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Attachment 1

VIEWPOINT

Urban Sprawl and Public Health

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When regular steam ferry service between Brooklyn and Manhattan began in 1814, the first commuter suburb became possible.[1] Suburbs continued to develop slowly but steadily during the 19th and early 20th centuries, thanks to transportation advances such as commuter trains and streetcars, the innovations of early real estate developers, and the urge to live in pastoral tranquility rather than in urban squalor. As automobile ownership became widespread starting in the 1920s, suburban growth continued, a trend that accelerated greatly during the second half of the 20th century. One in two Americans now lives in the suburbs.[2]

In recent years, the rapid expansion of metropolitan areas has been termed "urban sprawl"—referring to a complex pattern of land use, transportation, and social and economic development. As cities extend into rural areas, large tracts of land are developed in a "leapfrog," low-density pattern. Different land uses—housing, retail stores, offices, industry, recreational facilities, and public spaces such as parks—are kept separate from each other, with the separation enforced by both custom and zoning laws. Extensive roads need to be constructed; for suburban dwellers, most trips, even to buy a newspaper or a quart of milk, require driving a car. Newly built suburbs are relatively homogeneous in both human and architectural terms, compared with the diversity found in traditional urban or small town settings. With the expansion of suburbs, capital investment and economic opportunity shift from the center to the periphery. Regional planning and coordination are relatively weak.[1,3–7]

Clearly, the move to the suburbs reflects a lifestyle preference shared by many Americans. Such a major shift in the nation's de-

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mographics and in the form of our environment might also be expected to have health implications, both positive and negative. Some of these effects relate directly to heavy reliance on automobiles: air pollution, automobile crashes, and pedestrian injuries and fatalities. Other effects relate to land use patterns that typify sprawl: sedentary lifestyles, threats to water quantity and quality, and an expansion of the urban heat island effect. Finally, some mental health and social capital effects are mediated by the social dimensions of sprawl. Many of these health effects are individually recognized as environmental health issues, and certain aspects of sprawl, such as reliance on automobiles, have been analyzed as public health issues.[8,9] Yet the broad phenomenon of sprawl, a complex of issues related to land use, transportation, urban and regional design, and planning, has been the intellectual "property" of engineers and planners. Public health professionals have provided neither an intellectual framework nor policy guidance. This is a striking departure from the legacy of the 19th and early 20th centuries, when public health and urban design were overlapping and largely indistinguishable concerns.[10–12]

This article offers a public health framework for understanding the consequences of urban sprawl. For each of the health outcomes noted earlier, available evidence about the health effect and its connection with sprawl is presented, and issues that require further research are identified. Because the adverse impacts of sprawl do not fall equally across the population, the distribution of health impacts across the population and resulting equity concerns are addressed. Finally, some solutions are discussed.

DIRECT EFFECTS OF RELIANCE ON AUTOMOBILES

One of the cardinal features of sprawl is driving, reflecting a well-established, close relationship between lower density development and more automobile travel.[4,13–16] For example, in the Atlanta metropolitan area, one of the nation's leading examples of urban sprawl, the average person travels 34.1 miles in a car each day—an average that includes the entire population, both drivers and non-drivers.[17] More densely populated metropolitan areas have far lower per capita daily driving figures than Atlanta, e.g., 16.9 miles for Philadelphia, 19.9 for Chicago, and 21.2 for San Francisco.[17] On a neighborhood scale, the same pattern is observed. In the Los Angeles, San Francisco, and Chicago metropolitan areas, vehicle miles traveled increase as neighborhood density decreases (see Figure 1).[18]

Automobile use offers extraordinary personal mobility and independence. However, it is also associated with health hazards, including air pollution, motor vehicle crashes, and pedestrian injuries and fatalities.

Air pollution

Motor vehicles are a leading source of air pollution.[20] Even though automobile and truck engines have become far cleaner in recent decades, the sheer quantity of vehicle miles driven results in large releases of carbon monoxide, carbon dioxide, particulate matter, nitrogen oxides, and hydrocarbons into the air.[21] Nitrogen oxides and hydrocarbons, in the presence of sunlight, form ozone.

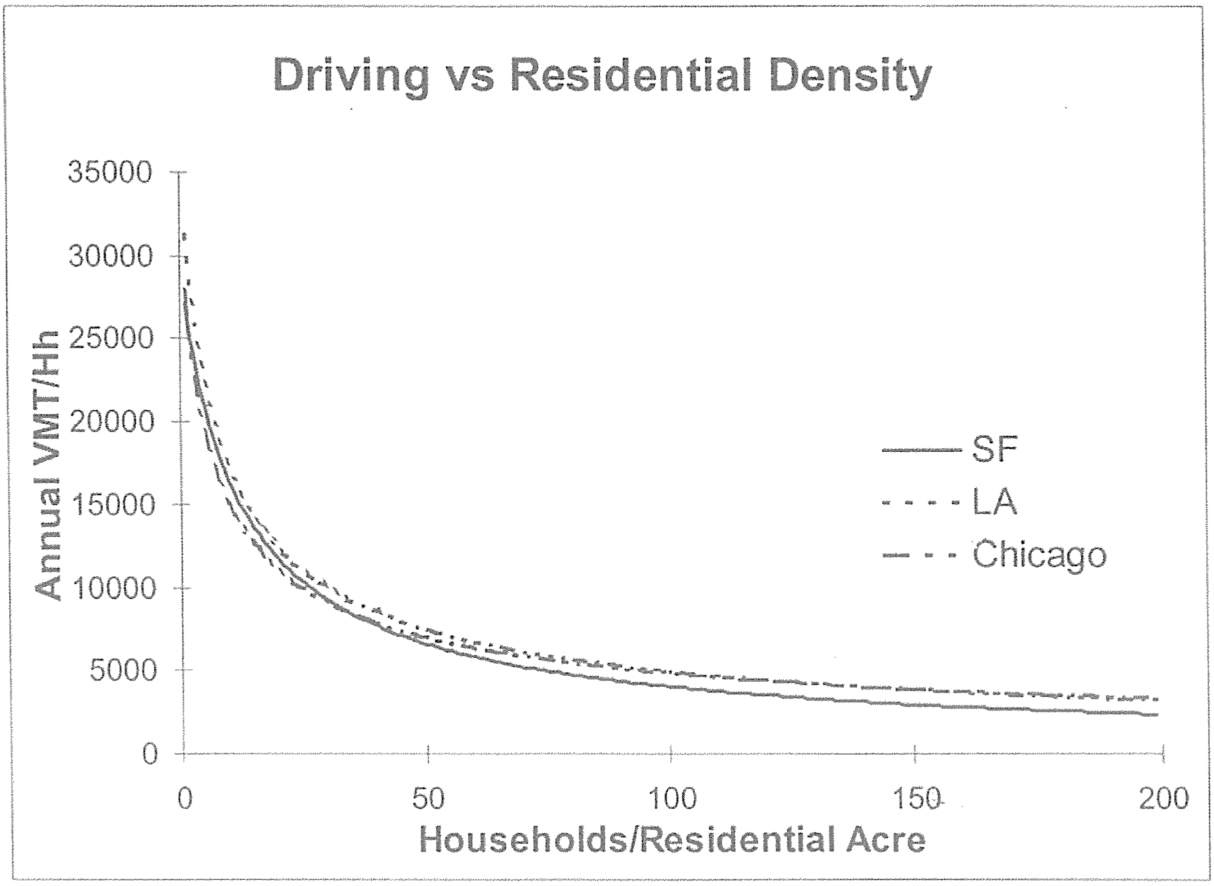
Nationwide, "mobile sources" (mostly cars and trucks) account for approximately 30% of emissions of oxides of nitrogen and 30% of hydrocarbon emissions.[22] However, in automobile-dependent metropolitan areas, the proportion may be substantially higher. In the 10-county metropolitan Atlanta area, for example, on-road cars and trucks account for 58% of emissions of nitrogen oxides and 47% of hydrocarbon emissions, figures that underestimate the full impact of vehicle traffic because they exclude emissions from related sources, such as fuel storage facilities and filling stations.[23]

In various combinations, the pollutants that originate from cars and trucks, especially nitrogen oxides, hydrocarbons, ozone, and particulate matter, account for a substantial part of the air pollution burden of American cities. Of note, the highest air pollution levels in a metropolitan area may occur not at the point of formation but downwind, due to regional transport. Thus, air pollution is a problem not only alongside roadways (or in close proximity to other sources) but also on the scale of entire regions.

The health hazards of air pollution are well known.[24] Ozone is an airways irritant. Higher ozone levels are associated with higher incidence and severity of respiratory symptoms, worse lung function, more emergency room visits and hospitalizations, more medication use, and more absenteeism from school and work.[24] Although healthy people may demonstrate these effects, people with asthma and other respiratory diseases are especially susceptible. Particulate matter is associated with many of the same respiratory effects and, in addition, with elevated mortality.[25–27] People who are especially susceptible to the effects of air pollution include the elderly, the very young, and those with underlying cardiopulmonary disease.

An additional driving-related emission is carbon dioxide, the end product of burning fossil fuels such as gasoline. Carbon dioxide is the major greenhouse gas, accounting for approximately 80% of emissions

Figure 1. Annual vehicle miles traveled per household, by neighborhood residential density



SOURCE: Reference 18.

with global warming potential.[28] Motor vehicles are also a major source of other greenhouse gases, including methane, nitrogen oxides, and volatile organic compounds. As a result, automobile traffic is a major contributor to global climate change, accounting for approximately 26% of U.S. greenhouse gas emissions.[28] During the decade of the 1990s, greenhouse gases from mobile sources increased 18%, primarily a reflection of more vehicle miles traveled.[28] In turn, global climate change threatens human health in a number of ways, including the direct effects of heat, enhanced formation of some air pollutants, and increased prevalence of some infectious diseases.[29–32]

Thus, the link between sprawl and respiratory health is as follows: Sprawl is associated with high levels of driving, driving contributes to air pollution, and air pollution causes morbidity and mortality. In heavily automobile-dependent cities, air pollution can rise to hazardous levels, and driving can account for a majority of the emissions. Although ongoing research is exploring the pathophysiology of air pollution exposure and related issues, there are also important research questions that revolve around prevention. Technical issues include such challenges as the development of low-emission vehicles and other clean technologies. Policy research needs to identify approaches to land use and transportation that would reduce the need for motor vehicle travel. Behavioral research needs to identify factors that motivate people to choose less-polluting travel behaviors, such as walking, carpooling, or use of more efficient vehicles.

Motor vehicle crashes

Automobiles now claim more than 40,000 lives each year in the United States, a number that has slowly declined from about 50,000 per year in the 1960s.[33]

Rates of automobile fatalities and injuries per driver and per mile driven have fallen thanks to safer cars and roads, seat belt use, laws that discourage drunk driving, and other measures, but the absolute toll of automobile crashes remains high. Automobile crashes are the leading cause of death among people 1–24 years old, account for 3.4 million nonfatal injuries annually, and cost an estimated $200 billion annually.[34]

The relationship between sprawl and motor vehicle crashes is complex. At the simplest level, more driving means greater exposure to the dangers of the road, translating to a higher probability of a motor vehicle crash.[35] Suburban roads may be a particular hazard, especially major commercial thoroughfares and "feeder" roads that combine high speed, high traffic volume, and frequent "curb cuts" for drivers to use in entering and exiting stores and other destinations.[36] However, available data from the National Highway Traffic Safety Administration (NHTSA) show fatal crashes aggregated into only two categories of roads: urban (accounting for approximately 60% of fatalities) and rural (approximately 40%).[33]

The NHTSA data do permit comparison of automobile fatality rates by city.[33] In general, denser cities with more extensive public transportation systems have lower automobile fatality rates (including drivers and passengers, but excluding pedestrians) than more sprawling cities: 2.45 per 100,000 population in San Francisco, 2.30 in New York, 3.21 in Portland, 6.67 in Chicago, and 5.26 in Philadelphia, compared with 10.08 in Houston, 16.15 in Tampa, 12.72 in Atlanta, 11.35 in Dallas, and 9.85 in Phoenix.[33] (There are notable exceptions to this pattern, such as 5.79 per 100,000 population in Los Angeles and 10.93 per 100,000 in Detroit.[33])

According to the American College of Emergency Physicians, "Traffic crashes are predictable and preventable, and therefore are not 'accidents.'"[37] In fact, the determinants of motor vehicle injuries and fatalities are well recognized. For some of these, public health interventions, from seat belts to traffic signals, have achieved dramatic reductions in injury and fatality rates in the three-quarters of a century since automobile use became widespread. A relatively overlooked risk factor, however, is the simple fact of driving and the number of miles driven. Primary prevention would consist of decreasing exposure, an approach that is currently impractical in many metropolitan areas.

Pedestrian injuries and fatalities

On December 14, 1995, 17-year-old Cynthia Wiggins rode the public bus to her job at the Walden Galleria in suburban Cheektowaga, New York, outside of Buffalo. The bus did not stop at the mall itself, so Cynthia had to cross a seven-lane highway on foot to complete her trip to work. On that day, she had made it across six lanes when a dump truck crushed her.[38] Her death received national media attention; it was seen as exemplifying inadequate mass transportation links, pedestrian-hostile roadways, and the disproportionate impact of these factors on members of minority groups.

Each year, automobiles cause about 6,000 fatalities and 110,000 injuries among pedestrians nationwide. Pedestrians account for about one in eight automobile-related fatalities.[39,40] Data from Atlanta show that as the city sprawled in recent years, the pedestrian fatality rate increased even as the national rate declined slightly.[41] The most dangerous stretches of road were those built in the style that typifies sprawl: multiple lanes, high speeds, no sidewalks, long distances between intersections or crosswalks, and roadways lined with large commercial establishments and apartments blocks.[41] Across the country, the pattern seen for driver and passenger fatalities is repeated for pedestrian fatalities, with lower annual rates in denser cities: 1.89 per 100,000 population in Portland, 2.22 in New York, 2.52 in Chicago, and 2.57 in Philadelphia, compared with 3.03 in Dallas, 3.61 in Atlanta, 4.08 in Phoenix, and 6.60 in Tampa. However, this pattern is not as consistent as for driver and passenger fatalities, and there are exceptions, e.g., 2.60 per 100,000 population in Los Angeles, 2.61 in Houston, 3.86 in San Francisco, and 4.73 per 100,000 in Detroit.[33]

While many factors contribute to the high toll of pedestrian fatalities, including alcohol abuse, inadequate lighting, and pedestrian behavior, the proliferation of high-speed, pedestrian-hostile roads in expanding metropolitan areas likely plays an important part. Walking offers important public health benefits, but safe and attractive sidewalks and footpaths are needed to attract walkers and assure their safety. Much of the knowledge needed to make progress is available, but further research might help clarify the best and most cost-efficient ways to build walkways and the most successful approaches to zoning, financing, and other incentives.

EFFECTS OF LAND USE DECISIONS

Land use and travel patterns are closely linked. If distinct land uses are separated, if the distances between them are great, and if roads are more available than sidewalks and paths, then people shift from walking and bicycling to driving. Accordingly, the U.S. is a nation of drivers, in which only 1% of trips are on bicycles and 9% are on foot.[42] For comparison, in the

Netherlands 30% of all trips are on bicycles and 18% are on foot, and in England the corresponding figures are 8% and 12%.[42] Approximately 25% of all trips in the U.S. are shorter than one mile; of these, 75% are by car.[43]

Physical activity

A considerable body of research establishes that sprawl—as measured by low residential density, low employment density, low "connectivity," and other indicators—is associated with less walking and bicycling and with more automobile travel than denser communities.[13,44–48]

Low levels of physical activity threaten health both directly and indirectly. A sedentary lifestyle is a well-established risk factor for cardiovascular disease, stroke, and all-cause mortality,[49–53] whereas physical activity prolongs life.[54,55] Men in the lowest quintile of physical fitness have two to three times the risk of dying overall, and three to five times the risk of dying of cardiovascular disease, compared with men who are more fit.[56] Among women, walking 10 blocks per day or more is associated with a 33% lower risk of cardiovascular disease.[57] The risk associated with poor physical fitness is comparable to, and in some studies greater than, the risk associated with hypertension, high cholesterol, diabetes, and even smoking.[56,58] Among diabetic patients, the higher the blood sugar, the more protective is physical fitness.[59] Physical activity also appears to be protective against cancer.[60–63]

In addition to its direct effects on health, lack of physical activity is also a risk factor for being overweight. Sedentary lifestyles may help explain the rapid increase in the prevalence of overweight in recent years. In 1960, 24% of Americans were overweight (defined as a Body Mass Index ≥ 25 kg/m^2), and by 1990 that proportion had increased to 33%.[64] During the same interval, the prevalence of obesity (defined as a Body Mass Index ≥ 30 kg/m^2) nearly doubled.[65] According to data from the Behavioral Risk Factor Surveillance System, this trend continued during the 1990s, with the prevalence of obesity rising from 12.0% in 1991 to 17.9% in 1998.[66,67]

Being overweight is itself a well-established risk factor for a number of diseases: ischemic heart disease (overweight increases the risk up to fourfold in the 30–44 age group, less at older ages[68]), hypertension, stroke, dyslipidemia, osteoarthritis, gall bladder disease, and some cancers. Overweight people die at as much as 2.5 times the rate of non-obese people.[51,68–71] Being overweight increases the risk of Type 2 diabetes up to fivefold, and the current epidemic of Type 2 diabetes tracks closely with the increase in being overweight.[72]

Sprawl does not fully account for Americans' increasingly sedentary lives, and physical inactivity does not tell the entire story of the national epidemic of being overweight. However, by contributing to physical inactivity and therefore to overweight and associated health problems, sprawl has negative health consequences. Further research will help provide a more complete understanding of the association between sprawl and physical inactivity.[73] In theory, a randomized trial might assign some people to live in walkable neighborhoods and others to live in subdivisions without sidewalks or nearby schools, stores, or workplaces. Then, the two groups might be followed for physical activity patterns and related health outcomes. Such residential randomization is, of course, impossible. Observational studies are underway to characterize the relationships among land use, travel patterns, and physical activity.[74] However, such research is challenging. People living in walkable neighborhoods may have chosen to live there because of better health and a greater inclination to walk. Because children do not choose their neighborhoods, an alternative might be to study adult physical activity and travel patterns according to the type of neighborhood of origin to test the hypothesis that childhood access to walkable neighborhoods predicts lifelong travel preferences and activity patterns. Research is also needed on design issues (how to build more walkable communities), policy issues (how to put incentives in place to encourage needed environmental and behavioral changes), and behavior issues (how to motivate more physical activity, including walking).

Water quantity and quality

Americans take for granted the availability of clean, plentiful, and cheap water. Indeed, the development of an excellent water supply—the result of social policy, civil engineering, and health advocacy over more than a century—is credited with a central role in improving public health during the first half of the 20th century.[12,75]

Sprawl may threaten both the quantity and quality of the water supply. As forest cover is cleared and impervious surfaces built over large areas, rainfall is less effectively absorbed and returned to groundwater aquifers.[76] Instead, relatively more stormwater flows to streams and rivers and is carried downstream. One study found that about 4% of rainfall on undeveloped grassland, compared with 15% of rainfall on suburban land, was lost as runoff.[77] The same is true for snowmelt, especially early in the melting process.[78] Modeling shows that higher density development patterns can reduce peak flows and total runoff volumes.[79] With less groundwater recharge, communities that depend on groundwater for their drinking water—about one-third of U.S. communities[80]—may face shortages.

Water quality may be affected in several ways. With better control of "point sources" of water pollution—factories, sewage treatment plants, and similar facilities—"non-point source" water pollution has emerged as the major threat to water supplies. Non-point source water pollution occurs when rainfall or snowmelt moves over and through the ground, picking up contaminants and depositing them into surface water (lakes, rivers, wetlands, and coastal waters) and groundwater. Much of this problem is specific to agricultural land, the primary source of contamination by fertilizers, herbicides, and insecticides. However, growing forms of non-point source pollution include oil, grease, and toxic chemicals from roadways, parking lots, and other surfaces, and sediment from improperly managed construction sites, other areas from which foliage has been cleared, or eroding stream banks. Studies of the movement of polycyclic aromatic hydrocarbons,[81] zinc,[82] and organic waste[83] suggest that suburban development is associated with high loading of these contaminants in nearby surface water.

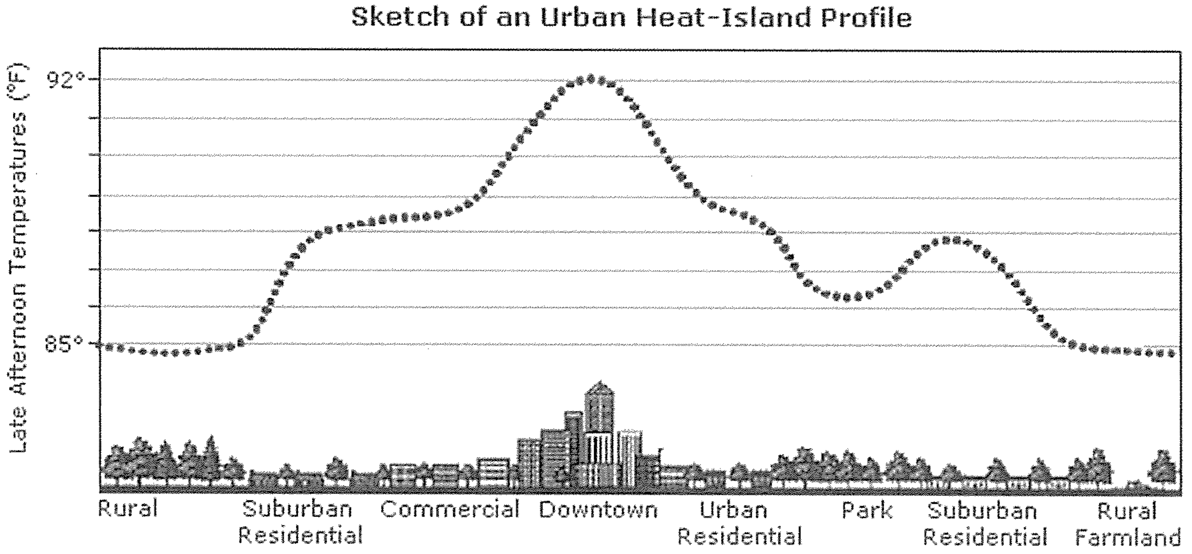
Both water quantity and water quality are directly affected by land use and development patterns, and evidence suggests that sprawl contributes to these problems in specific ways. Further evidence is needed to identify the precise features of land use that best predict non-point source pollution, the impact of this pollution on drinking water quality, and the optimal control methods.

The heat island effect

On warm days, urban areas can be 6°–8° F warmer than surrounding areas, an effect known as an urban heat island (see Figure 2). The heat island effect is caused by two factors. First, dark surfaces such as roadways and rooftops efficiently absorb heat from sunlight and reradiate it as thermal infrared radiation; these surfaces can reach temperatures of 50°–70° F higher than surrounding air. Second, urban areas are relatively devoid of vegetation, especially trees, that would provide shade and cool the air through "evapotranspiration." As cities sprawl outward, the heat island effect expands, both in geographic extent and in intensity. This is especially true if the pattern of development features extensive tree cutting and road construction.[84,85] NASA satellite imagery, available for public viewing on the Web, documents the heat island effect for several cities.[86]

Metropolitan expansion involves a positive feedback loop that may aggravate the heat island effect. Sprawling metropolitan areas, with greater travel distances, generate a large amount of automobile travel. This, in turn, results in more fuel combustion, with more production of carbon dioxide, and consequent contributions to global climate change.[87] Global climate change, in turn, may intensify the heat island effect in metro-

Figure 2. An urban heat island profile



SOURCE: Reference 93.

politan areas. Thus, not only does the morphology of metropolitan areas contribute to warming, but so may the greenhouse gas production that results from increased driving.

The magnitude of the contribution of sprawl to urban heat episodes is unclear. Data from the last half century show a clear increasing trend in extreme heat events in U.S. cities.[88] While global warming may contribute to this trend, the rate of the increase far exceeds the rate of global warming, suggesting that urban growth patterns may be a primary determinant.[89] Further research on this phenomenon is required.

Heat is of concern because it is a health hazard.[90] Relatively benign disorders include heat syncope, or fainting; heat edema, or swelling, usually of dependent parts such as the legs; and heat tetany, a result of heat-induced hyperventilation. Heat cramps are painful muscle spasms that occur after strenuous exertion in a hot environment. Heat exhaustion is a more severe acute illness that may feature nausea, vomiting, weakness, and mental status changes. The most serious of the acute heat-related conditions is heat stroke, which represents the body's failure to dissipate heat. The core body temperature may exceed 104°F, muscle breakdown occurs, and renal failure and other profound physiologic derangements may follow. The fatality rate is high.

There are several well-known risk factors for developing heat stroke or dying during a heat wave, including being elderly, bedridden, homebound, or socially isolated, having certain diseases or using certain medications, and living on an upper floor.[91,92] Poverty and minority race or ethnicity are also risk markers.[93]

Heat also has indirect effects on health, mediated through air pollution. As the temperature rises, so does the demand for energy to power air conditioners, requiring power plants to increase their output. The majority of U.S. power plants burn fossil fuels, so increased summer demand results in higher emissions of the pollutants they generate, including carbon dioxide, particulate matter, sulfur oxides, nitrogen oxides, and air toxics. Ozone formation from its precursors, nitrogen oxides and hydrocarbons, is enhanced by heat. In summary, through both the direct and indirect effects of heat, sprawl has potential adverse health consequences.

SOCIAL ASPECTS OF SPRAWL

Mental health

One of the original motivations for migration to the suburbs was access to nature.[1] People like trees, birds, and flowers, and these are more accessible in the suburbs than in denser urban areas. Moreover, contact with nature may offer benefits beyond the purely aesthetic; it may benefit both mental health and physical health.[94] In addition, the sense of escaping from the turmoil of urban life to the suburbs, the feeling of peaceful refuge, may be soothing and restorative to some people. In these respects, there may be health benefits to suburban lifestyles.

On the other hand, certain aspects of sprawl, such as commuting, may exact a mental health toll. For some time, automobile commuting has been of interest to psychologists as a source of stress, stress-related health problems, and even physical ailments. Evidence links commuting to back pain, cardiovascular disease, and self-reported stress.[95] As people spend more time on more crowded roads, an increase in these health outcomes might be expected.

One possible indicator of such problems is road rage, defined as "events in which an angry or impatient driver tries to kill or injure another driver after a traffic dispute."[96] Even lawmakers may be involved; one press account described a prominent attorney and former Maryland state legislator who knocked the glasses off a pregnant woman after she had the temerity to ask him why he had bumped her Jeep with his.[97]

Available data do not make clear whether road rage is on the rise. The only longitudinal study available in the U.S., published by the AAA Foundation for Traffic Safety in 1997, reported a 51% increase in reported annual incidents of road rage during the interval from 1990 to 1996.[98] The Foundation documented 10,000 reports of such incidents, resulting in 12,610 injuries and 218 deaths. A variety of weapons was used, including guns, knives, clubs, fists, or feet, and in many cases the vehicle itself. However, since the data sources included police reports and newspaper accounts, it is possible that the apparent increase reflected growing public awareness and media attention rather than a true increase in the number or rate of road rage incidents.

Road rage is not well understood, and there is a multiplicity of reasons for its occurrence. Stress at home or work may combine with stress while driving to elicit anger.[99,100] Data from Australia[101] and Europe[102] suggest that both traffic volume and travel distance are risk factors. Long delays on crowded roads are likely to be a contributing factor.

Episodes of road rage may reflect a reservoir of frustration and anger on the roads. In national telephone surveys conducted by Mississippi State University in 1999 and 2001,[103,104] large numbers of respondents reported both engaging in aggressive behaviors while driving and being the objects of such behavior (see Table). The surveys did not identify respondents who lived in suburban locations, although the responses differed in several respects across the geographic categories used (rural, small town, small city, and large city), suggesting an influence of density and other "built environment" factors on aggressive driving behavior. A similar survey, conducted for NHTSA in 1998, found somewhat lower but comparable numbers.[105] In the NHTSA survey, the two leading reasons cited for aggressive driving were (*a*) being rushed or being behind schedule (23% of respondents), and (*b*) increased traffic or congestion (22%)—common experiences on the crowded roadways of sprawling cities. Moreover, 30% of the NHTSA respondents perceived that aggressive driving—their own and others'—was increasing over time, and only 4% thought it was decreasing. More recently, Curbow and Griffin[106] surveyed 218 women employed by a telecommunications company. This was a stable, professional population; 67% of the respondents had more than a high school education, 76% were parents, and the average job seniority was 18 years. Among these women, 56% reported driving aggressively, 41% reported yelling or gesturing at other drivers while commuting, and 25% reported taking out their frustrations from behind the wheel of their cars. Aggressive driving behavior appears to be a widespread problem.

It seems reasonable to hypothesize that anger and frustration among drivers are not restricted to their cars. When angry people arrive at work or at home, what are the implications for work and family relations? If the phenomenon known as commuting stress affects well-being and social relationships both on the roads and off, and if this set of problems is aggravated by increasingly long and difficult commutes on crowded roads, then sprawl may in this manner threaten mental health.

Social capital

Since World War II, social commentators have ascribed to suburban living a sense of social isolation and loneliness,[107–114] although some of these claims have re-

Table. Prevalence of self-reported driving behaviors, 1999 and 2000 National Highway Safety Surveys

	Percent of respondents by response choice			
How often do you . . . (1999)	*Never*	*Rarely*	*Sometimes*	*Often*
Say bad things to yourself about other drivers	15.3	22.9	39.5	22.1
Complain or yell about other drivers to a passenger in your vehicle	25.5	22.2	39.0	13.1
Give another driver a dirty look	41.8	17.6	32.7	7.7
Honk or yell at someone through the window to express displeasure	61.1	17.9	17.9	2.9
Keep someone from entering your lane because you are angry	80.2	12.9	5.9	0.8
Make obscene gestures to another driver	83.7	9.2	6.1	0.8
Think about physically hurting another driver	89.0	5.4	4.4	1.1
Make sudden or threatening moves to intimidate another driver	94.6	4.0	1.1	0.1
Follow or chase another driver in anger	96.5	3.2	0.3	0.0

	Percent of respondents by place of residence				
Within the last year, another driver . . . (2001)	*Rural*	*Small town*	*Small city*	*Large city*	*Total*
Made an obscene gesture at you	39.7	37.1	44.9	44.3	41.8
Made a threatening move with car	25.4	23.5	30.0	25.9	26.4
Tailgated you	69.1	61.3	70.3	69.8	66.8
Followed or chased you in anger	9.9	6.4	9.9	11.5	9.4
Got out of car to argue with you	5.8	5.8	4.2	8.3	5.9
Cut you off	32.0	33.7	38.6	48.0	38.1

SOURCE: Adapted from references 103 and 104.

cently been challenged.[115] "It is no coincidence," observes Yale architecture professor Philip Langdon, "that at the moment when the United States has become a predominantly suburban nation, the country has suffered a bitter harvest of individual trauma, family distress, and civic decay." [116] Indeed, a perceived erosion of civic engagement and mutual trust—a loss of what is called "social capital"—has been widely noted and discussed in recent years.[117,118] Some authors have attributed this decline, in part, to suburbanization and sprawl.[119,120]

A full discussion of the complex sociology of suburban life is beyond the scope of this article. Several facts bear mention, however. First, as Robert Putnam argues in *Bowling Alone*, the simple fact of more driving time means less time with family or friends, and less time to devote to community activities, from neighborhood barbecues to PTA meetings.[118] Putnam estimates that each additional 10 minutes of driving time predicts a 10% decline in civic involvement.[118] Second, suburban development patterns often feature considerable economic stratification. Many housing developments are built to specific price ranges, so that buyers of $250,000 homes are effectively segregated from buyers of $500,000 homes (and those at the bottom of the economic ladders are excluded altogether).[121] This pattern creates income homogeneity within neighborhoods but may intensify income inequality across metropolitan areas. Third, both polling data and voting records have demonstrated that suburban residents prefer more individualized, less collective solutions to social problems relative to rural, small town, and urban voters, with the possible exception of schools.[122–125] Finally, suburban neighborhoods with capacious houses and lawns offer few options for older adults once their children have grown up and moved from the home. These "empty nesters" typically have to change neighborhoods if they wish to find smaller, lower maintenance homes. The inability to remain in a single neighborhood through the life cycle may also undermine community cohesiveness. Collectively, these trends suggest that certain features of sprawl tend toward greater social stratification and less social capital.

A large literature has explored the relationship between social relationships and health, focusing both on the individual level (one's own relationships) and on the societal level (social capital).[126] In general, a higher quantity and quality of social relationships is associated with health benefits. Conversely, social stratification, in particular income inequality, is associated with higher all-cause mortality, higher infant mortality, and higher mortality from a variety of specific causes, independent of income and poverty, according to data from the United States[127–130] and Great Britain.[131,132] There is evidence that this effect is mediated, at least in part, through effects on social capital.[133,134] Therefore, to the extent that sprawl is associated with social stratification and loss of social capital and these phenomena are in turn associated with increased morbidity and mortality, sprawl may have a negative health impact on this broad scale.

ENVIRONMENTAL JUSTICE CONSIDERATIONS

Research over the last 15 years has suggested that poor people and members of minority groups are disproportionately exposed to environmental hazards.[135–137] Could any adverse health consequences of sprawl disproportionately affect these same populations?

In general, the pattern of urban development of which sprawl is a part may deprive the poor of economic opportunity. When jobs, stores, good schools, and other resources migrate outward from the core city, poverty is concentrated in the neighborhoods that are left behind.[138–142] A full discussion of the impact of urban poverty on health is beyond the scope of this article, but a large literature explores this relationship.[143–147] To the extent that sprawl aggravates poverty, at least for selected groups of people, it may contribute to the burden of disease and mortality.

More specifically, there is evidence that several of the specific health threats related to sprawl affect minority populations disproportionately. Air pollution is one example. Poor people and people of color are disproportionately impacted by air pollution for at least two reasons: disproportionate exposure, and higher prevalence of underlying diseases that increase susceptibility. Members of minority groups are relatively more exposed to air pollutants than whites, independent of income and urbanization.[148,149] Environmental Protection Agency data show that black people and Hispanics are more likely than white people to live in areas that violate air quality standards.[150] As asthma continues to increase, asthma prevalence and mortality remain higher in minority group members than in white people.[151] The cumulative prevalence of asthma is 122 per 1,000 in black people and 104 per 1,000 in white people, and asthma mortality is approximately three times as high in black people as in white people.[152] Similarly, asthma prevalence is more than three times as high among Puerto Rican children as among non-Hispanic children.[153] Among Medicaid patients, black children are 93% more likely, and Latino children 34% more likely, than white children to have multiple hospitalizations for asthma.[154] Although some of this excess is related to poverty, the excess persists in analyses controlled for income.[155] Asthma prevalence and mortality are especially high, and rising, in inner cities, where minority populations are concentrated.[156,157] Both exposure to air pollution and susceptibility to its effects appear to be concentrated disproportionately among the poor and people of color. As sprawl contributes to air pollution in metropolitan areas, these populations may be disproportionately affected.

Heat-related morbidity and mortality also disproportionately affect poor people and members of minority groups. In the 1995 Chicago heat wave, black residents had a 50% higher heat-related mortality rate than white residents.[158] Similar findings have emerged following heat waves in Texas,[159] Memphis,[160] St. Louis,[161] and Kansas City[161] and are reflected in nationwide statistics.[162] Of special interest in the context of urban sprawl, one heat wave study considered transportation as a risk factor and found that poor access to transportation—a correlate of poverty and non-white race[163]—was associated with a 70% higher rate of heat-related death.[92]

There are significant racial/ethnic differences in motor vehicle fatality rates. Results from the National Health Interview Survey revealed motor vehicle fatality rates of 32.5 per 100,000 person-years among black men, 10.2 among Hispanic men, 19.5 among white men, 11.6 among black women, 9.1 among Hispanic women, and 8.5 among white women.[164] Much of the disparity was associated with social class.[164] However, differences in neighborhood design, road quality, automobile quality, and behavioral factors may be important, and need to be better understood.

Pedestrian fatalities disproportionately affect members of minority groups and those at the bottom of the economic ladder.[164] In Atlanta, for instance, pedestrian fatality rates during 1994–1998 were 9.74 per 100,000 for Hispanics, 3.85 for black people, and 1.64 for white people.[41] In suburban Orange County, California, Latinos represent 28% of the population but account for 43% of pedestrian fatalities.[165] In the Virginia suburbs of Washington, Hispanics represent 8% of the population but account for 21% of pedestrian fatalities.[166] The reasons for this disproportionate impact are complex and may involve the probability of being a pedestrian (perhaps related to low access to automobiles and public transportation), road design in areas where members of minority groups walk, and behavioral and cultural factors (such as being unaccustomed to high speed traffic).

These examples illustrate that the health effects of sprawl may have disparate impacts on different sub-

populations. In other cases, there is less evidence of disparities in the health outcomes associated with sprawl, or when such disparities exist, they are likely to relate to factors other than land use and transportation. Examples include physical activity, water-related health outcomes, and mental health outcomes.

Physical activity and overweight vary by ethnic and racial group. People of color are more likely to be overweight[64,167] and more likely to lead sedentary lifestyles[168,169] than white people.[170–173] In the Third National Health and Nutrition Examination Survey (NHANES-III), for example, 40% of Mexican Americans and 35% of blacks reported no leisure time physical activity, compared with 18% of white people.[174] In this same survey, the mean Body Mass Index was 29.2 among black people, 28.6 among Mexican Americans, and 26.3 among white people.[170] The relationships among race/ethnicity, genetic factors, social class, the environment, diet, physical activity, and body weight are complex. There is no evidence that sprawl disproportionately affects people of color with regard to physical activity. In fact, poorer people may be less likely to own cars and therefore more likely to walk than wealthier people. Given the public health importance of overweight, obesity, and related health conditions, and the fact that relatively little research has addressed disparities in environmental contributors such as sprawl, further data on these relationships are needed.

In contrast, there is no evidence that sprawl-related threats to the water supply disproportionately affect poor people or members of minority groups. Similarly, there is no evidence that the mental health consequences of sprawl, such as road rage, affect various racial/ethnic groups differently. In the driving behavior survey data cited previously, no racial/ethnic differences were found in self-reported aggressive behavior. Although black people were slightly less likely to be the victims of aggression than white people or members of other racial/ethnic groups, this difference was not statistically significant.[103,104]

In summary, some of the health consequences of sprawl appear disproportionately to affect vulnerable subpopulations, while others do not demonstrate this pattern. In many cases we do not have sufficient data to reach firm conclusions. Given the significance of the health outcomes involved, the moral imperative of eliminating racial and ethnic health disparities, and the steady increase in sprawl, these associations deserve continued public health attention.

SOLUTIONS

As discussed above, further research is needed to clarify the complex relationships among land use, transportation, and health. What approaches to urban planning, design, and construction are most likely to reduce air pollution, reduce urban heat, encourage physical activity, reduce automobile-related morbidity and mortality, and promote mental health and a sense of community? Although this article has focused on the health consequences of sprawl, other forms of built environment—dense cities, remote rural areas, and small towns—all have advantages and disadvantages that need to be assessed. It is likely that many different kinds of built environments can promote health, and that optimal approaches will borrow elements of cities, suburbs, and small towns.

Some interventions may be relatively simple, such as planting more trees or providing more sidewalks. Others are more complex and expensive to implement, such as mass transit and mixed-use zoning. For each of these, standard health research methods—ranging from clinical trials to observational epidemiology—may offer insights. This research will require innovative partnerships with other professionals, such as urban planners, architects, and real estate developers.

It is especially important for health researchers to recognize and study "natural experiments." Patterns of urban land use are changing, with migration back into inner cities, urban growth boundaries that restrict development to certain areas, development of mixed-use projects, innovations in mass transportation, green space programs, and related initiatives. Such efforts offer opportunities for health researchers who can examine their effects on relevant health endpoints.

As we recognize and understand the health costs of urban sprawl, we can begin to design solutions. Many potential solutions are found in an urban planning approach that has come to be known as "smart growth," characterized by higher density; more contiguous development; preserved green spaces; mixed land uses with walkable neighborhoods; limited road construction balanced by transportation alternatives; architectural heterogeneity; economic and racial/ethnic heterogeneity; a balance of development and capital investment between central city and periphery; and effective, coordinated regional planning.[116,175–178] Importantly, many of the health-related benefits that could flow from this approach—less air pollution, more physical activity, lower temperatures, fewer motor vehicle crashes—would also yield collateral benefits, such as a cleaner environment and more livable neighborhoods.

If the health consequences of sprawl represent a "syndemic"[179]—a combination of synergistic epidemics that contributes to the population burden of disease—then solutions may also operate synergistically, ameliorating several health problems.

Health professionals can play an important role in designing and implementing transportation and land use decisions. Similarly, those who have traditionally managed these issues—urban planners, architects, engineers, developers, and others—should recognize the important health implications of their decisions and seek collaboration with health professionals.

CONCLUSIONS

Urban sprawl is a longstanding phenomenon. It began with the expansion of cities into rural areas and accelerated greatly during the last half of the 20th century. As the 21st century begins, approximately half of Americans live in suburbs,[2] and the features of sprawl—low-density land use, heavy reliance on automobiles for transportation, segregation of land uses, and loss of opportunity for some groups, especially those in inner cities—are widespread and familiar.

This article has discussed the relationship between sprawl and health based on eight considerations: air pollution, heat, physical activity patterns, motor vehicle crashes, pedestrian injuries and fatalities, water quality and quantity, mental health, and social capital. The data show both health benefits and health costs. As is true for most public health hazards, the adverse impacts of sprawl do not fall equally across the population, and those who are most affected deserve special attention.

As we address sprawl on a variety of levels, from personal transportation decisions to local zoning ordinances, from regional mass transit and land use decisions to federal regulations, it is essential to incorporate health considerations into policy making. Because the health effects of sprawl are unevenly distributed across the population, it is equally essential to incorporate considerations of social justice and equity.

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Attachment 2

Clean Water, Healthy Sound

A Life Cycle Analysis of Alternative Wastewater Treatment Strategies in the Puget Sound Area

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GREEN BUILDING COUNCIL

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EXECUTIVE SUMMARY

Urban and suburban communities around Puget Sound and nationally rely largely on conveying wastewater from its point of generation to large-scale, centralized treatment facilities before discharging treated effluent into the Sound or other receiving water bodies.

Many of these systems, built in the mid 1900s, are outdated and in need of extensive repair or expansion. Further, new regulations requiring higher levels of treatment and greater protection against combined sewer overflows will require large investments to upgrade the existing big-pipe infrastructure or to finance new facilities in order to halt the introduction of polluted water into the region's waterways. Communities around the country are now facing tough decisions about how to address the economic costs of treating wastewater for their growing populations.

The Living Building Challenge^{SM} invites forward-thinking designers, developers and communities to realign how water is used in the built environment, redefining the concept of 'waste' so that water is respected as a precious resource. Technologies such as composting toilets, greywater reuse and on-site treatment of wastewater for beneficial reuse have been proposed as best practices for treating and reclaiming water and waste. However, regulatory obstacles, cultural fears and a lack of information have largely prohibited their use in all but a few "demonstration" projects.

This study analyzes the overall environmental impacts associated with conventional, centralized treatment systems against four alternative, smaller-scale decentralized approaches using Life Cycle Assessment (LCA). Alternatives were selected based on a wide range of scale (small to large footprint), costs and energy requirements. Mostly passive systems such as composting toilets and gravity-fed greywater wetland treatment systems were compared to more energy-intensive recalculating biofilters and membrane bioreactors. A separate conveyance analysis looked at how density relates to environmental impacts associated with moving wastewater from its point of generation to a central location, regardless of the treatment technology employed. The LCA results provide insight on the pros and cons of commonly proposed decentralized and distributed treatment systems and how they relate to conventional practices at different density scales.

RESULTS

The LCA results presented in this report are separated into two sections — those associated with the conveyance analysis and those related to the treatment analysis. Key findings from the conveyance analysis reveal that pumping wastewater to its point of treatment represents a significant portion of the overall impacts. As density increases, negative environmental impacts associated with conveyance systems decrease substantially. Results show a 71% reduction in global warming impacts alone at densities of 10 dwelling units per acre, and 96% reduction in global warming at 30 dwelling units per acre. This is due to the finding that operating energy associated with pressurizing and pumping waste far outweighs the impacts associated with the material and excavation components of the systems over its lifetime.

These findings indicate that more distributed methods of collection that rely mostly on gravity-fed pipes will have fewer negative environmental impacts than systems that expend large amounts of energy for conveyance. The concept of ‘wastesheds’ shows how locations of existing pumping stations could instead be viewed as optimal locations for smaller-scale treatment systems.

The treatment analysis results indicate that the lower-energy systems (composting toilets and constructed treatment wetlands) have fewer negative environmental impacts compared to the baseline centralized system, while the more energy-intensive decentralized treatment systems (recirculating biofilter and membrane bioreactors) have substantially greater negative impacts. Conclusions from the treatment analysis highlight optimal solutions for building and district-scale treatment alternatives that rely on passive, low-energy systems and gravity-fed conveyance.

RESULTS OF LIFE-CYCLE ENVIRONMENTAL IMPACTS RELATIVE TO BASELINE FOR TREATMENT + CONVEYANCE SYSTEMS

IMPACT	UNITS	COMP TOILETS	MEMBRANE BIOREACTOR	RECIRC BIOFILTER	CONSTRUCTED TREATMENT WETLAND
Acidification	kg SO2-Eq.	-55%	1160%	88%	-43%
Aq. Ecotoxicity	Kg TEG Eq.	-62%	1190%	92%	-43%
Eutrophication	kg PO4-Eq.	-58%	1098%	76%	-48%
Respiratory Effects	kg PM2.5-Eq.	-33%	1083%	79%	-36%
Global Warming	kg CO_2-Eq	-44%	1113%	85%	-40%
Ozone Depletion	kg CFC 11-Eq	221%	942%	81%	-6%
Smog Air	kg NOx-Eq	-29%	887%	52%	-41%

This report also identifies further areas of research needed to gain a greater understanding of life-cycle impact drivers for each system, to expand the boundaries of the LCA study in order to evaluate water reuse potential of decentralized systems and to apply the findings broadly to communities at different scales.

PART 1

Introduction

1.1 PROJECT OVERVIEW

PURPOSE

Current practices for managing wastewater in urban areas of the Puget Sound region and nation-wide involve conveying waste to large-scale, centralized treatment systems. These systems, some of which are outdated and in urgent need of maintenance or expansion, often result in the introduction of polluted water into the region's waterways, are energy intensive and extremely expensive to build and operate.

At the same time, green building programs and policies have advocated for a more holistic approach to water use and wastewater treatment in the built environment. Building owners and project design teams are seeking ways to maximize efficiencies and redefine 'waste' so that water is valued as a precious resource. Smaller-scale on-site or neighborhood-scale systems present an interesting alternative to capturing and treating waste from the built environment, but lack of information, current codes and regulations and cultural fears about wastewater have largely prohibited their use and broad-scale adoption.

The purpose of this study is to analyze and compare the environmental impacts associated with current models of centralized treatment systems against alternative, smaller-scale decentralized systems using Life-Cycle Assessment (LCA). Utilizing the LCA approach, this study seeks to provide insight on the pros and cons of commonly proposed decentralized or distributed treatment systems and how they relate to traditional methods at different density scales. In doing so, we have the ability to take a step back and assess a wider range of risks associated with conventional practices for planning, designing and regulating wastewater systems in our communities.

The longer-term and overarching goals of this research are to help raise national awareness about current and emerging small-scale wastewater technologies, and to help influence policy and infrastructure planning around wastewater in the future.

AUDIENCE

While the focus of the research contained here is specific to the Puget Sound region, Clean Water, Healthy Sound is intended to serve as a resource for other regions around the state and the nation. Primary audiences include:

- Local and state public health agencies
- Policy makers
- Environmental agencies
- Wastewater and stormwater utilities
- Local planning and building departments
- Architects, engineers, contractors and developers

RESEARCH OBJECTIVES

- Provide an understanding of the relative environmental impacts of various treatment options using the LCA framework
- Empower building owners and project design teams to advocate for decentralized or distributed systems
- Provide valuable research to help inform future policy and infrastructure planning around wastewater

METHODOLOGY AND APPROACH

The information in this report represents the results of a 12-month analysis of conventional and alternative wastewater treatment strategies. A preliminary literature review of existing research was conducted in order to gain an understanding of current practices for treating wastewater in the Puget Sound region, alternative technologies available today and any prior LCA research on wastewater systems from both national and international sources. A list of resources on these topics is contained in Appendix E. The following questions established the foundation of the study and provided the basis for the project approach:

- What is the optimal scale for wastewater treatment systems?
- What is the relative environmental impact of centralized treatment systems vs. small-scale distributed treatment options, and what are the major drivers of those impacts?
- What effect does density have (and the associated conveyance needed to carry wastes different distances) on the overall life-cycle impacts, regardless of the treatment technology employed?

In partnership with experts in the wastewater engineering and LCA fields, Cascadia's approach to this study involved selecting a mid-sized community in the Puget Sound region with an existing centralized wastewater treatment facility to inform the baseline of the analysis. Extensive research was then completed to categorize decentralized treatment systems and to select the most appropriate options for comparison. Ultimately, four small-scale treatment systems were chosen for the purposes of this study: composting toilets, constructed wetlands, recirculating biofilters, and membrane bioreactors.

CENTRALIZED VS. DECENTRALIZED

Decentralized wastewater management systems are those that provide collection, treatment, and dispersal or reuse of wastewater from individual buildings or clusters of buildings at or near the location where the waste is generated. These types of systems may treat sewage onsite through natural and/or mechanical processes, or may utilize more distributed management systems to collect and treat waste at a neighborhood, district, or small community scale.

By contrast, centralized systems typically convey wastewater (and sometimes stormwater) collected from a relatively large area, such as an entire city, through an extensive network of gravity-fed or pressurized pipes to a large, centralized treatment facility.

Data was gathered on both the centralized and the decentralized systems, including:

- Quantification of material and chemical inputs of each system broken down by weight
- Chemicals or materials consumed and emissions released per year during the use/operation of each system
- Process-specific data for the installation or construction of individual treatment technologies including manufacturing processes for each major product component
- Waste treatment capacity data and other data necessary to allow for adequate scaling of impacts for comparison

LCA modeling of each scenario was performed using GaBi version 4.3 Life-Cycle Modeling software. Results are presented in the following environmental impact categories:

Acidification
Water eutrophication
Respiratory effects
Global warming
Ozone depletion
Photochemical smog
Aquatic ecotoxicity

It is important to note that life-cycle cost, while a major driver in the decision to select one treatment option over another, was specifically excluded from this analysis. A number of valuable resources already exist for assessing financial costs and benefits of decentralized treatment systems. However, limited information is available on the environmental impacts over the life cycle of conventional and alternative systems. The findings of these environmental impacts, contained here, are intended to provide an overlay to the financial costs for a more comprehensive look at comparing various treatment and conveyance options.

1.2 BACKGROUND AND VISION

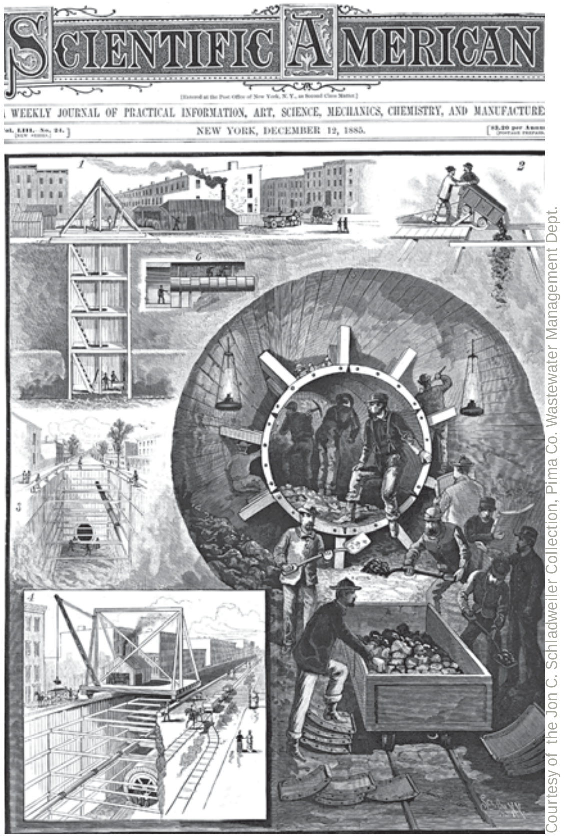
Cities across America are facing big decisions about how to meet the wastewater needs of their growing communities. Unfortunately, many communities are risking bankruptcy in order to maintain their aging and sprawling infrastructure. The risks associated with system selection are high due to potential health and safety hazards. Strategies for mitigating these risks have been born from the need to avail ourselves of the nuisances that arise when we do not properly dispose of our waste.

It has taken the efforts of scientists, outraged community members, and local, state and federal government agencies to forge the path toward healthy sanitation and environmentally sensitive waste treatment practices. As populations expand, water quality regulations become more strict and our infrastructure costs skyrocket, it will take the hard work of these same groups to negotiate the path to implement and manage waste treatment systems that will reduce the public health and safety, environmental and financial risks associated with dealing with our waste products. Understanding the events that shaped our existing centralized system, the problem with the present centralized waste treatment paradigm and the barriers that must be overcome to successfully integrate alternative waste treatment systems is imperative if we are to avoid the inevitable complications of continuing down the current path.

A BRIEF HISTORY OF WASTEWATER TREATMENT IN NORTH AMERICA AND THE PUGET SOUND REGION

Glancing back through history, waste disposal became increasingly urgent as population density increased. Solutions for how to best handle biological waste have been evolving ever since. In many areas serious waste treatment strategies did not emerge until the 19th century when correlations were drawn between waterborne illnesses and human contact with waste. Over time, centralized systems displaced decentralized systems because they were thought to better protect citizens from rampant disease, as well as easier to maintain and operate in compliance with impending laws.

In the United States, technologies for carrying away waste date back to the mid to late 1700s, about 100 years after communities began installing fresh water conveyance systems. In the Puget Sound, many early communities collected their waste in wood chutes, boxes and troughs and discharged it to the most convenient point, usually local water bodies at a lower elevation. The first large-scale strategy to replace the privy vault and cesspool systems was the centralized water-carriage sewer system. This system solved some problems and created others, especially in more densely populated communities.



Courtesy of the Jon C. Schladweiler Collection, Pima Co. Wastewater Management Dept.

1885 Scientific American illustration showing construction of a large sewer using new tunneling methods in Brooklyn, New York.

Many city residents accepted the sanitation problems and nuisance conditions such as odor as a necessary part of urban life.[1] But because it wasn't widely understood that biological waste could contaminate water sources, open sewers lined the streets. First-floor dwellers could often connect to the sewer system via a drainpipe but it was commonplace for upper-story households to cast their biological waste products out the window to the streets below. City boosters advocated for centralized waste management and sewer systems, believing it would help attract people and industries with a cleaner urban image. Opponents to centralized waste management and sewers argued that a source of fertilizer would be lost, soil and water supplies would be polluted at the system outfalls and "modern sewer systems" would create and concentrate "disease-bearing sewer gas".[2]

The design of the early centralized systems was also vigorously debated, pitting advocates for combined sewer systems against proponents for separated sewer systems. The combined sewer systems used a single pipe to transport both stormwater and wastewater to a designated disposal location, as opposed to the separated sewer systems which required laying two pipes. Many cities unwittingly installed combined systems because they were thought to be less expensive to build, unaware of the environmental problems that would later be imposed on discharge sites.

In Olympia, "adequate flushing and some dilution were seen as benefits over separate sanitary sewers."[3] It was a widely held belief that 'dilution was the solution to pollution', making combined systems the superior choice. But as populations in cities grew and it

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[1] Burrian, Steven J., Stephan Nix, Robert E. Pitt, and S. Rocky Durrans. "Urban Wastewater Management in the United States: Past, Present, and Future." Journal of Urban Technology. 7.3, 2000.

[2] Burrian, et al. "Urban Wastewater Management in the United States: Past, Present, and Future." 2000.

[3] City of Olympia, Wastewater Management Plan - 2007–2012, September 2007.

became necessary to treat sewage to alleviate nuisance pollution problems, cities with combined systems now had significantly more volume to clean.

Major advancements in sewer system design did not take place until the end of the 19th century when studies emerged demonstrating that sand filtration processes could help lower the infection rate of waterborne illnesses such as cholera, dysentery and typhoid. It was at this time that sewage treatment plants became commonplace.


Courtesy of Seattle Municipal Archives. # 10028

Six foot diameter sewer pipe, 1935.

Even after the King County Board of Health passed a resolution that required all wastewater discharged to Lake Washington to meet the United States Public Health Service bacteriological standard for drinking water, community members demanded that intercepting pipes divert the effluent away from Lake Washington. Outfalls were connected to the intercepting pipes by 1936, but large storm events continued to cause overflows that polluted Lake Washington. Many cities with similar situations began building ‘compound systems’ — combined sewer systems in some areas of town and separated sewer systems in newer districts — to alleviate this problem. In 1910, treatment of wastewater utilizing tanks and chemical reactions to filter, settle and bind contaminants found in wastewater became common in the U.S. However, Puget Sound communities fell a few decades behind this trend as it wasn’t until the 1940s that most of the waterfront communities began building wastewater treatment plants. Recognizing that there was a problem with water pollution, the state established the Pollution Control Commission in 1945. It took ten more years for the commission to require permits for wastewater discharge.

For the majority of the U.S., wastewater treatment became widespread after the introduction of federal funding with the passing of the Water Pollution Control Act of 1948, commonly known as the Clean Water Act. Supported by the federal government, the Act provided planning, technical services, research and financial assistance to state and local governments for sanitary infrastructure to protect national waters.

As populations grew, the amount of wastewater discharged into our navigable waters increased. Even though wastewater treatment plants were providing secondary treatment, the sheer volume of wastewater discharged caused problems. A beach on the north end of Lake Washington frightened parents one summer because there was a bloom of Oscillatoria rubescens, a type of blue-green algae capable of producing toxins that affect the nervous system and liver. “The State Pollution Control Commission, long worried about the lake, in August 1958 ordered that treatment-plant effluent be sprayed on the land, not dumped in the water."[4] Dilution was no longer the solution to pollution.

In the 1960s, pollution issues had become so problematic that the federal government amended the Water Pollution Control Act in 1965. The Act created the Federal Water Pollution Control Administration that was authorized to establish water quality standards where states failed to do so. The most ambitious and controversial goals were enacted with the 1972 version of the Clean Water Act. This version has been amended every year since its adoption.


Courtesy of the Seattle Municipal Archives. #36885

Sewage outfall extension at Alki Point, Seattle, 1934.

The Environmental Protection Agency now has the authority to implement and enforce the Clean Water Act. With the adoption of the 1972 Act, the federal government had intended that a zero pollution discharge policy was to be implemented and enforced by 1985. These exceptional goals were not met, and the Puget Sound Water Quality Authority thought it necessary to make a similar declaration in 1985.

Even with today's relatively strict laws and fines enforced by the EPA, Combined System Overflow (CSO) events still occur. Efforts are being made to find solutions to eliminate these events, but the high cost and complicated nature of these infrastructure interventions make the correction of these violations slow. "King County has 38 CSO outfalls that can discharge untreated sewage and stormwater during periods of heavy precipitation. Over the past three decades, the county has invested $360 million in projects that have reduced CSO volumes by 71 percent from an annual average of 2.3 billion gallons in 1983 to approximately 665.5 million gallons per year from 2000 to 2007. The county plans to invest an additional $388 million in capital projects scheduled through 2030 to further improve management and storage of storm flows in the sewage system."[5]

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[4] Lane, Bob, Better Than Promised: An informal history of the Municipality of Metropolitan Seattle, 1995.

[5] King County fined for sewer violations. Puget Sound Business Journal June 17, 2010.

KEY WASTEWATER MILESTONES IMPACTING THE PUGET SOUND

late 1800s	‘80-’90	Puget Sound communities, including Tacoma, Seattle, and Bellingham, begin to build sewer systems discharging waste into local water bodies, including Puget Sound.
early 1900s	‘25	King County Board of Health declares that all discharge into the Sound must comply with the US Public Health Service bacteriological standard for drinking water.
1940s	‘44	Tacoma citizens pass a $3 million bond issue to build a wastewater treatment plant to serve the central, southern, and eastern parts of the city.
	‘45	The State Pollution Control Commission is established to help protect the Puget Sound from point source pollution.
	‘47	Bremerton and Bellingham bring primary wastewater treatment plants online.
	‘48	The Clean Water Act provides federal funding for wastewater treatment projects.
1950s	‘52	Olympia and Tacoma bring waste treatment plants online.
	‘55	Washington State requires permits for wastewater discharge into open water bodies.
	‘58	The State Pollution Control Commission orders treatment plant effluent to be sprayed on land after beaches were contaminated with Oscillatoria rubescens at the outfall of the Lake City treatment plant.
	‘58	King County Metro (KC Metro) becomes the first regional agency to monitor wastewater. One of their first actions was to halt all wastewater discharge to Lake Washington.
1960s	‘65	KC Metro dedicates its largest secondary treatment plant, 144 mgd capacity, in Renton. Effluent is discharge to the Duwamish River.
	‘68	KC Metro stops discharging effluent to Lake Washington. Visibility increases by 7.5 ft in the lake.
1970s	‘70	The EPA is created to consolidate all of the agencies that work to provide environmental protection, and to ensure that all waters in the U.S. were “fishable” & “swimmable” by 1983.
	‘72	An amendment to the Clean Water Act declares that it is in national interest to reduce all U.S. waters to zero pollutant discharge by 1985.
1980s	‘85	The Puget Sound Water Quality Authority begins to require secondary treatment for permits to discharge effluent into Puget Sound.
	‘87	KC Metro completes an 11-mile tunnel to redirect the Renton Wastewater Treatment Plant discharge deep in the Puget Sound because ammonia and chlorine levels skyrocketed in the Duwamish.
1990s	‘96	KC Metro completes its expansion of the West Point Treatment Plant to comply with the 1972 Clean Water Act.
21st century	‘10	King County’s Bright Water Treatment Facility comes online and handles an additional 55 mgd.
	‘11	Sixty-five sewage treatment plants still discharge over 600 mgd of wastewater to the Puget Sound. Even with secondary treatment trace amounts of heavy metals, toxic chemicals, medicines and personal care byproducts are polluting the Sound.

PROBLEMS WITH THE CURRENT WASTE TREATMENT PARADIGM

The current waste treatment paradigm is problematic because it implies first and foremost that the biological byproducts we deposit in our toilets are waste products, i.e. are without any value or use. Cultural fears and a lack of understanding on how to properly handle waste products safely creates a need to simply make it “go away.” This convenience disconnects us from crucial nutrient cycles and affects our understanding about how to best use waste as a resource. Furthermore, our current waste treatment paradigm is rooted in the fact that bigger is better, though as this study reveals, that is not always the case.

Energy Use

Treatment of wastewater and the process of conveying that water from its point of generation to its point of treatment is energy intensive. According to the Northwest Energy Efficiency Alliance, “the wastewater industry consumes, according to EPRI (Electric Power Research Institute), approximately three percent of total energy nationally and approximately five percent of total energy in the Pacific Northwest.“[6] In 2003, Metcalf and Eddy projected that by 2030 energy use by wastewater treatment plants will rise an additional 30-40%.[7]

A conventional large-scale centralized system.

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[6] Easton Consultants, “Northwest Energy Efficiency Alliance - Assessment of Industrial Motor Systems Market Opportunities in the Pacific Northwest,” Final Report, August 1999.

[7] Rocky Mountain Institute. Valuing Decentralized Wastewater Technologies: A catalog of benefits, costs and economic analysis technique, 2004.

Combined sewer systems which convey both wastewater and stormwater require even more energy based on the larger volume of water requiring treatment. Once combined, the facility treats all waste as if it is the same low quality. By understanding this relationship it becomes clear that alternative strategies such as low-impact development and on-site wastewater treatment provide opportunities to substantially decrease the amount of wastewater conveyed offsite for treatment. This reduces energy use and expands an existing plant's ability to service a growing community without having to raise taxes or rates to build additional treatment facilities.

Ground and Surface Water Contamination

Wastewater conveyance pipes are also known to leak. Leaking is not only a risk as pipes crack; exfiltration has also been sited as a culprit of groundwater contamination due to aging pipes, manholes and pump stations that have had insufficient maintenance and repair. Exfiltration is more likely to happen in pipe conveyance systems that are laid above the groundwater table.[8]

A CSO event is a more noticeable form of contamination. It is typical for modern sewer systems to be designed for peak flows to handle even the largest storm event. However, many older combined sewer systems are subject to flows beyond their capacity during heavy rains. Use of CSOs provided an economical way to prevent sewage backups into homes and businesses by releasing overflow waste and stormwater into

Courtesy of Tristan Baurick | For the Kitsap Sun

Sewage pipe leak at Eagle Harbor, Bainbridge Island, June 2009.

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[8] Amick, Robert S., P.E., & Burgess, Edward H., P.E. Exfiltration in Sewer Systems. EPA, December 2000.

adjacent bodies of water.[9] However, the CSO is an obvious danger to the health of our waterways. Due to the rigid infrastructure of the big pipe system, it is difficult to respond to these fluctuations and concentrations of contaminants.[10] When major catastrophe or malfunctions do happen at a centralized wastewater treatment plant or within the conveyance system, it can disable an entire service population and leave homes and water bodies vulnerable to contamination.

Combined system overflows are reported regularly around the Puget Sound. In June 2009, approximately 493,000 gallons of sewage overflowed into Eagle Harbor on Bainbridge Island, WA. The Kitsap County Health District imposed a ten-day no-contact order in Eagle Harbor and the surrounding waters from Yeomalt Point to Rockaway Beach. According to the EPA, an estimated 1.94 billion gallons of untreated sewage and polluted runoff are discharged annually from Seattle and King County combined sewer overflow outfalls into Puget Sound or its tributary waters.[11]

Water Quality

A more contemporary water quality problem is the increased consumption of pharmaceuticals and hormones, resulting in the presence of these materials in our waste stream. The effects of these trace pharmaceuticals are not yet known as water quality standards do not currently test for them. While the levels to which wastewater must be treated has steadily become more stringent, treating to higher levels will require large infrastructure upgrades to current systems.

Financing Future Growth

Warning signs are posted in areas where sewage overflows occur.

Population growth will place additional strain on older systems, with larger densities demanding increased infrastructure in urban and rural areas. John Crittenden of Georgia Tech University's Brook Byers Institute for Sustainable Systems says, "We expect in the next 35 years to double the urban infrastructure, and it took us 5,000 years

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[9] King County. "Combined Sewer Overflow (CSO)." Public Health - Seattle & King County. King County, 03 Feb 2010. Web. 8 Sep 2010.

[10] Slaughter, S. "Improving the Sustainability of Water Treatment Systems: Opportunities for Innovation." Solutions. 1.3 2010.

[11] US EPA News Release. Seattle and King County Agree to Step Up Efforts to Reduce Sewer Overflows to Puget Sound. 2009.

to get to this point. So we better do that right. We better have a good blueprint for this as we move to the future, so that we can use less energy, use less materials, to maintain the life that we have become used to."[12] The costs of this increase in infrastructure and maintenance is being considered by the EPA, the Government Accountability Office, the Water Infrastructure Network and others as they project a wastewater funding gap of $350 billion to $500 billion over the next 20 years.

According to the 2004 Valuing Decentralized Wastewater Technologies report prepared by the Rocky Mountain Institute for the U.S. EPA, decentralized and distributed systems can be more flexible in balancing capacity with future growth. According to the report: *"In smaller scale systems, capacity can be built house-by-house, or cluster-by-cluster, in a "just in time" fashion. This means that the capital costs for building future capacity is spread out over time, reducing the net present value of a decentralized approach, and resulting in less debt to the community as compared to the borrowing requirements of a large up-front capital investment. This is especially true in the event that a community sees less growth than anticipated in their initial planning, leaving them with overbuilt capacity and a large debt load to be shared by fewer than expected residents."*[13] In other words, if we continue our dependence on the current centralized wastewater treatment system we will unnecessarily lock ourselves into a fixed solution. Therefore, it is appropriate to consider how developing a hybrid of appropriately scaled waste treatment strategies might provide us with the most resilient future solutions.

BARRIERS TO THE ADOPTION OF DECENTRALIZED TREATMENT SYSTEMS

Despite the problems with our current paradigm for large, centralized wastewater treatment, numerous barriers exist for widespread adoption of decentralized and distributed alternatives. The primary barriers affect the regulations pertaining to wastewater treatment, the financial challenges and the cultural acceptance of new or unfamiliar systems.

Regulatory Barriers

Currently, wastewater is regulated across multiple jurisdictions and agencies — from plumbing codes enforced by local or state building departments, to local and state public health agencies regulating waste treatment, departments of environmental quality and protection regulating on-site wastewater treatment as well as wetland and shoreline

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[12] IEEE Spectrum Podcasts. "Decentralized Water Treatment is more efficient, flexible and resilient." Web. 7 Sep 2010.

[13] Rocky Mountain Institute. Valuing Decentralized Wastewater Technologies: A catalog of benefits, costs and economic analysis technique, 2004.

protection that may involve approvals from local, state and national agencies such as the Corps of Engineers.

Regulatory barriers to decentralized and distributed waste treatment systems stem from the current bias toward centralized wastewater treatment and the associated lack of a body of authority with appropriate powers to operate, manage and regulate decentralized approaches. Particularly in urban and suburban areas where development codes and public health regulations require connections to public utilities, small-scale decentralized systems frequently lack any clearly defined regulatory pathways for approvals and instead rely on those developers with the will or financial means to navigate the regulatory system. Often times the regulations that do exist at the local, state and national levels overlap or conflict with each other, and sometimes there are gaps where no regulatory provisions are currently in place. Particularly in urban areas, developers hoping to install distributed or on-site systems are tasked with a lengthy or costly variance process to seek approvals for pursuing alternative waste treatment strategies, costs that are rarely recoverable. Furthermore, case-by-case approvals are seldom documented for the benefit of future projects or to guide future code updates.

Many regulatory agencies are responding to requests for alternative waste treatment strategies, though often in disjointed and incremental ways. For example, the International Association of Plumbing and Mechanical Officials (IAPMO) — the agency responsible for the development of the Uniform Plumbing and Mechanical Codes — has released a green supplement outlining voluntary provisions for water efficiency and water reuse strategies that jurisdictions can adopt. Additionally, local and state jurisdictions are beginning to open up legal pathways for reusing greywater for non-potable uses. But despite these and other efforts, regulatory resistance persists toward non-proprietary on-site treatment technologies such as constructed wetlands and waterless fixtures such as composting toilets.

In order to create support for alternative waste and wastewater treatment projects, a major shift from our current regulatory framework will be necessary. A more holistic approach to regulating waste is needed at all agency levels in order to support innovative projects and drive future policies. State and local building codes, land use codes and development standards must align to comprehensively address treatment practices with clearly defined roles and responsibilities for permitting, operating and maintaining these systems. Most importantly, wastewater regulations established to protect risks to public health will need to be assessed and updated to fully account for current environmental, social and economic risks related to centralized wastewater treatment systems, creating new standards in support of more integrated waste treatment systems at the site and neighborhood scales.

Financial Barriers

Decentralized and distributed wastewater treatment strategies should not necessarily be managed at the municipal level by publicly-owned utilities alone. As such, the cost burden for treatment systems, as well as their ongoing operation, maintenance and replacement needs can be shifted from the utility to the individual project owner. While this can create financial barriers for project owners, unique opportunities exist for utilities to develop fee structures and incentives to support the transfer of capital cost, expense and revenues to offset an owner's upfront investment in on-site water systems.[14] Utilities could even develop a new revenue stream by providing system maintenance and testing to ensure operations perform at required public health levels.

A project owner's upfront investments in on-site treatment systems can create burdensome financial barriers. Even when life-cycle costs are taken into account, artificially low utility rates for water and wastewater services translate to long payback periods. Not all utilities use full cost pricing — past and future, operations, maintenance and capital costs — to establish rates for water and wastewater services and therefore miss an opportunity to encourage conservation and reuse strategies employed by alternative waste treatment systems.

Financial barriers for distributed water systems can be directly related to the regulatory barriers noted above. Backup or redundant connections to municipal wastewater utilities may be required by codes even when a system is designed and operated not to use them. Composting toilets sometimes require backup sewer connections and associated plumbing, creating a financial disincentive for project owners to even consider their use. Likewise, capacity charges are established by utilities to recoup sunk costs for large investments in centralized infrastructure projects and are required to be paid by all building projects located within their service area, regardless of whether or not on-site systems can be utilized to meet individual treatment needs. Some municipalities have instituted innovative fee structures, such as the City of Portland's Bureau of Environmental Services in Oregon, which allows for emergency-only connections to their wastewater treatment facilities but charges large use fees in the event that the utility connection is actually needed.

Removing regulatory barriers to decentralized systems can help spur market innovations and new products available to designers and homeowners pursuing decentralized and distributed systems, thus bringing down upfront costs and reducing life-cycle cost payback periods. For years, financial incentives for energy efficiency measures and on-site renewable energy generation have been accelerating market adoption, serving as examples for similar approaches for decentralized and on-site wastewater systems.

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[14] Paladino and Company, Inc. Onsite Wastewater Treatment Systems: A Technical Review. Seattle: Seattle Public Utilities, 2008.

Cultural Barriers

In addition to regulatory and financial barriers, public perceptions about the safety of on-site wastewater management presents significant obstacles. Such fears are rooted in our historical management of water and waste and the resulting public health issues that surfaced. Previous generations suffered greatly from waterborne illnesses until laws and regulations were passed to support water-carriage removal of waste from urban areas. Today, education is needed to assure the public of the safety of modern decentralized water systems and inform them of their environmental, social and economic benefits.

Thanks to a history of disease outbreaks, coupled with marketing efforts by early flush toilet manufacturers, “flushing it away” is widely viewed as more civilized and advanced than any other solution for dealing with our water and waste. On-site systems are perceived to be a step backward in time and technology to a less developed age. Education and awareness building among regulators, designers, engineers and building occupants is necessary to fully highlight the environmental risks associated with wasteful practices. Water that has been treated for drinking purposes, that requires large inputs of energy to be conveyed to buildings and that is contaminated with human excrement and conveyed away again and treated with energy-intensive processes that release polluted water back into the environment does not represent our best technological advancements.

Addressing cultural barriers around decentralized water systems will require a shift in the fundamental ways in which we view human wastes. Education and perceived need will likely be the key tools to overcome the “ick” factor that has been prevalent over the past century. In doing so, we create opportunities to evaluate best practices for treating water and waste that respect water as the precious resource that it is, seek all possible ways to recover nutrients that are too important to flush away and ultimately discharge effluent back into the environment that is cleaner going out than it was coming in.

Moving Forward

If our wastewater treatment history is indicative of the future, the environmental and economic costs associated with maintaining and operating centralized wastewater systems will continue to escalate. It is through thoughtful evaluation of alternative systems that we can see how bigger isn’t always better. With a deeper understanding of the long and short term ecological, financial, public health and safety risks, we are in a better position to advocate for development and installation of appropriately scaled systems that can meet the fluctuating needs of a community while still providing the expected convenience of tidy and odorless waste elimination.

THE LIVING BUILDING CHALLENGE$^{\text{SM}}$
A VISIONARY PATH TO A RESTORATIVE FUTURE

The Living Building Challenge$^{\text{SM}}$, which was launched by Cascadia and is operated by the International Living Future Institute, is widely regarded as the world’s most advanced and stringent green building rating system. It applies to projects ranging from infrastructure to buildings to communities. The program was designed not only to recognize and reward the leading projects around the world, but also to shine a light on the issues and barriers that most need to be addressed in order to realize a truly sustainable future built environment. As part of this effort, a large focus has emerged around water issues in response to the significant regulatory, financial and cultural barriers preventing a truly sustainable water infrastructure from emerging.

Currently there are close to one hundred projects (primarily in North America) pursuing the challenge, and each project is asked to achieve close to twenty ‘imperatives’.[15] Of these, two of the imperatives deal with water and waste, both found in the Water Petal[16] of the Living Building Challenge.

LIVING
BUILDING
CHALLENGE™
2.0

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[15] Imperatives’ is the word used by the ILBI in place of ‘prerequisites’.

[16] ‘Petal’ is the word used by the ILBI in place of ‘categories’.

The intent of the Water Petal is to realign how people use water and redefine ‘waste’ in the built environment, so that water is respected as a precious resource.

Imperative Number Five requires that:
One hundred percent of occupants’ water use must come from captured precipitation or closed-loop water systems that account for downstream ecosystem impacts and that are appropriately purified without the use of chemicals.

Imperative Number Six requires that:
One hundred percent of storm water and building water discharge must be managed on-site to feed the project’s internal water demands or released onto adjacent sites for management through acceptable natural time-scale surface flow, groundwater recharge, agricultural use or adjacent building needs.

These two imperatives work together to keep sewage separate from storm water and to ensure that projects use the minimum amount of water possible and always within the water balance of the site. Any water that leaves the site eventually does so in a cleaner state than when it entered.

What is interesting is that this current vision for water and waste is illegal in most states. Due to a morass of regulations and outdated thinking, project teams are prevented from taking a progressive and responsible approach to water use.

Cascadia’s recent publication “Regulatory Pathways to Net Zero Water” highlights the issues that surround regulatory barriers to approval of Living Building projects in Seattle. Despite this, Living Building Challenge project teams are persevering — helping to change the mindsets of regulatory agencies, seeking approvals through ‘pilot ordinances’ and, in Oregon and Washington, literally changing state water law. As each new project is built, a new model and possibility for the future of a healthy and regenerative community emerges.

The first two projects certified as ‘Living Buildings’ each show different models for decentralized wastewater systems. With these two projects in mind, a new vision for the future of wastewater is explored in the following section.

TYSON LIVING LEARNING CENTER


Courtesy of Joe Angeles-WUSTL

Tyson Living Learning Center irrigates its landscape with greywater collected from building sinks.


Courtesy of Clivus Multrum.

The waterless toilet by Clivus Multrum helps reduce overall water requirements.

This innovative classroom building near St. Louis, Missouri, provides one possible model of waste treatment. The classroom's bathroom contains a simple composting toilet system that does not use water in its operation, and human waste is turned into useful compostable material.

This approach has several significant advantages:

- Cuts water use in the building by at least 50%
- Eliminates all pumping energy and energy used to treat the waste
- Eliminates the need for additional excavation and site impacts for sewage conveyance
- Provides a rich compost material that can enhance site landscapes
- Avoids downstream stormwater contamination and nutrient flows into local waterways

While this project is not the first to use composting toilets, it does so within the overall framework of the Living Building Challenge, completely powered by the sun and using no redlist chemicals with only a few exceptions. The possibility of using this approach as a model for all small and low-density communities is compelling.

THE OMEGA CENTER FOR SUSTAINABLE LIVING


Courtesy of Farshid Assassi

View inside the Eco Machine greenhouse. The system uses plants, bacteria, algae, snails, and fungi to clean the water before using it to recharge the aquifer.


Courtesy of BNIM Architects

Transverse section of the greenhouse and constructed wetland.

The Omega Center for Sustainable Living is a seasonal retreat center in Rhinebeck, New York. This certified Living Building is a small wastewater facility designed to accept and treat waste from several dozen surrounding buildings. Water is collected from toilets, sinks and showers and flows primarily through a gravity-fed network to the building. The wastewater is then treated through a proprietary technology known as an Eco Machine™, a series of interior constructed wetlands that house plants and millions of microbes that use our waste as food. As the water flows through the system (which is free of odor and completely solar powered) it is purified. The water exits the building and is further treated in an exterior constructed wetland that has the feeling of a park.

The Eco Machine processes approximately 52,000 gallons of wastewater per day when Omega's campus is open from April to October, and about 5,000 gallons per day in the off-season from November to March. The center is so beautiful that it is used as yoga studio and visitor center, drawing people out of their way to visit a sewage treatment plant.

This approach also has many advantages:

- Allows for existing buildings and infrastructure to be hooked up to an on-site, ecological system instead of pumping waste off-site for treatment
- Provides flexibility in scale based on population and density and can fit within the existing urban fabric wherever there are parks or open space
- Serves as an amenity within a community rather than a sunk cost
- Operates pollution free and without the use of chemicals

A VISION FOR THE FUTURE OF WASTEWATER

The current paradigm of waste treatment in America is to simply flush the toilet and never think, see or smell our waste again. This “out of sight, out of mind” paradigm has presented huge problems as outlined in the previous section of this report. Our existing infrastructure was built over a 30-50 year period when labor was undervalued and while we were undergoing a great national expansion. However, on a national scale we are learning that this rapid growth has expanded our communities too far, too fast, triggering the current crises around aging wastewater and stormwater infrastructure. Maintaining the current paradigm is signaling a path toward bankruptcy for many communities. Worse still, financial hardships for many citizens result in a lack of support for increased taxes for infrastructure that is largely taken for granted.

As encapsulated in the Living Building Challenge, envisioning the future of wastewater on a broad scale invites us to imagine “what if”:

What if every future dollar spent on water and waste was not viewed as a drain on our municipal budgets, but instead helped contribute to improving the social and cultural life of the city?

What if we could build a new infrastructure that eliminated the use of harsh chemicals, which was carbon positive and cleaned the air, which created multiple forms of value and was largely self-regulating?

What if we could create a new infrastructure that saved money annually, created meaningful jobs, helped the environment and specifically our ailing rivers, streams and lakes and enriched the lives of all citizens?

Signage reinforces a psychology of fear of waste.


Courtesy of 2020 Engineering

Students learn about the Living Machine® at IslandWood Environmental learning center on Bainbridge Island.

Over the next 30 years, every community in the U.S. and Canada will likely need to replace, repair or expand its existing wastewater infrastructure. Knowing this, communities are faced with the opportunity and choice of either:

1. Continuing to invest in the current paradigm, thus shifting the burdens further into the future. This paradigm is built around the idea of getting sewage away from buildings as fast as possible and into larger bodies of water, preferably with greater levels treatment, or,
2. Creating a new paradigm for water and waste, and transforming our relationships with our most valuable resources. In this paradigm, nutrients are recycled and water is used wisely, reused and only treated to the level necessary for its reuse purpose. When discharged back into the environment, it is done so in a way that mimics natural systems, is celebrated as an amenity and is cleaner than when it entered into the building.

To realistically apply a shifted approach to water and waste, visions for a new wastewater paradigm must be explored at different scales.

The Living Building District – The Urban Solution

Stormwater – as precipitation falls on the roofs of buildings, instead of flowing quickly to a storm sewer it is captured and used within the buildings. Stormwater loading is greatly diminished while buildings are designed and retrofitted to use water within the carrying capacity of their local climate conditions.

Excess building water and rainwater that falls on streets flows into specially designed bio-swales using native plants. A network of these swales, retention ponds and canals grace the district, moving water slowly, recharging groundwater and evaporating. Water is celebrated, and trees and landscape plants—potentially even urban food—have ample water.

Wastewater – water from ultra-efficient toilets, sinks and showers flows by gravity to one of several neighborhood-scale treatment systems that use a combination of Eco Machines and constructed wetlands. In addition to their treatment function, the systems also provide valuable community amenities, greenspace and urban habitat. Always located 'downhill,' these systems become cherished elements of urban infrastructure like the great public libraries, museums and parks of the last century. Some buildings—based on geography and size—may have their own decentralized systems, privately operated but publicly regulated.

This model consists of several key innovations:

1. Dramatic changes in policy that encourage rainwater collection, greywater reuse and decentralized wastewater treatment.
2. A significant change in the typical urban street section, with a new focus on daylighting stormwater and keeping it separate from much smaller, buried blackwater-only sewer systems.
3. A new service offering by community sanitation departments that provides visible public service and supports decentralized strategies as a key part of their integrated system.
4. A highly visible network of waste treatment facilities that serve multiple functions and community needs.


Courtesy of American Society of Landscape Architects

The face of urban landscapes is changing. Many cities are integrating green infrastructure to reduce stormwater issues.

The Living Building Village Paradigm: The Rural and Low Density Approach

Most Americans will be living in more dense urban cities over the next few decades, as rural communities play an important role in supporting food production. For these lower-density communities, the cycles of water and waste are quite different from urban areas.

Stormwater – as precipitation hits the roofs of buildings it too is captured and used within the structure or easily diverted to nearby landscaping or agriculture needs. Since densities are low, stormwater is easily infiltrated on-site as part of the natural hydrological cycle. Streets are not lined with curbs and gutters to channel water into storm sewers to be managed offsite. Instead, everything is surface flow, designed to support the water needs of agriculture or aquifer recharge.

Wastewater – in low-density communities, there is a true separation between greywater and blackwater to facilitate recapturing of nutrients from water and wastes. Toilets are connected to composting units and are part of a community-wide composting program that helps build and maintain healthy soils. Instead of water bills and traditional septic pumping, community 'night soil' companies collect and redistribute compost material safely. The problematic link between excessive nutrient flow in our waterways and the need for petrochemical fertilizers on impoverished soils is broken.

This model consists of several key innovations:

1. A moratorium on extending sewer systems out to sprawling areas and a slow process of retrofitting homes, where possible, with composting toilets and greywater irrigation systems. All new homes include these features by mandate.
2. New business opportunities for licensed 'night soil' operators that provide the connection between homes and farms.
3. New county and small community standards for water, waste treatment and street design.

This vision represents a far stretch from the path many communities are currently on to design, regulate and plan for the future. Yet the concepts and technologies are simple. Lack of information on the full economic and environmental impacts of current practices presents a major barrier to realizing a preferred path forward with respect to water and wastes. This life-cycle assessment helps provide important data for designers and decision-makers seeking ways to advocate for a more restorative future.

1.3 STRATEGIES FOR DECENTRALIZED TREATMENT

OVERVIEW OF SELECTED TECHNOLOGIES

A wide range of proprietary and non-proprietary decentralized technologies is currently used to manage water and waste in the built environment. These range from simple, passive systems that mimic the biological, chemical and physical processes occurring in natural wetlands to more energy-intensive activated sludge technologies. Table 1.1 on the following page provides a snapshot of the various distributed technologies used to treat water and wastes.

Various treatment options can achieve different qualities of water based on their design and performance efficiency. Primary treatment systems only remove a portion of the suspended solids and organic materials from wastewater. Secondary levels of treatment can include removal of biodegradable organic matter, suspended solids and nutrients such as nitrogen and phosphorous. Tertiary treatment systems include disinfection of treated water and advanced removal of residual suspended solids through filtration.

TABLE 1.1: SUMMARY OF TREATMENT TECHNOLOGIES

TECHNOLOGY	DESCRIPTION	EXAMPLES
Non-water discharging containment systems	Collection and processing of human wastes without the use of water	Composting toilets Incinerating toilets Evaporation systems
Primary treatment systems	Pretreatment and settling of particulate materials Usually coupled with more advanced treatment technologies or with a drainfield which relies on soil to filter, treat and disperse effluent	Septic tanks
Suspended growth	Treats water through active microorganisms suspended in aerated environments. Also known as activated sludge process	Sequencing batch reactors Membrane bioreactors
Attached growth	Treats water through active microorganisms attached to granule, organic or synthetic media. Also referred to as fixed-film processes	Recirculating biofilters Intermittent sand filters Fabric/synthetic filters
Hybrid	Utilizes both suspended and attached growth processes to treat water	Moving bed biofilm reactors
Natural	Treats water by mimicking the biological, chemical and physical processes occurring in natural wetlands	Constructed wetlands

In order to narrow down the list of potential decentralized treatment technologies for analysis as part of this study, the following criteria were used:

1. **Treatment Level** - Recognizing that not all decentralized systems achieve the same level of treated water quality, this study considers only those technologies (or combination of technologies) that are capable of achieving an advanced secondary level of treatment or greater to support water reuse or the release of nonpolluting water back into the environment, with consideration for the beneficial use and appropriate handling of nutrients. Systems that only achieve primary or secondary levels of treatment, such as traditional septic and drainfields, are not included in this study.

2. **Scalability** - The selection of the most appropriate decentralized wastewater treatment system will vary widely and is influenced by site conditions, capacity needs, desired inputs and outputs as it relates to a building's overall water use and reuse goals, and the treatment technology selected (eg. suspended vs. attached growth). For this study, systems were evaluated based on their applicability to various building scales — single family residential to commercial and neighborhood-level scales — as well as their required energy input and overall footprint size. In addition, only commonly used systems are considered.


Courtesy of Whole Water Systems, LLC.

Constructed Wetland


Courtesy of 2010 General Electric Company.

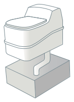
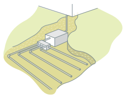
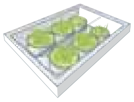
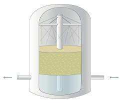
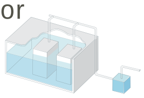
Membrane Bioreactor


Courtesy of Clivus Multrum

Composting Toilet

Based on this criteria, four decentralized treatment strategies were selected as alternative scenarios in evaluating life-cycle environmental impacts compared to centralized conveyance and treatment. Table 1.2 below provides a brief summary of the four sample technologies.

TABLE 1.2: SELECTED DECENTRALIZED TREATMENT TECHNOLOGIES

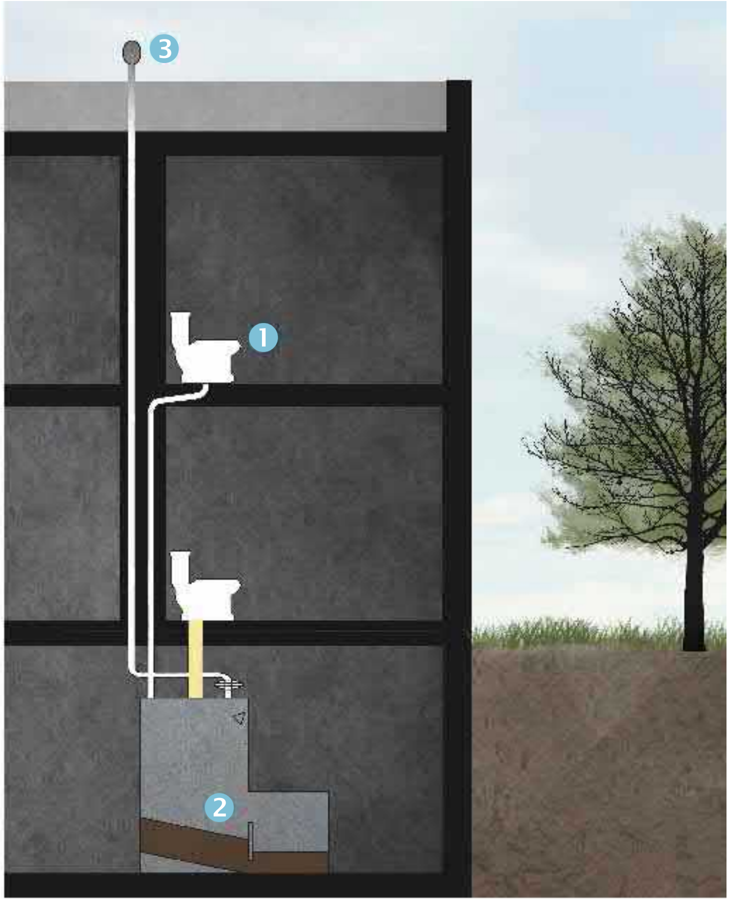
	FOOTPRINT	OPERATING ENERGY	TECHNOLOGY
Composting toilets + Constructed wetland*  	Small – Large**	Zero – Low	Non-water discharging containment system Nutrient recovery Attached growth aerobic treatment
Constructed wetland 	Small – Large	Zero – Low	Attached growth aerobic treatment
Recirculating biofilter 	Medium	Low – Medium	Attached growth aerobic treatment
Membrane bioreactor 	Small – Medium	High	Suspended growth aerobic treatment with synthetic membrane ultra-filtration

* Constructed wetland for treatment of greywater from sinks, baths/showers and laundry.
** Wetland and soil dispersal area for greywater can have large space requirements depending on generated flow.

COMPOSTING TOILETS

Composting toilets are non-water discharging systems, meaning that the processing of human waste is achieved with zero or minimal use of water for conveyance. This has the potential to greatly reduce a building's overall demand for wastewater handling as no blackwater is generated. Composting toilets rely upon biological and physical decomposition to turn excrement into valuable, nutrient-rich end products that can be used on- or off-site as a fertilizer or soil amendment. For the purposes of this study, composting toilets are paired with a constructed wetland to treat water generated from other plumbing fixtures within a building such as sinks, baths, showers and laundry.

FIGURE 1.1: COMPOSTING TOILET



System Components
- ① Toilet Fixture
- ② Composting Chamber
- ③ Ventilation

System Components

Toilet

Composting toilet fixtures come in a variety of shapes and sizes and are similar in design to a conventional water flush toilet. The fixtures are typically porcelain, polyethylene or ABS plastic and are classified as either dry, micro-flush, vacuum flush or foam flush depending on the technology used. Micro-flush units use approximately one pint of water per flush. Urine-diverting toilets separate liquid from solid waste at the fixture location to optimize nutrient separation and collection. Toilet fixtures can be mounted either directly above the composting chamber or may be located several stories above the chamber connected by a 4”-12”diameter piped chute. For foam flush and micro-flush models, chutes can bend up to 45 degrees, allowing for flexibility in the system layout at different stories of the building rather than stacking fixtures directly over a centralized chamber.

Composting Chamber

In many composting units, decomposition takes place in a tightly sealed plastic, fiberglass or concrete composting chamber. Some designs have sloped chambers to separate urine from feces. Others use electric or solar heat to ensure optimal temperatures for the composting process. Drums or mechanical stirring provide mixing and aeration.

All chambers include an access door for removal of composted end products and most require an overflow for the discharge of liquid wastes. Chambers are sized based on system loading and can serve individual or multiple toilet fixtures. Some designs feature dedicated urine collecting chambers that allow for the collection and processing of urine separately from solid wastes.

Ventilation

Ventilation ensures adequate oxygen and the proper moisture and temperature levels necessary for the composting process. A ventilation system includes an air inlet and exhaust vent for removing odors, excess heat, carbon dioxide, water vapor and other byproducts of aerobic decomposition. Passive systems require little or no energy input while more intensive systems require electricity (typically 12 volts or less) for air circulation and mixing of the composting material. Solar powered fans can be used to drive the ventilation system.

Courtesy of Clivus Multrum, Bilyana Dimesitrova, David Swift, The Bairds.

Technology

Composting toilets use an aerobic decomposition process to slowly break down human excrement to 10-30% of its original volume into a soil-like material called humus.[17] Organisms that occur naturally in the waste material, such as bacteria and fungi, perform the work of breaking it down. Sometimes compost worms are added to accelerate the process.

During the composting process, optimal moisture content of the waste should be maintained at around 40-70&. Urine can be separated from feces. Additionally, excess water vapor and carbon dioxide produced in the process are mechanically vented to the outside through the unit's exhaust system. This venting also controls odors. Mechanical or manual mixing of the waste improves aeration, and bulking agents such as hay, wood chips, saw dust or other carbon sources can be added to provide space for microbial colonization.

Composting toilet technology is defined by either a continuous or batch process. Toilets that utilize a continuous process deposit new waste materials on top of the composting mass while finished material is removed from the bottom or end of the unit. In this system, risk of contamination in composted end products is a concern and proper maintenance and oversight is essential. In a batch process, excrement is collected for a certain period of time and is then set aside for months or years while the composting process occurs.

Some composting toilet models do not use water or other liquids to carry waste to the collection chamber. Others feature a "micro-flush," utilizing 1/10th of a quart of water to flush urine only. Foam-flush toilets use a mixture of water and a compost-compatible soap to create a foam blanket that transports waste to the composting unit. With any of these technologies, the end products are either used on-site as fertilizers or hauled offsite to an appropriate handling facility. Depending on the size of the system, the time required for the composting process might range from three months up to several years.

Composting toilets address potential pathogens found in human waste through the process of composting, or through the natural production of predatory organisms toxic to most pathogens that occur during the composting process. One key advantage to composting toilets is that they keep valuable nutrients such as nitrogen and phosphorous in tight biological cycles without causing the potential environmental risks to receiving water bodies inherent in conventional wastewater treatment plant operations.[18]

Advantages/Disadvantages

Because they require little or no water supply, composting toilets are a good fit for geographic locations with limited water resources, such as areas affected by drought.

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[17] US EPA. Water Efficiency Technology Fact Sheet. Composting Toilets. 1999.

[18] US EPA. Water Efficiency Technology Fact Sheet. Composting Toilets. 1999.

Likewise, because they are non-water discharging systems, locations where on-site wastewater management options are limited due to site constraints, high water tables or shallow soils make composting toilets a feasible alternative. In cold climates, composting chambers might need to be heated and/or insulated to ensure optimal temperatures for decomposition and pathogen removal.

Composting toilets are an obvious fit for areas not already serviced by municipal sewers as they eliminate the need for extensive infrastructure brought in to service a building or neighborhood development. Utilizing them in urban locations presents opportunities to reduce demand on existing municipal wastewater treatment infrastructure and extend the life of these systems, which are often maintained and updated through expensive public funding. Composting toilets may be more challenging to incorporate into retrofit applications than new construction due to the space needed for the composting chamber. For retrofits, micro-flush or vacuum-flush toilets can be installed to convey wastes to a composting chamber located outside the building envelope.

Composting toilets are suitable for any building typology, and successful examples exist at all scales. Dry toilets may be best designed into single-family houses, while micro-flush or foam flush models are better suited for multifamily or commercial buildings. Like all decentralized water systems, composting toilets require a commitment by homeowners, building owners and/or maintenance staff to provide management and oversight of the system to ensure proper performance.

Costs

Costs for composting toilets can range from $1,000-$5,000 for individual, self-contained units. Larger scale centralized systems can require a substantial investment on the part of the building owner or developer, though there is great opportunity for considerable savings on water and wastewater utility fees over the life of the system. The payback period on any scale system is highly dependent on water and wastewater rates, with higher rates providing a financial incentive to curb water use altogether. Many commercial scale systems such as those used at the Chesapeake Bay Foundation Headquarters' in Annapolis, Maryland calculated a payback in less than ten years.[19]

Lifecycle costs and paybacks for utilizing composting toilets on a neighborhood-scale project can be minimized when compared to the upfront cost of installing infrastructure needed to convey wastewater from individual buildings to sewer mains, sometimes including the sewer mains to the development altogether.

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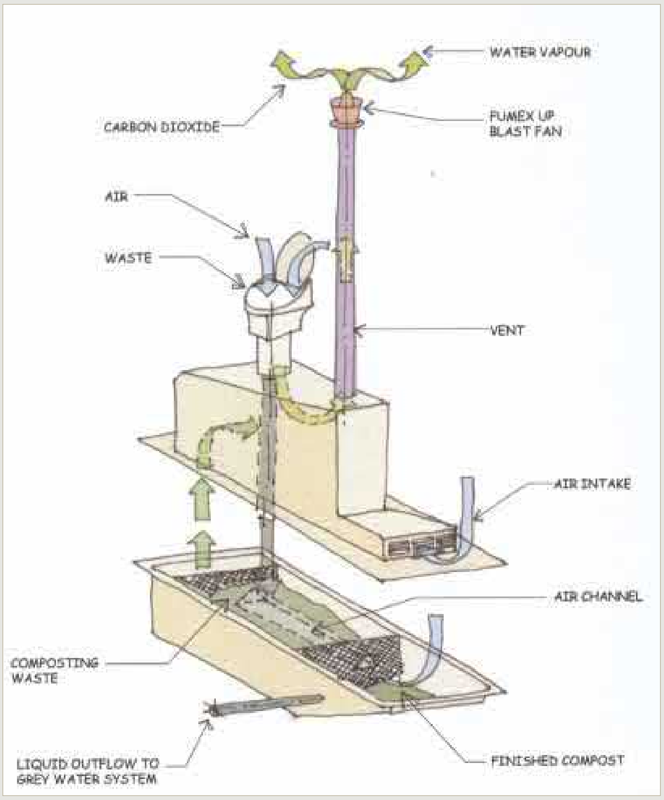
[19] WERF. Modeling Onsite Wastewater Systems at that Watershed Scale: A User's Guide. 2009.

C. K. CHOI BUILDING: THE INSTITUTE OF ASIAN RESEARCH

Date Completed: 1996
Location: Vancouver, British Columbia, Canada
Owner: University of British Columbia
Project Type: Campus / Office Building
Project Size: 34,400-sf
Site Area: 18,000-sf
Capacity: 225,000 uses / year
System Selected: Clivus Multrum Composting Toilet Model M28

Courtesy of Clivus Multrum

The CK Choi Building was the first of its size to install composting toilets in North America. The building eliminated the need to connect to the campus sewer system and reduced potable water demands by over 99,000 gallons per year. The building has ten composting toilets and three trapless ventilated urinals that require no water. The composting unit’s five-tray system allows maintenance staff to add wood chips and red wiggle worms that facilitate the process of turning solid waste into a humus-like topsoil rich in nitrogen and other useful elements. At the time the project was being designed, Vancouver’s plumbing code did not address a process for regulatory approvals, and there were no North American precedents to illustrate how the system would perform.



Courtesy of Jim Burns, Stantec.

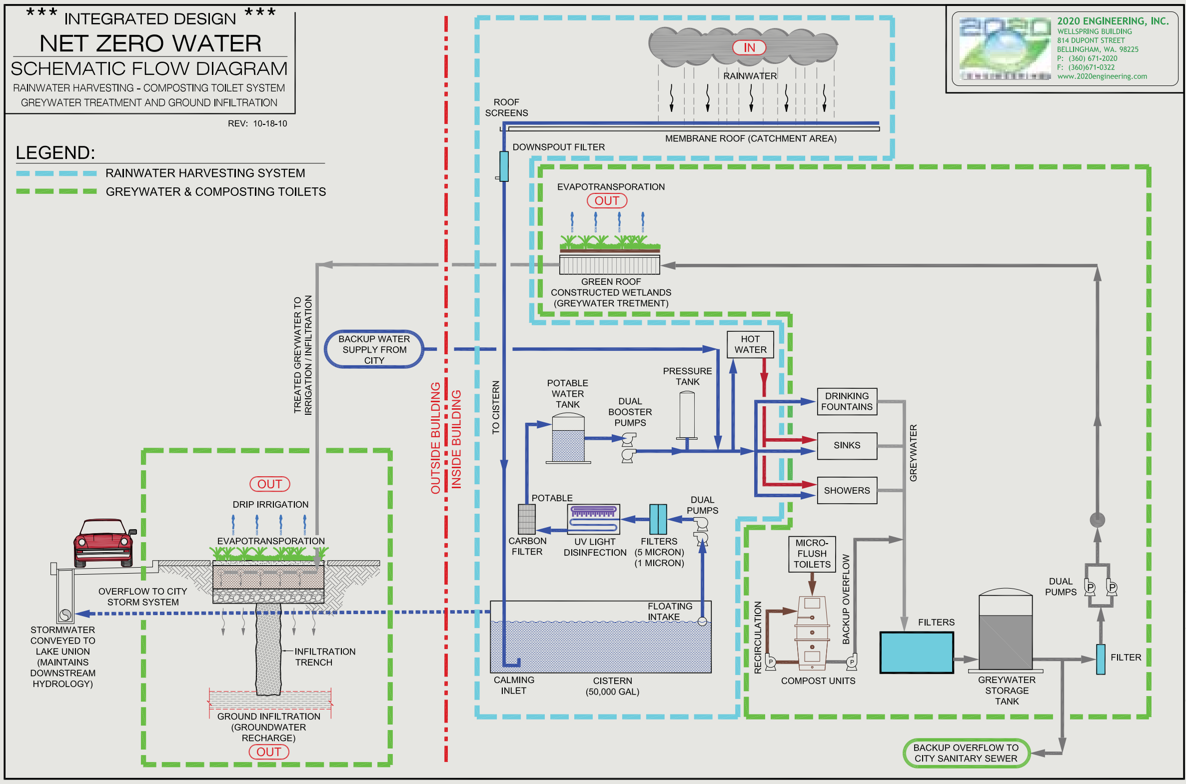
Courtesy of Clivus Multrum

BULLITT CENTER

Date Completed: Late 2012
Location: Seattle, WA
Owner: The Bullitt Foundation
Project Type: Commercial / Office
Project Size: 42,773-sf
Site Area: 10,000-sf
Capacity: 166 daily occupants
System Selected: Phoenix composting unit / constructed wetland

Courtesy of Miller Hull and Point 32

The Bullitt Center includes foam-flush and dry-flush (first floor only) composting toilets on each floor that reduce the building's overall water use and eliminate the discharge of blackwater. Greywater is collected in the basement and pumped up to a recirculating constructed wetland located on the third floor roof that uses natural, chemical, physical and biological treatment processes to treat the daily greywater flows.



Courtesy of 2020 Engineering

BERTSCHI SCHOOL LIVING BUILDING SCIENCE WING

Date Completed: February 2011
Location: Seattle, WA
Owner: Bertschi School
Project Type: Campus
Project Size: 1,425-sf
Site Area: 3,800-sf
Capacity: 17,500 uses/year
System Selected: Aqua2use, G-Sky Living Wall, Envirolet VF 750 FlushSmart

Courtesy of Benjamin Benschneider

The Bertschi School's Living Building Science Wing has a composting toilet and innovative greywater re-use system. Greywater from the sinks and lavatory is routed through a series of filters, and then evapotranspirated by vegetation on the living wall. The project gained approval for the greywater reuse system by installing a conventional overflow to the City's sewer system. The local health department permitted the system through an administrative ruling on the Uniform Plumbing Code. The composting toilet only uses .2L of water per flush, drastically reducing potable water demand. The system aerates and pulverizes waste for faster composting.

Courtesy of GGLO

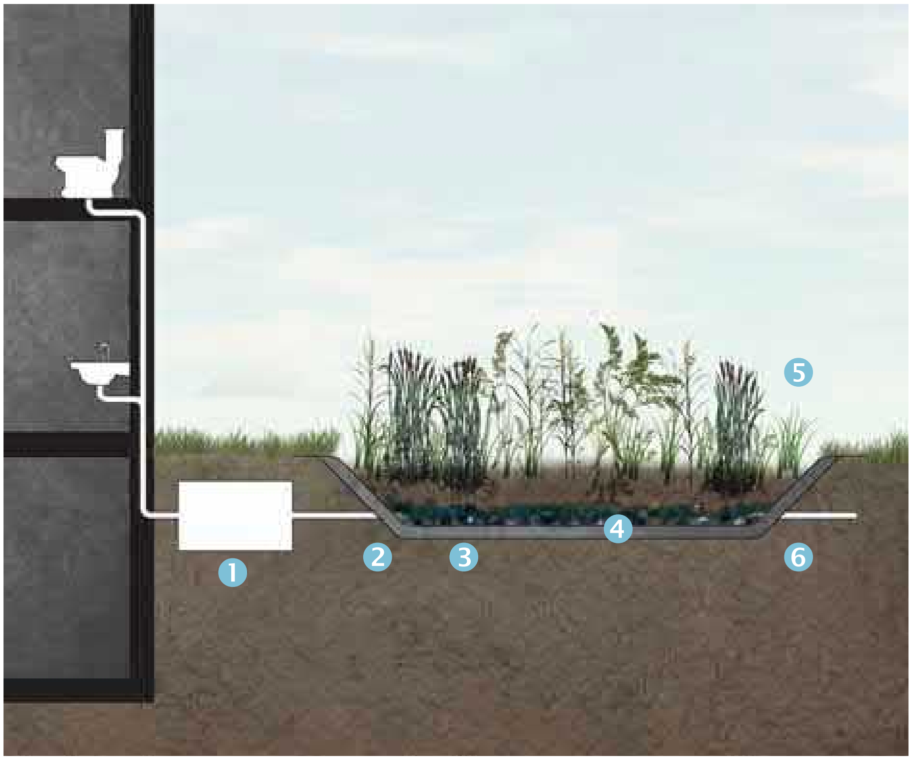
Classroom sinks drain to the greywater tank and pumped to the interior Living Wall. The Living Wall then evapotranspirates the greywater via a drip irrigation system.

CONSTRUCTED WETLANDS

Constructed wetlands treat wastewater by mimicking the biological, chemical and physical processes occurring in natural wetlands. These systems typically require little or no operating energy and can provide ancillary benefits as site amenities.

Constructed wetlands can stand alone as treatment systems or be utilized as a polishing step for improving effluent quality within a larger system. Surface flow wetlands are characterized by shallow, above-ground flooding which produces an anoxic environment to treat wastes. In these systems, the water surface is exposed to the atmosphere and carries the risk of odors, mosquitoes and potential human contact with wastewater. By contrast, subsurface flow constructed wetlands are designed as a bed or channel filled with media such as course sand or gravel. The water surface is maintained below the top of this medium, eliminating some of the risks associated with surface flow wetlands and increasing the treatment efficiency of the system. The following section highlights components and technologies associated with subsurface flow systems only.

FIGURE 1.2: CONSTRUCTED WETLANDS



System Components

① Primary Clarification Tank	③ Impermeable Liner	⑤ Wetland Vegetation
② Inlet	④ Planting Medium	⑥ Outlet

Systems can range in size from small on-site units to treat waste from individual homes or commercial buildings to large community-scale systems serving entire neighborhoods. In addition, there are more than 100 constructed wetlands in the U.S. treating municipal wastewater, the majority of which treat fewer than one million gallons per day.[20] Smaller scale systems typically treat anywhere from several hundred up to 40,000 gallons per day and are roughly 300-400 square feet in size for a single-family household.

System Components

Primary Clarification Tank

Constructed wetlands are generally preceded by a primary clarification tank for settling of solids. Depending on the geography of the site, primary clarified tank effluent is either pumped or gravity fed into the constructed wetland.

Planting Medium

Constructed wetlands consist of a shallow bed filled with porous packing material that supports wetland vegetation. Gravel and course sand is most often used as the planting medium, ranging in size from fine gravel (less than 0.25 inches) to crushed rock (typically less than one inch). The depth of the planting medium ranges from 1-3 feet deep.

Water level is controlled by the outlet structure and is typically maintained between 4 inches-24 inches below the top of the planting medium. The top of this porous material is typically at the same level as the surrounding terrain and is kept dry to control odor, insects and the potential for human contact with the water during the treatment process.

Wetland Vegetation

The bed is established with vegetation specifically selected to survive in fluctuating wet and dry conditions, and should ideally be native to the region and specific to the watershed, climate and altitude. While the planting medium provides the primary substrate for microbial growth, the vegetation provides additional surface area and supplies oxygen to the root zone.

In addition, the vegetation stabilizes the planting bed, provides a thermal barrier against freezing in cold climates, and improves the wetland aesthetics.[21]

Constructed wetlands are typically planted with a variety of species to provide a resilient and effective treatment process. Typical species include bulrush and reeds. Cattails, while often found in wetlands, are sometimes labeled as a noxious weed because they crowd out more desirable species. In addition, they do not have a favorable root structure for oxygen transfer or ideal root surface area for microbial growth.

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[20] US EPA. Wastewater Technology Fact Sheet. Wetlands: Subsurface Flow. 2000.

[21] California State Water Resources Control Board. Review of Technologies for the Onsite Treatment of Wastewater in California. 2002.

Inlet/Outlet Devices

Inlet and outlet devices and earth berms are used to control the depth of water in the wetland. These controls ensure uniform horizontal and vertical flow patterns through the planting medium and maintain the water level below the surface.

Impermeable Liner

An impermeable liner provides a separation between the wastewater treated in the bed of the wetlands and the surrounding area. The liner prevents leakage and contamination of groundwater. The impermeable layer may consist of an on-site or imported clay layer. In areas with permeable soils, a synthetic membrane or concrete liner is typically used.

Disinfection

Constructed wetlands are adept at nutrient removal and suspended solids reduction. However, like any treatment technology, the effluent from these systems should not be considered disinfected. Depending on the intended reuse application, additional disinfection by ozone, ultra-violet light or chlorine may follow constructed wetlands as a final stage in the treatment process.

Technology

Constructed wetlands are designed to filter and treat contaminated water in much the same way that natural wetlands do. As wastewater enters into the constructed wetland it is treated both aerobically and anaerobically. The submerged plant roots and the surfaces of the gravel particles or other planting medium provide a substrate for the microbial processes necessary for treatment. The level and rate of treatment is proportional to the size of microbe populations and the contact time within the system.

The combination of aerobic and anaerobic environments within a constructed wetland provides comprehensive treatment of wastewater, including removal of nitrogen and biological oxygen demand (BOD). These systems are typically designed to handle fluctuating flows and variable conditions without significant adverse effects on effluent water quality. Systems can be upgraded through the use of mechanical filters and ultraviolet disinfection to allow for water reuse applications.

Design variations for constructed wetlands include how the water flows through the system, either horizontally or vertically, and how the water is introduced such as in a tidal flow or recirculating manner. In a tidal flow wetland, the planting media in which the vegetation grows is completely flooded from below and then allowed to drain, maximizing the treatment capacity per unit volume. Whereas horizontal flow constructed wetlands are typically restricted to a depth approximating the root depth of the vegetation (typically about three feet), vertical flow tidal wetlands can be deeper, and therefore require less land area than conventional systems.

In a recirculating flow constructed wetland, a pump is used to periodically recirculate effluent back into the wetland inlet for additional treatment. As the treated effluent accumulates in the basin, another wetland recirculation cycle begins. Recirculating vertical flow constructed wetlands can remove up to 99% of the fecal bacteria (E. coli) and over 80% of other wastewater constituents prior to discharge.[22]

Courtesy of Whole Water

Constructed wetland in Sun Valley achieves high levels of water quality before infiltrating the processed wastewater at a location close to its source.

Advantages/Disadvantages

Constructed wetlands are appropriate for projects at various scales and within a variety of climates. According to the U.S. EPA, constructed wetlands are best suited for upland locations and outside of floodplains to avoid damage to natural wetlands.[23] However, designers of these systems believe they are logical solutions in wetland areas when effluent is treated to high levels and used to recharge these ecosystems.

While space constraints can limit the application of constructed wetlands, subsurface flow systems are specifically engineered to maximize the amount of treatment capacity in a minimum amount of space — an essential component for utilizing them in more urban applications. Wetlands also can be constructed in multiple cells to accommodate site constraints.

Design flexibility allows constructed wetlands to be modified to meet specific site conditions or target specific pollutant loads. Research has shown that wetlands are also known to sequester metals and are an effective means for removing pharmaceutical compounds, unlike electro-mechanical treatment plants which generally pass through these potentially damaging compounds. This makes constructed wetlands an interesting option for hospitals and other sites where these substances are most prevalent.

Depending on the size of the system, constructed wetlands can be located on a building site or in a centralized location serving multiple buildings. Where elevation allows, they can be located for gravity flow. Otherwise, pumps are required to convey effluent to wetland cells.

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[22] Garcia-Perez, Alfredo, Don Jones, William Grant, and Mark Harrison. “Recirculating Vertical Flow Constructed Wetlands for Treating Residential Wastewater.” Rural Wastewater. 8 Sep 2010.

[23] US EPA. Wastewater Technology Fact Sheet. Wetlands: Subsurface Flow. 2000.

Research shows that these systems operate well even in cold climate conditions, though they may require larger surface areas. While they are sometimes enclosed in a greenhouse, it is not a requirement with properly designed systems such as those utilizing plants that thrive in the local climate. In fact, there are built systems operating outside at altitudes of 10,000 feet in locations which receive no direct sunlight in winter and with temperatures routinely dropping to 40 degrees below zero for multiple days in a row.

Constructed wetlands have the advantage of being a potential amenity on a project site by integrating the treatment system into the surrounding landscape design. Constructed wetlands can also be used to treat on-site stormwater runoff, improving water quality and protecting downstream receiving water bodies.

Costs

Constructed wetlands are often less expensive to build than other wastewater treatment options because they are primarily passive systems. They also have lower operating and maintenance expenses.

Total costs for subsurface systems can range from $10,000-$15,000 for an individual home. This cost can be lowered when coupled with composting toilets as the volume of wastewater generated is reduced by roughly 50%, thereby shrinking the required area of the constructed wetland. Costs often differ based on soil conditions, system loading and regulatory requirements.[24] Larger community scale systems can realize lower costs based on economies of scale such as the residential cluster system installed at Lake Elmo, Minnesota which cost an average of $5,700 per home.

Because it has no or few moving parts, constructed wetlands can be more durable than other mechanized systems used to treat wastewater, allowing for longer lifecycles and larger lifecycle cost benefits.

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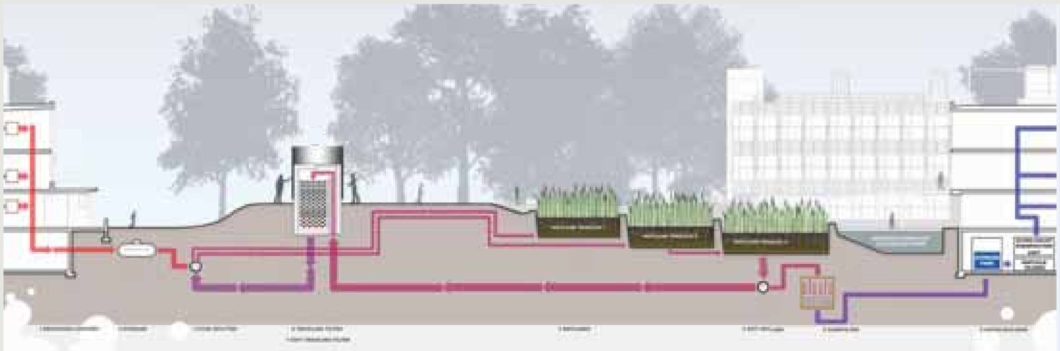
[24] California State Water Resources Control Board. Review of Technologies for the Onsite Treatment of Wastewater in California. 2002.

SIDWELL FRIENDS SCHOOL

Date Completed:	2006
Location:	Washington, D.C
Owner:	Sidwell Friends School
Project Type:	Campus
Project Size:	39,000-sf
Site Area:	72,500-sf
Capacity:	3,000 gpd
System Selected:	Recirculating sand filters, Trickling filters, Constructed wetland

Wastewater is routed through a subsurface constructed wetland integrated into the landscape. The system includes a primary treatment tank for anaerobic breakdown of solids, a trickling filter and a series of tiered, gravity-fed constructed wetland cells where micro-organisms and wetland plants help break down contaminants in the water. Disinfected water is then reused for irrigation and toilet flushing in the building. The school integrates monitoring of the system in their curriculum.



Courtesy of Andropogon Associates, Ltd. and Kieran Timberlake

ISLANDWOOD

Date Completed: 2002
Location: Bainbridge Island, WA
Owner: IslandWood
Project Type: Campus
Project Size: 70,000-sf
Site Area: 255 acres
Capacity: 3,000 gpd / 36,000 uses/yr
System Selected: Composting toilet / constructed wetlands / Living Machine®

Courtesy of Clivus Multrum

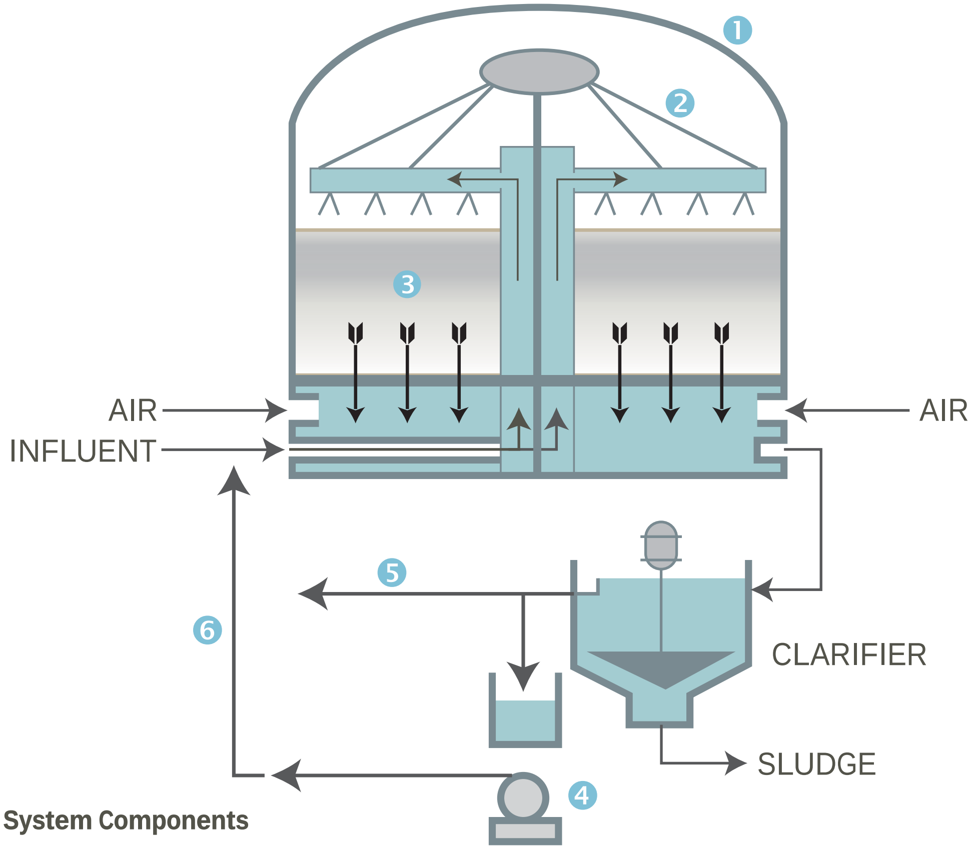
IslandWood treats all greywater and blackwater to tertiary standards on site via a Living Machine, composting toilets and constructed wetlands. Treated greywater is used on-site for toilet flushing and for subsurface irrigation. The facility has integrated its waste treatment systems into its educational programs.

Courtesy of Islandwood

RECIRCULATING BIOFILTERS

Biofilters are among the oldest technologies used for the biological treatment of wastewater. [25] These systems consist of chambers packed with highly porous materials such as plastics or rock. The media in the chamber provides growth surfaces for an active microbial community to treat the water. Biofilters are sometimes referred to as intermittent filters, packed bed filters, attached growth or fixed film processes.

FIGURE 1.3: RECIRCULATING BIOFILTERS



System Components

① Container
② Distribution System
③ Support Medium
④ Pump
⑤ Treated Water
⑥ Recirculation

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[25] California State Water Resources Control Board. Review of Technologies for the Onsite Treatment of Wastewater in California. 2002.

System Components

Container

A container is used to house the support medium necessary for the attached growth treatment process. These containers are typically made from concrete, plastics or fiberglass.

Support Medium

The medium housed in the container supports the microbial community within the treatment system and defines the biofilter type. A variety of organic, granular or synthetic materials can be used, such as sand, gravel, crushed glass, expanded aggregates, slag, peat moss, wood chips, rubber, fabric and open-celled foam. The type of materials utilized in biofilters are typically chosen for their surface area, porosity or infiltration capacity characteristics.

Distribution System

A distribution system is used to apply wastewater to the biofilter in such a way to support optimal performance of the system. Several distribution methods can be used, such as orifice systems, spray systems and gravity or pressure-driven dosing systems, and the method is dependent on the infiltration capacity of the support medium. For pressure-driven distribution, pumps or dosing siphons may be used. Control systems can be designed to dose the biofilter either on a timed or an on-demand basis as wastewater is generated.

Collection System

The collection system harvests the treated water and either recirculates it back into the biofilter for further treatment or carries it to separate mixing tanks or soil adsorption areas. The collection system can be a simple effluent drain located under the active biofilter medium. In some cases it is separated from the active medium by a coarse layer of gravel or rock to limit migration of the biofilter material.

Technology

Biofilters utilize an attached growth microbial aerobic process to treat wastewater. In these systems, post-primary settled water is sprayed over the top of the biofilter chamber and the wastewater percolates through the media. This simple process effectively oxidizes and reduces harmful chemical wastewater constituents. Oxidative reactions generally take place near the top of the open-air filter chamber. Oxygen concentrations are consumed by aerobic bacteria and gradually decrease with filter depth. Anaerobic conditions near the base of the chamber provide effective reductive conditions.

Biofilters can be single-pass systems or recirculating (multi-pass) systems. In a single-pass system, the wastewater is applied only once before being collected and conveyed to other treatment tanks or dispersal systems. Recirculating systems are designed to repeat application of the wastewater across the biofilter before it is discharged. In these systems, the return flow is combined with untreated wastewater from the septic tank or primary settling tank, diluting the influent introduced into the system. Recirculating systems can be smaller in size as compared to single-pass systems due to the increased hydraulic loading rate. They also require more energy for pumping and controls whereas single-pass systems can use little or no energy, such as gravity flow systems.

Advantages/Disadvantages

Recirculating biofilters are an extremely robust method of waste treatment. Long-term performance testing has shown they can handle overloading (up to double design capacity) conditions for several months before water quality begins to degrade. They require relatively little power, using a low horsepower pump to gently irrigate media for about 30 seconds every 20 minutes or so. These systems typically are controllable remotely by telephone or the internet, making off-site monitoring and adjustment possible. They are capable of attaining an advanced secondary and tertiary wastewater standard that is upgradable to a water reuse standard by the addition of a tertiary filter and ultraviolet light disinfection. In addition, effluent odors are eliminated, and dissolved oxygen concentration is enhanced in the recirculation process.

Courtesy of Orenco Systems, Inc.

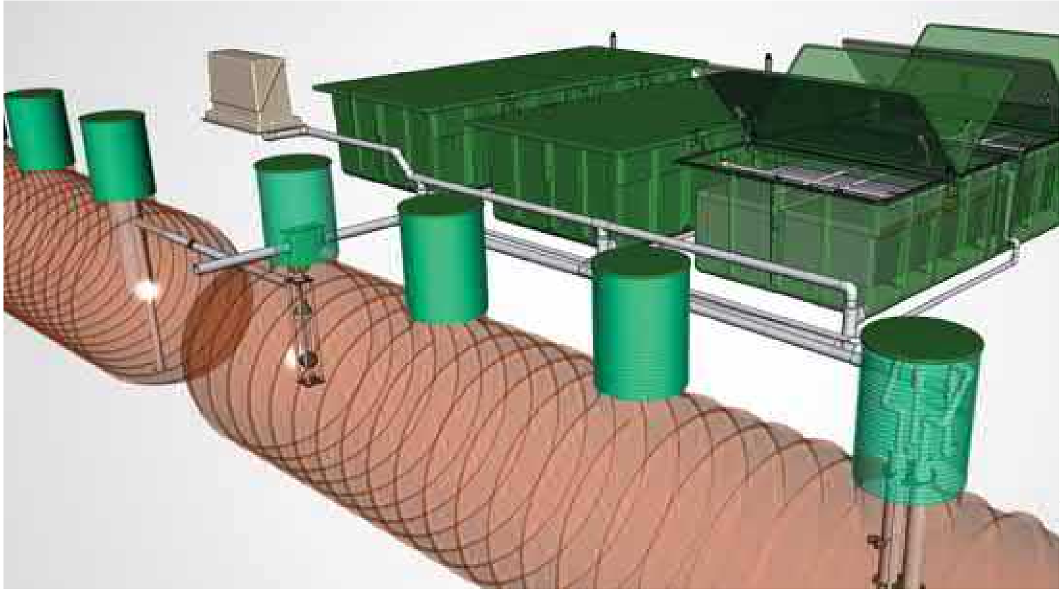
Advantex AX100 Filter Pod with hanging textile sheets.

Biofilter technology can be applied from individual residential projects up to the community scale. Proprietary models are engineered for commercial and industrial applications. Due to their reduced footprint size and ability to provide a reliable and high level of treatment, recirculating biofilters have often been used in areas not conducive to the traditional drainfield applications, such as places with poor permeability, high groundwater, shallow soils and limited drainfield area.

However, space constraints on site can be a limiting factor for biofilter technologies. Recirculating systems have a typical surface area footprint of 100 square feet for an individual home, while proprietary models such as the AdvanTex® system can be as small as 3 feet x 7.5 feet. Larger systems require approximately one square foot of land for every 25 gallons per day treated, making them more compact in size than passive subsurface flow constructed wetlands but less compact than packaged membrane bioreactors.

Costs

Recirculating biofilters can range in cost from $3,000-$10,000 for the biofilter alone, with septic settling tank and dispersal systems adding additional costs. Pumps and electrical components can be assumed to have at least a ten-year life span. Ongoing maintenance of the system is required to keep filters clean and functioning properly, though the level of effort required varies greatly across systems.



Courtesy of Orenco Systems, Inc.

The AdvanTex® filter pod with primary tank, recirculation tank, and vent fan assembly can treat 5000 gpd.

ROCKY BAY

Date Completed:	2007
Location:	San Juan Island
Owner:	Rocky Bay Residents
Project Type:	Clustered Residential
Project Size:	4.87 acres
Site Area:	4.87 acres
Capacity:	3,120 gpd
System Selected:	AdvanTex® Treatment System / Recirculating Biofilter

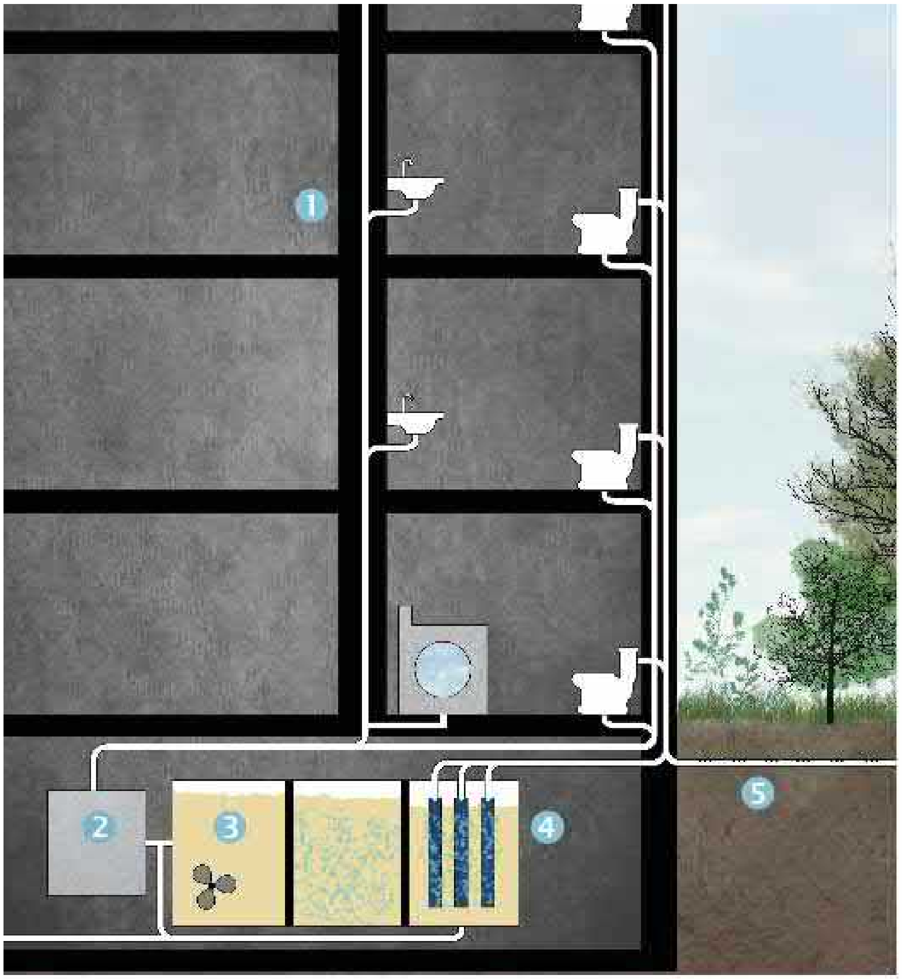
Rocky Bay is the result of hard work and commitment by each person living in the community. Eight homes clustered on site share the responsibility of ensuring that the AdvanTex 20® Pod Treatment system functions properly.

All photos courtesy of Homes for Islanders

MEMBRANE BIOREACTORS

The suspension of wastewater and the organisms used to treat the water in an aerated tank is referred to as an activated sludge process. Membrane bioreactors (MBRs) are packaged activated sludge systems in which the secondary clarifier has been replaced with an ultra-filtration membrane with pores small enough to filter out bacteria, micro-organisms and other insoluble solids. The result is a high-quality effluent without the need for further downstream tertiary treatment systems.

FIGURE 1.4: MEMBRANE BIOREACTORS



System Components

① Collection System
② Pretreatment
③ Aeration
④ Membrane
⑤ Distribution System

System Components

Pretreatment and Aeration Containers

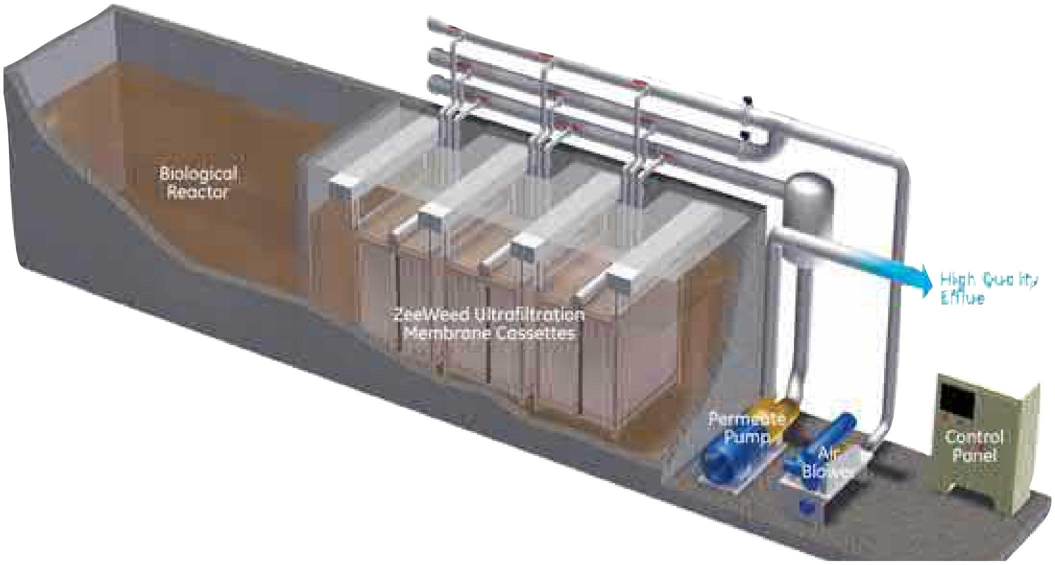
Processing tank containers typically include a primary separation chamber for pretreatment/settling and an aeration chamber. Aeration chambers are sized to provide sufficient volume for contact with the microbial biomass. Some small- to medium-sized systems do not require a separate pretreatment tank. Fine screens, typically 1-3 mm, are located in the containers after primary settling and before the membranes to prevent clogging.

Membrane

MBR membranes are porous and typically consist of cellulose or other polymer materials. Membranes are configured as hollow fibers grouped in bundles or as flat plates, and are designed to be easily removed for servicing and replacement. Pumps are used to force wastewater through the membrane.

Technology

MBRs are activated sludge systems with fine filters to prevent solids release, allowing these systems to maintain a higher concentration of bacteria as compared to conventional activated sludge systems. MBRs are capable of producing high-quality effluent similar to secondary clarification and microfiltration. The ability to eliminate secondary clarification has a number of benefits, such as shorter hydraulic retention times, less sludge production, simultaneous nitrification and denitrification, low effluent concentrations and comparatively smaller footprint than other conventional treatment technologies.



Courtesy of 2010 General Electric Company.

Cross-section of a General Electric's ZeeWeed membrane bioreactor.

The process consists of conventional extended aeration activated sludge process where the secondary clarifier has been replaced by an ultra-filtration membrane. The membrane pores are typically 0.1 to 0.5 microns in size to inhibit bacteria, micro-orgasms and other insoluble solids from passing through. This eliminates the need for downstream clarification and filtration. The pore size is not a complete barrier to viruses, however, so disinfection is still required.

Advantages/Disadvantages

Advantages of MBRs include high effluent quality, small space requirements and ease of automation. The primary disadvantages of MBR processes are the high cost of membranes, high energy demand, solids management and the potential for membrane fouling. Membrane manufacturers use several techniques to prevent fouling, including coarse air scrubbing and chemical treatment.

Because of their small footprint in comparison with other distributed technologies, MBRs have been used in urban areas as an alternative to discharge wastewater into the traditional sewage system. Their ability to produce high-quality effluent makes them suitable for applications where the treated water will be reused on-site. However, projects pursuing high performance energy use reductions may find that MBRs are not a feasible strategy due to their high energy demand.

Costs

Initial capital costs as well as ongoing operations and maintenance costs for MBR systems are typically much higher than for other wastewater treatment options. Installed costs can range from $7-$20 per gallon treated.[26] The expected life of a membrane is typically only seven to eight years, and may be considerably shorter depending on the propensity of the wastewater to produce fouling conditions.

MBRs require greater operator attention as compared with other decentralized treatment options, in addition to their considerably higher energy costs. Where these systems are used to treat water for reuse applications within buildings or at the community scale, their lifecycle costs may be offset by the reduction in potable water.

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[26] US EPA. Wastewater Management Fact Sheet. Membrane Bioreactors. 2007.

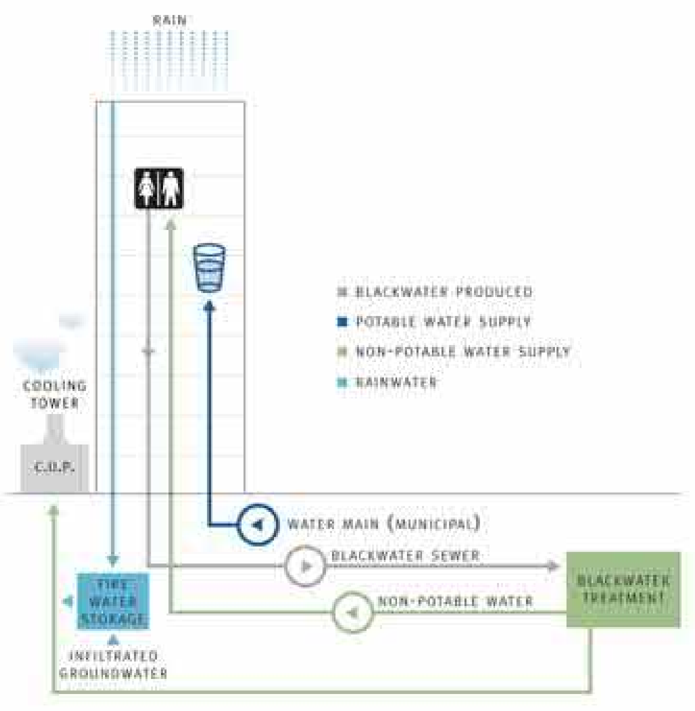
OREGON HEALTH AND SCIENCE UNIVERSITY CENTER FOR HEALTH AND HEALING

Date Completed: 2006
Location: Portland, OR
Owner: RIMCO LLC
Project Type: Commercial / Office
Project Size: 396,000-sf
Site Area: 20 blocks
Capacity: 35,000 gpd / 1600 average daily users
System Selected: Enviroquip, Inc Membrane Bioreactor

OHSU treats 100% of its building wastewater to nearly Class 4 standards. The reclaimed water is combined with rainwater for use in toilets, cooling towers and landscaping, reducing potable water use by almost 60% compared to a similarly sized conventional building. Approximately 15,000 gpd of excess reclaimed water is discharged to the Willamette River.


Courtesy of Walker Macy

The OHSU rooftop garden is irrigated by recycled greywater.



Courtesy of Interface Engineering

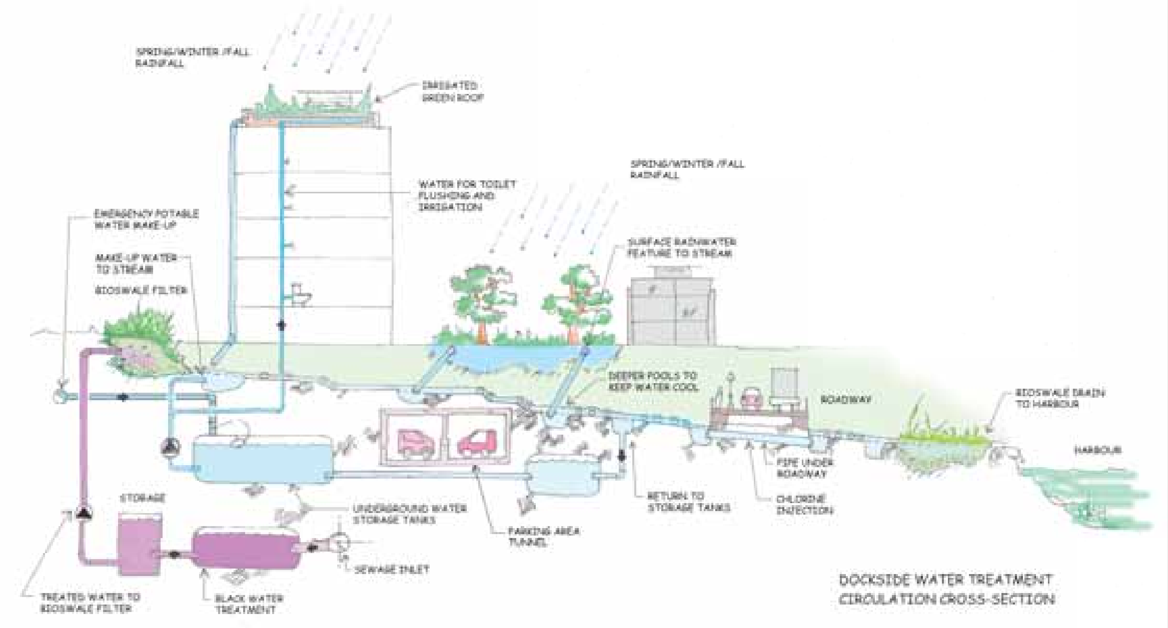

Courtesy of Kimberly Mathis

DOCKSIDE GREEN DEVELOPMENT

Date Completed: 2010 (first two phases)
Location: Victoria, B.C., Canada
Owner: Windmill West Development
Project Type: Mixed-Use
Project Size: 1.3 million-sf
Site Area: 16 acre
Capacity: 50,000 gpd
System Selected: GE ZeeWeed Z-Mod Membrane bioreactor


Courtesy of Dockside Green Development.

Water-saving fixtures and reuse of greywater reduce the development's municipal water needs by about 65%. An MBR system treats greywater , which is reused for landscape irrigation and toilet flushing. The development is able to sell an additional 18,000 gallons of treated water to nearby industrial users.



Courtesy of Jim Burns, Stantec.

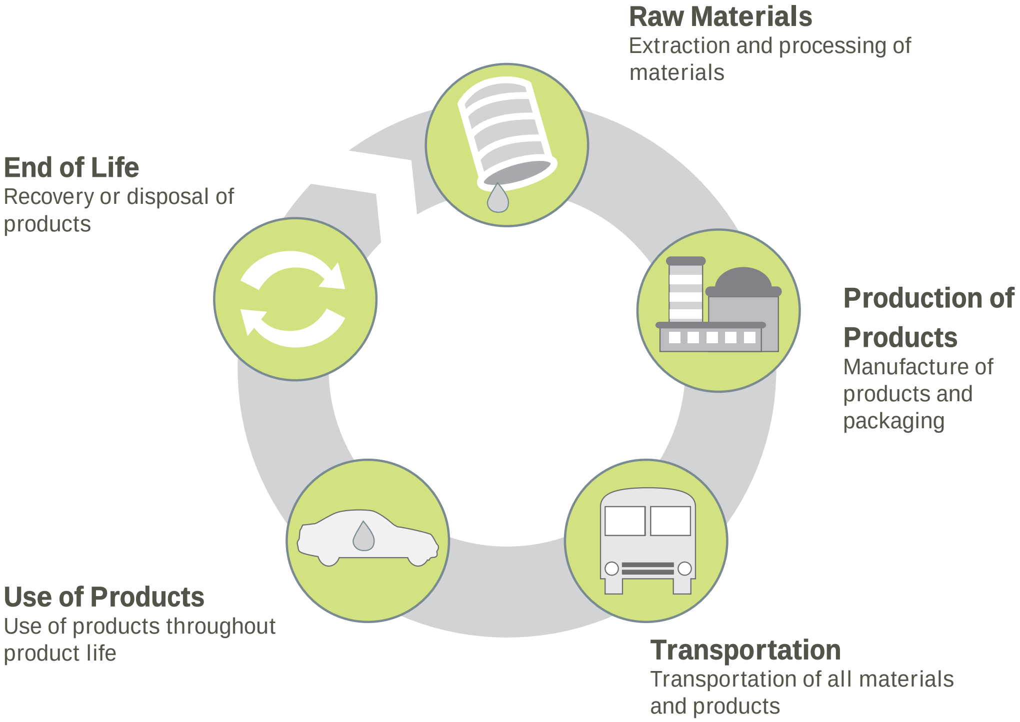
PART 2

Life-Cycle Analysis

2.1 INTRODUCTION

Life-cycle assessment (LCA) is a tool that evaluates the environmental impacts of a product across its entire life-cycle from materials acquisition to manufacturing, the use of the products, and its final disposal, as shown in Figure 2.1. LCA is performed by first identifying and quantifying the natural resources, energy and materials used, and the wastes and emissions released to the environment. Then their associated impacts to human health and the environment over a variety of impact categories are assessed.

FIGURE 2.1: LIFE-CYCLE STAGES



As defined by International Standards Organization (ISO) standard 14040, life-cycle assessment includes the following four components:

- Goal development and scoping
- Life-cycle inventory (LCI)
- Impact analysis
- Improvement analysis

The assessment begins with the establishment of goals and the definition of considered boundaries. Next, during the life-cycle inventory phase, a catalog of all input/output data for every unit process in the production chain is compiled; energy consumption, chemical use, water requirements, air emissions, solid waste and wastewater are characterized and quantified using algorithms specific to key reporting metrics. In the proceeding step, potential environmental impacts are calculated based on the LCI data during the impact assessment phase. Finally, during the valuation phase, a weighting system can be applied to the environmental and human health impacts to reflect the values of stakeholders.

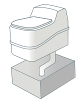
LCAs can be performed on a single product system to identify and prioritize efforts to improve a product, or can be used to perform comparative assessments of functionally similar products to determine the relative merits of each alternative. LCAs performed on a product life-cycle — from extraction through manufacturing — are termed “cradle-to-gate,” while “cradle-to grave” LCAs consider the impacts of the entire products system.

SCOPE

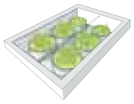
To determine the impacts and potential benefits of decentralized wastewater treatment systems, an LCA was conducted on a centralized treatment facility and a set of alternative distributed treatment options. Included in the analysis were the treatment technologies or set of technologies used to achieve an advanced secondary level of treatment, as well as the necessary conveyance systems for collecting wastewater from its point of generation to its point of treatment. Results of the LCA indicate whether the construction and use of alternative wastewater treatment systems will result in an improvement over traditional practices for conveyance and treatment systems, and whether those benefits are likely to be significant over the system’s life-cycle.

To facilitate the analysis, individual life-cycle scenarios were constructed based on the current treatment system for a mid-sized City in the Puget Sound region[27]. The actual existing conveyance and treatment systems for the City served as a baseline for the analysis. Scenarios for four different distributed treatment strategies were then constructed using the topography and geographical layout of the City as a template.

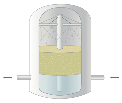
Decentralized technologies assessed in this report include:



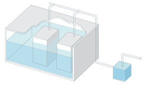
Composting toilets



Constructed wetlands



Recirculating biofilter



Membrane bioreactor

FUNCTIONAL UNIT

The functional unit describes the parameters that adequately define and quantify the critical function and performance of the product or system under evaluation. This unit serves as the basis by which all alternatives will be compared. The functional unit for each scenario in this study is defined as a system that provides the ability to treat the annual wastewater generated by a population of 83,000 customers over a 50-year time span. The functional unit establishes a fair basis of comparison between the centralized system and each of the distributed treatment systems. Since the treatment capacity of each of the distributed systems varies widely, each scenario required multiple treatment sites to service the required population. A conveyance system for each treatment technology suitable to collect the required amount of wastewater was included. Specific parameters for each of the scenarios are presented in the sections below. A 50-year time span was selected to match the estimated life span of a typical centralized treatment facility.

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[27] With respect to the City that provided valuable data to support this study, and in order to draw conclusions from the results of this study that apply broadly to a range of other communities throughout Puget Sound, the actual City selected for the baseline evaluation will remain anonymous.

A cradle-to-use analysis was conducted, comparing the environmental impacts of the various treatment systems in each of the following key impact categories:

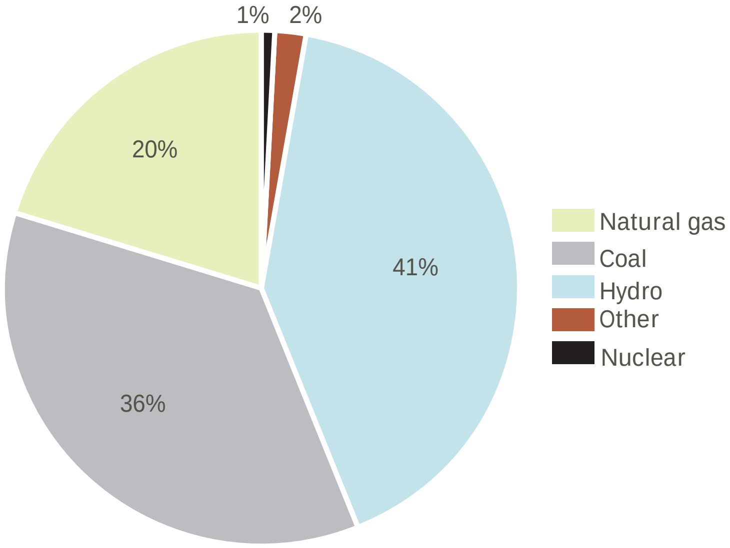
- Acidification
- Water eutrophication
- Respiratory effects
- Global warming
- Ozone depletion
- Photochemical smog
- Aquatic ecotoxicity

Descriptions of each of the impact categories, including the methods of calculation and the use of equivalencies where applicable, are presented in Appendix C.

DATA SOURCES

In support of the LCA, material breakdowns and key design factors were collected from manufacturers of primary components of both central and distributed treatment systems. Primary inventory data collected from previous evaluations were scaled and used to characterize key processes such as blow molding, metal fabrication and excavation. Secondary data were used to represent all upstream materials extraction and processing responsible for producing the raw materials used for the manufacture of individual treatment and conveyance components, as well as for the PSE energy production grid as shown in Figure 2.2. Sources of life-cycle data include both the GaBi Professional and EcoInvent life-cycle databases.

FIGURE 2.2: PSE POWER GRID, 2008



Methodology

GaBi version 4.3, a life-cycle design toolkit, was used to model the product life-cycles of both the conventional centralized treatment and conveyance systems, as well as each of the distributed treatment scenarios. The toolkit was used to construct models of each of the individual components of the treatment and conveyance systems, which were then combined into a master flow diagram for each system. The Life-Cycle Inventory Analysis for this study covered each of the life-cycle stages as shown in Figure 2.3.

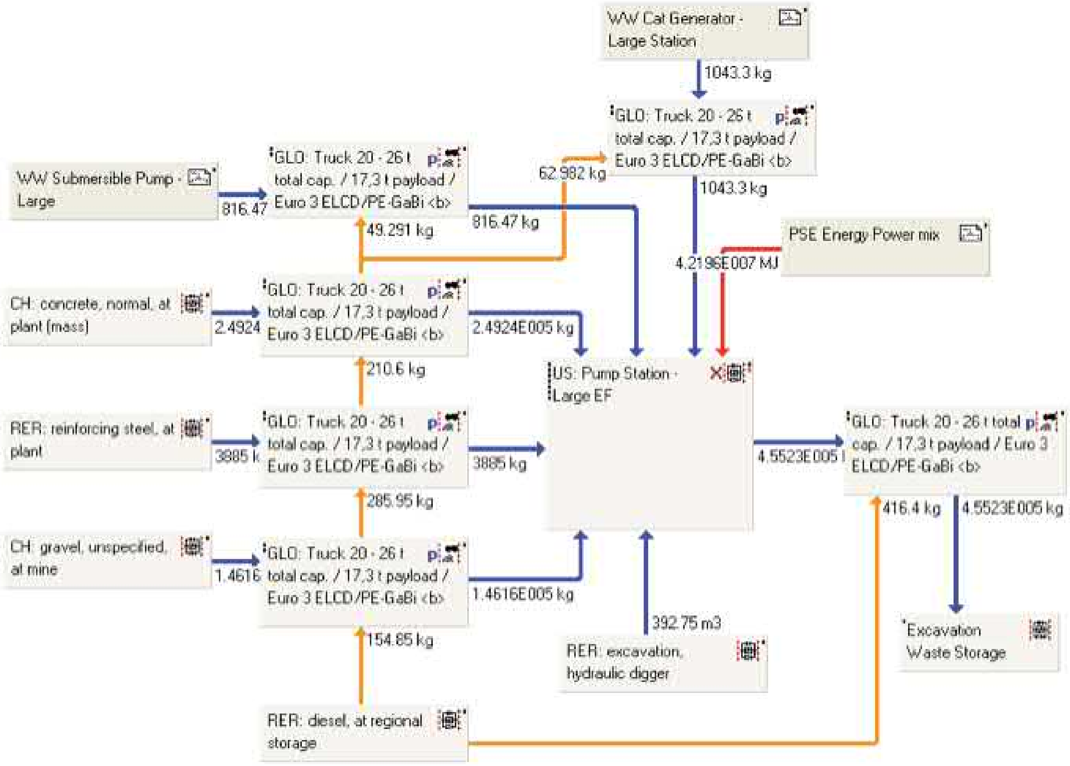
FIGURE 2.3: LIFE-CYCLE INVENTORY ANALYSIS

Materials	Production	Transport	Use	End-of-life
Includes raw materials extraction processes for all materials and chemicals in treatment systems	Limited production data for individual components were included for key system and conveyance components. No assembly processes were included.	Transport of all materials and construction wastes to and from the site of treatment. Average transport profile for US is assumed.	Included replacement of individual treatment components, as well as the energy and materials consumed over the 50-year timeframe.	Construction wastes to storage or landfill as appropriate. No other impacts from end-of-life are accounted for in analysis.

LIFE CYCLE INVENTORY ANALYSIS

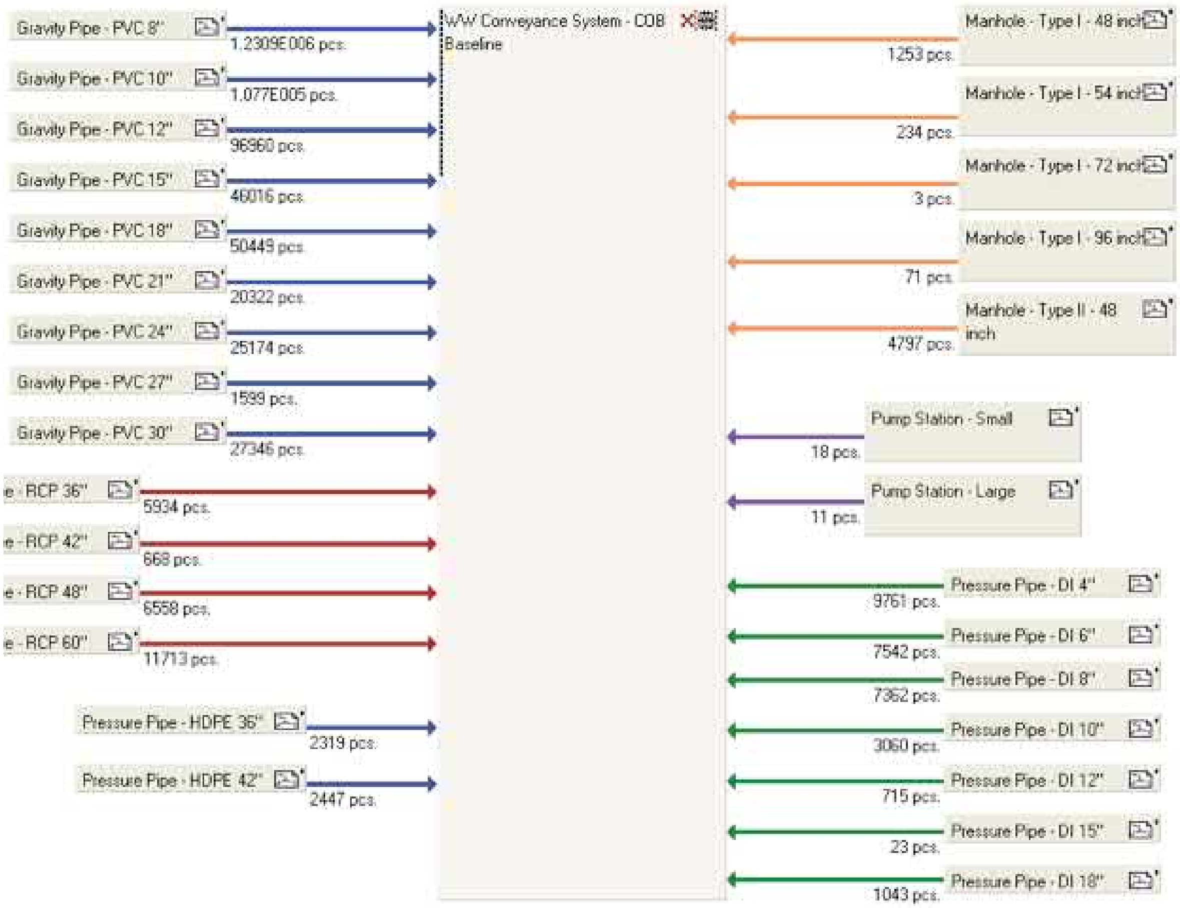
The example diagrams below demonstrate how the GaBi toolkit was used to construct and evaluate each of the scenarios in this study. Each treatment and conveyance system is comprised of components which were individually modeled. Figure 2.4 shows an example of the GaBi model diagram for one component, a large pump station. The model accounts for the production of each of the materials in the pump station (e.g. concrete, steel), as well as the support processes such as transportation and excavation activities required during construction of the station. In addition, the energy consumed during operation of the pump station over the 50-year lifespan of the evaluation was also included. In the model, processes are depicted by gray boxes in the diagram and are labeled for easy identification. Behind each process and flow indicated on the diagrams exists a set of data representing all of the materials, energy, solid waste and emissions generated or consumed by the process, typically normalized to one unit of production (e.g., per kg steel).

FIGURE 2.4: GABI MODEL OF LARGE PUMP STATION



A master diagram was then assembled for each treatment and conveyance system by connecting the individual components and scaling each appropriately. Figure 2.5 depicts the GaBi master flow diagram for the baseline conveyance scenario. The quantity of each flow was determined through an estimate of the Bill of Materials (BOM) and the accumulated material mass for each scenario.

FIGURE 2.5: GABI MASTER FLOW DIAGRAM FOR THE BASELINE CONVEYANCE SYSTEM



2.2 CONVEYANCE ANALYSIS

The conveyance analysis only evaluates the life cycling impacts of the system used to convey wastewater from its point of generation to its point of treatment (including pipe, manholes and pump stations). Life cycle impacts related to the wastewater treatment process is specifically excluded from this portion of the analysis. See Section 2.3 for treatment system LCA and results.

BASELINE SCENARIO

The City chosen for this study is located in the northeast portion of the Puget Sound. The population within City limits was approximately 67,000 in the 2000 census. The City's existing sanitary sewer service area covers over 30 square miles including both the City and the urban growth areas, servicing approximately 83,000 customers. Over 98% of the sanitary sewer conveyance system is operated via gravity flow, with the remainder conveyed via 29 pump stations located throughout the City to lift the sewage over hills and along the bay. Many of the pump stations have fewer than 1,000 linear feet of pressurized conveyance before returning to gravity flow.

Table 2.1 shows the size and length of the gravity and pressure conveyance lines within the City's system.

Both gravity and pressure lines are made of a variety of materials including asbestos cement (AC), cast iron (CI), cast in place pipe (CIPP), concrete (CON), ductile iron (DI), high-density polyethylene (HDPE), and polyvinyl chloride (PVC).

Normalizing to Current Conditions

While existing data on the City's conveyance system was utilized, parts of this system were installed over 60 years ago and do not represent current standards for construction. Some normalization of the system was done in order to assess how a similar system would be built today. The following assumptions were made:

- Portions of the existing gravity system include some older clay pipes (VIT), and some of unknown composition (UNK). If this system were to be built today, the materials of choice would most likely be PVC and reinforced concrete pipe (RCP) for gravity conveyance, and DI and HDPE for pressure mains. These four pipe types were used in the analysis.
- The 4" and 6" diameter pipes in the gravity system are assumed to be a minimum of 8".
- The lengths of 14", 16", 20", 23", and 28" pipes have been added to the next larger respective pipe diameter, to account for current typical pipe sizes.

TABLE 2.1: TOTAL LENGTH OF PIPE BY SIZE

DIAMETER (IN)	GRAVITY PIPE (FT)	PRESSURE PIPE (FT)
4	295	9,761
6	20,435	7,542
8	1,210,209	7,362
10	107,702	3,060
12	96,960	715
14	2,022	-
15	43,994	23
16	997	-
18	49,453	1,043
20	10,666	-
21	9,655	-
23	528	-
24	24,646	-
27	1,599	-
28	8,474	-
30	18,873	-
36	5,934	2,319
42	668	2,447
48	6,558	-
60	11,713	-
TOTAL (ft)	1,631,380	34,272
TOTAL (mi)	308.97	6.49

Courtesy of Hancor

Baseline Bill of Materials Summary

Table 2.2 summarizes the quantified materials used in the baseline conveyance scenario and includes excavation, bedding, backfill volumes and total pipe material weights for the entire pipe network. A full Bill of Materials for the Baseline Conveyance System, including manholes, pump stations and equipment hours is located in Appendix A.

TABLE 2.2: SUMMARY BILL OF MATERIALS FOR BASELINE CONVEYANCE

	EXCAVATION	PEA GRAVEL BEDDING	BACKFILL	RCP MATERIAL	PVC MATERIAL	DI MATERIAL	HDPE MATERIAL
Gravity Pipe	1,101,345	311,603	987,480	14,214	6,006	-	-
Pressure Pipe	24,426	8,769	18,474	-	-	276	278
TOTAL WEIGHT (tons)	1,125,771	320,373	1,005,954	14,214	6,006	276	278

The bill of materials summary includes a total of 6,357 manholes of various sizes located throughout the City. This count has been prorated for each pipe size based on length. Table 2.3 provides a breakdown on the excavation, backfill and concrete weights for all of the manholes.

TABLE 2.3: MANHOLE SUMMARY

	EXCAVATION	BACKFILL	CONCRETE
TOTAL WEIGHT (tons)	88,802	61,568	30,192

Pump Stations

The capacities of the 29 pump stations throughout the City range from 0.12-76 million gallons per day (MGD). For the purposes of this study, each of the 29 stations are classified as either a “small” or “large” pump station.

Eighteen of the 29 pump stations fall into the “small” category, handling less than 0.75 MGD and characterized as having:

- Two 96” diameter wet wells
- Two 25 hp pumps (assume typical submersible Myers pump)
- Control panels with communication capabilities
- No building

Eleven of the City's pump stations handle in excess of 0.75 MGD. These large pump stations are more complex and have more specialized designs unique to each. For the purposes of this study, they have been assumed to include:

- A large wet well
- A dry well
- Three pumps
- Controls
- A backup generator
- A building
- An access road with parking

Table 2.4 summarizes the excavation, backfill, concrete and steel material weights for both small and large pump stations, as well as annual energy demand.

TABLE 2.4: TYPICAL PUMP STATION MATERIAL AND ENERGY USE SUMMARY

	EXCAVATION	BACKFILL	CONCRETE	STEEL	ANNUAL ENERGY DEMAND (KW-HRS)
Small Pump Stations (tons)	506	456	168	-	8,965
Large Pump Stations (tons)	5,520	1,772	3,022	47	234,424
TOTAL WEIGHT (tons)	6,026	2,229	3,190	47	

Items not included in the pump station bill of materials include valves, process piping within the pump station, rails, fittings, controls, furniture, floats, wiring and other small items.

Equipment Hours

Equipment hours were calculated assuming a 50-hour time requirement to lay 1,000 feet of 8" diameter sanitary sewer main; these hours include manhole installations. All equipment is powered with 100 HP engines. Equipment hours for the various pipe diameters were prorated based on the excavation volumes in the tables above. Table 2.5 below includes total equipment hours for both gravity and pressure pipe.

TABLE 2.5: BASELINE CONVEYANCE EQUIPMENT HOURS

	GRAVITY PIPE	PRESSURE PIPE
Baseline Conveyance	153,571	2,242

ALTERNATIVE DENSITY SCENARIOS

In order to evaluate the results of the conveyance study to a broader range of scales of typical development or communities, two alternative density scenarios were assessed. Density scenarios were calculated by assuming the same population—67,000 residents—located within a smaller service area as shown in Figure 2.6.

Baseline City (Baseline): > 2 dwelling units/acre
Density Scenario 1 (DS1): 10 dwelling units/acre
Density Scenario 2 (DS2): 30 dwelling units/acre

FIGURE 2.6: DENSITY SCENARIOS

2 dwelling units/acre

29 pump stations
315.5 miles of pipe

10 dwelling units/acre

4 pump stations
90.4 miles of pipe

30 dwelling units/acre

0 pump stations
41.2 miles of pipe

Alternative Scenarios Bill of Materials

The bill of materials for DS1 and DS2 are calculated based on the topography and customer base of the baseline City. The annual average flow of 12.5 million gallons per day from 83,000 customers in the baseline City was prorated over each of the smaller areas for both alternative density scenarios. Based on these assumptions, a summary of the quantified materials including excavation, bedding, backfill volumes and total pipe material weights for each alternative conveyance system is shown in Tables 2.6 and 2.7 below.

TABLE 2.6: SUMMARY BILL OF MATERIALS FOR CONVEYANCE IN ALTERNATIVE DENSITY SCENARIOS

	EXCAVATION (TONS)	PEA GRAVEL BEDDING (TONS)	BACKFILL (TONS)	RCP MATERIAL (TONS)	PVC MATERIAL (TONS)	DI MATERIAL (TONS)	HDPE MATERIAL (TONS)
Density Scenario 1	450,156	135,183	385,693	9,925	2,386	31	277
Density Scenario 2	197,595	58,832	173,495	2,576	1,090	-	-

TABLE 2.7: MANHOLE SUMMARY FOR ALTERNATIVE DENSITY SCENARIOS

	EXCAVATION	BACKFILL	CONCRETE
TOTAL WEIGHT (tons)	25,546	17,635	8,610

Density Scenario 1 assumes one small pump station and three large pump stations to convey wastewater to its point of treatment. Materials and energy use from the baseline pump stations in Table 2.4 was used and scaled down to reflect fewer overall stations. Density Scenario 2 is entirely gravity-fed, and therefore includes no pump stations or pressure piping.

Equipment hours for DS1 and DS2 were calculated assuming the same 50-hour time requirement to lay 1,000 feet of 8” Ø sanitary sewer main as used in the baseline scenario. Table 2.8 provides a summary of equipment hours for both gravity and pressure pipe.

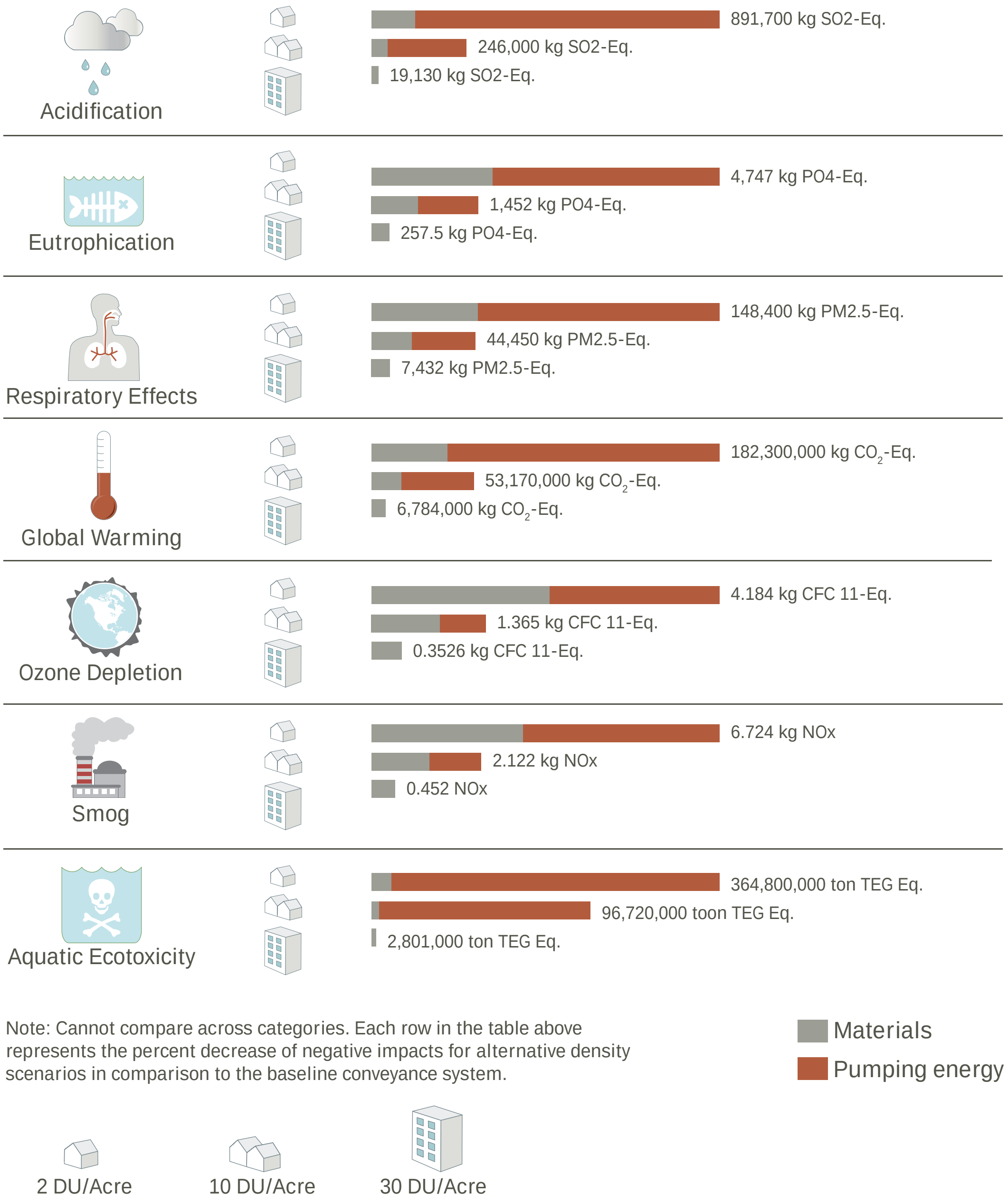
TABLE 2.8: ALTERNATIVE DENSITY SCENARIO EQUIPMENT HOURS

	GRAVITY PIPE	PRESSURE PIPE
DS1	30,732	290
DS2	10,889	-

RESULTS

Results of the life-cycle analysis of the conveyance portion of the baseline City's wastewater piping network compared to alternative Density Scenarios 1 and 2 are presented in Table 2.9.

TABLE 2.9: OVERALL LIFE-CYCLE IMPACTS OF CONVEYANCE SYSTEM

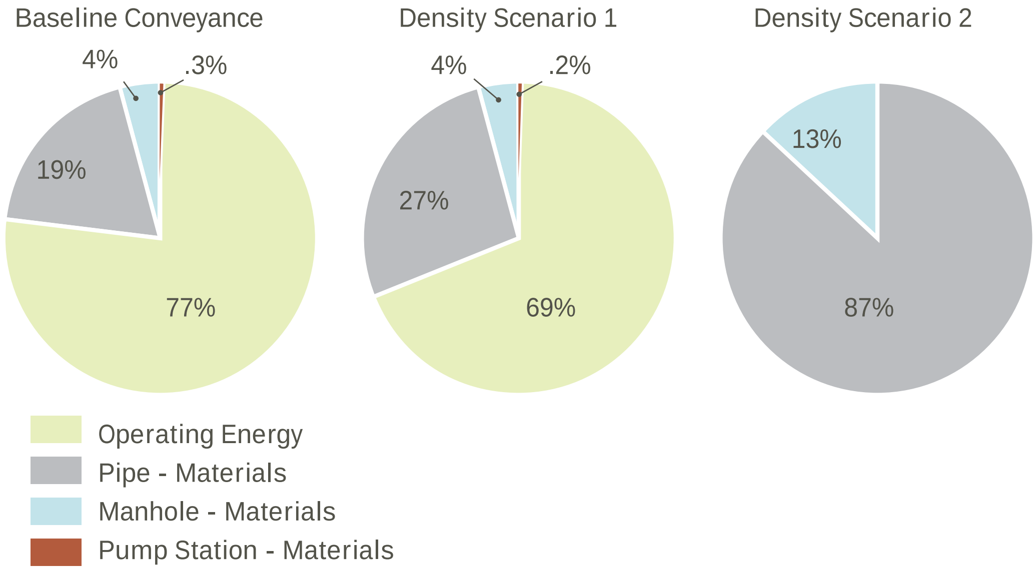


Note: Cannot compare across categories. Each row in the table above represents the percent decrease of negative impacts for alternative density scenarios in comparison to the baseline conveyance system.

Impacts of the baseline conveyance scenario are higher than both alternative density scenarios across all categories. Impacts associated with Density Scenario 1 are roughly one-third to one-quarter those of the baseline, ranging from a minimum of 67% reduction in the ozone depletion category and up to 72% reduction in aquatic acidification. Density Scenario 2 represents an even greater reduction in impacts compared to the baseline, with results showing between 91%-97% reductions across all categories.

As shown in Figure 2.7, operating energy contributes to the majority of the impacts in the baseline and DS1. Since DS2 is assumed to be an entirely gravity-fed system, 100% of the impacts are associated with materials including excavation, construction impacts and transportation of materials and waste to and from the site. These results show that shorter distances of larger diameter gravity-fed pipes have fewer overall environmental impacts than longer distances of smaller diameter pipe which require energy for conveyance. Conclusions can be drawn to indicate that smaller, more compact development patterns and shorter, gravity-fed conveyance systems for wastewater treatment have less of an environmental impact than the conveyance needed for more sprawling development patterns.

FIGURE 2.7: GLOBAL WARMING IMPACT DRIVERS FOR EACH CONVEYANCE SCENARIO



The impacts associated with materials in each chart above include those from the pipe material, manholes, and pump stations. Of the various pipe types, PVC contributes the largest share of the impacts by far, with RCP making smaller but non-negligible contributions.

Impacts associated with excavation include operation of equipment and transportation of removed waste offsite. Results indicate that the impacts due to excavation activities are relatively low compared to the contributions from other life-cycle stages, with the greatest influence in the respiratory effects category due to particulate matter. These impacts peaked at a little over 14% for the DS2 Scenario. Results in this density scenario were higher in large part due to the larger pipe sizes, the reduced amount of pipe (resulting in less impacts from other material and transportation) and the increased impacts from hauling the waste.

Impacts of Conveyance Per Mile

The impacts of conveyance per mile is determined by dividing the overall impacts by the total distance in miles of conveyance for each scenario as shown in Table 2.10.

When looking at the results of the impacts of conveyance on a per-mile basis, DS2 represents a substantial decrease in impacts across all categories. However, DS1 shows either only a small decrease as is the case with acidification, or a small increase as is the case in all other categories. This is explained by the efficiencies of scale for the baseline conveyance scenario. In this case, the overall impacts are averaged out over a longer distance of pipe. Likewise, while DS1 has fewer overall impacts compared to the baseline density, because it is averaged over a shorter distance of pipe the impacts per mile are roughly equal or slightly higher.

Conclusions can be drawn in cautioning decision-makers in looking at impacts on a per-mile basis rather than as absolute values when comparing across scenarios. The per-mile evaluation may be more informative in assessing efficiencies of scale when either the overall impacts or the distance in pipe is held constant.

Full results from the conveyance analysis are listed in Appendix B.

TABLE 2.10: NORMALIZED LIFE-CYCLE IMPACTS PER MILE OF CONVEYANCE

		BASELINE	DS1		DS2	
IMPACT CATEGORIES				% Difference		% Difference
Acidification	kg SO2-Eq.	2,826	2,745	-2.9%	463.9	-83.6%
Eutrophication	kg PO4-Eq.	15.05	16.07	6.8%	6.24	-58.5%
Respiratory Effects	kg PM2.5-Eq.	470.5	492.0	4.6%	180.2	-61.7%
Global Warming Air	kg CO_2-Eq.	578,000	588,500	1.8%	164,500	-71.5%
Ozone Depletion Air	kg CFC 11-Eq.	0.01327	.01511	13.8%	0.008549	-35.6%
Smog Air	kg NOx-Eq.	0.02132	0.02348	10.2%	0.01095	-48.6%
Aquatic Ecotoxicity	ton TEG Eq.	1,156,000	1,070,000	-7.4%	67,990	-94.1%

2.3 TREATMENT SYSTEM ANALYSIS

BASELINE SCENARIO: CENTRALIZED WASTEWATER TREATMENT

A conventional, centralized wastewater treatment plant was used as the baseline against which the environmental impacts of alternative decentralized treatment strategies were evaluated. The centralized treatment plant evaluated in this study is based on a mid-sized City in the Puget Sound region serving approximately 83,000 customers. The plant's average daily flow is approximately 12.5 million gallons per day (MGD). For the purposes of this study, only components associated with the treatment mechanisms of the plant were evaluated, including components used for odor control, primary screening, primary clarification, secondary treatment and sludge dewatering. Figure 2.8 shows all components inventoried for analysis. Disinfection and solids management, while key components of wastewater treatment processes, were not inventoried in either the baseline or the alternative scenarios. Management of solids was assumed to be similar in scope and scale for all treatment scenarios, allowing it to be excluded for the purposes of this LCA comparison.

Baseline System Summary

Wastewater entering the baseline centralized treatment facility first passes through two concrete carbon beds for odor removal. Wastewater effluent then undergoes primary treatment, beginning with bar screens to separate larger objects, followed by grit removal consisting of three mechanically reciprocating rake steel bar screens, each approximately six feet wide. Two eight-foot wide manually raked aluminum bar screens further screen the water.

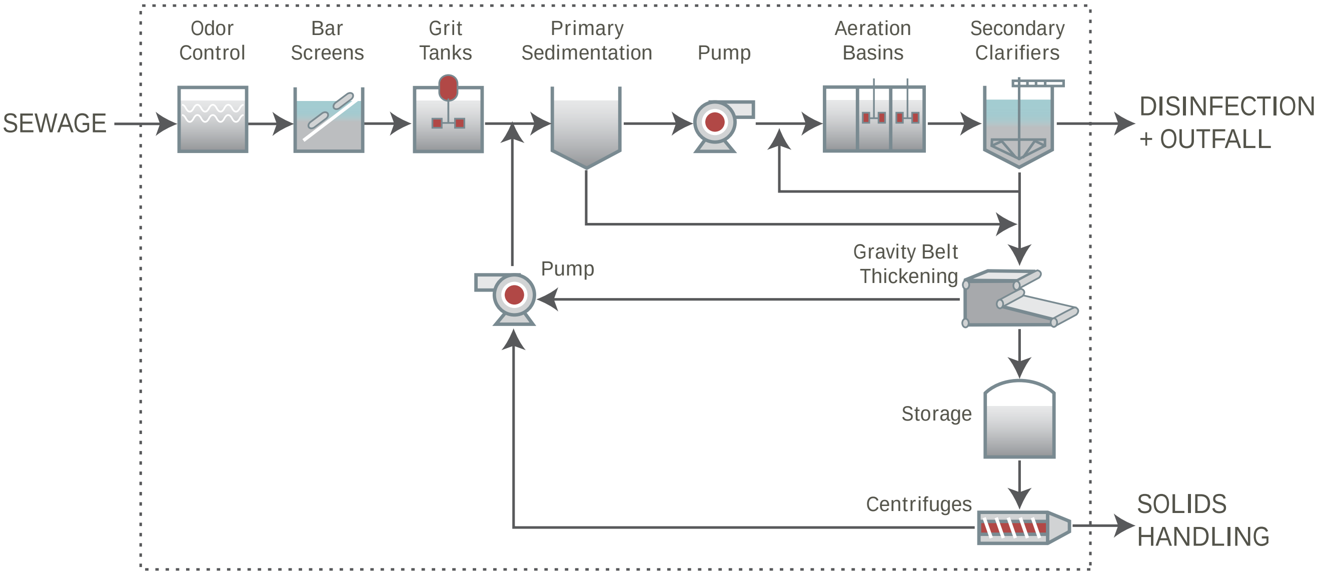
Septage pumps transport the screened water into two 30-foot diameter grit chambers. The resulting grit is classified and partially dewatered in two grit cyclones and two screw conveyors. A grit washdown sump pump and cast iron blowers are also used in the primary treatment system. All removed materials are de-watered in two screen presses; these dewatered materials are then stored and disposed off-site.

Primary clarification is accomplished in two 120-foot diameter clarifiers. Two sludge pumps and one scum pump remove the solid materials from the clarifiers, which are dewatered in two gravity belt thickeners. The clarified effluent is then transported to the secondary treatment system through four primary pumps.

The first part of the secondary treatment employs a high purity oxygen (HPO) activated sludge process, which occurs in two basins, each with three equally sized stages. In each stage of the HPO process the water is either mixed by impellors or oxygenated with aerators.

The basin effluent then enters three secondary 120-foot diameter clarifiers. A portion of the effluent and slurries are recirculated through the HPO basins by two pumps. Two scum pumps transfer slurries to two gravity belt thickeners for dewatering. The thickeners dewater slurries from both the primary and secondary clarifiers before the resulting sludge is stored in two concrete structures. The sludge is then dewatered by two centrifuges and removed by two sludge cake pumps. The plant also uses a polymer system to flocculate suspended solids remaining in the secondary clarifier. Two thickening blowers remove odors associated with the dewatering process.

FIGURE 2.8: BASELINE CENTRALIZED TREATMENT PLANT COMPONENTS



The dotted line shows the boundaries of analysis for the baseline, centralized treatment facility. Disinfection and solids handling components are excluded from the analysis.

Assumptions

An engineering analysis accounted for 100% of the materials in the baseline centralized treatment facility. Approximately 60% of all major components were inventoried based on a site visit to the facility and data provided by the city. The remaining 40% of materials —including concrete conduits, utilidors and on-site buildings — were calculated based on profiles consistent with the characterized materials (primarily concrete and steel). Table 2.11 provides a summary of inventoried materials, with a full bill of materials in Table A.18 located in Appendix A.

Additional assumptions:

- Concrete structures are not expected to require replacement in the assumed 50-year plant life span.
- Pumps have an assumed lifespan of 10 years.
- Other equipment such as screens, macerators and blowers have an assumed lifespan of 25 years; the equipment may outlast the expected 25-year lifespan but routine wear and tear will likely require that many of the major components be replaced.

The baseline centralized wastewater treatment plant's annual energy demand is approximately 8,218,821-kilowatt hours (kWhrs). This estimate was obtained from the municipality and includes only those demands associated with the treatment process. Energy demands associated with conveyance of wastewater to the treatment plant are accounted for in the Conveyance Analysis in the previous section of this report.

TABLE 2.11: SUMMARY OF MATERIALS FOR BASELINE CENTRALIZED TREATMENT

COMPONENT	ESTIMATED WEIGHT
Odor Control	
Activated Carbon	56,000 lbs.
Concrete Carbon Bed	129,000 lbs.
Primary Screening	
Steel Bar Screens	5,513 lbs.
Aluminum Bar Screens	13,000 lbs.
Cast Iron Blowers	850 lbs.
Chrome Iron Grit Pumps	1,700 lbs.
Steel	2,700 lbs.
Cast Iron	890 lbs.
Primary Clarification	
Concrete Clarifiers	8,951,826 lbs.
Cast Iron Primary Sludge Pumps	770 lbs.
Cast Iron Primary Scum Pumps	385 lbs.
Secondary Treatment	
Concrete HPO Basins	8,135,880 lbs.
Concrete Secondary Clarifiers	23,980,023 lbs.
Cast Iron Return Activated Sludge Pumps	30,400 lbs.
Steel	110 lbs.
Cast Iron	370 lbs.
Cast Iron Secondary Scum Pumps	770 lbs.
Aluminum	6,944 lbs.
Cast Iron	39,360 lbs.
Dewatering	
Steel Gravity Belt Thickener	15,400 lbs.
Aluminum	160 lbs.
Cast Iron	930 lbs.
Steel Sludge Dewatering Centrifuges	14,100 lbs.
Aluminum Centrifuge Feed Pumps	1,500 lbs.
Steel Scum Macerator	396 lbs.
Steel Scum Concentrator	15,000 lbs.
Polymer System	
Bulk Polymer	14 lbs./day/ton
Submersible Pump Stations	
Steel	1,050 lbs.
Chrome	8,400 lbs.
Cast Iron	1,050 lbs.
Cast Iron In-Plane Station Pumps	5,625 lbs.
Steel Dewatering Station Pump	9,705 lbs.

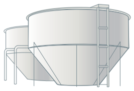
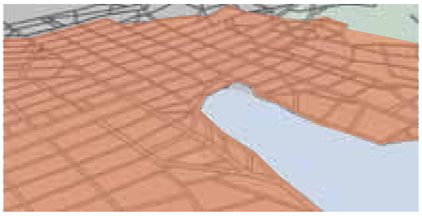
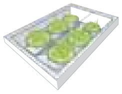
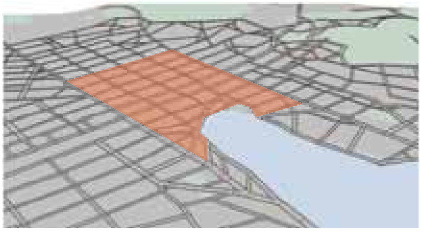
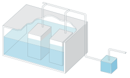
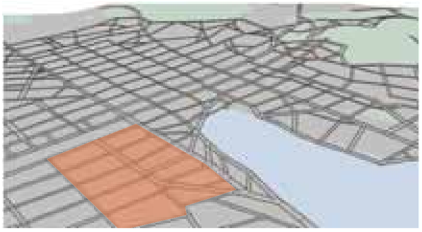
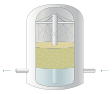
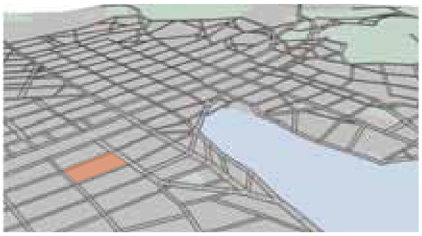
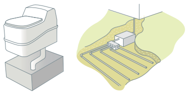
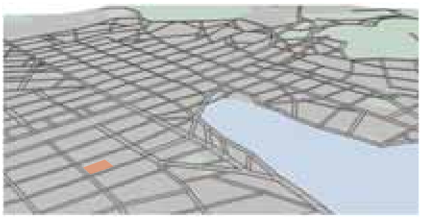
ALTERNATIVE DECENTRALIZED TREATMENT SCENARIOS

Four alternative wastewater treatment strategies were selected in order to compare their overall life cycle environmental impacts to each other as well as against the impacts associated with the baseline centralized treatment system. Each scenario serves 83,000 customers at scales appropriate to the technology employed in each treatment system (see Figure 2.9).

- City scale
  In the baseline scenario, one central treatment facility serves all 83,000 customers.
- District scale
  25 constructed treatment wetlands serve approximately 3,320 customers each.
- Neighborhood scale
  2,500 membrane bioreactor units serve approximately 33 customers each.
- City block scale
  5,000 recirculating biofilter units serve approximately 17 customers each.
- Building scale
  On-site composting toilet and greywater wetland systems serve 1 customer each.

A summary of inventoried materials for conveyance of wastewater in each scenario is located in Tables A.19-A.21 in Appendix A.

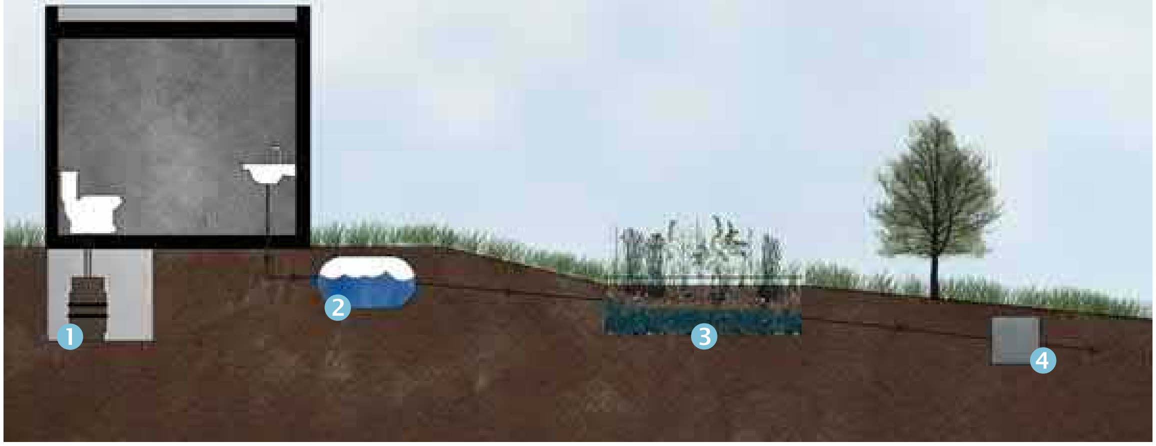
FIGURE 2.9: APPLIED SCALE FOR WASTEWATER TREATMENT

	APPLIED SCALE FOR TREATMENT SYSTEM	# OF TREATMENT SYSTEMS	# OF CUSTOMERS SERVED PER TREATMENT SYSTEM
 Centralized Wastewater Treatment	 City	1	83,000
 Constructed Wetland	 District	25	3,320
 Membrane Bioreactor	 Neighborhood	2,500	33
 Recirculating Biofilter	 Block	5,000	17
 Composting Toilet & Greywater Treatment	 Building	83,000	1

COMPOSTING TOILETS + GREYWATER CONSTRUCTED TREATMENT WETLAND

In this scenario, each customer is served by a composting toilet system coupled with an on-site, gravity-fed constructed treatment wetland and sand filter. The composting system treats liquid and solid wastes from the toilet while the constructed treatment wetland is designed to treat all other wastewater flows including greywater from sinks, showers, laundry machines and dishwashers. The wetland is then followed by a sand filter that polishes the treated water prior to discharge. Figure 2.10 outlines the boundaries of the composting toilet and constructed wetland scenario.

FIGURE 2.10: COMPOSTING TOILET + CONSTRUCTED TREATMENT WETLAND



System Components

① Composting Toilet Units
② Primary Tank
③ Treatment Wetland
④ Sand Filter

System Summary and Assumptions

Each customer within the existing wastewater treatment service area is assumed to have one composting unit designed to accommodate 4-8 full time users. Model 201 from the manufacturer Advanced Composting Systems was selected as the typical unit for the purposes of this study. Although the average household does not exceed four people, many commercial customers would potentially require multiple units. In addition, larger units prevent against treatment failure in the event that the units are not adequately maintained. Model 201 was chosen to best address potential variables in customer use. The analysis includes the composting units and all components associated with the composting process but specifically excludes the toilet fixtures themselves, since these are excluded from the baseline and all other alternative scenarios. Material weights and energy demands were supplied by the composting toilet manufacturer.

The composting units are assumed to be placed below grade and housed within a concrete ‘basement’ structure. Wood shavings are required after every 100 uses. Assuming a household of six and three uses per individual per day, each unit is expected to require 8 lbs. of bulking material added manually to the units on a monthly basis. A small fan is required to ventilate each unit.

Sizing of each constructed wetland to treat all other wastewater was determined by the average capacity of the centralized treatment plant. Based on this average of 12.5 MGD from 83,000 customer connections, the daily average wetland flow is assumed to be approximately 150 GPD/customer (or 12.5 MGD divided by 83,000 customer connections).

An HDPE primary tank was assumed to equalize and store greywater flows prior to entering the HDPE-lined constructed treatment wetland cell. Primary tank effluent is assumed to flow to the constructed treatment wetland via gravity.

The k-C* model (Kadlec and Knight 1996) was used to size the wetland based on the following formula.

$$\text{Area} = \frac{Q \quad \ln\left(\frac{C_i}{C_o}\right)}{K_v h \varepsilon}$$

Where Q= flow, ft^3/day
C_i=influent concentration, mg/l
C_o=effluent concentration, mg/l
k_v= volumetric rate constant, day-1
h= wetland media height, ft
ε= wetland media porosity

Biological oxygen demand (BOD) was used as the sizing nutrient and an influent BOD concentration of 450 mg/l was assumed. This is a conservative assumption, since the wetland is only used for greywater treatment. The wetland media (washed rock) depth and porosity was calculated at 3 ft. and 0.39, respectively. Based on these assumptions, each wetland area is assumed to be 235-ft^2.

Two-inch HDPE laterals evenly distribute the primary effluent over the wetland area. The laterals are covered with approximately 6” of topsoil which aid plant growth and act as a barrier between people and the treatment system.

Lastly, wetland effluent water gravity flows to a slow sand filter for polishing. The HDPE line sand filter was sized assuming a 1.7 gal/ft^2 loading rate with a 3 ft. media depth. These assumptions yielded a 90-ft^2 treatment area for each sand filter. A manifold and 2” HDPE laterals, spaced one foot apart, evenly distribute the wetland effluent over the sand filter.

Table 2.12 summaries the cumulative material weights inventoried for the composting toilet system, constructed wetland and sand filter serving the 83,000 customers. Cumulative annual energy requirements of this scenario are estimated at 3,635,400 kWhr/year.

TABLE 2.12: SUMMARY BILL OF MATERIALS FOR COMPOSTING TOILET SCENARIO

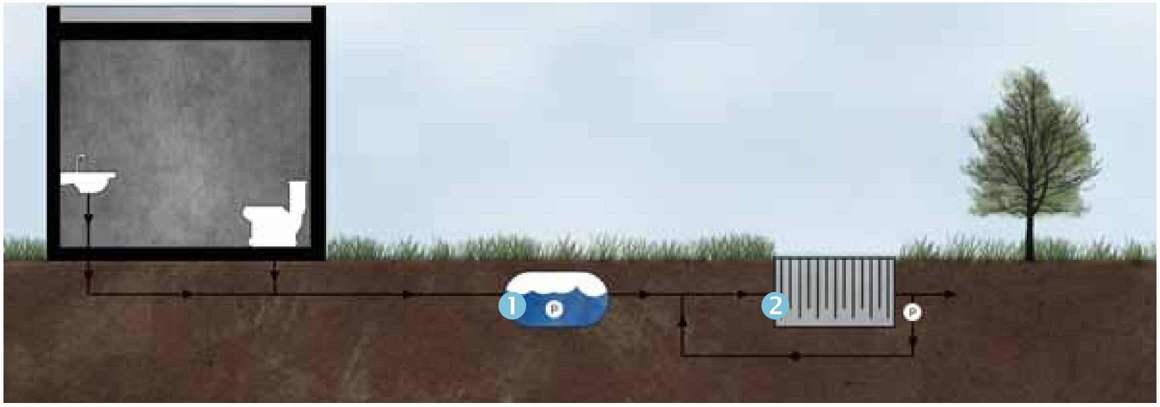
TREATMENT COMPONENT	CUMULATIVE WEIGHT (LBS)
Primary Treatment (primary tank, composting unit, fan)	
Excavation	5,873,089,919
Polyethylene	51,294,000
Polypropylene	581,000
Fiberglass	3,901,000
Nylon	581,000
Aluminum	290,500
Stainless Steel	249,000
Iron	373,500
Acrylonitrile-Butadiene-Styrene	166,000
Poly Vinyl Chloride	249,000
Steel	1,162,000
Wood Shavings (bulking agent)	399,396,000
Secondary Treatment (gravity-fed constructed wetland)	
HDPE	107,553
DR 17 HDPE	17,272,300
Excavation	8,967,735,000
Backfill	4,753,399,000
Rock Infill	4,388,625,000
Topsoil	975,250,000
Post Secondary Treatment (sand filter)	
Excavation	2,016,900,000
HDPE	5,395,000
Sand	2,353,050,000
DR 17 HDPE	5,354,129

RECIRCULATING BIOFILTER

For this scenario, the AdvanTex® Treatment System manufactured by Orenco Systems, Inc.,[28] was selected for analysis. These engineered systems are similar to recirculating sand filters; however, instead of sand, the treatment pods are packed with a textile media. The textile enhances attached growth surfaces, and biological organisms using nutrient-rich wastewater proliferate on the additional surface area, yielding comparatively higher treatment for a defined surface area.

Nozzles uniformly distribute the wastewater at the top of the filter. The wastewater then percolates through the textile media where microorganisms view the nutrients in the water as food. Pumps recirculate the water through the treatment pods several times prior to discharge in order to reach secondary levels of treatment.

FIGURE 2.11: RECIRCULATING BIOFILTER



System Components

- ① Primary Tank
- ② AdvanTex® Pod

System Summary and Assumptions

In this scenario, AdvanTex® pods are applied at the city block scale and are assumed to be located on each block such that wastewater is conveyed to it by gravity. Each pod treats 2,500 GPD of domestic wastewater. Therefore, approximately 5,000 AdvanTex® treatment pods are required to treat the 12.5 MGD cumulative wastewater flow from the entire service area.

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[28] Orenco Systems, Inc. www.orenco.com

A dual-compartment fiberglass primary treatment tank precedes each AdvanTex® pod. Water is pumped from the primary tanks to the biofilter where it percolates through engineered polyester fabric media. A second pump is used to recirculate water through the treatment pod approximately three times prior to discharge.

The manufacturer aided in system sizing and estimating weights for the AdvanTex® treatment pods — see Table 2.13 for a summary of materials inventoried. In addition, manufacturer's data was used for calculating this scenario's cumulative annual energy demands of 21,050,000 kWhr/year.

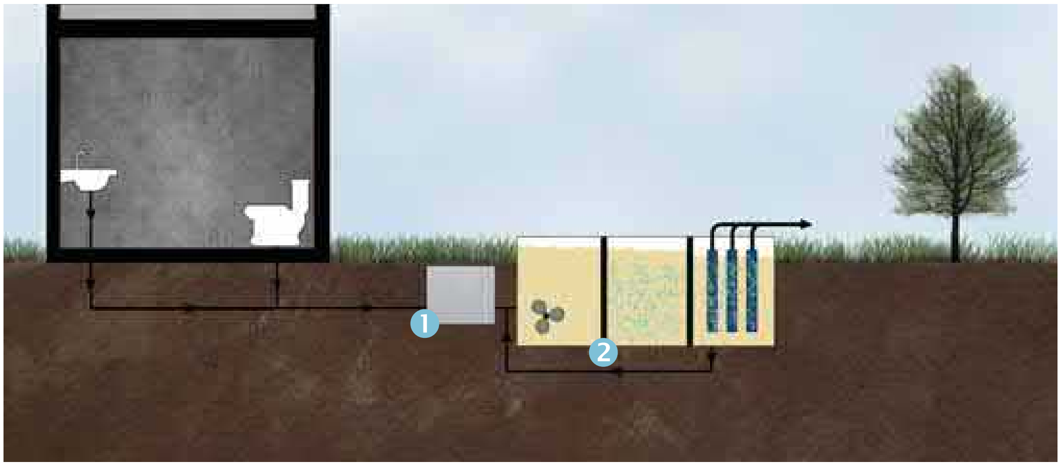
TABLE 2.13. SUMMARY BILL OF MATERIALS FOR RECIRCULATING BIOFILTER SCENARIO

TREATMENT COMPONENT	CUMULATIVE WEIGHT (LBS)
Primary Treatment (primary tank, filter, pump, vault)	
Excavation	1,534,500,000
Fiberglass	9,000,000
Polyethene/Polypropylene	425,000
HDPE	75,000
Steel	2,300,000
Secondary Treatment (AdvanTex Treatment Pod, pump)	
Excavation	238,500,000
Fiberglass	1,250,000
Polyester	8,250,000
HDPE	707,500
Polyethene/Polypropylene	300,000
Stainless Steel	2,300,000

MEMBRANE BIOREACTOR

Membrane bioreactors combine ultra-filtration and biological processes to treat wastewater. After screening, wastewater is mixed in an anoxic chamber where free-floating bacteria consume nutrients and alter the water chemistry. The water then flows through an aeration chamber before entering a third chamber containing the membrane bioreactor. Water is pumped through the fibrous membrane plate where free floating and attached growth microbes use the nutrient-rich wastewater as a food source. The highly-treated water is then discharged. Figure 2.12 shows the boundaries of the membrane bioreactor scenario included in this analysis.

FIGURE 2.12: MEMBRANE BIOREACTOR



System Components

- ① Effluent Screen
- ② MBR

System Summary and Assumptions

In this scenario, membrane bioreactors are placed at the neighborhood scale, allowing wastewater to be gravity-fed to its point of treatment. Based on manufacturer's suggested sizing, each standard package unit handles 5,000 GPD of wastewater flow. A total of 2,500 treatment units are needed to accommodate the 12.5 MGD cumulative wastewater flow from the city's service area.

Material and energy estimates were obtained from several manufacturers offering systems that use plate technology. Fine steel screens are used for pretreatment prior to entering the membrane bioreactor, eliminating the need for primary settling tanks and pumps. Each unit sits on a concrete pad and is housed within a steel container. MBR module membranes are made from polyvinylidene fluoride which accounts for less than 1% of total material composition; however, this was not included in the LCA modeling because a suitable material inventory was not available. Sodium hypocholorite is added to the units on a biannual basis for cleaning and was included in the analysis. Table 2.14 summarizes all inventoried materials.

Energy estimates vary significantly from manufacturer to manufacturer of these systems. The cumulative energy demand range for the MBR scenario is estimated at between 62,500,000 kWhrs/yr to 175,260,000 kWhrs/yr. The specific system analyzed for this study is assumed to have a cumulative annual energy requirement of 142,894,763 kWhr/year. This estimate assumes that the units are located slightly below grade to ensure that the influent wastewater will not need to be pumped into the MBR chamber.

TABLE 2.14: SUMMARY BILL OF MATERIALS FOR MEMBRANE BIOREACTOR SCENARIO

TREATMENT COMPONENT	CUMULATIVE WEIGHT (LBS)
Pre-Treatment (screen)	
Steel	750,000
Secondary Treatment (membrane bioreactor)	
Dirt	270,000,000
Concrete	56,875,000
Steel	28,025,000
PVC	177,500
Rubber	750,000
Cast Iron	1,962,500
Polyester	125,000
Sodium Hypochlorite	14,000,000

RECIRCULATING CONSTRUCTED WETLANDS

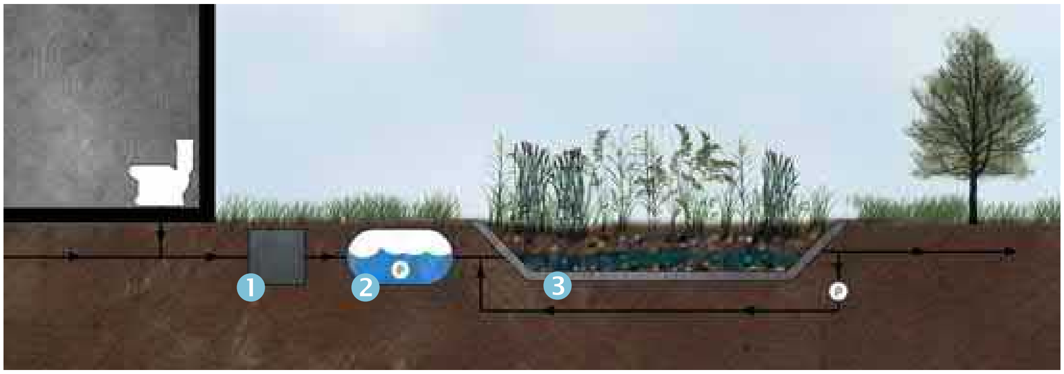
In this scenario, the Living Machine® system was selected as the basis of design for the constructed wetland. Living Machines are proprietary systems that utilize natural, chemical, biological and physical processes to treat wastewater. Figure 2.13 shows system components included in this scenario.

System Summary and Assumptions

Filtered wastewater is evenly distributed throughout the Living Machine approximately six inches below the system's surface. It then percolates through approximately six feet of highly-porous treatment media. Microbes attach to surfaces where they multiply, using the nutrients in wastewater as food. This media significantly increase attached growth surface area over traditional sand or gravel, resulting in higher bacteria growth rates. Since bacteria are largely responsible for wastewater treatment in Living Machines, the system's proliferating microbial community is able to treat wastewater to a higher level than traditional sand filters.

This scenario assumes that 25 Living Machines are strategically placed where the existing pump stations are currently located throughout the city, allowing the conveyance to each to be gravity-fed. The daily flow to each Living Machine is approximately 0.5 MGD (or 12.5 MGD divided by 25 Living Machines). Material quantities and weights were provided by system designers.

FIGURE 2.13: CONSTRUCTED TREATMENT WETLAND



System Components

- ① Screw Screen
- ② Primary Tank
- ③ Subsurface Flow Constructed Wetlands

The designed system includes two parallel primary screens, each with the capability of screening 100% of the daily flow. The second screen is intended solely as a backup in the event that the first is taken offline and to ensure that no wastewater backups occur. Wastewater from the conveyance system is gravity-fed through 2-foot wide by 6-inch thick concrete channels to the primary screens. Two 23-foot diameter concrete primary tanks were sized to equalize flow from one day. The base of the primary tanks is assumed to be approximately 18-feet below grade so that the primary screen can pump directly to the tanks.

After the flow is equalized, the wastewater enters the Living Machine where it recirculates eight times in both the stage 1 and stage 2 cells before being discharged. Based on the required flow rates to each wetland, the manufacturer sized the 25 Living Machines at 50,611-ft^2 each, and provided an estimated cumulative annual energy demand of 6,148,750 kWhr/year. Table 2.15 lists a material summary for the constructed wetland scenario.

TABLE 2.15: SUMMARY BILL OF MATERIALS FOR CONSTRUCTED WETLAND SCENARIO

TREATMENT COMPONENT	CUMULATIVE WEIGHT (LBS)
Primary Treatment (primary tank)	
Steel	42,500
Excavation	183,047,500
Concrete	66,570,300
Secondary Treatment (constructed wetland)	
Excavation	574,667,500
Concrete	5,467,500
Polyester	106,525
EPDM	441,325
Vitrified Slate	361,555,000
Washed Rock	69,415,325
Engineered Plastics	3,302,375
Stainless Steel	566,300
PVC	4,950
Fiberglass	450,000
HDPE	822,188

RESULTS

Life-cycle analysis results showing the environmental impacts of treatment and conveyance of the baseline and alternative wastewater treatment systems are presented below. Figure 2.14 shows the absolute impact values for the centralized treatment facility and each of the four distributed technologies over the 50-year life span.

FIGURE 2.14: OVERALL LIFE-CYCLE IMPACTS OF TREATMENT + CONVEYANCE SYSTEMS

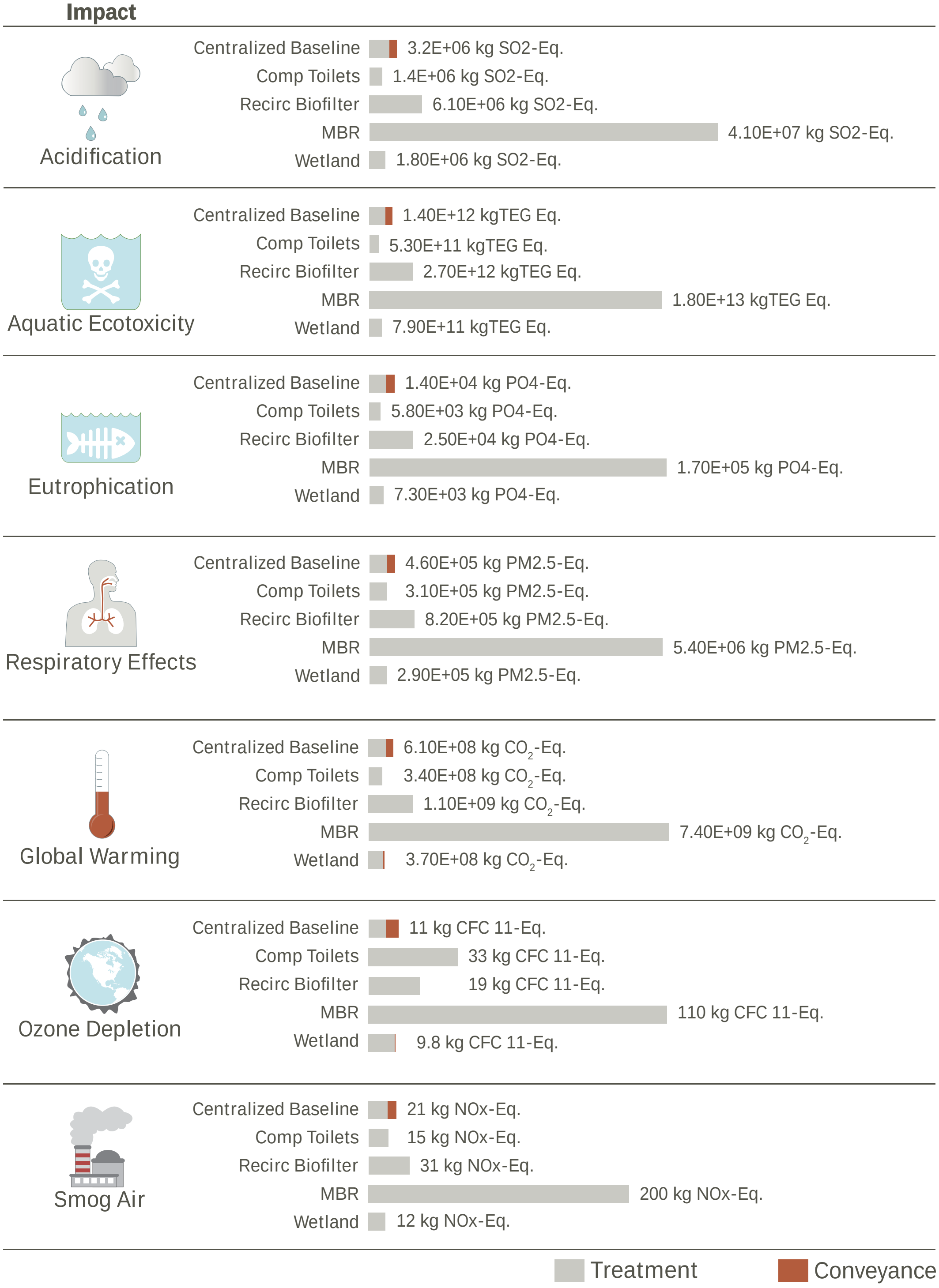


Table 2.16 shows the percent difference in environmental impacts of each of the four alternatives treatment systems compared to the baseline. These percentages take into account only those impacts associated with the treatment of the wastewater, excluding conveyance, in order to evaluate the various technologies themselves. Table 2.17, on the other hand, shows the percent difference in environmental impacts of each system compared to the baseline, taking into account both the treatment technology as well as conveyance of wastewater to its point of treatment.

TABLE 2.16: COMPARISON OF IMPACTS RELATIVE TO BASELINE FOR *TREATMENT SYSTEMS ONLY*

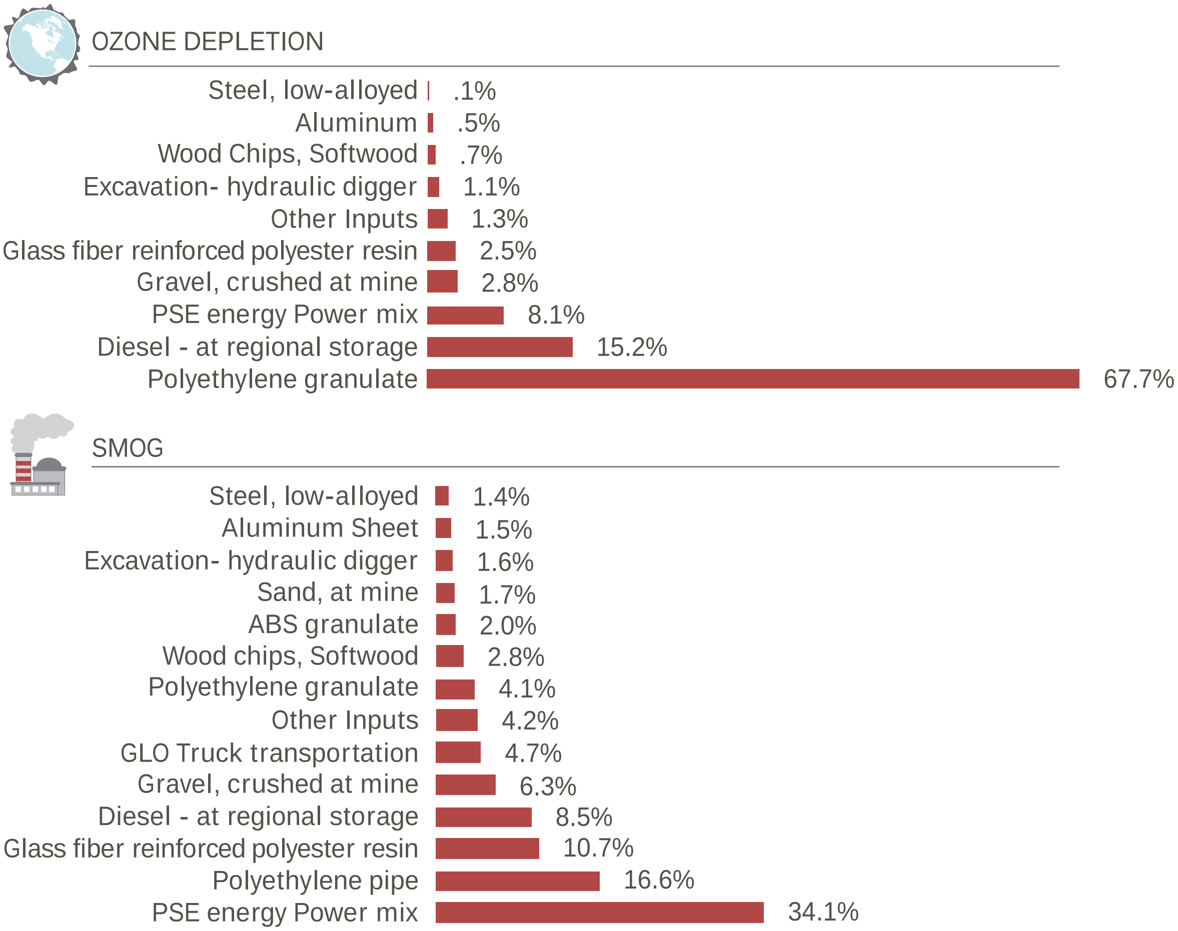
IMPACT	UNITS	COMP TOILETS	MBR	RECIRC. BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	-38%	1640%	160%	-22%
Aq. Ecotoxicity	Kg TEG Eq.	-49%	1645%	159%	-24%
Eutrophication	kg PO4-Eq.	-37%	1709%	166%	-22%
Respiratory Effects	kg PM2.5-Eq.	-1%	1649%	165%	-6%
Global Warming	kg CO_2-Eq.	-19%	1632%	164%	-15%
Ozone Depletion	kg CFC 11-Eq.	437%	1643%	203%	56%
Smog Air	kg NOx-Eq.	6%	1366%	126%	-13%

TABLE 2.17: COMPARISON OF IMPACTS RELATIVE TO BASELINE FOR TREATMENT + CONVEYANCE SYSTEMS

IMPACT	UNITS	COMP TOILETS	MBR	RECIRC BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	-55%	1160%	88%	-43%
Aq. Ecotoxicity	Kg TEG Eq.	-62%	1190%	92%	-43%
Eutrophication	kg PO4-Eq.	-58%	1098%	76%	-48%
Respiratory Effects	kg PM2.5-Eq.	-33%	1083%	79%	-36%
Global Warming	kg CO_2-Eq	-44%	1113%	85%	-40%
Ozone Depletion	kg CFC 11-Eq	221%	942%	81%	-6%
Smog Air	kg NOx-Eq	-29%	887%	52%	-41%

In comparison to the baseline centralized treatment and conveyance, the composting toilet and greywater wetland scenario has the least overall impact of all the alternative scenarios, including a 44% reduction in global warming impacts. The exception is in the ozone depletion category, where composting toilets represent a significantly higher impact over the baseline. This is due to the large quantity of polyethylene that makes up both the composting unit and the greywater wetland's primary treatment tank. Figure 2.15 shows the major drivers of ozone depletion and smog for the composting toilet scenario. If a material other than polyethylene were used, the environmental impact may be dramatically reduced.

FIGURE 2.15: IMPACT DRIVERS FOR COMPOSTING TOILET SCENARIO



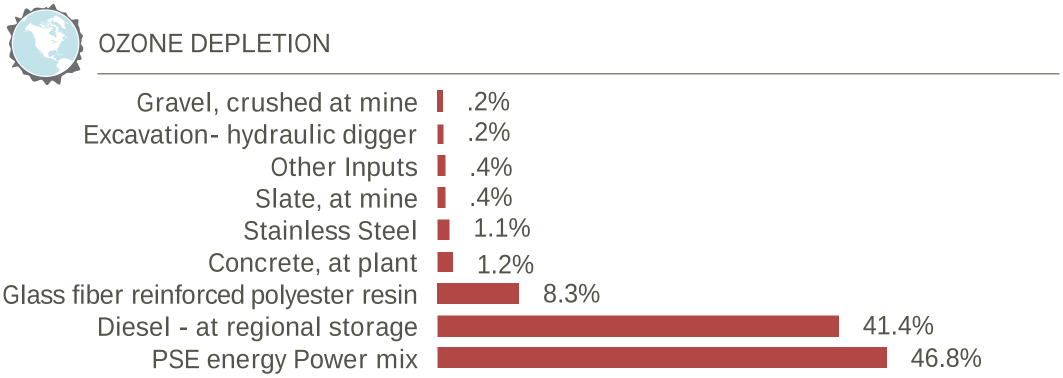
OZONE DEPLETION

SMOG

The above charts display the significant drivers of stratospheric ozone depletion and photochemical smog resulting from the manufacture, installation, and use of composting toilet-based treatment systems. Results are expressed in terms of percentage of the overall impact directly attributable to each driver. The top chart indicates that roughly two thirds of the ozone depleting emissions result from the manufacture of the polyethylene granulate used to form the primary tank and the composting unit itself. The bottom chart shows that roughy one third of the photochemical smog impacts are a result of the energy required to operate the system over the 50-year life-span.

Second only to composting toilets, the results indicate that the recirculating constructed wetland scenario had substantially lower environmental impacts compared to the baseline centralized treatment and conveyance system. Across most categories, this scenario represented a 35%-48% reduction in impacts, with 40% fewer global warming impacts than the baseline. Like the composting toilet scenario, ozone depletion impacts associated with the wetlands were notably larger (56% greater for treatment alone, and 6% less when conveyance is added to the analysis). Figure 2.16 shows the major drivers of ozone depletion for the constructed wetland scenario.

FIGURE 2.16: OZONE DEPLETION IMPACT DRIVERS FOR CONSTRUCTED WETLAND SCENARIO



The above chart displays the significant contributors, or drivers, of ozone depletion resulting from the manufacture, installation, and operation of a constructed wetland-based treatment system. Results are expressed in terms of percentage of impact attributable to each driver. The chart indicates that almost 90% of the overall ozone depleting impacts are attributable to the production of energy, either in the form of diesel used to transport the materials to and from the place of installation or as the energy required to operate the system over its lifespan.

The recirculating biofilter and membrane bioreactor scenarios both had much higher environmental impacts in relationship to the baseline. The biofilter was 52%-92% higher across impact categories while the MBR was upwards of 1,000% greater in comparison to the centralized facility. This is due to the fact that energy use was the major driver for both of these scenarios. Table 2.18 summaries the energy demands estimated for each of the scenarios.

TABLE 2.18: ENERGY USE SUMMARIES

	CUMULATIVE ANNUAL ENERGY REQUIREMENT (KW-HR/YEAR)	
SCENARIO	TREATMENT	CONVEYANCE
Centralized Baseline	8,218,821	2,740,034
Composting Toilet + Greywater Wetland	3,635,400	N/A*
Constructed Wetland	6,148,750	N/A*
Recirculating Biofilter	21,050,000	N/A*
Membrane Bioreactor	142,895,000 62,500,000 (low) 175,260,000 (high)	N/A*

* Alternative scenario assumed to be gravity-fed to point of treatment

A sensitivity analysis was run on the membrane bioreactor scenario using both the low and the high ends of the estimated range of energy use provided by system manufacturers. Table 2.19 shows that even when using the lower range of estimated energy consumption, which reduces the MBR impacts by roughly a third, the impacts are still significantly higher — approximately 400% — than those associated with the baseline scenario.

TABLE 2.19: MBR SENSITIVITY ANALYSIS
(TREATMENT + CONVEYANCE RELATIVE TO BASELINE)

IMPACT	MBR MODELED	MBR (LOW)	MBR (HIGH)
Acidification	1160%	453%	1444%
Ecotoxicity	1190%	468%	1481%
Eutrophication	1098%	456%	1357%
Respiratory Effects	1083%	427%	1347%
Global Warming	1113%	435%	1387%
Ozone Depletion	942%	370%	1172%
Smog Air	887%	349%	1104%

GAPS AND LIMITATIONS

In the baseline treatment system, an engineering analysis accounted for 100% of the materials, with 60% inventoried and the remaining 40% calculated based on profiles consistent with the characterized materials, primarily concrete and steel.

More than 99% of all materials in each of the four alternative treatment systems were included in the LCA modeling. Gaps do exist in the modeling, such as the polyvinylidene fluoride membranes in the MBR scenario where no data set was available. However, these gaps comprise a small fraction of the total weights of each alternative system.

A list of all gaps and limitations of the LCA modeling including parameters used to model the transportation of materials is listed in Appendix A, Table A.22.

PART 3

Conclusion

3.1 CONVEYANCE ANALYSIS

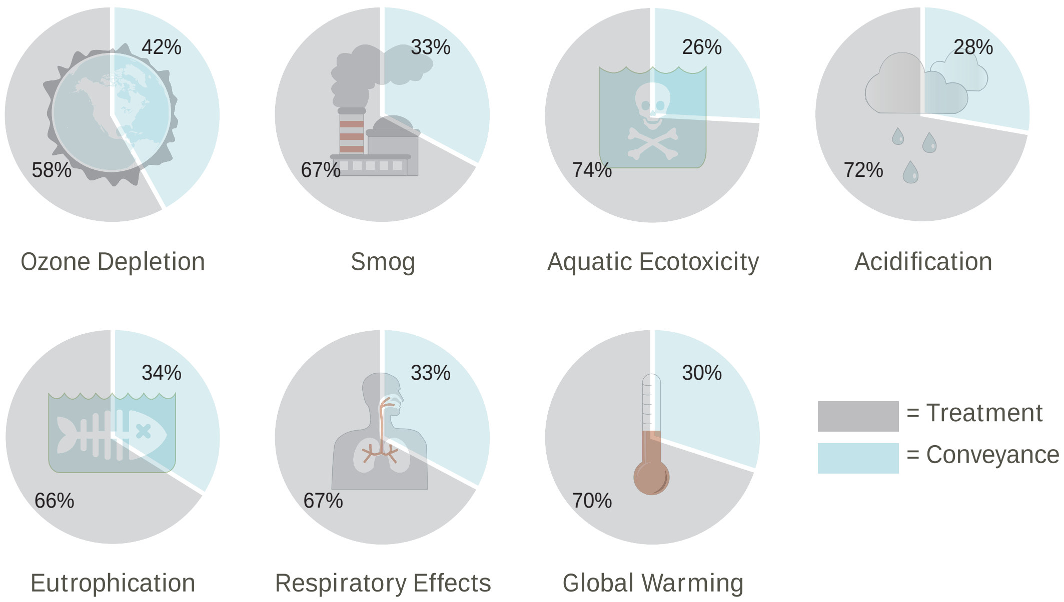
The conveyance analysis in this study looked at the existing network of pipes, manholes and pump stations to convey wastewater from 83,000 customers within a mid-sized Puget Sound-area community to a central location for treatment. Alternative density scenarios were then assessed by determining the conveyance necessary to serve the same number of customers within a smaller service boundary.

Results from the conveyance analysis highlight a number of key conclusions:

CONVEYANCE IMPACTS ARE SIGNIFICANT

For the baseline city studied, conveyance represented a significant portion of the overall impacts of the centralized treatment system — for instance, 30% of global warming and 42% of ozone depletion impacts, as shown in Figure 3.1. This is largely due to the fact that 25% of the energy of the entire system is used for conveyance, which is on the higher end compared to other cities. For communities with greater opportunity to rely on gravity flow, the negative environmental impacts associated with conveyance would likely be substantially less.

FIGURE 3.1: PERCENT CONTRIBUTION OF TREATMENT VERSUS CONVEYANCE IN BASELINE CENTRALIZED SCENARIO



In this study, the PSE 2008 power grid was used as the data source for the life cycle assessment. In this grid, hydroelectric—a comparably clean energy source—provides the majority of power in the baseline city. In areas of the country with dirtier fuel mixes—where coal is the primary energy source, for instance—conveyance will have even greater negative impacts.

For new developments, communities should be looking for ways to greatly reduce or eliminate the need for wastewater conveyance. Not only does this mean fewer negative environmental impacts, it also relates to fewer potential leaks and costly repairs. While the most appropriate technology for managing waste will be dependent on a number of factors including existing infrastructure, building scale and site characteristics, composting toilets (coupled with on-site treatment of greywater) offers a desirable alternative by eliminating the need for conveyance altogether.

A composting toilet system also significantly reduces the amount of water demand for the building. While outside of the scope of this study, further research is needed comparing the impacts associated with conveying fresh water to buildings for non-potable purposes such as toilet flushing in order to fully assess the value of composting toilets as an alternative.

Density Matters

Increasing the community's density from two dwelling units per acre up to ten dwelling units per acre achieved a 71% reduction in global warming impacts (kg CO_2-Eq.) associated with conveying wastewater. At even higher densities (30 dwelling units per acre), such as those found in more urban core areas, a 96% reduction in global warming impacts was achieved. This translates to removing over 637 passenger vehicles on the road annually for a mid-sized city in the Puget Sound region.

Results from the conveyance analysis can help support decisions around land use planning and wastewater treatment at different scales. Much study and analysis is underway around the relationship between land use planning and vehicle miles traveled as a means for reducing a community's carbon footprint. The results in this report can further support communities seeking to curb sprawling development patterns and incentivize increased density by also addressing the carbon impacts associated with wastewater conveyance.

FIGURE 3.2: IMPACT OF DENSITY ON CO_2 EMISSIONS BY WASTEWATER CONVEYANCE (EXPRESSED AS NUMBER OF CARS ON THE ROAD)

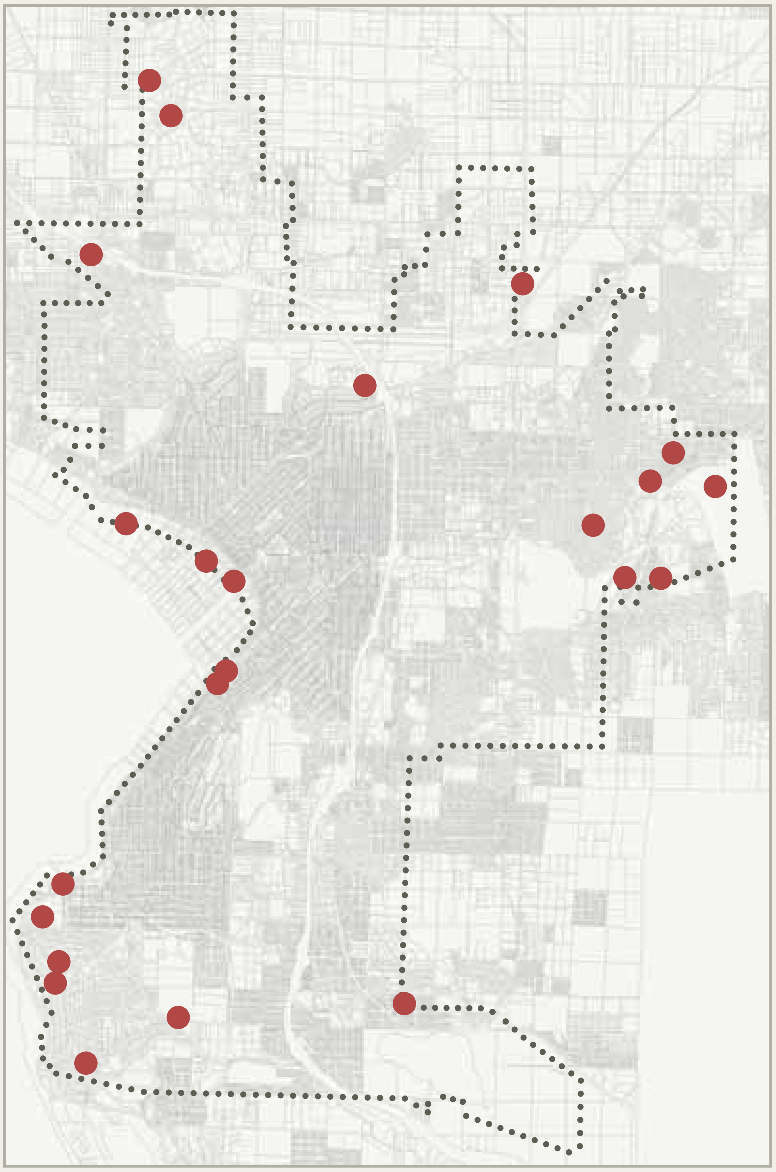
🚗 = 5 passenger vehicles on the road annually

Annual passenger car emissions in U.S. = 5.5 metric tons CO_2 equivalents (U.S. EPA)

PUMPING ENERGY DRIVES CONVEYANCE IMPACTS

For both the baseline conveyance and the ten dwelling units/acre density scenario, the annual operating energy needed to pressurize and pump wastewater to its point of treatment represented the majority of negative environmental impacts across all categories except ozone depletion.

FIGURE 3.3: CENTRALIZED SCENARIO WITH PUMP STATIONS



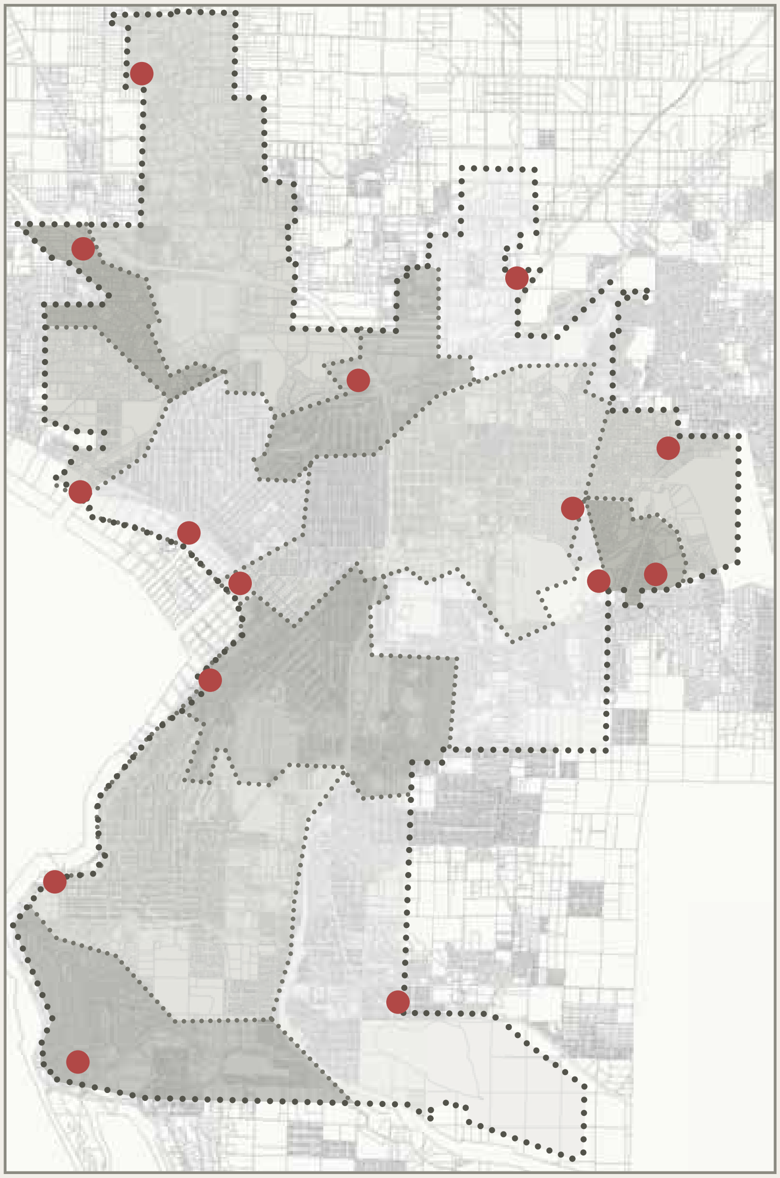
············ Service Area

● Pump Station

The current paradigm for centralized wastewater treatment assumes that all buildings, regardless of their location, are best served by conveying wastewater over long distances, even if this requires lift stations to pressurize and pump the water uphill.

It can be concluded that elevation and geography play a major role in assessing the appropriate scale for wastewater conveyance, with the goal of reducing or eliminating the need for pump stations altogether. For the baseline city used in this analysis, Figures 3.3 and 3.4 demonstrate how locations of existing pump stations might serve as optimal locations for distributed treatment systems.

FIGURE 3.4: THEORETICAL WATERSHED BOUNDARIES WITH DISTRIBUTED TREATMENT SYSTEMS



By contrast, more distributed methods of treatment would look at those existing pump station locations and instead, assess them as likely places for smaller-scale treatment systems.

This figure demonstrates the concept of “wastesheds.” Looking at treatment technologies such as constructed wetlands that also provide an asset, rather than an eyesore, for the community provides even further benefits.

3.2 TREATMENT SYSTEM ANALYSIS

The treatment analysis in this study evaluates four alternative scale technologies for treatment of wastewater from a mid-sized city in the Puget Sound region. The life cycle impact results from this analysis point toward the following key conclusions.

Treatment Energy Consumption Drives Overall Impacts

Annual operating energy demand can vary widely depending on the treatment technology employed. Further, it was determined that over a 50-year life span, energy demand was the major contributor of negative environmental impacts for each scenario with the exception of composting toilets. Table 3.1 shows the percent of wastewater treatment impacts that are attributed to the energy needed to construct and operate each system over its life span.

Regardless of conveyance, reducing the amount of energy needed to treat the wastewater will have a direct and significant impact on minimizing the negative environmental effects from treatment facilities. From these conclusions, community leaders and water utilities should be looking toward low-energy alternatives for upgrading and expanding their existing centralized treatment facilities.

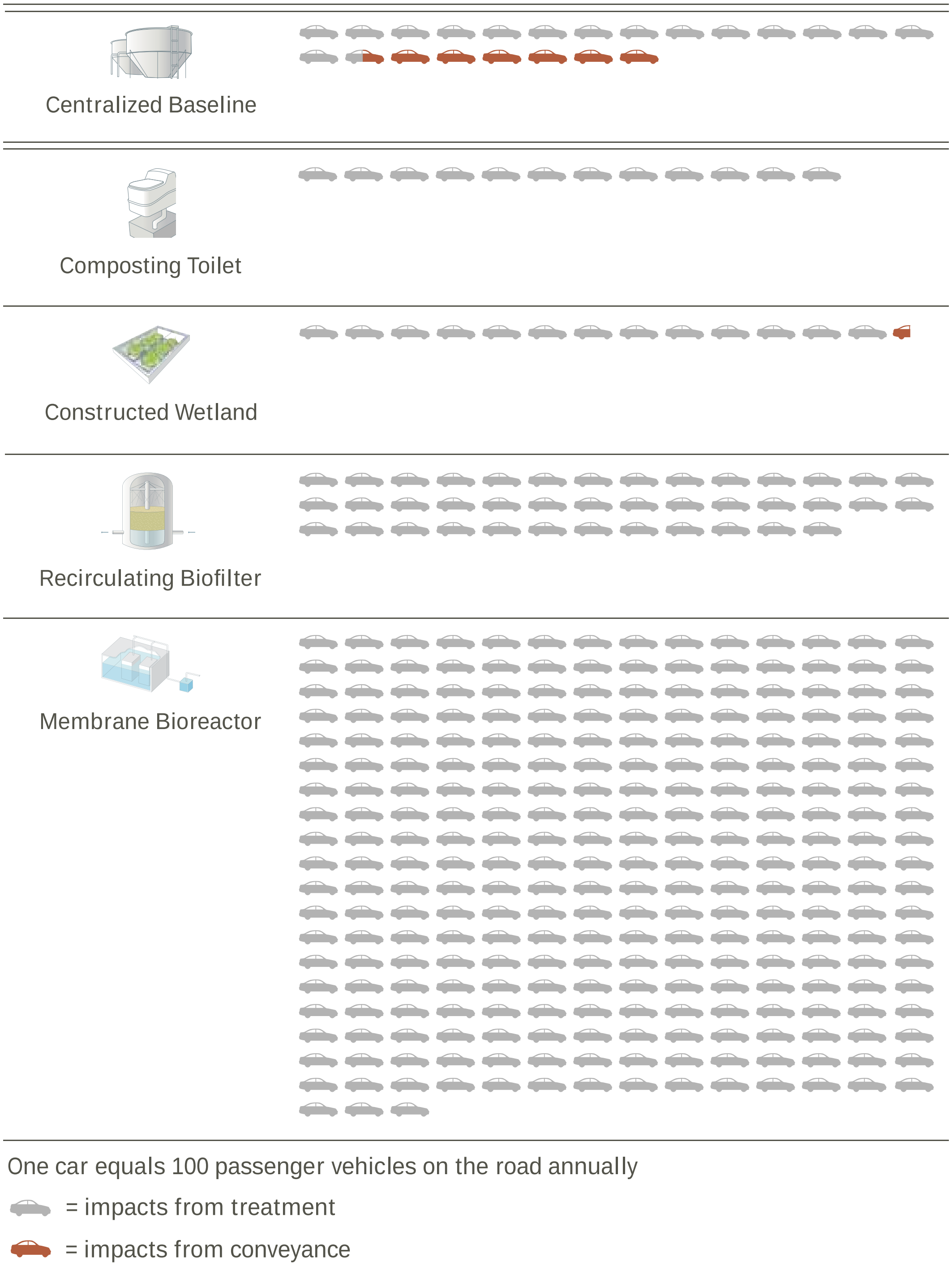
TABLE 3.1: PERCENT OF OVERALL TREATMENT IMPACTS DUE TO ENERGY

IMPACT	UNITS	CENTRALIZED BASELINE	COMP TOILETS	RECIRC BIOFILTER	MBR	WETLAND
Acidification	kg SO2-Eq.	99.80%	71.70%	98.30%	99.80%	95.70%
Aq. Ecotoxicity	kg TEG Eq.	99.80%	86.40%	98.70%	99.50%	97.60%
Eutrophication	kg PO4-Eq.	99.10%	69.90%	95.50%	95.10%	94.20%
Respiratory Effects	kg PM2.5-Eq.	99.10%	44.10%	95.90%	98.50%	78.70%
Global Warming	kg CO_2-Eq	99.00%	54.30%	96.10%	99.40%	86.40%
Ozone Depletion	kg CFC 11-Eq	97.80%	8.10%	82.80%	97.60%	46.40%
Smog Air	kg NOx-Eq	81.80%	34.10%	92.80%	96.90%	69.40%

On-Site Composting Toilets and Greywater Treatment Wetlands Have Lowest Environmental Impacts

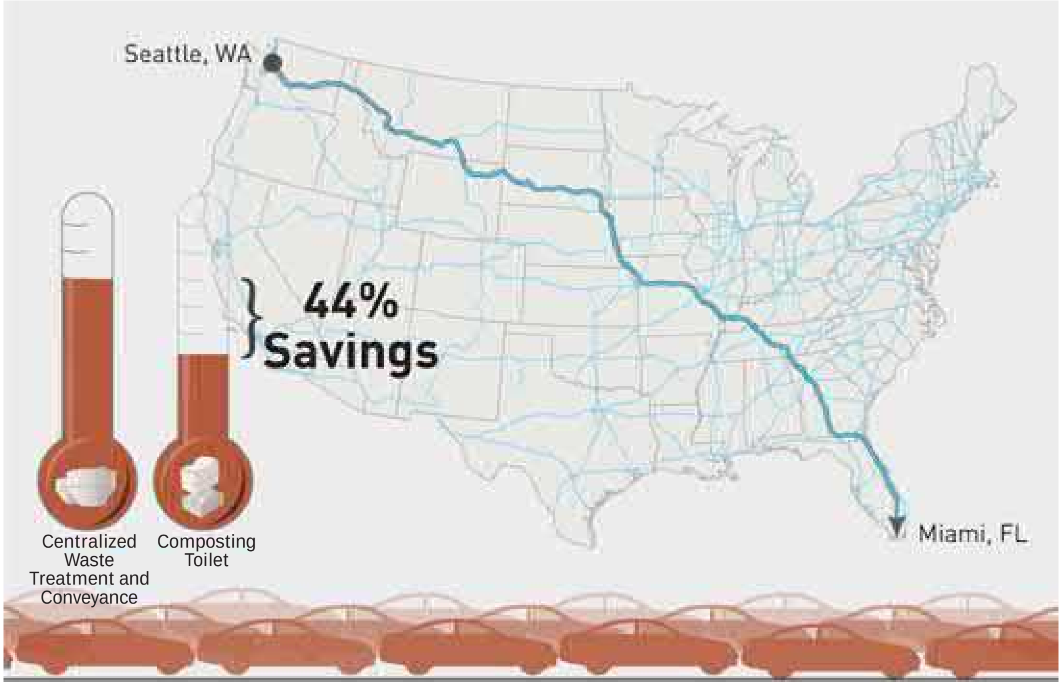
Results from the LCA clearly demonstrate that building-scale, low-energy wastewater treatment systems demonstrated by the composting toilet and greywater treatment wetland scenario have considerably lower impact on the environment compared to our current practices for centralized conveyance and treatment. Figure 3.5 relates the global warming impacts of the baseline and alternative treatment scenarios, including conveyance contributions, to an equivalent number of cars on the road. The composting toilet scenario equates to a 44% reduction in climate change impacts, which is equivalent to removing 1,000 passenger vehicles on the road annually based on a city population of 67,000. As shown in Figures 3.6, if scaled to the entire country, it equates to removing more than three lanes of bumper-to-bumper traffic between Seattle and Miami annually.

FIGURE 3.5: GLOBAL WARMING IMPACTS EXPRESSED AS EQUIVALENT CARBON EMISSIONS FROM PASSENGER VEHICLES ON THE ROAD



In comparison to the baseline centralized scenario, the percent difference for each scenario equates to: Composting Toilets (-44%), Constructed Wetland (-40%), Recirculating Biofilter (+85%), and Membrane Bioreactor (+1113%).

FIGURE 3.6: ESTIMATED CARBON SAVINGS SCALED TO NATIONAL LEVEL*



Annually, centralized waste treatment and conveyance emit 44% more CO_2 than if households switched to composting toilets and greywater treatment wetlands. This equates to the equivalent of removing approximately three lanes of cars stacked bumper to bumper between Seattle and Miami off the road annually.

* Based on findings from global warming impacts related to the baseline city used in this study. Estimated CO_2 savings are scaled up to address national population (2000 US Census). Actual savings may vary.

Based on these results, composting toilets coupled with on-site constructed wetlands to treat greywater prior to discharge should be a key strategy for new buildings and development projects, particularly in areas with increasingly scarce water resources that would especially benefit from systems that eliminate the need for water.

In addition to water conservation, this scenario also offers a range of additional environmental benefits outside the scope of this analysis, such as the ease of reclaiming nutrients from the composting process and integrating greywater into landscape irrigation or for on-site agricultural uses.

The viability of incorporating these systems broadly will be dependent on a number of factors including space constraints, capital costs, ongoing operations and maintenance requirements, regulatory support and public acceptance. These factors are not necessarily prohibitive. For instance, in urban areas where less land is available for on-site treatment, options include incorporating greywater treatment strategies into interior spaces such as irrigation of vegetated (living) walls or into exterior, rooftop vegetated areas. And, gaining public acceptance may be accomplished through educational outreach focusing on the proven success of the proposed technologies and exemplary models where such a system is already in place.

Constructed Wetlands Offer Benefits at the District Scale

The recirculating constructed wetland scenario evaluated in this study demonstrated a 35%-45% decrease in environmental impacts across almost all impact categories when compared to the baseline centralized treatment and conveyance scenario, including a 40% reduction in global warming impacts.

In this scenario, constructed wetlands were evaluated at the district-scale and strategically placed at locations of existing pump stations. Rather than pressurizing and pumping wastewater to a centralized location, smaller-scale treatment facilities located at these locations can help eliminate the negative impacts associated with energy-intensive conveyance of wastes. When this strategy is coupled with a lower-impact treatment technology such as constructed wetlands, the reductions in impacts are significant. Looking at the treatment systems alone (without conveyance impacts), the wetland system has shown to have 15% less global warming impacts compared to the activated sludge centralized treatment facility.

These results point toward the use of constructed treatment wetlands at the district or neighborhood scale as a viable strategy for communities seeking to lower the negative environmental impacts associated with wastewater treatment. Further assessing their benefits in terms of a low impact stormwater management strategy, as well as their ability to provide public amenities as open space for humans and wildlife, is likely to make them a fundamental part of waste treatment in the future. As such, there is a growing need for policy-makers and regulatory agencies to define standards and increase support for constructed treatment wetlands at the district-scale.

Reuse Potential Must be Considered with Higher Energy Treatment Technologies

Both the recirculating biofilter and the membrane bioreactor scenarios displayed results that greatly under-performed in comparison to the baseline centralized treatment scenario. Further analysis on biofilters may indicate that a community with larger conveyance energy requirements than what was used in this study may show the biofilter scenario in a more favorable light. However, the high-energy demands of these systems mean that they actually have greater negative environmental impacts when compared to a centralized treatment facility with a largely gravity-fed conveyance system.

When membrane bioreactors are used in the comparison, the enormous energy demands of the MBR are so much greater than the baseline that they are unlikely to be viewed as an ideal distributed scale solution for treatment within the boundaries of this study. Further analysis is needed to evaluate under what conditions MBRs are comparable to other alternatives. MBRs are capable of providing very high levels of treated water for the purposes of reuse, and when installed at the building scale they offer the benefit of using the reclaimed water directly on-site, reducing the need for fresh water supplied to the building. This is particularly valuable in locations where water resources are scarce.

It is likely that in a life-cycle analysis that includes wastewater treated to higher levels for reuse purposes and takes into consideration those impacts associated with supplying fresh water from centralized facilities, MBRs may have greater applicability.

3.3 FURTHER RESEARCH

Clean Water, Healthy Sound represents an in-depth investigation of various wastewater treatment and conveyance strategies and their environmental impacts over a 50-year life span. While it provides insight into how decentralized and distributed-scale technologies compare to conventional centralized systems, further research and analysis will provide an even greater level of understanding of impact drivers and how the data in this report can best serve as a resource for decision makers in assessing infrastructure alternatives. Building upon the findings of this study, the following topics highlight areas of further research needs.

Run Sensitivity Analysis for Composting Toilets Scenario

The composting toilet scenario in this analysis showed fewer negative impacts compared to centralized treatment in all categories with the exception of ozone depletion. The large quantity of polyethylene granulate — which makes up the system's piping, wetland liner and composting unit itself — are driving stratospheric ozone depletion impacts over 220% percent higher than the baseline. Further analysis is needed to assess how alternative materials to polyethylene, such as fiberglass tanks or clay liners, may perform differently.

Consider Lower Energy Constructed Wetland Systems

In this analysis, Living Machines were used in the recirculating constructed wetland scenario. Like composting toilets, ozone depletion impacts were higher when compared to the baseline centralized treatment system. Since approximately 90% of the wetland's ozone depleting impacts are attributable to the production of energy — either in the form of diesel used to transport the materials to and from the place of installation or as the energy required to operate the system over the product's lifespan — further sensitivity analysis is needed to determine how alternative wetland designs that require less operating energy will compare.

For Living Building projects that also meet all of their own power needs through on-site renewable energy, such as in the case of the Omega Center (see page 24), the life-cycle environmental impacts of the constructed treatment wetland scenario may vary greatly. Further analysis is needed to determine how net zero energy buildings with on-site constructed treatment wetlands compare to more conventional, centralized approaches.

Further Characterize Centralized Treatment System

Approximately 60% of all materials in the centralized wastewater treatment system were inventoried in the baseline analysis. This inventory was developed through a site visit to the actual facility and engineering estimates of material quantities. Due to the complexity of this large system and limitation of available data provided by the city, the remaining 40% of material composition was extrapolated based on engineering analysis of the existing inventory. Further research is needed to more comprehensively quantify the centralized baseline system in order to provide a more accurate comparison.

Evaluate Alternate Treatment Scenarios at Different Density Scales

The treatment analysis assessed four smaller-scale distributed treatment technologies applied at the baseline density scale of two dwelling units per acre. It is assumed that economies of scale may be realized as these systems are applied at increasing density scales. Further evaluation of the constructed wetland and recirculating biofilter scenarios applied at the ten and 30 dwelling units per acre scale may demonstrate interesting results for comparison to centralized treatment systems.

Expand Boundaries of Study to Include Water Reuse and Nutrient Reclamation

One advantage of smaller-scale treatment systems is the opportunity for treatment of the water for reuse applications either on-site or at the district scale. Analysis of life-cycle impacts associated with water reuse and the offsetting of fresh water supply will provide a more comprehensive understanding of how decentralized systems compare to conventional practices for both water supply and treatment.

Additionally, further research is necessary to assess how smaller-scale systems may provide opportunities for reclaiming valuable nutrients in the waste stream in comparison to reclamation at the centralized scale.

APPENDICES

APPENDIX A. BILL OF MATERIALS AND ASSUMPTIONS

TABLE A.1: BASELINE CONVEYANCE GRAVITY PIPE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	NUMBER OF MANHOLES	SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (CF)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	RCP PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF RCP MATERIAL (lbs)	POUNDS OF PVC MATERIAL (lbs)
										Manufacturer's Data according to ASTM D3034 and F679	Manufacturer's Data according to AASHTO M170	LxWeight per Foot	LxWeight per Foot
8	1230940	4797	48" Type II	6.00	2.0	14771276	3673671	10668144	PVC	4.24			5219184
10	107702	420	48" Type I	6.17	2.8	1881795	500740	1322342	PVC	6.64			715142
12	96960	378	48" Type I	6.33	3.0	1842232	505644	1260475	PVC	9.50			921116
15	46016	179	48" Type I	6.58	3.3	984550	280050	648058	PVC	14.19			652966
18	50449	197	48" Type I	6.83	3.5	1206581	352326	765149	PVC	21.43			1081130
21	20322	79	48" Type I	7.08	3.8	539795	160713	330227	PVC	29.88			607212
24	25174	98	54" Type I	7.33	4.0	738440	223042	436351	PVC	38.96			980782
27	1599	6	54" Type I	7.58	4.3	51531	15731	29446	PVC	49.47			79098
30	27346	107	54" Type I	7.83	4.5	963956	296536	533252	PVC	64.18			1755083
36	5934	23	54" Type I	8.33	5.0	247247	76755	128568	RCP		645	3827378	
42	668	3	72" Type I	8.83	5.5	32455	10110	15921	RCP		811	541764	
48	6558	26	96" Type I	9.33	6.0	367256	114374	170512	RCP		1011	6630290	
60	11713	46	96" Type I	10.33	7.0	847222	262073	355287	RCP		1488	17428568	
TOTAL VOLUME (cf) =						24474334	6471765	16663732					
TOTAL VOLUME (cy) =						906457	239695	617175					
TOTAL WEIGHT (lbs) =						2202690087	623206975	1974960821				28428000	12011713
TOTAL WEIGHT (tons) =						1101345	311603	987480				14214	6006

TABLE A.2: BASELINE CONVEYANCE PRESSURE PIPE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION, VE (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	DI PIPE WEIGHT PER FOOT (LB/ ft)	HDPE PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF DI MATERIAL (lbs)	POUNDS OF HDPE MATERIAL (lbs)
								Manufacturer's Data according to ANSI/AWWA C151/A21.51	Manufacturer's Data according to DR 17; ANSI/NSF-61	LxWeight per Foot	LxWeight per Foot
4	9761	4.17	3	122010	38192	82967	DI	10.9		106393	
6	7542	4.33	3	98046	32459	64107	DI	16.0		120672	
8	7362	4.50	3	99387	34242	62577	DI	21.1		155339	
10	3060	4.67	3	42837	15161	26008	DI	27.1		82920	
12	715	4.83	3	10366	3728	6076	DI	34.8		24878	
15	23	5.08	3	350	127	195	DI	49.3		1130	
18	1043	5.33	3	16692	5982	8868	DI	57.2		59673	
36	2319	6.83	4	63395	20723	26286	HDPE		98.6		228616
42	2447	7.33	5	89711	31522	34661	HDPE		134.2		328243
TOTAL VOLUME (cf) =				542793	182135	311745					
TOTAL VOLUME (cy) =				20103	6746	11546					
TOTAL WEIGHT (lbs) =				48851397	17538912	36947534				551005	556859
TOTAL WEIGHT (tons) =				24426	8769	18474				276	278

TABLE A.3: BASELINE CONVEYANCE MANHOLE SUMMARY

SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	NUMBER OF MANHOLES	VOLUME OF EXCAVATION (cf)	VOLUME OF BACKFILL (cf)	VOLUME OF CONCRETE (cf)
ø48" Type II	7	4,797	1,220,098	589,901	280,008
ø48" Type I	11	1,253	531,029	311,089	93,040
ø54" Type I	11	234	102,514	56,524	18,058
ø72" Type I	12	3	2,354	1,737	237
ø96" Type I	13	71	117,379	79,709	11,219
TOTAL VOLUME (cf) =			1,973,375	1,038,959	402,561
TOTAL VOLUME (cy)=			73,088	38,480	14,910
TOTAL WEIGHT (lbs)=			177,603,759	123,135,907	60,384,210
TOTAL WEIGHT (tons)=			88,802	61,568	30,192

TABLE A.4: BASELINE CONVEYANCE SMALL PUMP STATION MATERIALS

	TOTALS	WET WELLS	2 CYLINDERS	TOP SLAB	WET WELL BASES	VOLUME INSIDE WINGS (SF) SEC C-C	VOLUME INSIDE WINGS (SF) SEC B-B	FILLETS
Depth of Excavation (ft)	30							
Volume of Excavation (cf)	11,250							
Volume of Excavation (cy)	417							
Area of Concrete (sf)	519	284.4	53.4	177.6	231.0	15.0	42.4	57.4
Volume of Concrete, Vc (cf)	2,241	1,725.6	1,494.6	207.2	231.0	75.0	233.1	308.1
Weight of Concrete (lbs)	336,151							

TABLE A.5: BASELINE CONVEYANCE SMALL PUMP STATION MATERIALS AND ENERGY SUMMARY

	EXCAVATION	BACKFILL	CONCRETE	ANNUAL ENERGY DEMAND
Wet Wells	11,250	7,703	1,726	8,965 kW-hrs
Top Slab	-		207	
Interior Fillets	-		308	
Total Volume (cf) =	11,250	7,703	2,241	
Total Volume (cy) =	417	285	83	
Total Weight (lbs) =	1,012,500	912,948	336,151	
Total Weight (tons) =	506	456	168	

ASSUMPTIONS:
A=(pi*(Do2-Din2))/4
Do=outer dia of pipe (in)
Di=inner dia of pipe (in)
Vc=volume of concrete
lbs of conc = 150(lbs/cf)*Vc

ITEMS NOT INCLUDED IN ESTIMATE:
fittings
vents
rails
piping

TABLE A.6: BASELINE CONVEYANCE LARGE PUMP STATION MATERIALS

	TOTALS	WET WELL	PUMP STATION
Depth of Excavation (ft)		30	31
Volume of Excavation (cf)	122,665	43,560	79,105
Volume of Excavation (cy)	4,543	1,613	2,930
Volume of Concrete, Vc (cf)	40,295	12,805	27,490
Weight of Concrete (lbs)	604,4250		
Weight of Steel (lbs)	94,214	51,494	42,720
Volume of Backfill (cf)		14,130	15,777
Volume of Backfill (cy)		523	584

TABLE A.7: BASELINE CONVEYANCE LARGE PUMP STATION SUMMARY

	EXCAVATION	BACKFILL	CONCRETE	STEEL	ANNUAL ENERGY DEMAND
Wet Wells	43,560	14,130	12,805	105	234,424 kW-hrs
Building and Site	79,105	15,777	27,490	87	
Total Volume (cf) =	122,665	29,907	40,295	192	
Total Volume (cy) =	4,543	1,108	1,492	7	
Total Weight (lbs) =	11,039,807	3,544,543	6,044,250	94,214	
Total Weight (tons) =	5,520	1,772	3,022	47	

TABLE A.8: DENSITY SCENARIO 1 GRAVITY PIPE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	Number of Manholes	Size and Type of Manholes	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	Pea Gravel Bedding (cf)	Backfill (cf)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	RCP PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF RCP MATERIAL (lbs)	POUNDS OF PVC MATERIAL (lbs)
										Manufacturer's Data according to ASTM D3034 and F679	Manufacturer's Data according to AASHTO M170	LxWeight per Foot	LxWeight per Foot
12	429,798	1,675	48" Type I	6.33	3.00	8,166,162	2,241,397	5,587,374	PVC	9.50			4,083,081
15	9,726	38	48" Type I	6.58	3.25	208,096	59,192	136,975	PVC	14.19			138,012
18	2,987	12	48" Type I	6.83	3.50	71,439	20,860	45,303	PVC	21.43			64,011
21	4,803	19	48" Type I	7.08	3.75	127,580	37,984	78,049	PVC	29.88			143,514
24	2,585	10	54" Type I	7.33	4.00	75,827	22,903	44,807	PVC	38.96			100,712
27	1,836	7	54" Type I	7.58	4.25	59,173	18,063	33,813	PVC	49.47			90,827
30	2,372	9	54" Type I	7.83	4.50	83,613	25,721	46,254	PVC	64.18			152,235
36	1,879	7	54" Type I	8.33	5.00	78,292	24,305	40,712	RCP		645	1,211,955	
42	0	0	72" Type I	8.83	5.50	0	0	0	RCP		811	0	
48	8,479	33	96" Type I	9.33	6.00	474,824	147,874	220,454	RCP		1,011	8,572,269	
60	6,765	26	96" Type I	10.33	7.00	489,335	151,367	205,205	RCP		1,488	10,066,320	
TOTAL VOLUME (cf) =						9,834,340	2,749,666	6,438,944					
TOTAL VOLUME (cy) =						364,235	101,839	238,479					
TOTAL WEIGHT (lbs) =						885,090,576	264,782,693	763,134,153				19,850,544	4,772,391
TOTAL WEIGHT (tons) =						442,545	132,391	381,567				9,925	2,386

TABLE A.9: DENSITY SCENARIO 1 PRESSURE PIPE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION, VE (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	DI PIPE WEIGHT PER FOOT (lb/ft) Manufacturer's Data according to ANSI/AWWA C151/A21.51	HDPE PIPE WEIGHT PER FOOT (lb/ft) Manufacturer's Data according to DR 17; ANSI/NSF-61	POUNDS OF DI MATERIAL (lbs) LxWeight per Foot	POUNDS OF HDPE MATERIAL (lbs) LxWeight per Foot
18	1,067	5.33	3.0	17,072	6,118	9,070	DI	57		61,032	
36	2,329	6.83	4.0	63,659	20,810	26,395	HDPE		99		229,570
42	2,411	7.33	5.0	88,403	31,063	34,156	HDPE		134		323,460
TOTAL VOLUME (cf) =				169,135	57,990	69,621					
TOTAL VOLUME (cy) =				6,264	2,148	2,579					
TOTAL WEIGHT (lbs) =				15,222,120	5,584,246	8,251,338				61,032	553,029
TOTAL WEIGHT (tons) =				7,611	2,792	4,126				31	277

TABLE A.10: DENSITY SCENARIO 1 MANHOLE SUMMARY

SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	NUMBER OF MANHOLES	VOLUME OF EXCAVATION (cf)	VOLUME OF BACKFILL (cf)	VOLUME OF CONCRETE (cf)
ø48" Type II	7	1,675	426,013	205,971	97,768
ø48" Type I	11	68	28,936	16,951	5,070
ø54" Type I	11	34	14,804	8,162	2,608
ø72" Type I	12	0	0	0	0
ø96" Type I	13	59	97,933	66,504	9,360
TOTAL VOLUME (cf) =			567,686	297,589	114,806
TOTAL VOLUME (cy)=			21,025	11,022	4,252
TOTAL WEIGHT (lbs)=			51,091,725	35,269,778	17,220,852
S (tons)=			25,546	17,635	8,610

TABLE A.11: DENSITY SCENARIO 2 GRAVITY PIPE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	NUMBER OF MANHOLES	SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	RCP PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF RCP MATERIAL (lbs)	POUNDS OF PVC MATERIAL (lbs)
										Manufacturer's Data according to ASTM D3034 and F679	Manufacturer's Data according to AASHTO M170	LxWeight per Foot	LxWeight per Foot
12	197,730	771	48" Type I	6.33	3.0	3,756,870	1,031,162	2,570,490	PVC	9.5			1,878,435
15	6,571	26	48" Type I	6.58	3.3	140,592	39,991	92,542	PVC	14.2			93,242
18	4,235	17	48" Type I	6.83	3.5	101,287	29,576	64,231	PVC	21.4			90,756
21	1,386	5	48" Type I	7.08	3.8	36,816	10,961	22,523	PVC	29.9			41,414
24	803	3	54" Type I	7.33	4.0	23,555	7,115	13,919	PVC	39.0			31,285
27	523	2	54" Type I	7.58	4.3	16,856	5,146	9,632	PVC	49.5			25,873
30	301	1	54" Type I	7.83	4.5	10,610	3,264	5,870	PVC	64.2			19,318
36	1,656	6	54" Type I	8.33	5.0	69,000	21,420	35,880	RCP		645	1,068,120	
42	3,810	15	72" Type I	8.83	5.5	185,103	57,660	90,805	RCP		811	3,089,910	
48	294	1	96" Type I	9.33	6.0	16,464	5,127	7,644	RCP		1,011	297,234	
60	468	2	96" Type I	10.33	7.0	33,852	10,472	14,196	RCP		1,488	696,384	
TOTAL VOLUME (cf) =						4,391,004	1,221,893	2,927,730					
TOTAL VOLUME (cy) =						162,630	45,255	108,434					
TOTAL WEIGHT (lbs) =						395,190,360	117,663,749	346,990,222				5,151,648	2,180,323
TOTAL WEIGHT (tons) =						197,595	58,832	173,495				2,576	1,090

TABLE A.12: DENSITY SCENARIO 2 MANHOLE SUMMARY

SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	NUMBER OF MANHOLES	VOLUME OF EXCAVATION (CF)	VOLUME OF BACKFILL (cf)	VOLUME OF CONCRETE (cf)
ø48” Type II	7	771	195,988	94,758	44,979
ø48” Type I	11	48	20,141	11,799	3,529
ø54” Type I	11	13	5,604	3,090	987
ø72” Type I	12	15	13,427	9,905	1,354
ø96” Type I	13	3	4,895	3,324	468
		TOTAL VOLUME (cf) =	240,057	122,877	51,317
		TOTAL VOLUME (cy)=	8,891	4,551	1,901
		TOTAL WEIGHT (lbs)=	21,605,088	14,563,160	7,697,494
		TOTAL WEIGHT (tons)=	10,803	7,282	3,849

TABLE A.13: ASSUMPTIONS

ASSUMPTIONS
Length of 4” and 6” gravity mains were added to the length of 8”, as the smaller mains would not be constructed today
Length of 14” gravity mains were added to the length of 15”, as 14” is a non-standard size
Length of 16” gravity mains were added to the length of 18”, as 16” is a non-standard size
Length of 20” gravity mains were added to the length of 21”, as 20” is a non-standard size
Length of 23” gravity mains were added to the length of 24”, as 23” is a non-standard size
Length of 28” gravity mains were added to the length of 30”, as 28” is a non-standard size
With a total of 6,357 manholes, the total was prorated based on pipe length for each pipe size
HDPE = High Density Polyethelyne
PVC = Polyvinyl Chloride
DI = Ductile Iron
RCP = Reinforced Concrete Pipe
PVC gravity sewer pipe is SDR 35
SDR= Standard Dimension Ration
SDR= D_o/T
D_o=outer dia of pipe (in)
D_i=inner dia of pipe (in)
T=wall thickness (in)
$A=(pi*(Do^2-Din^2))/4$
D=density
V_m=volume of material
L=length
V_e=volume of excavation
V_c=volume of concrete
Weight of excavated earth = 90 pcf
Weight of pea gravel bedding= 1.3 ton/cy
Weight of Backfill = 1.6 ton/cy
Weight of Concrete = 150 pcf
Density of Steel = 490 pcf

TABLE A.14: COMPOSTING TOILET/GREYWATER SYSTEMS MATERIAL AND ENERGY SUMMARY

SYSTEM COMPONENT	SYSTEM/MAJOR COMPONENT LIFE EXPEC-TANCY	MATERIAL	ASSUMPTION	ESTIMATED ITEM WEIGHT INDIVIDUAL/ CUMULATIVE	TOTAL ESTIMATED 50-YR WEIGHT INDIVIDUAL/ CUMULATIVE	ANNUAL KWH INDI-VIDUAL/ CUMULA-TIVE	TOTAL 50-YR KWH INDIVIDU-AL/ CUMU-LATIVE
Primary Treatment: 83,000 Primary Units						43.8 kW-Hrs/yr/3,635,400 kW-hrs/year	2,190 kW-Hrs/181,770,000 kW-hrs
Primary Tank Excavation	50 years	Excavation		12,440 lbs./ 1,032,529,919 lbs.	12,440 lbs./ 1,032,529,919 lbs.		
Dual Compartment Primary Tank	50 years	Polyethylene	Snyder 300 Gallon Dominator Spherical Pump Tank	257lbs./ 21,331,000 lbs.	257lbs./ 21,331,000 lbs.		
Composting Unit Excavation	50 years	Excavation		58,620 lbs./ 4,840,560,000 lbs.	58,620 lbs./ 4,840,560,000 lbs.		
Composting Unit	50 years	Polyethylene	Pheonix Composting Unit, Model 201 (PF or R)	343 lbs./ 28,469,000 lbs.	343 lbs./ 28,469,000 lbs.		
Composting Unit	50 years	Polypropylene		7 lbs./ 581,000 lbs.	7 lbs./ 581,000 lbs.		
Composting Unit	50 years	Fiberglass		47 lbs./ 3,901,000 lbs.	47 lbs./ 3,901,000 lbs.		
Composting Unit	50 years	Nylon		7 lbs./ 581,000 lbs.	7 lbs./ 581,000 lbs.		
Composting Unit	50 years	Aluminum		3.5 lbs./ 290,500 lbs.	3.5 lbs./ 290,500 lbs.		
Composting Unit	50 years	Stainless Steel		3 lbs./ 249,000 lbs.	3 lbs./ 249,000 lbs.		
Composting Unit	50 years	Iron		4.5 lbs./ 373,500 lbs.	4.5 lbs./ 373,500 lbs.		
Composting Unit	50 years	Acrylonitrile-Butadiene-Styrene		2 lbs./ 166,000 lbs.	2 lbs./ 166,000 lbs.		
Composting Unit	50 years	Poly Vinyl Chloride		3 lbs./ 249,000 lbs.	3 lbs./ 249,000 lbs.		
Composting Unit Fan	5 years	Polyethylene & Steel	Pheonix Composting Unit, Model 201 (PF or R)	1.8 lbs. & 1.4 lbs./ 149,900 lbs. & 116,200 lbs.	18 lbs. and 14 lbs./1,494,000 lbs. & 1,162,000 lbs.		
Bulking Material	12 x/year	Wood Shavings		8 lbs./ 665,775 lbs.	4,812 lbs./399,396,000 lbs.		
Secondary Treatment (Constructed Wetland): 83,000 Primary Units							
Flexible Liner	50 years	HDPE	60 mm HDPE Liner	1,295 lbs./ 107,553 lbs.	1,295 lbs./ 107,553 lbs.		
Piping	50 years	DR 17 HDPE	4” diameter for all plumbing from the house to the wetland, 3” diameter for laterals	208 lbs./ 17,272,300 lbs.	208 lbs./ 17,272,300 lbs.		
Soil Excavation	50 years	Excavation		108,045 lbs./ 8,967,735,000 lbs.	108,045 lbs./ 8,967,735,000 lbs.		
Backfill (from excavation)	50 years	Backfill - from excavation	0.5’(h)x7’(w)x49’(l) + edges	57,053 lbs./ 4,753,399,000 lbs.	57,053 lbs./ 4,753,399,000 lbs.		
Gravel/Rock Infill	50 years	Rock Infill	2.5’(h)x5’(w)x47’(l)	52,875 lbs./ 4,388,625,000 lbs.	52,875 lbs./ 4,388,625,000 lbs.		
Soil Infill	50 years	Topsoil - from storage	0.5’(h)x5’(w)x47’(l)	11,750 lbs./ 975,250,000 lbs.	11,750 lbs./ 975,250,000 lbs.		
Plants	10 years	Wetland Plants (i.e. sedges)-not modeled	500 start plants=40 lbs; 1 plant/ft^2	20 lbs./ 1,553,760 lbs.	100 lbs./ 7,768,800 lbs.		
Post Secondary Treatment (Sand Filter): 83,000 Primary Units							
Sand Filter Excavation	50 years	Excavation		24,300 lbs./ 2,016,900,000 lbs.	24,300 lbs./ 2,016,900,000		
Flexible Liner	50 years	HDPE	60 mm HDPE Liner, 0.3017 lbs/ft^2	65 lbs./ 5,395,000 lbs.	65 lbs./ 5,395,000 lbs.		
Sand	50 years	Sand	3’(h)x15’(w)x6’(l)	28,350 lbs./ 2,353,050,000 lbs.	28,350 lbs./ 2,353,050,000 lbs.		
Piping	50 years	DR 17 HDPE	2” HDPE from LM to Sand Filter and manifold, 1” diameter for laterals	64.5 lbs./ 5,354,129 lbs.	64.5 lbs./ 5,354,129 lbs.		

TABLE A.15: RECIRCULATING BIOFILTER MATERIAL AND ENERGY SUMMARY

SYSTEM COMPONENT	SYSTEM / MAJOR COM-PONENT LIFE EXPECTANCY	MATERIAL	ASSUMPTION	ESTIMATED ITEM WEIGHT INDIVIDUAL/ CUMULATIVE	TOTAL ESTIMATED 50-YR WEIGHT INDIVIDUAL/ CUMULATIVE	ANNUAL KWH INDI-VIDUAL/ CUMULA-TIVE	TOTAL 50-YR KWH INDIVIDUAL/ CUMULA-TIVE
Primary Treatment: 5,000 Primary Treatment Units						4,210 kW-hrs/yr/21,050,000 kW-hr/yr	210,500 kW-hrs/1,052,500,000 kW-hrs
Excavation	50 years	Excavation		306,900 lbs./ 1,534,500,000 lbs.	306,900 lbs./ 1,534,500,000 lbs.		
Dual Compartment Primary Tank	50 years	Fiber Glass	10,000 gallons, 8' Diameter	1,800 lbs./ 9,000,000 lbs.	1,800 lbs./ 9,000,000 lbs.		
Effluent Filter	50years	Polyethene/ Polypropylene	FT1236-54	25 lbs./ 125,000 lbs.	25 lbs./ 125,000 lbs.		
Filter Body	50 years	HDPE		15 lbs./ 75,000 lbs.	16 lbs./ 75,000 lbs.		
Pump	12 years	Steel	PF503012 (Dual Pumps)	110 lbs/ 550,000 lbs.	460 lbs./ 2,300,000 lbs.		
Pump Vault	50 years	Polyethene/ Polypropylene/HDPE	PVU84-2419	60 lbs./ 300,000 lbs.	60 lbs./ 300,000 lbs.		
Secondary Treatment (AdvanTex ® Treatment Pod): 5,000 Primary Treatment Units							
Excavation	50 years	Excavation		56,700 lbs./ 238,500,000 lbs.	56,700 lbs./ 238,500,000 lbs.		
Advantex Filter Holder	50 years	Fiber Glass		500 lbs./ 1,250,000 lbs.	500 lbs./ 1,250,000 lbs.		
Advantex Filter Treatment Media	50 years	Polyester		1,500 lbs./ 8,250,000 lbs.	1,500 lbs./ 8,250,000 lbs.		
Control Panel	25 years	HDPE		20 lbs./ 100,000 lbs.	40 lbs./ 200,000 lbs.		
Float Switch	5 years	HDPE		8 lbs/ 40,000 lbs.	80 lbs/ 400,000 lbs.		
Splice Boxes	50 years	HDPE		2 lbs./ 10,000 lbs.	3 lbs./ 10,000 lbs.		
Discharge Assembly	50 years	HDPE		7 lbs./ 35,000 lbs.	7 lbs./ 35,000 lbs.		
Recirculation Splitter Vlave	50 years	HDPE		25 lbs./ 62,500 lbs.	25 lbs./ 62,500 lbs.		
Pump Vault	50 years	Polyethene/ Polypropylene/HDPE	64" Biotube	60 lbs./ 300,000 lbs.	60 lbs./ 300,000 lbs.		
Pump	12 years	Stainless Steel	PF503012 (Dual Pumps)	110 lbs/ 550,000 lbs.	460 lbs./ 2,300,000 lbs.		

TABLE A.16: MBR SYSTEMS MATERIAL AND ENERGY SUMMARY

SYSTEM COMPONENT	SYSTEM/MAJOR COMPONENT LIFE EXPECTANCY	MATERIAL	ASSUMPTION	ESTIMATED ITEM WEIGHT INDIVIDUAL/ CUMULATIVE	TOTAL ESTIMATED 50-YR WEIGHT INDIVIDUAL/ CUMULATIVE	ANNUAL KWH INDIVIDUAL/ CUMULATIVE	TOTAL 50-YR KWH INDIVIDUAL/ CUMULATIVE
Pretreatment: 2,500 MBR						57,158 KW-hrs/yr/ 142,895,000 KW-hrs/yr	2,857,900 KW-hrs/ 7,144,750,000 KW-hrs
Fine Screen	50 years	Steel		1,500 lbs/ 3,750,000 lbs.	1,500 lbs/ 750,000 lbs.		
Secondary Treatment (MBR): 2,500 MBR							
Concrete Pad Excavation	50 years	Dirt	14' wide X 13' long X 0.83' tall	108,000 lbs./ 270,000,000 lbs.	108,000 lbs./ 270,000,000 lbs.		
Concrete Pad	50 years	Concrete	14' wide X 13' long X 0.83' tall	22,750 lbs./ 56,875,000 lbs.	22,750 lbs./ 56,875,000 lbs.		
Steel Container	50 years	Steel	12' wide X 11' long x 11.5' high	7,380 lbs./ 18,450,000 lbs.	7,380 lbs./ 18,450,000 lbs.		
Mixer	10 years	Steel	22 7 /8" propeller diameter	330 lbs./ 825,000 lbs.	1,650 lbs./ 4,125,000 lbs.		
Aeration System Piping	50 years	PVC	3" diameter, 50 LF of piping (WF)	71 lbs./ 177,500 lbs.	71 lbs./ 177,500 lbs.		
Aeration System Rubber Piping	50 years	Rubber - Silicon-based		300 lbs./ 750,000 lbs.	300 lbs./ 750,000 lbs.		
Pump	10 years	Steel		160 lbs./ 400,000 lbs.	800 lbs./ 2,000,000 lbs.		
MBR Module Steel Houseing	50 years	Steel	WF Estimate	880 lbs./ 2,200,000 lbs.	830 lbs./ 2,075,000 lbs.		
MBR Module Membranes	10 years	PVDF (Polyvinylidene Fluoride) - Not modelled	3'(l)X2.5'(w)X6.9'(h)	50 lbs./ 125,000 lbs.	250 lbs./ 625,000 lbs.		
Recycle Pump	10 years	Steel		110 lbs/ 275,000 lbs.	550 lbs/ 1,375,000 lbs.		
Air Blower	15 years	Cast Iron	3 Air Blowers	235 lbs./ 587,500 lbs.	785 lbs./ 1,962,500 lbs.		
Controls/Portable Instruments	25 years	Polyester		25 lbs./ 62,500 lbs.	50 lbs./ 125,000 lbs.		
Chemicals	2/year	Sodium Hypochlorite		56 lbs./ 140,000 lbs.	5,600 lbs./ 14,000,000 lbs.		

TABLE A.17: CONSTRUCTED WETLAND MATERIAL AND ENERGY SUMMARY

SYSTEM COMPONENT	SYSTEM/MAJOR COMPONENT LIFE EXPECTANCY	MATERIAL	ASSUMPTION	ESTIMATED ITEM WEIGHT INDIVIDUAL/ CUMULATIVE	TOTAL ESTIMATED 50-YR WEIGHT INDIVIDUAL/ CUMULATIVE	ANNUAL KWH INDIVIDUAL/ CUMULATIVE	TOTAL 50-YR KWH INDIVIDUAL/ CUMULATIVE
Primary Treatment: 25 Constructed Wetlands						245,950 kW-Hr/yr/6,148,750 kW-Hr/yr	12,297,500 kW-Hr/307,437,500 kW-Hr
Screw Screen Compactor	50 Years	Steel		1,700 lbs./ 42,500 lbs.	1,700 lbs./ 42,500 lbs.		
Primary Tank and Channel Excavation (500,000 gallons)	50 Years	Excavation		7,321,900 lbs./ 183,047,500 lbs.	7,321,900 lbs./ 183,047,500 lbs.		
Primary Tank and Channel (500,000 gallons)	50 Years	Concrete		2,662,812lbs./ 66,570,300lbs.	2,662,812lbs./ 66,570,300lbs.		
Secondary Treatment (Constructed Wetland): 25 Constructed Wetlands							
Excavation (Stage 1 and 2 Wetland Cells)	50 years	Excavation		22,986,700 lbs./ 574,667,500 lbs.	22,986,700 lbs./ 574,667,500 lbs.		
Concrete Walls	50 years	Concrete	1,242 ft^3	218,700 lbs./ 5,467,500 lbs.	218,700 lbs./ 5,467,500 lbs.		
GeoTextile	50 years	Polyester	72,480 ft^2	4,261 lbs./ 106,525 lbs.	4,261 lbs./ 106,525 lbs.		
Flexible Liner	50 years	EPDM (Ethylene Propylene Diene Monomer)	72,480 ft^2	17,653 lbs./ 441,325 lbs.	17,653 lbs./ 441,325 lbs.		
Filter Media	50 years	Vitrified Slate or Shale		14,462,220 lbs./ 361,555,000 lbs.	14,462,220 lbs./ 361,555,000 lbs.		
Transition Media	50 years	Washed Rock		2,776,613 lbs./ 69,415,35 lbs.	2,776,613 lbs./ 69,415,35 lbs.		
Plants	10 years	Wetland Specific, Bare Root (not modeled)	38,400 Plants, 0.5 lbs each	25,312 lbs./ 632,800 lbs.	126,560 lbs./ 3,164,000 lbs.		
Recirculation Storage	50 years	Atlantis Raintanks-D (engineered plastic)	34,549 ft^2, 2.9 lbs./ft^2	132,095 lbs./ 3,302,375 lbs.	132,095 lbs./ 3,302,375 lbs.		
Pumps	10 years	Stainless Steel Housing and Impellers	Influent Dosing Pumps (2), Recirculation Pumps (10)	4,270 lbs./ 106,750 lbs.	21,350 lbs./ 533,750 lbs.		
Actuated Valves	50 years	PVC	10 Total to Drain Cells	198 lbs./ 4,950 lbs.	198 lbs./ 4,950 lbs.		
Actuated Valves	50 Years	Stainless Steel		402 lbs./ 10,050 lbs.	402 lbs./ 10,050 lbs.		
Level Sensor	10 years	Stainless Steel housing, polyurethane cord		180 lbs./ 4,500 lbs.	900 lbs./ 22,500 lbs.		
Level Sensor Basins and Overflow	10 years	Fiberglass		3,600 lbs./ 90,000 lbs.	18,000 lbs./ 450,000 lbs.		
Piping	50 years	HDPE	cell penetration and connection	32,888 lbs./ 822,188 lbs.	32,888 lbs./ 822,188 lbs.		

TABLE A.18: SUMMARY BILL OF MATERIALS FOR BASELINE CENTRALIZED TREATMENT

COMPONENT	ESTIMATED WEIGHT
Odor Control	
Activated Carbon	56,000 lbs.
Concrete Carbon Bed	129,000 lbs.
Steel Fans	N/I
Primary Screening	
Steel Bar Screens	5,513 lbs.
Aluminum Bar Screens	13,000 lbs.
Screen Presses	N/I
Cast Iron Blowers	850 lbs.
Septage Pumps	N/I
Grit Chambers	N/I
Chrome Iron Grit Pumps	1,700 lbs.
Grit Cyclones	
Steel	2,700 lbs.
Cast Iron	890 lbs.
Grit Classifiers	N/I
Washdown Area Pump	N/I
Primary Clarification	
Concrete Clarifiers	8,951,826 lbs.
Cast Iron Primary Sludge Pumps	770 lbs.
Cast Iron Primary Scum Pumps	385 lbs.
Primary Effluent Pumps	N/I
Secondary Treatment	
Concrete HPO Basins	8,135,880 lbs.
Concrete Secondary Clarifiers	23,980,023 lbs.
Cast Iron Return Activated Sludge Pumps	30,400 lbs.
Waste Activated Sludge Pumps	
Steel	110 lbs.
Cast Iron	370 lbs.
Pressure Tanks	N/I
Cast Iron Secondary Scum Pumps	770 lbs.
Blowers	N/I
Emergency Generator	
Aluminum	6,944 lbs.
Cast Iron	39,360 lbs.
Fuel Tanks	N/I
Dewatering	
Steel Gravity Belt Thickener	15,400 lbs.
Sludge Storage	N/I
Thickening Blowers	
Aluminum	160 lbs.
Cast Iron	930 lbs.
Steel Sludge Dewatering Centrifuges	14,100 lbs.
Aluminum Centrifuge Feed Pumps	1,500 lbs.
Scum Storage	N/I
Scum Concentrator Feed Pumps	N/I
Steel Scum Macerator	396 lbs.
Steel Scum Concentrator	15,000 lbs.
Polymer System	
Bulk Polymer Storage	N/I
Polymer Hopper	N/I
Liquid Feed Pump	N/I
Transfer Pump	N/I
Mix Tank	N/I
Feed Tank	N/I
Feed Pumps Odor Control	N/I
Bulk Polymer	14 lbs./day/ton
Submersible Pump Stations:	
Raw Sewage Station Pumps	
Steel	1,050 lbs.
Chrome	8,400 lbs.
Cast Iron	1,050 lbs.
Cast Iron In-Plane Station Pumps	5,625 lbs.
Steel Dewatering Station Pump	9,705 lbs.

N/I: Materials not inventoried. All N/I materials assumed to be primarily concrete and steel and their weights extrapolated from inventoried materials.

TABLE A.19: CONSTRUCTED WETLAND CONVEYANCE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	NUMBER OF MANHOLES	SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF PVC MATERIAL (lbs)
8	49,238	192	48” Type II	6.00	2.0	590,851	146,947	426,726	PVC	4.24	108,767
10	4,308	17	48” Type I	6.17	2.8	75,272	20,030	52,894	PVC	6.64	28,606
12	3,878	15	48” Type I	6.33	3.0	73,689	20,226	50,419	PVC	9.50	36,845
15	1,841	7	48” Type I	6.58	3.3	39,382	11,202	25,922	PVC	14.19	26,119
18	2,018	8	48” Type I	6.83	3.5	48,263	14,093	30,606	PVC	21.43	43,245
21	813	3	48” Type I	7.08	3.8	21,592	6,429	13,209	PVC	29.88	24,288
24	1,007	4	54” Type I	7.33	4.0	29,538	8,922	17,454	PVC	38.96	39,231
27	64	0	54” Type I	7.58	4.3	2,061	629	1,178	PVC	49.47	3,164
30	1,094	4	54” Type I	7.83	4.5	38,558	11,861	21,330	PVC	64.18	70,203
					TOTAL VOLUME (cf) =	22,980,155	6,008,453	15,993,444			
					TOTAL VOLUME (cy) =	851,117	222,535	592,350			
					TOTAL WEIGHT (lbs) =	2,068,213,909	578,591,769	1,895,519,283			12,011,713
					TOTAL WEIGHT (tons) =	1,034,107	289,296	947,760			6,006

TABLE A.20: RECIRCULATING BIOFILTER CONVEYANCE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	NUMBER OF MANHOLES	SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF PVC MATERIAL (lbs)
8	500	1	48” Type II	6.00	2.0	6,000	1,492	4,333	PVC	4.24	2120
					TOTAL VOLUME (cf) =	30,000,000	7,461,111	21,666,667			
					TOTAL VOLUME (cy) =	1,111,111	276,337	802,469			
					TOTAL WEIGHT (lbs) =	2,700,000,000	718,477,366	2,567,901,235			10,600,000
					TOTAL WEIGHT (tons) =	1,350,000	359,239	1,283,951			5,300

TABLE A.21: MEMBRANE BIOREACTOR CONVEYANCE MATERIAL SUMMARY

DIAMETER (in)	LENGTH (ft)	NUMBER OF MANHOLES	SIZE AND TYPE OF MANHOLES	DEPTH OF EXCAVATION (ft)	WIDTH OF TRENCH (ft)	VOLUME OF EXCAVATION (cf)	PEA GRAVEL BEDDING (cf)	BACKFILL (cf)	MATERIAL	PVC PIPE WEIGHT PER FOOT (lb/ft)	POUNDS OF PVC MATERIAL (lbs)
8	1,000	2	48” Type II	6.00	2.0	12,000	2,984	8,667	PVC	4.24	4,240
					TOTAL VOLUME (cf) =	30,000,000	7,461,111	21,666,667			
					TOTAL VOLUME (cy) =	1,111,111	276,337	802,469			
					TOTAL WEIGHT (lbs) =	2,700,000,000	718,477,366	2,567,901,235			10,600,000
					TOTAL WEIGHT (tons) =	1,350,000	359,239	1,283,951			5,300

TABLE A.22: LIFE-CYCLE ANALYSIS GAPS AND LIMITATIONS

CENTRALIZED BASELINE
Model accounted for an estimated 60 percent of the Bill of Materials for the system.
Inventory for the model was adjusted to account for missing 40 percent assuming an inventory profile consistent with the characterized materials
Composting Toilet Scenario
Model accounted for more than 99.9 percent of the Bill of Materials for the system
No inventory was identified for Wetland Plants, which were not accounted for in the model
On-site excavation material was assumed to be used for backfill
Remaining excavation material was assumed to go to storage for reuse elsewhere
Topsoil was assumed to come from off-site storage, meaning there were no upstream impacts associated with its production
Constructed Wetland Scenario
Model accounted for more than 99.9 percent of the Bill of Materials for the system
No inventory was identified for Wetland Plants, which were not accounted for in the model
Atlantis Rain Tanks were assumed to be made of an engineered plastic, consistent with that suitable for use in underground storage tanks.
Recirculating Biofilter Scenario
Model accounted for 100 percent of the Bill of Materials for the system
Polyethylene/polypropylene blends were assumed to be 80/20 blends
Membrane Bioreactor Scenario
Model accounted for more than 99.5 percent of the Bill of Materials for the system
No inventory was identified for PVDF (polyvinylidene fluoride), which was not accounted for in the model
Rubber was modeled as Silicon-based rubber (SBR).

TABLE A. 23: TRANSPORTATION DISTANCES

MATERIAL	DISTANCE	% OF FULL LOAD
Metals		
Steel	2,400 miles	85%
Cast Iron	2,400 miles	85%
Aluminum	2,000 miles	85%
Plastics		
All plastics	2,000 miles	85%
Stone/Sand/Soil		
Slate	1,500 miles	85%
Stone, Aggregate	30 miles	85%
Sand/Soil	30 miles	85%
Concrete	60 miles	95%
Chemicals	2,000 miles	85%
Excavation Waste	30 miles	95%

APPENDIX B. LIFE-CYCLE ASSESSMENT FULL RESULTS

CONVEYANCE ANALYSIS

The following are the results of a life-cycle analysis of the conveyance portion of wastewater systems only (excluding treatment). The results are organized and presented in response to specific questions posed by the research team. These results reflect three modeling scenarios, including the current conveyance system used for the Baseline City (Baseline) as well as two alternative scenarios that contemplate the conveyance needed at alternative density scales.

Baseline – Analysis modeled after Baseline City's existing conveyance system (2 DU/A)
DS1 – Density Scenario 1, slightly more dense population (10 DU/A)
DS2 – Density Scenario 2, dense population (30 DU/A)

TABLE B.1: OVERALL LIFE-CYCLE IMPACTS OF CONVEYANCE SYSTEM (BY SCENARIO)

IMPACT CATEGORIES	BASELINE	DS1	% FROM BASELINE	DS2	% FROM BASELINE
Aquatic acidification [kg SO2-Eq.]	891,700	248,000	-72.2%	19,130	-97.9%
Aquatic Ecotoxicity [ton TEG Eq.]	364,800,000	96,720,000	-73.5%	2,801,000	-99.2%
Aquatic Eutrophication [kg PO4-Eq.]	4,747	1,452	-69.4%	257.5	-94.6%
Respiratory effects [kg PM2.5-Eq.]	148,400	44,450	-70.1%	7,432	-95.0%
Global Warming Air [kg CO_2-Eq.]	182,300,000	53,170,000	-70.8%	6,784,000	-96.3%
Ozone Depletion Air [kg CFC 11-Eq.]	4.187	1.365	-67.4%	0.3526	-91.6%
Smog Air [kg NOx-Eq.]	6.724	2.122	-68.4%	0.452	-93.3%

Impacts of Conveyance Per Mile- Results

Results of the baseline modeling divided by the distance in miles of the overall conveyance system for each scenario.

Total Miles of conveyance per scenario: Baseline – 315.5 miles
DS1 – 90.4 miles
DS2 – 41.2 miles

TABLE B.2: NORMALIZED LIFE-CYCLE IMPACTS PER MILE OF CONVEYANCE (BY SCENARIO)

IMPACT CATEGORIES	BASELINE	DS1	% FROM BASELINE	DS2	% FROM BASELINE
Aquatic acidification [kg SO2-Eq.]	2,826	2,745	-2.9%	463.9	-83.6%
Aquatic Ecotoxicity [Ton TEG Eq.]	1,156,000	1,070,000	-7.4%	67,990	-94.1%
Aquatic Eutrophication [kg PO4-Eq.]	15.05	16.07	6.8%	6.24	-58.5%
Respiratory effects [kg PM2.5-Eq.]	470.5	492.0	4.6%	180.2	-61.7%
Global Warming Air [kg CO_2-Equiv.]	578,000	588,500	1.8%	164,500	-71.5%
Ozone Depletion Air [kg CFC 11-Equiv.]	0.01327	.01511	13.8%	0.008549	-35.6%
Smog Air [kg NOx-Equiv.]	0.02132	0.02348	10.2%	0.01095	-48.6%

Pumping Energy Relative to the Embodied Energy of the System – Results

Results display the overall impacts associated with the operation of the conveyance system (i.e. pumping energy). Results were calculated by modeling the impacts associated with the entire system (baseline model) minus the contribution associated with the production of the energy consumed (found under the pumping station model).

Annual energy consumption per pump station:	Small Pump stations 448,250 kWh over 50 yr lifespan
	Large Pump stations 11,721,200 kWh over 50 yr lifespan

TABLE B.3: PERCENT CONTRIBUTION TO OVERALL IMPACTS – OPERATING ENERGY

	BASELINE			DS1		
RESULTS	OVERALL	OPERATING	% CONT	OVERALL	OPERATING	% CONT
Acidification [kg SO2]	8.92E+05	7.79E+05	87.3	2.48E+05	2.02E+05	81.6
Aquatic Ecotoxicity [Ton TEG Eq.]	3.65E+08	3.45E+08	94.5	9.67E+07	8.96E+07	92.7
Eutrophication[kg PO4]	4.75E+03	3.08E+03	64.8	1.45E+03	8.00E+02	55.1
Respiratory [kg PM2.5]	1.48E+05	1.02E+05	69.0	4.44E+04	2.66E+04	59.9
Global Warming [kg CO_2]	1.82E+08	1.41E+08	77.3	5.32E+07	3.66E+07	68.9
Ozone Depletion [kg CFC 11]	4.19E+00	2.03E+00	48.4	1.36E+00	5.27E-01	38.6
Smog [kg NOx]	6.72E+00	3.78E+00	56.2	2.12E+00	9.82E-01	46.3

Pumping Stations Relative to the Overall Impacts of the System

Analysis assessed the impact of the entire pump station including materials and operating energy. Results were calculated by totaling all of the impacts associated with the pump stations and comparing them to the overall impacts of the entire conveyance system.

TABLE B.4: PERCENT CONTRIBUTION TO OVERALL IMPACTS – OPERATING ENERGY PUMP STATIONS

	BASELINE			DS1		
RESULTS	OVERALL	OPERATING	% CONT	OVERALL	OPERATING	% CONT
Acidification [kg SO2]	8.92E+05	7.79E+05	87.4	2.48E+05	2.03E+05	81.7
Aquatic Ecotoxicity [Ton TEG Eq.]	3.65E+08	3.46E+08	94.8	9.67E+07	8.98E+07	92.9
Eutrophication[kg PO4]	4.75E+03	3.11E+03	65.6	1.45E+03	8.09E+02	55.7
Respiratory [kg PM2.5]	1.48E+05	1.03E+05	69.4	4.44E+04	2.68E+04	60.2
Global Warming [kg CO_2]	1.82E+08	1.41E+08	77.6	5.32E+07	3.68E+07	69.1
Ozone Depletion [kg CFC 11]	4.19E+00	2.06E+00	49.1	1.36E+00	5.34E-01	39.1
Smog [kg NOx]	6.72E+00	3.82E+00	56.8	2.12E+00	9.92E-01	46.8

Impacts from Excavation

This analysis identifies and totals the impacts associated directly with excavation of the conveyance system. Impacts include operation of equipment and transportation of removed waste. Results were calculated by totaling the life-cycle impact contributions from both the excavation and hauling of waste associated with each component, and then comparing those total impacts to the overall impacts of the system. Results are expressed as a percent of overall life-cycle impacts.

TABLE B.5: PERCENT CONTRIBUTION OF EXCAVATION AND TRANSPORTATION OF WASTE TO OVERALL LIFE-CYCLE IMPACTS OF CONVEYANCE SCENARIOS

	BASELINE		DS1		DS2	
IMPACT CATEGORIES	EXCAVATION	TRANS	EXCAVATION	TRANS	EXCAVATION	TRANS
Aquatic acidification [kg SO2-Eq. to air]	0.12%	0.02%	0.16%	0.02%	0.92%	0.12%
Aquatic Eutrophication [kg PO4-Eq.]	0.33%	0	0.42%	0	1.03%	0
Respiratory effects [kg PM2.5-Eq. to air]	1.25%	2.90%	1.61%	3.80%	4.24%	9.87%
Global Warming Air [kg CO_2-Equiv.]	0.37%	1.77%	0.49%	2.38%	0.22%	1.04%
Ozone Depletion Air [kg CFC 11-Equiv.]	1.99%	0	2.35%	0	4.01%	0
Smog Air [kg NOx-Equiv.]	0.79%	1.40%	0.97%	1.73%	2.00%	3.54%

Impacts Associated with Piping

Results display the percentage of impacts associated with piping (including manholes) and pump stations (including operating energy). Results were calculated by modeling the impacts associated with the entire system (baseline model) and totaling the impacts associated with each category. Results are expressed as percentages of the total. Results for DS2 are excluded since there are no pumping stations in the scenario and the impacts from type of pipe are not the focus of this analysis.

TABLE B.6: PERCENT IMPACTS OF PIPING FOR SYSTEM – BASELINE

IMPACT CATEGORIES	PVC	RCP	DI	HDPE	MANHOLES	PUMP STATIONS
Aquatic acidification [kg SO2-Eq]	10.7%	0.4%	0.1%	0.3%	1.1%	87.4%
Aquatic Eutrophication [kg PO4-Eq]	15.9%	5.1%	0.7%	0.0%	12.7%	65.6%
Respiratory effects [kg PM2.5-Eq]	21.7%	2.0%	0.8%	0.4%	5.7%	69.4%
Global Warming Air [kg CO_2-Equiv.]	16.4%	1.6%	0.3%	0.4%	3.7%	77.6%
Ozone Depletion Air [kg CFC 11-Equiv.]	36.7%	4.2%	1.1%	0.3%	8.6%	49.1%
Smog Air [kg NOx-Equiv.]	25.5%	3.4%	1.7%	1.0%	11.7%	56.8%

TABLE B.7: PERCENT IMPACTS OF PIPING FOR SYSTEM – DS1

IMPACT CATEGORIES	PVC	RCP	DI	HDPE	MANHOLES	PUMP STATIONS
Aquatic acidification -[kg SO2-Eq.]	15.2%	1.0%	0.1%	1.0%	1.1%	81.7%
Aquatic Eutrophication [kg PO4-Eq.]	20.4%	11.7%	0.2%	0.1%	11.9%	55.7%
Respiratory effects -[kg PM2.5-Eq.]	28.1%	4.7%	0.3%	1.2%	5.4%	60.3%
Global Warming Air [kg CO_2-Equiv.]	21.9%	3.7%	0.1%	1.4%	3.7%	69.2%
Ozone Depletion Air [kg CFC 11-Equiv.]	41.1%	8.9%	0.3%	3.2%	7.5%	39.1%
Smog Air [kg NOx-Equiv.]	33.5%	7.5%	0.6%	1.0%	10.6%	46.8%

TABLE B.8: LCA IMPACTS OF TREATMENT SYSTEMS ONLY – ABSOLUTE VALUES

IMPACT	UNITS	CENTRALIZED BASELINE	COMP TOILETS	MBR	RECIRC BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	2.30E+06	1.40E+06	4.10E+07	6.10E+06	1.80E+06
Aq. Ecotoxicity	kg TEG Eq.	1.00E+12	5.30E+11	1.80E+13	2.70E+12	7.90E+11
Eutrophication	kg PO4-Eq.	9.30E+03	5.80E+03	1.70E+05	2.50E+04	7.30E+03
Respiratory Effects	kg PM2.5-Eq.	3.10E+05	3.10E+05	5.40E+06	8.20E+05	2.90E+05
Global Warming	kg CO_2-Eq.	4.30E+08	3.40E+08	7.40E+09	1.10E+09	3.60E+08
Ozone Depletion	kg CFC 11-Eq.	6.20E+00	3.30E+01	1.10E+02	1.90E+01	9.70E+00
Smog Air	kg NOx-Eq.	1.40E+01	1.50E+01	2+00E+02	3.10E+01	1.20E+01

TABLE B.9: COMPARISON OF TREATMENT SYSTEMS ONLY IMPACTS TO CENTRALIZED BASELINE

IMPACT	UNITS	COMP TOILETS	MBR	RECIRC. BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	-38%	1640%	160%	-22%
Aq. Ecotoxicity	Kg TEG Eq.	-49%	1645%	159%	-24%
Eutrophication	kg PO4-Eq.	-37%	1709%	166%	-22%
Respiratory Effects	kg PM2.5-Eq.	-1%	1649%	165%	-6%
Global Warming	kg CO_2-Eq.	-19%	1632%	164%	-15%
Ozone Depletion	kg CFC 11-Eq.	437%	1643%	203%	56%
Smog Air	kg NOx-Eq.	6%	1366%	126%	-13%

TABLE B.10: LCA IMPACTS OF ALL TREATMENT SYSTEMS + CONVEYANCE – ABSOLUTE VALUES

IMPACT	UNITS	CENTRALIZED BASELINE	COMP TOILETS	MBR	RECIRC. BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	3.20E+06	1.40E+06	4.10E+07	6.10E+06	1.80E+06
Aq. Ecotoxicity	kg TEG Eq.	1.40E+12	5.30E+11	1.80E+13	2.70E+12	7.90E+11
Eutrophication	kg PO4-Eq.	1.40E+04	5.80E+03	1.70E+05	2.50E+04	7.30E+03
Respiratory Effects	kg PM2.5-Eq.	4.60E+05	3.10E+05	5.40E+06	8.20E+05	2.90E+05
Global Warming	kg CO_2-Eq.	6.10E+08	3.40E+08	7.40E+09	1.10E+09	3.70E+08
Ozone Depletion	kg CFC 11-Eq.	1.10E+01	3.30E+01	1.10E+02	1.90E+01	9.80E+00
Smog Air	kg NOx-Eq.	2.10E+01	1.50E+01	2+00E+02	3.10E+01	1.20E+01

TABLE B.11: TREATMENT + CONVEYANCE RELATIVE TO CENTRALIZED BASELINE-NEW

IMPACT	UNITS	COMP TOILETS	MBR	RECIRC BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	-55%	1160%	88%	-43%
Aq. Ecotoxicity	Kg TEG Eq.	-62%	1190%	92%	-43%
Eutrophication	kg PO4-Eq.	-58%	1098%	76%	-48%
Respiratory Effects	kg PM2.5-Eq.	-33%	1083%	79%	-36%
Global Warming	kg CO_2-Eq	-44%	1113%	85%	-40%
Ozone Depletion	kg CFC 11-Eq	221%	942%	81%	-6%
Smog Air	kg NOx-Eq	-29%	887%	52%	-41%

TABLE B.12: MBR SENSITIVITY RESULTS – (TREATMENT + CONVEYANCE RELATIVE TO CENTRALIZED BASELINE)

IMPACT	CENTRALIZED BASELINE	MBR	MBR + CONVEYANCE	
			(low)	(high)
Acidification	3.20E+06	1160%	453%	1444%
Ecotoxicity	1.40E+12	1190%	468%	1481%
Eutrophication	1.40E+04	1098%	456%	1357%
Respiratory Effects	4.60E+05	1083%	427%	1347%
Global Warming	6.10E+08	1113%	435%	1387%
Ozone Depletion	1.00E+01	942%	370%	1172%
Smog Air	2.10E+01	887%	349%	1104%

Low and High scenarios reflect range of values for energy consumption received from manufacturers of MBR technologies. All other BOM materials entries are identical to baseline MBR.

TABLE B.13: PERCENT CONTRIBUTION OF TREATMENT VERSUS CONVEYANCE

IMPACT	CENTRALIZED BASELINE	COMP TOILETS	MBR	RECIRC BIOFILTER	WETLAND
Acidification	72/28	100/0	100/0	100/0	99.8/0.2
Aq. Ecotoxicity	74/26	100/0	100/0	100/0	99.9/0.1
Eutrophication	66/34	100/0	100/0	100/0	99.3/0.7
Respiratory Effects	67/33	100/0	100/0	100/0	99.4/0.6
Global Warming	70/30	100/0	100/0	100/0	99.6/0.4
Ozone Depletion	58/42	100/0	100/0	100/0	99.2/0.8
Smog Air	67/33	100/0	100/0	100/0	99.2/0.8

TABLE B.14: PERCENT OF OVERALL TREATMENT IMPACTS DUE TO ENERGY

IMPACT	UNITS	CENTRALIZED BASELINE	COMP TOILETS	RECIRC BIOFILTER	MBR	WETLAND
Acidification	kg SO2-Eq.	99.80%	71.70%	98.30%	99.80%	95.70%
Aq. Ecotoxicity	kg TEG Eq.	99.80%	86.40%	98.70%	99.50%	97.60%
Eutrophication	kg PO4-Eq.	99.10%	69.90%	95.50%	95.10%	94.20%
Respiratory Effects	kg PM2.5-Eq.	99.10%	44.10%	95.90%	98.50%	78.70%
Global Warming	kg CO_2-Eq	99.00%	54.30%	96.10%	99.40%	86.40%
Ozone Depletion	kg CFC 11-Eq	97.80%	8.10%	82.80%	97.60%	46.40%
Smog Air	kg NOx-Eq	81.80%	34.10%	92.80%	96.90%	69.40%

TABLE B.15: PERCENT OVERALL IMPACTS DUE TO ENERGY - TREATMENT + CONVEYANCE

IMPACT	UNITS	CENTRALIZED BASELINE	COMP TOILETS	MBR	RECIRC BIOFILTER	WETLAND
Acidification	kg SO2-Eq.	96.4	71.7	99.8	98.3	95.7
Aq. Ecotoxicity	kg TEG Eq.	98.5	86.4	99.5	98.7	97.6
Eutrophication	kg PO4-Eq.	87.5	69.9	95.1	95.5	94.2
Respiratory Effects	kg PM2.5-Eq.	89.3	44.1	98.5	95.9	78.7
Global Warming	kg CO_2-Eq	92.6	54.3	99.4	96.1	86.4
Ozone Depletion	kg CFC 11-Eq	78	8.1	97.6	82.8	46.4
Smog Air	kg NOx-Eq	73.5	34.1	96.9	92.8	69.4

APPENDIX C. LIFE-CYCLE IMPACT CATEGORY METHODOLOGIES

Several key life-cycle impact category methodologies were used during the assessment of the environmental impacts of the wastewater treatment technologies in this report. A brief description of each and how the impact data are calculated is presented here.

TABLE C.1: IMPACT CATEGORIES

IMPACT CATEGORY	SOURCE	TYPE	UNITS/EQUIVALENTS
Aquatic acidification	IO2+ v2.1	Midpoint	kg SO2-Eq.
Aquatic Ecotoxicity	IO2+ v2.1	Midpoint	kg TEG-Eq
Aquatic Eutrophication	IO2+ v2.1	Midpoint	kg PO4-Eq.
Respiratory effects	IO2+ v2.1	Midpoint	kg PM2.5 Eq
Global Warming Air	Traci	Midpoint	kg CO_2-Eq
Ozone Depletion Air	Traci	Midpoint	kg CFC 11-Eq
Smog Air	Traci	Midpoint	kg NOx-Eq

Eutrophication

Eutrophication (nutrient enrichment) impacts to water are based on the identity and concentrations of eutrophication chemicals released to surface water after treatment. Equivalency factors for eutrophication have been developed assuming nitrogen (N) and phosphorus (P) are the two major limiting nutrients. Therefore, the partial equivalencies are based on the ratio of N to P in the average composition of algae (C106H263O110N16P) compared to the reference compound phosphate (PO4 3-) (Heijungs et al., 1992; Lindfors et al., 1995). If the wastewater stream is first sent to a publicly-owned treatment works (POTW), treatment is considered as a separate process, and the impact score would be based on releases from the POTW to surface waters. Impact characterization is based on eutrophication potentials (EP) and the inventory amount:

$$(ISEUTR)_i = (EFEP \times AmtEC)_i$$

where:

ISEUTR equals the impact score for regional water quality impacts from chemical i (kg phosphate equivalents) per functional unit;

EFEP equals the EP equivalency factor for chemical i (phosphate equivalents); and

AmtEC equals the inventory mass (kg) of chemical i per functional unit of eutrophication chemical in a wastewater stream released to surface water after any treatment, if applicable.

Global Warming Potential

The build-up of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere generates a "greenhouse effect" of rising temperature and climate change. Global Warming Potential (GWP) refers to the warming, relative to CO_2, that chemicals contribute to this effect by trapping the Earth's heat. The impact scores for the effects of global warming and climate change are calculated using the mass of a global warming gas released to air, modified by a GWP equivalency factor. The GWP equivalency factor is an estimate of a chemical's atmospheric lifetime and radiative forcing that may contribute to global climate change compared to the reference chemical CO_2; therefore, GWPs are in units of CO_2 equivalents. GWPs having effects in the 100-year time horizon were used in this analysis. The equation to calculate the GWP impact score for an individual chemical is as follows:

$$(ISGW)i = (EFGWP \text{ x } AmtGG)i$$

where:

ISGW	equals the global warming impact score for greenhouse gas chemical i (kg CO_2 equivalents) per functional unit;
EFGWP	equals the GWP equivalency factor for greenhouse gas chemical i (CO_2 equivalents, 100-year time horizon); and
AmtGG	equals the inventory amount of greenhouse gas chemical i released to air (kg) per functional unit.

Respiratory Effects caused by Air Particulate Impacts

Air particulate impacts refer to the release and build-up of particulate matter primarily from combustion processes. Impact scores are based on the amount released to the air of particulate matter (PM) with average aerodynamic diameter less than 2.5 micrometers (PM2.5), the size of particulate matter that is most damaging to the respiratory system. Air particulate releases may cause decreased respiratory capacity and may trigger respiratory distress in populations with current respiratory illness. Impact characterization is based on the inventory amount of particulates released to air. This loading impact score is calculated by:

$$IS_{PM} = Amt_{PM}$$

where:

IS_{PM}	equals the impact score for particulate (kg $PM_{2.5}$) per functional unit; and
Amt_{PM}	equals the inventory amount of particulate release ($PM_{2.5}$) to the air (kg) per functional unit.

Photochemical Smog Impacts

Photochemical oxidants are produced in the atmosphere from sunlight reacting with hydrocarbons and nitrogen oxides. At higher concentrations they may cause or aggravate health problems, plant toxicity and deterioration of certain materials. Photochemical oxidant creation potential (POCP) refers to the release of chemicals that contribute to this effect. The POCP is based on simulated trajectories of tropospheric ozone production both with and without volatile organic carbons (VOCs) present. The POCP is a measure of a specific chemical compared to the reference chemical ethene (Heijungs et al., 1992). Photochemical smog impacts are based on partial equivalency because some chemicals cannot be converted into POCP equivalency factors. For example, nitrogen oxides do not have a POCP; however, VOCs are assumed to be the limiting factor, and if VOCs are present there is a potential impact. Impact scores are based on the identity and amount of chemicals with POCP equivalency factors released to the air and the chemical-specific equivalency factor:

$$(IS_{POCP})_i = (EF_{POCP} \times Amt_{POC})_i$$

where:

IS_{POCP}	equals the photochemical smog (POCP) impact score for chemical *i* (kg ethene equivalents) per functional unit;
EF_{POCP}	equals the POCP equivalency factor for chemical *i* (ethene equivalents); and
Amt_{POC}	equals the amount of photochemical smog-creating oxidant *i* released to the air (kg) per functional unit.

Acidification

Acidification impacts refer to the release of chemicals that may contribute to the formation of acid precipitation. Impact characterization is based on the amount of a chemical released to air that would cause acidification and the acidification potentials (AP) equivalency factor for that chemical. The AP equivalency factor is the number of hydrogen ions that can theoretically be formed per mass unit of the pollutant being released compared to sulfur dioxide (SO2) (Heijungs et al., 1992; Hauschild and Wenzel, 1997). The impact score is calculated by:

$$(ISAP)_i = (EFAP \times AmtAC)_i$$

where:

ISAP	equals the impact score for acidification for chemical *i* (kg SO2 equivalents) per functional unit;
EFAP	equals the AP equivalency factor for chemical *i* (SO2 equivalents); and
AmtAC	equals the amount of acidification chemical *i* released to the air (kg) per functional unit.

Aquatic Ecotoxicity

Aquatic ecotoxicity refers to the release of potentially toxic substances and their impacts on fresh water ecosystems. Impact characterization is based on the amount of chemical released into air, water or soil that would contribute to increased toxicity in the receiving waters, along with the characterization factors (CF) for each chemical. The CF for each chemical is then expressed in terms of the reference chemical triethylene glycol (TEG) equivalents. The impact score is calculated by:

$$(\mathrm{ISAE})i = (\mathrm{CFAE} \times \mathrm{AmtAE})i$$

where:

ISAE	equals the impact score for aquatic ecotoxicity for chemical *i* (kg TEG equivalents) per functional unit;
CFAE	equals the CF for chemical *i* (TEG equivalents); and
AmtAE	equals the amount of aquatic ecotoxin chemical *i* released to the air, water or ground (kg) per functional unit.

Emissions into ocean can be considered as having no fresh water aquatic ecotoxicity. No specific CFs for ocean emissions are currently available. Aquatic ecotoxicity characterization factors for heavy metals only apply for metals emitted in dissolved form (ions).

Ozone Depletion

The stratospheric ozone layer filters out harmful ultraviolet radiation from the sun. Chemicals such as chlorofluorocarbons, if released to the atmosphere, may result in ozone-destroying chemical reactions. Stratospheric ozone depletion refers to the release of chemicals that may contribute to this effect. Impact scores are based on the identity and amount of ozone depleting chemicals released to air. Currently identified ozone depleting chemicals are those with ozone depletion potential (ODP), which measure the change in the ozone column in the equilibrium state of a substance compared to the reference chemical chlorofluorocarbon (CFC), CFC-11 (trichloroflurommethane) (Heijungs et al., 1992; CAAA, 1990). The individual chemical impact score for stratospheric ozone depletion is based on the ODP and inventory amount of the chemical:

$$(\mathrm{ISOD})i = (\mathrm{EFODP} \times \mathrm{AmtODC})i$$

where:

ISOD	equals the ozone depletion (OD) impact score for chemical *i* (kg CFC-11 equivalents) per functional unit;
EFODP	equals the ODP equivalency factor for chemical *i* (CFC-11 equivalents); and
AmtODC	equals the amount of ozone depleting chemical *i* released to air (kg) per functional unit.

APPENDIX D. PROJECT HIGHLIGHTS DESIGN TEAMS

Bertschi School Living Building Science Wing
Restorative Design Collaborative: KMD Architects / 2020 Engineering / GGLO / GeoEngineers / Quantum Consulting Engineers / Rushing / O'Brien and Company / Back To Nature Design LLC / Parsons Public Relations / Skanska

Bullitt Center
The Miller | Hull Partnership / 2020 Engineering / PAE Consulting Engineers / The Berger Partnership / Integrated Design Lab / Schuchart Construction Co. / The University of Washington's Integrated Design Lab

C. K. Choi Building: The Institute of Asian Research
Matsuzaki Wright Architects Inc. / Keen Engineering / BNIM Architects / Country West Construction, Ltd.

Dockside Green Development
Busby Perkins + Will / Stantec / PWL Landscape Architects / Farmer Constructors / Aqua-Tex / BuildGreen Consulting

IslandWood
Mithun / KEEN Engineering / 2020 Engineering / The Berger Partnership / Archemy Consulting

Omega Center for Sustainable Living
BNIM Architects / John Todd Ecological Design, Inc / Natural Systems International / Conservation Design Forum / Tipping Mar + associates / BGR Engineers / The Chazen Companies / Dave Sember Construction

Oregon Health and Science University: Center for center for Health and Healing
Gerding Edlen Development / GBD Architects / Interface Engineers / Renee Worme / Peterson Kolberg Associates / KPFF / Otak / Walker Macy / Hoffman Construction / Brightworks

Rocky Bay
Orcas Sewage Design

Sidwell Friends School
Kieran Timberlake Associates, LLP / Natural Systems International / Andropogon Associates

Tyson Living Learning Center
Hellmuth + Bicknese, Solutions AEC, Williams Creek Consulting, ASDG LLC, Bingman Construction

APPENDIX E. GLOSSARY OF TERMS

5-tray system – Special tray system designed to utilize composting worms in processing waste, usually comprised of five trays stacked on top of each other.

Acidification – The lowering of the pH in water due to chemical inputs or biochemical processes.

Activated sludge – A method of aerobic wastewater treatment wherein microbial flocs leaving a mixed aeration treatment tank are settled in a clarifier and concentrated as a sludge, followed by returning a high fraction to the aeration tank. This increases the concentration of microorganisms in the aeration treatment tank to more rapidly biodegrade the organic content of the wastewater.

Aerator – An apparatus that adds air to water.

Aerobic – A condition in which oxygen is present or required.

Anaerobic – A condition in which oxygen is not present or required.

Anoxic – A condition in which water lacks significant oxygen, but has aqueous nitrate-nitrogen.

Aquatic ecotoxicity – The effects of water-borne pollutants on the environment.

Bar screen – A stationary screen comprising longitudinal bars, spaced at intervals, onto which the material to be screened is fed at the upper end.

Biochemical oxygen demand (BOD) – The amount of oxygen used by microorganisms to stabilize a given volume of wastewater with decomposable organic matter under aerobic conditions.

Bill of materials – A specification of the materials authorized for production of a specific item.

Blackwater – Water containing human waste from toilets and urinals. Black water contains pathogens that must be neutralized before the water can be safely reused.

Carbon bed – A layer of carbon in a reservoir or tank, used to filter water or wastewater.

Carbon positive – A description for any item or event that takes more greenhouse gases out of the atmosphere than it emits.

Cast-in-place pipe (CIPP) – Cementitious mixture that is deposited as plastic concrete and hardens as a pipe.

Clean Water Act – The primary federal law in the United States governing water pollution.

Closed-loop water system – A water loop is defined to be “closed,” for water treatment purposes, if the make-up rate is less than 10% of the system capacity per year.

Combined sewer overflow – An event that takes place, often with the aid of a control device, that allows for a combined stormwater and wastewater sewer to overflow into area waterways in order to prevent flooding.

Composting toilet – A non-water discharging toilet waste system designed to aerobically biodegrade human waste.

Constructed wetland – A system that mimics the processes of a natural wetland used to treat wastewater.

Conveyance – A means of transporting water or wastewater.

Daylighting – The exposing of streams currently running through culverts to a more natural setting.

Decentralized wastewater management – A system that provides collection, treatment and dispersal or reuse of wastewater from individual buildings or clusters of buildings at or near the location where the waste is generated. These types of systems may treat sewage on-site through natural and/or mechanical processes, or may utilize more distributed management systems to collect and treat waste at a neighborhood, district or small community scale.

Dewatering – The process of removing water from waste solids.

Disinfection – The destruction of pathogenic and other kinds of microorganisms by physical or chemical means.

Drainfield – The network of pipes in a septic system through which wastewater is dispersed into the soil.

Dry well – An underground storage and infiltration system used for stormwater.

Ductile iron (DI) – A type of iron used for water mains that generally has the properties of high strength, ductility and resistance to impact.

Earth berm – A bank of earth constructed for a specific purpose, generally water or land control.

Eco Machine – A wastewater system that uses aquatic plants and microorganisms to treat water, sometimes in a greenhouse.

Effluent – Liquid waste discharged from a processing facility.

Eutrophication – The accumulation of high enough concentrations of nutrients in a body of water to lead to excessive algae growth and depletion of oxygen levels in the water.

Evapotranspiration – The process by which water is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

Exfiltration – Wastewater leaking from a sewer pipe into the surrounding soil.

Flocculate – Formation of small clumps of organisms in water.

Foam flush – The use of a mixture of compostable soap and water to moves waste down a composting toilet.

Global warming – An increase in the temperature of the air near the surface of the earth thought to be caused by human activities.

Gravity belt thickener – A machine used to drain water from sludge, thereby reducing the sludge volume.

Green building – A comprehensive process of design and construction that employs techniques to minimize adverse environmental impacts and reduce the energy consumption of a building.

Greywater – Wastewater stemming from non-fecal contaminated activities such as laundering clothes or bathing.

Grit – Small, loose, dense particles present in wastewater.

Grit cyclone – A system that separates the lighter substances of organics and excess water from the denser grit.

Grit washdown sump pump – A sump pump that removes grit after it settles in a tank.

Groundwater – Water held underground in saturated soil or in pores and crevices in rock.

High-density polyethylene (HDPE) – A polyethylene thermoplastic made from petroleum, used in some wastewater pipes.

High purity oxygen (HPO) – A gas that is 99.99 percent oxygen.

Humus – The organic component of soil, formed by the decomposition of leaves and other plant material by soil microorganisms.

Impact analysis – Any assessment in which the environmental impacts of a process, product or facility are determined.

Incinerating toilet – An independent unit that receives and incinerates waste into water and a clean ash.

Intermittent sand filter – A bed of sand with microbes to filter and treat measured intermittent doses of wastewater.

Life-cycle analysis – A tool that evaluates the environmental impacts of a product across its entire life-cycle.

Life-cycle inventory (LCI) – An accounting of the energy and waste associated with the creation of a new product through use and disposal.

Liquid scrubber system – A system that removes pollutants from a waste stream, generally gas, by running the gas through a stream of liquid.

Living Machine® – A trademark and brand name for a form of biological wastewater treatment designed to mimic the cleansing functions of wetlands, developed and marketed by Worrell Water Technologies.

Macerator – A pump that is constructed to empty holding tanks and grind waste down to small particle size.

Membrane bioreactor – A packaged activated-sludge system in which the secondary clarifier has been replaced with an ultra-filtration membrane with pores small enough to filter out bacteria, micro-organisms and other insoluble solids.

Nutrient cycle – A pathway by which a chemical element or molecule moves through the environment.

Night soil – Human excrement generally used for fertilizer.

Open-celled foam – Foam containing pores that are connected to each other and form an interconnected structure, such as soap.

Oscillatoria rubescens – A blue-green algae from the cyanobacterium phylum sometimes responsible for algae blooms.

Oxidative reaction – The process or result of oxidizing or being oxidized.

Ozone depletion – The reduction of the protective layer of ozone in the upper atmosphere by chemical pollution.

Passive system – A system that does not use external mechanical power.

Photochemical smog – Air pollution produced by the action of sunlight on hydrocarbons, nitrogen oxides and other pollutants.

Polymer hopper – A structure used for the storage of polyelectrolytes in the polymer system.

Polymer system – A system that uses polyelectrolytes to initiate flocculation in wastewater.

Polyvinyl chloride (PVC) – A chemically-resistant plastic often used in pipes.

Polyvinylidene fluoride – A thermoplastic fluoropolymer of high purity and resistance to solvents, acids and alkalis.

Primary clarification – A process in which the rate of flow of the raw wastewater is greatly reduced and solids are allowed to settle out.

Privy vault – A cistern filled with wastewater; synonymous with cesspool.

Reciprocating rake bar screen – a type of mechanical bar screen that simulates the movement of a person raking the bar screen.

Recirculating biofilter – A system of chambers with highly-porous materials that provide growth surface for an active microbial community to treat the water multiple times.

Redlist chemical – Referred to here as a list of chemicals deemed hazardous as defined by the Living Building Challenge Imperative 11.

Respiratory effects – Negative impacts on the action of breathing.

Screw conveyor – A device for moving loose materials that consists of a shaft with a broad, helically-wound blade rotating in a tube or trough.

Scum pump – A suction pump that removes the filmy layer of organic matter that rises to the surface of a wastewater tank.

Septage pump – A pump that removes the partially-treated waste stored in a septic tank.

Septic tank – A tank, typically underground, in which sewage is collected and allowed to settle and decompose through passive bacterial activity before draining to a leaching field.

Sodium hypochlorite – An unstable oxidizing salt (NaOCl) used as a bleaching agent and disinfectant.

Stormwater – Runoff from urban areas that is not absorbed into the ground but rather is conveyed to waterways by natural and man-made conduits and drains.

Suspended solids – Small particles of solid materials suspended in water that cause cloudiness or turbidity.

Thickening blower – A blower used in wastewater treatment to dewater the sludge.

Trapless ventilated urinal – A nonstandard urinal, missing the dipped section of pipe that always contains water, used in composting toilets.

Sludge cake pump – A pump that moves sludge that has been dewatered by a treatment process to a moisture content of 60-85%, depending on the type of sludge and manner of treatment.

Ultra-filtration membrane – A device that forces water under high pressure through a 0.1 micron membrane to catch small particles (including bacteria).

Utilidor – A utility corridor built underground or above ground to carry utility lines such as electricity, water and sewer.

Wastewater treatment –The process of removing or reducing hazards in water, typically including some or all of the following steps:

Primary treatment – A physical treatment process, with or without chemical assistance, in which some heavy metals are removed.

Secondary treatment – A process using biological treatment and sedimentation that removes dissolved and suspended solids ; such as biodegradable organics, volatile organics and some nitrogen and phosphorus.

Tertiary treatment – A process that may include filtration, membrane filtration, and detention in lagoons or wetlands, and is usually combined with coagulation, sedimentation, filtration and disinfection; it removes more nitrogen and phosphorus, dissolved solids and heavy metals.

Wet well – A tank containing a submersible pump for holding and pumping water or sewage.

APPENDIX F. REFERENCES

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APPENDIX G. RESEARCH PROJECT TEAM

CASCADIA GREEN BUILDING COUNCIL

Founded in 1999, Cascadia is a chapter of both the Canada and U.S. Green Building Councils and serves the green building movement in Alaska, British Columbia, Washington and Oregon. Cascadia's mission is to lead a transformation toward a built environment that is socially just, culturally rich and ecologically restorative. Through an extensive network of partners, Cascadia advocates for progressive policies at the local and state levels and provides valuable research to help decision makers make informed decisions for the health of their communities and the environment.

In 2009, Cascadia launched the International Living Building Institute. The Institute is dedicated to encouraging the creation of Living Buildings, Sites and Communities in countries around the world while inspiring, educating and motivating a global audience about the need for fundamental and transformative change.

ECOFORM

Ecoform is the leading technical analysis company in the United States that focuses on the environmental performance of companies and their products and processes. Founded in 2006, Ecoform takes pride in its ability to work with leading corporations across multiple industry sectors providing critical information that can be used to shape corporate policy. Through services such as Life-Cycle Assessment, Ecoform assists organizations with the tools necessary for lowering their environmental footprint, enhancing their market brand and public perception and often saving valuable financial resources.

2020 ENGINEERING

2020 ENGINEERING is at the forefront of research and design of more sustainable methods and systems that reduce material consumption and waste, restore and protect ecological systems and create and maintain healthy communities. Based in the Puget Sound region but working nationally, 2020 ENGINEERING has a track record of over 100 projects that have utilized sustainable and low-impact development methods at residential, commercial, educational and municipal scales. 2020 ENGINEERING has been a leader in promoting the Living Building Challenge and in designing water systems that support net zero water goals and innovative, on-site wastewater treatment and reuse.