ADVANCING THE SCIENCE AND ENGINEERING AND INTEGRATION OF ON-SITE WASTEWATER SYSTEMS

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ABSTRACT

There is a need in the U.S. and globally for solutions to wastewater infrastructure that are effective in protecting public health and preserving water quality while also being acceptable, affordable and sustainable. On-site and decentralized systems have the potential to achieve these goals in rural areas, peri-urban developments, and urban centres in small and large cities. These systems encompass the building-level water cycle, spanning water supply and use to wastewater generation, treatment, and disposal/reuse. A growing array of approaches, devices and technologies have evolved that include point-of-use water purification, waste source separation, conventional and advanced treatment units, localized natural treatment systems, and varied resource recovery and recycling options. Moreover, there is a growing movement toward integration of on-site systems into sustainable infrastructure planning and design practices. To achieve advancements in science and engineering and help assure integration of the outcomes into practice, research and educational efforts has been essential. As highlighted in this paper, continued research along with enhanced outreach and higher education will enable future progress and realization of a grander vision regarding the possibilities for on-site and decentralized wastewater systems.

Keywords: wastewater treatment, water reuse, public health and water quality, sustainability

1 INTRODUCTION

1.1 Context and Historical Perspectives

Water and wastewater infrastructure can underpin a healthy society if solutions are effective in protecting public health and preserving water quality while being affordable, socially acceptable, and sustainable. In the U.S. today, most people have ready access to safe drinking water and adequate sanitation as a result of major investments during the 20th century. The situation is similar in many other industrialized nations around the world. As the U.S. and other industrialized nations entered the 21st century, centralized water treatment plants and piping networks produced and distributed drinking water while sewers collected wastewater for treatment at remote plants. In the U.S., centralized water and wastewater systems were serving 85% and 75% of the population, respectively. However, there were growing concerns about the sustainability of large centralized systems. Why...? In the U.S., many of the components of large centralized systems were at or approaching the end of their design life spans and rehabilitation options were often limited and extremely costly. In addition, some of the potential flaws in centralized systems were becoming more apparent. For example, nearly 50% of the safe drinking water produced is typically wasted as a result of water distribution losses (~20%) and clean water use for flushing toilets (~30%). Centralized systems can also lead to unplanned urban sprawl, localized water resource depletion, excess consumption of chemicals and energy, release of untreated sewage through leaking sewers and sewer overflows, and barriers to beneficial recycling and reuse. As evidenced by recent events in the U.S. and abroad, centralized systems are also subject to upsets during natural disasters and may be targets of terrorist activities.

In contrast to the larger centralized systems established in urban areas, private wells and septic systems were used in rural and suburban/peri-urban areas. During much of the 20th century, many viewed these systems as temporary with a vision that, sooner or later, they would be replaced by connection to centralized systems as these systems gradually expanded across the U.S. During this period, on-site and decentralized wastewater systems were commonly not designed or implemented to achieve explicit treatment and reuse objectives over long-term permanent use. Not surprisingly, there were performance deficiencies ranging from hydraulic failures to localized contamination of ground
waters and surface waters. These were attributed to varied causes including poor system siting, improper design, faulty installation, and/or inadequate operation and maintenance. To support a growing vision that on-site and decentralized systems were not temporary, but rather were a permanent component of a sustainable wastewater infrastructure, research and educational initiatives along with changes in regulatory requirements sought to improve the standard-of-practice for on-site and decentralized wastewater systems and mitigate many of these past performance deficiencies.

A landmark event that helped clearly solidify the role and impact of on-site and decentralized wastewater systems occurred 10 years ago when the U.S. Congress required the U.S. Environmental Protection Agency (USEPA) to prepare a report on overcoming barriers to the use of decentralized systems (USEPA 1997). Congress also authorized the USEPA to establish the National Decentralized Water Resources Capacity Development Project (NDWRCDP) (see www.ndwrcdp.org/). During the past decade, the NDWRCDP has sponsored workshops, applied research projects, and educational initiatives. Earlier this year, to help guide the future of the NDWRCDP, the Water Environment Research Foundation (WERF) and USEPA convened a 2-day workshop in March 2007 with the goal of identifying short-term and long-term, basic and applied, research and demonstration projects to advance the decentralized wastewater and stormwater fields. One outcome of this workshop was the preparation and signing of the Baltimore Charter for Sustainable Water Systems, which reads: "Water is at the heart of all life. In the past, we built water and wastewater infrastructure to protect ourselves from diseases, floods, and droughts. Now we see that fundamental life systems are in danger of collapsing from the disruptions and stresses caused by this infrastructure. New and evolving water technologies and institutions that mimic and work with nature will restore our human and natural ecology across lots, neighbourhoods, cities, and watersheds. We need to work together in our homes, our communities, our workplaces, and our governments to seize the opportunities to put these new designs in place. Our group of scientists, engineers, environmentalists, government officials, manufacturers, and members of the private sector are part of the solution. We have both the opportunity and obligation to participate with others on this task of transforming how we think and act in relation to water. We commit to implementing more sustainable water systems by expanding uses and opening new markets for small-scale treatment processes, advancing research on microbiological and macro-ecological scales, inventing new technologies based on nature's lessons, creating new management and financial institutions, reforming government policies and regulations, and elevating water literacy and appreciation in the public.”

1.2 The Continuing Evolution of On-site and Decentralized Systems

Based on research and development efforts over the past decade or more, modern on-site and decentralized systems have evolved that include a growing array of approaches, devices and technologies that can be applied at the development-level up to watershed scale (USEPA 2002). Ultra low-demand fixtures or source separation plumbing can enhance water infrastructure by minimizing water demands and maximizing reuse in buildings and developments spanning rural, peri-urban, and urban areas. Treatment and dispersal units include point of use water purifiers, anaerobic and aerobic bioreactors, constructed wetlands, porous media biofilters, soil-aquifer treatment units, membrane separation units, and other technologies. Effluent reuse can occur through toilet flushing, landscape irrigation, and other applications. To enable more widespread use of on-site and decentralized systems, education and training have helped improve the standard-of-practice while modifications to regulatory codes and development of management structures facilitate deployment of conventional and innovative systems.

While measurable progress has been made in many areas, the vision of on-site and decentralized systems is still unfolding and the possibilities for the future are open-ended. One vision is that as planning and design of sustainable water and wastewater infrastructure occurs, on-site and decentralized systems will be universally and equitably considered across all scales of development (e.g., individual buildings, cluster developments, communities, watersheds). Any automatic predisposition toward more centralized infrastructure will have vanished. Modern infrastructure will be characterized by low demand plumbing systems, treatment of wastewater at or near the point of generation, reclaimed and reuse of wastewater resources, use of sensors and monitoring devices to verify performance, and remote process control and system management to monitor and automatically
correct any system malfunction. Systems will commonly mimic natural processes to achieve performance objectives while minimizing water, energy and chemical use and enabling reuse.

2 ADVANCING SCIENCE & ENGINEERING & SYSTEM INTEGRATION

Further research along with effective outreach and higher education are essential to advance an on-site vision and fully realize the benefits afforded by on-site and decentralized systems. In response to this need, the Small Flows Program was established at the Colorado School of Mines in Golden, Colorado, USA (CSM) nearly a decade ago. This Program now encompasses research and educational activities carried out by a team of more than 20 faculty, staff and students (www.mines.edu/research/smalky/). Several theme areas are presented below for research and educational efforts that the authors of this paper view as critical to advancing the widespread application of on-site and decentralized wastewater systems. Along with each of these themes, highlights are provided for selected CSM research efforts.

2.1 Research Themes

While research is needed in many areas related to on-site and decentralized wastewater systems, critical needs exist in the following theme areas: (1) source characterization and manipulation, (2) performance dynamics in treatment units and systems, (3) microbial ecology and biotechnology, and (4) modelling and decision support.

1. Source Characterization and Manipulation. Knowledge of water use and waste stream characteristics can aid manipulation schemes that enable sustainable treatment technologies while enhancing resource recovery (e.g., water, plant nutrients, organic matter). Such knowledge can help identify the factors affecting composition and source stream treatability, and enable assessment of environmental risk of source separation and treatment/reuse as well as life cycle costs. Recent and ongoing CSM research projects have been focused on advanced characterization of modern waste streams. For example, in an ongoing CSM project, the compositions of wastewaters generated from different sources are being characterized through a comprehensive literature review and field-monitoring program (Lowe et al. 2006). Over 150 literature sources have been identified that include characterization data for raw wastewater and primary treated effluent (i.e., septic tank effluent (STE)) from domestic (single and multiple), food, medical, and non-medical sources. The dataset assembled includes conventional constituents, microorganisms, and trace organic contaminants and enables analysis through summary tables (e.g., Table 1) and cumulative frequency distributions (CFD) (e.g., Figure 1). In an ongoing phase of this project, field monitoring is being conducted in three regions of the U.S. A specialized sampling apparatus is being used to collect 24-hr composite samples of raw wastewater during each season of the year with analyses made for a suite of wastewater parameters (e.g., temperature, pH, organic matter, nutrients) as well as microorganisms and trace organics.

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<td>BOD₅ (mg/L)</td>
<td>343 [30-1147]</td>
<td>210 [110-400]</td>
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<tr>
<td>TSS (mg/L)</td>
<td>293 [18-2232]</td>
<td>210 [100-350]</td>
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<tr>
<td>Total N (mg-N/L)</td>
<td>63 [44.1-189]</td>
<td>35 [20-85]</td>
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<td>Total P (mg-P/L)</td>
<td>19 [13.0-25.8]</td>
<td>7 [4-15]</td>
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<tr>
<td>Faecal coliform (cfu/100mL)</td>
<td>4.9×10⁵ [3.0×10⁴-7.4×10⁵]</td>
<td>10⁴-10⁶ [10³-10⁶]</td>
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1 Median and [range] are given. Range values for Lowe et al. (2006) encompass all reported values. Range values for U.S. EPA (2002) and Critics and Tchobanoglous (1998) are "typical" ranges. A "-" indicates statistic not reported.

In another CSM effort being completed in collaboration with the U.S. Geological Survey (USGS), a range of organic wastewater compounds (OWCs), including surfactant metabolites, steroids, stimulants, antimicrobial agents, and pharmaceutical compounds, were quantified in 30 on-site treatment systems in Colorado (Conn et al. 2006). Eighty percent of 24 target OWCs were detected in one or more samples, and several compounds were detected in every wastewater sampled. The wastewater matrices were complex, and showed unique differences between source types due to
differences in water and consumer product use. Non-residential sources generally had more OWCs at higher concentrations than residential sources (Figure 2).

FIGURE 1. CFDs for BOΔ5 in raw wastewater (left) vs. septic tank effluent (right) (Lowe et al. 2006)

FIGURE 2. OWCs in septic tanks as a function of wastewater source (Conn et al. 2006).

[Res = residential (n=13); Ret = retail (n=3); Inst = human institution- schools and church (n=5); Vet = veterinary hospital (n=5); Food = food establishment (n=4); Con = convenience store (n=2); Left box- fall 2003; right box- spring 2004; Upper limit of box = maximum concentration, lower limit = minimum concentration.]

2. Performance Dynamics in Treatment Units and Systems. On-site and decentralized systems involve unit operations that can be combined to achieve up to tertiary treatment levels with disinfection, and enable different discharge and reuse options (Figure 3). Due to the inherent nature of these systems where flow and composition can vary, usage can be discontinuous, and the design life can be undefined but often decades long, the dynamics of performance as affected by design, operation, and environment can be quite complex. Moreover, when systems are comprised of unit operations that exploit natural systems (e.g., constructed wetlands or soil infiltration trenches), the function and performance of the natural system unit operation can be interdependent with that of the upstream tank-based operations.

FIGURE 3. On-site systems are comprised of unit operations, ideally combined in configurations to reliably and cost-effectively achieve performance objectives.
Research at CSM has included a focus on exploring the design and performance dynamics of unit operations and the interdependencies within different types of on-site systems (Figure 3). In one area of emphasis, laboratory experiments and field studies have quantified the performance effects of effluent composition, hydraulic loading rate, and infiltrative surface architecture on wastewater treatment in sand filters and soil infiltration trenches (e.g., Van Cuyk et al. 2001, Van Cuyk et al. 2005, Beach et al. 2006, Siegrist 2006, Lowe and Siegrist 2007, Lowe et al. 2007, Van Cuyk and Siegrist 2007). In addition to revealing the time-dependent and dynamic interaction of unit hydraulics and purification processes for conventional pollutants like BOD₅, TSS, N and P, these studies have revealed new insights about the transformation of organic matter and fate of virus and trace organics.

To illustrate, in one study a replicated factorial design was employed to evaluate three infiltrative surface architectures (ISA) (open, gravel laden, or synthetic-stone laden) with STE applied at three daily hydraulic loading rates (HLR) (4 or 8 cm/d) (Siegrist et al. 2005, Lowe and Siegrist 2007). Pilot-scale infiltration trenches were established in native sandy loam soils at the Mines Park Test Site located on the CSM campus. Based on two years of monitoring, the effluent infiltration rate declined to very low levels with a time-dependent behavior that was consistent with model simulations (Figure 4). After this period of decline, an open ISA maintained an infiltration capacity that was 40 to 80% higher than the other ISA’s tested. Purification of STE in the soil was very high; the cumulative mass removed for dissolved organic carbon (DOC), total N, and total P averaged 94%, 42%, and 99%, respectively while removal of bacteria and virus exceeded 99.9%. While there was no significant difference in purification based on ISA or HLR, a slight increase in purification was associated with an increase in the soil vadose zone depth (120 cm vs. 90 cm).

**FIGURE 4.**
(Lowe & Siegrist 2007)

Simulated and observed infiltration rate decline

Cumulative mass removal over 2 years for total N at 60 and 120 cm depth below the infiltrative surface

In a companion effort at CSM, a controlled field experiment has examined the purification performance of on-site systems employing different combinations of treatment units (a septic tank (ST), a septic tank with a textile filter unit (TFU), or a septic tank with a membrane bioreactor (MBR)) followed by soil infiltration and dispersal (Van Cuyk et al. 2005, Lowe et al. 2007). Based on 16 to 28 months of monitoring, the overall effluent quality produced followed the following relative ranking: ST-MBR > ST-TFU > ST. With the STE as the influent, the TFU achieved an average removal efficiency (mg/L) of 90% for cBOD₅, 30% for nitrogen (under high loading conditions), and >95% for fecal coliform bacteria. The removal efficiency of the MBR was 99% for cBOD₅, 61% for nitrogen, and 100% for fecal coliform bacteria. Organic carbon fractionation revealed that, in addition to reducing the total concentration of organic matter in the STE, the TFU and MBR transformed the organics to relatively more aromatic, and therefore more altered compounds. Consistent with the increased treatment efficiency achieved, the relative operational complexity, operation and maintenance requirements, energy use, and cost, followed the pattern of MBR > TFU > ST.

Addition of a treatment unit, such as a TFU or MBR, to produce effluent of higher quality than typical STE has the potential to retard soil clogging and enable application of higher HLRs resulting in smaller soil treatment units. The results of bromide tracer tests and infiltration rate measurements revealed that some degree of soil clogging occurred in the sandy loam soil at the Mines Park Test Site, even with application of the higher quality TFU or MBR effluents. Combined with the findings of
other studies, the increases in HLRs enabled by higher effluent quality are likely limited by the hydraulic properties of the natural soil (e.g., maximum HLR = 3 to 5% of the soil Ksat). Regarding system-wide purification (i.e., ST-soil vs. ST-TFU-soil vs. ST-MBR-soil), the on-site systems including a TFU or MBR compared to just a ST achieved generally higher purification when soil treatment occurred with only 60 cm of soil. However, when the soil depth was increased to 120 cm, the differences in removal of pollutants (e.g., DOC, N, P) diminished between the three system types. The ability of a sandy loam soil to remove virus was quite high (>99.99% by 60 cm soil depth) and insensitive to whether STE, TFU effluent, or MBR effluent had been applied at either 2 or 8 cm/d.

Studies of operating systems in Colorado have also been insightful regarding system design and performance. For example, in the project noted above where OWCs were characterized in septic tanks at 30 sites, additional monitoring was completed to assess the removal of OWCs in different types of on-site treatment units (Conn et al. 2006). Removal mechanisms included volatilization, biotransformation, and sorption yielding removal efficiencies ranging from <1% to >99% depending on treatment unit type and physico-chemical properties of the OWC. Additional aerobic biofilter-based treatment (e.g., TFU) beyond the traditional anaerobic septic tank treatment enhanced removal for many OWCs. Even with high removal rates, OWCs can be discharged to soil infiltration units at loadings up to 10 mg/nm²/d, emphasizing the importance of understanding removal mechanisms and efficiencies in on-site systems that employ soil-based treatment and dispersal. Further experimental work at the CSM Mines Park Test Site is ongoing to examine OWC fate in these systems.

3. Microbial Ecology and Biotechnology. Understanding the role of microbial ecology and biotechnology is critical to achieving sustainable wastewater treatment while enhancing resource recovery. Research can now apply modern molecular methods to characterize on-site wastewaters, treatment process effluents and residuals, and soil- and plant-based dispersal units. At CSM, a program of research is ongoing to quantify and interpret microbial diversity in a range of unit operations and systems. In one recent study, microbial community characterization was completed for soil samples taken from pilot-scale infiltration trenches installed in sandy loam soil that had received STE for ~30 months (Tomaras et al. 2006). Three samples were taken at depth intervals of 0.5, 1.0, and 1.5 cm beneath the infiltrative surface and additional core samples were taken to a depth of 10 cm. Samples were analysed using plate counts, biomass determination, and molecular methods with DNA sequencing. Heterotrophic plate counts, faecal coliform levels, as well as *E. coli* counts revealed a decrease in culturable organisms with depth, with one order of magnitude higher counts in the top 0.5 cm compared to soil at 10-cm depth. Total biomass data indicated a decrease in biomass with depth, with the top 0.5 cm having nearly double the biomass of the next lower 0.5 cm interval. Molecular characterization indicated there was a higher diversity of bacteria at the infiltrative surface zone than in soil samples taken from beneath this zone, but no dominant species have been identified.

In another recent study, samples were collected from a traditional septic tank as well from two septic tanks outfitted with aerobic bacterial generator treatment units, that had been supplemented with a bacterial blend of *Bacillus* species (Tomaras et al. 2007 unpublished). Two Phyla, Proteobacteria (80-95%) and Bacteroidetes (4-19%) primarily dominated the wastewater environments. A comparative microbial community analysis revealed little difference in composition between system types, but suggested that a significant community change occurs during septic tank treatment.

4. Modeling and Decision-Support Tools. Models and decision support tools are essential to proper planning and design of on-site and decentralized systems. At CSM, modelling and decision support projects have been focused on development of chemical and bacterial source tracking tools to allocate water quality impacts to different sources (e.g., Albert et al. 2003) and of models to aid system design and performance prediction and to support assessment of development-level impacts and watershed-scale cumulative effects (e.g., Beach and McCray 2003, McCray et al. 2005, Poetter et al. 2005, Bumgarner and McCray 2007, Heiwolle and McCray 2007, Geza and McCray 2007, Lemonds and McCray 2007). Exemplifying the scope and potential impacts of modelling, a CSM research project was recently completed that encompassed modelling to describe individual system performance and assess the cumulative effects of multiple systems on water quality within a watershed (McCray et al. 2005, Siegrist et al. 2005). This project included application of a numerical model, HYDRUS 2-D, to on-site systems with soil infiltration trenches to enable site-scale scenario analyses regarding hydraulic
and purification performance. To examine relative, cumulative effects at the watershed scale, the Watershed Analysis Risk Management Framework model (WARMF) as well as the HASINS/SWAT and MANAGE models were set up for the Dillon Reservoir watershed in Summit County, Colorado. This watershed contains over 1000 on-site wastewater systems as well as other non-point and point sources of pollution, and over 600 on-site drinking water wells along with community wells and surface water supplies. Compared to urbanized development and centralized wastewater treatment plant discharges, on-site wastewater systems were not a principal source of water pollutants as evidenced by (1) source load mass balance calculations, (2) model simulation results, and (3) water quality monitoring and analysis of spatial and temporal trends. Moreover, based on WARMF simulations of different wastewater management scenarios, extending central sewers and conversion of on-site systems to a central treatment plant offered little or no benefit to water quality protection.

2.2 Educational Themes

While research such as described above is critical to achieving advancements in on-site and decentralized systems, the research findings and innovations that result must be effectively disseminated and incorporated into outreach and educational programs. To help accomplish this, existing curriculum in higher education needs to be enhanced through incorporation of modules about on-site and decentralized systems in current course offerings (e.g., courses covering sanitary engineering, water supply engineering, wastewater engineering) as well as development of new courses (e.g., Decentralized Water Systems Engineering). Toward this goal, the Consortium of Institutes for Decentralized Wastewater Treatment (CIDWT) received funding from the USEPA NDWRCDP and developed a series of educational modules designed to support training of practitioners and education of technical school and university students (www.on-siteconsortium.org).

At CSM, on-site system modules have been developed and introduced in various undergraduate courses and a semester-long course for seniors and graduate students is now routinely delivered. This 15-week course is focused on the selection, design, and implementation of on-site and decentralized wastewater systems. Topics covered include process analysis and system planning, waste stream characteristics and source manipulation, engineered and natural system treatment units (anaerobic bioreactors, aeration units, packed bed biofilters, pond and wetland systems, soil and land treatment systems, disinfection units), and effluent dispersal and reuse options. The course also covers cluster approaches using alternative conveyance technologies and systems using source separation and resource recovery. A textbook is being prepared to support delivery of this type of course.

3 SUMMARY

On-site and decentralized systems have been and will remain a necessary and appropriate component of sustainable wastewater infrastructure in the U.S. and around the world. To support and enable advancements and help assure integration of the outcomes into practice, research and enhanced outreach and higher education, such as that carried out within the CSM Small Flows Program, have been essential. Laboratory and field research have improved fundamental process understanding and helped resolve emerging system design and performance questions. This has enabled development of new devices, technologies, and integrated systems. Modelling studies have led to development of decision-support and design tools, including validated models at the micro- to macro-scale. While not described herein, efforts have also addressed strategies for risk assessment, system management, socioeconomic analysis, and regulatory frameworks. To help assure that the research findings and innovations that result are being integrated into practice, developments have occurred to more effectively accomplish outreach and higher education of current and future decision-makers.

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