waterlogged, needs to be artificially drained, requires natural watercourses to be diverted or where it is likely to harm fringing vegetation to waterways and wetlands. These areas provide significant natural (but fragile) water quality benefits that sustain aquatic ecosystems and filter pollutants in stormwater runoff.

• 3: Irrigated sites should be placed sufficiently high in the landscape to minimise contamination risks to natural waters, wetlands and their associated vegetation, and to allow for the effective operation of filter zones and sediment control systems.

Consultation during the project planning stage

• 32: The department of health’s environmental health branch should advise on appropriate community safeguards if the wastewater may contain harmful micro-organisms. Where wastewater containing human or animal waste is planned to be used for irrigation, Department of Health advice should be sought on water quality and access restrictions to avoid human exposure to disease-causing organisms.

On-site storage of nutrient-rich water

• 39: Sufficient on-site storage for wastewater should be provided to allow for interruptions in the site water supply, rainfall events and the maintenance of irrigation equipment. This storage may be in purpose-built tanks or ponds that are lined to prevent seepage. Where practical the storage should be designed to capture any run-off from the fertigated land for recycling. Facilities should also be available for storage of wastewater during the wet season and when rainfall meets the water needs of the vegetation. A monthly water balance should be calculated to ensure adequate storage capacity, with free board against overflow.

Water and chemical application rates
• 41: Irrigation rates should be matched to seasonal evapotranspiration rates and the water uptake needs of the irrigated vegetation. The water needs of shallow-rooted plants can normally be calculated at 60-80 per cent of pan evaporation, depending on the water application method.

• 42: Irrigation rates should also consider site factors including soil infiltration capability, root-zone soil moisture content, irrigation method, land slopes and depth to water table. To minimise contaminant leaching, fertigation should not occur if the topsoil remains moist from past irrigation cycles or recent rainfall. Soil moisture meters linked to irrigation controllers provide for optimum watering management.

Application criteria for organic matter and trace elements

• 48: For wastewater with biochemical oxygen demand concentrations exceeding 150 milligrams per litre, effective chemical or biological stabilisation methods should be used prior to irrigation.

Nutrient application criteria

• 53: Nutrients should be applied to match the seasonal needs of the selected vegetation species. Fertigation should not occur at times when plants cannot effectively use available nutrients e.g. during dormancy periods, as nitrogen and phosphorus leaching is likely to result.

Monitoring and reporting

• 65: well-planned monitoring programs should assess water quality and contamination risk at three stages:
  
  A. The point of supply
  
  B. Lysimeter (sub soil) sampling for selected leachate contaminants in irrigated soils
C. The condition of local water resources upstream and downstream of the irrigated land.

Note 33: Nutrient and irrigation management plans

Nutrient and irrigation management plans (NIMPs) provide detailed guidelines for minimising water wastage and fertiliser losses when establishing or growing corps, gardens, trees and turf. NIMPs demonstrate that inputs such as water and fertiliser are well-matched to the plant growth cycle resulting in healthy plants and minimal contaminant leaching into the surrounding environment. Good planning and operational practice is vital for irrigated and fertilised plants so that water is used effectively and plants flourish with a maximum uptake of essential nutrients (principally nitrogen and phosphorus).

The following points should be covered in a NIMP to ensure safe and efficient water and nutrient application to any site as outlined in Water quality protection note 33.

A. watering schedules and nutrient application rate and frequency
B. site environmental factors such as soil types, climate and land slope
C. proximity of the intensive land use area to surface or ground water
D. potential travel pathways for any leached contaminants or eroded soils
E. site history (animal usage, fertiliser applications and waste disposal to land)
F. contaminant contributions from surrounding land areas
G. value and importance of local water resources to the community
H. present quality of local waters and their sensitivity to harm
I. protection measures employed onsite such as contaminant barriers, buffers and drainage controls.
The urine separating toilet

EcoFlush is the toilet that wastes extremely low volumes of flushing water. It works as a classic toilet, but has a urine separating bowl in the front, which makes it possible to save up to 80% water.

**Ecologic and economic**

EcoFlush is a dual flush toilet (0.3/2.5 liter). Out of 6 toilet stalls, 5 of them contains only urine. Flushing in the front urine bowl requires very little water (0% of a regular toilet). EcoFlush is mostly connected to separate tanks and individual sewage. Used mainly to save water and the ability to not empty the tank as often. It installs to new or already installed 1.0mm-outlet. Read more about the different possibilities in the installation manual.

**Details:**

- **Water connection:** Flexible stainless steel hose 1/2” R15
- **Flush volumes:** Big flush: 2.5 l, Urine flush: 0.3 l
- **Size:** Height toilet seat: 465 mm, Height: 820 mm, Width: 360 mm, Depth: 650 mm.
- **Urine outlet:** 50 mm ID. Delivered with the choice of valise or concealed outlet. Choice when ordered.
- **Outlet:** Fits regular 1.00 mm. If separate urine outlet, use 50 mm
- **Toilet seat:** Standard white plastic seat included.

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Wostman Ecology
Sprängsvägen 18 | 132 38 Sollentuna | SWEDEN
Tel +46 (0) 8 715 15 20 | Fax +46 (0) 8 715 13 21 | info@wostman.se | www.wostman.se

A Swedish company with long experience of eco-toilets and individual sewage.

Wostman Ecology AB