THESIS

CONSIDERATIONS FOR IMPLEMENTING SOURCE SEPARATION AND TREATMENT OF URINE, GRAYWATER, AND BLACKWATER

Submitted by

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ABSTRACT

CONSIDERATIONS FOR IMPLEMENTING SOURCE SEPARATION AND TREATMENT OF URINE, GRAYWATER, AND BLACKWATER

Source separation integrated with decentralized wastewater treatment offers the possibility of recovering nutrients, reducing release of micropollutants to the environment, and increasing water recycling more efficiently than centralized wastewater treatment. Nutrient effluent discharge limits and guidelines for wastewater treatment plants are becoming stricter, and nutrient removal or recovery is very costly for the large volumes present. This is driving innovation in wastewater treatment.

Three waste streams are identified for potential source separation and treatment: urine, graywater (non-kitchen sinks, showers/bath, and laundry), and blackwater (feces and kitchen wastewater). Urine is only 1% of the domestic wastewater stream, but contains 50-80% of the nutrients (nitrogen, phosphorus, and potassium) and the majority of pharmaceuticals and hormones. Blackwater has high organic and nutrient content, solids, and pathogens, and carries the remaining pharmaceutical/hormone residues. Graywater is the largest contributor to total volume but is the least contaminated of the three streams (low in nutrients and pathogens, but contains detergents and personal care products). In the absence of kitchen wastewater, graywater is also low in organic content. If these streams are separated at the source, maximum reuse of water can be achieved with minimal treatment (e.g. graywater). More importantly, avoiding dilution of nutrients and pharmaceuticals/hormones allows for more advanced treatment without excess cost.

A literature review led to the conclusion that the best options for urine treatment are struvite precipitation for phosphorus recovery and ammonia stripping for nitrogen recovery. Anaerobic digestion is ideal for blackwater and constructed wetlands can be used for graywater treatment. A neighborhood system of 500-1000 homes with decentralized treatment of urine, graywater, and blackwater is proposed. Almost complete recovery of nutrients could be achieved from urine, graywater could be treated and “locally” recycled, and energy and nutrients could be recovered from blackwater. A wastewater treatment system combining these components has not yet been tested in a pilot project; however, the individual treatment systems have been operated in pilot projects (or at larger scales) with similar waste streams. Modification of regulatory framework will be necessary to accommodate water reuse and effluent regulations at the proposed decentralized scale. Although nutrient reuse is a goal in the proposed system, farmer and consumer acceptance in the U.S. are unknown, but critical.

Technical obstacles to implementation include improving urine diversion toilets and treatment systems (primarily decreasing maintenance and increasing automation), managing urine scale (spontaneous precipitation in pipes), avoiding or capturing volatilized ammonia in urine transport, and better characterizing waste streams for treatment optimization. Research and development should focus on decreasing maintenance of urine diversion components and increasing automation. It is also necessary to better define influent quality and effluent goals and to optimize treatment systems for the proposed configuration. The waste stream produced from urine treatment also needs consideration, as it is likely to by highly concentrated with pharmaceuticals. A pilot project in the U.S. is recommended to resolve technical issues.

A preliminary review of costs reveals that, as is typically the case with new technologies, urine diversion toilets and struvite precipitation reactors have high investment and operational costs. Despite this, early estimates indicate that urine diversion systems are less costly than adding nutrient removal in wastewater treatment plants. In addition, the high costs of urine diversion systems are largely due to maintenance requirements and economies of scale (aspects that will change with research and development). In moving forward, it will be beneficial to conduct an economic analysis of greater breadth, with consideration of water reuse, energy use/carbon footprint, cost of fertilizer production, potential revenue of recovered nutrients, and economic externalities. It is also important to consider the reality of transition: that unless conventional wastewater treatment becomes more expensive (due to nutrient regulations) or homeowners are willing to cover the extra cost of a decentralized system with urine diversion, developers/homeowners are likely to choose tapping into the current system.

Although technical issues are pressing and infrastructure requirements are extensive for the proposed decentralized system, the technical, social, and regulatory issues are not insurmountable. The potential in improved treatment (nutrient and micropollutant removal), energy generation and increased water recycling suggests moving forward with research and development in the U.S., including a pilot project.

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Thanks, first and foremost, to my advisor, Dr. Sybil Sharvelle for her guidance and generosity. Her passion for both teaching and research in sustainable water management is inspiring. Dr. Brian Bledsoe has also provided invaluable inspiration and instruction during my studies at Colorado State University. Thanks also to Chris Goemans, for taking the time to serve on my committee and guide this research.

This research, which began prior to the birth of my first child and now finishes the week my second turns 2, would not have been possible without the patience and confidence of Dr. Sharvelle, and, most notably, my husband Yarrow.

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BOD- Biological Oxygen Demand

CSO- Combined Sewer Overflow

COD- Chemical Oxygen Demand

CECs- Contaminants of Emerging Concern

PPCPs- Pharmaceuticals and Personal Care Products

SSO- Sanitary Sewer Overflow

TSS- Total Suspended Solids

WWT- Wastewater Treatment

WWTP- Wastewater Treatment Plant

UD- Urine Diversion

UDT- Urine Diversion Toilet

UDDT- Urine Diversion Dehydration Toilet

U.S. EPA- United States Environmental Protection Agency

Chapter 1

1.1 Introduction

Sustainability in wastewater management involves not only protection of human health and the environment, but also efficient and effective long-term water management, minimization of energy requirements, and closing the loop on natural resource cycles. To address future demands of wastewater treatment (e.g. contaminants of emerging concern, more stringent nitrogen and phosphorus regulations, increased population, water quality impairments associated with combined or sanitary sewer overflows, etc.), improvements to conventional, end-of-pipe treatment can be made, and/or source separation of wastewater streams can be implemented. Of these options, source separation has emerged as an innovative option for addressing aging infrastructure with great potential for meeting sustainability criteria defined by the U.S. EPA (U.S. EPA, 2010a). In particular, source separation can be an efficient way to address the discharge of nutrients into the environment after human consumption (Figure 1).

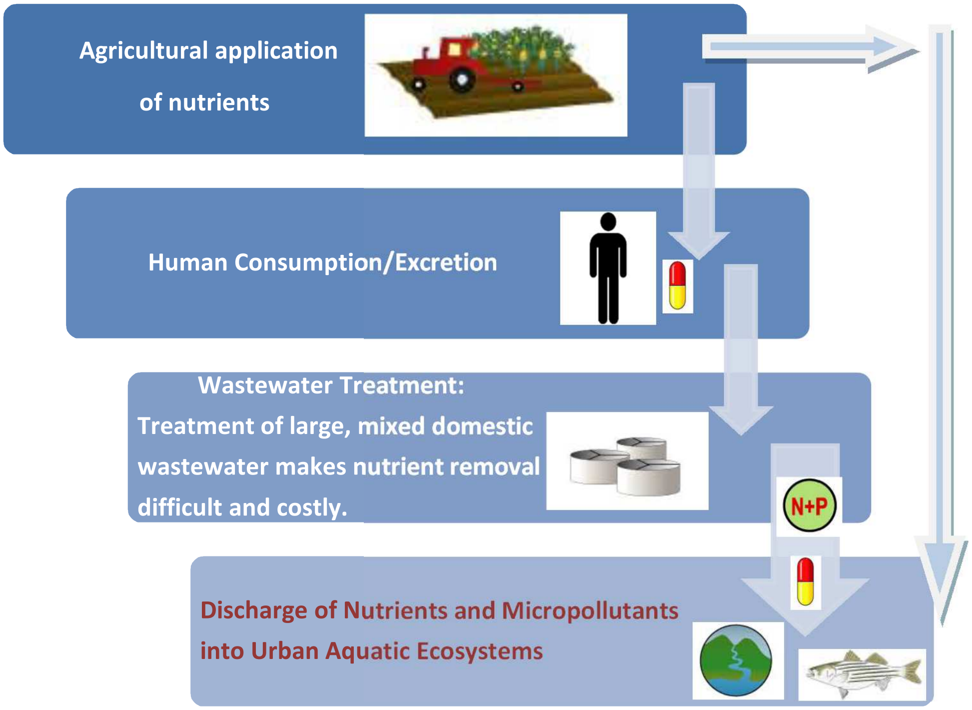


Figure 1 Flow of nutrients from agriculture to aquatic ecosystems

On the domestic scale, three wastewater streams can be differentiated: graywater, blackwater, and urine (also called yellow water if diluted with flushwater). Other differentiations of domestic wastewater have been defined in the literature, such as brownwater (feces, toilet paper, and flushwater), beigewater, and fecal sludge (Larsen et al., 2013). Graywater is defined in this report as wastewater from showers, baths, laundry, and non-kitchen sinks. Blackwater is a mix of feces, toilet flush water, and kitchen wastewater. Urine and feces can be separated with urine diversion (UD) toilets (Figure 2) or urinals. In UD toilets, the bowl has a divider to separate urine and feces. In some, the urine drain closes prior to flushing to allow for undiluted collection.

Figure 2 Urine diversion toilet: Roediger NoMix

Feces, urine, and graywater differ greatly in terms of nutrient content, chemical oxygen demand (COD), biological oxygen demand (BOD), and total suspended solids (TSS). Conventional wastewater treatment combines graywater, blackwater, and urine. The mixture is then transported to a wastewater treatment plant (WWTP), where it is treated to regulatory standards before release into the environment. Alternatively, the mixture is treated in a septic system on a decentralized scale. Separation of these wastewater streams provides the opportunity for individualized treatment of each to maximize water reuse, capture nutrients, and minimize energy input for wastewater management. Developing appropriate technology and planning for unintended consequences is a complex problem (especially because current wastewater treatment strategies and infrastructure are well established), but despite challenges, the benefits of decentralized wastewater treatment are driving the path forward.

1.2 Background: Water Environment Research Foundation Project

The foundation of this work was an investigation of the status of source separation and treatment of anthropogenic urine for the Water Environment Research Foundation (WERF). The published report (Fewless et al., 2011) included an extensive literature review, identified barriers for implementation, noted key benefits of urine separation, presented pilot projects, and provided a path forward for implementing UD in the United States. Source separation and treatment of urine is becoming more interesting to environmental and wastewater process engineers because, although it is only 1% of domestic wastewater, it contains 50-80% of the nutrients and a majority of excreted pharmaceuticals and hormones. Separating this relatively small fraction can enable more efficient treatment.

The world-wide search and review of urine diversion knowledge and technology indicated urine source separation as a means to recover nutrients, conserve water, and decrease overall energy requirements for both nutrient and micropollutant removal as compared to conventional wastewater treatment. Separating urine enables a means to partially close the nutrient cycle (Figure 3).

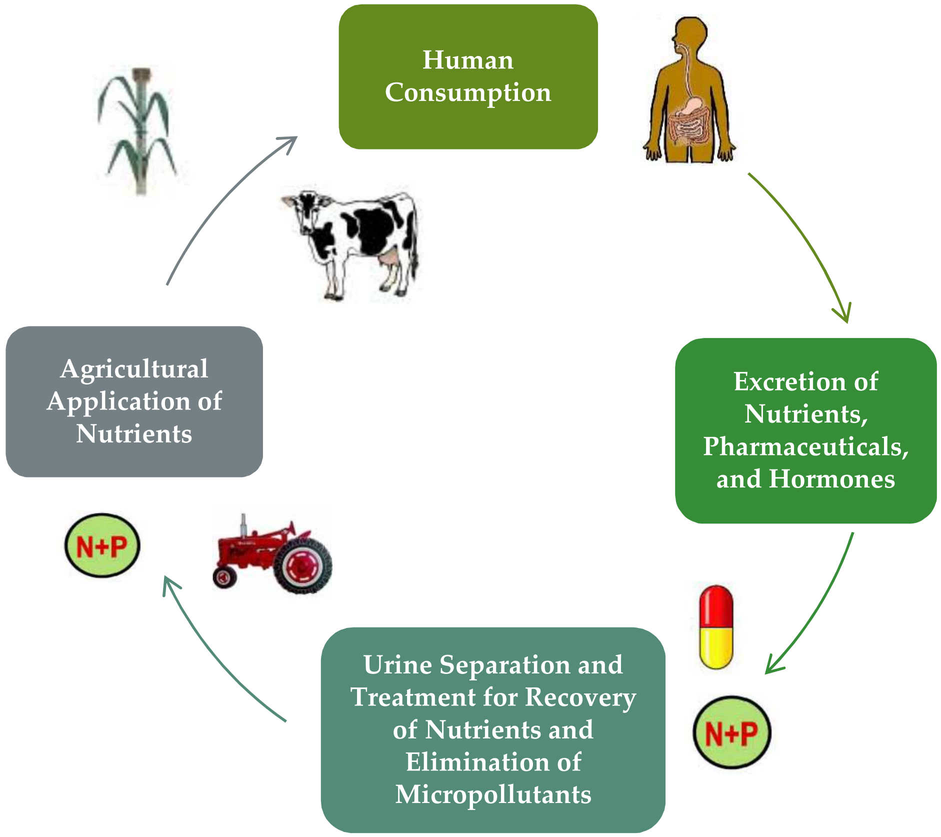


Figure 3 Closing the nutrient cycle with source separation

Initial findings also indicated that urine diversion may be a sustainable method, in combination with other source-separation/decentralized treatment methods, to address deteriorating water infrastructure in the United States. Research has matured beyond the laboratory scale to include pilot projects in office buildings, private homes, and schools, but the majority of the projects relevant to development of urine diversion in the U.S. have been conducted in Europe. Despite high social acceptance in Europe, and the advancement to date of urine diversion technology, continued research is necessary to create marketable products (by addressing technical issues), develop life cycle and/or cost-benefit analysis (relative to U.S. parameters), determine social acceptance in the U.S., and assess the most appropriate means and setting for urine treatment.

1.3 Questions Generated by the Water Environment Research Foundation Project

A key question resulting from the WERF project is how urine diversion could be implemented in the U.S. (in a decentralized context). Various pilot projects have attempted to do this in other parts of the world, with the goal of maximizing efficiency and nutrient/resource cycling, but precedence among choices of technology and scale of implementation are only just beginning to become evident. Many pilot projects have only tested the functionality of UD toilets, have employed direct application of urine to agriculture (rather than an advanced treatment to recover nutrients), or have sent remaining waste streams to established wastewater treatment facilities (rather than treat for reuse). Graywater and blackwater have also been treated with membrane bioreactors in at least one pilot project.

Aerobic treatment of graywater is common in decentralized wastewater treatment, regardless of separation of urine and blackwater. In addition, studies are beginning to emerge in which anaerobic treatment of kitchen wastewater and brownwater show promise. Because of recent advances in aerobic treatment of graywater and anaerobic treatment of blackwater (at Colorado State University and internationally), the obvious question of how to design a system with both these treatments and urine treatment emerged. The resulting questions became:

- How does urine diversion, on its own or in the context of de- or semi-centralized wastewater treatment, compare to maintaining or upgrading current U.S. wastewater collection and treatment practices (for more stringent nutrient removal or for micropollutant removal)?
- Can separate treatment of urine, graywater and blackwater maximize water reuse and energy/nutrient recovery?
- Which technologies can maximize benefits (water reuse, energy/nutrient recovery) and minimize cost?
- What do systems that integrate urine separation with resource recovery into existing U.S. infrastructure look like?
- How can we assess the costs and benefits of a system with source separation? Can benefits such as micropollutant removal, nutrient recovery, and water demand reduction achieved via water recycling be quantified?
- Are the technical issues evident in UD pilot projects manageable?

1.4 Objectives

An initial goal of this work was to conceptualize a decentralized wastewater treatment system which included urine separation and to develop costs which would be compared to conventional wastewater treatment. However, after initial investigations of urine treatment technology and pilot projects it became evident that the urine separation technology was too costly (largely due to maintenance and economies of scale) to merit a full economic analysis at this time. Thus the overarching goal of this current work evolved to be an investigation of technical, social, and economic aspects of combining urine separation with aerobic treatment and reuse of graywater and anaerobic treatment of blackwater. Specifically, to explore how urine separation affects graywater and blackwater treatment, and the potential for decentralized domestic wastewater treatment of urine, graywater, and blackwater to sustainably address emerging concerns in wastewater management (with an emphasis on application in the U.S.). Combined treatment of these streams is possible on a decentralized scale, but separating urine at the source provides a unique opportunity for nutrient recovery and isolation of the majority of pharmaceuticals/hormones. It was also important to consider cost. If the same goals can be achieved through centralized WWT as currently managed, there is little reason to innovate.

The specific objectives of this work are thus to:

- Evaluate options for decentralized treatment to be implemented in conjunction with source separation of urine
- Assess the most important economic, social, and technological barriers
- Evaluate risks and unintended consequences
- Develop guidance for further development of environmentally and economically sustainable wastewater treatment alternatives

Chapter 2 provides a basic description of urine, graywater and blackwater, and how separate treatment can address issues in wastewater management. Chapter 3 points to the most practical treatment options available at this time for decentralized systems and proposes a scale for implementation. Preliminary design information is also offered. Chapter 4 summarizes technical, social, and regulatory barriers, as well as risks and unintended consequences. Chapter 5 provides cost information and Chapter 6 includes a final discussion and guidance for continued research.

Chapter 2: A Review of Waste Source Separation Including Resource Recovery

2.1 Characteristics of Graywater, Blackwater, and Urine

Graywater, blackwater, and urine differ substantially in volume, strength, and quality. Urine contains the most nutrients and its isolation enables recovery from a much smaller volume. Graywater is the largest portion of domestic wastewater, yet is minimally contaminated and thus appropriate for reuse. Light graywater, which excludes kitchen wastewater, is especially low in solids, organic content and nutrients. Blackwater contains the most organic matter, making it ideal for energy recovery. Table 1 provides a brief summary of the quantity and quality of urine, blackwater, and graywater, and details are provided throughout this chapter. Transport and storage issues are discussed more thoroughly in Chapter 3.

Table 1 Summary of urine, blackwater, and graywater: quality, quantity, and concerns in treatment design

	URINE	BLACKWATER	GRAYWATER
SOURCES	Toilet, urinals (with or without flush water)	Toilet (with flush water), kitchen sink, dishwasher	Non-kitchen sinks, bath/shower, laundry
PERCENT OF TOTAL[1]	1	45 (kitchen contribution is almost half of this)	54 (bath and shower contribute 28% of total domestic wastewater)
PRIMARY CONTAMINANTS	Nutrients, pharmaceuticals, hormones, salts	Solids, organic matter, pathogens, nutrients	Personal care products, detergents
TREATMENT/NUTRIENT RECOVERY	Nutrient recovery, removal of micropollutants	Energy generation, nutrient recovery	Water reuse
TRANSPORT AND STORAGE ISSUES	Urine scale, ammonia losses	High solids transport, Recovered nutrients	How to store graywater in non-growing season

[1] Friedler et al (2013)

Vandegrift (2014) reports 20 gallons/capita-day for the graywater sources listed in table 1, and 17 gallons/capita-day for blackwater (also see Appendix A). These values are from a residential water use study conducted by the city of Fort Collins, Colorado.

The visual representation of the relative volumes and concentrations of nutrients, BOD, COD, and TSS shown in Figures 4 and 5 demonstrates the potential for improved treatment efficiency with source separation. Graywater is the largest fraction of domestic wastewater, but is minimally contaminated and therefore suitable for reuse without extensive treatment. Kitchen wastewater and brownwater (feces, flushwater) contain the highest levels of organic matter which can be converted to energy. Urine contains high levels of nutrients in a very small volume.

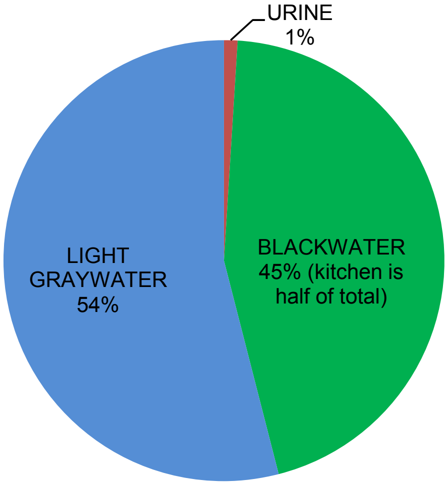


Figure 4 Relative proportions of urine, light graywater, and blackwater

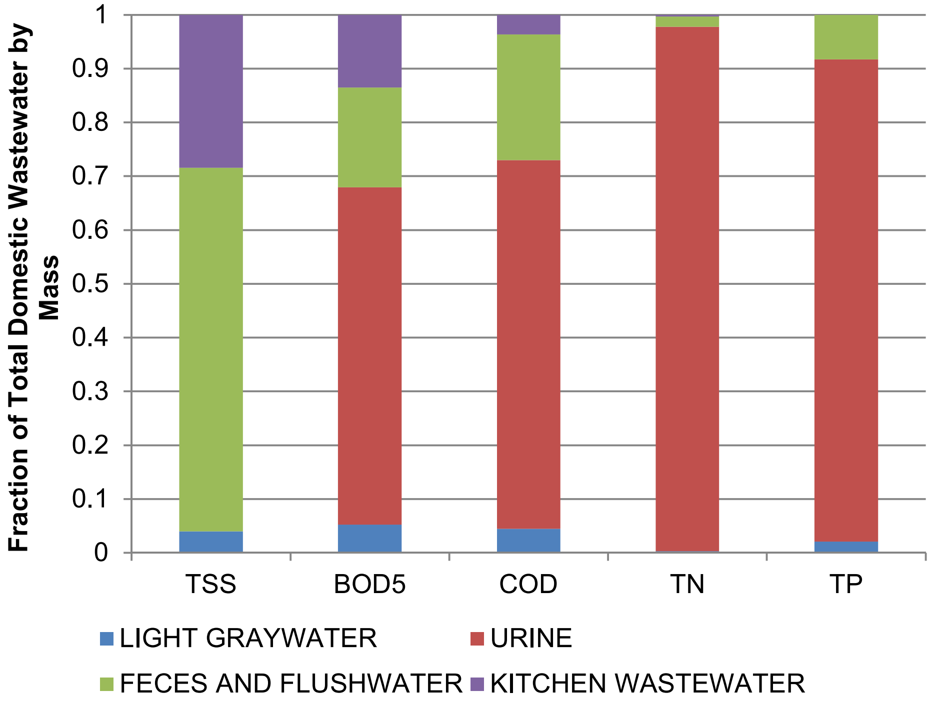


Figure 5 Comparing important water quality parameters of domestic wastewater fractions

*Light graywater values from Gross et al 2007 (graywater without kitchen sources)
**Urine and feces values from Larsen et al 2013; originally reported in g/p-d
***Feces and flush water estimated to be 7L/day to convert to mg/L

2.2 Urine Quality

A description of urine quality (Table 2) illustrates the value of urine diversion and informs treatment design (also see Figure 5 above). On average, an adult produces 0.8-1.5 L of urine per day, and a child produces approximately half this amount (WHO, 2006). 95% is water and 5% is dissolved salts (Udert et al., 2013). The quality of urine excreted per capita depends on diet, but common design figures have emerged in the scientific community. While urine is only 1% of total domestic wastewater, it contributes 50-80% of the total nutrients (75-80% of the nitrogen, 50-55% of the phosphorus, and 70% of the potassium), and the majority of the pharmaceuticals and subsequent metabolites (Larsen and Gujer, 1996; Winker et al., 2008). Macronutrients (nitrogen, potassium, phosphorus, and sulfur) consumed by adults are largely excreted (Figure 5). In total, this amounts to 4 kg N/cap/yr., 0.36 kg P/cap/yr. and 1.0 kg K/cap/yr. excreted in urine (Von Munch and Winker, 2009). Remaining anthropogenic nitrogen and phosphorus, pharmaceuticals, and natural and artificial hormones are excreted in feces. The exact proportion of pharmaceuticals and subsequent metabolites excreted in urine and feces respectively is still under investigation, but studies indicate that urine source separation alone would provide an effective means for removal of these compounds from wastewater (Lienert et al., 2006; Winker et al., 2007).

Table 2 provides a summary of urine quality:

Table 2 Urine quality (N/A is not available)

Substance	Concentration (mg/L) NASA 1990	Concentration (mg/L) Fresh Urine Eawag (2007)	Average Concentration (mg/L) for Fresh Urine Udert et. al. (2006)
Urea (H_2NCONH_2)	4800-23300	N/A	7700
Chloride	1870-8400	4970	3800
Sodium	1170-4390	3450	2600
Potassium	750-2610	2737	2200
Total Phosphorus	470-1600	800-2000	740
Total Ammonia	200-960	463	480
Total N	N/A	8830	9200
Sulfur, organic	48-470	N/A	N/A
Sulfate	N/A	N/A	1500
Calcium	30-390	233	190
Magnesium	47-160	119	100
pH	N/A	6.2	6.2
COD	N/A	N/A	10000

Urine has a high salt content (Table 3), and therefore the removal of urine from wastewater has the potential to improve the quality of reuse water for irrigation. This is because impacts of salinity and sodicity have emerged as potential drawbacks for reclaimed wastewater reuse (Parsens et al., 2010).

Table 3 Sodium, calcium, and magnesium concentrations of urine and reclaimed wastewater

	Fresh urine (Von Munch and Winker, 2009)	Fresh Urine (NASA, 1990)	Reclaimed wastewater: Colorado (Qian et al., 2005)	Reclaimed wastewater: California (Sheikh et al., 1990)	Reclaimed wastewater: Central Iran (Heidarpour et al., 2007)	Reclaimed wastewater: Texas (Duan et al., 2007)
Na (mg/L)	3450	1170-4390	99	78-415	202	117
Ca (mg/L)	230	30-390	61	17-61	64	52
Mg (mg/L)	120	47-158	15	16-40	24	24

Pathogens are not present in urine in the bladder of a healthy human (Von Munch and Winker, 2009). (See Wolfe et al 2012 for possible evidence of bacteria in urine of healthy people. It is noted, however, that they may not be viable or may be due to bacterial infection). Of the few diseases transmitted by pathogens in excreted urine, only *Schistosoma haematobium* is of concern, and is only of concern in areas where this is an endemic disease (primarily Africa and the Middle East) and in cases when urine is directly applied to agriculture (WHO, 2006). The majority of pathogens, should they be present in the population, are excreted via feces. As a result, sterilization of urine is generally only necessary if potential for cross-contamination exists. It would be necessary, however, to ensure that any fertilizer products recovered from urine are safe for agricultural application. Finally, the concentration of heavy metals present in urine is typically much lower than other wastewater streams (blackwater, graywater) and in other organic fertilizers (Jonsson, 1997).

Change in urine quality during storage

Urine from a healthy person is generally stable and free of microorganisms. Once urine has been diverted and stored, however, contact with bacteria within the collection system or via cross-contamination with feces is likely (Udert et al., 2006). The high fraction of biodegradable organic compounds may be a substrate for aerobic or anaerobic microorganisms in urine, resulting in urea hydrolysis, among other impacts. Microbial urea hydrolysis, mineral precipitation, and ammonia volatilization are the primary contributors to the transformation of urine once it has been excreted, diverted, and stored (Udert et al., 2006)

Urea-hydrolyzing bacteria have the greatest influence on the alteration of urine quality, by catalyzing the hydrolysis of urea to ammonia and bicarbonate. Prior to this transformation, approximately 85% of the nitrogen in urine is fixed as urea and approximately 5% as ammonia, compared to 90% as ammonia after urea hydrolysis (Udert et al., 2006).The effects of this shift include a rapid rise in pH, from about 6 to 9, volatilization of ammonia (should the urine not be in a closed storage tank designed to minimize volatilization), and the precipitation of struvite, hydroxyapatite, and occasionally calcite (Udert et al., 2003). Calcite precipitation tends to occur when urine is highly diluted with tap water. These precipitates are referred to as urine scale (management of this technical issue is discussed in Chapter 3).

Table 4 Composition of fresh and stored urine (N/A is not available)

Parameter	Fresh urine[1]	Fresh urine[2] (average values)	Fresh urine[2] (data range)	Stored urine[2] (simulated values)
pH	6.2	6.2	N/A	9.1
Total Nitrogen (mg/L)	8830	9200	N/A	9200
NH_4^+ and NH_3 (mgN/L)	460	480	N/A	8100
NO_3 and NO_2 (mgN/L)	0.06	N/A	N/A	N/A
COD (mg/L)	6000	10,000	N/A	10,000
TP (mg/L)	800-2000	740	N/A	540
K	2740	2200	1300-3100	2200
SO_4 (mg/L)	1500	1500	N/A	1500
Na (mg/L)	3450	2600	1800-5800	2600
Mg (mg/L)	120	100	N/A	0
Cl (mg/L)	4970	3800	2300-7700	3800
Ca (mg/L)	230	190	N/A	0
Urea (mgN/L)	N/A	7700	N/A	0
Total carbonate	N/A	0	N/A	3200
Alkalinity	N/A	22	N/A	490

[1]Von Munch and Winker, 2009; [2]Udert et al., 2006

A shift in pH and subsequent precipitation has several impacts on the choice of urine treatment/reuse technologies. First, up to 33% of total ammonia is volatile, so ammonia losses and odor issues will occur during transport and land application of stored urine (the buffer capacity is so high that acid addition to prevent this is uneconomical). Another issue is a shift in phosphorus concentration, which is a strong function of precipitation. In undiluted urine, 30% of soluble phosphorus is incorporated in the solid phase of the precipitates (Udert et al., 2003), but this percentage increases with dilution. Phosphorus precipitation is limited by calcium and magnesium concentrations, and typically all calcium and magnesium is precipitated in stored urine. The hardness and volume of flushing water are therefore factors to consider in urine collection choices as the partitioning of phosphorus into soluble and solid phases is important when considering possible recovery methods. Addition of calcium and magnesium is also a promising phosphorus recovery method (see struvite precipitation in Chapter 3). Precipitation may affect the potassium concentration, but not notably (Udert et al., 2006).

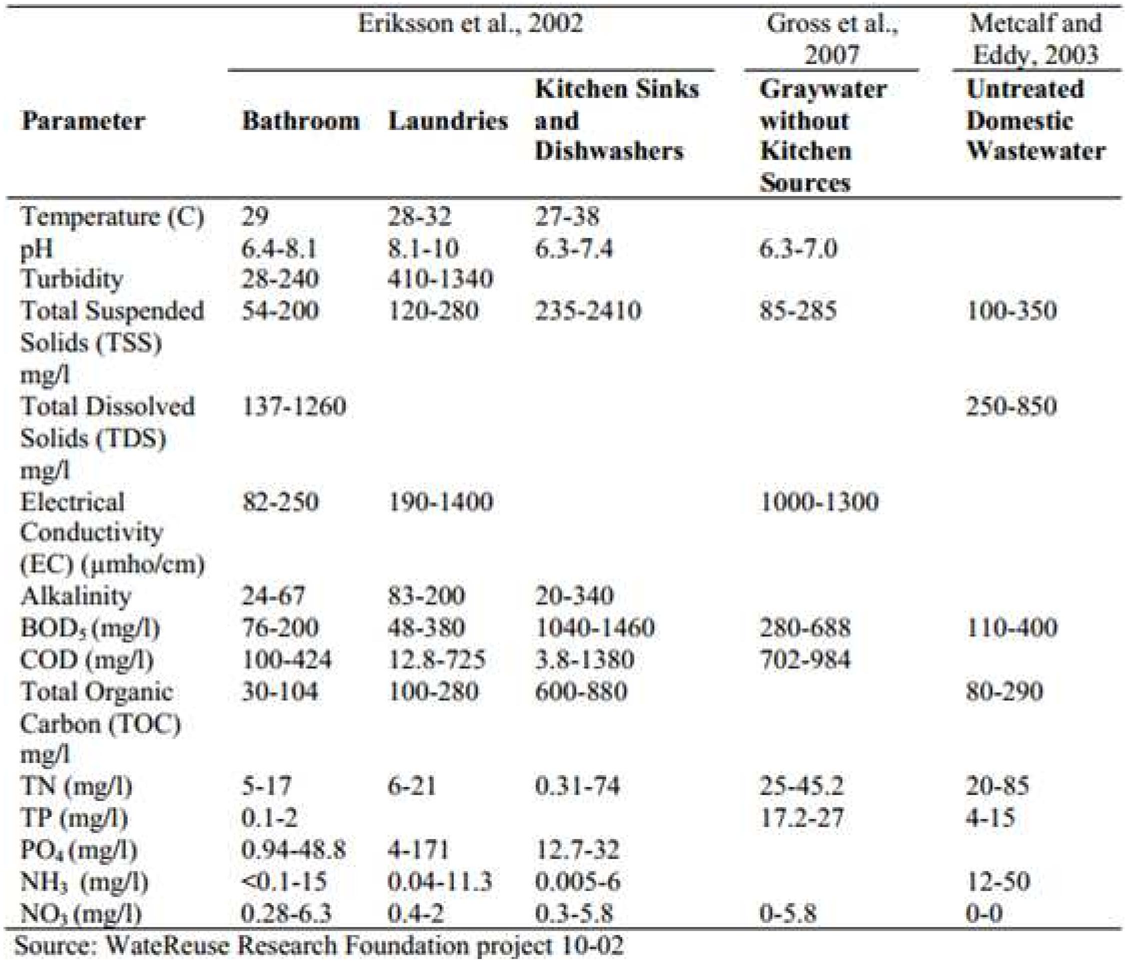
Both precipitation and biological reduction affect sulfur concentration. Precipitation is negligible, but due to the seriousness of sulfide gas production, the biological reduction of sulfur necessitates further investigation (Udert et al., 2006). Because sulfur is the most favorable electron acceptor in stored urine (nitrate, nitrite, and oxygen are absent and iron concentrations are very low), sulfate reducing bacteria (if present) will reduce sulfate to hydrogen sulfide. Hydrogen sulfide is a corrosive gas with issues related to both odor and toxicity.

Removal of pathogens occurs during storage, prior to the struvite precipitation process. During storage of urine, both a natural rise in pH and other processes have a sanitizing effect (Von Munch and Winker, 2009). Guidelines on urine storage are widely available in the literature, as direct reuse of urine is a promising option for nutrient recovery in developing countries.

2.3 Graywater Quality

Graywater (in this research) is wastewater from non-kitchen sinks, laundry, and showers. In the literature, this is referred to as “light graywater”. “Dark graywater” includes kitchen sinks, which are the highest source of pollutants when compared to other graywater sources (Friedler et al., 2013). Kitchen wastewater contributes 40-60% of the pollutant load (VSS, COD, BOD, total oil, and methylene blue active substances) according to Almeida et al. (1999) and Friedler (2004) (also see Figure 5). The physical and chemical quality of graywater cited in literature varies and is dependent on its source. This is because quality is affected by cleaning and bathing product choices, the number of people in a particular household and other sink disposal practices and personal habits (Erikkson et al., 2002).

In general, graywater is low in solids and nutrients when separated from urine and blackwater/kitchen wastewater (Table 1 and Figure 5 above). According to Friedler et al. (2013), BOD ranges between 5 and 900 mg/L and COD ranges between 23 and 1600 mg/L. The variability of these values relative to source is made evident in figure 6. Biodegradability is low and there can be a high presence of micropollutants (cleaning products, shampoo/soap, perfumes, cosmetics, etc.). Concentrations of surfactants (from detergents) vary as expected depending on graywater sub-stream. If phosphorus is present in detergents, dishwashers and washing machines can contribute a significant P load, but there is a general push towards eliminating phosphates from detergents. Also, heavy metals (from plumbing) and salts (from detergents) may be high in graywater. Pathogens are generally lowest in light graywater (as compared to all other domestic sources), but washing hands after using the toilet and skin/mucus pathogens removed during a bath/shower can be present (Briks and Hills 2007 or Friedler et al., 2013). (For more, see Maimon et al. (2010) for fecal indicator bacteria or Roesner et al. (2006) for microbial bacteria of concern in graywater.) Fecal contamination will certainly occur if cloth diapers are included in the household wash, so this may need to be considered in the development of a treatment system. Temperature fluctuations and flow variability of graywater are also concerns in treatment design.



	Eriksson et al., 2002			Gross et al., 2007	Metcalf and Eddy, 2003
Parameter	**Bathroom**	**Laundries**	**Kitchen Sinks and Dishwashers**	**Graywater without Kitchen Sources**	**Untreated Domestic Wastewater**
Temperature (C)	29	28-32	27-38		
pH	6.4-8.1	8.1-10	6.3-7.4	6.3-7.0	
Turbidity	28-240	410-1340			
Total Suspended Solids (TSS) mg/l	54-200	120-280	235-2410	85-285	100-350
Total Dissolved Solids (TDS) mg/l	137-1260				250-850
Electrical Conductivity (EC) (μmho/cm)	82-250	190-1400		1000-1300	
Alkalinity	24-67	83-200	20-340		
BOD_5 (mg/l)	76-200	48-380	1040-1460	280-688	110-400
COD (mg/l)	100-424	12.8-725	3.8-1380	702-984	
Total Organic Carbon (TOC) mg/l	30-104	100-280	600-880		80-290
TN (mg/l)	5-17	6-21	0.31-74	25-45.2	20-85
TP (mg/l)	0.1-2			17.2-27	4-15
PO_4 (mg/l)	0.94-48.8	4-171	12.7-32		
NH_3 (mg/l)	<0.1-15	0.04-11.3	0.005-6		12-50
NO_3 (mg/l)	0.28-6.3	0.4-2	0.3-5.8	0-5.8	0-0

Source: WateReuse Research Foundation project 10-02

Figure 6 Graywater quality (Sharvelle et al., 2013)

Additional information about graywater quality can be found in Sharvelle et al. 2013, Jefferson et al 2004, and Friedler et al. 2013. Graywater research is a rapidly growing field, largely due to water reuse applications, so there is ample information in published literature on graywater quality and treatment. Most of the available qualitative data are for mixed graywater, but an increasing number of studies are differentiating “light” and “dark” graywater. Aside from quality, a great deal of information is available on treatment, reuse (irrigation and flushing water), and concerns in reuse such as safety, effects on soil, and persistence of PCPs, salts, pathogens, and surfactants.

2.4 Blackwater Quality

Blackwater is defined in this study as wastewater from kitchen sinks and feces. The feces portion (along with flushing water and toilet paper) is often referred to as brownwater. Defining characteristics of brownwater include high organic and solids content, pharmaceutical and hormone residues, high levels of pathogens and indicator microorganisms, and lower nutrient loads than urine (Figure 5 above). Toilet paper contributes TSS and COD, and isn't easily degraded because of its cellulose content (Friedler et al., 2013).

Kitchen sink wastewater is often paired with brownwater because of its high organic content (relative to other graywater streams). Kitchen sink and dishwasher wastewater contains food residues, cleaners (detergents, drain cleaners, bleach, etc.), and oils/fats. It is the most polluted of the graywater streams (VSS, COD, BOD, total oil and methylene blue active substances) (Friedler et al. (2013) and Figure 6), so combining it with brownwater also creates a "cleaner" graywater stream. Kujawa-Roeleveld and Zeeman (2006) and Zeeman et al. (2008 and 2011) have additional information on this topic.

2.5 Summary

The main driver for urine source separation is the fact that it carries the largest proportion of nutrients (Figure 5) and pharmaceutical/hormone residues (greater than half), but is the smallest in volume (Figure 4). Blackwater (feces and kitchen wastewater) has high organic and nutrient content, solids, and pathogens, and carries pharmaceutical/hormone residues. Graywater is the largest contributor to total volume, but is the least contaminated of the three streams. Light graywater has the highest amount of detergents and personal care products, but is low in nutrients and pathogens. Without kitchen wastewater, it is also low in organic content.

2.6 Emerging and Key Issues in Wastewater Treatment Addressed through Waste Source Separation

Source separation offers a potential for improved effluent quality, more energy efficient treatment (by treating smaller, more contaminated volumes specific to end use), maximizing water reuse while minimizing transport of reclaimed water, and creating opportunities to recover nutrients and generate energy from high organic wastewater streams. Source separation of urine and decentralized treatment therefore shows promise in regards to addressing the following key or emerging issues in wastewater and nutrient management:

- Combined sewer overflows, sanitary sewer overflows, failing septic systems, and settling in sewers resulting from water-saving devices: by providing an alternative to centralized systems
- More stringent nutrient discharge regulations
- Phosphorus supply concerns
- Increased awareness of contaminants of emerging concern (pharmaceuticals, hormones, personal care products, etc.)
- Increased interest in water reuse
- Interest in environmental sustainability

2.6.1 Environmental Sustainability

Source separation of urine, blackwater, and graywater has been under investigation since the 1990s, but until recently was only considered for wastewater treatment in rural and under-developed areas (Larsen, 2009). Recent developments, however, have revealed that source separation could be a solution for sustainable wastewater management in urban and industrialized areas as well (Hellstrom et al., 2008; Larsen et al., 2009; Remy and Jekel, 2008). Brown et al. (2010), for example, in an investigation of sustainable wastewater management strategies for Melbourne, Australia (a large city with primarily centralized wastewater treatment), included urine separation as a key component in meeting sustainability criteria through decentralized treatment. While identified as a priority, urine separation has not been widely adopted in this area at this time due to the major infrastructure modification required.

Many of the environmental benefits of source separation are associated with the ability to treat each wastewater stream in a manner specific to its quality and end use. This has the potential for more efficient treatment and resource recovery when compared to mixing these streams and treating a large volume through conventional WWT for discharge into surface water. Graywater can be minimally treated and reused for irrigation or toilet flushing, decreasing the use of potable water (which requires high levels of treatment at an environmental cost) for these purposes. Treating and reusing water close to the source has obvious benefits. Blackwater, which contains pathogens and high levels of organic matter, can be used to generate energy through anaerobic digestion. Nutrients can be recovered from urine. In addition, source separation may provide a more efficient way to decrease the release of contaminants of emerging concern into the environment (as compared to advanced wastewater treatment, such as membrane bioreactors).

In summary, elements of source separation of domestic wastewater address the following goals of the U.S. EPA for increasing the sustainability of water infrastructure (U.S. EPA, 2010a):

- *Resource recovery and/or energy production*: Nutrients can be recovered from source-separated urine and energy can be produced from high BOD waste (e.g. black water).
- *Energy efficiency and potential to reduce costs associated with water conveyance and treatment*: Source separation prevents dilution of nutrients and contaminants of emerging concern, and thus can be a way to minimize exergy (extractable/utilizable energy) losses by reducing energy/chemical treatment requirements.

- *Water conservation and reuse*: Less contaminated wastewater streams can be minimally treated specific to the end use without the need for large-scale treatment and transport infrastructure. Graywater (and/or captured rainwater) can be reused for irrigation and/or toilet flushing. Urine diversion toilets usually have dual flush capabilities, and no or minimal flush water is desirable for urine treatment. Waterless urinals also conserve water.
- *Minimization of post-treatment water quality deterioration*: Reduces combined sewer overflows (CSO's) and sanitary sewer overflows (SSO's), provides an alternative to on-site systems (e.g. septic tanks), and can more efficiently address nutrients and contaminants of emerging concern (CEC's).

For true environmental benefit analysis, much work is necessary to quantify and compare source separation and decentralized treatment to current centralized infrastructure. Energy and water use are major factors, but nutrients and contaminants of emerging concern will also play into how this analysis is executed (e.g. considering the environmental harm of releasing excess nutrients and micropollutants into the environment). A good starting point may be to first consider the cost and environmental impact (in terms of resource use, carbon footprint, etc.) of nutrient removal/recovery in WWTPs.

2.6.2 Nutrient Cycle

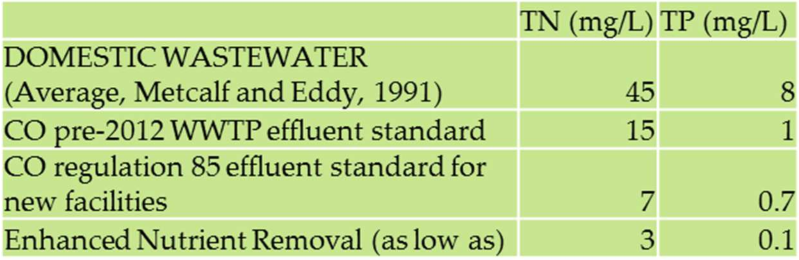
Nitrogen (N) and phosphorus (P) are essential for human survival because they are necessary for plant growth (and, by extension, feeding cattle and other animals consumed by humans). However, virtually all of the nitrogen and phosphorus consumed by humans is excreted (Larsen et al., 2013). Nitrogen fertilizers are largely generated by the energy intensive Haber-Bosch process. Phosphorus rock is mined, and many sources point to a rapid decrease in the "easy to access" supply of quality phosphorus following a peak by 2033 (Cordell, 2009). A substantial carbon footprint results from the transport and creation of fertilizer. Fertilizers pass nutrients into plants and animals, which are excreted after consumption. Failure to remove the nutrients in WWTPs contributes to eutrophication, which degrades freshwater resources and affects aquatic ecology, the economy, the livelihood of fisherman, and a myriad of other beneficial uses of downstream water (www.unep.org and Novotny, 2013).

The obvious solution is closing the nutrient loop, which is partly being done on farms using manure for fertilizer and via the use of biosolids produced at WWTPs. The question now is how to expand and/or streamline the closing of the plant/human nutrient loop. Separating urine is a promising idea in this regard (Figure 3). The plant availability of nutrients in human urine is ideal and its use on actual soils is equal to or better than chemical fertilizers (Jonsson and Vinneras, 2013). Urine is also low in pollutants and pathogens (Jonsson and Vinneras, 2013). Phosphorus recovery from human waste will not meet the world's growing agricultural demand, but it can be a key element which might be more easily achieved than other options (e.g. reducing meat and dairy consumption) (Cordell, 2013). And regardless of its ability to meet agricultural demand, impending regulatory changes is motivating its removal and recovery.

2.6.3 Nutrient Removal in WWTPs

A more pragmatic reason to consider alternatives to advanced nutrient removal in WWTPs is impending changes to nutrient effluent regulations (Table 5). The Colorado Department of Public Health and Environment Water Quality Control Commission regulation #85 is reported in Table 5. The pre-2012 standard in Table 5 refers to WWTPs built before 2012.

Table 5 Comparing domestic wastewater quality to nutrient effluent standards



	TN (mg/L)	TP (mg/L)
DOMESTIC WASTEWATER (Average, Metcalf and Eddy, 1991)	45	8
CO pre-2012 WWTP effluent standard	15	1
CO regulation 85 effluent standard for new facilities	7	0.7
Enhanced Nutrient Removal (as low as)	3	0.1

Enhanced nutrient removal is occurring in regions such as Chesapeake Bay, Virginia, due to stringent regulations imposed as a result of severe water quality impairment. In most cases, regulations for new WWTPs more closely resemble the CO Regulation 85 concentrations. However, this level of nutrient removal (or recovery) is still costly for large volumes. In addition, low concentrations (such as CO regulation 85) are difficult to achieve.

The following technologies can be employed in WWTPs for nutrient removal (Breidt, 2015):

- Modified Bardenpho process
- Centrate and Recycle Activated Sludge Reaeration Basin
- Anaerobic Ammonium Oxidation
- Selective Adsorption
- Electrodialysis
- Ammonia Stripping
- Struvite Precipitation

Of these, only the last four recover nutrients. Process descriptions of the treatments employed in urine treatment are discussed in more detail in Chapter 3.

According to an analysis by Breidt (2015) (using a BioWin model and data from the Drake Water Reclamation Facility in Colorado), the following removal percentages were achievable:

Table 6 Wastewater treatment plant nutrient removal technology effectiveness

Treatment Summary	CaRRB	ANAMMOX	Ammonia Precipitation	Electrodialysis	Struvite Precipitation	Selective Adsorption
Effluent Nitrogen	8.74	9.99	5.75	5.75	9.27	11.24
% Side stream TN Removal	26%	28%	73%	73%	38%	0%
Effluent Phosphorus	2.19	2.43	1.85	1.85	1.11	1.24
% Side stream TP Removal	0%	0%	0%	0%	82%	82%

Although ammonia stripping and electrodialysis achieve Regulation 85 effluent standards for nitrogen, no technologies achieve phosphorus effluent standards. The advantage of urine separation is that equal (or possibly improved) effluent quality can be achieved with lower input of energy and capital (Wilsenach and Loosdrecht, 2003). According to Ronteltap et al. (2007) and Wilsenach et al. (2007) struvite precipitation can result in 95-98% recovery of phosphorus from source separated urine. Lind et al. (2000) achieved almost complete recovery of potassium and phosphorus and 65-80% recovery of nitrogen by combining struvite precipitation with zeolite adsorption. Ganrot et al. (2008) recovered greater than 97% of P and 50-60% of N by using struvite precipitation and pretreated (washed or washed and thermally treated) zeolite. In laboratory experiments conducted by Kabakci et al. (2007), ammonia was stripped from urine with air in a batch system and absorbed in sulfuric acid solution with an estimated ammonia recovery of 97%.

2.6.4 Contaminants of Emerging Concern

Pharmaceuticals and hormones excreted from human metabolism, although not currently regulated, are known to be present in U.S. surface waterbodies, have known effects on aquatic ecosystems, and are costly and difficult to remove at the scale of conventional wastewater treatment (Kolpin et al., 2002). In addition, it is well understood in the water treatment community that effluent from wastewater treatment plants often becomes a portion of the influent to water treatment plants downstream, to the point that a drop of water is used many times in multiple urban centers. This issue is complicated by metabolic byproducts and the variability of household use (type and amount). Additional changes can also occur during wastewater treatment (via oxidation, hydrolysis, photolysis) and during drinking water treatment (Kummerer 2013). Kummerer (2013) noted one case in which a fungicide (tolylfluanid) became carcinogenic during ozonation in drinking water treatment (it was banned after this discovery). This is an extreme case, and not a product that is consumed/excreted by humans, but worth noting.

Currently, at the observed concentrations, the potential effects to human health are not well understood. The exact portions and relative ecotoxicity of micropollutants respectively in urine and feces are still under investigation (Battaglin and Koplin, 2009; Lienert et al., 2007; Winker et al., 2008), but it is largely recognized that urine diversion would help address micropollutant removal. It has been estimated that diverting urine from wastewater could reduce the ecotoxicological hazard posed by micropollutants in the environment by as much as 50% (Larsen, 2007).

Current municipal WWTPs are generally not equipped for removal of pharmaceuticals (although some removal does occur through adsorption and biological modification). As a result, some of the most frequently detected compounds in a recent USGS survey of U.S. streams were nonprescription drugs, antibiotics, other prescription drugs, and reproductive hormones

(Kolpin, 2002). Concerns about pharmaceuticals and personal care products (PPCPs) have been raised by the U.S. EPA and research has shown that even low exposure to some pharmaceuticals and hormones can cause harmful effects to aquatic organisms (Daughton and Ternes, 1999). Another potential route of exposure is through agricultural application of municipal sludge. A comparison of human pharmaceutical concentrations in raw municipal wastewater and urine revealed that urine separation and treatment is a promising approach to reduce the environmental impact of pharmaceuticals (Winker, 2008; Zhang and Geissen, 2010). Multiple sources also indicate that municipal wastewater effluent is a significant contributor to pharmaceuticals and hormones in the environment (Daughton and Ternes, 1999; Eawag, 2009).

Although some connections have been made between various anthropogenic hormones and pharmaceuticals and adverse effects in marine organisms, the degree of the problem has not yet been thoroughly evaluated. This is because analytical methods have only recently been developed that enable accurate assessment via ecotoxicological studies (Kolpin, 2002). It is largely recognized, however, that because of the large number of medicines and hormones secreted in urine and feces, cautionary measures could be beneficial (Larsen et al., 2007). Therefore, urine source separation could improve water quality by preventing pharmaceuticals and hormones from entering aquatic ecosystems. Technologies for removing micropollutants (e.g. membrane filtration, reverse osmosis, ozonation) are costly and energy-intensive. By removing urine from domestic wastewater, these technologies can be employed for a much smaller volume, potentially decreasing capital cost, maintenance, and energy requirements (Larsen et al., 2004; Dodd et al., 2008).

Because removal of pharmaceuticals and hormones from domestic wastewater is not currently necessary from a regulatory standpoint, and because there is still some debate about the exact proportion of these contaminants present in urine, micropollutant removal should be considered an “added bonus” of urine source separation. Contaminants of emerging concern have lately received a higher level of attention by the U.S. EPA and others engaged in water management and research as well as within the popular press, but negative effects (to human health and the environment) must be validated before regulations will be implemented. Should discharge limits be set, urine diversion may be an efficient way to address removal of pharmaceuticals and hormones. Technologies for removing micropollutants can be energy intensive and expensive. Reducing the flow needing treatment would likely result in substantial capital savings.

Chapter 3: Integrating Technologies for Source Separation and Decentralized Wastewater Treatment

Decentralized wastewater treatment could be implemented at various scales; single household, multi-resident (cluster), or city wide. The most likely of these scales is multi-resident (cluster) treatment, which includes a small group of neighborhoods (or single large neighborhood), apartments, and commercial or institutional buildings (offices, hospitals, educational institutions etc.). City wide systems would likely have technical issues with urine transport. Single-household systems would be inefficient. Due to piping requirements, retrofit is unlikely for the foreseeable future. A decentralized source separation system is most likely to occur in new developments or in new commercial/institutional buildings.

3.1 Urine Separation and Treatment

A number of treatment methods have been considered with the goal of recovering nutrients from source separated urine. Separating nutrients from micropollutants (pharmaceuticals and hormones) is a primary goal for technologies considered. Before a discussion of urine treatment technologies, it is important to explain how undiluted urine can be captured without sacrificing the convenience of modern sanitation.

3.1.1 Urine Separation

Methods for separation of urine from feces with little or no dilution include urine diversion dehydration toilets, urine diversion toilets, and waterless urinals. Urine diversion dehydration toilets (UDDTs) do not utilize water for flushing; instead, the urine is drained into a storage container and a separate straight drop allows for feces collection. The feces are ventilated for drying, and composted separately. UDDTs are often used in developing countries where water is scarce and demand for cheap fertilizer is high. The first water-flushed urine diversion (UD) toilets were developed in the 1990's in Sweden (Larson and Lienert, 2007). Manufacturers include Wost Man Ecology, Dubbletten (www.dubbletten.nu), Gustavsberg, and Roediger (www.roevac.com). All UD toilets have separate outlets for urine and feces, but they can differ in flushing mechanisms. The Dubbletten toilet (Figure 7), for example, has a physical barrier between the front and rear portions of the toilet (preventing overflows of flushing water contaminated with bacteria).

Figure 7 Dubbletten urine diversion toilet

As with all UD toilets, feces are collected in the back, and urine is collected in the front. Separate flush volumes for each section allow for minimal dilution of urine, with adequate volumes for flushing of feces. In most other models, a single flush rinses the entire bowl, meaning less control over minimizing urine dilution. The Roediger NoMix toilet, (Figure 8), employs a mechanism which allows for almost completely undiluted collection of urine. To achieve this, urine collection is initiated when the user sits, opening a valve to the urine collection opening. When the user stands, the valve closes, and a full flush rinses the entire toilet basin.

Figure 8 Roediger NoMix toilet

The primary features of waterless urinals (Figure 9) are: (1) a drain trap insert siphon which collects and discharges urine without using water, and (2) a hydrostatic float which seals the insert and prevents odors from escaping. Manufacturers of waterless urinals include Ernst, Uridan, Keramag (www.pro.keramag.com), and Urimat.

Figure 9 Keramag waterless urinal

A detailed list of worldwide manufacturers of waterless urinals, UDD, and UD toilets is available through the organization ECOSAN (http://www.gtz.de/en/dokumente/gtz2010-en-urine-diversion-appendix-suppliers-lists-2010-02-17.pdf). Feedback related to UD toilets and waterless urinals, including maintenance requirements and both technical and social issues, is detailed in the WERF report and summarized here and in following chapters:

- Several improvements to UD toilets are needed, primarily methods for preventing or removing mineral deposits (urine scale) and for increasing user acceptance. Odor can also sometimes be an issue, but can be mitigated with proper maintenance. Ease of use, especially for children, is a key issue.
- UD technology requires increased cleaning and maintenance; removing urine scale in valves requires 3 days of soaking and then scrubbing. Replacement valves and maintenance is a significant portion of UD project costs (Bischer, 2012).
- Acceptance of NoMix toilets and waterless urinals in Europe is high in public facilities, but less so in private homes.
- Costs of UD technology are currently much higher than conventional sanitation.

Despite these challenges, successful urine diversion at the scale of a large office building and small neighborhoods shows promise for separation and treatment at a larger scale.

3.1.2 Stabilization

Stabilizing urine is sometimes a necessary pretreatment measure and entails preventing the hydrolysis of urea, thereby preventing odor issues which result from ammonia formation and breakdown of organic matter, clogging of pipes (from precipitates), and volatilization of ammonia. Urease inhibitors, acidification (Hellstrom et al., 1999), microfiltration, and ultrafiltration have been considered as potential methods for stabilization. Studies conducted by Eawag (The Swiss Federal Institute of Aquatic Science and Technology) during its Novaquatis project (Larsen and Lienert, 2007) revealed that sterile filtration was not able to remove enzymes responsible for decomposition because the enzymes were present in dissolved form and could pass through filter. Both chemical acidification and biological processes prevent ammonia volatilization and odor issues. Udert and Wachter (2013) proposed that nitrification is a more resource-efficient alternative for stabilization than acid dosage. More information is available in the source separation WERF report and Larsen et al. (2013). Fortunately, many of the treatment options that show promise function best with hydrolyzed urine.

3.1.3 Struvite Precipitation

Struvite precipitation (Figure 10) is the most effective method of concentrating nutrients present in urine (Maurer et al., 2006) and was successfully tested in an office building in Germany. Struvite is magnesium ammonium phosphate ($MgNH_4PO_4$ with 6 waters of hydration), and is also known as MAP. It is a commonly used slow-release fertilizer, and may also be converted to a potentially more marketable “enhanced struvite” (two parts slow release ($MgHPO_4$), one part easily soluble ($(NH_4)2HPO_4$)). Precipitation of struvite is triggered by the addition of magnesium (several forms are available) to ureolyzed urine. The process by which this occurs is as follows:

1. Addition of magnesium oxide or magnesium chloride causes a rise in pH.
2. Phosphate equilibrium shifts towards PO_4^{3-} (most phosphate in urine is in the form H_2PO_4 or HPO_4^{2-}) .
3. Phosphorus then precipitates with magnesium as struvite.

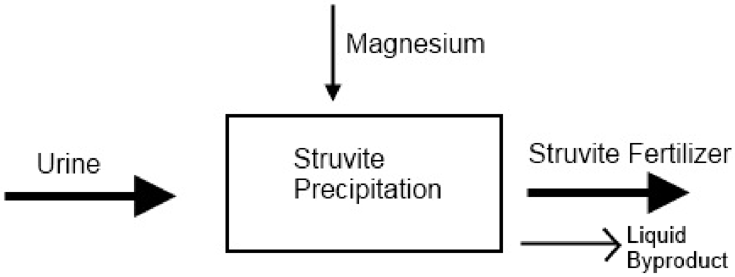


Figure 10 Simple process diagram for struvite precipitation

Laboratory studies by Eawag revealed that the more that urine is diluted with flushing water, the lower the yield of struvite, but this can be somewhat offset by adding magnesium.

Struvite precipitation can result in 95-98% recovery of phosphorus (Ronteltap et al., 2007; Wilsenach et al., 2007). Greater than 90% of the phosphorus can be recovered with a 1.1:1 mol Mg*mol^{-1}P magnesium dose according to Kabdasli et al. (2013). Nitrogen can also be recovered from ureolyzed urine (more than 95%) with dosing of magnesium and phosphate, but substantial quantities of base are necessary for process control. More efficient methods for nitrogen recovery are discussed below.

Laboratory studies have shown that pharmaceuticals and hormones stay in solution, resulting in a fertilizer free of micropollutants (Ronteltap et al., 2007). Struvite precipitation has been shown to remove micropollutants at comparable levels to electrodialysis and nanofiltration (Approximately 98% removal; electrodialysis and nanofiltration remove more than 99% (Escher et. al. 2006).) It is beneficial to have a solid fertilizer product free of micropollutants, but the concentrated liquid product is of concern. Of the pilot projects using struvite precipitation in the literature (most in rural settings), none have published information on the management of this product.

In addition, although the heavy metal content of urine is already lower than most commercial fertilizers, the majority of heavy metals also stay in solution, so that only 20-40% of heavy metals contained in urine would end up in struvite. Ureolyzed urine has a high buffer capacity, so the pH decreased during phosphate recovery from undiluted urine is small (Liu et al 2008).The simplicity of this process, and the end result: a fertilizer primarily free of pharmaceuticals, hormones, and metals, make this an ideal candidate for nutrient recovery. A number of studies are available for additional details on struvite precipitation from human urine (Liu et al., 2008; Ronteltap et al., 2003, 2007, 2010; Wilsenach et al., 2007; Kabdasli et al., 2006; Ban and Dave, 2004; Lind et al., 2000). Figure 11 shows a form of struvite used as fertilizer.

Figure 11 Struvite in granular form

A struvite reactor was operated at GIZ (German Technical Corporation) headquarters in Eschborn, Germany. The project was known as SANIRESCH (www.saniresch.de/en). Key features of this project that will inform future projects include: use of NoMix toilets and waterless urinals, user surveys, detailed descriptions of a struvite reactor developed by the company Huber SE, and an economic feasibility study (Bischer (2012)).

Advantages of struvite precipitation (Table 7) are that it is a proven technology, the process is simple, energy requirements are low, and magnesium salts are the only chemical requirement. Disadvantages are partial nutrient recovery (additional treatment is necessary for ammonia removal) and a liquid product with isolated micropollutants. One possible method of managing this liquid product could simply be utilizing evaporation to create a solid product for disposal.

3.1.4 Nitrogen Removal/Recovery from Urine

Ammonia Stripping

Ammonia stripping is a physicochemical process reliant on mass transfer of ammonia between liquid and gas phases (Figure 12). It is the most common process utilized in wastewater treatment to selectively recover ammonia. Two systems, air stripping with ammonia adsorption in acid and steam stripping with ammonia recovery in the condensate, have been tested on urine. Passive stripping in urine-collecting systems may also be a low-energy option in on-site systems (Siegrest et al., 2013).

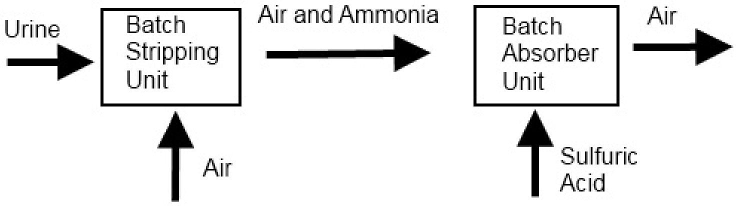


Figure 12 Simple process diagram for ammonia stripping

Because of the low volatility of ammonia, pH and temperature must be optimized (Kabakci et al., 2007). In laboratory experiments conducted by Kabakci et al. (2007), ammonia was stripped with air in a batch system and absorbed in sulfuric acid solution with an estimated ammonia recovery of 97%. Based on these experiments, it was concluded that stripping and absorption is an effective means for ammonia recovery from urine. The end product, an ammonia sulfate solution, could be directly applied as fertilizer. If converted to crystalline form (ammonium sulfate, a well-known fertilizer), approximately 8-10% of ammonia would be lost. Behrendt et al. (2002) also used batch experiments to design an ammonia stripping unit for recovery of nitrogen from urine with promising results in terms of ammonia recovery. Results also indicate that, relative to conventional wastewater treatment plants with nitrogen removal, the unit size for ammonia stripping and adsorption is small.

Full-scale stripping reactors (with adsorption in acid) have also been developed to test process parameters, determine ammonia recovery, and calculate energy requirements. Antonini et al. (2011) performed batch mode experiments which utilized upstream struvite precipitation (with magnesium oxide) to avoid clogging of the stripper. In these experiments, 94%of the ammonia was stripped and recovered on acid in its entirety. Steam stripping has also been successfully tested (Tettenborn et al 2007) with laboratory reactors and an 800-person equivalent pilot plant. Steam stripping has the possibility of using less energy than stripping with acid adsorption, but is a more complex process that may not be suitable for smaller decentralized reactors (Siegrist et al 2013).

Passive ammonia stripping (within the urine collection system)

In theory, stored urine (without losses due to passive ventilation or dilution with flushing water) can contain approximately 8000 mgN/L of ammonia. Measurements of stored urine, however, can be substantially lower (2400 mgN/L ammonia in an Eawag pilot project). (Udert and Wachter 2012) Ammonia losses are problematic from both a resource recovery and environmental pollution standpoint, and can cause odor issues. They most often occur while urine is in pipes. Stopping airflow in pipes can solve the pollution/odor issues, but Siegrist et al (2013) suggest encouraging the airflow in pipes with the goal of recovering ammonia in acid traps at the top of the pipe. A description of how the process works is provided in Siegrist et al 2013, with data from two operational urine-collecting systems.

Application in Decentralized Systems

Advantages and disadvantages are summarized in Table 7. Ammonia stripping is better suited for medium sized reactors (serving several hundred people) than for smaller reactors, due to the need for strong bases and acids for the acid adsorption method and high pressure and temperature requirements of steam stripping (Siegrist et al 2013). Process details are readily available, and operation is relatively simple (if temperature and pH are controlled). Disadvantages include pumping requirements, the addition of a base to control pH, and the possibility of scale formation.

Ion Exchange with Zeolites

Studies have indicated that zeolite can be used for nitrogen recovery, and that, if combined with struvite precipitation for phosphorus recovery, significant nutrient recovery can be realized (Ganrot et al., 2008, Lind et al., 2000). The process by which nitrogen is recovered by zeolites is selective adsorption (Figure 13). Selective adsorption relies on the ion exchange potential of a resin. The resin has active groups in the form of electrically charged sites which can adsorb ions. In the case of nitrogen, it is useful if the relative concentration of nitrogen and its affinity for the sites is high. Natural zeolites, especially clinoptilolite, as well as natural wollastonite show excellent ammonium adsorbent qualities in contact with human urine (Lind et al., 2000). Zeolites can also be made from silica and alumina (widely available). Once zeolite has adsorbed the nitrogen from urine, it can be used as a soil conditioner. 64-80% of the nitrogen in urine can be recovered with use of zeolite adsorption (Maurer et al., 2006).

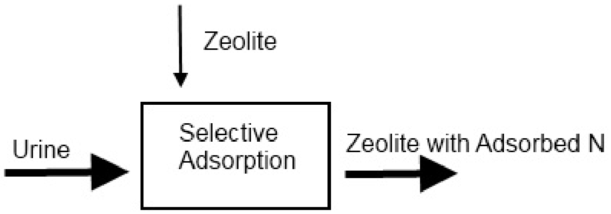


Figure 13 Simple process diagram for selective adsorption on zeolite

This process does not enable phosphorus recovery, but can be combined with struvite precipitation to optimize recovery of both phosphorus and nitrogen. Lind et al. (2000) achieved almost complete recovery of potassium and phosphorus and 65-80% recovery of nitrogen by combining struvite precipitation with zeolite adsorption. Ban and Dave (2004) projected 99% recovery of P and 90% recovery of N using struvite precipitation and zeolite adsorption, but acknowledged a need for further verification and pilot experiments. Ganrot et al. (2008) recovered greater than 97% of P and 50-60% of N by using struvite precipitation and pretreated (washed or washed and thermally treated) zeolite.

Advantages of this process (Table 7) are that it is easy to apply, not energy-intensive, and operational thermodynamics and kinetics are well understood. Zeolites in particular function well as a slow release carrier of nutrients (over course of entire growing season according to

Rehakova et al (2004)) due to their high ion-exchange capacity. Zeolites can also be regenerated with NaCl or NaOH. Disadvantages (Table 7) include the large amounts of zeolite required to remove ammonia from urine, the need for acid addition for effective ammonia adsorption, little understanding of the uptake/release of organic micropollutants, and the fact that zeolites adsorb heavy metals (urine, however, has a low concentration of heavy metals).

Beler-Baykal et al (2011) tested nitrogen recovery using the natural zeolite clinoptilolite, recovered the nitrogen, and applied it to the landscape plant *Ficus elastica.* 97% of the ammonium in stored urine was recovered to the clinoptilolite by ion exchange, and 88% of that was then recovered and tested as a fertilizer. Salinity was eliminated through this process, and the recovered product performed as well as a synthetic fertilizer.

3.1.5 Electrodialysis and Ozonation

Electrodialysis and ozonation have been specifically tested for removal of micropollutants from source-separated urine (Maurer, 2006), although other possible removal mechanisms exist, including biological transformation/degradation, sorption, and stripping (Larsen, 2004). Eawag researchers, after studying various methods to produce a fertilizer from urine, have proposed that a combination of electrodialysis and ozonation is a promising option due to its ability to effectively separate micropollutants from nutrients and then eliminate any remaining micropollutants in the nutrient solution (Lazarova and Spendlingwimmer, 2008). Electrodialysis is a membrane processes which enables separation of nutrients from micropollutants. This is desirable when creating a fertilizer product from urine. Ozonation (or chemical oxidation) has been shown to effectively eliminate micropollutants. Descriptions of processes included in this section were referenced from Metcalf and Eddy (2006).

Electrodialysis is an electrically driven process through which mineral salts and other species are transported through ion selective membranes from one solution into another (via electrical potential differences) (Figure 14). Positive ions are attracted to the cathode, and negative ions are attracted to the anode. Low-molecular weight nutrients migrate to the concentrate and pharmaceuticals/hormones (higher-molecular-weight) remain in the diluent. Electrodialysis does not remove colloidal matter, non-ionized matter, or bacteria. Pronk et al. (2006a and 2007) tested electrodialysis for the separation of micropollutants from nutrients, and achieved almost complete separation. Ozonation was added as a secondary step for elimination of remaining micropollutants. The dose of ozone required was higher than in other applications, but effectively eliminated pharmaceuticals. A combination of electrodialysis and ozonation were tested to the point of technical maturity in the Eawag laboratories and is being tested in a pilot project (Basel-Landschaft Cantonal Library) (Fewless, 2015).

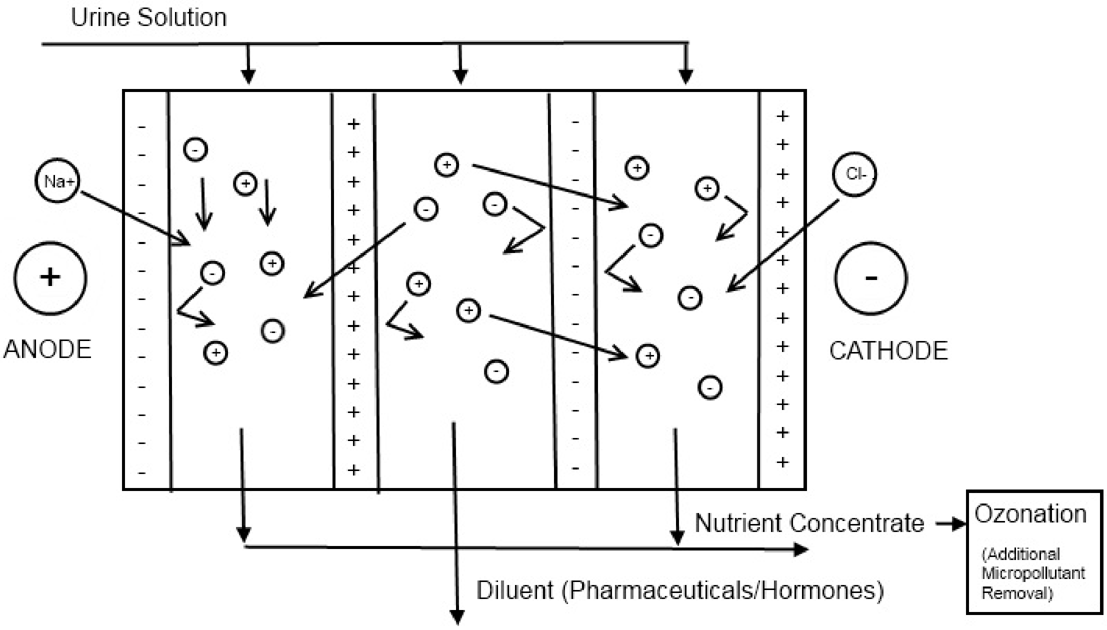


Figure 14 Simple process diagram for electrodialysis followed by ozonation

Ozone can both directly oxidize micropollutants and create hydroxyl radicals (which react with micropollutants) (U.S. EPA, 2010). Dodd et al. (2008) conducted bench-scale, semibatch experiments to examine physical-chemical constraints on 1) ozone absorption and micropollutant oxidation during ozonation of source-separated hydrolyzed urine and 2) the concentrate and diluate streams produced via electrodialysis of hydrolyzed urine. Besides operational analysis, Dodd et al. (2008) estimated per capita energy requirements for treatment of source-separated urine under hypothetical scenarios of ozonation with and without electrodialysis and compared these estimates to energy requirements for comparable end-of-pipe treatment. Suggestions were made for increased operational efficiency, and it was generally concluded that the high energy costs of ozonation could be offset with inclusion of electrodialysis for nutrient recovery. Additional details about membrane and advanced oxidation treatment of urine can be found in: Lazarova and Spendlingwimmer (2008), Larsen et al. (2004), Pronk et al. (2006a/b, 2007), Dodd et al. (2008), Escher et al. (2006).

Boller (2013) reported that NoMix toilets were used to separate urine at the Liestal Public Library in Switzerland which was then treated via electrodialysis and ozonation. N and P were almost completely separated in a liquid fertilizer called “urevit” after electrodialysis. Ozonation then aided in almost complete removal of micropollutants. The final product contained up to 12 mg N/L, 0.6 g P/L, and 5.6 g K/L and performed almost equally to a commercial ammonium nitrate fertilizer. Approximately 90% of investigated pharmaceuticals and hormones were removed (Pronk et al 2006, 2007). The project was operated for about a year without problems. Fouling occurred during standstill because of a lack of urine. According to Boller (2013), “Taking into account the energy needed for industrial N and P fertilizer production, the net energy consumption amounts to 0.379 MJ/pd, while advanced WWT consumes 0.375 MJ/pd.”

3.1.6 Urine Storage

Storage is the primary method of urine sterilization investigated in both laboratory studies and pilot projects. The risk of transmission of infectious diseases from diverted urine is largely dependent on cross-contamination with feces and the time, pH, and temperature in which urine is stored before potential use as fertilizer (Schonning et al., 2002; Hoglund et al., 2002a/b). Research conducted at the Swedish Center for Infectious Disease Control indicates that “enteric viruses may persist for a long time in urine and that they pose a greater risk than bacterial and protozoan pathogens in relation to the handling and reuse of source-separated urine” but that urine can be used as fertilizer in agriculture with minimal risk for transmission of microbial diseases if either storage at high temperatures (20°C) for at least six months is employed or if a suitable crop and safe application technique is selected (Hoglund et al., 2002b). Difficulties associated with extended urine storage for sterilization include precipitation of phosphorus compounds and ammonia volatilization (Udert et al., 2006). Vinneras et al. (2008) also studied the inactivation of bacteria and viruses in source separated urine relative to variations in storage temperature and urine dilution rate. The study validated Hoglund’s recommended storage parameters (20°C for six months) for unrestricted use. A project in Australia reused stored urine for turf pasture fertilization with good results (20 dwellings, vacuum truck for removal), and a variety of projects have been initiated throughout the world (Fewless et al., 2011).

Winker et al. (2009) compared the potential values and risks of fertilizer products from new sanitation systems, and proposed that direct stored urine reuse is “perhaps the most promising product” due to its nutrient content and low NH_3 emissions (less than 10%) after field application when compared to liquid slurry (Rodhe et al., 2004). Drawbacks to direct reuse of urine include transportation, spontaneous precipitation (if stored, the precipitate would have to be recovered to reclaim phosphorus), sodium content (e.g. potential for accumulation and crop/plant damage), and pharmaceuticals/hormones (could possibly enter the food chain, runoff into water bodies, or leach into groundwater). Winker (2010) investigated the potential impacts of pharmaceutical residues in urine when considering direct application for fertilizer and found that:

- Pharmaceutical residues remain after urine storage
- Polar and persistent compounds can be taken up by plants and thereby enter the food chain
- Low levels of pharmaceuticals are unlikely to negatively affect plant growth
- Evaluating pharmaceutical toxicity related to ingestion of urine-fertilized plants is difficult and yet to be determined

These issues have not been well researched, possibly because wastewater treatment plant biosolids/effluent and animal manure from operations where antibiotic and hormone treatment is commonplace are already being used in agriculture, because these compounds aren’t currently regulated by the Clean Water Act, and because the presence of pharmaceuticals/hormones may not be a high concern in areas currently without adequate sanitation.

The obvious advantage of storing and directly reusing urine is its simplicity and lack of need for chemical or energy inputs. However, it is not considered a strong candidate for U.S. implementation because micropollutants aren’t separated, because direct reuse would not be socially acceptable (and may not be compatible with current agricultural practice) and because of storage and transport issues.

3.1.7 Summary of Urine Treatment Options

An extensive review of urine treatment is available through the WERF publication “Source Separation and Treatment of Anthropogenic Urine” as well as Larsen et al.’s “Source

Separation and Decentralization for Wastewater Management" (2013). The result of this research is the conclusion that struvite formation for phosphorus recovery combined with ammonia stripping is the most practical treatment option available at this time for immediate implementation into a pilot project. The products are stable and largely free of micropollutants, energy use and chemical requirements aren't exceptionally high, and, perhaps most importantly, pilot projects have revealed that these are robust systems that are adaptable to decentralized systems. However, additional analysis and lab work may increase the viability of other treatments, such as electrodialysis/ozonation, ion exchange with zeolites, and storage, which is why a description of these technologies was included here. In addition, it is unclear how to manage the liquid effluent from struvite precipitation, which would be high in pharmaceuticals. This and other unintended consequences are discussed in Chapter 4. A summary of all urine treatment technologies discussed here can be found in Table 7.

Membrane bioreactors are not included because of energy use and issues with fouling (e.g. maintenance requirements). It has also been noted in the literature that MBRs are not always the most efficient way to remove micropollutants. Other options include biological nitrogen conversion processes, transfer into the solid phase (other precipitation processes besides struvite), and concentration processes. This list is by no means all-inclusive. A variety of systems are under investigation for nutrient removal in decentralized systems (most aim for recovery), and continued innovation and analysis is necessary if we are to find the most efficient system possible. One of the advantages of a decentralized system is that improvements in design may be more easily incorporated after implementation relative to a large system with an extensive sewer network.

Table 7 Summary of urine treatment technologies

Treatment options	Basic Process Description	Advantages	Disadvantages
Struvite Precipitation	Addition of magnesium results in recovery of struvite.	• Simple • Low-energy • Only chemical addition is magnesium salts • Successfully tested with urine- used in an office building pilot project • Separates nutrients from micropollutants	• Doesn't recover appreciable amount of N • Liquid product containing micropollutants
Ammonia Stripping	Physicochemical process reliant on mass transfer of ammonia between liquid and gas phases.	• Successfully tested. • Operation is simple and well understood.	• Pumping requirements • Base addition to control pH • Possibility of scale formation (need pretreatment such as struvite precipitation)
Ion Exchange with Zeolites	Selective adsorption of ammonia onto zeolites (natural or manmade).	• Simple, • Low-energy • Operational thermodynamics and kinetics are well understood • Successfully tested with urine • zeolites can be regenerated or used as directly	• Acid addition for effective ammonia adsorption • Possible uptake/release of organic micropollutants • Still need to employ a method for P removal such as struvite precipitation.
Electrodialysis with Ozonation	Electrodialysis is a membrane process.	• N and P almost completely separated from micropollutants • Because of added ozonation step, 90% of investigated pharmaceuticals and estrogens removed • "Urevit", liquid fertilizer product is as effective as commercial fertilizer • Energy consumption is just slightly greater than advanced WWT	• Membrane processes can be problematic in terms of maintenance.
Urine Storage	Storage eliminates pathogens through natural processes.	• Simple • No chemical or energy additions	• Transport • Acceptance for use in agriculture might be more difficult • Nutrients aren't separated from micropollutants

3.2 Blackwater Treatment

Because of its high organic and solids content, blackwater is ideal for anaerobic digestion. Anaerobic digestion requires less energy than aerobic treatment (due to absence of aeration), produces energy in the form of biogas containing methane, and generates an organic fertilizer high in nitrogen and phosphorus rather than sewage sludge (Wendland et al., 2007).

The anaerobic process occurs in an oxygen free environment where microorganisms derive energy and grow by consuming organic material. There are four key steps: (1) the conversion of bio-polymers to soluble monomers and dimers by acidogenic bacterial enzymes during hydrolysis, (2) the conversion of organic compounds to volatile fatty acids and carbon dioxide, (3) the bacterial conversion of volatile fatty acids to acetate, H_2 and CO_2; and, finally, (4) the production of CH_4 by methanogenic bacteria utilizing acetic acid or H_2 and CO_2.

Research conducted at Colorado State University indicates that the concept of neighborhood-scale anaerobic digestion applied to blackwater shows promise (Gallagher and Sharvelle, 2011). Biogas, the product of anaerobic digestion, can be used in several ways:

- Cogeneration: Using biogas to generate electricity and hot water. However, generators are high maintenance.
- Feed back to natural gas lines: Must use high quality purification (precision membranes) and on-line monitoring- this is probably too expensive for small-scale systems.
- Water heater: Simple and it is possible to use fairly dirty gas, but requires separate plumbing. In addition, it is necessary to remove sulfides. This can be achieved through the use of iron fillings to oxidize sulfur (need to be replaced approximately once per year).
- Digester heating

Other options for blackwater treatment include composting, vermicomposting, Terra Preta sanitation, dehydration, and pasteurization (Larsen et al., 2013), but anaerobic digestion is a better fit for the goals of this project (sustainability and application in the U.S.).

Kujawa-Roeleveld and Zeeman (2006) investigated the use of anaerobic digestion in the context of decentralized wastewater treatment with source separation and concluded that the most efficient systems include anaerobic digestion of brown or blackwater along with the solid fraction of kitchen waste. Solid kitchen waste biodegrades easily and has organic loads similar to blackwater. Vacuum systems can be attached to kitchen sinks to decrease water use associated with typical garbage disposal operation.

Removal of urine improves the process by lowering salt and ammonia content. Lowering water content via low-flush toilets also adds to efficiency. Adding kitchen waste to blackwater can substantially increase methane production. According to Kujawa-Roeleveld et al. (2006) a fully optimized digestion process may lead to a CH_4 production of approximately 35L/p-d (similar values reported by Wendland et al., 2007).

Published data on combining brownwater with kitchen wastewater and compost are limited. Laboratory studies would be necessary to further understanding of this topic. A primary design consideration is variability in the composition of fecal sludge and kitchen wastewater (related to nutrition, processes that occur during transport and storage, environmental conditions). Transport (to the reactor and for nutrient reuse) is also a concern.

3.2.1 Anaerobic Digester Design Considerations

Kujawa-Roeleveld and Zeeman (2006) offer three systems for anaerobic digestion of blackwater: a completely stirred tank reactor (CSTR), a fed batch or accumulation system (AC), or an upflow anaerobic sludge blanket septic tank (UASB). In situations where long storage is necessary (digested medium can’t be used in agriculture during cold months), a combined digestion/storage system will be preferred. Generally speaking, choice of a system will depend on the quality/concentration of the blackwater at the specific site as well as how often the digested sludge-liquid mixture will be used.

Enabling release to the environment or reuse in agriculture of the products of anaerobic digestion typically requires post-treatment for removal of pathogens, removal of any remaining organic matter, and removal/recovery of nutrients depending on reuse situation (Kujawa and Zeeman, 2006). Post treatment might also be deemed necessary for removal of pharmaceuticals and hormones as these aren't sufficiently removed during anaerobic digestion. De Graff et al. (2010) tested the ability of anaerobic digestion to remove hormones and pharmaceuticals, and also concluded that advanced physical and chemical treatment would be necessary.

Various post treatment options have been proposed in the literature, including waste stabilization ponds, rotating biological contractors, trickling filters, integrated duckweed and stabilization pond systems, the down-flow hanging sponge reactor, activated sludge, baffled pond system, soil adsorption field, and reed bed systems (Kujawa and Zeeman, 2006). These options were not suggested, however, in an effort to provide hormone and pharmaceutical removal.

In a situation where a constructed wetland is used for graywater treatment, the liquid byproduct of anaerobic digestion can be treated in the wetland. The solids generated from the digester could be land applied (micropollutants would need to be considered and transport logistics/cost would be an issue, but recovery might also provide revenue). Nutrients could also be recovered from effluent through stripping, struvite precipitation, ion exchange, "SHARON"/Annamox (Single reactor system for High activity Ammonia Removal Over Nitrite/ANaerobic AMMonium Oxidation), or the CANON process (Completely Autotrophic

Nitrogen Removal Over Nitrite). In these cases, suspended solids and colloidal matter would need to be removed (Kujawa-Roeleveld and Zeeman, 2006).

Heat from the digester could be used to heat the treatment facility or for other uses previously mentioned. Heating the digester is often necessary for efficient operation. Research at CSU (Bruun, 2010), has indicated that the most economically feasible use of biogas from blackwater digestion at this scale would be digester heating.

Anaerobic digestion of blackwater (urine, brownwater, and kitchen wastewater) has been tested in pilot projects utilizing vacuum sewers (Zeeman et al., 2008 and Zeeman and Kujawa, 2011). The most notable is called DeSaR (Decentralized Sanitation and Reuse project in Sneek, the Netherlands), which connected 32 houses to an anaerobic digester with vacuum sewers. An UASB septic tank was used for treatment. Post-treatment included an OLAND (oxygen limited autotrophic nitrification-denitrification) reactor and struvite precipitation. The potential for nutrients in present in blackwater to meet synthetic fertilizer demand was estimated for the Netherlands. According to their calculations, the amount of N in blackwater could meet 25% of demand, P could meet 45%, and K could meet 66%.

3.3 Graywater Treatment

The vast majority of graywater treatment systems tested or in operation utilize aerobic biological treatment (90% according to Larsen 2013). This is likely because these processes can tolerate a variable organic load and a high contribution of xenobiotic organic compounds (XOCs) within the COD fraction (Jefferson and Jeffrey, 2013). Other treatment systems have been tested and/or utilized in various scales (membrane bioreactors, for example), but constructed wetlands have become the most prevalent due to simplicity of design/operation and energy efficiency.

The main goals in treatment for reuse are biodegradation of organics and elimination of pathogens. Difficulties in design can arise with variability of flow and strength. Toxic chemicals put down the drain may impair biological processes or may not be biodegradable. Without the nitrogen and phosphorus present in urine and blackwater, it may also be necessary to add nutrients (Jefferson et al., 2001).

Additional information on graywater treatment can be found in a large number of sources, including Pidou et al. (2007), Li et al. (2009), and Abu Ghunmi et al. (2011). Information about reuse standards is available in Dixon et al. (1999) and Maimon et al. (2010). Because graywater often includes kitchen wastewater, additional work may be necessary before designing a wetland in the context of urine and blackwater separation. It will be important to manage flow and graywater quality variability, without sacrificing cost efficiency.

After aerobic treatment, graywater is often reused for irrigation, toilet flushing, or both. Post-treatment chlorine or UV disinfection may be utilized for pathogen removal. Increased levels of salinity, boron and surfactants may alter the properties of soil, damaging plants and contaminating groundwater supplies (Gross et al., 2005). A discussion of these potential environmental impacts is available in Sharvelle et al. (2013). In most cases where concern exists about damage to soil and plants, studies have shown that although caution and best management practices should be employed, there isn’t evidence that great harm is being done. In addition, voluntary or regulatory practices could improve risk-free reuse by, for example, eliminating boron in detergents. Preliminary design of a constructed wetland is presented in Appendix A.

3.4 Combining Treatment Systems for Neighborhood Application

The system conceptualized for implementation in a pilot project in the U.S. would separate urine, blackwater (brownwater plus kitchen wastewater and compostable materials), and graywater. It would be developed on a neighborhood scale (500-1000 homes). The neighborhood size is based on new urban developments with minimal lawns and condensed housing (single family homes, but with smaller lots) and efficiency in treatment systems (details to follow). Each home would have 3 sets of pipes for collection of undiluted urine, blackwater, and graywater. The Roediger NoMix toilet (or other urine separation toilet) could allow for collection of toilet flush water because of the specially designed urine drain, which closes prior to flushing of the entire bowl. Vacuum sewers would be used for each urine and blackwater collection.

It is likely that anaerobic digesters would be semi-centralized (e.g. would serve multiple neighborhoods) or municipal scale, while graywater and urine would be neighborhood scale. Anaerobic systems need to be large enough to efficiently produce energy, so there could be a combination of decentralized and centralized systems within a source separation based design. Perhaps existing WWTPs are repurposed into Biogas generation facilities. Optimization of scale is an obvious first step in system design.

The most promising technologies (in terms of practicality, efficiency, and robustness) at this time are presented in Table 8. Struvite precipitation (followed by ammonia stripping) of urine, aerobic treatment of graywater, and anaerobic digestion of blackwater are strong candidates for a decentralized system when the goal is recycling nutrients and water in the most efficient manner possible. These conclusions are based on the WERF literature review and Larsen et al. (2013), as well as graywater and blackwater research conducted at CSU. These treatments have yet to be combined in a pilot project, although several have been tested independently or in combination with other treatment systems (e.g. struvite precipitation along with MBR’s for graywater and blackwater in a German office building). It is recommended that treated graywater be used for both irrigation and toilet flushing. Use in toilet flushing provides a non-growing season use of treated graywater, and saves valuable potable water otherwise used for that purpose.

Table 8 Summary of promising treatment technologies for source separation and decentralized treatment

	URINE	GRAYWATER	BLACKWATER
TREATMENT GOALS	Nutrient recovery, micropollutant removal	Water reuse	Nutrient recovery, energy generation
SOURCES	Undiluted urine	Laundry, bathroom sinks, shower/tub	Kitchen sinks, dishwasher, brownwater, compostable kitchen and yard waste
MOST PRACTICAL TREATMENT SYSTEM(S)	Struvite precipitation, ammonia stripping	Aerobic treatment (constructed wetland)- with post-treatment as necessary	Anaerobic digestion, with post-treatment as necessary
SOURCES FOR LAB WORK, PILOT PROJECTS, OR OTHER TREATMENT DETAILS	GIZ ecosan program, Eawag office building, library in Liestel, NOVOQUATIS project in Switzerland, Sustainable Sanitation Alliance, Siegrist et al (2013)	Prolific in literature but may need adaptation based on the proposed system.	Kujawa-Roeleveld and Zeeman (2006) for research in the context of urine diversion, DeSaR (Decentralized Sanitation and Reuse project in Sneek, the Netherlands)

Wetland effluent would be of adequate quality for irrigation reuse, saving potable water that would otherwise be used for that purpose. Storage for the wetland would be necessary in the winter months, or discharge to a leach-field, as irrigation demand would be less than graywater generated. There are several reasons that the proposed treatment systems were selected for this case study:

- Constructed wetlands and anaerobic digestion have been tested and validated for treatment of graywater and blackwater, respectively. Operation and maintenance requirements are understood, and cost information is available. Anaerobic systems have also been tested with the addition of kitchen waste to brownwater, with a positive effect on methane generation. Removing urine from blackwater improves efficiency and isolates a large portion nutrients and pharmaceuticals.
- A struvite reactor has been developed for urine treatment. Feedback about UD toilets, waterless urinals, urine transport, urine storage, and the reactor is available. This feedback (social and technical) can be taken into account in new project design. Ammonia stripping is a well understood process for high ammonia wastewater streams, but ion exchange might be a viable alternative.
- The ability to reuse water for irrigation and toilet flushing, rather than to use potable water, is likely to conserve energy, especially if distance between treatment and reuse is minimized by decentralized systems.
- Smaller decentralized systems are ideal for “new urbanism” developments (smaller yards and clustered homes), which are becoming more popular. It also allows for adaptations should further innovation provide more efficient or economical treatment processes.
- The process controls for selected technologies are relatively simple.

Figure 15 provides a basic visual description of the proposed system. System components are detailed in following sections.

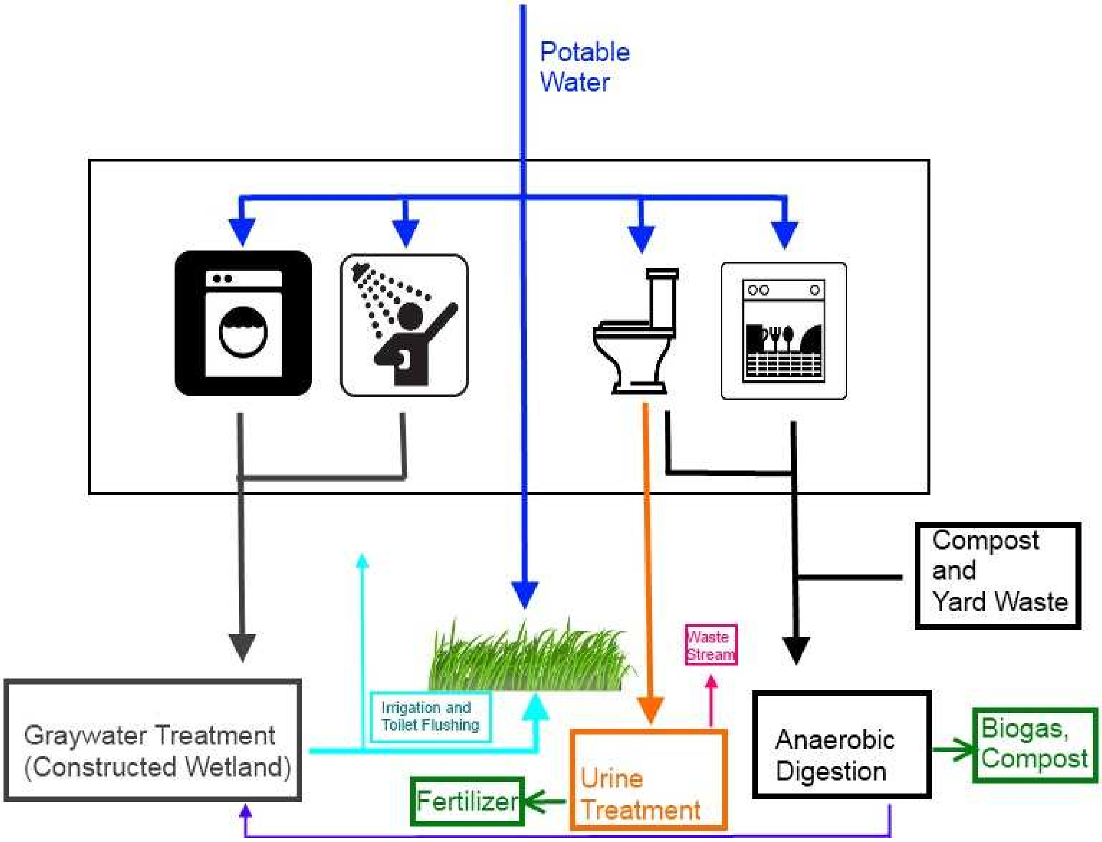


Figure 15 Proposed system with source separation

3.5 System Components

A de- or semi-centralized wastewater treatment system would have piping, storage, and treatment components. Each would be optimized for household and neighborhood flow patterns. Source separation adds a degree of complexity, as 3 separate sewage lines are necessary within the home, and because of the specific qualities of urine, graywater, and blackwater. Transport (1-8), treatment (10-13), and products of treatment (14-17) are illustrated in Figure 16, and described below.

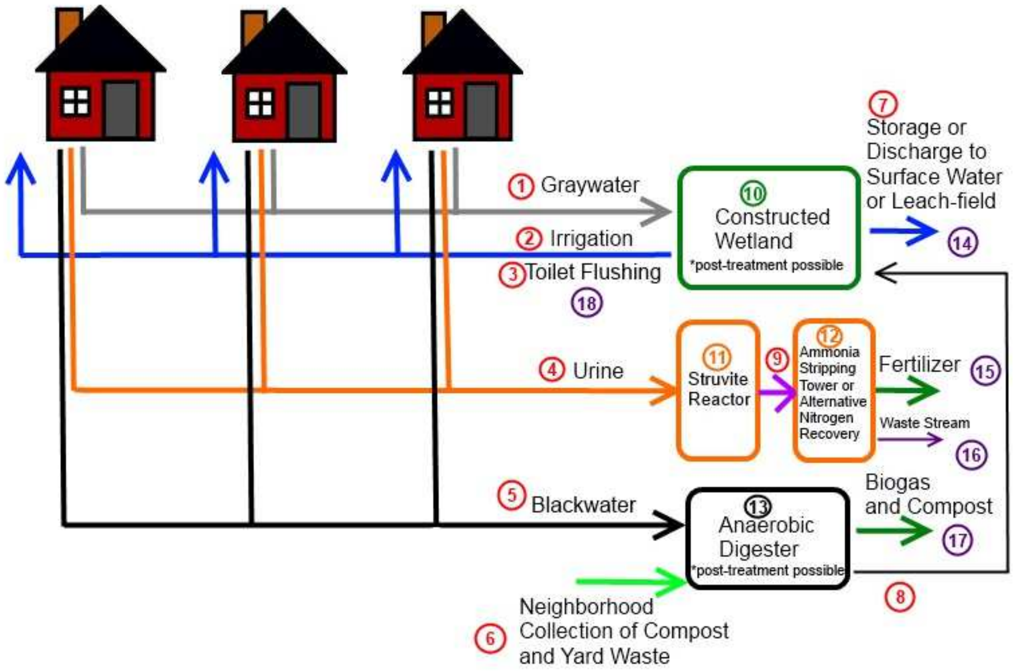


Figure 16 Piping and treatment requirements of proposed system

3.5.1 Piping and Transport Requirements

Transport of 3 separate waste streams from each home to a de- or semi-centralized treatment system is a key attribute of source separation systems. Urine and blackwater transport pose specific challenges, detailed below. The following piping networks are necessary (numbers correspond to Figure 16):

- Graywater collection (1)
- Graywater reuse: irrigation (2)
- Graywater reuse: toilet flushing (3)
- Urine collection (4)- vacuum system
- Blackwater collection (5)- vacuum system

- Storage or discharge to leachfield (7)- capacity is dependent on irrigation and flushing demand and capacity of wetland
- Effluent from digester to wetland (8)
- Transport (neighborhood collection by truck): compost and yard waste (6)
    - Alternatively, heavy duty garbage disposals could be utilized to combine compost collection with kitchen wastewater (5)

Vacuum Sewers: Transport of Urine and Blackwater

Vacuum sewers will be necessary for transport of urine and blackwater to minimize detention time as well as odors and leaks. Neighborhood layout may need to account for ideal piping distance given optimized treatment system size, vacuum sewer function, and other unintended consequences. WERF fact sheet C4 on vacuum sewer systems provided the information provided below.

Vacuum sewers rely on differential pressure. A negative pressure is drawn into the collection system. Opening a line to atmospheric pressure pulls wastewater and air into the system. A wastewater “plug” is pushed by air pressure towards the vacuum station, which provides the differential pressure.

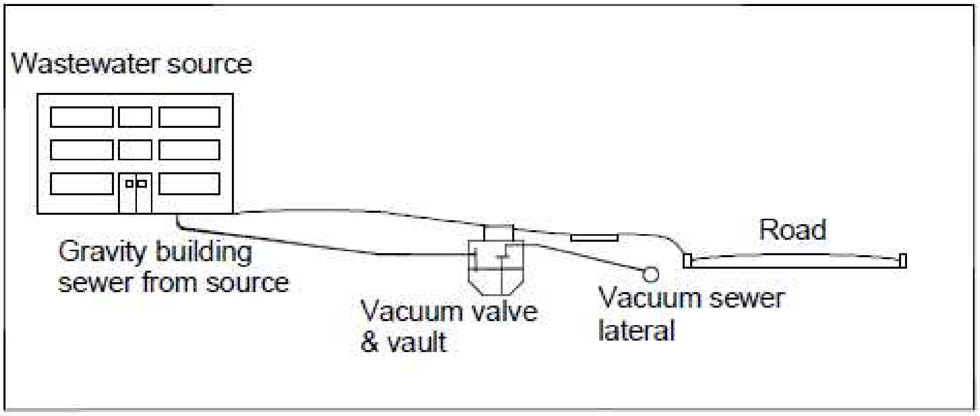


Figure 17 Vacuum sewer schematic from WERF fact sheet C4

Each valve pit in the system has a pneumatic pressure-controlled vacuum valve, which automatically opens after a predetermined volume of sewage has entered the sump. The pressure differential between the valve pit and the main vacuum line transports sewage. Larger suspended solids tend to break up in transport due to inputs of energy (pulsing) from opening and closing of valve pits in the network.

Pipes for vacuum sewers are installed in a saw-tooth or zigzag configuration to maintain a vacuum throughout the system.

Figure 18 Vacuum station and pipe installation (from AIRVAC and WERF fact sheet C4)

Other attributes noted in the WERF fact sheet are as follows:

- A typical vacuum station is able to serve about 1200 connections and pull from a 15,000 foot radius and 150-200 connections are needed before the cost of a vacuum station can be justified
- Vacuum sewers are appropriate for areas with “unstable soil; flat terrain; rolling land with many small elevation changes; high water table; rocky conditions; new and denser urban development in rural areas; and sensitive ecosystems”
- Vacuum pumps and sewage pumps require electricity, but larger stations are more efficient (in terms of power consumption per connection)
- Access points for valve boxes or cleanouts are visible, but not obtrusive
- Conventional gravity and pressure networks require multiple lift stations, but vacuum systems typically require only a single pump station

- A standby electric generator is necessary for power failure events
- Maintenance requirements include:
    - Changing/removing/cleaning vacuum pump components, testing alarm systems, and checking motor couplings, shut-off operation of vacuum station, and valves
    - Controllers need to be rebuilt every 3-6 years, and valves every 8-12
    - Annual visual inspection of valve pits and valves is also necessary
    - Correcting vacuum valve failures
    - The total estimated time commitment for maintenance is 2.5-3 hours per year per service connection

Advantages are that vacuum systems transport wastewater at a faster rate than gravity sewers, are water and odor tight, scalable, require only a single pump station, and can be remotely monitored. Vacuum sewers are generally shallower than conventional sewers, enabling easier access for maintenance. Faster transport, as well as the violent action within the pipe network can aid in limiting settling of blackwater solids. It may also have an effect on urine scale.

Disadvantages of vacuum systems:

- More expensive than gravity sewers (WERF provides a Cost Estimation Tool for vacuum systems for localized cost estimates: http://www.werf.org/i/c/DecentralizedCost/Decentralized_Cost.aspx)
- Limited capacity to transport uphill
- Larger and more expensive than gravity sewers (but aesthetics are improved by incorporating the landscape into design), long pipe runs (with few connections) can result in poor performance

In addition, central vacuum stations generate noise and odors (exhaust air can be passed through a bio-filter to absorb gas and reduce odor). Ammonia capture in the central vacuum station could be a part of design specifications. Regular inspection or remote monitoring is critical for effective operation. Vacuum valve failures can be problematic. A stuck open valve reduces whole system vacuum and can be difficult to locate. A stuck shut valve causes backup of wastewater in the valve pit (and potentially into homes). This is easier to locate, but has obvious negative effects.

Additional research/experimentation might be necessary before a pilot project was initiated, but vacuum sewers have already been successfully tested for urine and blackwater (Wang and Bao (2007), Zhang (2008), Zeeman and Kujawa (2011), Germer (2009) are a few examples). A project in the Netherlands, for example, has successfully used vacuum sewers for blackwater transport for a neighborhood of 32 homes (Zeeman and Kujawa, 2011). Vacuum sewers may also be connected to in-sink kitchen disposals to aid in the collection of kitchen waste as an alternative to weekly curb pick-up of kitchen compost.

Innovation within the treatment system is still possible to minimize transport issues. For example, it may be possible to design a toilet with built-in treatment (Larsen et al. 2013, pg. 142). Both transport and treatment systems must be adaptable to variable loading (domestic wastewater peaks occur in morning and evening).

Ammonia Loss and Urine Scale in Urine Collection Systems

Pipe systems need to be designed to minimize ammonia losses (or capture ammonia) and enable management of urine scale. Spontaneously occurring precipitation as a result of urea hydrolysis (urine scale) is a significant maintenance issue in urine collection systems.

These precipitates, which include struvite and various calcium phosphates, accumulate in pipes (Figure 19) and can cause blockages after only a few thousand uses (Larsen and Lienert, 2007).

Figure 19 Precipitation in a urine collection system

Currently, waterless urinals have exchangeable traps which make urine scaling less problematic as compared to urine diversion (UD) toilets. Essentially, the trap is a compartment of the urinal designed to accommodate precipitates and then be removed and replaced. This concept could also be incorporated into UD toilets (Lienert and Larsen, 2007). Through its pilot projects, Eawag found that scaling could be slowed by reducing urine residence time (e.g. using sloped pipes with large diameters) and with regular flushing with a 10% citric acid solution. Strong acid, caustic soda, or mechanical means (e.g. steel brushes, plumber's snake, jet cleaning) can be used to remove blockages if they occur, but this would require increased homeowner maintenance. In an Eschborn, Germany office building pilot project, urine scale was removed by soaking for 3 days and then scrubbing (Figure 20).

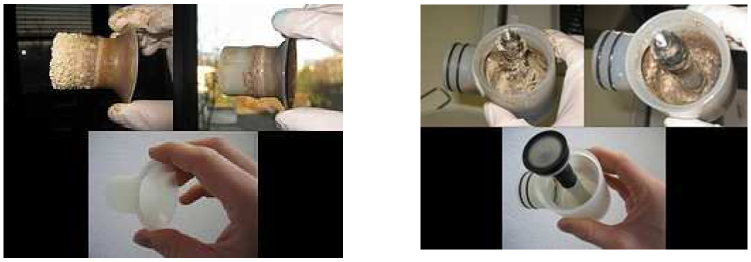


Figure 20 Cleaning urine scale from components of a collection system

A preventative option is to use soft flushing water (e.g. rain or possibly recycled graywater), which decreases the precipitation potential of urine as compared to tap water (Udert et al., 2003c). Avoiding dilution of urine does not prevent precipitation (Lienert and Larsen, 2007) because the mass concentration of precipitates decreases with water volume (Udert et al., 2003a). Eawag (Swiss Federal Institute of Aquatic Science and Technology) conducted studies through the program “Novaquatis” to understand the mechanisms behind precipitation, and believe that the sanitary industry “needs much ingenuity to find elegant solutions” (Lienert and Larsen, 2007). Practical, pilot project-based recommendations for urine transport and storage is also available in the literature, including the report “Urine Diversion-One Step towards Sustainable Sanitation (report 2006-1)”, published by EcoSanRes (Kvarnstrom et al., 2006).

3.5.2 Treatment Systems

The following treatment systems are identified in figure 16 and have been discussed throughout this chapter:

- Constructed wetland (10): section 3.3
- Struvite reactor (11): section 3.1
- Ammonia stripping tower or alternative nitrogen recovery (12): section 3.1
- Anaerobic digester (13): section 3.2

A key aspect of a de- or semi-centralized system will be the capacity for remote/online control and monitoring. Low maintenance is also desirable. In other words, a central office should be able to monitor a number of systems and only need to deploy assistance for either regularly scheduled maintenance or periodic trouble-shooting.

3.5.3 Products

By design, most of the products of treatment processes are recovered nutrients, water, or energy (numbers correspond to figure 16):

- Effluent from wetland not used for irrigation or toilet flushing (non-growing season) (14)
- Fertilizer products from urine treatment (15)
- Waste stream from urine treatment (16)
- Biogas and compost from digester (17)
- Reclaimed graywater used for irrigation and toilet flushing (18)

The waste stream from urine treatment will likely contain a concentrated mix of pharmaceuticals and hormones. Further research is necessary to determine if an additional treatment step can create recoverable water, or how to safely and sustainably manage the waste stream “as is”.

3.5.4 Indoor plumbing and fixtures

Within each home, potable water would be provided for all uses except for toilet flushing. After use, graywater sources (non-kitchen sinks, shower/bath, and laundry) would be combined and blackwater sources (brownwater, kitchen sink, and dishwasher) would likewise be combined before transport for treatment. A separate piping network would provide treated water from the constructed wetland to homes for irrigation and flushwater use. Urine diversion toilets would be necessary for separation of urine and feces.

Figure 21 summarizes indoor pipe requirements (numbers below correspond to Figure 21):

1. Potable water for all uses except toilet flushing
    a. Requires connection to city water lines to each home
    b. City water line would be connected to sinks, shower/bath, laundry, and dishwasher.
2. Combination of light graywater sources: laundry, bath/shower, and non-kitchen sinks
    a. Another piping system would combine light graywater sources before transport to the neighborhood treatment facility.
3. Combination of brownwater from toilets and kitchen wastewater

   a. A vaccum collection system would transport combined brownwater from UD toilets and kitchen wastewater.

4. Urine
   a. Separate pipes may be necessary if urinals are used in addition to UD toilets.
   b. A vacuum system would be employed for transport to the treatment facility.
   c. Non-corrosive pipes would be necessary.
5. Return of treated graywater for toilet flushing
   a. A single pipe would return flow from the graywater treatment system to each home for irrigation and toilet flushing.
   b. Additional indoor plumbing will be necessary to separate the flow used for toilet flushing from that used for graywater.

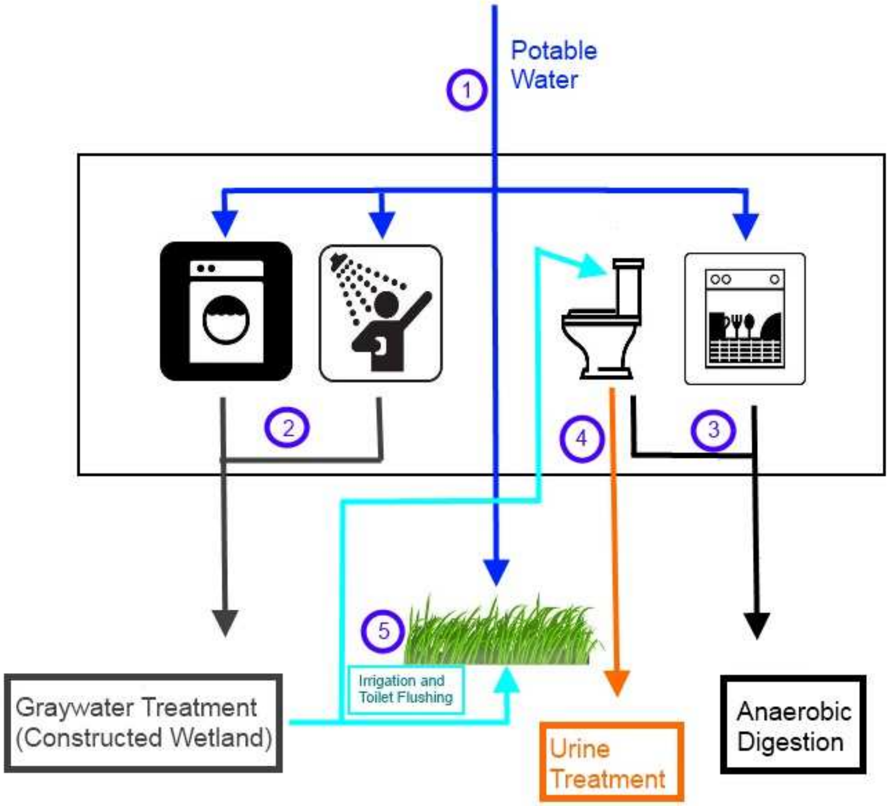


Figure 21 Indoor pipe requirements. Note that a UD toilet is necessary for this configuration.

It is important to note that this exact configuration has yet to be utilized in a pilot project. Other configurations have utilized urine diversion, but with other treatment systems for the remaining wastewater streams. Regardless, there are pilot projects which have employed some of the elements presented in the proposed design.

3.6 Other Projects to Inform Design

The WERF report “Source Separation and Treatment of Anthropogenic Urine”, the text “Source Separation and Decentralization for Wastewater Management” (Larsen et al 2013), and the websites http://www.susana.org/en/resources/case-studies (Sustainable Sanitation Alliance) and http://www.eawag.ch/index_EN (Eawag) are all sources for pilot projects employing various aspects of source separation and decentralization. Most pilot projects aim to develop a sustainable method of wastewater treatment for developing countries, where improved sanitation is a pressing issue in public health and where nutrient and water recovery are invaluable aspects to sanitation design. A very important study for implementing a UD project in the United States is Sanitary Recycling Eschborn (SANIRESCH). Of note is the degree of feedback published online regarding technical, social, and economic aspects of the SANIRESCH office building pilot project with UD and treatment of graywater and blackwater with MBRs.

Projects in Western European countries, the U.S., Australia and China are less prevalent, but are on the rise. Motivations include water shortages, concerns about micropollutants in the environment, and aiming to close the anthropogenic/agricultural nutrient cycle. Some office buildings (and single residences) have employed graywater treatment and reuse, and/or direct composting of feces or urine reuse. Other systems employ separate graywater and blackwater treatment with goals of reuse and energy/biosolids recovery respectively (http://semizentral.de/en/projects/projects-china/implementation-of-semizentral-qingdao/).

A great deal can be learned from these and other projects. Graywater treatment and reuse has been shown to be feasible, as well as co-digestion of brownwater and food waste/biowaste. Urine treatment is also feasible. The next logical step is to piece these systems together, trouble shoot transport issues, and attempt a neighborhood, apartment complex, or office building system in the U.S.

3.7 Summary

The proposed system separates urine, blackwater, and graywater. A struvite reactor would be combined with nitrogen recovery (ammonia stripping) for nutrient recovery from urine. Blackwater would be treated in an anaerobic digester for energy generation and nutrient recovery. Aerobic treatment of graywater enables local reuse with minimal investment of energy.

A reasonable, but not insurmountable, amount of experimental work will be necessary before implementation of separate urine, graywater, and blackwater into pilot project. Transport of three separate waste streams to individualized treatment is not without complexity. Infrastructure requirements are extensive and a large diversion from current infrastructure. In addition, it may be beneficial to justify a pilot project by quantifying benefits such as increased water reuse and nutrient removal/recovery. Chapter 4 summarizes knowledge gaps and risks associated with implementation.

Chapter 4: Implementation: Technical, Social, and Regulatory Aspects

Despite the many advantages of waste source separation, there are barriers to implementation. Many were identified in initial WERF research (Fewless et al., 2011) and are included throughout this chapter. Although the treatment technologies proposed in this work have been tested and are robust, design needs to be optimized for the selected waste streams according to site specifications. Pilot projects have tackled some of the technical problems related to piping separated wastewater streams, but more work is necessary. And, a crucial question is how urine diversion, on its own or in the context of de- or semi-centralized wastewater treatment, compares to maintaining or upgrading current U.S. wastewater treatment practices (for more stringent nutrient removal or for micropollutant removal).

4.1 Technical: Treatment and Transport

The major technical hurdles to overcome for implementation are treatment optimization, managing transport of urine and blackwater, planning pipe networks, and designing a robust system which can be remotely monitored. Reducing maintenance and increasing automation are key elements. First and foremost, a clear understanding of the quantity and quality of each wastewater stream should be pursued for the area of intended implementation. Most of this information is available for specific countries, but in many cases a wide range of values exists. This is largely related to diet (for urine and brownwater quality). The quality and strength of graywater is related to the type and quantity of products used in the bath and laundry. A rigorous design will not be possible without a well-defined influent composition. Effluent goals should match or exceed current or upcoming regulations (especially in regards to nutrients); particularly if an energy or cost analysis will be conducted.

Work is necessary to solve transport issues. Ammonia losses and urine scale can be problematic in urine transport. Vacuum systems and additional pipe networks add complexity. These topics were discussed in section 3.5.1. Pilot projects will play an important role in addressing these issues.

4.2 Social Considerations

Often one of the primary issues with alternative wastewater treatment is social resistance. Reusing nutrients captured from anthropogenic waste carries a social stigma, as does recovering “used” water. In addition, our current centralized wastewater system is a convenient, safe, reliable, “out of sight, out of mind” process. The problems cited in Chapter 1 necessitate a shift in perception. For these reasons, social surveys might be necessary to gauge the willingness of the general U.S. population to accept changes in wastewater infrastructure. Education will certainly be crucial should the recovery of nutrients and water become a more pressing environmental and economic issue. If the current design of urine separation toilets is used, modified practice is necessary and extra cleaning may be necessary. This will not be easily accepted in the U.S., except by those aware of the benefits of source separation. Social feedback presented from the WERF report as well as findings from the Novaquatis source separation project (Larsen and Lienert, 2007) revealed that:

- Odor can also sometimes be an issue, but can be mitigated with proper maintenance.
- Acceptance of NoMix toilets and waterless urinals in Europe is high in public facilities, but less so in private homes. With adequate education, pilot projects are possible in private homes.
- Habits/ergonomics are an issue: Men may need to sit depending on the UD model employed, some women and children have difficulty with the correct sitting position, and the cleaning needs may be higher than with conventional toilets

- The majority of users were positive about UD technology: Eawag conducted surveys of approximately 1250 users at two of its urine diversion pilot projects: the vocational college and the Eawag building. 72% of responders liked the idea of urine diversion, and 86% would move into an apartment with a UD toilet. Some complaints (not a majority) were associated with design, hygiene, and odor. Additional user feedback from 501 users of UD toilets/waterless urinals at the Basel-Landschaft Cantonal Library in Liestel was similar. Eawag also conducted a citizen focus group study. Volunteers familiarized themselves with urine diversion through an interactive computer tool and visited a urine diversion toilet, and were subsequently asked questions. The majority liked the idea of UD toilets, would move into an apartment with a UD toilet, and would buy food grown with a urine-based fertilizer. About half of the survey participants would buy a UD toilet.
- About 50% of surveyed farmers were positive about urine-based fertilizer in a European study: Eawag conducted a survey of Swiss-German farmers. 57% liked the idea of a urine-based fertilizer. 30% were concerned about potential for residual micropollutants (pharmaceuticals and hormones).
- User surveys should be employed in pilot studies.

Additionally, a review of the acceptance of urine diversion in 7 European countries (Lienert and Larsen, 2009) revealed that 80% of users like the idea of urine diversion, 75-85% were satisfied with design, hygiene, and seating comfort of NoMix toilets, 85% thought that urine-based fertilizer was a good idea (50% of farmers), and 70% would purchase food grown with urine-based fertilizer. 60% of users also encountered problems, however, indicating that NoMix toilets require further development. Education would be important in implementation, assuming source separation continues to be a promising method for sustainable wastewater treatment.

4.3 Regulatory Considerations

Looking further out into implementation, incorporating decentralized systems as described in this research will require an understanding of regulatory framework. Stakeholders (current wastewater treatment management, legislators, farmers, etc.) will need to be involved to determine responsibility for maintenance requirements and feasibility of nutrient reuse/transport. These are complex issues that should not be taken lightly. Additionally, there are issues with the current regulatory framework. For example, wastewater treatment regulations are designed for WWTP discharge, not reuse. Regulations will also need to be adapted to neighborhood scale systems.

4.4 Unintended consequences/risks/Unknowns

New technologies almost always have risks. This can be especially the case with wastewater systems, as human waste is not an easily discussed topic, and because centralized wastewater treatment has been a reliable “out of sight, out of mind” management scheme for decades. In thinking through the system outlined above, possible unintended consequences, and risks become apparent and are included below:

Will existing WWTPs experience inefficiency if anticipated steady state or increases in flow do not occur as a result of transitions to decentralized treatment systems?

WWTPs are designed for anticipated flows (present and future). This includes pipe networks. If areas of anticipated development employ alternative wastewater treatment, or if current service areas retrofit for alternative treatment, reduced flows could result in settling in sewer lines or treatment of lower volumes. Treating lower volumes may result in treatment inefficiency or higher costs per volume treated.

How will effluent containing high levels of pharmaceuticals (such as the liquid product of struvite precipitation) be treated or handled?

Martz (2012) noted several technologies for treatment of pharmaceutical wastewater: UV oxidation, combustion, adsorption on activated carbon, ozonation, membrane processes for non-biodegradable compounds, and biological processes for biodegradable compounds. Degree of degradation or transformation is linked to the specific qualities of each compound. It is unclear, at this point, how the resulting waste stream would be dealt with. It seems likely that the waste stream might be disposed of rather than treated, but it is not known how to safely do this.

Will fertilizer from urine and blackwater be accepted by consumers and farmers?

Because one of the promising benefits of source separation is more efficiently closing the nutrient cycle, it is important to understand the complex dynamics of “reusing” nutrients in agriculture. Farmers will, understandably, not be willing to consider any option that will require significant changes in practice without increased profit, or, even worse, decrease crop yields or profit. An unintended consequence would be if fertilizer generated from urine and blackwater were less effective, or carried a social stigma. Another could be if application techniques required costly adaptations.

What if UD toilets are not socially accepted or used properly?

UD toilets still have ergonomic issues, especially for children. Is there an incentive for improved design or a commitment to proper use?

How will incoming flows be managed in the case of operational failures?

The possibility of operational failure creates risk. This can be especially true with newer technologies. Remote monitoring will be necessary, and risk can be minimized by testing these systems in pilot projects. Safety plans will, of course, be a part of design.

Would large scale reuse of treated graywater cause problems not seen in studies thus far (related to pathogens, salinity, surfactants and other micropollutants)?

This could be related to use of a leachfield in cold weather months (permeation to water table), transmission through the food chain (through consumption of irrigated plants) or atmospheric transport after irrigation. Studies of graywater reuse (presented in section 3.3) indicate that risk to vegetation is minimal, but additional research or review of the literature is necessary to determine if long term persistence creates unforeseen issues.

4.5 Summary

In addition to technical issues, social and regulatory considerations may prove to outweigh the perceived benefits of the decentralized source separation system outlined in this report. Before a pilot project can be initiated, treatment system optimization (including clarifying influent quality) and finding solutions to transport issues (urine scale, UD toilet operation, complex pipe networks, remote monitoring) are necessary steps. Social acceptance of the technology and reuse of water and nutrients is key, as well as adaptation of regulations to this scale of treatment and reuse.

Although separating domestic waste streams, recovering nutrients, and local reuse of graywater seems more efficient than current practice, it is important to consider risks and unintended consequences before further research. Implementation on a large scale would ultimately involve consumers, farmers, municipalities, and regulatory agencies. The complexity of these dynamics is an important consideration. Education, user surveys, and stakeholder involvement are essential.

Chapter 5: Cost Feasibility Considerations

Cost is always a consideration when proposing a new technology. Obtaining a general (order of magnitude) comparison of centralized and decentralized wastewater treatment was therefore a goal in this research. It became clear early on, however, that a rigorous cost analysis would be difficult with the complexity of cost allocation in the wastewater treatment sector and with the relative immaturity of urine diversion technology.

5.1 Decentralized WWT System vs. Tapping into Current System

The reality of implementing the system proposed in Chapter 3 is that a new housing development would have a choice between either constructing a new decentralized WWT system (Figure 25) or tapping into an existing sewer system (Figure 26).

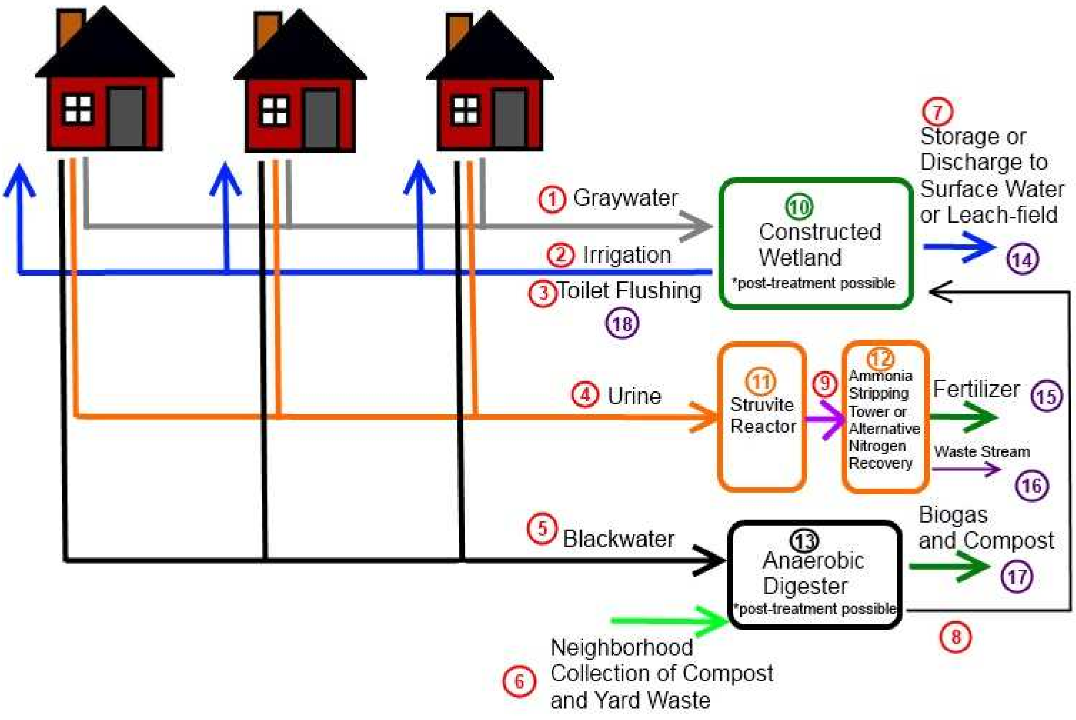


Figure 22 Proposed Dencentralized Treatment System

In addition to operation and maintenance costs, the following (external) infrastructure components would be necessary for the proposed system (discussed thoroughly in Chapter 3):

- Graywater collection pipes (1)
- Graywater reuse pipes: irrigation (2)
- Graywater reuse pipes: toilet flushing (3)
- Urine collection vacuum system (4)
- Blackwater collection vacuum system (5)
- System for storage or discharge to leachfield (7)
- Pipes to transport effluent from digester to wetland (8)

- Transport of compost and yard waste (6) (neighborhood collection by truck)
    - Alternatively, heavy duty garbage disposals could be utilized to combine compost collection with kitchen wastewater (5)
- Constructed wetland (10): section 3.3
- Struvite reactor (11): section 3.1
- Ammonia stripping tower or alternative nitrogen recovery (12): section 3.1
- Anaerobic digester (13): section 3.2
- Transport of effluent from wetland not used for irrigation or toilet flushing (non-growing season) (14)
- Systems for managing treatment products:
    - Collection of fertilizer products from urine treatment (15)
    - Evaporation or transport of waste stream from urine treatment (16)
    - Biogas and compost from digester (17): transport of nutrients and system for energy recovery

Despite the extensive infrastructure required for a single neighborhood, there are benefits, including:

- Fertilizer products from urine and blackwater treatment
- Energy production from blackwater treatment
- Potable water demand reduction via graywater reuse for irrigation and toilet flushing
- Reduced nutrient loading to environment compared to than centralized WWT, even when advanced nutrient removal processes are installed at WWT
- Micropollutant separation from a large proportion of the nutrients

The other option for a new neighborhood would simply be to tap into an existing sewer system feeding into an already established WWTP, assuming such a facility can accommodate increased wastewater flows (Figure 26).

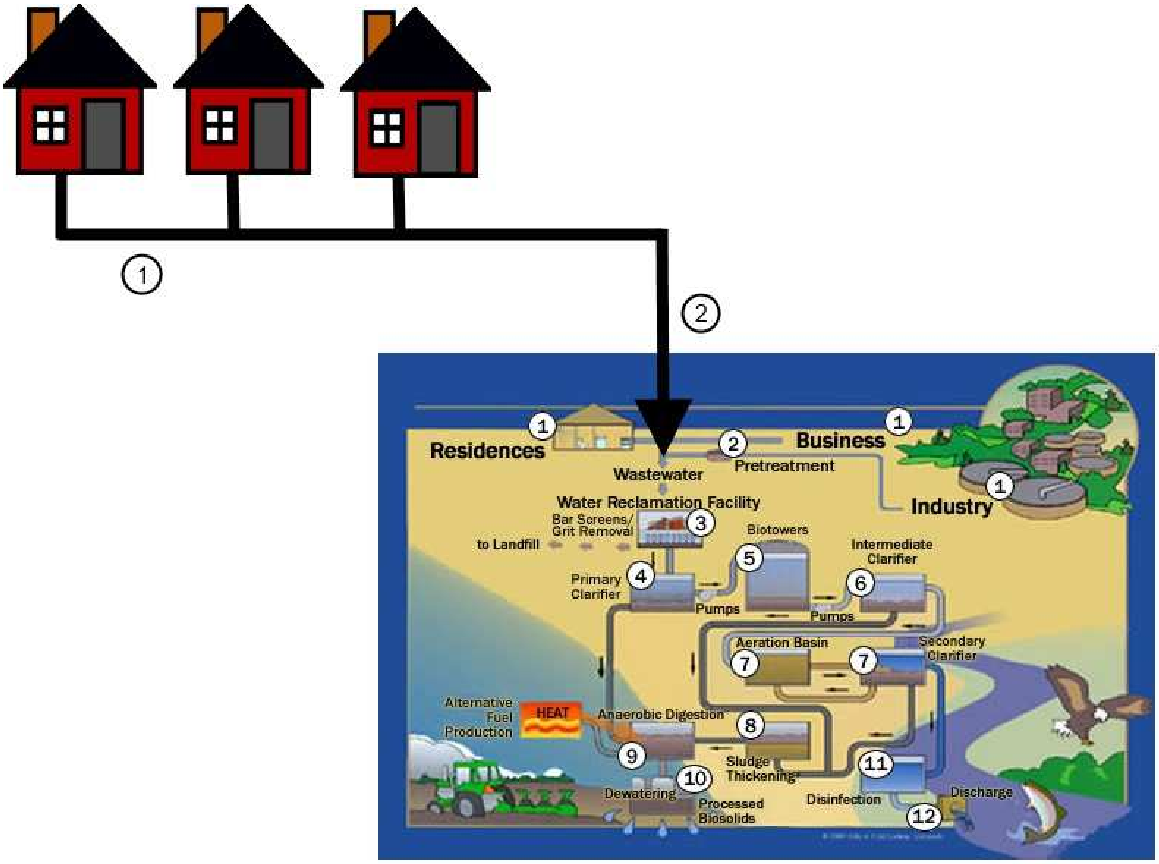


Figure 23 Tapping into a Centralized Wastewater Treatment System

For this secondary scenario, the new development would combine all waste streams within a single household. Neighborhood infrastructure/costs would simply include:

- Combined sewer collection system to centralized WWTP (1)
- Tap fee to WWTP for treatment (2)
- Monthly WWT fees

Connecting to an existing WWTP also has important benefits:

- One pipe connecting all domestic wastewater streams to the central sewer system (e.g. design simplicity within the single neighborhood)
- Security of an established process
- Lower costs (at least in the near term)

From the perspective of the developer (or collective homeowners), tapping into an existing sewer system seems the obvious choice. However, there are factors which may influence this choice in the foreseeable future. For example, monthly wastewater treatment and tap fees may increase as WWTPs struggle to meet lower nutrient regulations. If a new system provides improved results (at lower cost) as compared to adding flow from new neighborhoods to existing WWTPs, city wastewater managers may propose city-wide incentives for implementation. This is because strict nutrient discharge limits are driving the costs of WWT very high (Breidt, 2015). Finally, sustainable wastewater treatment (from the perspective of nutrient recovery, water recycling, and energy generation) may be a marketable feature for a new neighborhood. In other words, residents may be willing to pay more for a wastewater treatment system with environmental benefits.

5.2 Cost Estimates from the Literature

To date, cost data for urine separation systems are limited, especially the types of systems which would be employed in the United States. In addition, UD systems reflect economies of scale, resulting in higher costs than might be the case if increased production occurred. Struvite reactors such as the system used in the Eschborn project are prototypes (Bischer, 2012). UD toilets are manufactured and marketed by several companies, but are still much more expensive than an average flush toilet. This is despite the fact that the change in plumbing (for UD as compared to a conventional toilet) is not as complex as is reflected in the current cost difference.

Three cost analyses from the literature are presented below. The first is a product of the Eschborn pilot project (Bischer, 2012). The benefit of this analysis is its incorporation of a struvite reactor and UD toilets. The second takes a different approach. Conducted by lead researchers in the field of UD, the goal was to generate the cost of conventional WWT, and to use this as a benchmark for new technologies (Mauer et al, 2006). Finally, the third study is an analysis of the cost and effectiveness of nutrient removal in conventional WWTPs (Breidt, 2015). This study is presented to address regulatory changes in regards to nutrients, and because considering the cost of an equal level of nutrient removal in WWTPs (as compared to source separation) may place more value on source separation systems.

5.2.1 Costs of a System with Source Separation

At least one study has attempted to compare a source separation system (SANIRESCH in the Eschborn project) with conventional WWT (Bischer, 2012). In this particular system, urine was treated in a struvite reactor (no additional nitrogen removal), and brown/gray water were treated in MBRs. Several scenarios were analyzed (direct application of urine, struvite production, and conventional WWT) and a sensitivity analysis was conducted. Key lessons from this study were:

- MBR's and struvite reactors were "stable and reliable". The main problem was constant blockage of valves (and subsequent replacement) in the urine separation process (due to urine scale). Also:
    - Odor stop rubber ring on urinals had to be replaced annually, although this was less expensive than the valves

  - Running costs of struvite reactor were high because of manual labor: increased automation and decreased capital cost will be necessary for feasibility
  - Key cost issues are parts replacement and manual labor (operational) costs
- Operational costs of toilets and urinals (for urine diversion) are 43% of the total project cost (due to cleaning and spare parts)

The overall conclusion was that alternatives to conventional WWT were substantially more expensive than the source separation alternatives. However, Bischer states that the costs associated with the conventional scenario included toilets, urinals, pipes, and the operational and reinvestment costs associated with these. Wastewater fee rates were not mentioned in the summary of conventional wastewater costs. So, even if they were included without mention, it is unclear what level of treatment (especially in regard to nutrients) was achieved in the conventional scenario. Therefore, the comparison is not a true comparison of alternatives. A true comparison would involve a complete WWT system which achieved a similar degree of nutrient removal.

Despite this discrepancy, the sensitivity analysis revealed that increased automation, increased service life of UD toilets' spare parts, decreased investment costs of UD toilets and waterless urinals, increased freshwater and wastewater fees, and increased energy prices were significant contributing factors. It was concluded that automation of the struvite precipitation process is necessary to create a marketable product (It could reduce overall cost by 12%). Cost reduction of parts, UD toilets, and waterless urinals (capital, not operational) is important but not as significant. These are important findings for the future development of source separation projects.

Based on these results, it is clear that improvements are required in technologies for urine diversion and nutrient. The most critical technology improvements are increased automation and increased service life of UD toilets' spare parts. The significance of "running costs" is illustrated in Figure 22. Scenario A is urine separation and storage with graywater/brownwater treatment in MBRs. Scenario B is urine separation with struvite precipitation and MBRs for the remaining graywater and brownwater. Scenario C is “conventional” treatment. As stated previously, it is unclear if the conventional scenario includes costs outside of interior plumbing and conventional toilets/urinals.

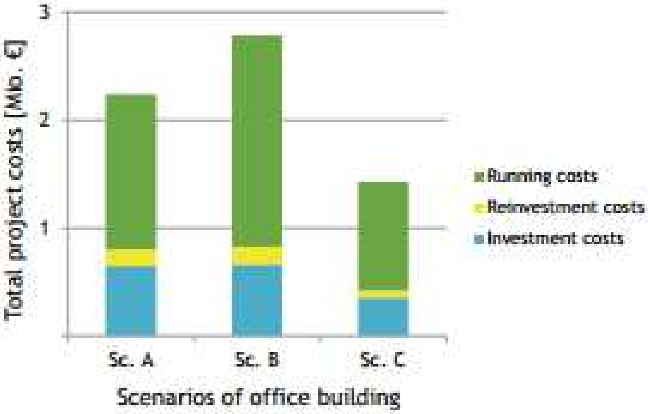


Figure 24 Total project costs for the Eschborn source separation project (Bischer, 2012)

In summary, alternative treatments were substantially more expensive than the conventional scenario (as defined), but the difference is largely due to higher maintenance and reinvestment costs. According to the study’s authors, increased automation of the struvite precipitation process is feasible and will likely make this scenario feasible. Investment costs are also higher than conventional, but it is less of a factor than operational costs, and it is unclear if investment costs included a wastewater fees (or a proportional amount of WWTP investment costs) and what level of treatment was achieved by the conventional treatment. Investment costs are also subject to economies of scale.

5.2.2 Costs of Centralized WWT

An alternative to estimating the cost of a new system is to generate the cost of conventional WWT (with nutrient removal and projected effluent regulations) to be used as a non-exceedance value. Maurer et al. (2006) published an important paper on this subject in terms of taking a first estimate of generating this exceedance value. In this paper, replacement/investment costs, and annual costs (operation and maintenance, depreciation, capital financing), were calculated for several western European countries and the United States.

Some of the U.S. data had to be estimated (replacement costs couldn't be found) and were based on previous and forecast investments. For all countries, replacement costs and investments range from $1700 to 5300 per capita, with a revised minimum of $2600 for current effluent requirements (as of 2006). Differentiations were noted between large and small countries (costs were higher for small countries), and it was noted that not all sewers were accounted for (private sewers are a significant investment). When comparing different WWTPs, if BOD and nutrient removal are employed (degree of removal not specified in report), the technical portion of this amount is significantly different, but the cost difference was not reported. WWTPs are responsible for the majority of operating costs, and sewer systems make up most of the investment costs.

Four hypothetical scenarios were evaluated to determine how much could be invested in an alternative to centralized WWTP's. In all scenarios O&M costs were assumed to be similar, and it was assumed that a new WWTP was constructed. A distinction was made between "small" and "large" countries. Because large countries tend to have larger cities, costs were lower as a result of economies of scale. Estimates are based on a 15 year lifespan and only large country values are reported in Table 9.

Scenario 1A is a situation where no existing infrastructure is present. Therefore the full cost of establishing a new WWTP could instead be allocated to an alternative. Scenario 1B is a situation where a sewer exists, but is abandoned to create an alternative system. In this case, remaining capital finance costs will reduce the available capital for an alternative system. In scenario 2A, the existing sewer would be used for a new decentralized treatment system. The capita available is lower because of the costs allocated to maintenance of the sewer. In scenario 2B, the existing sewer would also be used but urine separation would be employed, thereby alleviating the need for nutrient removal at the WWTP.

Table 9 Available capital for alternative wastewater treatment: Maurer et al. (2006) study results

Scenario	US$/capita available for a new system with a 15 year lifespan
1A: No existing infrastructure	$1167
1B: Existing sewer abandoned	$655
2A: Use existing sewer with new decentralized treatment system	$345
2B: Use existing sewer but employ urine separation	$262

Scenario 1A or 1B are the most likely situations if a new decentralized WWT system with urine separation were to be initiated in the U.S. If the system had a 15 year lifespan, the following would be true for a 500 home neighborhood (with an average of 2.5 people per home):

- Scenario 1A: From the provided data, $1167/capita would mean that $1,460,000 could be invested in a neighborhood system.
- Scenario 1B: Use $655 per capita to conclude that $820,000 could be invested in a new system.

Factors to be considered (according to the findings of this study) are capital-financing costs (included here, but may affect costs in other analyses), lifespan (newer systems have shorter lifespans, which adds to replacement costs but offers the possibility of more rapid evolution of WWT), and operation and maintenance (this is clearly still being determined for new systems).

It was noted throughout that the results of this research were meant to be preliminary, especially because of difficulties compiling data (investment capital sources-public and private, different lifespan assumptions, differentiating investments vs. maintenance, interest rate and depreciation variability, etc.). However, it is an important concept worth revisiting as cost is often a primary concern in engineering design.

5.2.3 Accounting for Nutrient Removal

Another way to assess the financial viability of source separation is to consider the cost of upgrading current U.S. infrastructure to meet upcoming nutrient discharge standards. Breidt (2015) performed a Colorado case study in an attempt to compare various strategies for reducing N and P discharge through WWTP upgrades and stormwater best management practices. The following processes were compared: modified Bardenpho process, centrate and recycle activated sludge rearation basin, anaerobic ammonium oxidation (ANNAMOX), selective adsorption, electrodialysis, ammonia stripping, and struvite precipitation. Of these, only selective adsorption, electrodialysis, ammonia stripping, and struvite precipitation allow for nutrient recovery (as opposed to just removal). Baseline data were collected from a WWTP and BioWin was used to model the selected processes.

Capital and maintenance net present values were included in a 20-year life cycle cost estimate. Pounds of nitrogen/phosphorus removed as well as cost (US$) per pound were reported for each process. Struvite precipitation and selective adsorption both had high P removal with relatively low cost per pound of P removed. ANAMMOX and ammonia stripping had high N removal, but ammonia stripping was cheaper. Removal rates were reported in Chapter 2. Table 10 shows relative removal effectiveness.

Table 10 Removal effectiveness of nutrient removal in WWTPs from Breidt (2015)

Wastewater Technology	Removal Effectiveness	
CaRRB	322 – 9,150	$/lb.-N
ANAMMOX	270-1,140	$/lb.-N
Ammonia Stripping	150-400	$/lb.-N
Electrodialysis	1,000-3,730	$/lb.-N
Struvite Precipitation	310-1,070	$/lb.-P
Selective Adsorption	400-2,000	$/lb.-P

The impact to cost of treatment per capita-year was also calculated, with a current average wastewater charge of $918 per household. Table 11 details the cost per capita and monthly utility rate for various nutrient removal processes.

Table 11 Cost per capita and monthly utility rate for nutrient removal in WWTPs from Breidt (2015)

Scenario	Cost per Capita			Monthly Utility Rates		
	Capital	O&M (y^{-1})	Total (yr^{-1})	Per 1000gal - cap	Per household	Per capita increase
Current Rate (M. Bardenpho)	$0	$96	$96	$3.44	$21.97	N/A
CaRRB	$14	$208	$209	$8.19	$52.29	$10
ANAMMOX	$37	$132	$134	$5.28	$33.71	$4
Selective Adsorption	$6	$300	$300	$11.73	$74.93	$18
Struvite Precipitation	$14	$148	$149	$5.73	$36.59	$5
Ammonia Stripping	$42	$194	$197	$7.73	$49.38	$9
Electrodialysis	$23	$1,283	$1,284	$50.31	$321.34	$100
Current Rate (Approximate)	$0	$420	$420	N/A	N/A	N/A
BMP Retrofits	$21	$9	$10	N/A	N/A	N/A
Bioretention Implementation	$1,746	$38	$125	N/A	N/A	N/A

Figure 23 displays capital rate increases compared to existing wastewater or stormwater base charges.

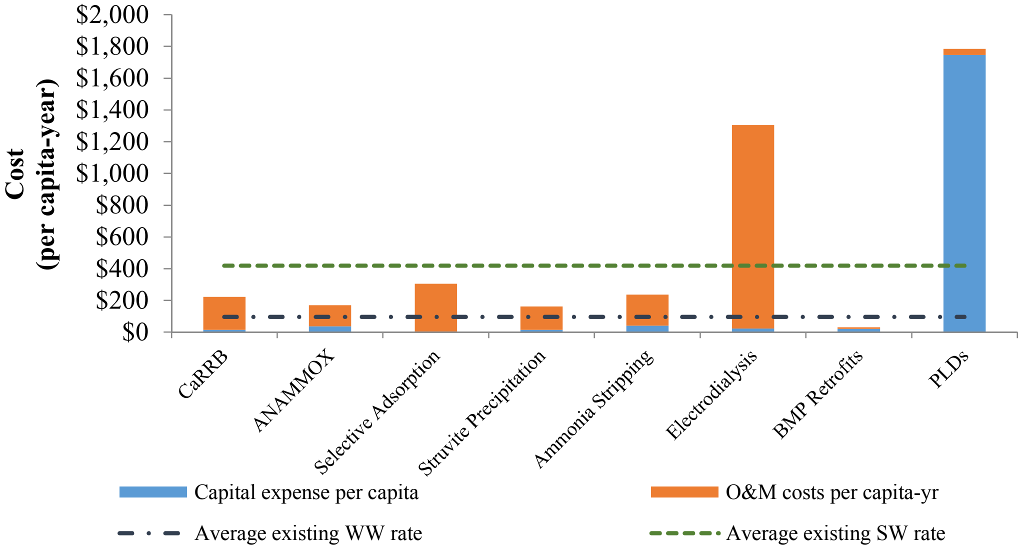


Figure 25

Cost (per capita-year) of nutrient removal strategies from Breidt (2015)

Assumptions made by Breidt (2015):

- Approximately 70 gallons of wastewater produced per person per day
- An average of three people per residence
- The capital cost was divided by the planning horizon (20 years) to calculate the total per capita-year cost
- Storm water rates are calculated per square footage of land owned, and is on average $35 per monthly bill; per household and capita-use is therefore ignored
- Inflation/interest rates were not included in the calculation of consumer rates; therefore these rates (meant for a rough estimate only) are most applicable near the initial start-up of the technology or implementation of BMPs

According to personal communication with the study's author (March 25, 2015), the data primarily describe the costs for nutrient removal (side-stream treatment), but the costs of modified Bardenpho (the current mainline technology) are included. Most of the alternatives reduce the cost of maintaining this main treatment, but have a higher net cost resulting from the modification for improved nutrient removal. The costs of maintaining and pumping water to the primary clarifier, tertiary treatment, and out of the plant, are not considered. The costs presented are therefore reasonable for a preliminary (alternatives comparison) study, but are not detailed enough for a plant-specific feasibility study that would be a precursor to a design plan.

Using the total $/capita-year values above, and considering a 500 home neighborhood, it can be estimated that adding struvite precipitation and ammonia stripping to wastewater treatment would result in an approximately $350/capita-year increase in wastewater charges. Using the average yearly cost of $918, the resulting household cost could increase to approximately $1795 per year (assuming 2.5 people per household on average). It should, however, be noted that none of these treatments could achieve the same levels of nutrient removal as source separation of urine (Table 6 in Chapter 2).

5.3 Comparing Estimates from the Literature

An effort was made to compare the cost of nutrient removal/recovery in WWTPs and to compare this value to the "available" funds estimated by Mauer et al (2006) for establishing a new wastewater treatment system. This estimate is not rigorous, and not intended to be used to guide future research, but it may give some sense of comparison.

Using the values from Breidt (2015) reported as $/household:

- As already calculated above, adding struvite precipitation and ammonia stripping to wastewater treatment added approximately $350/capita-year, the resulting household cost could increase to approximately $1795 per year (assuming 2.5 people/household on average).

- For a 15 year lifespan in a 500 home neighborhood, this sums to approximately $13.5 million.
    - A 15 year lifespan was used rather than 20 (more typical for a conventional WWTP planning horizon) because of the technical maturity of UD systems and. Although Breidt (2015) and Mauer et al. (2006) used 20 years as the planning horizon, the value used here in calculations was a $/household value.

It is important to note, that in reality, the higher costs reported in table 11 would more closely reflect the effluent quality expected with source separation of urine and decentralized treatment. Some discharge of nutrients would still occur by using struvite precipitation and ammonia stripping in centralized WWT.

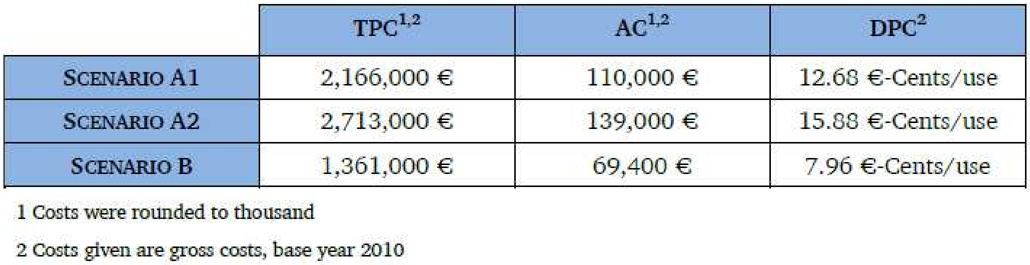
In comparison:

- Values from the Mauer et al. (2006) study indicated that less than $820,000-$1,460,000 could be spent on a new system without exceeding the cost of a conventional WWTP. This value is based on using the current estimated/calculated cost of current WWT. The nutrient removal achieved by the WWTPs in the Mauer (2006) study was not reported. It is unlikely that removal comparable to the Breidt (2012) report or urine separation systems was achieved in the WWTPs whose cost data were used.

Clearly, additional research will be necessary to clarify the drastic difference in these values. Both should represent a “cap” on what could be spent on a new system without exceeding the cost of current wastewater treatment, or advanced nutrient removal. Contributing factors could be the values used for nutrients, assumptions included in BioWin estimations, lack of full cost data in the Mauer et al. (2006) study, or other inconsistencies. As stated above, it is unclear what degree of nutrient removal (if any) is achieved at the WWTPs studied by Mauer. Additionally, the calculations performed here, although based on sound cost estimates, were not intended to be rigorous.

The most important lesson illustrated by the Breidt study is that the high cost of removing nutrients at a centralized WWTP will be a driving factor in continued analysis. It is clear from both the Bischer and Mauer report that developing costs for conventional WWT can be difficult. Moving forward, it seems best to focus on the cost to achieve the same or equal effluent goals when comparing new technologies to conventional. Both the Breidt and Mauer studies indicated an increase in costs once any degree of nutrient removal was added. In addition, even if nutrient removal is added in WWTPs, the same level of removal can’t be achieved.

In that regard, it would be helpful to generate a $/capita estimate for source separation systems. The Bischer (2012) report included the table presented in Figure 24. Scenarios A1 and A2 involve urine separation, and scenario B is “conventional”. Cost of each scenario in cents/use is reported.



	TPC^{1,2}	AC^{1,2}	DPC^{2}
SCENARIO A1	2,166,000 €	110,000 €	12.68 €-Cents/use
SCENARIO A2	2,713,000 €	139,000 €	15.88 €-Cents/use
SCENARIO B	1,361,000 €	69,400 €	7.96 €-Cents/use

1 Costs were rounded to thousand

2 Costs given are gross costs, base year 2010

Figure 26 Total project costs and operational costs for the source separation system in Eschborn (Bischer, 2012)

<u>Scenario A1</u>: urine separation and storage, graywater/brownwater treatments with MBRs.

<u>Scenario A2</u>: struvite precipitation, graywater/brownwater treatment with MBRs.

<u>Scenario B</u>: conventional treatment.

TPC: total project costs

AC: annual costs

DPC: dynamic project costs

for a urine diversion project such as the Eschborn project can be generated using these cents/use values. To create a urine diversion system above for a 500 home neighborhood, operating for 15 years with 2.5 people per household and 4 uses per day, the cost would be $4.6 million. This estimate was generated using the struvite reactor/MBR scenario value of 17 cents (US$) per use (converted from Figure 24 above).

To summarize, for a 500-home neighborhood, with 2.5 people per home and a 15 year lifespan:

- Adding nutrient removal: $13.5 million
- Cost of current WWT: $800,000-1.5 million
- UD system with MBRs: $4.6 million

Although this cost comparison is over-simplified, the range in values illustrates the complexity of this endeavor. Mauer (2006) attempted to calculate (estimating when necessary) the actual cost of WWTPs, so that this value could be used to estimate the "available funds" for an alternative. Breidt (2015) estimated the cost of advanced nutrient removal. Bischer (2012) reported the cost of a UD system (with MBRs for remaining graywater and blackwater) for the Eschborn office building. The similarity in these studies lies in the attempt to either clarify how much can be spent on an alternative, or how much must be spent for a high degree of nutrient removal. The disparities abound, however. So although the rough cost comparison is presented here, much work is needed to generate an accurate depiction of the cost of a UD system as compared to equal treatment in a WWTP.

5.4 Factors to Consider When Comparing Source Separation Systems to Current WWT Systems

Once research advances to the point that urine diversion technology is more easily adapted to decentralized treatment in neighborhoods or other appropriate settings, and costs have decreased through increased automation and better parts, the following factors should be considered:

- To compare two systems with similar results centralized treatment can be assumed to be activated sludge with advanced nutrient removal, so as to most closely replicate the end result of improved water quality discharge (primarily in terms of nutrient removal). Micropollutant removal could be considered an “added bonus”. This is because causal relationships between human/ecological health to the presence of micropollutants in the environment (and drinking water sources) are yet to be validated on a large scale. As a result, there is not yet a need for regulatory changes.
- It can be difficult to correctly calculate the true cost of both water and wastewater treatment, due to complexities in cost allocation.
- The volumes per day of separated wastewater streams can easily be calculated, but do exhibit variability from household to household. The costs for anaerobic digestion, wetlands, and vacuum sewers can be calculated, although a rigorous analysis would

also include improving the understanding of influent/effluent so as to best estimate system design. Influent quality will influence reactor size and additional costs, and effluent requirements may deem post treatment necessary. Difficulties arise in estimating the costs of urine separation systems, largely due to urine scale issues, parts replacement, and operation (Bischer, 2012).

- Piping systems will have to include transport to treatment facilities, to irrigation and toilet flushing reuse, and to a leachfield.
    - Neighborhood layout will, of course, affect pipe costs. New urbanism might involve lower irrigation demand, which might necessitate alternative water reuse scenarios like use for toilet flushing. Growing season length will affect how much storage is necessary.
- Urine diversion toilets are currently in low production, and are, as a result of economies of scale, very expensive. The costs would likely decrease substantially if they were to move into mass production after wide scale adoption of the practice.
- Anaerobic digestion of multiple waste streams will have added costs:
    - Heavy duty garbage disposals with vacuum sewers
    - Yard waste collection
- A true comparison would involve reclamation of wastewater for reuse from WWTP: this would involve more pipes for the conventional scenario.
- Estimating costs (especially operational) will be hard to determine without further pilot projects. Some information is available from Bischer, 2012.
- How would neighborhood system operation be handled? How would costs be appropriated?
- What is the water reuse potential? Can the real value of “saved” potable water be calculated?

5.5 Potential Revenue and Accounting for Economic Externalities

Treated graywater used for irrigation and toilet flushing and recovered nutrients are valuable resources. Although the value of produced struvite and compost (from the digester) could be considered, it is not known at this point if its use in agriculture would be accepted. If recovered nutrients were considered "revenue", then it would also be valuable to calculate the real cost of generating commercial fertilizer. This might include accounting for mining, transportation, nitrogen fixation (Haber Bosch process), etc. At the very least, the cost of advanced nutrient removal in WWTP must be considered for comparative purposes.

It is also worth noting the economic externalities present in current nutrient management. Economic externalities happen when a party is negatively affected by an activity/situation that they did not initiate. By definition, those affected are not compensated, although harm is done. For example:

- Degradation of downstream beneficial uses resulting from eutrophication
- The carbon footprint of commercial fertilizer production (and the cascading effects of climate change)
- The potential health risks caused by release of micropollutants into the environment and, hence, downstream drinking water sources

In essence, these are all "quantifiable" issues, yet the costs are difficult to calculate. This quality of externalities should not, however, preclude their inclusion in an economic justification for innovation. (Novotny, 2003)

The savings associated with water reuse could be quantified with available information and considered "revenue". This would be especially important if the "true" value of potable water was calculated. However, the high costs of separate pipelines may diminish its benefits in the eyes of stakeholders. In addition, reuse of graywater might not be enough to meet irrigation demand, depending on landscape selection.

5.6 Summary

An effort was made to find preliminary cost information from the literature, resulting in the following conclusions:

- Determining the cost of current WWT for purposes of comparison is difficult, especially because of variability in degree of nutrient removal and a mix of public and private investment in sewer systems.
- The relative immaturity of UD technology results in high costs. Increased automation and increased life of spare parts is necessary before the cost of UD will be comparable to conventional systems.
- The UD system utilized in the Eschborn pilot project is less than half of the cost of adding nutrient removal in WWTPs. This is in contrast to the findings of Bischer (2012), but this may be due to discrepancies in calculations (it is unclear if Bischer included the full costs of WWT and what level of treatment was achieved in the conventional scenario).

Additional research is recommended, especially in regard to comparing costs only when equal levels of nutrient removal are achieved, incorporating potential revenue, and accounting for economic externalities. This analysis may be more beneficial once UD technology has become more highly automated and technologically sophisticated. In addition, although the simplicity of connecting to a centralized sewer network discourages implementation of decentralized systems with source separation, increasing costs associated with centralized WWT and the marketability of a sustainable WWT system may create incentive for innovative approaches.

Chapter 6: Discussion and Conclusions

A decentralized wastewater system with urine diversion was proposed with a focus on water reuse and nutrient recovery. Urine, blackwater (kitchen wastewater, brownwater), and light graywater (non-kitchen sinks, laundry, bath/shower) would be separated at the source and transported to decentralized treatment systems on a neighborhood scale. Urine would be treated with struvite precipitation for phosphorus recovery, and ammonia stripping for nitrogen recovery. Graywater would be treated in a constructed wetland and reused for irrigation and toilet flushing. Blackwater (along with other compostable materials) would be treated in an anaerobic digester for energy recovery and nutrient recovery. Anaerobic digestion could occur on a larger scale than graywater and urine treatment for improved process efficiency. The recovered energy could be used to heat the digester, or other neighborhood uses. These systems provide near complete nutrient recovery, generate energy, and allow for water reuse without extensive treatment. However, issues are evident.

The system proposed requires extensive infrastructure. Retrofit is unlikely, so the most likely installation scenario would be new neighborhoods. The necessary piping networks are more complex than the conventional scenario. The additional capital and maintenance may prove to be a key disadvantage. Vacuum sewers, despite the benefits of shallow installation depth, faster transport, and air tight transport, have issues. Vacuum sewer systems are expensive, involve noisy vacuum stations, and require monitoring. Valve failures can be problematic.

Constructed wetlands, anaerobic digesters, and ammonia stripping towers are more common than struvite reactors; however, optimization is still necessary according to the specific quality of the waste streams proposed here for separate treatment. The struvite reactor used in the Eschborn pilot project (Bischer, 2012) is a prototype. UD toilets are also relatively immature.

Technological advances are necessary for feasibility, especially in regards to increased automation and decreased maintenance/cleaning. In addition, the waste stream generated from urine treatment is likely to be highly concentrated with pharmaceuticals. The question of how to dispose of or treat this waste stream is important, especially with sustainability as an overarching goal.

There are also social and regulatory concerns. The U.S. regulatory framework is largely designed around centralized WWTP discharge. Adaptations for reuse and effluent from smaller decentralized systems will be necessary. Social issues related to acceptance of UD toilets and water and nutrient reuse are important. Nutrient reuse is only possible if farmers are able and willing to use treatment products, and if a regulatory framework is developed to ensure consumer safety.

An important issue is the high cost of UD as presented by Bischer (2012) as compared to the “conventional” scenario. Comparing the Eschborn pilot project UD scenario to the current cost of WWT (Maurer, 2006) and to the added cost of nutrient removal processes in WWT (Breidt, 2015) revealed that although UD technology is more costly than conventional treatment, it is much less costly than adding nutrient removal in WWTPs. It was indicated in the Eschborn pilot project cost analysis, that automation, reduced cleaning/maintenance requirements and improvements to UD spare parts could reduce costs enough that the UD scenario would be feasible relative to the conventional scenario. In future cost analysis, it will be necessary to compare the cost of UD systems with treatment systems that achieve the same levels of nutrient removal. An improved cost analysis could also account for treatment products (fertilizer, energy) and environmental externalities (related to eutrophication, greenhouse gas emissions).

Risks and unintended consequences are inherent to innovation. In this case, questions are largely centered on consumer/ farmer acceptance and technological improvements.

Managing waste streams, automating processes, improving UD technology and developing a robust system for remote monitoring are essential.

As effluent water quality standards become more stringent and the need for water reuse becomes more pressing, the drive to develop alternatives involving urine separation will probably increase in the U.S., especially considering the difficulty and high cost of nutrient removal in WWTPs. The potential benefits of urine separation lay the basis for a strong argument in favor of further development of urine separating toilets and piping systems, but the obstacles evident in pilot projects indicate that design work is far from complete. Despite high social acceptance in Europe, and the advancement to date of urine diversion technology, continued research is necessary to create marketable products, develop life cycle and/or cost-benefit analysis (relative to U.S. parameters), determine social acceptance in the U.S., and assess the most appropriate means and setting for source separation and decentralized treatment.

In summary, disadvantages of source separation and decentralized treatment include extensive infrastructure requirements, technological issues, and high cost (although this is likely to decrease with research and development). Advantages are improved effluent quality (in terms of nutrients and micropollutants) through treatment of smaller, more concentrated streams and the possibility of nutrient reuse and increased water reuse. UD may also be less costly than adding nutrient removal to WWTP processes.

6.1 Future Research

The path forward for decentralized wastewater treatment will involve a multidisciplinary team comprised of experts in engineering, agriculture, environmental policy, aquatic ecology, and economics. Key steps in the continued investigation of decentralized treatment with source separation are as follows:

I. Resolve technical issues related to transport of waste streams, refine understanding of influent quality and effluent goals, and optimize treatment systems.

II. From the social/political perspective, investigate regulatory framework for water and nutrient reuse, conduct social surveys to assess acceptance, and consult with stakeholders (farmers, WWTP operators, etc.) for feedback regarding risks or unintended consequences.

III. Implement a pilot project in the U.S. It is a necessary precursor for acceptance and broader scale implementation.

IV. Conduct an economic analysis of greater breadth, with consideration of the following in addition to capital and operating costs:
    a. Water reuse (incorporating cost and projected cost of potable water treatment)
    b. Energy use/carbon footprint of all treatment options and nutrient recovery (vs. phosphorus mining and industrial fertilizer production)
    c. Cost of fertilizer production, potential revenue of recovered nutrients
    d. Comparable effluent (enhanced nutrient removal is difficult and expensive to achieve in conventional WWT)
    e. Economic externalities (carbon footprint, eutrophication, contribution of micropollutants to downstream water treatment facilities)

Depending on the scale, an economic analysis could occur before, during, or after successful operation of a pilot project. This is because a cost analysis might be better informed once maintenance requirements are well understood (and possibly improved), however, if the pilot project is somewhat large scale (or otherwise deemed risky) a cost analysis may be necessary to justify implementation.

6.2 Conclusions

Improved effluent quality can be achieved by adding nutrient removal to conventional WWTPs, but it is costly and not as effective as applying the same treatment methods to source separated urine. Source separation and decentralized treatment also offers the possibility of increased water reuse because graywater, especially light graywater, requires relatively minimal treatment before reuse as flushing and irrigation water. Separating urine from blackwater improves anaerobic digestion efficiency, and anaerobic digestion can be used to generate energy and recover nutrients.

Technical concerns with urine diversion remain, and risks and unknowns of decentralized treatment with urine diversion are evident. Costs of urine diversion are also currently high, but early estimates indicate that it may be cheaper than adding nutrient removal processes in WWTPs. However, an integrated cost analysis considering comparable levels of nutrient removal and a broader context of sustainability (closing the nutrient cycle, minimizing carbon footprint) should be performed. Additionally, technical work to reduce maintenance requirements and increase automation is necessary. Specifically, research and development work is necessary to improve UD toilets and struvite reactors so that operating costs are reduced. Pilot projects are crucial as a means to characterize waste streams, optimize treatment, validate transport networks, increase automation, and develop remote monitoring capabilities. Despite these challenges, urine diversion and decentralized treatment shows promise as an efficient, sustainable innovation in wastewater treatment.

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Appendix A: Preliminary Design-graywater treatment

The operational parameters of aerobic biological systems are well understood, so a preliminary design was conducted with the neighborhood design proposed in this research. The constructed wetland was designed as a free water surface (FWS) wetland. FWS wetlands provide low velocity (laminar flow) via a large area of shallow water and emergent vegetation, which is ideal for particulate removal (characterized by total suspended solids (TSS)). BOD components, fixed form of TN, TP, trace levels or metals and more complex organics are all contained in TSS. When these particulates are oxidized/reduced, soluble forms of BOD, TN, and TP can then be adsorbed by soils or removed by microbes or plants. Aerobic activity occurs as a result of available oxygen (at the water surface, living plant surfaces (microsites), and on root and rhizome surfaces). Most of the liquid in a FWS is anoxic or anaerobic, however. Without oxygen, nitrification is limited, but BOD, TSS, trace metals, and some complex organics will be removed because the treatment of these occurs under both aerobic and anoxic conditions. (http://water.epa.gov/infrastructure/septic/upload/free_water_surface_wetlands.pdf)

The inputs to the wetland include both graywater and leachate from the anaerobic digester. Effluent from the struvite reactor was not accounted for at this time because characterizations of this flow are not available in the literature. It is also expected that this effluent may be high in pharmaceuticals/hormones and thus need a different approach for disposal.

Because of the digester effluent, the wetland will treat wastewater that is higher in BOD, N, and P than a graywater-only load. However, these parameters are lower than raw wastewater because: 1) removal of urine results in much less N and P, and 2) the digester will remove a sizeable fraction of the BOD. These characteristics were taken into account for parameter selection. The area of the wetland can be calculated according to Kadlec and Knight (1996).

$$A = \left(\frac{0.0365Q}{k}\right)\ln\left(\frac{C_i - C^*}{C_e - C^*}\right)$$

Where:

A = required wetland area, ha

Q = water flow rate, m^3/day

C_e = outlet target concentration, mg/L

C_i = inlet concentration, mg/L

C^* = background concentration, mg/L

k = first order areal rate constant, m/yr

Typically, nitrogen, phosphorus, and BOD are the primary considerations when designing a wetland. Because the influent does not include urine (reducing the amount of N and P) and because the effluent will be used for irrigation (N and P can be beneficial), sizing was based on BOD. For those states where reclaimed water reuse is allowed, effluent guidelines exist and would be used for design. BOD limits range from 5 mg/L to 30 mg/L depending on the end use, with most being 20-30 mg/L. The U.S. EPA recommends a maximum of 10 mg/L for urban reuse (irrigation, firefighting, vehicle washing, toilet flushing, etc.) and 30 mg/L for "restricted access area irrigation" and "non-food crops". For the purposes of this study, a BOD effluent concentration of 30 mg/L was chosen. This is the 30-day average CO regulation (for discharge). TSS should be 30 mg/L or less and $CBOD_5$ should be 25 mg/L or less for the same averaged sample period (https://www.colorado.gov/pacific/sites/default/files/Regulation-62.pdf).

Influent BOD was determined by calculating the fractions of graywater and anaerobically treated blackwater and developing a composite BOD. Blackwater, as defined for this study, has not been extensively analyzed. Both Palmquist (year) and Bruun (year) have determined BOD for a combination of toilet and kitchen wastewater to be an average of 1037 mg/L and a range of 410-1400 mg/L respectively. An influent blackwater BOD of 1000 mg/L was chosen. A conservative estimate of 70% BOD removal was assumed for the anaerobic digester. The composition of graywater has been more extensively studied but many samples include kitchen wastewater. Studies at CSU, Casanova 2001, and Eriksson 2003 indicate that 75 mg/L is a representative BOD level for graywater without kitchen wastewater. Given that 27% of the wetland influent is digester leachate and 73% is graywater, this results in an influent with approximately 134 mg/L BOD.

The rate constant, k, was chosen to be 20 m/year. Studies at CSU with graywater only indicate a summer and fall BOD rate constant of approximately 15. Increased nutrients, provided by the digester leachate, will increase k. (Bergdolt et al., 2011) Kadlec and Knight (1996) indicate that 34 m/yr is an average k value for surface flow wetlands treating wastewater. Because the influent is mostly graywater (73%), k is likely to be lower than the Kadlec and Knight average. This is because, although digester leachate will be present, the majority of the influent will be very low in nutrients (see Chapter 2). Background BOD concentration was chosen to be 6.2 mg/L, the average reported in Kadlec and Knight, further validated by wetland studies at CSU (Bergdolt et al., 2011).

Table 12 shows a flow rate calculation for the proposed wetland, with background data presented in Figure 13. It is assumed that there is 85% water recovery from the anaerobic digester. Water draining from baths, showers, clothes washers, and non-kitchen faucets goes directly to the wetland. Water going from the digester to the wetland was originally from toilet flushing, kitchen sinks, and dishwashers.

Table 12 Flow rates of graywater and blackwater for constructed wetland design: Data from REUWSU Fort Collins, 2012

		Individual flow rate Gal/cap/day	Neighborhood flow rate Gal /day
GRAYWATER	BATH	.73	
	SHOWER	9	
	CLOTHES WASHER	6.8	
	FAUCETS	7.8	
	SUM	20-24	25,000-30,000
BLACKWATER	TOILETS	11.2	
	KITCHEN SINK	2-3	
	DISHWASHER	.73	
	SUM	14-17	17,500-21,250
WETLAND INFLUENT (GRAYWATER PLUS 85% OF BLACKWATER)			40,000-48,000

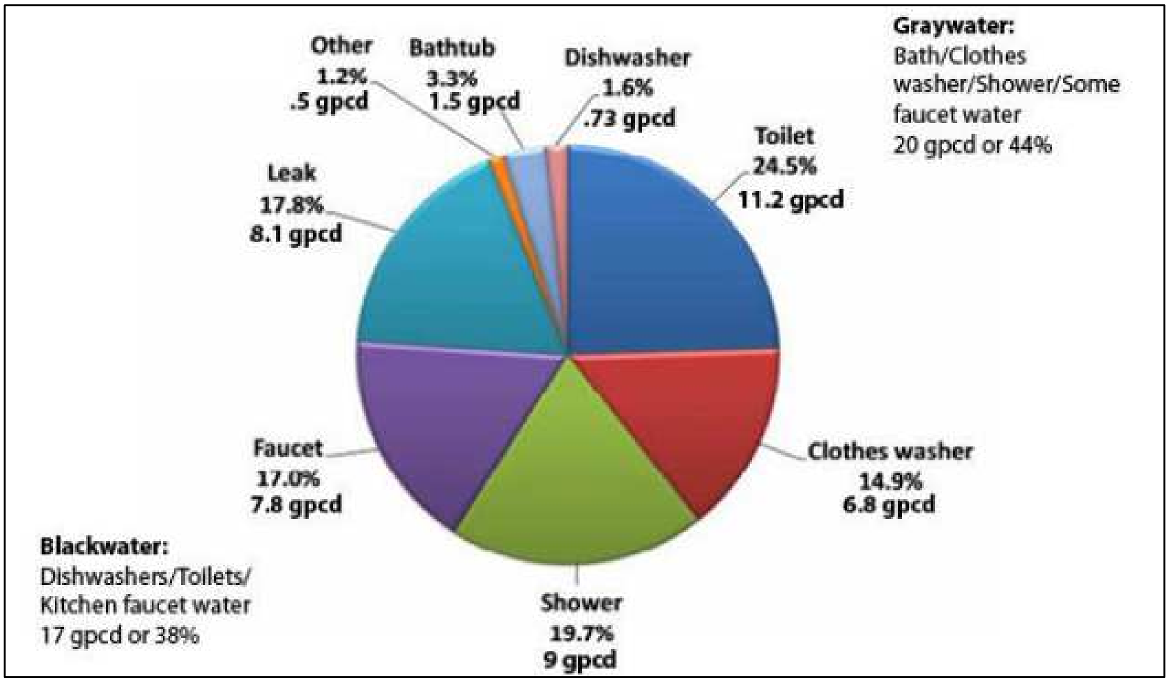

Figure 27 Average indoor residential water use for the city of Fort Collins, Colorado (Vandegrift, 2014)

Once area is calculated, cost can be determined via Kadlec and Knight or other sources.