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Sociotechnical Aspects of Decentralized Wastewater Treatment Systems

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ABSTRACT

Decentralized wastewater treatment systems are utilized in areas where sewer systems are not feasible and septic service is unaffordable. Approximately 25% of the US population uses decentralized wastewater systems for their wastewater treatment. The Black Belt, which extends from the East Coast of the US from Virginia through the Carolinas, Georgia, Alabama, and Mississippi is an area that has a large population that depends on decentralized wastewater systems. In the State of Alabama, the Black Belt area is a 17-county region where, depending on the county, up to 85% of the residents rely on decentralized wastewater treatment. These decentralized systems are largely unaffordable for the residents in this region due to a median household income of $29K, which is half of the national average. One proposed system is a low-cost lab-scale hybrid evapotranspiration/lateral flow sand filter. The hybrid sand filter system is designed to treat 55 gallon per day (GPD) of septic tank effluent, sized at 13 ft × 12 ft × 3 ft. The influent is treated physically, chemically, and biologically within the sand layers of the system. Hydraulically, influent flows laterally and rises via capillary action within the sand layers. The system has a correlation to ambient temperature and humidity. Lower discharge rates are directly proportional to higher temperature and humidity. The following data represents the percent reduction for our wastewater treatment system: Ammonia (64%), Phosphorus (92%), COD (76%), and BOD (96%). The hydraulic and treatment data for the hybrid sand filter system are promising. In this analysis, the authors identify sociotechnical factors that can affect the performance and useful life of the system in a multiple decision matrix. Sociotechnical factors, such as persons per residence, electricity usage, and distance of the decentralized system from the residence, are analyzed to build a simple agent-based model (ABM) which will determine the impacts on the overall performance of the system.

Keywords: Decentralized wastewater treatment, Onsite wastewater treatment, Agent based model, Multiple decision matrix, SysML

INTRODUCTION

Access to wastewater infrastructure and management is believed by the public to be universal right (Capone et al., 2020; Maxcy-Brown et al., 2021). However, that belief may not be consistent with the reality for some residents of the United States. Consecutively for the past 3 years, the United

States has earned a D+ (Poor Below Standard) for its wastewater infrastructure in a report from the American Society of Civil Engineers (ASCE). The grading scale set by ASCE ranges from A (Exceptional) to F (Failing/Critical, Unfit for Purpose) (ASCE, 2021). Wastewater treatment in the United States is divided into two broad categories: decentralized and centralized. Centralized wastewater treatment is the treatment of wastewater of many homes by sending their wastewater using a collection network of pipes to one large treatment plant. Centralized treatment of wastewater is used by 80% of the population with 16,000 publicly owned wastewater treatment plants treating 62.5 billion gallons of wastewater per day (ASCE, 2021). Many of these treatment systems and other related infrastructure were built with funding provided by the Clean Water Act in the 1970s with plans of a 40 to 50-year lifespan for each system (ASCE, 2021). Currently, many of these systems have reached the end of their 40 to 50 year-lifespan. Decentralized wastewater treatment is the treatment of wastewater at the home with an at-home wastewater treatment system unit. With the reduction of funding and lack of attention, many of the decentralized treatment systems currently in operation have reached or surpassed the end of their lifespan or are overcapacity. Many of these systems have been identified as being out of compliance with regulations set by the United States Environmental Protection Agency (EPA). Straight pipes are direct unpermitted wastewater discharges from the home with or without solid settling, usually by a PVC pipe into the backyard (Maxcy-Brown et al., 2021). Unpermitted wastewater treatment systems are either not visible straight pipes or a created in-ground disposal system.

Alabama Black Belt

Some of the communities facing inadequate wastewater infrastructure and management are the residents of the Alabama Black Belt. The Alabama Black Belt is a 17-county region in the region south-central Alabama. Barbour, Bullock, Butler, Choctaw, Crenshaw, Dallas, Greene, Hale, Lowndes, Macon, Marengo, Montgomery, Perry, Pike, Russel, Sumter, and Wilcox are the 17 counties. The Alabama Black Belt's name comes from the fertile clay, vertisol soils making this region rich in farming history. These soils are suited for growing agricultural products (i.e. sweet potatoes, cotton, etc.) as the soil tends to retain and swell water. This swelling of water is known for forming impermeable clay barriers for water. This impermeable layer does not let water pass through, which is necessary for functioning and disposal of wastewater treatment with decentralized wastewater treatment systems. Up to 50% of residents in the Alabama Black Belt use decentralized wastewater treatment (McCaskill, 2023). The lack of drainage necessitates the use of expensive advanced wastewater treatment options, which are unaffordable to residents relying on decentralized treatment systems. Over 50% of the soil area in the Alabama Black Belt is unsuitable for septic tank systems (He et al., 2011). A field survey in 2005 of Bibb County of 4000 homes reported 35% of homes had septic tank failure and 15% of homes had no septic tank/drainfield (White and Jones, 2006). A field study conducted in 2017 on Wilcox

County reported 172 homes with straight pipes and 98 homes with unpermitted wastewater treatment systems (Elliott et al., 2017). A study in Hale County in 2017 reported 24 homes with and 243 homes with unpermitted wastewater treatment systems (Elliott et al., 2017). The lack of wastewater treatment is a public and environmental health hazard. Unprotected contact to raw sewage/wastewater exposes individuals to pathogens associated with fecal materials, heavy metals, microplastics, endocrine disruptors, and pharmaceuticals (Dickin et al., 2016; Wear et al., 2021). Further increasing the challenge for these counties to gain access to sustainable wastewater infrastructure is their rural nature and low economic basis. In a 2018 survey of 11 of the 17 Black Belt Counties the average median house income was reported to be less than $29,000 (approx. 50% the median house income of the United States) and the population density was reported to be 26.4 people per square mile (29% of the United States) (White and Elliot, 2018). In a more recent study, reported from the 10 poorest counties of Alabama, 9 of those counties are considered Alabama Black Belt counties (Capone et al., 2023). The vertisol soil, prevalent poverty, and rural spread of homes are some of the challenges which have made abstaining wastewater infrastructure/management for this region unattainable.

Evapotranspiration/Lateral Flow Sand Filter

In the exploration of more affordable wastewater treatment options for the residents of the Alabama Black Belt, the University of South Alabama designed a hybrid evapotranspiration/lateral flow sand filter with design heavily inspired by the Evapotranspiration Design Guidelines as described by the EPA (EPA, 2000) and On-Site Sewage and Disposal Systems: Technical Guidelines by the Nova Scotia Department of Environment and Climate Change (Department, 2013). A Systems Engineering approach was taken to develop the proposed "Hybrid Sand Filter System." The authors used a Model-Based Systems Engineering (MBSE) approach to model the overall logical architecture of the proposed decentralized wastewater treatment system (Figure 1) using Systems Modeling Language (SysML). MBSE is a formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases (SEBoK, 2023). In this study, the authors chose to model various SysML diagrams such as Block Definition Diagrams to develop a System context diagram, Domain diagram, and logical architecture. A Hybrid Sand Filter System is denoted as a "System of Interest" (SoI) for this project. The authors used the V-model approach to develop stakeholder definition, mission and system requirements analysis, the concept of operation (ConOps), specification, analysis, design, verification, and validation models of the SOI; the proposed model represents views of these systems, not the systems themselves. SysML parametric diagrams can be used to analyze and display various mathematical relationships; it will also be helpful to calculate the disposal output volumes in two use cases:

1. The amount of water outflow from the Hybrid Sand Filter.
2. The amount of water inflow into the Hybrid Sand Filter.

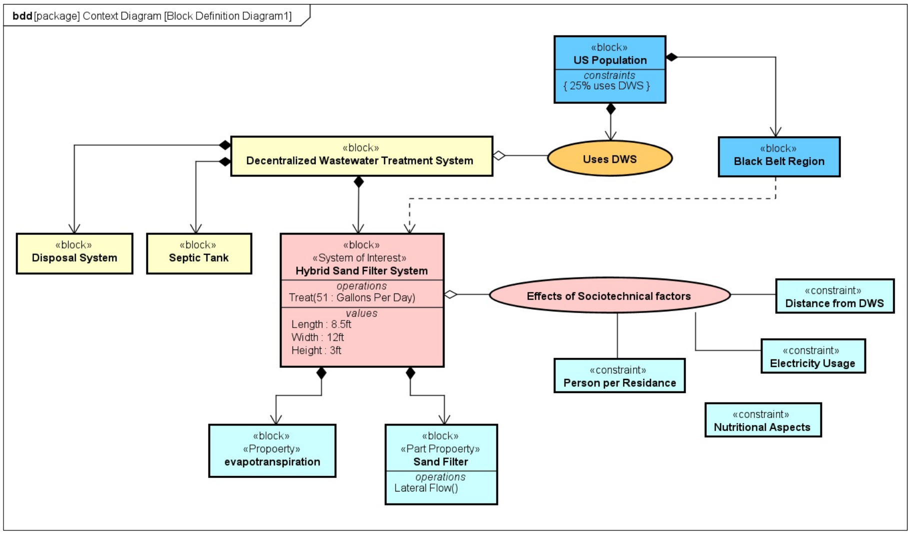

Figure 1: Illustration of the application of the MBSE demonstrating a top-level hybrid Sand filter system domain diagram with the important use case and its constraints.

The hybrid sand filter was designed with three major subsystems for a treatment flow of the following in corresponding order: a septic tank, a lateral flow/evaporation sand filter, and constructed wetland as illustrated in Figure 2. For testing purposes, the hybrid sand filter was sized at 13-ft × 12-ft × 3-ft (Length × Width × Height) designed to treat synthetic wastewater dosed at 55 GPD with continuous dosing. The constructed wetland had the modification from typical design with the addition of 48-qt of biochar, 36-cubic ft of #57 gravel, and 20-lb of sawdust with sizing of 6-ft × 4-ft × 1.5ft. Design of the hybrid sand filter corresponded to the temperature and environmental conditions of the Alabama Black Belt.

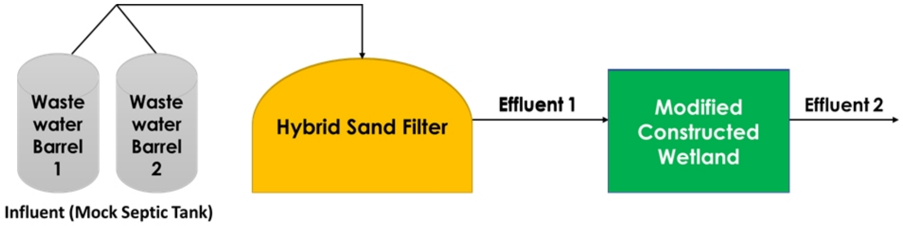

Figure 2: Treatment configuration of hybrid sand filter (McCaskill, 2023).

Testing of the treatment efficacy of the hybrid sand filter was recorded over the period October 8th, 2022, until January 3rd, 2023. The treatment results of the hybrid sand filter systems can be seen in Table 1. The influent, in this system, is defined as untreated wastewater. Effluent (Eff) can be described as treated wastewater after it has gone through the wastewater treatment system. In Figure 2, wastewater barrels are representative of the septic tank. Biological Oxygen Demand (BOD), Chemical Oxygen Demand

(COD), Nitrate (NO3), Ammonia (NH3), Total Nitrogen (TN), and Total Phosphorus (TP) are given in Table 1 in each test parameter in Table 1 is a discharge contaminant regulated by the EPA.

Table 1. Treatment results of hybrid sand filter (Bakchan et al., 2023).

Test Par	Avg Influent (mg/L)	Avg Eff 1 (mg/L)	Avg Eff 2 (mg/L)	% Reduct (I-E1)	% Reduct (E1-E2)	% Reduct (I-E2)	# of Tests
NO3	7.6	22.4	10.6	-195	53	-39	21
NH3	30.1	34.2	30.4	-14	11	-1	21
TN	94.2	61.7	45.2	35	27	52	20
COD	269.7	32.7	17.7	88	46	93	20
TP	5.0	1.4	1.3	72	8	74	21
BOD	118.2	6.4	4.9	95	23	96	21

The Avg Influent is the characteristics of the synthetic wastewater, Avg Effluent 1 is the treated wastewater characteristics after the hybrid sand filter and Avg Effluent 2 is the treated wastewater characteristics after the hybrid sand filter and constructed wetland. The rates of COD and BOD removal were satisfactory at 93% and 96%. The addition of the constructed wetland improved Total Nitrogen removal from 35% to 52%. Additionally, the constructed wetland greatly improved the reduction of nitrate and ammonia. Depending on the state standards and disposal requirements, the hybrid treatment system has the potential to scale to larger systems. From a cost perspective, material costs of the hybrid sand filter and modified constructed wetland were $7,500. This estimate did not consider the costs of the septic tank, piping, or labor costs. Material costs can be considered cost effective for the wastewater treatment in the Alabama Black Belt in comparison to other advanced wastewater treatment technologies which can exceed $10,000 (Maxcy-Brown et al., 2021).

The results show that the proposed model in this study is easy to understand and produces a shared understanding of how MBSE methods are useful in developing a decentralized wastewater treatment system. The SysML models developed in this study are useful in understanding the relevance of the sociotechnical factors and their impact on the proposed hybrid sand filter system. More specifically the treatment factors and their impact on the overall decentralized wastewater treatment environment. The authors recommend further research into this area by understanding socio-technical factors of the Black Belt Area population in the state of Alabama. We believe that our model will help stakeholders determine, design, and develop the size of the hybrid sand filter per their requirements, environment, and socio technical factors.

Domain Matrix

A Multiple Domain Matrix is a conceptualization tool used to structure information and acknowledge concerns/limitations of a system. The framework can be visualized as a matrix with identical column and row headings

(Table 2). These headings serve as systems components and relationships. The combination helps the user visualize the interactions between the relationships, thus identifying actors and interactions for an Agent Based Model (ABM). System Drivers are factors that influence the system development and operation. These drivers are economic, political, social, and technical in nature. System Drivers constrain and enable the system and its expansion. Stakeholders are actors within the systems. They contribute to goals and control aspects of the system. Objectives are defined as the goals of the systems. What does the stakeholder want the system ultimately made to do? Functions are the behaviors of the system. How does the system perform to achieve its objectives? Objects are physical components of systems. Activities are the processes of the system (Bartolomei et al., 2012).

Table 2. Multiple decision matrix.

	System Drivers	Stakeho-lders	Objectives	Functions	Objects	Activities
System Drivers	System Drivers x System Drivers	Stakeho-lders x System Drivers	Objectives x System Drivers	Functions x System Drivers	Objects x System Drivers	Activities x System Drivers
Stakehol-ders	System Drivers x Stakeho-lders	Stakeho-lders x Stakeho-lders	Objectives x Stakeho-lders	Functions x Stakeho-lders	Objects x Stakeh-olders	Activities x Stakeho-lders
Objectives	System Drivers x Objectiv es	Stakeho-lders x Objecti-ves	Objectives x Objectives	Functions x Objecti-ves	Objects x Objecti-ves	Activities x Objecti-ves
Functions	System Drivers x Functio-ns	Stakeho-lders x Functions	Objectives x Functions	Functions x Functions	Objects x Functi-ons	Activities x Functions
Objects	System Drivers x Objects	Stakeho-lders x Objects	Objectives x Objects	Functions x Objects	Objects x Objects	Activities x Objects
Activities	System Drivers x Activit-ies	Stakeho-lders x Activities	Objectives x Activities	Functions x Activities	Objects x Activit-ies	Activities x Activities

Highlighted in blue are identified system components that are used in determining the interaction between domains. The identified system domains for the hybrid sand filter system can be seen in Table 3. These domains were identified by viewing the social, technical, political barriers of the hybrid sand filter system for permitting, construction, and use of the system.

Table 3. System components.

System Drivers	•Environmental factors (i.e. Temperature, Water Table, Soil Porosity)
x	•Proximity Bodies of water
System Drivers	•Proximity of Houses
	•Regulations of County (i.e. City officials)
	•Regulation of Local State (ADPH, ADEM)
	•Regulations of National government (i.e. EPA)
	•Available Funding
	•Provided Treatment Volume
	•Energy Usage
Stakeholders	•Local Government
x	•Users
Stakeholders	•Health Department
	•Property Owners
	•Funding Agencies
	•Engineering Companies
	•Parts Manufactures
	•Surrounding Environment
	•Management companies
Objectives	•Protect the surrounding environment
x	•Protect the public health
Objectives	•Prevent Waste Accumulation
Functions	•Treats raw sewage (influent)
x	•Pumps water from provider to disposal
Functions	•Disposes of treated wastewater
Objects	•Pump systems
x	•Drainfield
Objects	•Pipes
	•Wastewater treatment system (i.e., Septic tank, Hybrid Sand Filter & Constructed Wetland)
Activities	•Collect wastewater
x	•Clean wastewater
Activities	•Pumping water through pipes
	•Disposing of clean water

Examples of the resulting interaction of those systems domains can be seen in Table 4. All the resulting interactions were too large to display in a table and are available upon request. System drivers served as the system components with stakeholders and objects as the determining relationship. Many of the interactions for stakeholders were coupled by natural interactions. Many of the interactions on proximity bodies of water had similar or the same interactions with proximity of houses. This similar interaction was shown true from regulations set by county, state, and national governments. As displayed, the functions and activities are very similar in definition and have almost identical system components. Much of the interactions of the multiple domain matrix focus on the use of the systems. Thus, identifying actors as users of the systems, providing various volumes of water into the system, and the objects identified as physical components need to be modelled with a few of the system drivers that affect the system. Chosen system drivers are energy usage, environmental factors, and provided treatment volume of wastewater. One of the most important interactions identified in the multiple decision matrix is the disposal of the treated wastewater from the system. If the water cannot be disposed, the system cannot continue to function, and the treated water will back up to the system and ultimately to the home. The back-up water in the system will fail the objective of preventing the waste accumulation. The back-up in the system will cause system failure. The resulting system failure because the objectives of protecting the surrounding environment and public health will also fail cannot be achieved. System drivers affecting the disposal of the wastewater is the surrounding environment, proximity to bodies of water, regulations, set and energy usage. This makes disposal one of the key activities that will need to be modelled in the ABM. Other important interactions are the movement of water throughout the wastewater treatment system. The movement of water is necessary to flow from the provider of wastewater (user) to the system, and eventually out of the system. The movement of the water is represented physically by the pipe and pump systems which use energy to move water through the system. Systems drivers that affect this interaction are funding available, proximity of houses, and surrounding environment. If water does not flow through the system, the system failures its objectives as it will accumulate waste and pose as a danger to public health and the surrounding environment.

Table 4. Interactions of the system.

	System Drivers	Stakeholders	Objectives	Functions	Objects	Activities
System Drivers	• Environmental factors (i.e. Temperature, Water Table, Soil Porosity) • Proximity Bodies of water • Proximity of Houses • Regulations of Country (i.e. City officials) • Regulation of Local State (ADPH, ADEM) • Regulations of National government (i.e. EPA) • Available Funding • Provided Treatment Volume • Energy Usage	• Engineers design wastewater treatment based on environmental factors • Engineers design wastewater treatment systems sized based on amount of water used by users • Engineers locate treatment to avoid contamination of the environment and bodies of water • Local Government provide assistants for wastewater treatment upgrades based on available funding • Users pay maintenance fees based on energy usage and volume of wastewater provided • Engineer chose wastewater treatment system depending of area available and location of houses • Local Government permit wastewater treatment system based by regulations set by the state and country	• The cleaning of wastewater to protect the surrounding environment limits algae growth from excess nutrients (from wastewater) in the surrounding bodies of water • The cleaning of wastewater to follow the regulation set by the local state and country • Chosen wastewater technology to meet the needs of the community of energy usage to continue protecting the public health and community • Chosen wastewater technology to meet the needs of the community of funding provided usage to continue protecting the public health and community and not bankrupt the community • Chosen wastewater technology that continues to treat wastewater with the surrounding environment	• Treating raw sewage helps keeps bodies of waters clean • Proximity of houses will add or less the pipes need to provide water from provider to disposal • Disposing of treated water adds water back to water bodies and the surrounding environment necessary for the community	• The pump system adjusts water disposal depending on the soil porosity and other environmental factors • The sizing of the septic tank will depend on the users of the household • The drainfield of the environment will be designed and located based on the surrounding environment and proximity to bodies of water. • The size and materials used in the piping systems are determined by the proximity of boxes of water and proximity to the house	• The disposal of the wastewater adds water back to the water table affecting the environmental factors. • The collection of wastewater determines the treatment volume used to design the wastewater treatment system. • The energy needs of the wastewater treatment system will depend on the pumping of the wastewater. • The cleaning of the wastewater of the wastewater will prevent contaminants from going back in the environment.

CONCLUSION

In a challenging area like the Alabama Black Belt where there are social, environmental, and political complexities, cost effective alternatives are needed like the hybrid sand filter is needed for wastewater treatment infrastructure and management. Using modelling with SysML and following local and national regulations, engineers can design and implement hybrid sand filters treatment systems that effectively treat wastewater and achieve stakeholder desires for this region. In this study, the authors have gained some insights for design implementation from bench-scale testing and use of the multiple decision matrix. Further insights will be gained using the insights gained from multiple decision matrix in an ABM with goals of helping solve the problem of wastewater infrastructure for the Alabama Black Belt. The author recommends taking a digitalization approach by setting a sustainable development goal of developing a Model-Based Patterns Library for the proposed Wastewater treatment system. The proposed patterns will further assist in developing a generic taxonomy and ontology of the overall wastewater treatment (Lohar, 2022; Lohar and Cloutier, 2022). That can be used further to analyze sociotechnical applications and constraints not only in the Black Belt area but also applicable in underdeveloped nations where wastewater systems are needed or do not exist.

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