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Cost and Performance Report

(ER-201020)

Water Conservation: Tertiary Treatment and Recycling of Waste Water

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14. ABSTRACT
This report encompasses the results of a four year project led by the Naval Facilities Engineering and Expeditionary Warfare Center to demonstrate the potential to treat black water (or sewage) for reuse. The system mimics a tidal wetland system but treats or process wastewater more efficiently, esthetically and economically while using a smaller footprint compared to conventional sewage treatment systems. The system did not meet POTW discharge limits which were chosen at the beginning of the project because they are more stringent. However, the system meets the General Waste Discharge Requirements for Small Domestic Wastewater Treatment Systems (General Order) under the San Diego Regional Water Quality Board (SDRWQCB). In November 2014, the SDRWQCB issued a permit to MCRD that allows the treated reclaimed water to be used for subsurface irrigation. Installation of the subsurface irrigation system in the quadrangle that is home to the Drill Instructor (DI) memorial and the Living Machine was funded by MCRD and completed shortly after demonstration of the Living Machine. Design, equipment and funding to tie in both systems to allow clean water from the Living Machine to be used for irrigation are being pursued by MCRD.

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ACRONYMS AND ABBREVIATIONS

af	acre feet
BOD	biochemical oxygen demand
BOD_5	five day biochemical oxygen demand
°C	degrees Celsius
COD	chemical oxygen demand
DEM/VAL	Demonstration/Validation
DI	Drill Instructor
DoD	Department of Defense
EPA	U.S. Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
FOB	Forward Operating Base
FY	fiscal year
gpd	gallons per day
gpm	gallons per minute
HRT	hydraulic retention time
kWh	kilowatt hour
LEED	Leadership in Energy and Environmental Design
LET	load equalization tank
µg/L	micrograms per liter
MBAS	methylene blue active substances
MCRD	Marine Corps Recruit Depot
MDL	minimum detection level
mg/L	milligram per liter
MPN	most probable number
NA	not applicable
NCRP	North City Reclamation Plan
ND	not determined
NECPA	National Energy Conservation Policy Act
NESDI	Navy Environmental Sustainability and Development to Integration
NH_3	Ammonia
NPDES	National Pollutant Discharge Elimination System
NRDC	Natural Resources Defense Council

ACRONYMS AND ABBREVIATIONS (continued)

NTU	nephelometric turbidity unit
O&M	operation and maintenance
PARCC	precision, accuracy, representativeness, completeness, and comparability
POTW	Publicly Owned Treatment Works
ppm	parts per million
PT	Physical Training
QA	quality assurance
QC	quality control
ROI	return on investment
RPD	relative percent difference
SDHR	San Diego Hydrologic Region
SDRWQCB	San Diego Regional Water Quality Control Board
TDS	total dissolved solid
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TOC	total organic carbon
TP	total petroleum
TSS	total suspended solids
USGS	U.S. Geological Survey
USMC	U.S. Marine Corps
UV	Ultraviolet

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ACKNOWLEDGEMENTS

Primary support for this project was provided by the Environmental Security Technology Certification Program (ESTCP). Steve Crover (retired) and Richard Hatcher at the Marine Corps Recruit Depot consented to host the project and provided substantial additional funding. Supplemental funding provided by the Navy Environmental Sustainability Development to Integration (NESDI) Program supported implementation and tech integration. Eric Lohan and Nate Nickerson (key Living Machine employees) devoted significant time and effort to the project and demonstrated an uncanny ability to work through problems that arose during installation and start-up. Unfortunately, a recent restructuring at Living Machine eliminated the technical group and Eric and Nate are no longer with the company.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objective of this project is to demonstrate that on-site water reclamation is technically feasible and cost-effective. Current and future water shortages and degraded water quality are and will continue to jeopardize the ability of the Department of Defense (DoD) to maintain training capacity and military readiness. Specific technical objectives of the project were:

- Conduct full-scale on-site performance testing of blackwater treatment and reuse;
- Compile, analyze, and evaluate test results;
- Calculate life cycle costs;
- Develop engineering requirements for integration with local reuse water standards; and
- Develop guidance for mobile deployment.

A number of technologies are available, however on-site water reclamation is particularly attractive because it is relatively easy to implement and it captures and reuses water that has already been delivered and paid for. On-site treatment of wastewater can also be integrated into existing or future construction with concomitant reductions in water and sewer costs.

TECHNOLOGY DESCRIPTION

Operationally, Living Machine mimics tidal wetland ecology; at regular intervals blackwater (i.e., sewage) is pumped into media-filled treatment cells, allowed to react, and then subsequently drained. A typical cycle (fill, react, and drain) takes ~40 minutes. An innovative feature of the Living Machine is that as the treatment cells drain, air is drawn into the media, which eliminates the need to operate a costly aeration system. As the wastewater passes through the treatment cells, most of the organic compounds along with ammonia are captured and consumed by a diverse microbial population that grows as a biofilm on the surface of the media. To enhance the aesthetics of the above ground portion of the cells, an upper layer of gravel (10"-12" deep) in each treatment cell is planted with a variety of wetland plants or more correctly hydrophytic vegetation. The plants remove some nutrients, promote microbial growth, and the roots help maintain treatment layer porosity. The highly flexible cells may be aesthetically integrated into exterior landscaping or buildings.

At the Marine Corps Recruit Depot (MCRD) there are four treatment cells: two primary or Stage 1 cells filled with a coarse media that is less susceptible to plugging by solids in the incoming blackwater; and two secondary or Stage 2 treatment cells filled with a less coarse higher surface area media. Following secondary treatment, the treated water is sent to a disinfection unit (filtration, ultraviolet light, and chlorinator) and stored on site in a clean water tank. The treated clean water is then plumed into a new sub-terrain irrigation system that provides enough water to sustain approximately 2 acres of adjacent grass lawn.

DEMONSTRATION RESULTS

The Living Machine is producing ~8,500 gallons of clean water per day at an average energy consumption of 0.006 kilowatt hours (kWh) per gallon of water treated. Because the nitrogen loading (total Kjeldahl nitrogen [TKN]) was significantly higher (average 180 parts per million [ppm]) than expected (≤ 100 ppm), incoming blackwater was diluted with recycled treated water. The higher TKN value appears to be due to the extreme heterogeneity of the blackwater at MCRD. With this adjustment, all analytes commonly used as indicators of organic matter degradation were reduced by more than 95% (see following table). The exceptions are residual color and phosphate along with total nitrogen, which remains elevated because ammonia is converted to nitrate (and an insignificant quantity of nitrite). Performance objectives were met and results are summarized in the following table.

<table>
<tr><th rowspan="2">Performance Objective</th><th rowspan="2">Metric</th><th rowspan="2">Data Requirements</th><th colspan="3">Results</th></tr>
<tr><th>Success Criteria</th><th colspan="2">Results</th></tr>
<tr><td rowspan="10">System Effectiveness</td><td rowspan="10">Reduced contaminant levels in the effluent</td><td rowspan="10">Effluent water quality compared to influent</td><td rowspan="10">Meet treatment goals Table 4</td><td>Analyte</td><td>% Reduction</td></tr>
<tr><td>NH_3</td><td>98.5</td></tr>
<tr><td>TKN</td><td>98.4</td></tr>
<tr><td>TN</td><td>64.8</td></tr>
<tr><td>TOC</td><td>94.8</td></tr>
<tr><td>TP</td><td>86.7</td></tr>
<tr><td>COD</td><td>95.1</td></tr>
<tr><td>Color</td><td>83.8</td></tr>
<tr><td>Turbidity</td><td>99.3</td></tr>
<tr><td>BOD</td><td>97.6</td></tr>
<tr><td>System Capacity</td><td>Flow rate</td><td>Volume of wastewater treated per day</td><td>10,000 gpd</td><td colspan="2">Total - 10,000 gpd
Wastewater - 8,500 gpd
Lost/Recycle -1,500 gpd</td></tr>
<tr><td>Water Recovery</td><td>Volume of water recovered</td><td>Volume of water reclaimed</td><td>Water recovery ≥ 90%</td><td colspan="2">Wastewater recovery per day 85%</td></tr>
<tr><td>Return on Investment</td><td>Capital and O&M costs</td><td>Costs for system purchase, installation and O&M</td><td>8-10 year return on investment</td><td colspan="2">Estimated 9.7 years based on current and projected utility rates</td></tr>
<tr><td>Water Reuse</td><td>Contaminant levels in the effluent</td><td>Effluent water quality</td><td>Meet reuse requirements Table 4</td><td colspan="2">Did not meet POTW discharge limits (Table 4) for Phosphate and Nitrogen. However, the system met and is permitted under General Waste Discharge Requirements by the SDRWQCB</td></tr>
<tr><td>System Reliability</td><td>Total hours of operation and hours of downtime</td><td>Hours system is operating with adequate performance over total hours of system operation</td><td>>95% once the system is fully operational</td><td colspan="2">>95%</td></tr>
</table>

% – percent
BOD – biochemical oxygen demand
COD – chemical oxygen demand
gpd – gallons per day
NH_3 – Ammonia
O&M – operation and maintenance
POTW – Publicly Owned Treatment Works
SDRWQCB – San Diego Regional Water Quality Control Board
TN – total nitrogen
TOC – total organic carbon
TP – total petroleum

The system did not meet POTW discharge limits (Table 4), which was chosen at the beginning of the project because it was more stringent. However, it turns out that POTW limits is not the most applicable discharge standard for the system. The system meets the California water reuse standards (Tittle 22) for water reuse. The system also meets the General Waste Discharge Requirements for Small Domestic Wastewater Treatment Systems (General Order) under SDRWQCB. Based on this order, the effluent limits specified in table above do not apply because the flow rate is below 20,000 gpd. In November 2014, the SDRWQCB issued a permit to MCRD that allows the treated reclaimed water to be used for subsurface irrigation.

IMPLEMENTATION ISSUES

Although DoD agencies have mandates to reduce water usage and promote water reuse, funding is difficult to obtain especially for items with large capital cost. With budget cuts, furloughs, and uncertainties in future budget, it is more difficult for someone in charge to champion a new technology/system. Even if a technology is proven to work in certain DoD applications, there is a strong reluctance to take a chance on the new system because of uncertainties it brings (e.g., O&M procedures).

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1.0 INTRODUCTION

> The good Lord didn't make any new water today. The glass of water you had at breakfast is used water. It went through seven Indians, 10 settlers, and 50 buffaloes before you got it. But you like to think the good Lord made it new, just for you, today.
>
> John R. "Jack" Sheaffer, 2004

1.1 BACKGROUND

For both civilians and the Department of Defense (DoD), reliable supplies of clean water are vital. However, water availability and quality in many regions of the country are increasingly at risk (Roy et al., 2010). Because military facilities and their civilian neighbors often share a water supply, increased demand, drought, over pumping of groundwater, and heavy irrigation may lead to disagreements (and potentially shortages) over allocations required to meet the requirements of civilians and neighboring DoD facilities. This problem is exacerbated in the United States and most of the developed world because water treated to drinking water standards is used for many purposes other than drinking (e.g., equipment and work pad wash down, irrigation of lawns, golf courses, and cemeteries and toilet flushing). Continuing to use potable water for these applications is not only costly, it is increasingly difficult to justify let alone sustain.

While disputes over water allocations in the west and southwest are well known, new supplies are limited nationwide (in reality almost all available water supplies in the United States have been developed, and, in many cases, over allocated) and chronic shortages are increasingly common in both number and intensity locally and regionally (Bartolino and Cunningham, 2004; Stockdale et al., 2010). Even areas that are described as wet, such as metropolitan Washington, D.C., and Atlanta, GA, experience regular water shortages that will intensify as population increases and the climate changes (Drought Coordination Committee of the Metropolitan Washington Council of Governments, 2010; James et al., 2010; Neff et al., 2000; Ries et al., 2010; U.S. Geological Society [USGS] Georgia Drought Watch). As demand increases, disagreements over allocations of shared resources are more frequent and acrimonious and are not limited to the west. For example, allocations from the Delaware River watershed are the subject of ongoing dispute (Bauers, 2010), and in the Midwest the useful life of some portions of the Ogallala aquifer, which is shared by eight states, may be limited by withdrawals that exceed recharge (http://drought.unl.edu/dm/12_week.gif). Fracking also requires substantial amounts of water and has become a contentious issue in drought stricken areas. While fracking uses substantially less than agriculture, more than half of current fracking activity is in drought stricken areas (Mauter et al., 2014). In addition, there are unanswered questions about potential contamination of surface water and groundwater associated with drilling fracking wells and the discharge of spent fracking fluids.

In the west, areas like Phoenix, Arizona, Las Vegas, Nevada, and Los Angeles, California, have depleted much of their available groundwater (Figure 1) and are almost entirely dependent on imported water, as are the DoD facilities in these states. The tenuous nature of the water supply is vividly illustrated by the drop in the water level of Lake Mead to within 8 feet of the level at which rationing would commence (Barringer, 2010). This has spurred Las Vegas to construct a deeper outlet in Lake Mead (Glionna, 2014). The current drought has also highlighted the lack of infrastructure that could be used to capture water during heavy rain events (Boxall, 2010).

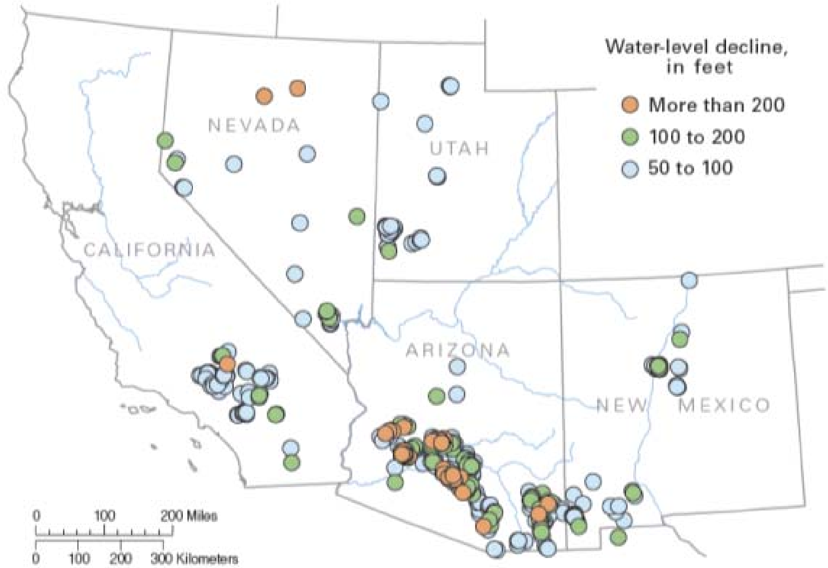

Figure 1. Order of magnitude declines in ground-water levels in selected basins.
(Bartolino and Cunningham, 2004)

At Ft. Huachuca, Arizona, mission expansion is limited by the water supply that is shared with the city of Sierra Vista (Army Environmental Center [AEC], 2006; Alaimo, 2005) and has been a major concern for more than a century (Jackson Research Projects, 1990). As a partial remedy, Yuma County has proposed that the mothballed Colorado River desalination facility be reactivated and used to reclaim near surface (6 feet below ground surface) non-potable water that is a byproduct of heavy irrigation. Currently, this water is pumped without reuse to prevent flooding (Yuma County, 2010).

Fort Irwin, California, uses reverse osmosis to produce potable water from non-potable brackish groundwater. However, the drawdown of the aquifer is estimated to be 1500 acre feet (af) per year, but the recharge rate (estimated to be 300 af per year) cannot sustain the current rate of use. Overpumping and recharge are causing further degradation of the groundwater, which increases treatment costs (California's Groundwater Bulletin 118; CEQ#20080261).

Camp Pendleton, California, relies on groundwater in the Santa Margarita river watershed, which is involved in an extended water rights dispute (O'Leary, 2008). San Diego, California, which is almost entirely dependent on imported water, has declared a Stage 2 drought emergency (San Diego City Water Department). Along with restricted use, the drought emergency requires that recycled or non-potable water be used when available (City of San Diego, 2008; USGS, San Diego Hydrogeology Project).

Population growth and climate change will put additional pressure on already limited water supplies. A recent study prepared for the Natural Resources Defense Council (NRDC) calculated a water sustainability index (i.e., the ratio of available precipitation to demand) for each county in the continental United States. The calculation uses population growth, energy demand (water is required to generate energy and energy is required to produce water), annual county level water use, and global climate model outputs for temperature and precipitation projected 20-40 years into the future. The models show the impact on water supplies without (Figure 2) and with climate change (Figure 3) (Nelson et al., 2007; Roy et al., 2010).

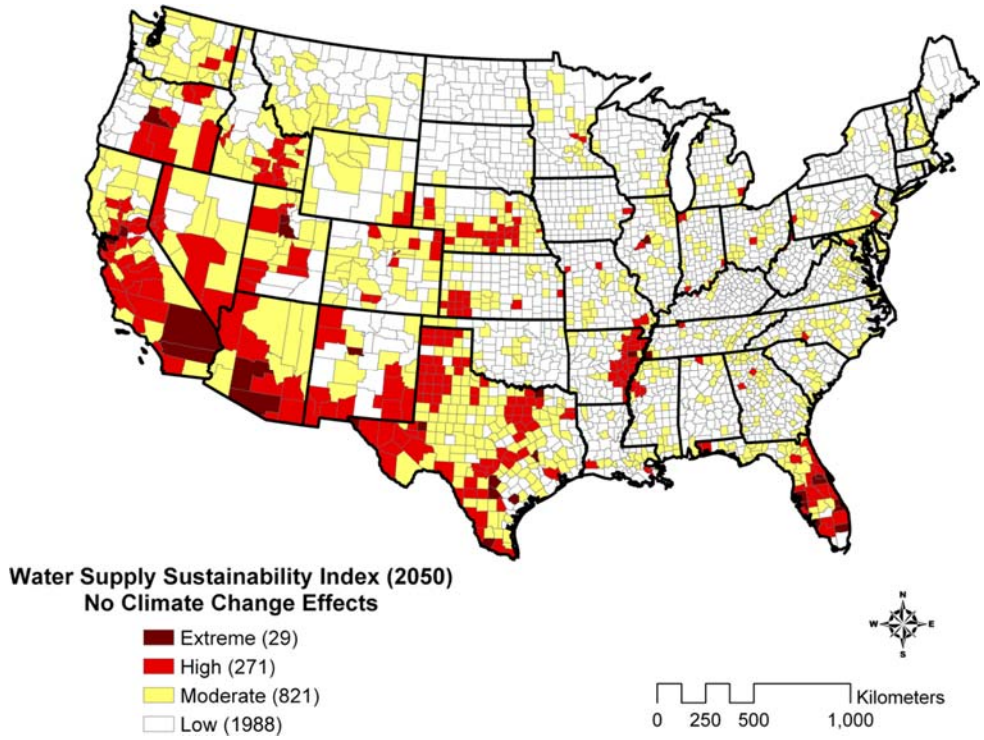

Figure 2. Projected water supply sustainability in 2050 with no climate change shown as the degree of risk and number of counties (in parenthesis) in each category.
(Roy et al., 2010)

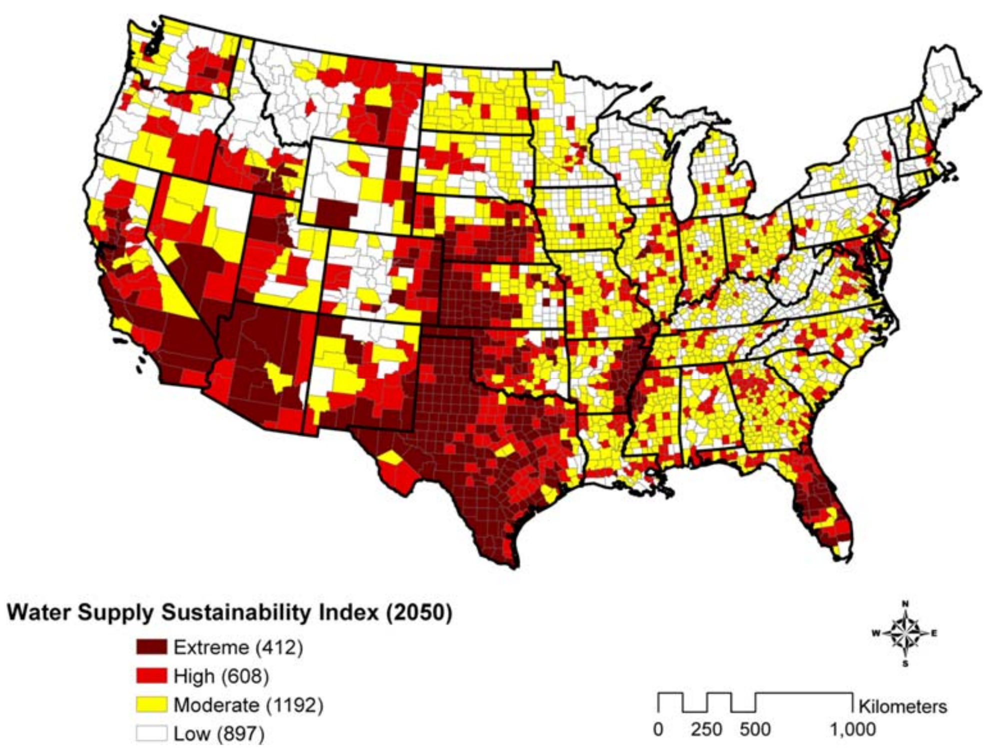

Figure 3. Projected water supply sustainability in 2050 with climate change shown as the degree of risk and number of counties (in parenthesis) in each category.
(Roy et al., 2010)

Even without taking climate change into account, water supplies in the most vulnerable parts of the country (primarily the west, southwest, and parts of Texas and Florida) will continue to be at risk (Figure 2). However, when climate change is included, the number of counties with water supplies at risk increases and includes large parts of the Ogallala and Edwards aquifers in the Midwest and Texas, respectively (Figure 3). With or without climate change, the areas of highest risk today and in the future are home to some of the country's largest mission critical DoD facilities (Figures 2 and 3).

Globally, diminished and degraded water supplies and competition for potable water is increasingly seen as a security threat. A number of studies have shown that water risk is especially high in some of the most volatile areas of the Middle East and Africa (Guner, 1997; James, 2010; Turkish Ministry of Foreign Affairs, 2012; Vaughn, 2010; Vörösmarty et al., 2010). In Somalia, only 30 percent of the population has access to a reliable source of water and Mauritania and Niger depend on external supplies for more than 90 percent of their water. Ethiopia and Sudan are claiming rights to more Nile River water thereby decreasing water quantity and quality in Egypt, which is almost entirely dependent on the Nile. Pakistan and India claim water that originates in the disputed Kashmir and Tajikistan, Kyrgyzstan, and Uzbekistan competes for water from the Amu Dari and Syr Daria rivers (the overuse of both has contributed to the dramatic shrinkage of the Aral Sea).

In many areas of the world, regardless of how water will be used (with the exception of farmland irrigation), it is treated to potable standards and discharged without reuse (Asano, 2001; Asano et al., 2007; Eddy, 2004). Knowing the lack of reuse is wasteful and costly, water managers have emphasized the importance of water conservation and reclamation (Dobbs, 1998). With respect to reclamation, the issue is not that water is being reclaimed—almost all of the water that we use is reclaimed. For example, more than 250 sewage treatment plants discharge to the Mississippi River, which provides drinking water for millions most of whom live downstream. Rather, a large part of the issue is the response to producing drinking water directly from the sewage plant effluent (commonly referred to as the yuck factor). Although reclaimed water can be treated to drinking water standards, non-potable uses that reduce the demand for new and increasingly expensive supplies are more common (California Water Plan Update, 2009; Cody et al., 2009).

From the start of this project, drought in the west and southwest has intensified (as of July 2014, all of California is experiencing severe, extreme, or exceptional drought; http://droughtmonitor.unl.edu/Home/StateDroughtMonitor.aspx?CA) and water shortages have become more severe (Hess and Frohlich, 2014; McDonald et al., 2014; Nagourney and Lovett, 2014). Given the absolutely essential requirement for water and the growing magnitude of the problem, we, as a people, are required to reevaluate how water is used, reclaimed, and reused—a role for which on-site technologies, exemplified by the Living Machine and confirmed by the results of this project, are ideally suited.

1.2 OBJECTIVE OF THE DEMONSTRATION

As the previous (albeit brief) discussion suggests, current and future water shortages and degraded water quality are and will continue to jeopardize the ability of DoD to maintain training capacity and military readiness. The objective of this project is to demonstrate that on-site water reclamation is technically feasible and cost-effective. At fixed installations, on-site reclamation has the additional advantage that reducing wastewater discharge to a central sewage treatment plant is a *de facto* increase in plant capacity, which reduces the need for new and costly infrastructure—needs that may be required when facilities are modernized or mission requirements increase. On-site treatment of wastewater can also be integrated into existing or future construction with concomitant reductions in water and sewer costs. Overall, on-site wastewater reclamation is an attractive treatment technology that boosts existing water supplies and reduces the demand for new and expensive supplies, which may not be available.

In remote locations, potable water and wastewater treatment are mission critical requirements; when they are not available or inadequate they are supplied by portable reverse osmosis systems (drinking water) and activated sludge plants (wastewater treatment) adapted and packaged to meet DoD requirements (Balling, 2009). While the activated sludge process is a proven technology, it is energy intensive, which may limit its use. In contrast, the modular construction of the Living Machine® is easily scaled and transported and the operating principal based on tidal wetlands reduces energy consumption (see Figure 2.3 in the Final Report). Specific technical objectives of the project were:

- Conduct full-scale on-site performance testing of blackwater treatment and reuse;
- Compile, analyze, and evaluate test results;
- Calculate life cycle costs;
- Develop engineering requirements for integration with local reuse water standards; and
- Develop guidance for mobile deployment.

1.3 REGULATORY DRIVERS

The primary federal drivers of water conservation and reclamation are:

- The Energy Policy Act of 1992, which amended the National Energy Conservation Policy Act (NECPA) to include the requirement that not later than January 1, 2005, each agency shall, to the maximum extent practicable, install in Federal buildings owned by the United States all energy and water conservation measures with payback periods of less than 10 years, as determined by using the methods and procedures developed pursuant to section 544.

- Executive Order 13423 (2007) Reducing Water Intensity – mandates that Federal agencies reduce water intensity (defined as gallons used per square foot) by 2 % each year through Fiscal Year (FY) 2015 for a total reduction of 16% using consumption in FY 2007 as the baseline.

- Executive Order 13514 (2009) Water Efficiency – Federal agencies must improve water efficiency and management by:

- Reducing potable water consumption intensity 2% annually through FY 2020, or 26% by the end of FY 2020, relative to a FY 2007 baseline;
- Reducing agency industrial, landscaping, and agricultural water consumption 2% annually, or 20% by the end of FY 2020, relative to a FY 2010 baseline and
- Identifying, promoting, and implementing water reuse strategies consistent with state law that reduce potable water consumption.

In addition, state specific regulations and/or local conditions may require:

- A more consistent and reliable water supply;
- Comprehensive water planning that integrates water and wastewater management;
- Reduced freshwater demand to benefit ecosystems stressed by water withdrawals; and
- Enhanced DoD facilities sustainability.

Reducing potable water use provides an essential service and is eligible for Leadership in Energy and Environmental Design (LEED) credits, which further the adoption of sustainable facilities.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

For centuries, natural wetlands have been used (intentionally and unintentionally) to remediate wastewater (Brix, 1994; Cooper, 2001). More recently, constructed wetlands that enhance the processes in natural wetlands are used to capture and treat stormwater runoff and low concentrations of groundwater contaminants that are difficult and expensive to treat by more intensive biotic and/or abiotic technologies (Babatunde et al, 2008; Barber et al., 2001; Gillette, 1996; Kadlec and Wallace, 2009; Reed et al., 1995; Young, 1996). The mining industry has also used constructed wetlands to recover metals from low-grade ores and restore ecosystems degraded by past practices (Francis et al., 1989). The extended residence time of contaminated water in a surface flow wetland and the presence of a diverse and robust community of plants and microorganisms that are adept at capturing and degrading many organic and some inorganic (e.g., perchlorate, sulfides, nitrate, ammonia) contaminants are primarily responsible for wetland treatment effectiveness (Stottmeister et al., 2003).

Wetlands and wetland related technologies have also been promoted as an alternative to domestic sewage treatment plants (Baillon-Dhumez et al., 2010; Brix and Johansen, 1999; Burkhard et al., 2000; Hencha et al., 2003; Lin et al., 2002; Platzer, 1999; Vymaza, 2005). One of the earliest proponents was Jack Sheaffer who developed the Sheaffer System, which is marketed by the Center for the Transformation of Waste Technology (http://ctwt.org/index.htm) and Sheaffer International (http://www.sheafferinternational.com/). In this system, raw sewage passes through a grinder pump and is injected at the bottom of a deep (12-20 feet) open basin. To promote degradation of the solids, the bottom few feet of the basin is kept anaerobic. Flow through the basins is gravity driven and blowers are used for aeration and circulation in the upper portion of the first basin and throughout the secondary basins. The system is simple to operate (usually it is self-regulating), produces little or no sludge, can be sited where sewage is generated and where the reclaimed water can be used—advantages that reduce the need for costly infrastructure. However, just as the size of conventional sewage treatment plants increases with treatment capacity, so do surface flow wetlands that, along with aesthetics of open systems, may limit their use.

In the 1970s, John Todd developed a wetlands based sewage treatment system that he referred to as the Living Machine (U.S. Environmental Protection Agency [EPA], 2002). The system uses a series of anaerobic and aerated tanks populated by bacteria and aquatic plants and animals. Early versions required a secondary clarifier, produced sludge, did not provide consistent treatment, and the cost-effectiveness was in some cases questionable all of which diminished interest in the technology. An improved version of the original system referred to as the Eco-Machine wastewater treatment system is still marketed by John Todd Ecological Design (http://toddecological.com/). A similar system is marketed as the Solar Aquatics System by the Ecological Engineering Group (http://www. ecological-engineering.com/solaraquatics.html). Improvements to the technology have yielded systems that produce less sludge than conventional sewage treatment plants and have the advantage that they can be scaled for on-site use and reclamation. As treatment standards have become more stringent, these systems have evolved to accommodate primary, secondary, and tertiary treatment and in cold climates they are enclosed in a greenhouse.

In 1999, Worrell Water Technologies purchased the rights to and copyrighted the term Living Machine. They also changed the design from an open surface flow-through system to tidally driven subsurface flow. The description of the system as tidally driven refers to the rhythmical filling and draining of each treatment cell (i.e., tidal flow or fill and drain). The advantage of this design is that as the cell empties air is passively drawn into the treatment cell matrix, which eliminates the need for a costly aeration system—the major consumer of energy in a conventional treatment plant. Compared to surface flow wetlands, vertical flow tidal wetlands handle higher loadings of organic waste (Lee and Scholz, 2006; Sun et al., 2006; Zhao et al., 2004) and experience less pore space clogging (Kadlec and Watson, 1993; Langergraber et al., 2003), which extends their useful life and reduces costs.

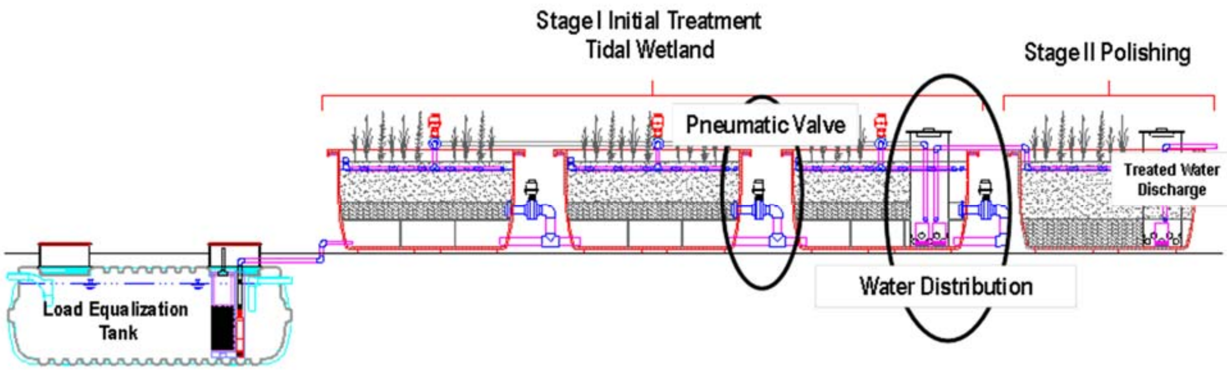

Figure 4. A schematic illustration of an early version of the Living Machine.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

To be competitive, on-site wastewater reclamation not only has to treat the wastewater (see the previous discussion) but it has to offer advantages that are either not available (e.g., easily deployed, simple to operate) or lacking in currently available technologies including energy efficiency. To compare wastewater treatment energy requirements, energy use is expressed as kilowatt hours (kWh) used per cubic meter of water treated. Using this metric, energy use was calculated for the Living machine, a traditional surface flow wetland, and three conventional technologies (activated sludge, membrane bioreactor, and Orenco AdvanTex® – an enhanced septic tank treatment system). The results (Figure 5) show that energy use by the Living Machine is significantly less than any of the other technologies and requires one-fifth to one-sixth the area of a conventional surface flow wetland with the same treatment capacity. This project included energy use and the results (Section 5) are in accordance with the data in Figure 5. Additional advantages and potential limitations of the Living Machine, compared to the most common current practice which is discharge to a publically owned treatment works (POTW), are summarized in Table 1.

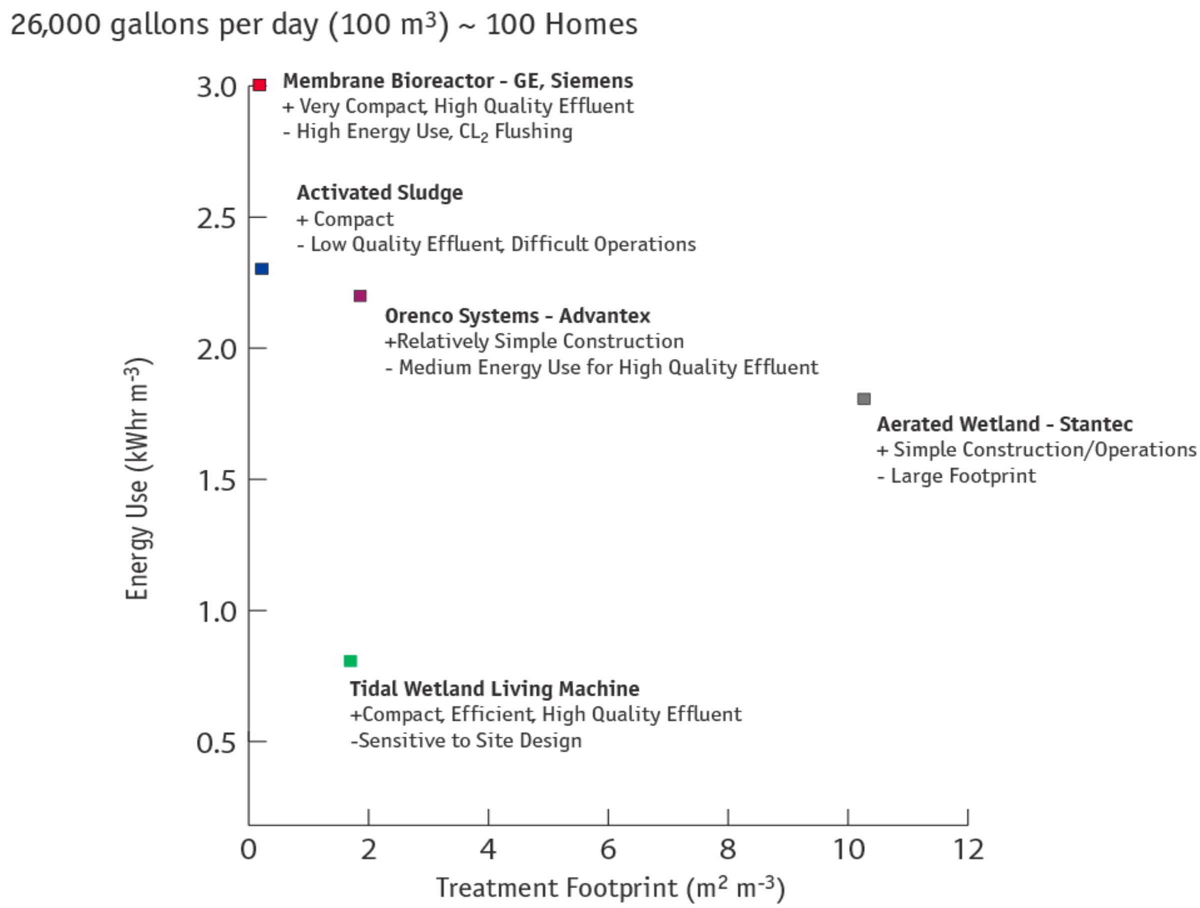

Figure 5. Comparison of treatment technologies energy consumption (kWhr m^{-3}) and footprint (m^2 m^{-3}) normalized to equal capacity.

Even though the technology was demonstrated and validated at an established DoD facility (i.e., Marine Corps Recruit Depot [MCRD], San Diego, CA), the basic technology is modular and readily deployed for use in areas where water may be limited and no sewage treatment is available. On-site sewage treatment in such an environment helps protect public health and can be used to produce non-potable water that can be used to replace potable water in toilets and vehicle wash down (Brix and Arias, 2005; Massoud et al., 2009; Regelsbergera et al., 2007) or potable water when it is used with disinfection technologies (e.g., reverse osmosis, forward osmosis, chlorination or ultraviolet light).

Table 1. Comparison of Living Machine and the current practice—discharge to a POTW.

Advantages	Limitations
Living Machine®	
• Modular construction permits rapid deployment • Reclamation reduces water demand and cost • Potable water supply is increased when reclaimed water replaces potable water for non-potable use • Reduced wastewater discharge is a *de facto* increase in sewage capacity • Encourages comprehensive water planning • Reducing the demand for potable water may decrease stress on ecosystems that supply freshwater • Reducing discharge to a sewer reduces sewage fees • On-site reclamation is an example of sustainable infrastructure • Energy efficient and simple to operate • No chemicals are used • Generates little or no sludge • Almost 100% of influent is recovered - in contrast to filters that generate a concentrated waste stream that has to be disposed • Energy efficient design	• Requires inspection, maintenance, monitoring • Limited to treating common components of domestic sewage • Payback ~12.5 years • Footprint requirement may limit volumetric treatment capacity • Aesthetics may limit implementation • Water reclamation may be reduced by high evapotranspiration • Treatment may be sensitive to temperature extremes
Discharge to POTW	
• Little concern for waste composition • Large volumetric capacity • No land requirement at site of generation • Generation site has no labor requirement	• Water reclaimed off-site may not be available for on-site use • Recurring and increasing sewage fees • Cost, maintenance, and infrastructure requirements of centralized treatment systems limit expansion • Inability of infrastructure to accommodate DoD requirements may limit facility/activity function(s)

3.0 PERFORMANCE OBJECTIVES

Quantitative and qualitative data requirements for assessing project goals and objectives (Section 1.2) are summarized in Tables 2 and 3, respectively. Data requirements that were used to assess the quantitative measures of success are discussed in more detail in Section 3.1.1; Section 3.1.2 discusses how project success was evaluated. Project costs and cost accounting are discussed in Section 6.

3.1 QUANTITATIVE AND QUALITATIVE DATA REQUIREMENTS

Overall, technology effectiveness was assessed by the how well the quantitative performance objectives (Table 2) were met.

Table 2. Quantitative performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
System Effectiveness	Contaminant levels in the effluent	Effluent water quality compared to influent	Meet treatment goals (Table 4)	Did not meet Nitrogen, Phosphate and color. See Table 4
System Capacity	Flow rate	Volume of waste treated per day	10,000 gpd	Total - 10,000 gpd Reclaimed - 8,500 gpd Lost/Recycle - 1,500 gpd
Water Recovery	Volume of water recovered	Volume of water reclaimed	Water recovery ≥ 90% input	Actual per day - 85%
Return on Investment	Capital and O&M costs	Costs for system purchase, installation and O&M	8-10 year ROI	Estimated 9.7 years based on current and projected utility rates.
Water Reuse	Contaminant levels in the effluent	Effluent water quality	Meet reuse requirements Table 4	Permitted for reuse by the SDRWQCB
System Reliability	Total hours of operation and hours of downtime	Hours system is operating with adequate performance over total hours of system operation	>95% once the system is fully operational	System has been producing reclaimed water continuously for 9 months

gpd = gallons per day
O&M = operations and maintenance
ROI = return on investment
SDRWQCB = San Diego Regional Water Quality Control Board

System effectiveness measures the ability of the treatment system to meet the treated water quality goals (Table 4). Concentrations of these analytes are measured in the influent and effluent to determine: () removal efficiency, and 2) confirm that residual concentrations of these analytes are at or below the California Water Quality requirements for reclaimed water. The design capacity of the treatment system is 10,000 gpd of incoming blackwater with greater than 90% recovery of the incoming wastewater (i.e., the Living Machine produces ≥ 9,500 gpd of reclaimed water – evapotranspiration is the primary mechanism of water loss). This volume was selected to meet the MCRD irrigation requirement. Since the concentration of nitrogen in the incoming wastewater was higher than expected, a significant amount of nitrate is produced. To reduce the nitrate concentration and the nitrogen loading in the treatment cells, 1000 gallons of reclaimed water are recycled back through the load equalization tank (LET) each day. In the anaerobic LET, the nitrate undergoes denitrification, which removes both nitrogen as nitrogen gas and some of the organic matter. As a result, the total volume of wastewater treated each day was reduced to 8,500 gallons, however, more than 95% is recovered.

The predicted ROI is 8-10 years (Section 6). Reuse of the reclaimed water for subsurface irrigation requires a permit, which was granted to MCRD by SDRWQCB. The reclaimed water is disinfected (filtration, ultraviolet [UV] light, chlorination) to meet the California requirements for reuse of water that individuals may contact; it is then tested to confirm that the requirements (Table 6) are met. System reliability is a collective measure of the reliability of all the components. Since individual components—motors, seals, valves, and controllers—have a limited lifetime and will fail, the goal is to achieve a minimum reliability of 95% expressed as total satisfactory operation time divided by total operation time.

Qualitative performance objectives (Table 3) used feedback from the user (MCRD) to assess: 1) the aesthetics of the system (does it blend into the site without creating an eyesore or generating offensive odors); 2) ease of use and maintenance; and 3) portability as indicated by the effort required to assemble and install the system.

Table 3. Qualitative performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria Assessment
Aesthetics	User feedback	Feedback from client on appearance and odors	The Living Machine does not foul the air and complements the drill instructor (DI) monument.
Ease of O&M	User operation and service	O&M logs maintained at the site	An MCRD facilities employee conducts daily monitoring and routine maintenance
Portability	Effort required to assemble and dismantle	Feedback from vendor and user	Not assessed in this DEM/VAL

DEM/VAL = Demonstration/ Validation

3.1.1 Data Requirements

The primary measures of system performance and treatment effectiveness are reductions in 5-day biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), and total nitrogen (TN) (Table 4). Even though these analyses are non-specific, collectively along with total dissolved solids (TDS) and turbidity, they are indirect measures of how much organic and particulate matter is in the wastewater (Grady and Lim, 1980; Tchobanoglous et al., 2003). The treatment goals for these analytes (Table 4) are based on Federal and state experience with values that are protective of human and ecological health and are typical of the values specified in a National Pollutant Discharge Elimination System (NPDES) permit for a POTW.

The methylene blue active substances (MBAS) test is used to measure (indirectly) anionic soaps and detergents, which at high concentrations, will cause foaming and may be toxic to some organisms. The color of water is reported as true color and is determined on samples that have been filtered to remove turbidity (the color of turbid samples is reported as apparent color). Either inorganic (e.g., iron) or organic species (e.g., phenols) can discolor water.

The system is not designed to remove nitrogen, phosphate or coliforms; however, total nitrogen and phosphorous are significantly reduced and there is a slight reduction in coliforms (fecal and total) that are reduced to near or below non-detect after passing through the disinfection unit. Because the treatment goals are typical of a POTW, it was not unexpected that nitrogen and phosphorous in the effluent did not meet these targets. In a POTW, additional treatment (e.g., chemical precipitation by the addition of a coagulant or biological processes) is required to meet NPDES targets for these analytes (EPA, 2007).

The system is permitted through the San Diego Department of Public Health under the General Order WQ2014-0153-DWQ (http://www.waterboards.ca.gov/board_decisions/adopted orders/water_ quality/2014/wqo2014_0153_dwq.pdf) as a General Waste Discharge disposal. This type of permit was sought after by MCRD because it is easier and less costly to obtain and comply.

Table 4. Primary water quality parameters, treatment goals, and results.

Parameter	Units	POTW Treatment Goals	Results	
			Value	% Reduction
Treatment Goals Met				
TSS	mg/L	<5 - 30	<5	>99
TDS	mg/L	500 - 2000	1318±210	NA
Coliforms	MPN/100 ml	<1 - 200	15±11	ND
COD	mg/L	<20 - 90	22.5±2.12	95.1
BOD_5	mg/L	<10 - 45	7.48±3.02	97.6
TOC	mg/L	<1 - 10	6.29±1.18	94.8
Turbidity	NTU	<0.1 - 30	0.66±0.80	99.3
pH	pH Units	6.5 - 8.5	7.33±0.33	NA
Treatment Goals Not Met				
TN	mg/L	3.8	70±24	64.8
Phosphate as Total Phosphate	mg/L	0.2	2.03±1.37	86.7
Color	Units	12.7	14.6±7.11	83.8

mg/L – milligram per liter
ml – milliliter
MPN – most probable number
TOC – Total Organic Carbon
NA – not applicable
ND – not determined
NTU – nephelometric turbidity unit

Data required for the remedial effectiveness assessment are the pre- and post-treatment concentrations of select analytes (Table 4). To track system performance during the DEM/VAL, pre- and post- treatment samples were collected at regular intervals and analyzed for the parameters in Table 4. All analyses were conducted by a commercial lab. The concentrations of analytes in the pre- and post-treatment samples were used to determine the reduction in concentration of each analyte, which collectively measures treatment system capacity and the effluent concentrations are used to demonstrate that the water meets reclaimed water requirements.

Even though the system was completed in May 2012, and charged with wastewater, fouling of the transfer pump by gun cleaning rags delayed continuous operation until August 2012, and the first samples were collected in September 2012. Because the media was exposed to wastewater for almost 5 months, the results cannot be used to trace the establishment of the biofilm. Due to unexpectedly high laboratory costs, a limited set of samples were collected in October 2012. Subsequently, the pump and microprocessor failed and continuous operation was not reestablished until May 2013, and samples were collected in August 2013. A fourth set of samples was collected in September 2013. Although the data set are not as comprehensive as anticipated, collectively they show that the Living Machine met almost all of the treatment performance goals. The exceptions (nitrogen and phosphorous) were not unexpected, although the elevated nitrogen loading was not anticipated. The elevated nitrogen was addressed by mixing incoming wastewater with high nitrate reclaimed water, however, the budget was exhausted and no sampling has been conducted to confirm this.

Cumulative flow meters were used to track real flow through the system, which was compared with the design capacity (10,000 gpd). It should be noted that actual residence time (i.e., hydraulic retention time [HRT]) is a function of the time required to meet the reductions in the concentrations of BOD_5, COD, TSS, and nitrogen, which can only be determined once the system is operating. Ultimately, cost effectiveness and ROI are dependent on the amount of water treated and recovered per unit time. The expected results are compared to the actual performance in Section 5 and in more detail in the Draft Technical Report.

Influent and reclaimed water were sampled and analyzed for secondary indicators of water quality (Table 5). Sampling and analysis for these analytes is not required; however, they provide a useful comparison to exhaustive data generated by the City of San Diego Water Reclamation facility. With the exception of nitrates in the effluent, the values of these analytes are not significantly different from those measured at the San Diego Reclamation facility. With the exception of iron, which is an essential nutrient and may have been captured and/or precipitated and the increase in nitrate and nitrite previously discussed, the concentrations of the other species do not show any significant change.

Table 5. Secondary water quality parameters.

Parameter	Units	San Diego Influent Average Value	MCRD Value	
			Influent	Effluent
Sodium	mg/L	150	146±7.1	146±9.61
Iron	mg/L	0.5	0.42±0.03	<0.05
Manganese	mg/L	0.2	0.09±0.05	0.07±0.05
Boron	mg/L	0.75	0.33±0.01	0.55±0.02
Nitrate/Nitrite	mg/L	0.5	0.02±0.02	67±26

3.1.2 Success Criteria

Technical project success is achieved by meeting the quantitative treatment targets (Table 2). Although, the system did not meet POTW discharge limits for nitrogen, phosphate, and color, it meets the California water reuse requirements under Title 22 for water reuse. It is also expected that MCRD personnel will be able to operate and maintain the system, and the installation will not detract from the appearance of the DI Monument. The ultimate success is reuse of the reclaimed water by MCRD. Reuse is regulated by the California Department of Public Health—specifically

Title 22 of the California Administrative Code, which is also referred to as the Purple Book. California grants permitting authority to the local regulatory body, which for MCRD is SDRWQCB. In January 2014, SDRWQCB granted MCRD a permit to use the reclaimed water for subsurface disposal (irrigation).

Permit requirements for reclaimed water with human contact are given in Table 6. Because virus concentrations in wastewater are usually low (Nelson et al., 2004) and the assays are highly specialized, expensive, and time consuming, Title 22 allows the use of technologies that have been shown to meet the virus reduction requirements. At MCRD, these requirements are met by filtration, UV light, and chlorination. To be effective, the chlorination contact time (defined as the total residual chlorine concentration times the modal contact time—measured at the same point) has to be ≥ 450 milligram-minutes per liter at all times and the minimum modal contact time has to be at least 90 minutes, based on peak dry weather design flow. To ensure compliance with the chlorination and turbidity requirements, water in the storage tank is periodically recirculated through the disinfection unit. The clean water tank is equipped with an oxidation reduction probe and there is an in-line turbidity meter in the disinfection unit. Even though the reclaimed water will meet the State requirements for human contact, no human contact is anticipated. The results also show that the total coliform and turbidity requirements are met.

Table 6. California Title 22 requirements for water reuse with human contact.

Parameter	Units	Value	Method	Results
Viruses	%	Remove 99.999% of polio virus or bacteriophage MS2	Infectivity (plaque formation) or quantitative reverse transcriptase polymerase chain reaction	Not Required
Total Coliforms	MPN	Median concentration of 2.2/100 mL for the last 7 days, not to exceed 23/100 mL in more than one sample in a 30 day period, no sample to exceed 240/100 mL	MPN	5±4
Turbidity	NTU	Average value ≤2; not to exceed 5 in any 24 hour period	Standard Method 2130 B	0.66±0.8

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4.0 SITE DESCRIPTION

Because of on-going and developing problems with water quality and availability, DoD activities in the West and Southwest are prime candidates to DEM/VAL on-site water reclamation technology. Although Fort Irwin and Fort Huachuca were contacted, the MCRD San Diego, California, showed the most interest and provided substantial additional funding. The urban location of MCRD allows easy access, convenient shipping, and a pool of local contractors (excavation, fabrication) that helped allay project costs. At MCRD, energy and water saving technologies that benefit the facility, Corps, and DoD are a high priority and the DEM/VAL is highly visible to the Corps, recruits (future Marines), and the metropolitan San Diego water authority. In addition, and consistent with the need for a more sustainable approach to supplying water, MCRD and the city of San Diego are almost entirely dependent on imported water. San Diego enacted water restrictions more than 3 years ago and, in response to the most serious drought in California history, the governor declared a drought state of emergency in January 2014 (Chappell, 2014) and a second emergency proclamation in April 2014 (Feldman, 2014).

4.1 SITE LOCATION

The Living Machine is located on an open, grassy area adjacent to three of the recruit barracks with easy access to a sewer line, which is the blackwater source (Figure 6). Because MCRD selected a location for the test site that is slightly removed from the sewer lines and adjacent to the highly visible Drill Instructors monument (Figure 7), additional excavation and landscaping (funding provided by MCRD) were required. A Google Earth view dated 13 November 2013 shows the completed installation (Figures 8 and 10).

Figure 6. Aerial view of MCRD (left) shows the general location of test site (highlighted) adjacent to the H-shaped barracks. A close-up view (right) shows the sewer lines and the location (highlighted) adjacent to the DI Monument selected by MCRD.

Marine Advanced Expeditionary Base, San Diego, was commissioned in December 1921 by General Joseph H. Pendleton, U.S. Marine Corps (USMC). In 1923, the area of the base was increased from 232 acres to 388 acres (~368 acres is reclaimed tidal lands) and the Marine Recruit Depot for the West Coast relocated from Mare Island Navy Shipyards in Vallejo, California, to the San Diego Marine Base, which, in 1924, was renamed Marine Corps Base, San Diego.

Throughout World War II, the principal activity of the base was Marine recruit training. After the war, Marine recruit training remained the principal activity and in 1948 the base was renamed the Marine Corps Recruit Depot, Western Recruiting Region, San Diego (see MCRD San Diego, CA History). Recruit basic training for all male recruits from west of the Mississippi remains the primary activity. Recruits from east of the Mississippi River and women from all states undergo basic training at the much larger and better known Paris Island, SC facility.

Today, MCRD is bordered on the south by the San Diego International Airport (Lindbergh Field) and lies just northwest of downtown San Diego (Figure 7). Because of its completely urbanized location, closing the base has been considered; however, the costs were judged to be prohibitive and the Corps prefers to keep recruit training separate and distinct from the advanced training offered at nearby facilities (Camp Pendleton and Twenty-Nine Palms). To upgrade the training facilities and accommodate expansion of the adjacent Lindberg Field, the Port of San Diego and the Corps agreed to a land swap that enabled Lindbergh Field to expand a taxiway. Tenant commands at MCRD include the Marine Corps drill instructor training school and small Navy and Coast Guard contingents.

Figure 7. Map showing the location of MCRD (highlighted) San Diego, CA.

The primary function of MCRD is physical training (PT) during which recruits are built up to Corps standards. Conditioning includes an 11-station obstacle course designed to build confidence and strength, circuit courses, and 3-, 5- and 10-mile conditioning marches. Recruits also undergo combat water survival training. Classroom instruction includes Marine Corps history, customs and courtesies, and basic lifesaving procedures. Recruits are also taught the Corps' core values—Honor, Courage and Commitment—along with integrity, discipline, teamwork, duty and esprit de Corps. During basic training, recruits are not allowed to leave MCRD.

The final test is The Crucible (held at Camp Pendleton along with rifle training), which is a 54-hour test of endurance that includes food and sleep deprivation and approximately 40 miles of marching. The Crucible is built around team-building Warrior Stations each of which is named for a Marine hero whose actions epitomize the values the Corps works to instill in the recruits. Shortly after completing the Crucible, the recruits graduate and are awarded the Eagle, Globe and Anchor, which signifies the new Marine's successful completion of recruit training.

4.2 SITE GEOLOGY/HYDROGEOLOGY

MCRD is located in the mostly urban (population density greater than 13 persons per acre) Pueblo San Diego hydrologic unit which at, ~36,000 acres, is the smallest unit in the ~3.3-million-acre greater San Diego Hydrologic Region (SDHR). Ecosystems in SDHR cover the entire spectrum from ocean to montane forests and are home to rare, threatened, and endangered animal and plant species including the California gnatcatcher, the Arroyo toad, the Southwestern Pond turtle, the Salt Marsh daisy, and the Otay Mesa mint. However, rapid economic development and urbanization has degraded and depleted much of the water in the SDHR that supports the habitats which support these species. In addition to loss of habitat, environmental degradation is associated with elevated levels of coliform bacteria, trace metals, nonspecific aquatic and sediment toxicity, nutrient enrichment, and sedimentation. Restoring SDHR water quality and protecting and restoring the ecological integrity of the County's diverse habitats have been identified as one of the region's most important challenges and water reclamation and beneficial reuse has been identified as one of the primary mechanisms for reversing environmental degradation and loss of habitat while maintaining the high quality of life for which the region is noted.

4.3 CONTAMINANT DISTRIBUTION

A wide variety of mostly enteric bacteria, solids (i.e., fecal waste), low concentrations of common anions and cations (sodium, chloride, fluoride, sulfate, potassium), and usually low numbers of viruses are typically found in blackwater from residential sources such as the MCRD barracks. In general, the complex composition of blackwater precludes the use of analytical methods that would detect and quantify individual compounds. Rather, analytical methods that have been developed and refined over many years, and are accepted by the regulatory agencies, measure the aggregate concentration of compounds with similar properties. For example, BOD_5 measures compounds that biodegrade under the test conditions (i.e., not all biodegradable compounds will be detected). However, the methods are widely accepted and provide a relatively rapid and inexpensive way to characterize wastewater and assess treatment efficacy. Table 7 shows the concentrations of commonly measured parameters in blackwater pumped to the North City Reclamation Plant (NCRP) (www.sandiego.gov/mwwd/pdf/pm/2007annualnc.pdf) and the average values for these parameters in the blackwater at MCRD. Using these values, the wastewater at MCRD would be classified as medium to high strength (Metcalf and Eddy, 2003).

Table 7. Comparison of blackwater at the NCRP and MCRD.

Source	BOD_5 mg/L	TDS mg/L	TSS mg/L	Kjeldahl Nitrogen mg/L	MBAS mg/L	COD mg/L	Turbidity NTU
NCRP	259	1050	320	49.7	0.16	314	138
MCRD	312	921	85	185	1.79	455	97

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The location selected by MCRD for the treatment system is adjacent to the DI Monument (Figure 8), which is a prominent landmark at MCRD. To ensure that the completed treatment system complements the site additional landscaping was required (Figure 8). An aerial view of the completed installation (Google Earth) is shown in Figure 13.

Figure 8. The Living Machine at MCRD with the DI memorial in the foreground.
The two center cells are the Stage 1 cells and the outermost cells are the Stage 2 cells (photo taken on 22 October 2013).

Installation and planting of the cells was completed in May 2012 (Figures 9 and 10).

Figure 9. Installation of the Living Machine at MCRD showing the cast-in-place cells (left), the inlet/outlet (center) and the completed treatment cells (right).
(Right and center photos December 2011; left photo February 2012)

In order to ensure that all components were working correctly and that there were no leaks, the system was filled with clean water and the pumps, valves, and controller were subsequently tested. When the system was tested, it was found that the soil around the pump chambers had settled and some of the pipes cracked and had to be replaced. When these repairs were completed (June 2012), the system restarted.

Figure 10. Photos of the completed installation.
Filters in the LET can be removed and rinsed with a hose (left) and the treatment cells after they were planted (right) (May 2012).

Concurrent with the installation of the Living Machine, the subsurface irrigation system was installed (Figure 11).

Figure 11. Installation of the subsurface irrigation system.
Water is delivered from the clean water tank to the subsurface soil through the flexible perforated purple pipe (March 2012).

Shortly after the system was started, the pump used to transfer blackwater from the sewer to the LET failed. Over the next year, the pump failed two more times and was traced to gun cleaning rags that are flushed down the toilets when the recruits finish cleaning their weapons. To protect the pump, a diverter was installed in the main sewer line and a protective screen was fabricated to house and protect the pump. A more robust version was installed in October 2013 (Figure 12) and the system has been running continuously with no reports of fouling leading to pump failure. The pump and screen are secured with lines and can be pulled from the interceptor and cleaned with a hose. All wash water flows back into the sewer. An aerial view of the completed installation is shown in Figure 13.

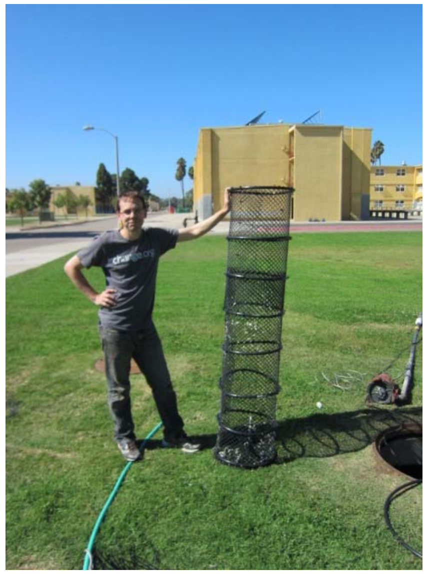

Figure 12. The protective screen houses and protects the transfer pump (October 2013) was fabricated on-site by Eric Lohan (pictured).

Figure 13. Aerial view (Google Earth 13 November 2013) shows the completed installation.

The DEM/VAL was scheduled to proceed in two stages (Section 5.4). The first stage allowed time for a biofilm to become established on the media in the treatment cells. A fully functional biofilm can be considered to have been established when the values of key indicators of system performance—specifically BOD_5, COD, and TN—in the reclaimed water are not only lower than in the influent, but start to stabilize at or near the target values (Table 8) at which point full-scale testing was scheduled to begin. However, problems with the transfer pump and a controller failure prevented the collection of any meaningful data during startup.

During full-scale testing, influent and effluent were sampled and assayed for the parameters in Table 8 and the values used to calculate the difference between the influent and effluent values (i.e., removal efficiency) and show that the reclaimed water target values were achieved. In addition, treated and reclaimed water volumes and energy consumption were tracked.

5.2 BASELINE CHARACTERIZATION

With the exception of total Kjeldahl nitrogen (TKN), the average concentrations of target analytes in blackwater at MCRD (Table 7) fall in the range that the Living Machine is designed to treat. However, the gun cleaning rags disposed of by the recruits, which were not detected during site characterization, fouled the intake pump impellor. The motor failed and had to be replaced and a protective cage built to protect it which delayed project start-up. Also, the TKN was higher than the initial measurements suggested (possibly as was the case for the gun cleaning rags because of time of sampling (day rather than evening) and the treatment volume had to be reduced. The total volume processed per day is 10,000 gallons and consists of 8,500 gallons of wastewater and 1,000 gallons of recycled treated water (500 gallons lost through evapotranspiration).

5.3 FIELD TESTING

Phase I Start Up: As discussed in the previous section, unexpected issues with the transfer pump prevented a normal start up. Therefore, it was not possible, as originally proposed, to follow biofilm development. Because the media in the treatment cells was intermittingly exposed to blackwater over a 6 months, it was assumed that the biofilm had become established and full scale or Phase II testing commenced. Phase II testing included tracking costs, and periodic sampling and analysis for the parameters in Table 8.

Phase II – System Performance: The primary performance data was derived from an analysis of influent and effluent samples that were analyzed for water quality parameters (Table 8). The controller is also equipped to track water input and production, energy consumption, and real time sensor data (Table 9). These data were compiled, analyzed, and, at regular intervals, reports summarizing all of the data were prepared. Regular auditing of these data was conducted to ensure that the system was operating as designed and to identify problems – specifically UV lamp and filter performance. In addition, these data were used to determine if the project objectives were met (Table 13). At the end of the project, the treatment system was transferred to and is the responsibility of MCRD San Diego.

Table 8. Parameters used to assess Living Machine performance.

Metric	Measurement	Units	Goal
Treatment - Effectiveness	TSS	mg/L	<5 - 30
	TDS	mg/L	500 - 2000
	Coliforms	MPN/100 ml	<1 - 200
	TKN	mg/L	3.8
	Phosphate	mg/L	0.2
	COD	mg/L	<20 - 90
	BOD_5	mg/L	<10 - 45
	TOC	mg/L	<1 - 10
	Turbidity	NTU	<0.1 - 30
	MBAS	mg/L	NR[1]
	Color	Units	12.7
Treatment - Capacity	Waste water treated	gpd	10,000
Water - Reclamation	Water produced	gpd	≥9,000
Energy Use	Kilowatts/gallon/day	kW/g/d	TBD
System Efficiency	Hours Satisfactory Operation/Total Hours	%	≥95%

[1]NR – not required

Table 9. Real time monitoring of system performance.

Parameter	Method	Medium and Sampling Frequency	Range	Resolution
Turbidity	Turbidity	Continuous monitoring influent and effluent	0 - 1000 NTU	±0.02 NTU
Electrical Use	Electric Meter	Continuous Monitoring	Cumulative Memory	±50 watts
Water Volume	Calibrated Flow Meters	Volume - incoming wastewater and reclaimed water recovered	0-200 gallons per minute (gpm)	±5 gpm

Gpm - gallons per minute

5.4 SAMPLING METHODS

Table 9 lists the parameters, expected range, and resolution of the real time sensors. A data logger was used to archive these data; while the microprocessor was used to operate and monitor the Living Machine collected and archived power consumption and volumetric flows. Standard methods promulgated by the EPA and/or specified in Standard Methods for the Examination of Water and Wastewater were used to analyze all samples (Tables 8 and 10) and were performed by certified labs (EMAX Laboratories, Inc., Torrance, CA; and Capco, Ventura CA). Method summaries, sampling frequency, and quantitation limits are summarized in Table 10. Samples included influent, each of the treatment cells, and effluent. Because of higher than expected lab costs, the number of samples and sampling frequency was severely curtailed. However, the number of samples was sufficient to calculate means and variations, which were used to compare values, delineate trends in the data, and ensure that the treatment goals were met.

Table 10. Analytical methods, sampling frequency, and quantitation limits.

Parameter	Standard Method	Quantitation Limit
Solids – Total and Soluble	2540	1 mg/L
Coliforms	9221	2 – 1600 cells/100ml
Nitrogen and Phosphorous	4110	0.03 – 0.05 mg/L
COD	5220 D	3 mg/L
BOD_5	5210 A	1 mg/L
TOC	5310 B	2.5 mg/L
Turbidity	2130 B	0.1 NTU
MBAS	5540 C	0.05 mg/L
Color	2120	1 Unit

Blackwater influent and reclaimed water were sampled and analyzed for secondary indicators of water quality discussed in Section 3.1.1, Table 5. As was discussed, sampling and analysis for these analytes is not required, however, these analyses provide a useful water quality comparison to the comprehensive water quality data collected by the City of San Diego North City Water Reclamation facility. The methods and quantitation limits for these analytes are summarized in Table 12.

Table 11. Summary of analyses and methods for secondary indicators of water quality.

Parameter	Standard Method	Quantitation Limit
Sodium	3500	100 µg/L
Iron	3500	5 µg/L
Manganese	3500	1 µg/L
Boron	4500	15 µg/L
Nitrate/Nitrite	4500	0.05 mg/L

µg/L – micrograms per liter

5.5 SAMPLING RESULTS

Standard Excel based statistical analyses were used to analyze and compare data sets collected at discrete times.

5.5.1 Calibration of Equipment

Sensors (turbidity, flow meters, power consumption, pressure, and oxidation reduction potential) were calibrated as specified by the manufacturer. Continuing calibration will require an acceptance criterion within ± 10% of the true value or as specified by the manufacturer. When discrepancies appeared in the data, the sensors were recalibrated and replaced, if necessary.

5.5.2 Quality Assurance Sampling

Data quality objectives are based on precision, accuracy, representativeness, completeness, and comparability (PARCC) criteria. Table 12 summarizes these criteria for the analyses that will be performed for this project.

Table 12. Target quality assurance (QA)/quality control (QC) objectives for primary water quality analytes.

Analyte	Standard Method	Units	Precision (%) RPD	Accuracy (%) Recovery	MDL	(%) Completeness
Solids - Total, Soluble	2540	mg/L	≤30	60-120	1	≥80
Coliforms	9221	MPN	≤30	30-120	1	≥80
Nitrogen and Phosphorous	4110	mg/L	≤30	90-110	0.02 - 0.22	≥80
COD	5220 D	mg/L	≤30	75-125	40	≥80
BOD_5	5210 A	mg/L	≤30	85-115	100	≥80
TOC	5310 B	mg/l	≤30	90-110	0.06	≥80
Turbidity	2130 B	NTU	≤30	80-120	0.1	≥80
MBAS	5540 C	mg/L	≤30	80-120	0.04	≥80
Color	2120	Units	≤30	80-120	1	≥80

MDL = Minimum Detection Level
RPD = Relative Percent Difference
NTU = nephelometric turbidity unit

- ***Precision*** is a measure of agreement among replicate measurements of the same property under prescribed similar conditions. It is the RPD between duplicate samples and is calculated using the formula:

  $$RPD = \left\{\frac{[X_s - X_d]}{[X_s + X_d]}/2\right\} * 100$$

  X_s = result for the sample
  X_d = result for the duplicate sample

- ***Accuracy*** is a measure of how close an individual measurement is to the true value and is influenced by random error and systematic error. Spiked samples are used to calculate accuracy from the formula:

  $$A = \{X_{ss} - X_s/T\} * 100$$

  A = Percent recovery
  X_{ss} = Result for the spiked sample
  X_s = Result for the sample
  T = True value of the added spike

- ***Representativeness*** is the degree to which sample data accurately and precisely represent a characteristic of a population parameter at a sampling point.

- ***Completeness*** is a measure of the amount of valid data obtained from the measurement system compared to the amount that should have been collected. This project has a completeness goal of 80% or better.
- ***Comparability*** is the confidence with which two data sets can contribute to a common analysis and interpretation.

Precision and bias will be measured by analysis of field and laboratory QC samples and comparison of statistics calculated using these results to determine the acceptance criteria. Representativeness and comparability will be assured by the adequacy of the sampling procedures. Method detection limits ensure that a meaningful comparison of the concentration data to performance standards can be completed. Audits conducted by the contracted laboratory will be reviewed for compliance with standard QC objectives. In case of discrepancy:

- Measurements may be repeated;
- Calibrations may be checked/repeated;
- Instruments/sensors will be replaced as necessary; and
- Spikes will be submitted blindly with field samples.

The QA/QC assessment and audit results will be summarized in project reports that will include the following information:

- Overall assessment of pilot and full-scale implementation activities;
- Summaries of accuracy, precision, completeness, and comparability of data;
- Corrective actions taken, if necessary; and
- Summary of significant observations.

Samples will be identified in accordance with standard practices and will include a chain of custody form. In addition to following specified procedures for collecting, storing, and holding samples for specific analyses, samples will contain trip, field, and equipment blanks as well as matrix spike and duplicates. All data will be compiled and stored electronically.

6.0 PERFORMANCE ASSESSMENT

The following discussion summarizes the measured and assessed quantitative and qualitative performance of the Living Machine. A more complete discussion and presentation of the results can be found in the draft technical report.

6.1 QUANTITATIVE PERFORMANCE OBJECTIVES

Quantitative measures of blackwater treatment use a variety of non-specific parameters that over many years of use have been shown to be an accurate assessment of wastewater treatment effectiveness. For example, BOD, TKN, and TOC measure organic matter biodegradability - without having to measure the hundreds of individual compounds that are present. Collectively, these parameters along with the other parameters in Table 13, provide an accurate and reproducible assessment of treatment performance.

Because the funds for analyses were committed to a contract with a commercial lab, the analytical costs were three times higher than budgeted (see Section 5). As a result, a complete set of triplicate samples was collected in September 2012 and a limited set in October 2012. The remaining two sampling events (August and November 2013) collected single samples. To compensate for this limitation, successive rounds of data were grouped and an Excel-based propagation of error routine was used to calculate the averages and standard deviations shown in Table 13. Even though the sampling was not as extensive as originally proposed, the data clearly demonstrate the ability of the Living Machine to reclaim blackwater and maintain treatment effectiveness.

Table 13. Average values and standard deviation for assessment parameters.
(units parts per million [ppm]; color - color units; turbidity – NTU, and pH)

Analyte	BW[1]	T1	T2	T3	T4	CW
Ammonia	157.5±30	36.92±9.26	48.05±20.15	11.8±02.10	4.71±7.55	2.33±2.92
Nitrate Nitrite	0.02±0.02	22.82±21.94	14.23±16.79	73.63±27.28	77.79±30.29	67.48±26.51
TKN	184.88±45.82	44.5±14.89	63.91±26.08	14.30±4.58	6.21±10.51	2.92±2.94
TN	199.13±48.92	72.54±27.34	82.46±25.27	85.07±21	84.21±20.12	70.06±24.45
TOC	120±30	14.8±2.18	14.72±2.07	8.38±1.13	7.99±3.40	6.29±1.18
Total Phosphate	15.3±5.18	9.02±3.99	10.63±3.98	3.10±0.87	2.15±0.78	2.03±1.37
COD	455±21	50.5±4.95	94.2±41.6	29.5±7.78	35.8±7.36	22.5±2.12
TSS	85.2±30.94	5.10	5.40	5.60	9.80	BDL
TDS	921±106	888±111	893±70	12363±231	1252±186	1318±210
MBAS	1.79±0.63	0.3±0.11	0.21±0.13	BDL	0.13	BDL
Color	90.13±17.76	50.4±22	57.75±20.84	20.2±5.89	15.8±5.54	14.57±7.11
pH	8.08±0.34	7.07±0.44	7.19±0.3	7.18±0.31	7.27±0.51	7.33±0.33
Turbidity	96.76±21.57	10.94±5.06	10±4.34	2.21±1.39	1.38±2.02	0.66±0.80
BOD	311.57±132.56	17.68±9.91	56.35±66.74	3.15±1.37	7.60±3.11	7.48±3.02
Fecal Coliforms	>1600	>1600	>1600	307±168	1367±404	5±4
Total Coliforms	>1600	>1600	>1600	633±231	>1600	15±11

[1]Blackwater (BW), Stage 1 Cells (T1 and T2), Stage 2 cells (T3 and T4) and clean water (CW)
BOD = biochemical oxygen demand

Furthermore, the analyses were run by two different labs and the volume of water being treated prior to and during each sampling period differed. In addition, extended interruptions to wastewater flow may have impacted the development and maturity of the biofilm. Thus, data from the individual sampling events data are not strictly comparable. However, even with this caveat, clear trends in the data are apparent.

Results - Nitrogen. There is a rapid decrease in ammonia and Kjeldahl nitrogen that measures organic nitrogen as the blackwater passes through the treatment cells (Table 13). Part of the decrease may be due to volatilization of ammonia and possibly organic amines, which are the predominant forms of nitrogen in the anaerobic and slightly alkaline (see pH Table 13) wastewater. As the wastewater passes through the treatment cells, it becomes less alkaline and becomes aerobic, which favors the growth of nitrifying bacteria that rapidly oxidize the remaining ammonia to nitrate that, along with minute amount of nitrite, is the primary form of nitrogen in the reclaimed water (sample CW, Table 13).

Results - Phosphate. The first sampling event (September 2012) showed a significant decrease in phosphate as the wastewater passed through the treatment cells (Table 14). Originally it was thought that once the design treatment capacity of the Living Machine was achieved and adsorption sites for phosphate on the media were saturated and the biofilm was established, the phosphorous concentration was not expected to show much change as wastewater passed through the system. However, the November 2013 sampling results suggest that phosphorous uptake (presumably physical and biological) is ongoing (Table 14). One possibility is that the physical adsorption sites are not saturated (doubtful). Alternatively, phosphorous stored in dead biomass that accumulates in the treatment cells may not be as readily available as phosphorous in the incoming wastewater.

Table 14. Concentration of total phosphorous (average and standard deviation; units ppm) in samples of Blackwater (BW), Stage 1 Cells (T1 and T2), Stage 2 cells (T3 and T4) and clean water (CW) taken during each of the sampling events.
The average values and standard deviation for all sampling events are shown in the last row.

Date	BW	T1	T2	T3	T4	CW
November 2013	13	7	7.1	1.6	2.2	1.5
August 2013	3.20	2.90	2.20	3.10	3.50	3.20
October 2012	17.77±0.86		13.33±0.55			3.30±0.04
September 2012	17.63±0.12	11.73±0.25	11.90±0.26	3.60±0.14	1.69±0.03	0.55±0.17
Average	15.30±5.18	9.02±3.99	10.62±3.98	3.10±0.87	2.15±0.78	2.03±1.37

Some of the variation may be due to differences in methodology - in 2012 total phosphate was measured using SM 4500-PB5 and the 2013 analyses used EPA Method 200.7. The methods used to digest the samples and the detection methods are different—SM 4500-PB5 is a colorimetric method; EPA Method 200.7 uses Inductively Coupled Plasma-Atomic Spectrometry. Also, the analyses were run by two different labs; however, there were not large differences in any of the other analyses, which suggest that differences may be method specific.

Results - Bacteria. Although numerous bacterial genera and species are found in blackwater, the MPN methodology is traditionally used to enumerate total and fecal coliforms, which are used as indicators of fecal contamination and disinfection effectiveness. The terms total and fecal coliforms do not refer to specific genera or species of bacteria; rather both terms include a wide assortment of aerobic and facultative anaerobic non-spore forming gram-negative bacilli. To estimate how many of each class of bacteria are present in the water samples, test tubes containing a lactose-rich broth are inoculated with serial dilutions of the samples and incubated at either 35 degrees Celsius (°C) or 44.5°C. A colorimetric pH indicator included in the media detects acid production and a small inverted test tube is used to detect carbon dioxide production. Total coliforms are defined as bacteria that produce carbon dioxide (no acid) within 48 hours when the media is incubated at 35°C and fecal coliforms are defined as bacteria that produce acid and carbon dioxide within 48 hours when the incubation temperature is 44.5°C. The positive tubes (acid; acid and gas) at each temperature are counted and along with the dilution factor are used to estimate the number of bacteria of each type, which is expressed as MPN per 100 ml.

The results (Tables 13 and 15) show, as expected, that there is no significant decrease in either total or fecal coliforms until the water passes through the disinfection unit and into the clean water (CW tank). Because the objective of the test is to determine disinfection effectiveness, the test is designed to establish if the number of residual bacteria exceed some lower threshold. The test does not provide an estimate of the total number of bacteria, which in raw wastewater, will be in the millions. As performed, the upper measureable limit is 1600 bacteria per 100 ml.

Table 15. Fecal and total coliforms; units most probable number per 100 ml (MPN/100 ml), values are averages ± standard deviation.

	Coliforms – MPN/100ml					
	Fecal			Total		
Sample Date	T3	T4	CW	T3	T4	CW
September 2012	307±168	1367±404	<2	633±231	>1600	6±7
October 2012			5±4			23±6
August 2013			-			+
November 2013			-			+

The laboratory used for the August 2013 and November 2013 sampling events reported the results as detect (+) or non-detect (-) (Table 15); no fecal coliforms were detected, which is consistent with previous results that detected few, if any, fecal coliforms (primarily E. coli) in the clean water.

Discussion. Overall, the data suggest that most of the degradation occurs in the two Stage 1 cells. For example, changes in BOD and TKN that measure degradation effectiveness exhibit similar behavior— specifically rapid and substantial decreases occur almost exclusively in the two Stage 1 cells whether the data are plotted for the individual sampling events (BOD and TKN; Figures 14 and 15).

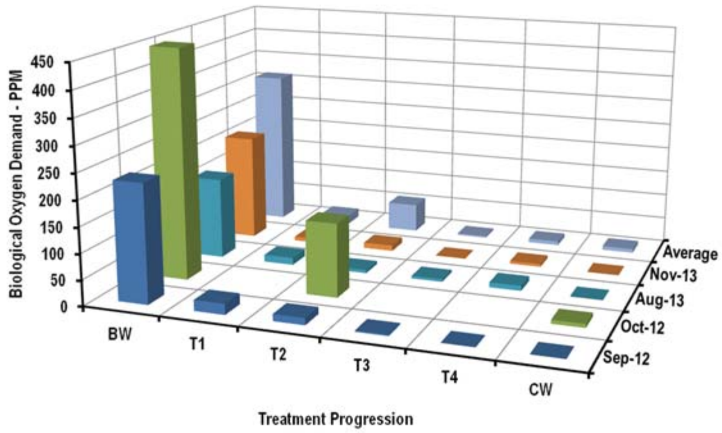

Figure 14. Value of the BOD for each sampling event and the average values (last row) at each sampling point as treatment progresses.

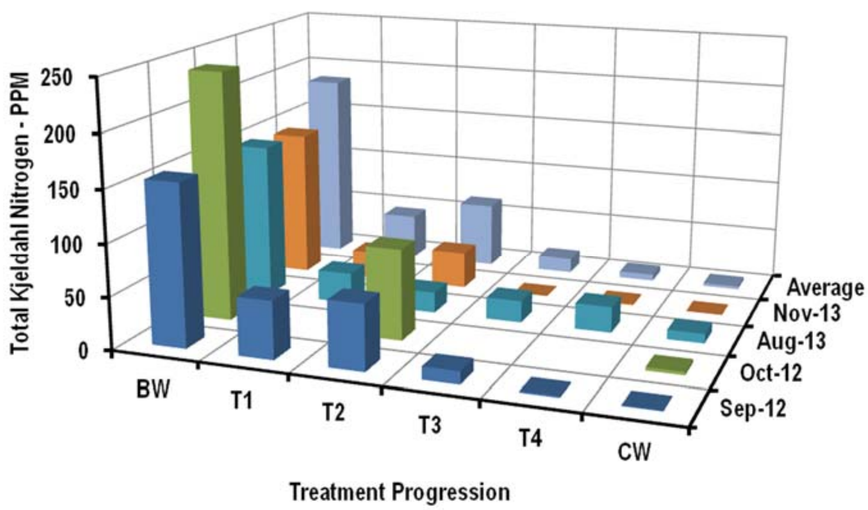

Figure 15. TKN value at each sampling point is shown as treatment progresses along with the average values (last row).

Data collected at MCRD suggests that, to a first approximation, degradation of organic matter in the wastewater as it passes through the Living Machine can be modeled using a simple first order kinetic expression, which has the familiar form:

$$\frac{dx}{dt} = -kx$$

$$\int_{xo}^{x} dx/x = -k\int_{0}^{t} dt$$

$$x = x_o e^{-kt}$$

Unfortunately, Excel curve fitting routines are not very useful for the analysis of nonlinear data. However, the Excel add-on Solver can be used to analyze and fit nonlinear data, and is much more precise than the traditional approach in which nonlinear equations are rearranged to a linear form (e.g., $\ln x = \ln x_o - kt$). In the following examples, solver along with weighted least squares was used to fit the turbidity and biological oxygen demand data to a first order kinetic expression.

For these analyses, the wastewater residence time in each cell was assumed to be forty minutes. A more accurate estimate of the rate constants was calculated by using solver in conjunction with the statistical method "Jackknife." This calculation yields turbidity and BOD degradation rate constants (k; Table 16) that were used to calculate regression lines for each data set (Figure 16). Previously compiled average values and standard deviations are also plotted on each graph. The rate constant was also used to estimate the time ($t_{1/2}$) required for half the substrate to degrade (Table 16).

Table 16. Rate constants (k; units - min-1) and the corresponding $t_{1/2}$ values for turbidity and BOD data collected at MCRD.

Parameter	Rate Constant (k) ± Standard Deviation Units Minutes^{-1}	$t_{1/2}$-(ln 2/ k) Units Minutes
Turbidity	0.04097±0.00905	17
BOD	0.06370±0.01320	11

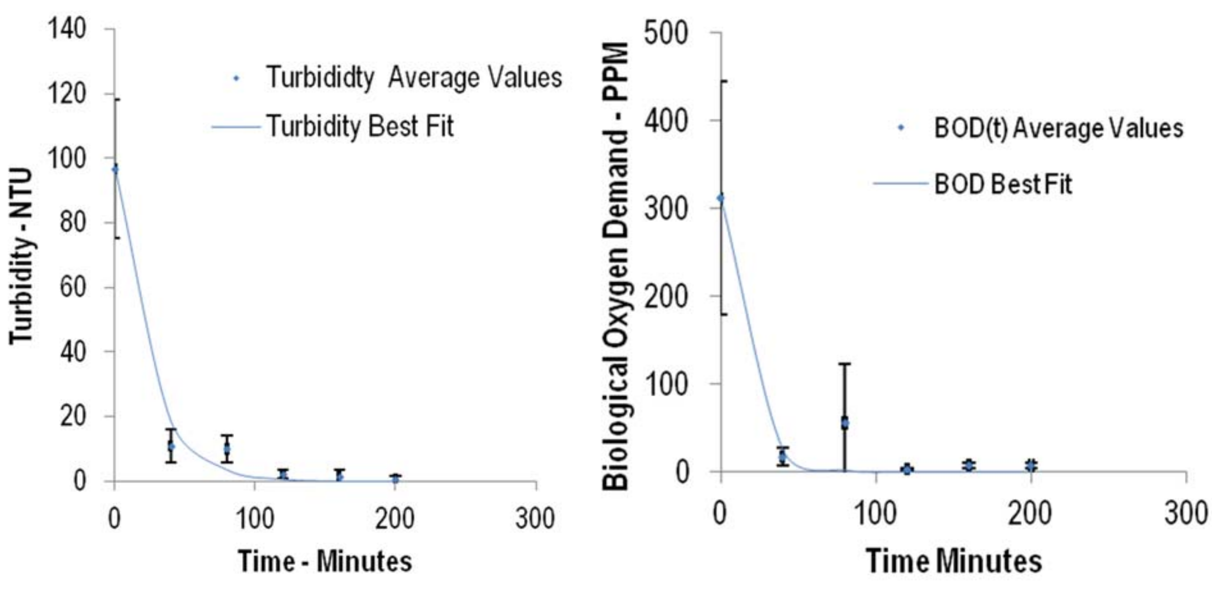

Figure 16. Regression lines fitted to turbidity (left) and BOD (right) data.
The Excel add-on Solver in conjunction with the statistical technique "Jackknife" were used to calculate the rate constants, which were used to calculate the regression lines. Previously compiled averages and standard deviations for each data point are also plotted.

In addition, parameters that are measures of degradation (TKN, BOD, Turbidity, COD, and TOC) are strongly correlated with each other. For example, Figure 17 suggests that turbidity and BOD are linearly correlated.

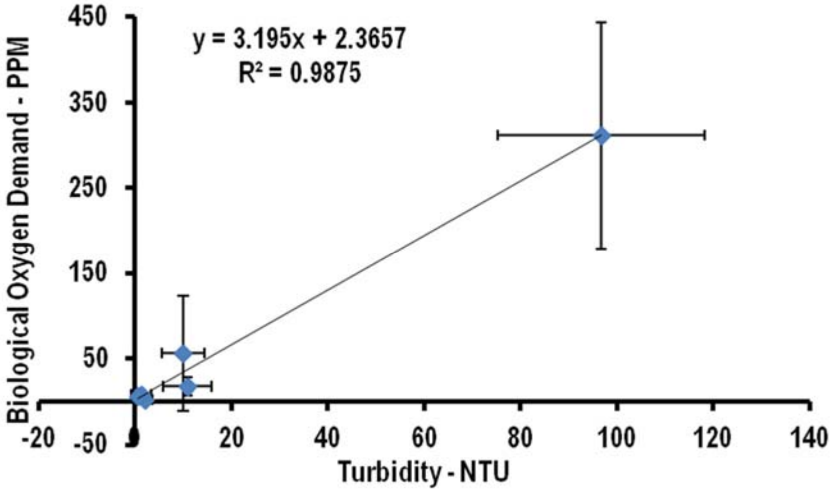

Figure 17. Plot of biological oxygen demand vs. turbidity.
(inset shows best fit equation and correlation coefficient)

Conclusions. Even though this is an open air wastewater treatment plant operating in a highly visible location, there is no odor and visually it does not appear to be a sewage treatment facility (Figure 8); odor, solids, and color have been eliminated (Figure 18). Although some of the nitrogen (ammonia and possibly amines – the primary form of nitrogen in the alkaline and anaerobic wastewater) may have volatilized, there is no odor characteristic of these compounds. By the time the water enters the clean water tank, almost all of the ammonia has been oxidized to nitrates and nitrites and most of the organic matter as measured by BOD, TOC, COD, MBAS and to a lesser extent, TKN and color have been degraded (Table 13).

Figure 18. Photos of blackwater entering the Living Machine and reclaimed water.

These data confirm one of the major operational benefits of the Living Machine; namely fill and drain is a very effective method for aerating the treatment cells (as shown by the rapid oxidation of ammonia to nitrates and nitrites) and maintaining treatment effectiveness—specifically removal of BOD and other measures of organic matter. Even though the performance of the Living Machine would be expected to improve as the biofilm in each treatment cell matures (e.g., more rapid degradation and lower residual concentrations of some analytes), the data do not support this supposition. Rather, it appears that a diversely populated biofilm was rapidly established and quickly came to equilibrium. The observation that degradation follows first order kinetics and the linear correlation between some of parameters suggests that it may be possible to use these relationships along with an optimization algorithm to increase treatment effectiveness.

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7.0 COST ASSESSMENT

7.1 COST MODEL

Project performance criteria and data that were collected and analyzed to establish project costs are summarized in Table 17. Costs and revenues (approximate) used to estimate the ROI, which is predicted to become positive during the ninth year of operation (Figure 19) are shown in Tables 18 and 19, respectively. These estimates do not include site-specific costs for the enhancements requested by MCRD. Because they are prescribed in the reuse permit and are usually site-specific and may be subject to negotiation, the costs for operation and compliance when the system becomes the responsibility of MCRD are not included.

Table 17. Summary of project performance criteria and metrics.

Cost Element	Data Tracked During the Demonstration	Value
Site Preparation	Support Labor & Materials (DoD) Permits (SDRWQCB)	\$32,000 \$1,900
System Procurement and Installation	Pre-Design Site Assessment Engineering Design, Purchase, Shipping, Labor, Material, and Utility Connection	\$448,000
System Operation	Power Water Volume Treated Water Volume Reclaimed Water Recovery Reliability	0.006 kWh/g/d 9,000 gpd 8,500 gpd >90% of Input >95%
System Maintenance	Labor and Material per Event Event 1 (pipe leak repairs, pump replaced) Event 2 (UV bulb and level sensor replacement) Event 3 (Screen clean-out, chlorine tablets)	 \$3,000 (gratis) \$1,450 \$2,100
Operator Training	Training Materials (O&M manual) Training Time	\$3,000 32 hours
ROI	Current Practice vs. On-Site Reclamation	ROI 8 - 10 Years

Startup costs include: labor and materials required to prepare the site (grading and excavation); purchase and install the system (capital costs, labor, materials); connect the system to the sewer (permit, labor, materials); and utilities (power, makeup water). Operations and maintenance costs include: labor, replacement parts, equipment calibration, sample collection and analysis, and disposal of solids that accumulate in the LET.

An on-site electric meter is used to track power consumption and cost. Flow meters track how much wastewater is treated and reclaimed. These volumes are used to calculate the value of the reclaimed water and sewer avoidance charges and are the basis for calculating actual cost-savings.

Table 18. Installation and operation costs for the Living Machine installed at MCRD.

Costs	Per Year	Ten Years
Living Machine capital cost – one time	$448,000	NA[1]
Power - San Diego Gas and Electric Schedule AL-TOU (standard commercial rate for non-residential customers). Yearly rate increases assumed to be 6%.	$2,062	$21,533
O&M	$3,050	$30,500
Biosolids Disposal	$400	$4,000
Cost Per Year	**$5,512**	**$56,033**

[1]NA – Not Applicable

Table 19. Estimated revenue for a 10,000 gpd Living Machine.

Revenue	Per Year	Ten Years
Sewer Fee Savings - City of San Diego Public Utilities rate schedule with escalations of 7.9% based on historical sewer rates	$32,680	$347,528
Water Reuse Savings - City of San Diego Public Utilities rate schedule with escalations of 6.4% based on historical water rates	$23,482	$246,052
Gross Revenue	**$56,162**	**$593,580**
Net Revenue	**$50,650**	**$537,547**

Personnel at MCRD were trained to monitor and operate the system. Because the Living Machine® installed at MCRD is a full-scale system, no scaling is necessary; however, increasing the treatment capacity would also increase the capital cost.

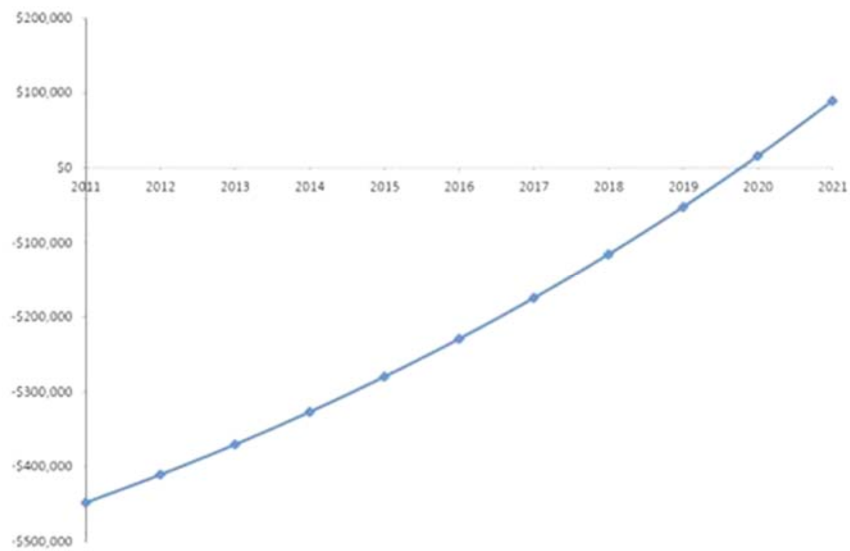

Figure 19. Project ROI – MCRD Living Machine.

The Building Life-Cycle Cost Program (BLCC5, version 5.1-03a) run in the MILCON ECIP project mode was used to project the payback and savings to investment ratio for this project at ten and twenty year intervals. Because the system will be installed adjacent to the DI memorial, which is a highly visible location, MCRD requested that the installation blend into the site—a primarily cosmetic request that increased the capital cost from $250,000 to $480,000 and was funded by MCRD.

7.2 COST DRIVERS

As mentioned in the problem statement, the technology is most beneficial to DoD activities with water quality and supply issues. This technology will greatly reduce potable water demand and discharge to POTWs. The technology is more beneficial to Forward Operating Bases(FOB) by reducing the need to transport potable water to bases and wastewater away from bases, which will enhance security, environment, and stewardship of foreign lands.

7.3 COST ANALYSIS

Using the capital cost of the system installed at MCRD skews the economic analysis and the results are not representative of a more typical and less costly system. The difference was demonstrated by running a cost analysis for a standard and less costly installation with the same capacity as the MCRD installation. The comparative analysis shows that the break-even point for the less costly system comes 5 years sooner than the costlier installation. By way of comparison, the cost analysis shown in Figure 19 used a more traditional straight line break-even analysis that predicts the break-even point for the higher cost system around year nine, which is 3 years sooner than the 12.7 years projected by the MILCON ECIP analysis.

A less expensive system, originally planned for this demonstration, would have consisted of fiberglass tanks installed above ground (see Figure 20). This type of system would have avoided the big expense in construction (burying concrete tanks and system auxiliaries). The estimated system cost for this above ground system was $250K compared to cost of the more expensive system of $448K that was installed. The installation cost difference was absorbed or paid for by MCRD to get a more aesthetic looking system.

Figure 20. Basic and less expensive Living Machine system (with above ground tanks).

The more complex MILCON ECIP analysis estimates that the break-even point for the higher capital cost installation at MCRD will occur at year 12.7 and the lower capital cost system early in the seventh year. Because the expected life of either system is at least 20 years, this is not unreasonable and, as expected, the economics of the project measured by the savings to investment ratio for both systems becomes more favorable with the longer the system is operated. As the operational lifetime increases from 10 to 20 years, the savings to investment ratio for the higher capital cost system increases from 1 to 2.55 and that for the lower capital cost system increases from 1.8 to 4.56. As water availability and quality is increasingly impacted by demand, global warming and climate change, the ROI is expected to become even more favorable than this analysis suggests.

8.0 IMPLEMENTATION ISSUES

For many years concerned citizens and a smattering of public agencies have promoted more efficient use of water resources - often with little or no impact. However, climate uncertainty driven by global warming is prompting the agencies that have to deal with the consequences of increasingly threatened water supplies to start taking action. In California, conservation actions include a so far unsuccessful 20% voluntary reduction in residential consumption (Boxall, 2014), rain barrels, rain gardens, xeriscaping, and relatively low-tech (but cost effective) and easily implemented conservation technologies (waterless urinals, high efficiency toilets, reduced flow shower heads, and smart irrigation). Water saving technologies can be found on the EPA Water Sense webpage (http://www.epa.gov/WaterSense/products/toilets.html).

The problem in California and other drought stressed states is that residential conservation measures have been a way of life for decades and it is difficult to achieve more savings with these technologies. For example, even though the population of Los Angeles has grown by almost one million, the per capita daily water consumption has dropped from 187 gallons in 1987 to 129 gallons in 2013. For comparison, water consumption in San Diego is 166 gpd, while Las Vegas, at 219 gpd, is one of the highest per capita rates in the country (with Palm Springs, CA at 948 gpd being the highest). Comparably, Scottsdale, AZ at 220 gpd is slightly higher than Phoenix at 184 gpd (Dostis, 2013; Glionna, 2014; Rogers and St. Fleur, 2014). Per capita consumption rates in Texas range from a high of 302 gpd in Galveston to a low of 143 gpd in El Paso (Magala, 2014). Drought in Texas has greatly diminished surface water supplies and the already overtaxed Ogallala and Carrizo-Wilcox aquifers are being rapidly drawn down to provide water to some of the fastest growing cities in the country. In some cities, desalination of brackish groundwater is being used to make up part of the water deficit. These include a joint project between the city of El Paso and Fort Bliss. However, high cost has limited production to less than 5% of annual water need (http://www.window.state.tx.us/specialrpt/water/).

Suburban landscape irrigation accounts for 40-60% of potable water consumption, therefore, to achieve significant reductions in residential consumption this use will have to be targeted. Because distributed reclamation (i.e., the Living Machine) with irrigation reuse does not require the extensive infrastructure that centralized treatment does, it saves money and along with xeriscaping can help reduce the demand for one of the major residential consumers of potable water. In California and other Western states, agriculture is responsible for 70% of total consumption and nationwide agriculture and thermal electric power plants each account for 40% of water consumption (80% total). Ultimately, significant reductions in water consumption will require developing and implementing more efficient water use technologies by and for these industries.

Moreover, increasing demand coupled with more severe weather fluctuations will require technologies that offer more efficient reclamation and reuse of available water. A relatively easy target is greywater (also gray water), which is defined as wastewater from sinks (bath and kitchen), showers, baths, laundry, and dishwashers. It does not include water from toilets (blackwater or sewage), which contains human waste. Because it requires relatively simple disinfection (filtration and chlorination), greywater is relatively easy to recycle on site and is commonly used for toilet flushing and irrigation. Commercial greywater treatment systems are available, but retrofitting existing structures to separate greywater and blackwater often requires extensive (read expensive) replumbing. Thus, greywater reclamation is more easily incorporated into new construction; however separate grey- and black-water plumbing systems are still required. In either case (retrofitting or new construction), extreme diligence is required to ensure the plumbing is correctly installed—referred to as a cross-connection control. In contrast, the technology tested in this project is one example of a more advanced on-site blackwater or grey water capture-and-reuse technology. Because the system taps directly into the sewer it is not necessary to install and maintain separate plumbing systems; however, purple pipe has to be used for the reclaimed water. The Living Machine is also energy efficient, can produce water for human contact, and as this project has demonstrated, it can be unobtrusively configured to meet site-specific facility water reclamation requirements.

Guidelines for wastewater reclamation and beneficial reuse are produced by the EPA (EPA, 2004; EPA, 2012); however, states, tribal nations, and territories have primary jurisdiction over water reuse regulation. The primary regulatory agency in California is the California Department of Health (http://www.cdph.ca.gov/certlic/drinkingwater/pages/lawbook.aspx), which has delegated regulatory and permitting authority to the nine regional water quality control boards. At MCRD, permitting and regulatory authority is the responsibility of the SDRWQCB, which granted the reuse permit to MCRD. The installation of additional systems in California would require working with the board that has authority where the installation is located. In some areas water rights may be a more contentious issue than permitting. For example, the San Margarita River provides much of Camp Pendleton's water; however, upstream water rights include the Pechanga Band of the Luiseno Mission Indians, which are reclaiming their traditional water rights. Obviously, regulations and water rights are highly specific to the site and have to be considered in any project.

Although the Living Machine is a commercially available off-the-shelf technology, it like all technologies incorporates new technologies as they become available and to keep it competitive the vendor is expected to update the system. Thus, just as the version installed at MCRD incorporates new design ideas, the next version of the Living Machine would not be expected to be exactly the system installed at MCRD; however, the basic operating principle and treatment effectiveness is expected to remain unchanged. At MCRD, the presence of gun cleaning rags was unexpected and caused the system to fail. As is discussed in Section 5, this was corrected by installing a diversion weir in the sewer line and fabricating a cage to protect the transfer pump. It is reasonable to assume that this would be a recurring issue at any small arms training facility. Likewise, the unexpectedly high TKN loading required reducing by approximately 15% the volume of blackwater that could be treated. The vendors' technical staff felt that neither increasing treatment time nor capacity was a cost-effective solution. Rather, they recommended diluting 8500 gpd of the incoming blackwater with 1500 gpd of reclaimed water. Unfortunately, the sampling budget was exhausted, the impact of this change has not been assessed.

From the beginning of the project, MCRD has had three major concerns; summarized in an email from Mr. Rick Hatcher:

1. Will we be able to use the treated water?

   Answer: Reclaimed water has been permitted for irrigation reuse.

2. Will we have the expertise to operate and maintain the system once the responsibility is ours?

Answer: Two responses to this question:

1) Change job description(s) to include maintenance and provide requisite training; or
2) Contract with an outside vendor to provide required service.

3. Will future budgets cuts still allow us to fund the periodic maintenance requirements?

   Answer: As with all technologies, continuing budget justification is often required.

As the following statement from Mr. Hatcher shows, MCRD has been pleased with the project and remains committed to this and similar technologies.

> *We continue to work through these issues and the help and guidance from the Environmental Security Technology Certification Program (ESTCP) program has been great. This project is still a major talking point when we talk conservation, sustainability, and investing in the advancement of the technology.*

It should be noted that MCRD has and continues to showcase this technology to numerous DoD and civilian visitors as an example of a technically successful and economically viable on-site water reclamation technology that can significantly reduce the demand for additional water supplies, which allows critical facilities to meet their primary mission.

Although DoD agencies have mandates to reduce water usage and promote water reuse, funding, especially for items with large capital cost, is difficult to obtain. With budget cuts, furloughs, and uncertainties in future budget; it is more difficult for someone in charge to champion a new technology/system. Even if a technology is proven to work in certain DoD applications, there is a strong reluctance to take a chance on the new system because of the uncertainties it brings (e.g., operation and maintenance procedures).

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APPENDIX A

POINTS OF CONTACT

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