GEORGIA DOT RESEARCH PROJECT 10-24

FINAL REPORT

LIFE CYCLE COST ASSESSMENT AND PERFORMANCE EVALUATION OF SEDIMENT CONTROL TECHNOLOGIES

Georgia Department of Transportation

OFFICE OF RESEARCH

15 Kennedy Drive

Forest Park, GA 30297-2534

TECHNICAL REPORT STANDARD TITLE PAGE

<table>
<tr><td colspan="2">1.Report No.:</td><td colspan="2">2. Government Accession No.:</td><td colspan="2">3. Recipient's Catalog No.:</td></tr>
<tr><td colspan="3" rowspan="2">4. Title and Subtitle:
Life Cycle Cost Assessment And Performance Evaluation Of Sediment Control Technologies</td><td colspan="3">5. Report Date:
October 2015</td></tr>
<tr><td colspan="3">6. Performing Organization Code:</td></tr>
<tr><td colspan="3">7. Author(s):
S.E. Burns and C.F. Troxel (Georgia Institute of Technology)</td><td colspan="3">8. Performing Organ. Report No.:
10-24</td></tr>
<tr><td colspan="3" rowspan="2">9. Performing Organization Name and Address:
Georgia Instiitute of Technology, School of Civil and Environmental Engineering
790 Atlantic Drive
Atlanta GA 30332-0355</td><td colspan="3">10. Work Unit No.:</td></tr>
<tr><td colspan="3">11. Contract or Grant No.:</td></tr>
<tr><td colspan="3" rowspan="2">12. Sponsoring Agency Name and Address:
Georgia Department of Transportation
Office of Materials & Research
15 Kennedy Drive
Forest Park, GA 30297-2534</td><td colspan="3">13. Type of Report and Period Covered:
Final; October 2010 – October 2015</td></tr>
<tr><td colspan="3">14. Sponsoring Agency Code:</td></tr>
<tr><td colspan="6">15. Supplementary Notes:</td></tr>
<tr><td colspan="6">16. Abstract:</td></tr>
<tr><td colspan="3">17. Key Words:</td><td colspan="3">18. Distribution Statement:</td></tr>
<tr><td>19. Security Classification
(of this report):
Unclassified</td><td colspan="2">20. Security Classification
(of this page):
Unclassified</td><td colspan="2">21. Number of Pages:</td><td>22. Price:</td></tr>
</table>

Form DOT 1700.7 (8-69)

GDOT Research Project No. RP 10-24

Final Report

LIFE CYCLE COST ASSESSMENT PERFORMANCE EVALUATION OF SEDIMENT CONTROL TECHNOLOGIES

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Georgia Department of Transportation

In cooperation with

U.S. Department of Transportation
Federal Highway Administration

October, 2015

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AHP	Analytical hierarchy process
AOS	Apparent opening size
AP	Acidification potential
API	Active pharmaceutical ingredients
ASTM	American Society for Testing and Materials
BMPs	Best management practices
CALTRANS	California Department of Transportation
CS	Compost sock
CWA	Clean Water Act of 1972
DDRF	Denver Downs Research Facility
E&SC	Erosion and sediment control
EI	Environmental Impact (EI)
ELG	Effluent limitation guidelines
EP	Eutrophication potential

ETP	Ecological toxicity potential
FU	Functional unit
GAEPD	Georgia Environmental Protection Division
GVWR	Gross vehicle weight rating
GWP	Global warming potential
GSWCC	Georgia Soil and Water Conservation Commission
ICP-OES	Inductively coupled plasma optical emission spectroscopy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MUSLE	Modified Universal Soil Loss Equation
NPDES	National Pollutant Discharge Elimination System
NREL	National Renewable Energy Laboratory
NTU	Nephelometric turbidity units
NW	Non-woven geotextile
PAF	Potential affected fraction
PAM	Polyacrylamide
PP	Polypropylene fibers
PPA	Pollution Prevention Act of 1990
SETAC	Society of Environmental Toxicology and Chemistry
SF	Silt fence

SW	Straw wattle
SWPPP	Storm water pollution prevention plans
TDS	Total dissolved solids
TN	Total nitrogen
TP	Total phosphorus
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
TS	Total solids
TSS	Total suspended solids
UNEP	United Nations Environmental Programme
USEPA	United States Environmental Protection Agency
W	Woven geotextile

ACKNOWLEDGEMENTS

The authors are pleased to acknowledge the contributions of Mr. Zhi Ge, who worked as graduate research assistant on this project. In addition, the authors are very grateful to Mr. Darrell Richardson for his significant contributions in the formulation of this project and throughout the course of this work. Thanks for Mr. Jon D. Griffith for review of the final document.

EXECUTIVE SUMMARY

This study was performed for the Georgia Department of Transportation (GDOT) to better understand the environmental impacts associated with sediment control technology currently employed on transportation projects. In this study, a review of current and past methods for testing sediment control devices (SCDs), both in the field and in the laboratory, as well as procedures for conducting a life cycle assessment was performed. Life cycle analysis (LCA) is discussed in depth in this report to facilitate future LCA on this subject. Field and laboratory testing is executed to measure performance of five different SCDs for retention of sediment, metals, and nutrients. Results of the tests are combined with existing data for the production and disposal of metal, plastic, and timber and emission data for trucks and machinery to model the life cycle of each SCD. An environmental impact analysis was performed using GaBi 6.0 software and USEPA TRACI methodology. Results of the impact analysis indicate:

- Straw bale installations significantly increase eutrophication potential in downstream water systems due to high levels of phosphate present in the straw bales.
- Production of steel sections and wire mesh for support of low permittivity Type C silt fence result in large increases in global warming and acidification potential.
- Performance of high permittivity Type A silt fence suggests that it is a good alternative to low permittivity silt fence in high volume and high sediment runoff conditions.

- The overall low global warming and acidification potentials of mulch berms, as well as their low aquatic toxicity levels, suggests that their use as an alternative to geotextile silt fence is favorable.

INTRODUCTION

Sediment control is a critical aspect of any construction project. Contamination of waterways by suspended sediments, nutrients, and metals have clearly demonstrated detrimental impacts on the environment (Welsch 1991). High induced nutrient loads lead to eutrophication that can reduce infiltrating sunlight and result in a reduction in aquatic vegetation and animals. Transport of dissolved toxic chemicals or chemicals attached to suspended solids flowing in runoff waters increase toxicity in aquatic environments. Increased toxicity in surface water not only degrades the water environment, but it may lead to degradation in adjoining air and soil environments. Due to the substantial adverse impacts that result from runoff of solids to water ways, significant resources are invested in preventing erosion and retaining solids on land, with retention most commonly accomplished through the use of silt fences.

Currently, silt fence is GDOT’s predominant method for erosion control on construction projects in the early phases of construction, with GDOT installing approximately 1.0 – 1.5 million linear feet of silt fence per year. Silt fences are comprised of slit film, woven geotextiles, typically manufactured from polypropylene. Research and assessment of environmental impacts from silt fence largely focuses on impacts from effluent passing the silt fence installation. The focus on impacts due to effluent is likely because current regulations only describe impacts from construction site effluent and encourage minimal site runoff. While silt fence is a reliable form of sediment control, it impacts the environment in other ways; primarily due to construction from materials derived from fossil fuels, and due to the relative non-degradability of plastics in the long term. However, alternative erosion control technologies also exist, which rely on more environmentally friendly materials such as compost.

This report is a presentation of the following research findings:

1. A comparison of the performance of multiple sediment control devices,
2. A performance a life cycle assessment of sediment control technologies (e.g., silt fence) that are currently in use by the Georgia Department of Transportation (GDOT) and,
3. A comparison of the performance and life cycle impacts for alternative technologies that are biodegradable and likely less dependent on fossil fuels for manufacture (e.g., straw bales, mulch berms, and compost filter socks) than plastic silt fence.

Performance of sediment control devices (SCDs) is measured using a combination of large-scale field testing and laboratory filter testing. Results of the performance tests are combined with material descriptions and used to generate 'use' phases for each SCD. The use phases are combined with industry standard production information for polypropylene, steel, and timer to map the life cycle of each SCD for a model site. The life cycle maps, inventories, and impact assessment is performed using the GaBi 6.0 LCA software by PE INTERNATIONAL. Results of the life cycle impact analysis are modified using assumed impact category weighting factors. The results of the LCA are compared with typical SCD performance results to demonstrate the importance of life-cycle analysis.

LITERATURE REVIEW

Erosion and sediment control

Non-point source pollution

Recent assessment of waterways performed by the Georgia Environmental Protection Division (GAEPD) indicates the major contributor to impairment of rivers and streams is due to non-point source pollution (GAEPD 2010). Figure 1 shows the results of the river and stream assessment from 2008 – 2009. Non-point source pollution can generally be described as a mix of water and contaminants that results from overland flow of rainfall and snowmelt (GAEPD 2010). Contamination of surface water by non-point source runoff waters has been proven to be harmful to aquatic life and vegetation (Welsch 1991). Suspended soil particles increase turbidity of waterways, thus blocking sunlight and debilitating growth of aquatic plants. Deposited sediment disrupts aquatic life at the bottom of stream beds and reduces flow areas, which increases the risk of flooding (Welsch 1991). Deposition of eroded sediments in waterways important for drainage and/or navigation may lead to costly dredging operations (Harbor, 1999). Transport of dissolved nutrients or nutrients attached to sediments cause algae blooms that limit light penetration below the water surface, preventing photosynthesis in lower aquatic plants and lowering dissolved oxygen concentrations.

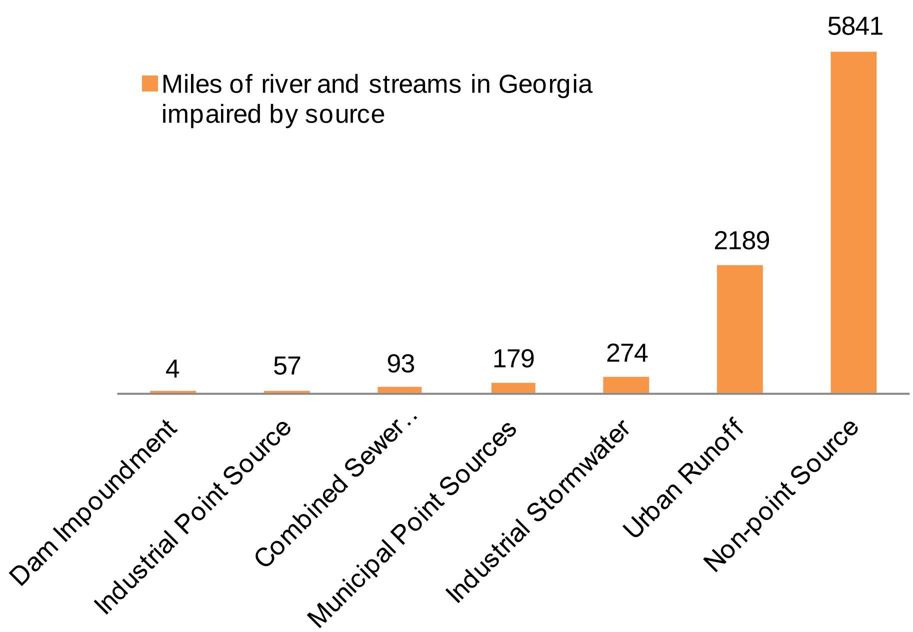

Figure 1: Source of impairment of Georgia rivers and streams (data from GAEPD 2010).

Suspended solids concentrations in runoff water from cleared farmland can be as high as 20,000 mg/L (Carter et al. 1993). Erosion occurring on active construction sites is amplified by clearing and grubbing activities, soil stockpiling and general earth moving. McCaleb and McLaughlin (2008) report turbidity and total suspended solids (TSS) concentrations leaving five sediment traps at construction sites in the Piedmont region of North Carolina as varying from a minimum of 0 to over 30,000 nephelometric turbidity units (NTU) and from 2 to greater than 168,000 mg/L, respectively.

Construction sites are also a source for environmentally harmful chemicals and heavy metals from machinery emissions and leachate from concrete or other pavements. High nutrient loadings in runoff water during time of grassing and seeding slopes are also possible. A study by the California Department of Transportation (CALTRANS) was conducted from 1998 to 2002 in order to characterize runoff from transportation construction sites (CALTRANS 2002). Minimum, maximum and mean values reported through the study are shown in Table 1. The large range in contaminant concentrations is due to the variability in construction processes and in impacts associated with each process.

Table 1: Construction site runoff contaminants (from CALTRANS 2002).

Contaminant	Unit	Min	Max	Avg
TSS	mg/L	12	3,850	472
TDS	mg/L	22	1,270	225
Turbidity	NTU	15	16,000	636
Nitrate	mg/L	0.12	3.90	0.95
Nitrite	mg/L	0.10	2.80	0.16
Total Phosphorous	mg/L	0.05	15.00	1.02
Ammonia	mg/L	0.06	4.00	0.29

Copper, Dissolved	μg/L	1.00	29.80	7.29
Lead, Dissolved	μg/L	0.50	36.50	1.11
Zinc, Dissolved	μg/L	1.00	209.00	17.50

2.1.2 Erosion and sediment control regulation

Federal and state (Georgia) legislation pertinent to erosion and sediment control regulations is summarized in the following paragraphs. Unless otherwise noted, descriptions are according to the United Stated Environmental Protection Agency (USEPA 2002).

- Clean Water Act of 1972 (CWA) – Prohibited unauthorized release of pollutants into navigable and other connected waterways. Established the National Pollutant Discharge Elimination System (NPDES) which requires permits for all point-source discharges to significant waterways. Required USEPA to develop effluent limitation guidelines (ELGs) for major point source categories.
- Georgia Erosion and Sedimentation Act of 1975 (Act 599) – Required counties and municipalities of Georgia to develop plans to reduce releases of sediment from land-disturbing activities on sites 1 acre or larger. Plans developed are reviewed and approved by Soil and Water Conservation District. Plans must include permit process completed before land-disturbing activities commence (GSWCC 2000).
- Water Quality Act of 1987 – Defined municipal and industrial storm water discharges as point sources thereby including them in NPDES regulation.
    - NPDES Phase I (promulgated 1990) – Required construction sites of 5 or more acres to have individual or general discharge permit for storm water discharges. Permit requires preparation of storm water pollution prevention plans (SWPPP) that use best management practices (BMPs) as defined by state or local authorities.
    - NPDES Phase II (promulgated 1999) – Extended most requirements of Phase I to small construction sites between1 to 5 acres.
- Pollution Prevention Act of 1990 (PPA) – Prioritizes pollution prevention and environmentally safe pollution disposal. Related to site stabilization, erosion control and

proper maintenance as prevention measures versus sediment barriers as response measures.

The most recent NPDES general permit for discharges from construction sites (NPDES 2012) requires that sites contain natural buffers or equivalent sediment controls when surface waters are located within 50 feet of the project's earth disturbances. Linear construction projects (e.g. highways, pipelines, sewers) are exempt from the requirement provided they limit disturbance, or provide supplemental sediment controls, to treat runoff within 50 feet of the surface water.

2.1.3 Erosion prevention

Two modes of sediment management exist on construction sites: erosion prevention and sediment control. Erosion prevention is an attempt to stabilize slopes, disturbed areas and other surfaces susceptible to erosion and prevent detachment of soil particles from the ground surface. Sediment control is the capture and containment of eroded sediment and other pollutants being transported in runoff water. Erosion and sediment control (E&SC) represents a combined offensive (erosion prevention) and defensive (sediment control) approach to site runoff (Theisen 1992). Various materials are used for erosion prevention. Mulch applied as thin as 0.75 inches was shown to reduce soil erosion in sloping erosion test beds (Demars et al. 2004). Laboratory scale test results on erosion control products indicate erosion control performance to be closely related to the geotextile induced roughness, water-holding capacity and 24-hour wet weight (Rickson 2006). Geotextile is common in erosion control applications; one of the first major applications of geosynthetics was by the U.S. Army Corps of Engineers when they used a plastic sheet to stabilize soil under concrete blocks set to armor shorelines (Theisen 1992). Other erosion prevention practices are establishing vegetation (seed or sod), polyacrylamide (PAM), and soil tackifier and binders (GSWCC 2001).

Sediment control, not erosion prevention, is the topic of this study and erosion prevention is not discussed in this paper beyond this section. It is briefly described here primarily because erosion prevention devices are an important part of any E&SC plan when the construction site has exposed soil slopes. Also, testing of erosion prevention and sediment control devices is performed with similar methods but erosion products show more consistent results between studies. This may be due to erosion products being less installation dependent and/or more dependent on geotextile index properties. In contrast, performance of sediment control devices is very installation-dependent and often not dependent on material index tests. This topic is reviewed in detail in the next section.

2.1.4 Sediment control

Sediment control is the effort to contain sediment in motion on site. Sediment controls operate by trapping sediment-laden runoff water and reducing sediment loads by sedimentation or filtering. Sediment control devices that are installed along the outer edge of sites to prevent sediment from escaping the site are termed perimeter controls or barriers. Other devices that are installed in concentrated flow conditions to slow the rate of runoff flow and to filter suspended solids are termed checks or dams. Perimeter control devices represent a significant portion of E&SC measures installed on highway construction and other linear projects because site perimeters are much larger for linear construction sites than for approximate square sites, as shown in Figure 2.

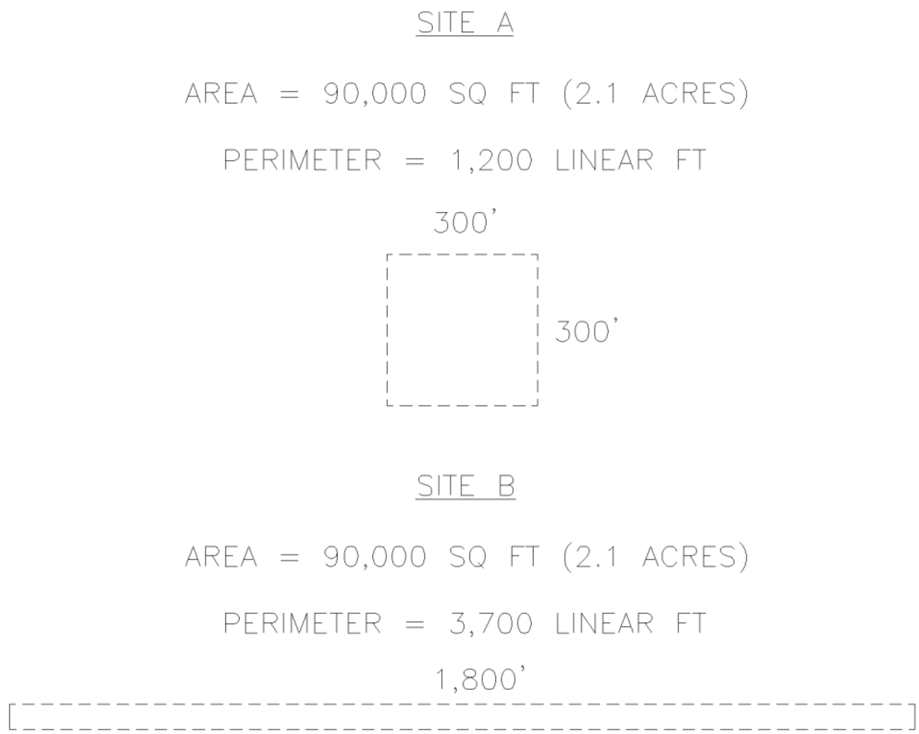

Figure 2: Site perimeter for a linear project.

Many different perimeter sediment control devices are currently being used by state DOTs. An online review of current DOT perimeter controls was performed by visiting state DOT websites and searching for erosion and sediment control best management practices (BMPs) related manuals or guidance documents. All but one state provided DOT-specific guidance on E&SC BMPs or provided links to the governing state procedures. No searchable guidelines or links were found for Oklahoma. The results of the search are summarized in Figure 3. Each of the forty-nine states investigated include geotextile silt fence as a temporary sediment control best management practice (BMP). Twenty-two states list straw or hay bales as perimeter controls, three states do not allow bale installations. Earth berms and wattles are common. Less common perimeter controls are filter socks, brush barriers and vegetated buffer strips. Seven sites list a triangular filter dike as a perimeter control. The triangular filter dike is a long three-sided wire (typical) mesh prism wrapped in geotextile fabric. The triangular dikes ranged in height from 8 to 18 inches. The dikes were transportable, reusable, did not require trenching and appeared to be an innovative approach to perimeter control.

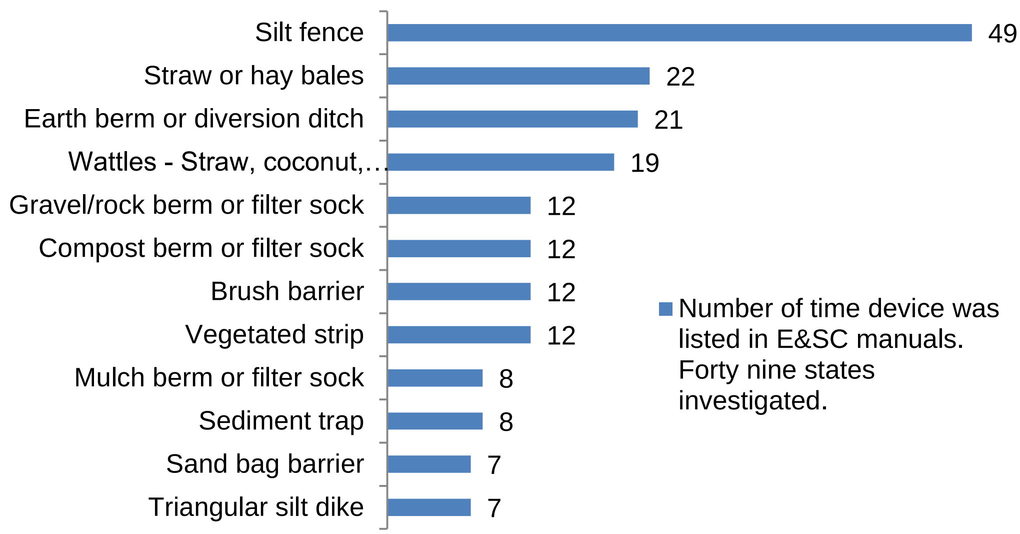

Figure 3: Sediment control devices used in states.

2.1.5 Temporary perimeter sediment control devices

The following represent the five most commonly referenced perimeter sediment control BMPs recommended by state DOTs or other responsible E&SC authority (i.e. silt fence, bales, berms, wattles and socks). More information, figures, and installation procedures can be found in the provided reference or references listed in Appendix A, or in the USEPA national menu of stormwater BMPs at: http://cfpub.epa.gov/npdes/stormwater/menuofbmps/.

Geotextile silt fence (filter fence) is the most commonly installed perimeter control device seen on highway projects. Silt fence is typically woven polypropylene geotextile supported vertically by wooden or metal stakes. Some filtration occurs with new installations; however, geotextiles clog rapidly and the primary mode of sediment removal becomes flow retardation and subsequent sedimentation of suspended solids (Barrett et al. 1998, USEPA 2012).

Silt fence requires trenching, burial, and soil compaction and is easily damaged so performance is very installation dependent (Barrett et al. 1998, Zech et al. 2008)

Straw or hay bales remove solids by retention and sedimentation. Individual bales have very low permeability but linear installations of bales are susceptible to leaks forming at the bale connections. Bales readily degrade in the field and may require replacement in as little as three months (USEPA 2010). The USEPA and many state entities do not recommend using bales for sediment control. USEPA (2010) recommends silt fence as a perimeter control alternative.

Berms are linear piles of material used to retain and filter sediment-laden runoff water. Berms can be made of soil (also referenced as "diversion dike"), stone, mulch or compost. Minimum widths at the bottom of the berm and minimum berm heights are normally required and will vary depending on material Type and location. Soil, mulch and compost berms may require some compaction. Larger berms are less susceptible to erosion, offer greater filtration capabilities and are less likely to clog. For better confinement of materials, berms may be covered with geotextile (TxDOT 2004). Berms formed from brush debris created during site clearing (slash) are termed brush barriers. Brush barriers are typically installed on large sites that have been cleared and have sufficient working room at the perimeter for large berm installation.

Filter socks are essentially a contained berm. Filter socks are often larger than wattles (subsequently discussed) and are normally filled with compost, mulch, or stone. With proper equipment for heavy lifting, installation of filter socks is not difficult. Performance depends on filter material and connection with the ground surface. Removal of sediment as well as pollutants (i.e. nutrients, coliform, e. coli, hydrocarbons) is possible with compost filter socks (Faucette et al. 2009).

Wattles (fiber rolls) are usually smaller in diameter than filter socks. Wattles are typically less than 12-inches in diameter and are filled with straw, coconut or wood fibers and wrapped with polypropylene netting, burlap, jute or coir. The best application of wattles is on contours along slopes to minimize sheet flow velocity and reduce surface erosion (EPA 2012). Wattles should be partially buried and staked.

2.2 Performance of sediment control devices (SCDs)

2.2.1 Comparison to geotechnical and environmental filters

The performance of SCDs is directly related to their ability to filter sediment from runoff water. Soil filters have many applications in geotechnical and environmental engineering. Landfill leachate collection, soil stabilization, wall drainage and subsurface drains are some uses. Typically, these filters are designed to optimize soil retention and fluid discharge (Giroud 2006, Bhatia and Huang 1995). The first goal implies containment while the latter implies permeability and with good design, the proper balance is achieved. Filter criteria dictate that the filter media is selected to retain the largest soil particles to be filtered (Terzaghi and Peck 1967). Proper function of filters requires the development of a bridging pattern within the retained soil adjacent to the filter material (Bhatia and Huang 1995, Hoare 1982, Hongo and Veneziano 1989). If successful, the filter retains the largest soil particles, which in turn retain smaller and smaller particles. After some initial fall out, the retained soil develops a stable network with no additional release of soil particles. A stable bridging network and successful filter is shown in Figure 4.

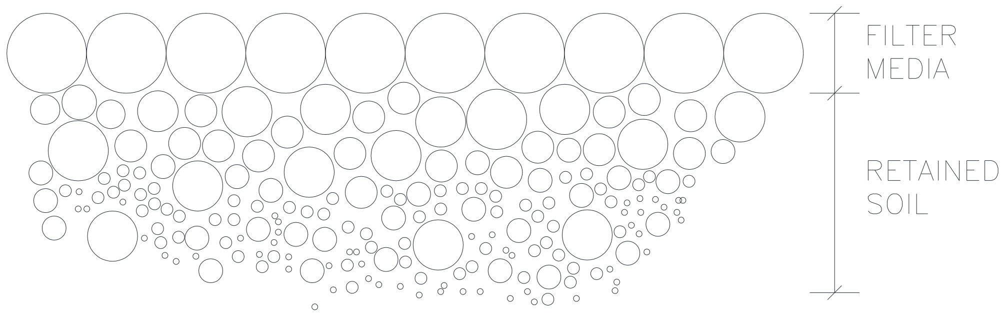

Figure 4: Bridging network at filter/soil interface .

The function of filters for sediment control is significantly different from that of filters in other geotechnical applications. The difference is because the formation of a stable filter layer is not possible, which is true for two reasons. First, eroded soil approaching sediment control devices is predominantly comprised of fine particles (Barrett et al. 1998) that pass through the filter unabated or clog filter pores. Second, coarse soil particles that have eroded will likely settle and deposit before reaching the sediment barrier. Many SCDs reduce sediment loads by retaining sediment-laden water and allowing for sedimentation of suspended solids. In this way, SCDs resemble Type I sedimentation basins, common during the initial steps of water treatment. Type I sedimentation refers to the settling of individual particles due to gravity forces. Type II and Type III sedimentation refers to flocculated and zone settling, respectively (Droste 2005). When SCDs are installed across contours, runoff water will flow behind and along the barrier (Beighley and Valdes 2009). This flow will induce turbulence or shear forces that may also remove filter cakes.

2.2.2 Sedimentation of solids

Sedimentation is the process of removing solids from runoff flow long enough that suspended particles will be pulled down, out of suspension due to gravity forces. Figure 5 shows sedimentation occurring behind a vertical SCD. The rate of mass settling behind the barrier is found with a simple mass balance:

$$\frac{dm}{dt} = Q_1C_1 - Q_2C_2$$

Where *dm/dt* is the positive change in mass settling behind the barrier, Q_1 and C_1 are the influent flow rate and concentration and Q_2 and C_2 are the effluent flow rate and concentration, respectively. Units of flow rate are volume per time; units of concentration are mass per volume.

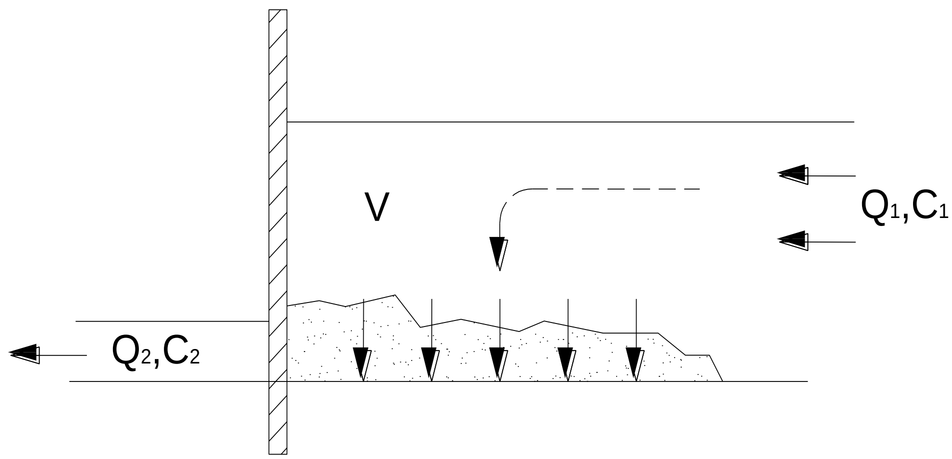

Figure 5: Sedimentation behind barrier (adapted from McFalls 2009).

Settling particles can be sorted into two sizes, (1) large particles with settling velocities much higher than the velocity of water draining through the filter and (2) small particles that settle after a long detention time behind barriers. Settling velocity for spherical particles in water is calculated with the following equation:

$$v = \sqrt{\frac{4}{3}\frac{gd}{C_D}\frac{\rho_s - \rho_f}{\rho_f}}$$

Where v = settling velocity (L/T), g = gravitational constant, d = diameter of sphere, C_D = drag coefficient, ρ_s = density of solid particle, and ρ_f = density of the fluid. The drag coefficient varies according to the Reynold's number (Re) for laminar and transitional flow according to the following equations:

Laminar flow (Re < 1.0) $$C_D = \frac{24}{Re}$$

Transitional flow (1<Re<1,000) $$C_D = \frac{18.5}{Re^{0.6}}$$

Figure 6 shows settling velocities calculated as spherical particles with diameters of fine sand to fine gravel. Settling velocities for these particles range from 0.02 to 2 m/s (7.2 to 720 m/hr) and are sufficiently high to settle particles before reaching the barrier in most flow conditions. For Reynolds numbers greater than 1000, particle settling will be disrupted by increasingly turbulent conditions that will promote mixing. Figure 7 shows settling velocities for spherical particles with diameters ranging from clay to fine sand in the laminar flow regime. For particles with settling velocity below 2 m/hr, long retention times behind vertical silt barriers are required for sedimentation to occur..

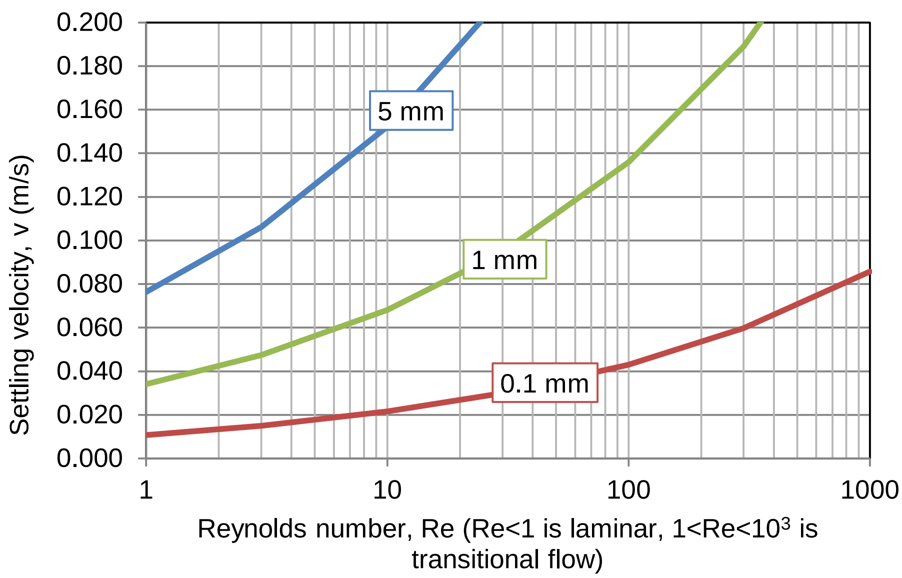

Figure 6: Settling velocity for 0.1, 1 and 5 mm diameter particles in transitional flow.

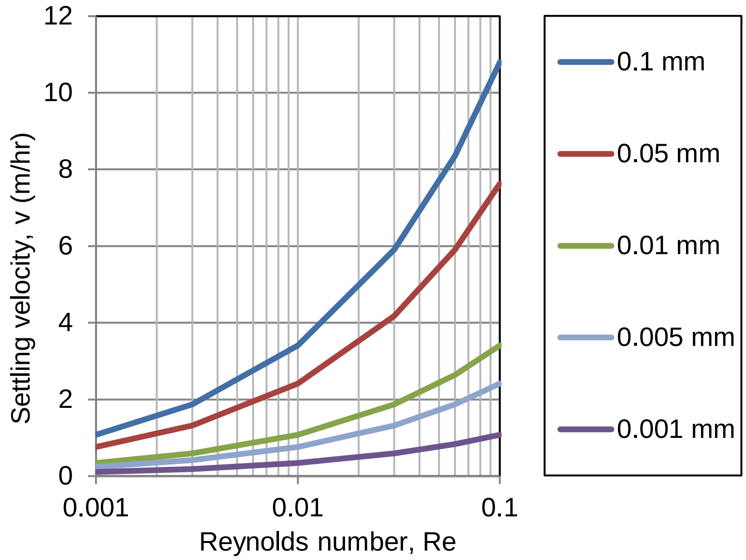

Figure 7: Settling velocity for 0.001 to 0.1 mm particle diameters in laminar flow.

2.2.3 Filtration of solids

Filtration in granular filters has been studied extensively by researchers. The principles of filtration in granular material apply to geotextile filter material and sediment retention devices in general. Removal of particles with diameters larger than the filter pore diameter is by blocking or straining. Subsequently small grains will be removed as filter cakes develop at the filter entrance (Xiao and Reddi 2000).

Removal of small particles in filters is by particle adhesion to the surface of filter grains and already filtered particles (Gregory 1973). To enable particle-to-particle adhesion, repulsion forces between particles must be adequately low for attraction or random collision to occur. Suspensions with particle attraction or zero net repulsion forces are considered “colloidally unstable” (Gregory 1973). Particle surface charges are described by DLVO theory, particle repulsion is due to electrical charges at the particle surface and attraction is due to van der Waals forces (Gregory 1973, Santamarina and Klein 2001). Electrical forces at the particle surface are from the surface potential of the particle as well as alignment of dipoles adhering to the surface. Gregory (1973) describes the sum electric force as:

$$\phi = \psi + \chi$$

Where Φ = overall electric force, Ψ = surface potential, and X = force from the aligned electric dipoles. Surface potential and the dipole arrangement are developed by isomorphous substitution, adsorption at the particle surface, and dipole orientation (Gregory 1973). Electric charges resulting from dipoles at the particle surface form the electric double layer. The thickness of the double layer is the Debye length (Santamarina and Klein 2001). The charge distribution at distance away from the particle is shown in Figure 8.

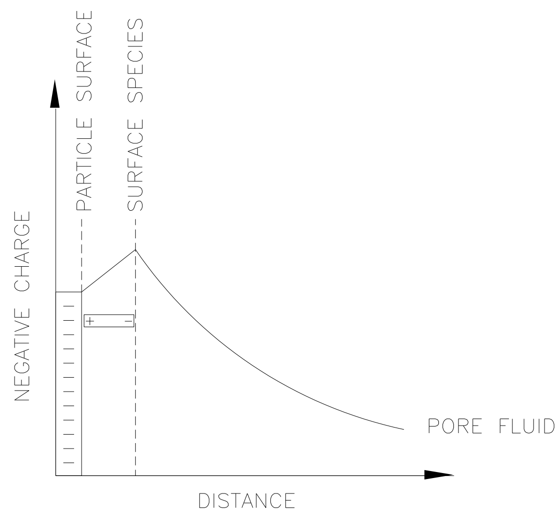

Figure 8: Surface charge on particle (adapted from Santamarina and Klein 2001) .

Small particles typically have a negative surface charge; however, species aligned at or near the particle surface alter the charge at distances away from the particle (Gregory 1973, Santamarina and Klein 2001). At a large distance from the particle surface, the charge approaches that of the surrounding fluid, determined by ionic concentration and pH. Chang and Vigneswaran (1990) found that salt concentrations of about 5 g/l were sufficient to influence the filtration of suspensions consisting of small (12 micron) kaolinite particles. At close distances van der Waals forces are strong enough for particle attraction (Santamarina and Klein 2001).Movement of particles within the filter is due to the combined effects of particle interception, inertia, gravity, diffusion and hydrodynamic forces (Ives 1973). For different particle sizes and traveling velocity, the primary mode of particle transport varies. The descriptive equations of each force are summarized in Table 2.

Table 2: Filtration mechanisms (adapted from Ives 1973).

TRANSPORT MECHANISM	DESCRIPTIVE EQUATION	NOTES
Interception	$I = \frac{d}{D}$	as I → 1, interception becomes particle straining (blocking)
Inertia	$E = \frac{\rho_s d^2 U}{18\mu D}$	ratio of particles striking to particles approaching upstream
Gravity	$S = \frac{g(\rho_s - \rho)d^2}{18\mu v}$	Stokes' Law adjusted for velocity
Diffusion	$\frac{1}{P} = \frac{kT}{3\pi\mu d v D}$	Brownian velocity/advective velocity, equal to 1/Peclet Number P
Hydrodynamic	$R = \frac{v d \rho}{\mu}$	Reynolds number adapted for filtration

In each case, d = particle diameter, D = pore diameter, ρ_s = particle solid density, ρ = density of pore fluid, μ = pore fluid dynamic viscosity, U = fluid velocity away from filter grain, v = stream velocity, k = Boltzmann's constant, and T = absolute temperature.

Interception is particle collision with filter media with probability described by the ratio of the particle and filter grain sizes. As the size of the particle approaches the size of the filter grain, interception becomes straining (blocking). Transport from particle inertia is when flow paths approach the surface of a filter grain directly (Ives 1973). As the flow path curves around the face of the filter grain the transported particles are carried forward by inertia forces, across bending flow lines, to the filter grain surface. Sedimentation within filters occurs when the settling velocity on particles is greater than the fluid velocity. The effect of gravity force was confirmed by Ison and Ives (1969) by observing water flowing upwards and then downwards through filter material. In both cases, particle accumulations were observed at the top face of the filter grains. Diffusion of particles is a result of Brownian motion of water particles due to thermal energy gradients that create irregular flow paths; diffusion typically only affects very small particles. Hydrodynamic forces occur from unbalanced drag forces acting on particles by varying velocities in the filter pores. Hydrodynamic forces can be described by the Reynolds number. Figure 9 shows the influence of transport mechanisms for varying particle sizes. For particles of sizes greater than 1 micron, the dominant mechanism is sedimentation.

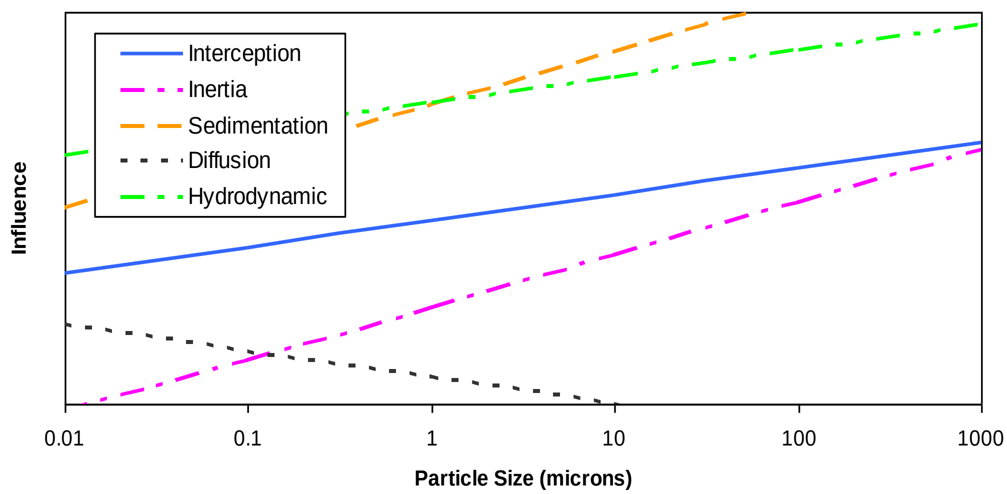

Figure 9: Dominant transport mechanism by particle size.

2.2.4 Removal of dissolved contaminants

Sorption is the attachment of contaminants to solids and organic material by means of adsorption, absorption, and chemisorption (Sharma 2004) or in general, groupings of molecules at a phase interface (Benjamin 2002). Adsorption is the attachment of contaminants to a solid surface, absorption is the incorporation of contaminants into the sorbent, and chemisorption is the chemical attachment of contaminants to solids. The individual processes are difficult to distinguish and so they are typically grouped together under a general category known as sorption. Among other factors, sorption of contaminants depends on the polarity of the sorbate, surface area of the sorbent, and pH of the fluid phase (Sharma 2004). Sorption capacity is different for all contaminants, but for most contaminants, sorption increases with increasing organic content (Site 2001). High porosity of organic material may increase surface area for sorption of non-polar molecules; and organic material may be substrate for bacteria growth. Sorption is the primary removal mechanism for contaminants in the environment at low concentrations (Benjamin 2002). Sorption also affects the transport of contaminants as molecules may sorb to suspended solids in runoff water or other waste streams.

The sorption potential for sorbents at different sorbate concentrations may be evaluated by generating isotherms. Column filter tests are used to approximate removal efficiencies of a sorbate in different sorbents. Chang et al. (2008) performed column filter tests using 5-cm diameter plastic tubes and a 22.5 cm thick mixture of sand, tire crumbs and wood waste. The tests indicate 1-hour removal efficiencies for ammonia, nitrate and ortho-phosphate of 76, 86 and 76 percent, respectively.

To increase removal of nitrogen from waste streams, methods other than sorption may be employed. Denitrification is the process or reducing nitrate (NO_3^-) to nitrogen gas (N_2) by micro-organisms that have the ability to accept electrons from nitrate oxygen while oxidizing organic material (Droste 2005). Kim et al. (2003) performed column filter tests with organic material as substrate for support of denitrifying organisms in anoxic conditions. Results shown in Figure 10 indicate high nitrate removal for sawdust, wheat straw, and woodchips. Alfalfa and newspaper (not shown) were also effective.

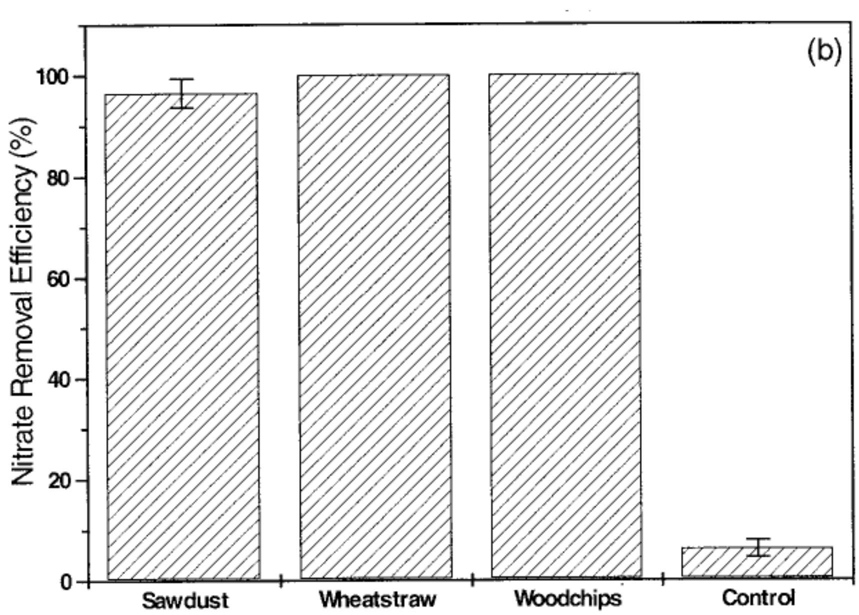

Figure 10: Nitrate removal by denitrification (from Kim et al. 2003)

2.2.5 SCD selection

Selection of geotextile material for filters is often guided by laboratory index tests. Most commonly, the referenced tests are apparent opening size (AOS) and permittivity. AOS is the sieve size equivalent to the largest discovered opening in the geotextile (ASTM D4751). Permittivity is the flow rate of fluid flowing normal to the geotextile per unit area and unit head when measured under laminar conditions with water as the permeating fluid (ASTM D4491). A typical soil retention criterion for geotextile according to Bhatia and Huang (1995) is given as:

$$\frac{O_{95}}{D_{85b}} \leq 2$$

Where O_{95} is the geotextile opening that is larger than 95% of openings, taken as the apparent opening size (AOS), and D_{85b} is the diameter larger than 85% of soil to be retained.

Although it is commonly used for SCD selection, AOS has been shown to have little effect on the retention capability of the sediment barrier as the eroded materials are fine soil particles with low settling velocity and are significantly smaller than geotextile AOS (Barrett et al. 1998). Sediment removal of geotextile silt fence barriers in the field was achieved by sedimentation of soil particles retained behind the silt fence after clogging of the geotextile occurred. Montero and Overman (1990) investigated the ability of geotextile to filter fine clay (65% particles < 0.075 mm) and water slurry. Eight needle punched geotextile materials were able to retain at least 88% (three samples retained 99%) of the clay particles. No heat-bonded materials retained over 30% of clay particles. Montero and Overman observed filter cakes developing above the successful geotextile samples.

2.2.6 Measuring SCD performance

The performance of SCDs is difficult to measure in-situ due to the irregularity of runoff waters, sediment disturbance during sampling and inconsistent barrier installation and maintenance (Barrett et al. 1998). Also, observations and measurements of SCD performance are dependent on construction activity ongoing at the time of visit (Stevens et al. 2004). Measuring field performance is possible, but requires planning to determine the proper number, method, and location of samples needed to best characterize the target device (Geosyntec et al. 2009). For example, sampling required to characterize the performance of a certain device or portion of a device through the duration of a single storm event is different than sampling to determine the performance of an entire site over many months. The former will likely require numerous paired samples taken upstream and downstream of the device at time periods on the scale of seconds, minutes or hours, while the latter would require samples upstream and downstream of the device on a weekly or monthly interval.

As an alternative to field observation and monitoring, large-scale laboratory flume tests with sediment-laden water have been used to determine the capability of different retention devices at removing suspended solids from sediment-laden water. Flume tests have been used to test geotextile materials(Barrett et al. 1998) and geotextile and compost filled geotextile socks (Keener et al. 2007). Tests have been performed using sloping soil beds with rain synthesizers to generate runoff to test geotextile silt fence (Zech et al. 2008) and straw wattles and geotextile wrapped perforated tubing (Beighley and Valdes 2009). Flume tests are performed by attaching a sediment barrier device at the end of a sloping trough and either releasing sediment-laden water towards the device or simulating rainfall over a sloping bed of soil to generate runoff. Effluent from the retention device is sampled at intervals over the test duration. Runoff during sloping-bed tests is generated by soil erosion so it closely resembles field conditions. Compared to tests using sediment laden water, these tests better represent soil loadings and suspended solid particle sizes experienced on active construction sites. Flume tests with synthetic runoff water allow for greater control of upstream suspended solid concentrations. ASTM D5141 titled *Determining Filtering Efficiency and Flow Rate of the Filtration Component of a Sediment Retention Device Using Site-Specific Soil* uses a flume to test sediment retention devices. The flume apparatus is shown in Figure 11.

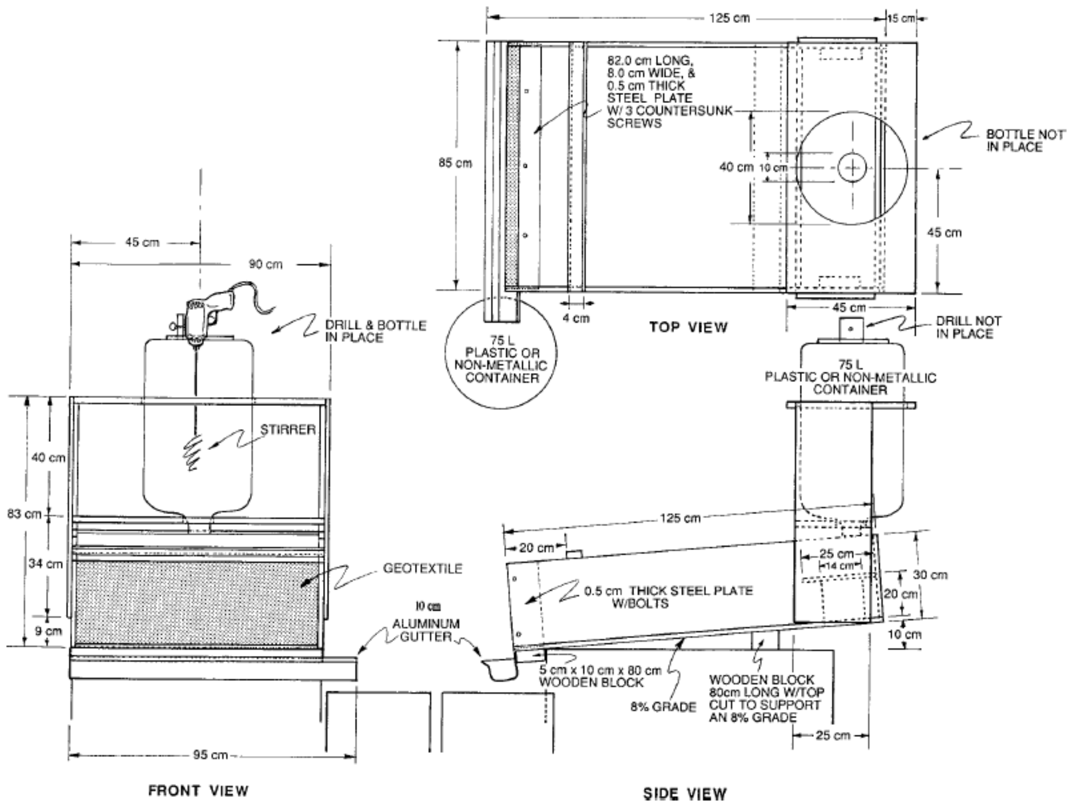

Figure 11: Flume for testing SCDs (figure from ASTM D5141)

Shallow soil trenches sloping at 10% and rainfall simulators have been used to measure and compare performance of compost filled geotextile socks, mulch berms and straw bales (Faucette et al. 2009). Sediment barriers were installed near the toe of shallow trenches cut into a hill slope. Barrier performance was compared to a control test with no barrier for multiple rainfall rates. Results from studies using flume, sloping soil bed and cut soil trench tests are summarized in Table 3. In some instances, values for test volume and rainfall intensity were calculated from reported information to allow for comparison with other methods. Simulated rainfall intensity is provided for tests with sloped soil beds and rain simulators. Zech et al. (2008) measured the ability of silt fence with tiebacks to arrest flow behind and along barrier installations. Silt fence with tiebacks resulted in a 90% increase in solid discharge relative to silt fence without tiebacks.

Table 3: SCD performance from flume, sloping soil bed and cut trench testing.

SCD tested	Volume of test fluid per unit length SCD (L/m)	Simulated rainfall intensity (cm/hr)	Upstream solids concentration (mg/L)	TS or TSS removal efficiency (%)	Source
W NW	250	NA	3,000	68 – 90 90	**Barrett et al. (1998)**
20 cm CS 30 cm CS 61 cm CS	372 - 933	NA	1,000	20 – 42 26 – 50 32 - 56	**Keener et al. (2007)**
20 cm SW 20 cm W pipe	203	0.5 - 5	340 – 400	89 – 98 76 - 96	**Beighley and Valdes (2009)**
SF w/o tieback SF with tieback	95	7.6	10,000 – 130,000	NA	**Zech et al. (2008)**
20 cm CS 20 cm CS 20 cm CS+P 30 cm CS+P Mulch berm Straw bale	1140	2.5	6,080	76.3 72.7 77.1 80.7 54.8 65.1	**Faucette et al. (2009)**

Notations: not applicable (NA), woven geotextile (W), non-woven geotextile (NW), silt fence (SF), compost sock (CS), straw wattle (SW), compost sock with flocculating polymer

Tests similar to the laboratory flume and sloping soil bed tests have been performed at large scales. Storey et al. (2005) used a sloping (3 to 7%) 60-foot long and 12-foot wide rectangular soil channel to observe and measure the performance of mulch and compost berms, straw bales and geotextile silt-fence. McFalls et al. (2009) used a sloping (3%) 18-foot long and 15-foot wide cylindrical concrete channel with a 4-foot long soil installation zone to test a geotextile dike, straw wattles, geotextile silt fence and rock check dam. The cylindrical channel allowed installed retention devices to slope up, away from the center of the channel, minimizing boundary effects along at the installation (the significance of boundary effects will be discussed in the Chapter 3). Stevens et al. (2004) measured performance of three geotextile silt fences using 20-foot long by 40-foot wide (along the fence installation) sloping (5%) exposed soil area and 20-foot long flat to sloping (0 to 14%) barrier installation area. The exposed soil area was used to generate runoff water using a rainfall simulator. The runoff was sampled at locations upstream and downstream of the barrier installation. The performance of the large scale soil channel, flume and sloping soil bed tests is summarized in Table 4.

Table 4: SCD performance from large scale testing.

SRD	Volume of test fluid (L)	Release rate towards SRD (L/s)	Upstream solids concentration (mg/L)	TS or TSS removal efficiency (%)	Source
Berms Filter socks Straw bale Silt fence	6255	7.1 – 9.9	NA	Variable	**Storey et al. (2005)**
Geosyn. dike Straw wattle (SW) SW + polymer Silt fence Rock dam	1251 265 265 5685 5685	NA	2,000 – 4,000	18 46 59 14 2	**McFalls et al. (2009)**
Various geotextiles	NA	0.62 – 1.59	6,395 – 66,110	21 – 91	**Stevens et al. (2004)**

Notations used: not applicable (NA)

Although material with high organic content may demonstrate a greater sorption capacity for contaminants, it may also be a significant source of nutrients. Ho (2011) performed column filter tests using synthetic rain water to measure leachate from wood compost and hay . The study measured nutrient, chemical, and microbial contents, pH, and toxicity of the effluent released from each sample. Results indicate concentrations of total nitrogen (TN) and total phosphorus (TP) decrease to approximately 5 and 15 percent of initial values at 100 days after initial testing, respectively (Ho 2011).

2.2.7 Environmental impacts related to SRD manufacture and installation

The purpose of erosion and sediment control products is to decrease the offsite transport of eroded soil and nutrient and metal concentrations and subsequently reduce the impact of a construction site on the surrounding environment. The manufacture of SCDs also uses resources and creates emissions that have their own environmental impacts (e.g., CO_2 emissions from the production of steel for fence posts). Some impacts associated with steel, plastic, and timber production are briefly discussed in the following paragraph. The scope of production processes to be included in the study is outlined in the following sections pertaining to LCA.

Operation of blast furnaces for the reduction of iron ore to iron is the most energy intensive process of steel manufacture. According to Fruehan et al. (2000), the theoretical absolute minimum energy required to produce liquid hot metal is 9.8 GJ per metric ton. The absolute minimum emission of CO_2 for the same process is 1,091 kg per metric ton. Actual reported energy requirements and CO_2 emissions are 25 to 30 percent higher than absolute minimum values. Electric arc furnaces to recycle scrap steel operate at lower energy, but are associated with additional environmental impacts of transporting heavy loads of scrap metal to the facility. Polypropylene is a polymer of high grade (> 98% pure) propylene and accounts for one half of the world consumption of propylene (Aitani 2006). The majority of propylene is created in parallel processes during the steam cracking of naphtha or gas oil for ethylene and gasoline production. A high amount of energy and water as steam and quenching fluid is required for steam cracking reactions (Aitani 2006). Timber production includes various processes (i.e. debarking, sawing) with power requirements. Timber also requires a large amount of land usage (GaBi 6.0). Production of steel, plastic and timber require a high amount of diesel operated trucks for transport. Operation of diesel fueled cargo trucks increase emissions with potential for global warming.

2.3 Life cycle assessment (LCA)

2.3.1 Introduction to LCA

Life-cycle assessment or analysis (LCA) is a procedure used to measure the environmental impact of a product over the entire life of the product (SAIC 2006). The analysis is performed by summing the inputs and outputs for product phases that include raw-material extraction, production, distribution, use, and disposal or recycling and determining the effects of the cumulative inventory on the environment. LCA is also referred to as a cradle-to-grave assessment because it sums impacts from the product's creation (cradle) to the products disposal (grave). Figure 12 shows a typical flow through life-cycle stages and inputs used and outputs required by the entire system.

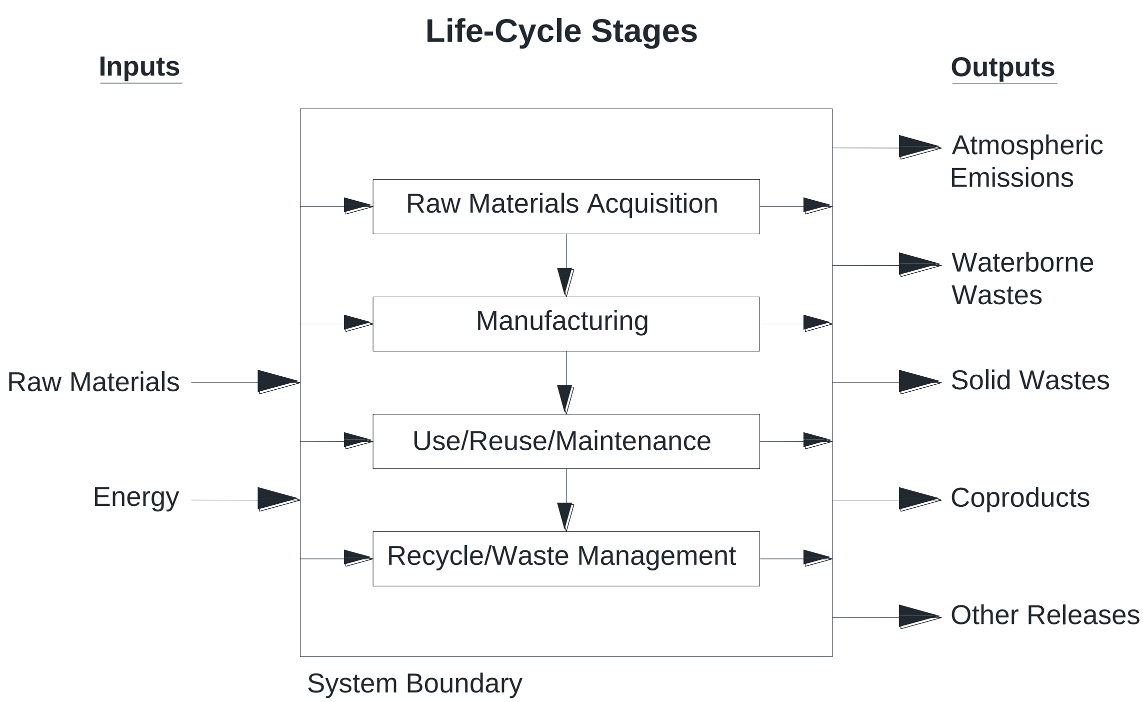

Figure 12: Definition of life-cycle (USEPA 1993).

LCA has become an important feature in environmental analyses of industrial processes because of its ability to describe the interaction of large systems and their environments (Curran 1996). The holistic approach used by LCA is a popular method of environmental analysis in development of regulatory guidelines, product research and development, and as a rating tool used for product promotion (PRé 2010). LCA is used to identify environmental impacts that are not apparent. Cook et al. (2012) used LCA to evaluate disposal options for active pharmaceutical ingredients (APIs). The increase in APIs encountered in water sources and the resulting potential environmental impacts has instigated API take-back or incineration programs, however; APIs are commonly discarded in municipal solid waste or flushed in drains. The analysis compared trash, toilet and take-back disposal options. Results show that while take-back programs remove APIs from the environment entirely, non-API emissions increase by more than 200% and global warming emissions increase by 1700% over baseline values.

Internationally, the following three organizations perform research, develop guidelines and promulgate information on the useful application of LCA; (1) Society of Environmental Toxicology and Chemistry (SETAC), (2) International Organization for Standardization (ISO), and (3) United Nations Environmental Programme (UNEP). SETAC is a professional organization with members from academia, industry and government that assesses scientific research focused to improve the environment (Guinée 2002). ISO provides worldwide standardization for many activities. ISO's biggest addition to LCA is the 14000 series of standards focused on environmental management systems. Included in the series is standard 14040, a framework for completing LCA that has been accepted worldwide (Guinée 2002). UNEP generally is concerned with global application of LCA.

Nationally, LCA research has been performed by the United States Environmental Protection Agency (USEPA), the National Renewable Energy Laboratory (NREL), and the American Society for Testing and Materials (ASTM). ASTM has developed multiple standards for analysis of construction materials. The USEPA has developed a large amount of information pertaining to environmental LCA. The USEPA links to a wide range of LCA resources online at http://www.epa.gov/nrmrl/std/lca/resources.html.

2.3.2 Performing an LCA

Life-cycle analysis is generally performed in four connected processes: description of goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The four processes are described in Figure 13. Development and standardization of the LCA process began at an LCA workshop sponsored by SETAC in 1990 (Curran 1996). However, increased availability of process databases and processing capabilities of computers have allowed for added sophistication to LCA (Bare et al 2003). A discussion of each of the four LCA steps follow:

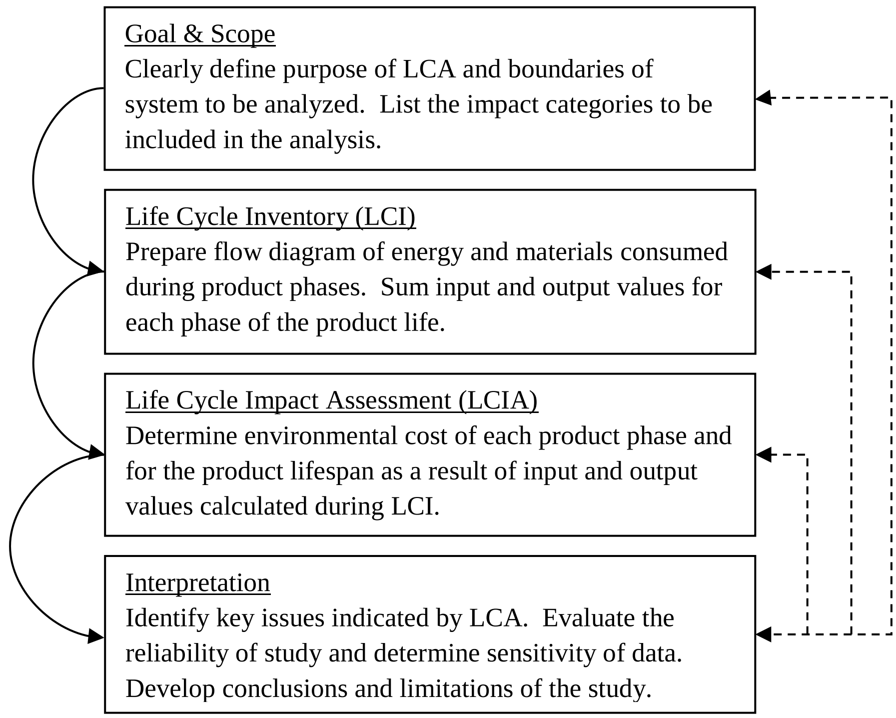

Figure 13: LCA flowchart and description

2.3.3 Goal and scope

The initial step of performing an LCA is defining the goals of the study and outlining the project scope. The goal of the study should identify the specific purpose of the study, as well as the intended audience. The scope of the study should include the best definition of the functional unit to be compared, clearly state the system boundaries and define the limits for including inputs and outputs (PRé 2010).

When two items are compared, a functional unit (FU) is the best description of a task to normalize variations between the items. For example, consider three cups with characteristics defined in Table 5. To compare each cup a FU must account for volume and lifetime differences. Based on volume differences, 1.5 of cups B and C are required for comparison to cup A. Based on lifetime differences, more of cups A and B are needed for comparison with cup C. For the cup example, the impact of washing the reusable cup should be evaluated.

Table 5: Developing a functional unit for cup comparison.

	Cup A (disposable)	Cup B (disposable)	Cup C (reusable)
Volume (ounces)	24	16	16
Uses per lifetime	1	1	50
Functional unit (FU)		**50 uses at 24 ounces per use**	
Cups required per FU	50	75	1.5

System boundaries are used to outline the extent of data to be analyzed in the study. Three orders of analysis are normally considered in LCA analysis:

- **1st order –** only production of materials and transport included,
- **2nd order –** all life cycle processes included, but no capital goods and
- **3rd order –** same as 2nd order with capital goods included (PRé 2010).

Capital goods are typically considered as equipment used for manufacture or installation. For LCA of complex systems with specialty manufacturing equipment, inclusion of the items is important. For comparison of products that use common procedures or machines, capital goods are normally not included.

LCA is performed by developing a model of complex systems; inevitably, the model will be a simple version of the real system (PRé 2010, Bare et al. 2003). A well defined goal is important to be able to properly determine the project's scope. For example, the scope of a study aimed to compare two interchangeable steps in a large manufacturing train may be much narrower than for a study to outline two different manufacturing trains.

2.3.4 Life cycle inventory (LCI)

Compiling an LCI is the second step of performing an LCA and includes defining the process chain that occurs within the system boundaries and determining the inputs and outputs required/generated for each process. Requirements for each process are added together to determine the overall inputs and outputs required and created by an entire system. The resulting inputs and outputs for the entire system are shown in Figure 12. Creating a descriptive process chain for a complex system is difficult because it requires collaboration between groups with knowledge of systems occurring within a system. Overall, the LCI phase is the most data-intensive step of an LCA and requires diligent data management (PRé 2010).

Two types of processes are used to define systems, unit processes and system processes. A unit process is the smallest divisible function in a chain of processes. System processes represent a large combination of processes grouped together to describe a system occurring within a system (PRé 2010). System processes are also known as cradle-to-gate or gate-to-gate processes because they represent multiple steps to get from one point to another (GaBi 6.0). An example of a chain of unit processes lumped into a system process for lumber manufacturing is shown in Figure 14.

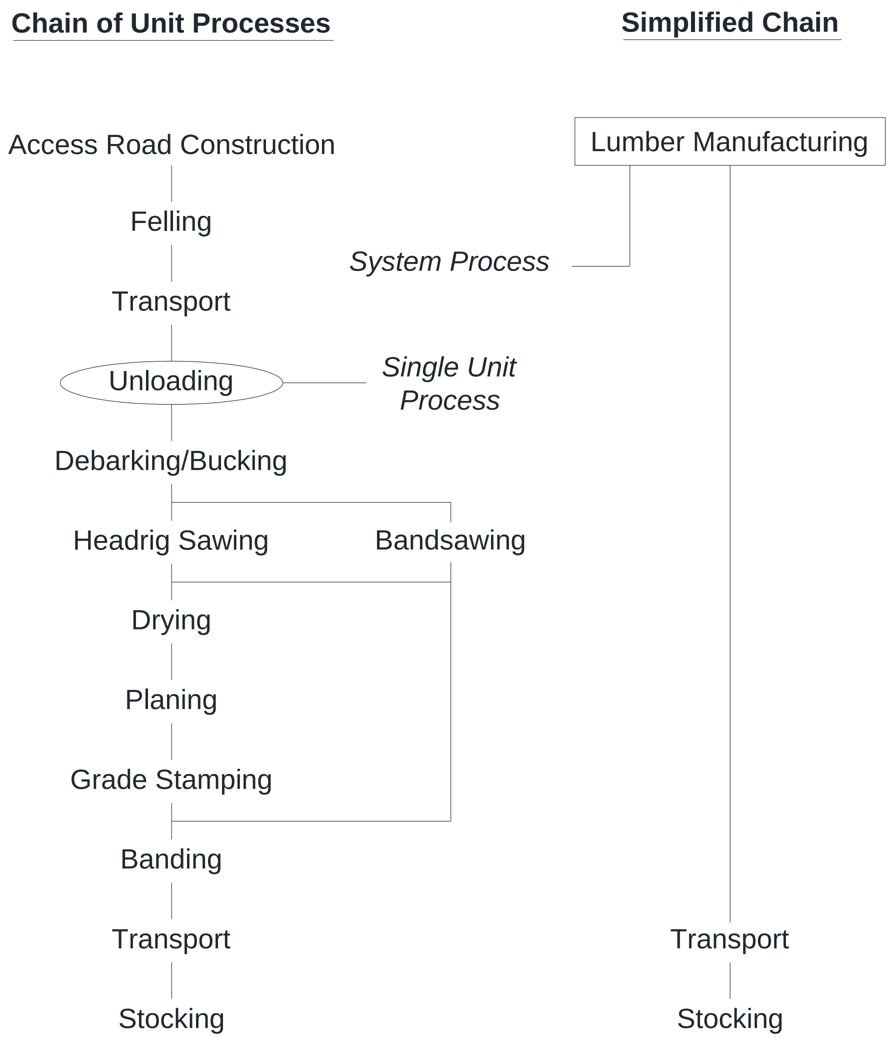

Figure 14: Unit versus system process (Processes adapted from www.madehow.com/Volume-3/Lumber).

Developing a comprehensive LCI is simplified by the use of background data (PRé 2010). Background data is information compiled and made available by the LCA industry that describes common processes. Background data are available in the form of LCI databases and usually come as part of any LCA software. The ecoinvent database by the Swiss Centre for Life Cycle Inventories ecoinvent is an extensive database with over 4,000 LCI datasets that cover multiple industries. The GaBi professional database has over 2,000 datasets that include metals, plastics, wood products, power generation and transport. Numerous other general or spatial and industry-specific databases are available commercially. The databases are combinations of data developed by industry partners, government and private research that are reduced into a single format for easier application. Up to 80% of some LCIs can be completed by using information available in databases. When using background data, providing a process that adequately resembles the process it is going to represent is important (PRé 2010). Power generation varies on the local level and represents a significant part of most life cycle assessments so power processes are usually developed using region-specific information. The historic distribution of power sources for the United States is shown in Figure 15.

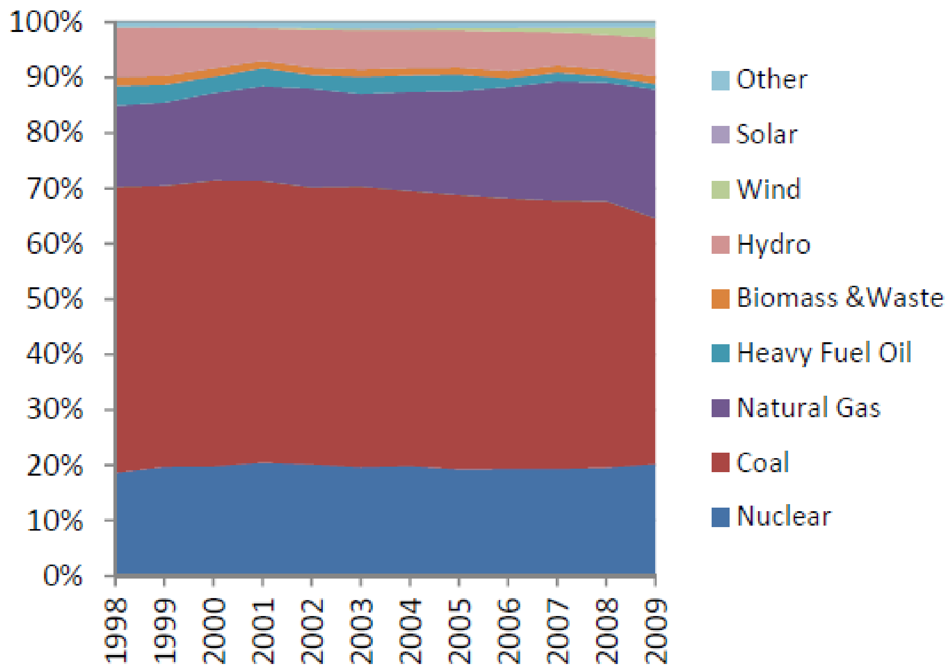

Figure 15: Power grid mix in United States (PE INTERNATIONAL 2012)

Not all data required to complete an LCI will be available via an LCI database. Data that are not background data are termed foreground data and must be developed for the LCA study being performed. Foreground data are required for less common manufacturing processes, proprietary processes or items and processes performed on a local scale (GaBi 6.0). Developing foreground data can be difficult. The most common sources of foreground data are industry surveys. Survey data requires a good understanding of the qualifications for persons providing survey information (PRé 2010).

Results of the LCI can be used to compare two processes. This type of comparison is called *loading* (Curran 1996). For example, if it is found that one process produces 2 metric tons of CO_2 and another process produces 3 metric tons of CO_2 per year then the first process is environmentally favorable. Comparisons using loading have many shortcomings. If two processes emit different levels of two different gasses it is not clear which process is better without knowing the environmental impacts of each gas (Curran 1996).

2.3.5 Life cycle impact assessment (LCIA)

During LCIA, the environmental impacts associated with the LCI are assessed. LCIA uses results from the inventory phase as inputs into impact assessment metrics previously developed by the scientific community (Bare et al. 2003). Impact assessments are based on the best scientific knowledge of how material and energy uses and emissions effect the environment. LCIA is performed in the following order:

1. **Compile** stressors from LCI for process or item to be compared,
2. **Classify** stressors to impact categories,
3. **Characterize** stressors as equivalent units for each category (PRé 2010).

The compiling step aggregates inputs and outputs from each process in the life cycle inventory. Classification sorts emissions into impact categories. Inventory items can broadly be divided into two impact types; (1) depletions of raw materials by system inputs, and (2) pollutant emissions by system outputs. Inventories are further divided by potential damage to specific environmental or human health categories such as global warming potential, eutrophication potential, or human cancer risk. Different emissions have different potential for impact. For comparison, emissions are usually converted to equivalent values of a standard unit. In the case of global warming, emissions are expressed as equivalent kg of CO_2. The last part of the impact analysis is presenting the results of the LCA, usually in a graphical or tabular format.

Characterizing the potential impact of material extraction or pollutant emission on a general impact area is considered characterization at the midpoint level. Global warming potential is a midpoint impact level. Sea-level rise and soil moisture loss are two of many possible results associated with global warming. Characterization at this level is considered endpoint characterization. At this time, there is little scientific consensus on how to properly quantify of emission impacts at end-point levels (Bare et al. 2003).

2.3.6 TRACI

The impact assessment methodology used for this research is the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) developed by the USEPA. TRACI was created to provide a detailed impact analysis tool for use in the United States (Bare et al. 2003). TRACI quantifies impacts at midpoint levels only. Impact categories considered in TRACI are listed in Table 6.

Table 6: Impact categories considered in TRACI (Bare et al. 2003)

Ozone depletion	Climate change
Acidification	Eutrophication
Photochemical smog	Ecotoxicity
Human health: air pollutants	Human health: cancer
Human health: non-cancer	Fossil fuel depletion
Land use	Water use

For this research, impact categories of climate change, acidification, eutrophication and ecotoxicity to water are considered; each category is described below.

Climate change is the warming of the planet with possible endpoint effects including drought, floods, sea-level rise, loss of polar ice caps and change in weather patterns (Bare et al. 2003). Climate change is described in terms of global warming potential. Global warming potential (GWP) is presented in terms of equivalent mass of CO_2. The Intergovernmental Panel on Climate Change (IPCC) is a Nobel Prize winning panel that provides most information on climate change. IPCC (2007) provides a list of emissions and GWPs for 20, 100 and 500 year periods. Degradation of pollutants in the atmosphere occurs at different rates and so GWP varies differently over time for different pollutants. Some notable emissions listed [and the associated 100-yr global warming potential] are carbon dioxide (CO_2) [1], nitrous oxide (N_2O) [298], methane (CH_4) [25], Chloroflourocarbons (CFCs) [4,750 – 14,400] and hydrochloroflourocarbons (HCFCs) [124 – 14,800]. Cumulative GWP for products and processes is reported as the summation of each emission (kg) multiplied by its individual GWP value.

Acidification is the increase in acidity of soil and water systems generally by acid rain (Bare et al. 2003). Acidification endpoint effects are reduction in lake alkalinity, corrosion of buildings and other structures and plant and animal death. Acidification potential (AP) is described in terms of equivalent kg of hydrogen (H+) ions. Major contributors to AP are sulfur dioxide (SO_2), nitrogen oxides (NO_X), strong acids and ammonia (NH_4). Unlike GWP, AP depends on deposition characteristics of emissions in the local environment, therefore; cumulative AP for products and processes is the summation of each emission converted to equivalent kg H+ ions and multiplied by an environmental deposition factor (Bare et al. 2003).

Deposition factors describe the amount of H+ ions expected from Emissions of SOx and NOx. The deposition factors are determined by atmospheric chemistry and transport equations and vary for different regions within the United States.

Eutrophication is the release of nutrients to the environment at levels much higher than normal. The addition of fertilizing nutrients increases plant life (algae) at the water surface that leads to reduction of sunlight infiltration into the water body and reduction of oxygen levels (SAIC 2006). Eutrophication potential (EP) is described as an equivalent mass of nitrogen (N). Nitrogen and phosphorous (P) emissions are responsible for the majority of EP. The effect of N and P releases into the environment is dependent on existing N and P levels in the local environment. Cumulative EP for products and processes is the summation of each emission converted to equivalent nitrogen (kg) and multiplied by two environmental impact factors, one for transport capability and one for existing nutrient levels (Bare et al. 2003).

Ecotoxicity is a measure used to quantify possible damages due to discharging toxic materials into the soil, water and air environments. For harmful contaminants, an ecological toxicity potential (ETP) is developed that describes the potential impact for that contaminant when released into the environment (Bare et al. 2003). Ecotoxicity is reported for water, air and soil but each is related; emissions to soil may lead to damage in the air and water and vice-versa. Cumulative ecotoxicity for products and processes is the summation of each emission multiplied by a cumulative ETP and reduced for transportation and degradation characteristic of the individual contaminant (Bare et al. 2003).

2.3.7 Valuation

At times, a best-performing alternative can be identified from the unmodified results of the LCIA. The best-performing option performs better in every impact category analyzed, or significantly better in one or more categories and equal to the alternatives in the remaining categories. When more than one option performs significantly better than other options in different impact categories, a best option cannot be determined without comparing the significance of the impact categories. Applying weighting factors to impact categories based on their supposed importance to facilitate comparison is referred to as valuation or weighting (SAIC 2006). Using weighting factors, a single environmental impact can be calculated for each process or unit to be compared. Calculating the total environmental impact is expressed by the following equation from Finnveden (1999).

$$EI = \sum_{i=1}^{n} V_i I_i$$

Where *EI* is the total environmental impact from *n* impacts, *V* is the value weighting factor for impact category *i*, and *I* is the impact from one unit in category *i*.

Multiple problems arise when developing weighting factors. First, no consensus for relative importance of impact categories has been determined. Therefore, weighting factors are subjective values selected based on opinion and will vary from person to person. Second, the relative importance of impact factors may change with location and time (SAIC 2006). Although there are obvious shortcomings, thoughtfully developed weighting factors will greatly aid the decision-making process. Three commonly used systems to develop weighting factors are panels, distance to target, and monetization (Pré 2010). Detailed descriptions and comparison of other available weighting methods are discussed in Finnveden (1999). Weighting factors using the monetization method are developed and discussed in Johansson (1999). Berrittella et al. (2007) developed weighting factors to aid in selecting transport policies to reduce climate change impacts using the analytical hierarchy process (AHP) and pair-by-pair comparisons.

Table 7: Common weighting factor development methods.

Panels	A panel is developed with industry, environmental, and political professionals. Weighting factors are either voted on or developed using a multi-criteria analysis and comparison by pairs.
Distance to Target	Weighting factors are determined based on the distance to reduction target (determined by environmental policy).
Monetarisation	Environmental impacts are expressed as a monetary cost required for clean-up. Higher cost is weighted higher.

No investigation was performed to determine the best weighting factors to be used for interpretation of LCIA results in this study. Determining weighting factors will require discussion between GDOT, environmental experts, and the USEPA. To demonstrate the benefits of an LCIA valuation process, this study includes a simple value calculation with assumed weighting factors. The weighting factor assumptions, LCIA valuation, and areas of improvement are discussed in section **Error! Reference source not found.** of this report.

MATERIALS AND METHODS

A combination of field and laboratory testing was performed to characterize SCD performance during the utilization (use) phase. Performance was based on suspended solid, nutrient, and metal retention capability. Material production and approximated installation and maintenance processes were combined with the use-phase and used to compile an inventory of materials and emissions. Life cycle impact analysis was performed using GaBi 6.0. The flow of work is described in Figure 16.

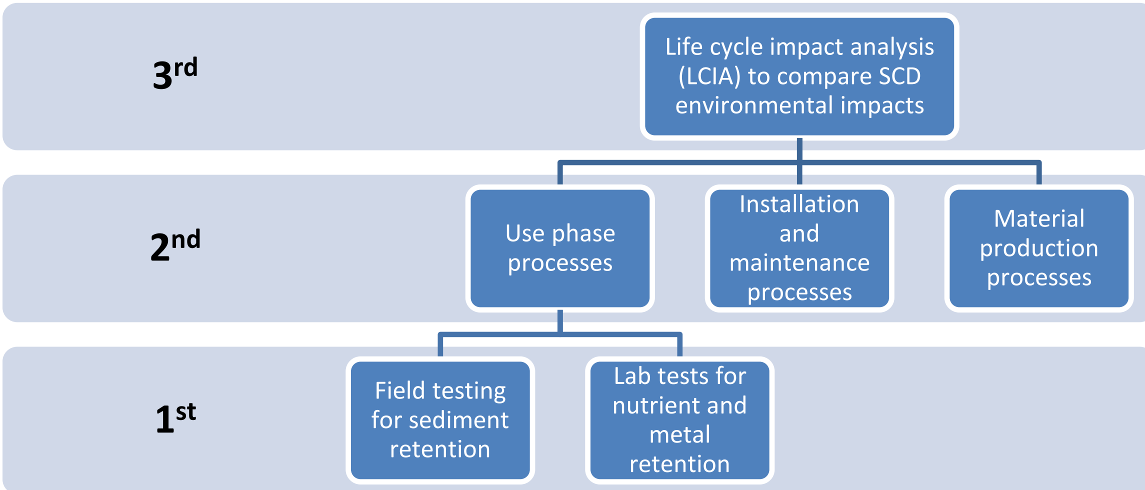

Figure 16: Flow of work.

3.1 Materials

3.1.1 Sediment control devices (SCDs)

Large-scale field testing of SCD performance testing were performed on five different commonly used SCDs. The five devices were:

1. Silt fence - Type A,
2. High-flow silt fence - Type C,
3. Compost sock,
4. Straw bale, and
5. Mulch berms.

Silt fence materials were purchased from a construction supply warehouse, compost socks were provided and delivered to the test facility by Filtrexx, straw bales were available at the test site, mulch was purchased from a local bulk supplier in Anderson, SC. Initial testing of a 12" diameter compost sock resulted in significant undermining of the sock. A retest was performed using a larger diameter (18 inch) sock. Table 8 lists the source and provides a short description of each material tested. Table 9 shows the measured distribution of material type per unit (meter) length of SCD device. Lengths of polypropylene geotextile and steel wire mesh were cut and measured for length and weight. Wood and steel stakes were weighed individually and divided over the installation increment (4’ for Type C, 6’ for Type A and compost sock, 2 per straw bale). An approximate moist density of installed compost and mulch samples was determined using laboratory index tests and the equivalent weight per length value calculated by multiplying by the installed device volume for one unit length.

Table 8: Description of sediment control devices tested

Material	Type	Description
Silt fence (Type A)	ErosionTech ET-GA-A	Polypropylene monofilament woven fabric with wood fence stakes
High-flow silt fence (Type C)	ErosionTech ET-GA-C	Polypropylene monofilament heat bonded fabric with 4 inch square steel wire mesh and steel fence stakes
Compost sock	12” *Filtrexx®* silt sock 18” *Filtrexx®* silt sock	Polypropylene mesh sock with compost fill
Straw bale	Available at test site	Typical 36” straw bale
Mulch berm	Coastal Bark & Supply, local mulch supplier	Unpainted , unspecified mixed hardwood mulch, typical for landscaping

Table 9: Material weight by unit length of device

Device	Material	Measured [calculated] weight (g)	Length increment (m)	Weight per length (kg/m)
Type A fence	PP	331.570	3.048	0.109
	Wood stakes	779.380	1.829	0.426
Type C fence	PP	546.570	3.048	0.179
	Metal stakes	2117.170	1.219	1.737
	Metal wire mesh	989.390	3.048	0.325
Compost sock	PP	170.190	1.029	0.165

	Compost	[103600]	0.305	103.600
	Wood stakes	1385.560	1.829	0.758
Straw bale	Straw	14288.148	0.914	15.626
	Wood stakes	1385.560	0.457	3.031
Mulch berm	mulch	[59400]	0.305	59.400

Laboratory filtration tests were performed using samples of compost and straw from the field SCD devices and samples of two different types of mulch. Mulch samples were provided by a local Atlanta bulk supplier. Mulch samples were a cypress wood waste from southern Georgia and a mixed bark, cambium, and hardwood mulch. A description of each material tested is included in Table 10. Size gradation analysis was performed on samples of mulch and compost from each compost sock used. Gradation was performed by separation through a stack of eight sieves ranging in opening size from 76.2 mm (3 in.) to 0.81 mm (#20 sieve). Gradation of the mulch is shown in Figure 17. Gradation of both compost samples is shown in Figure 18.

Table 10: Description of field and laboratory test material

Sample	**Source**	**Description**	**Moisture Content (%)**
Compost 1	18” compost sock	Dark brown to black ½ to 3-inch long rounded wood pieces with a significant amount of organic soil fines, some fine to medium crushed stone and plastic waste	67
Compost 2	12” compost sock	Light brown to brown ¼ to 5-inch long slender wood mulch with a significant amount of reddish brown fine soil	75
Field mulch	Mulch berm	Dark brown ½ to 3-inch long chopped wood fragments, some fine wood particles	177
Cypress mulch	Atlanta supplier	Yellowish brown ½ to 2-inch long chopped wood fragments, small amount of fine particles	

Mixed hardwood mulch	Atlanta supplier	Dark reddish brown mix of 1/8 to 2-inch long broken round wood particles, ½ to 5-inch long wood cambium strips and ¼ to ½-inch wood bark pieces	
Straw	Straw bale installation	Standard yellow straw	< 10

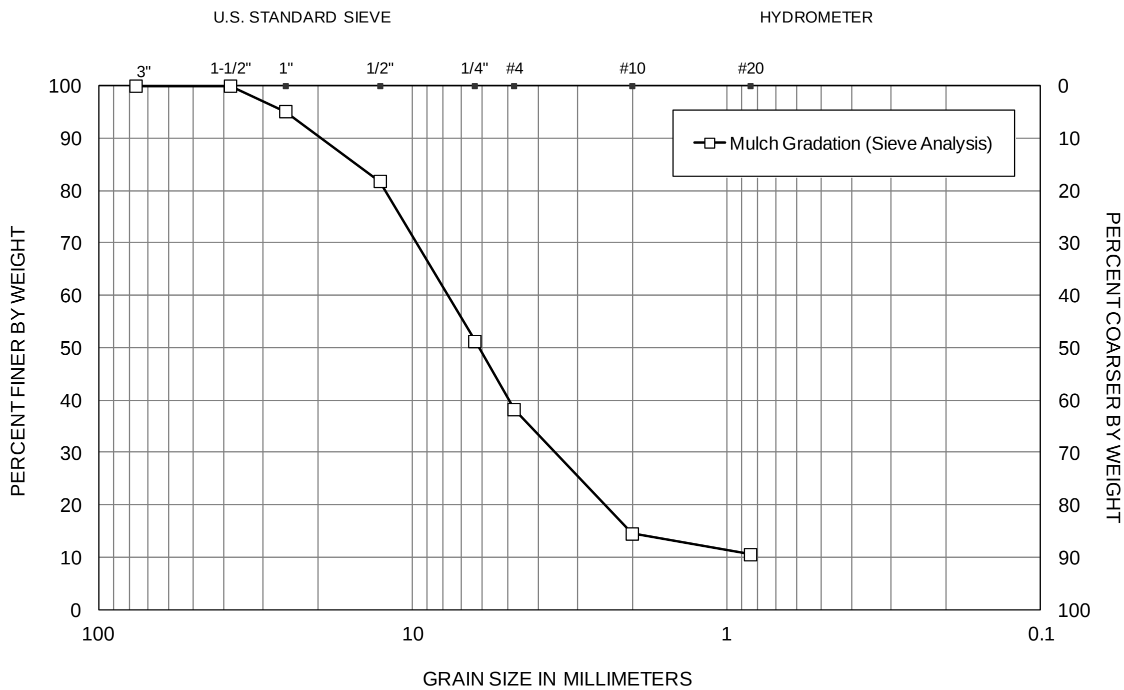

Figure 17: Mulch size gradation by sieve analysis.

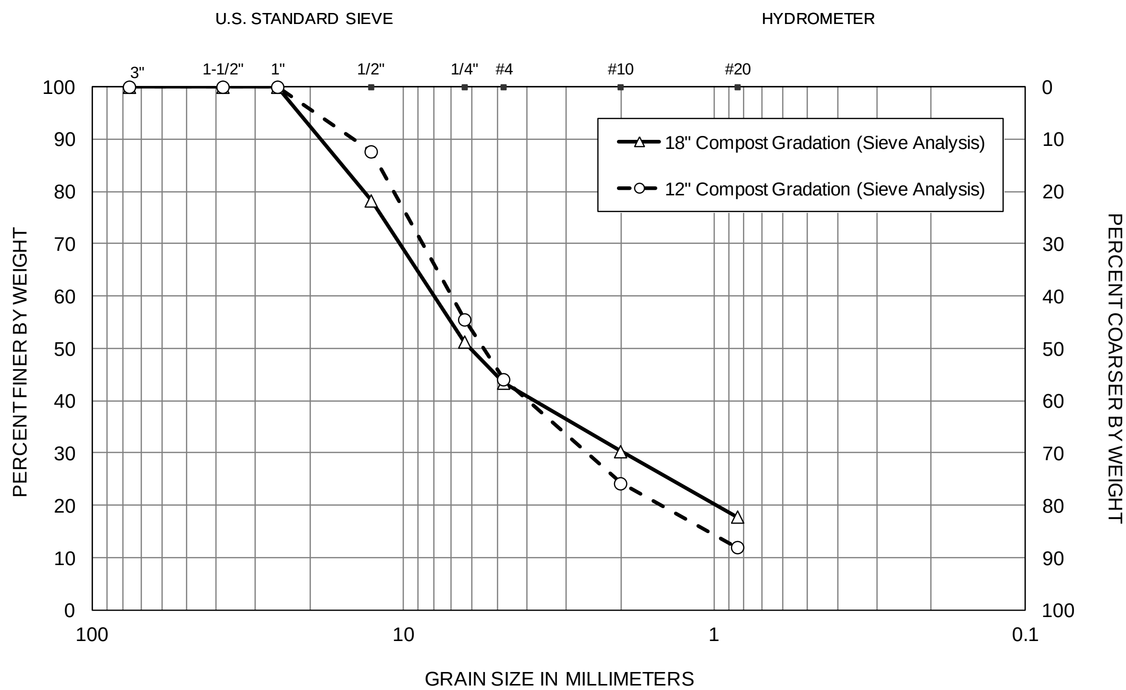

Figure 18: Size gradation for two types of compost by sieve analysis

The field density of compost and mulch material is variable along the installation, therefore; laboratory compaction testing was performed to determine the likely moist field density of the mulch and compost material. The compaction testing was performed by filling a deep pan with material using increasing amounts of force and agitation. The first compaction test was performed by loosely dropping the materials into the pan and leveling the top of the pan. The next two tests were performed by shaking the pan laterally while adding material in three and five layers. The final two tests were performed by shaking and compacting with hand pressure while adding material in three and five layers. Three test iterations were performed with the field compost and mulch samples, one check was performed on the cypress and mixed hardwood sample. The results shown in Figure 19 indicate that only small amounts of agitation increase material density and that physical compaction does not significantly increase field density.

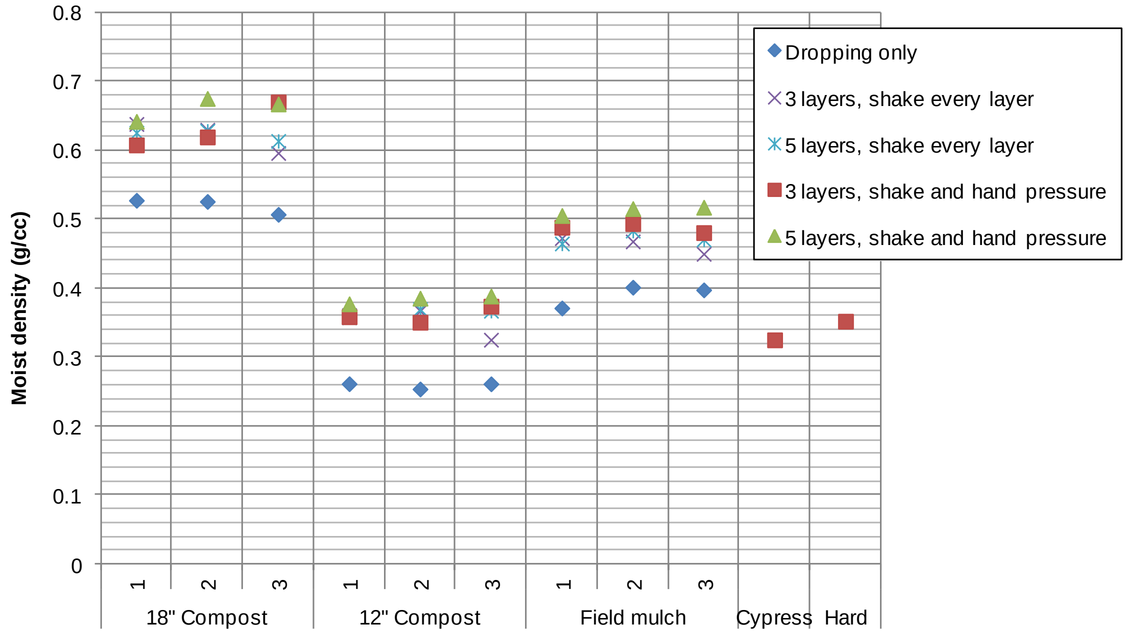

Figure 19: Determination of moist density.

3.1.2 Test soil

Soil for the large-scale field testing of SCDs was red to reddish brown sandy clay stockpiled at the testing facility. Sieve and hydrometer gradations for two soil samples are shown in Figure 20. Sample 1 is representative of soil material used all tests performed except the 18" compost sock. Sample 2 was taken from the material used to test the 18" compost sock. This material was sourced from a different stockpile of similar red sandy clay soil.

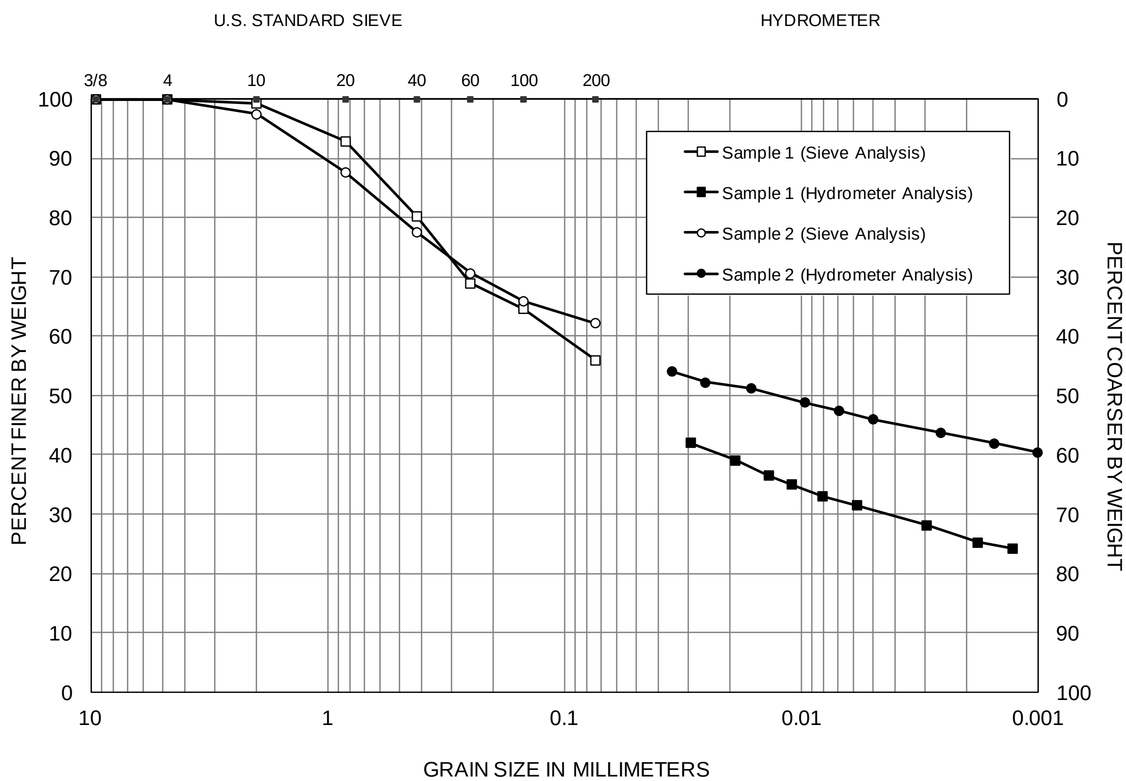

Figure 20: Test soil size gradation.

3.2 SCD field testing

3.2.1 ASTM D7351 test equipment

Initial testing of the five selected sediment control devices was performed according to ASTM standard D7351, *Standard Test Method for Determination of Sediment Retention Device Effectiveness in Sheet Flow Applications*. This method assumes a 10-year, 6-hour storm event with a 100 mm (4 in) rainfall. Eroded soil is approximated for a 30 meter slope length using the Modified Universal Soil Loss Equation (MUSLE). Testing was performed using the ASTM D7351 test setup at the TRI Environmental Denver Downs Research Facility (DDRF) in Anderson, South Carolina. The test setup includes a large mixing tank, sloping (~21°) fluid ramp, soil installation zone, downstream fluid ramp and downstream collection tank. Figure 21 shows the testing equipment used at DDRF with labels.

Figure 21: ASTM D7351 testing equipment at DDRF.

The test area was prepared by compacting sandy clay soil in the soil installation zone, installing the SCD to be tested and mixing soil-water slurry. The test was performed by releasing the slurry at a controlled rate towards the SCD while making observations and collecting samples at regular intervals. Test soil was compacted in the soil installation zone using a jumping jack compactor and hand tamp. The surface of the soil zone was brought level to the edge of the upstream and downstream fluid ramps. The sediment control device to be tested was installed along the installation zone, generally centered, with an equal amount of soil exposed in front and behind the SCD. ASTM D7351 specifies a range for test soil as shown in Table 11. The previous soil test gradation meets the test gradation.

Table 11: Soil gradation indicated in ASTM D7351.

Acceptable Range (mm)
$D_{100} < 25$
$0.5 < D_{85} < 5.0$
$0.001 < D_{50} < 1.0$
$0.005 < D_{15}$

3.2.2 SCD installation

Installation of each SCD was according to specifications in Georgia Soil and Water Conservation Commission (GSWCC) (2000). Installation procedures for each device are described in the following paragraphs.

Geotextile silt fence was installed by placing the fabric in an 8-inch deep trench and then attaching the fence to wooden or steel posts. Each post was driven to a depth of 12 inches below the bottom of the trench using a large hammer. The low-flow (Type C) silt fence was stapled to a metal mesh backing that was attached to steel posts with two short segments of fence wire per post. The toe of the fence was configured into an L-shape by turning the bottom edge of the fabric in the upstream direction and covering with loose soil in accordance with the GSWCC guidance. The remaining portion of the trench was backfilled with the excavated trench soil and compacted on both sides of the silt fence. The approximate configuration of both geotextile silt fence installations is shown in Figure 22.

Compost sock was delivered to DDRF pre-filled with compost and wrapped in a long coil. Before installation, the compost sock was unwrapped and a segment was cut to the length of the soil installation zone. The compost sock was positioned along the middle of the installation zone and staked to the ground using 2-inch square stakes spaced 6 feet along the length of the installation. The arrangement of the stakes is shown in Figure 22. The sock was flattened with blows of a hand tamp and by walking along the top of the sock. Some soil was pressed into the upstream crevice between the bottom of the 12-inch sock and the soil surface. Loose compost was pressed into the upstream crevice of the 18-inch compost sock.

Straw bales were installed in a 4-inch deep trench cut along the soil installation zone. The straw bales were positioned in the trench, end-to-end so that the twine-wrapped bale surfaces faced in the upstream and downstream directions. The bales were pressed together tightly and set in place by driving stakes through the bales and into the soil. Two stakes were driven through each bale, positioned in the center of the bale width, approximately 12 inches from the end of the bale. Remaining portions of the soil trench not filled by straw bale were filled with soil and compacted. Configuration of the straw bales is shown in Figure 22.

Mulch berm was installed by setting small wooden stakes spaced approximately 4 feet apart, 6-inches from the back of the soil installation zone, as shown in Figure 22 . Pieces of long, approximately 10-inch wide planks of ½-inch plywood were propped against the stakes to form a short, reinforced vertical barrier. Loose mulch was distributing along the front of the plywood barrier and compacting using foot pressure. Configuration of the mulch berm is shown in Figure 22.

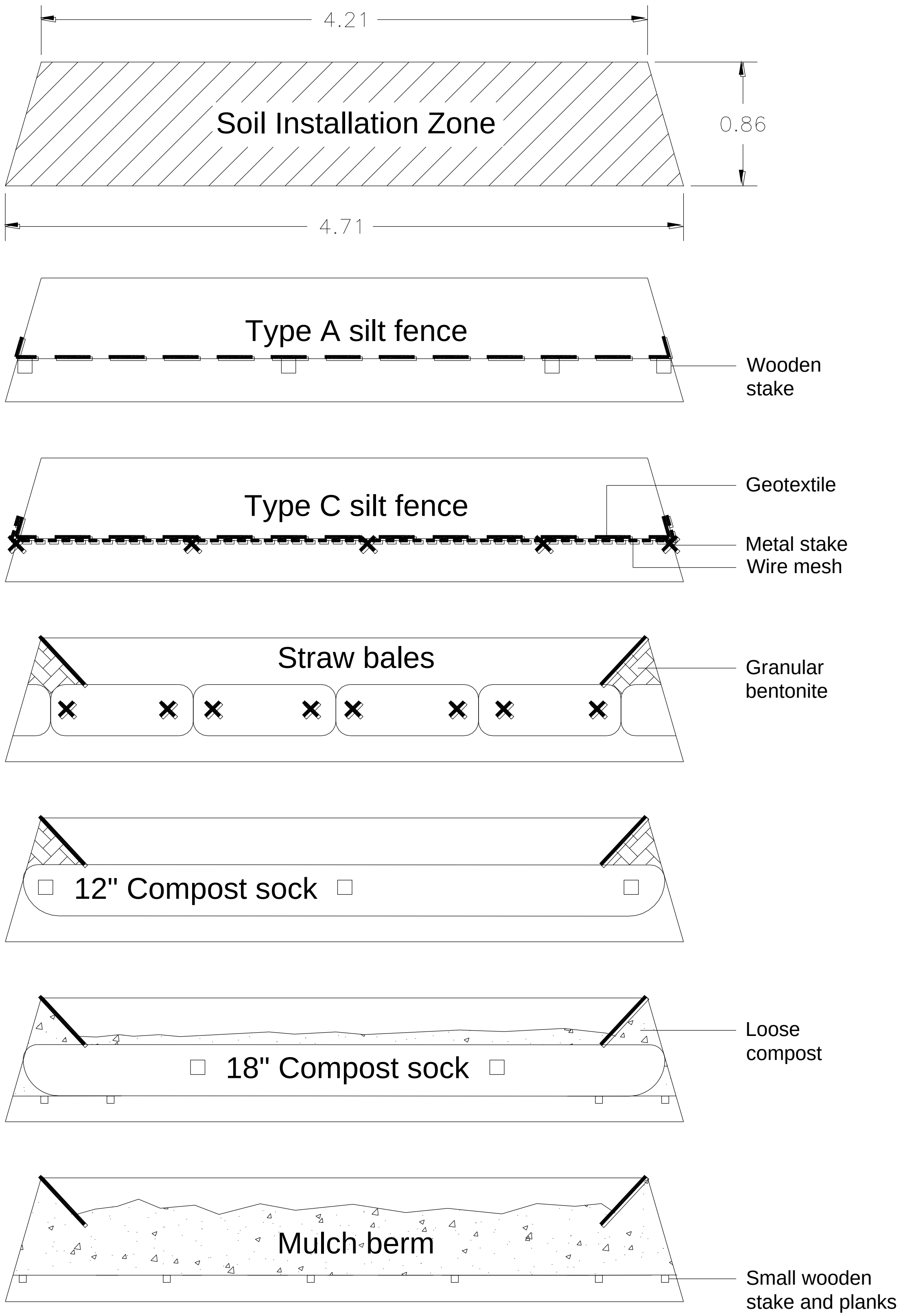
4.21
Soil Installation Zone
0.86
4.71
Type A silt fence
Wooden stake
Type C silt fence
Geotextile
Metal stake
Wire mesh
Straw bales
Granular bentonite
12" Compost sock
18" Compost sock
Loose compost
Mulch berm
Small wooden stake and planks

Figure 22: Approximate configuration of installed SCDs.

3.2.3 SCD end connections

The end connection of the SCD was an important detail for the project, as it was important to minimize the potential for stormwater to "by-pass" the SCD and flow (untreated) around the ends of the installation. Connection of the high and low silt fence to the test barrier panels at either end of the soil installation zone was achieved by wrapping the geotextile fabric along the barrier wall in the upstream direction. Wooden abutment stakes were driven in-line with the installed silt fence and immediately adjacent to the barrier wall. Between 6 and 12 inches of geotextile fabric was sandwiched between the barrier wall and the abutment stake. Silicone sealant was applied generously in the vertical void space between the geotextile and the wall panel. The abutment stakes were secured to the barrier wall with multiple wood screws.

Direct connection between the barrier wall and the three-dimensional SCDs was not possible. For these installations, plywood wing walls were attached to the barrier panel with silicone sealant and screws and embedded in the soil installation zone upstream of the SCD installation. Each wall was approximately 18 inches long and embedded approximately 4 inches into the soil installation zone by trenching and placing and compacting soil. The wing walls were installed to form approximate interior 45 degree angles between the barrier wall and wing wall. To minimize flow of test water around the SCD installation, both wing walls were backfilled with granular bentonite clay during testing of the 12-inch compost sock and straw bales. During testing of the mulch berm and 18" compost sock, the wing walls were backfilled with mulch and loose compost, respectively.

3.2.4 ASTM D7351 test

After installation of each SCD was complete, the test equipment was prepared for use. The test runoff water and soil mixture was prepared by filling the upstream mixing tank with 5,000 pounds of water from a ground water well on site. The test soil was sieved through a ¼-inch sieve and weighed using a portable scale then added to the mixing tank with the mixing blades in operation. Mix water was weighed using a four point truck scale under the upstream mixing tank. Approximately 5 minutes after adding the soil, a gate valve was partially opened to release the test fluid onto the upstream approach ramp. Release of the test fluid was monitored periodically by comparing the weight of the upstream tank with target weights based on an even release of 5300 pounds of combined soil and water over the 30 minute release period.

The weight of test fluid passing the installed SCD was measured using the downstream collection tank and scale and recorded at 5 minute intervals. Samples of test water flowing through the upstream distributer (upstream samples) and flowing into the downstream collection tank (downstream samples) were collected in 500 mL, high-density polyethylene, sample containers at five minute intervals beginning five minutes after the first release from the upstream mixing tank. Each sample bottled was marked according to SCD being tested, sample time interval, and sample location.

3.3 Laboratory analysis

3.3.1 Turbidity

Upstream and downstream samples were tested for turbidity using an Orbeco-Hellige TB200-10 portable turbidimeter with a measurement range of 0.01 to 1100 nephelometric turbidity units (NTU). Samples with turbidity greater than 1100 NTU were diluted with measured portions of deionized water until the sample was within the readable range of the turbidity meter. A volume correction was applied to each diluted sample to approximate the actual turbidity reading. When calculating actual turbidity readings, turbidity of the de-ionized water was assumed to be zero; however, intermittent measurements of clear de-ionized water indicate the actual turbidity ranges between 0.1 and 5.0 NTU.

3.3.2 Total, suspended and dissolved solids

Samples collected downstream of the installed SRD were filtered to determine total suspended solids (TSS) in accordance with EPA Method 160.2. Before filtering, each sample was thoroughly mixed by shaking. Filtering was performed by passing between 20 to 100 mL of sample water through clean glass fiber filter paper. The glass filter and retained soil material was oven dried and weighed. Total dissolved solids were determined by measuring electrical conductivity of the TSS filtrate. Conductivity readings were correlated to total dissolved solids (TDS) readings using a liner relationship. Upstream samples were tested for total solids (TS). Total solid testing was performed by oven drying the entire sample volume and recording sample weights before and after drying.

3.3.3 SCD nutrient retention

The ability of the SCDs to capture nutrients was measured using cylinder filter testing. Samples of compost from the 12-inch and 18-inch socks, cypress and hardwood mulch and straw were placed in 12.7 cm (5 in) diameter 30.5 cm (12 in) long acrylic cylinders. The compost, mulch and straw samples were compacted to the field density indicated in previous material characterization tests. Initial nutrient content was determined by rinsing the materials with multiple 1 L portions of deionized water. Samples of the passing rinse water were collected after the first, fifth and ninth liter of water drained through each material. Nutrient retention capability was determined by filtering water with initial nutrient concentrations. Test water was prepared by diluting nutrient stock solutions with deionized water to concentrations of 0.5 mg/L nitrite, nitrate, ammonia and phosphate. The test setup for nutrient retention is shown in Figure 23.

Nutrient analysis included spectrophotometric tests for phosphorous, nitrite and nitrate and potentiometric measurement of ammonia. A list and description of each test method is included in Table 12.

Table 12: Nutrient test methods and description.

Nutrient (Range)	EPA Test Method	Description
Phosphorous, P (0.01 – 0.5 mg/L)	365.2	Antimony-phosph-molybdate complex reacts with to form blue color. Color intensity proportional to P content. Read at 650 nm.
Nitrite-Nitrogen, NO_2-N (0.01 – 1.0 mg/L)	354.1	Nitrite, sulfanilamide and N-ethylenediamine dihydrochloride make red-purple complex. Read at 540 nm.
Nitrate-Nitrogen, NO_3-N (0.1 – 2 mg/L)	352.1	Nitrate reacts with brucine sulfate in acid at 100C to make yellow color. Absorbance read at 410 nm.
Ammonia-Nitrogen, NH_3-N (0.03 – 1400 mg/L)	350.3	Potentiometric ammonia electrode measures ammonia diffusion through gas-permeable membrane. Fisher Scientific accumet® ammonia combination electrode.

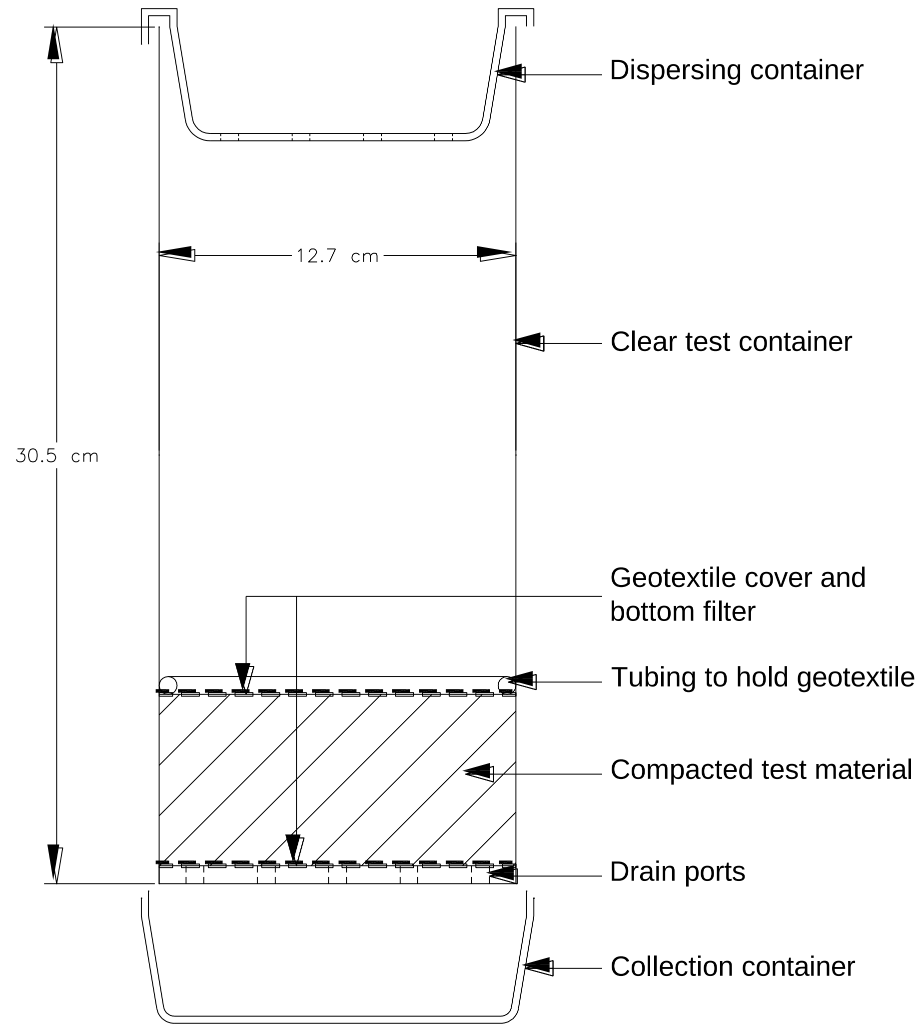

Figure 23: Laboratory filter test configuration.

3.3.4 Metal retention

Metal testing was performed using the same filter device shown in Figure 23. Metal concentration of the initial 1 L portion of passing deionized water was measured. Metal retention capability was determined by passing and sampling 1 L of deionized water with 0.5 mg/L of lead, copper, and zinc concentrations and 1 L of rinse water through the filter materials. Initial and retained metal concentrations were determined using inductively coupled plasma optical emission spectroscopy (ICP-OES). ICP-OES testing was performed using axial readings.

3.4 Life cycle analysis (LCA)

Life cycle analysis (LCA) of each sediment control device was performed using GaBi software version 6.0 by PE INTERNATIONAL. The GaBi software was used to generate LCA plans, balance life-cycle inventory and perform impact assessment according to USEPA TRACI methodology.

3.4.1 Goal and scope

The purpose of the life cycle analysis is to compare the environmental impacts of five different SCD devices. Comparison of production, use and disposal phases of each SCD is also performed.

3.4.2 Functional unit (model conditions)

The functional unit for the life cycle analysis is a 1,000 meter installation of SCD over a 1 year time period. Runoff and eroded soil is assumed to be generated by 11.5 10-year, 6-hour storm events. This was determined by dividing the mean yearly precipitation of 46 inches for Macon, Georgia (The Weather Channel 2012) into 4-inch storms. Nutrient and metal concentrations of runoff water is assumed as 0.5 mg/L. The model conditions equate to approximately 1.3 m^3 per meter of installation per year. On the basis of erosion assumed in the ASTM D7351 test, the model conditions result in 348 kg of eroded soil generated per meter of installation per year. On the basis of on the assumed nutrient and metal concentrations, approximately 2.9 g of metal and nutrients are generated per meter of installation per year.

3.4.3 System boundaries

System boundaries include production of all SCD materials, energy required for installation and maintenance, pollution from SCD effluent and end-of-life disposal. The system does not include energy and materials required for production of construction machinery. Figure 24 shows a general LCA flow chart and system boundaries.

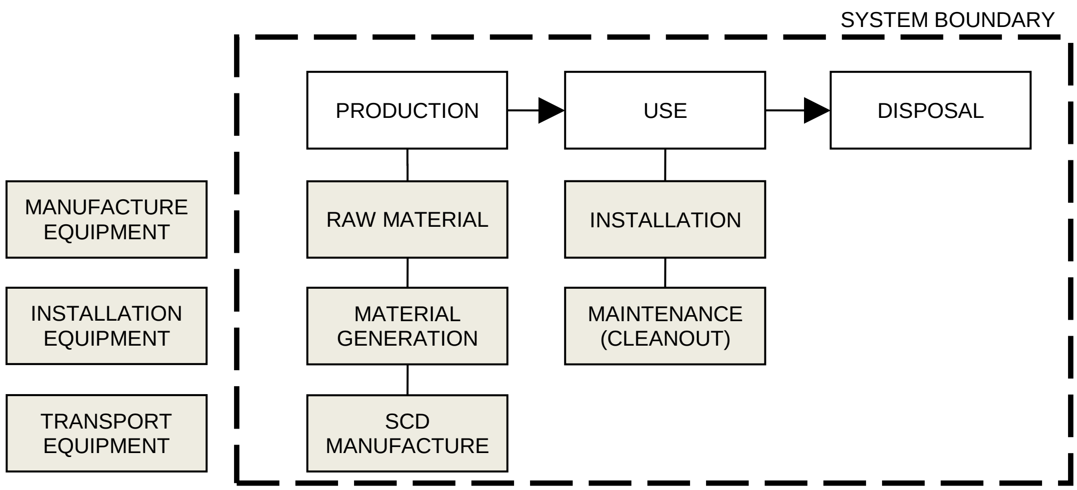

Figure 24: LCA system boundary

3.4.4 Processes

A plan for each SCD was generated using a combination of processes developed by PE INTERNATIONAL distributed in their standard professional database and other processes developed using results of field and laboratory tests. Additionally, other processes were approximated based on fuel requirements and power performance from literature. Processes from within the PE INTERNATIONAL professional database are compilations of sub-processes that represent the majority of production and disposal steps included in the LCA. These processes and sub-processes are responsible for a significant amount of material and energy usage and are described in detail in the following paragraphs. The name of the process as shown on the plan pictographs is bolded and followed by the description. A use-phase process was developed for each SCD using results of field and lab testing. Brief descriptions of the use phase processes are listed in Table 13; assumed conditions and generation of the use-phases is discussed in detail in Chapter 4. Unit processes for SCD installation and maintenance were approximated on the basis of simple energy requirements and are described in Table 14.

European Union-27 Polypropylene fibers (PP) is an ISO compliant cradle-to-gate description of manufacture of polypropylene fibers compiled by PE INTERNATIONAL. Propylene from the cracking of refined crude oil is polymerized to polypropylene. The process assumes polymerization by gas-phase reactor methods. Fibers are formed by spinning; in this research spinning is assumed to be an acceptable model substitute to polypropylene strands by extrusion. Major inputs are water, crude oil, energy mix and various other elemental materials. The utilizable output is polypropylene fiber. Other process outputs as byproducts include radioactive waste, emissions to air and water from technosphere, waste heat, mixed hydrocarbons and heavy metals. A flow diagram of the processes included is shown in Figure 25.

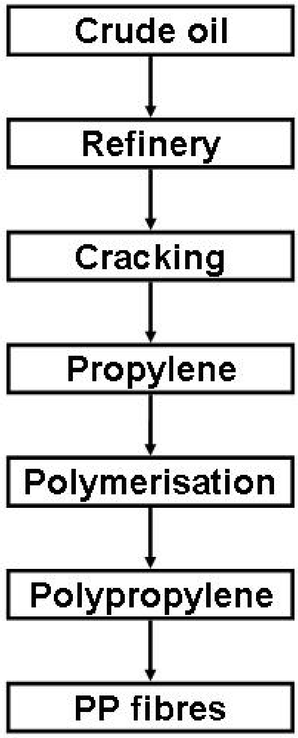

Figure 25: Polypropylene fibers flow diagram (from GaBi 6.0).

DE: Timber pine (40% water content) is an ISO compliant cradle-to-gate description of the generation of timber compiled by PE INTERNATIONAL. The utilizable output is timber with 40% moisture content. In this research, timber resulting from this process is assumed as wooden stakes used for staking SCDs. Required inputs are water, land use, energy mix, fuel for transportation sub-processes and various non-renewable elements. Output byproducts include radioactive and non-radioactive emissions to air and water, water from technosphere and hydrocarbons. Beneficial outputs from timber manufacture include oxygen production and erosion resistance. A descriptive flow diagram is included in Figure 26.

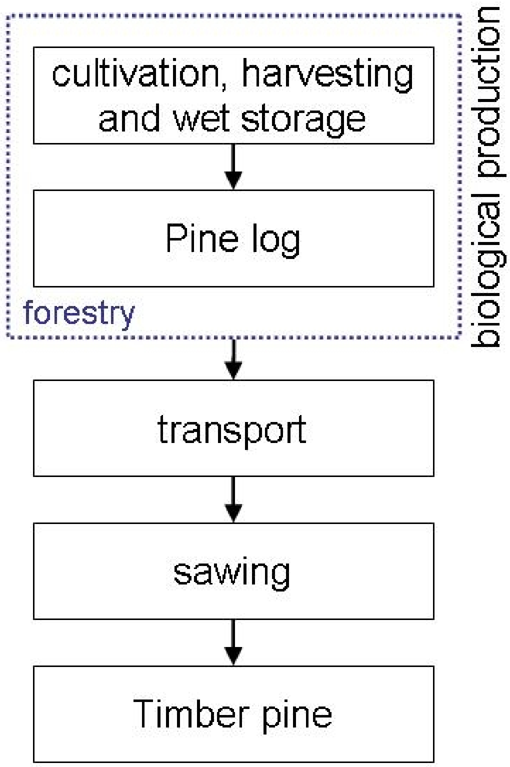

Figure 26: Timber process flow diagram (from GaBi 6.0)

GLO: Steel wire rod is an ISO compliant cradle-to-gate process based on high quality worldsteel steel production data. This process describes the extraction of materials (i.e. coal, iron), processing (i.e. furnace) and forming required for steel production. Wire rod is considered a small-section strand coiled material. In this research, wire-mesh backing for Type C silt fence is considered as steel wire rod. Inputs for this process are air, water, coal, power, iron ore, steel scrap and various other renewable and non-renewable resources. The functional output is steel wire rod; output byproducts are sludge, slag, radioactive emissions, waste water and other hazardous and non-hazardous emissions to soil, water and air.

GLO: Steel section is the same as the previous steel wire rod process with the utilizable output being hot-rolled steel sections instead of wire rod. Steel sections are considered I, H and wide-flange beams and sheet-piling. In this research, steel fence posts for support of Type C silt fence are considered steel sections.

GLO: Truck is an ISO compliant unit process compiled by PE INTERNATIONAL that describes the operation of a 3.3 metric ton (t) payload truck (7.5 t gross weight) for cargo transportation. In this research, transport of SCDs to the site and transportation of waste SCDs to landfill is assumed as a 3.3 t payload truck. Distances from SCD warehouse to site for each SCD plan is assumed as 10 kilometers (6.2 miles), distance from the site to landfill is assumed as 25 kilometers (15.5 miles). A 7.5 metric ton gross weight is roughly equivalent to a Ford F-550 truck. The corresponding FHWA gross vehicle weight rating (GVWR) is class 5 (medium duty) commercial. Inputs to the truck process are cargo at start and refined diesel fuel. Outputs are cargo at delivery and emissions to air from fuel combustion. The fuel requirement for this truck is roughly 0.004 kg diesel fuel per kg of payload per km travelled.

US: Diesel mix at refinery is an ISO compliant cradle-to-gate process compiled by PE INTERNATIONAL that describes the production of refined diesel fuel used for transportation and electricity. Petrol refineries are complex plants that use different sub-processes to produce a combination of end-products of different quality. Sub-processes also differ based on the quality of raw petroleum. To represent diesel production in the United States, the utilization of separate refining processes is chosen to reflect the quality and quantity of product from 130 crude oil refineries located in the States. The refining procedure includes various distillation, hydro-treatment, conversion (i.e. cracking, coking) and finishing processes. The data set also includes elements of petroleum production such as crude oil exploration, well operation and transportation. Process inputs are water, crude oil and other renewable and non-renewable resources. The utilizable output is diesel fuel; output byproducts include radioactive and non-radioactive waste, hydrocarbons, water from the technosphere and waste heat.

EU-27: Landfill of untreated wood is an ISO compliant gate-to-grave process compiled by PE INTERNATIONAL that describes the cost of land-filling untreated wood. The process includes elements of municipal landfill construction (i.e. materials for clay and polyethylene barriers), operation (i.e., diesel for compactor, emissions from flare, partial reuse of methane), closure and maintenance. The process assumes a 30 m high landfill with cover area of 40,000 square meters that meets European code requirements for emissions. In this research, waste wooden stakes for installation of SCDs are assumed as waste wood. The utilizable input is untreated wood for landfill. Output byproducts are water and various emissions to air, water and soil.

EU-27: Landfill of ferro-metals is a cradle-to-grave process similar to land-filling of wood waste with slightly different emissions that are associated with degradation of ferro-metal.

EU-27: Landfill of plastic waste is a cradle-to-grave process similar to land-filling of wood waste with slightly different emissions that are associated with degradation of plastic. Land-filling sub-processes considered in both processes are shown in Figure 27.

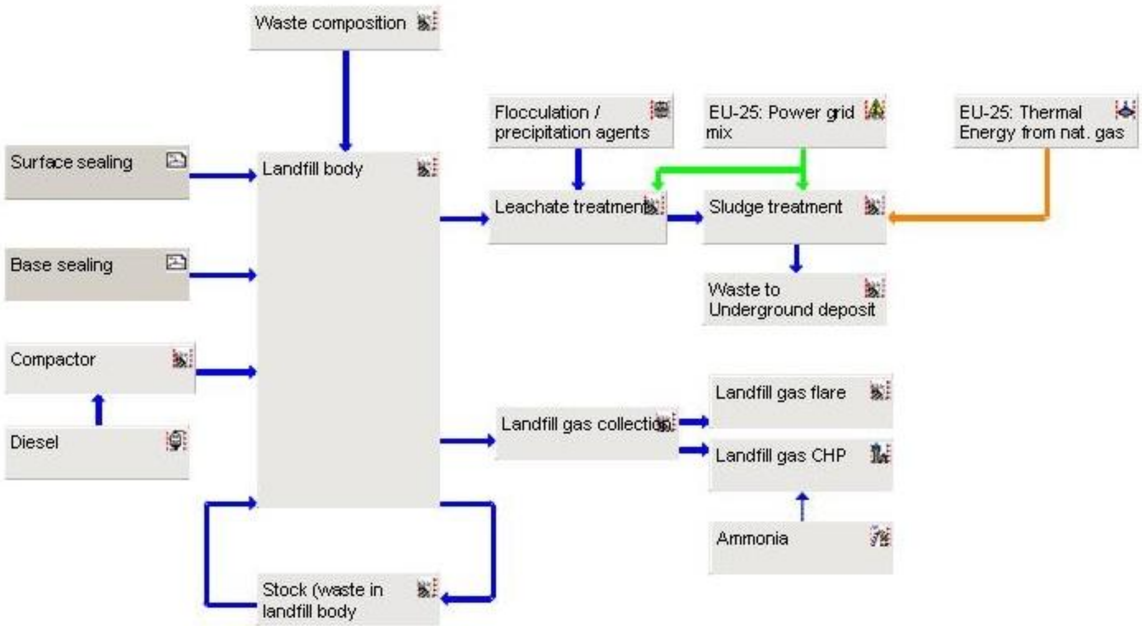

Figure 27: Municipal landfill processes (GaBi 6.0)

3.4.5 Plans

Processes relevant to the life cycle of each SCD are loaded into a GaBi plan editor. The processes are linked so that utilizable outputs from production stages (i.e., geotextile fabric, steel sections) are linked to corresponding use phases. When required, installation and maintenance processes are linked to use phases. Outputs from use phases become inputs for disposal phases. Transportation by truck is included as an intermediary between production, use and disposal phases. Emissions are byproduct outputs that are not transferred between life-cycle processes. Raw materials and emissions are compiled during the life-cycle balance.

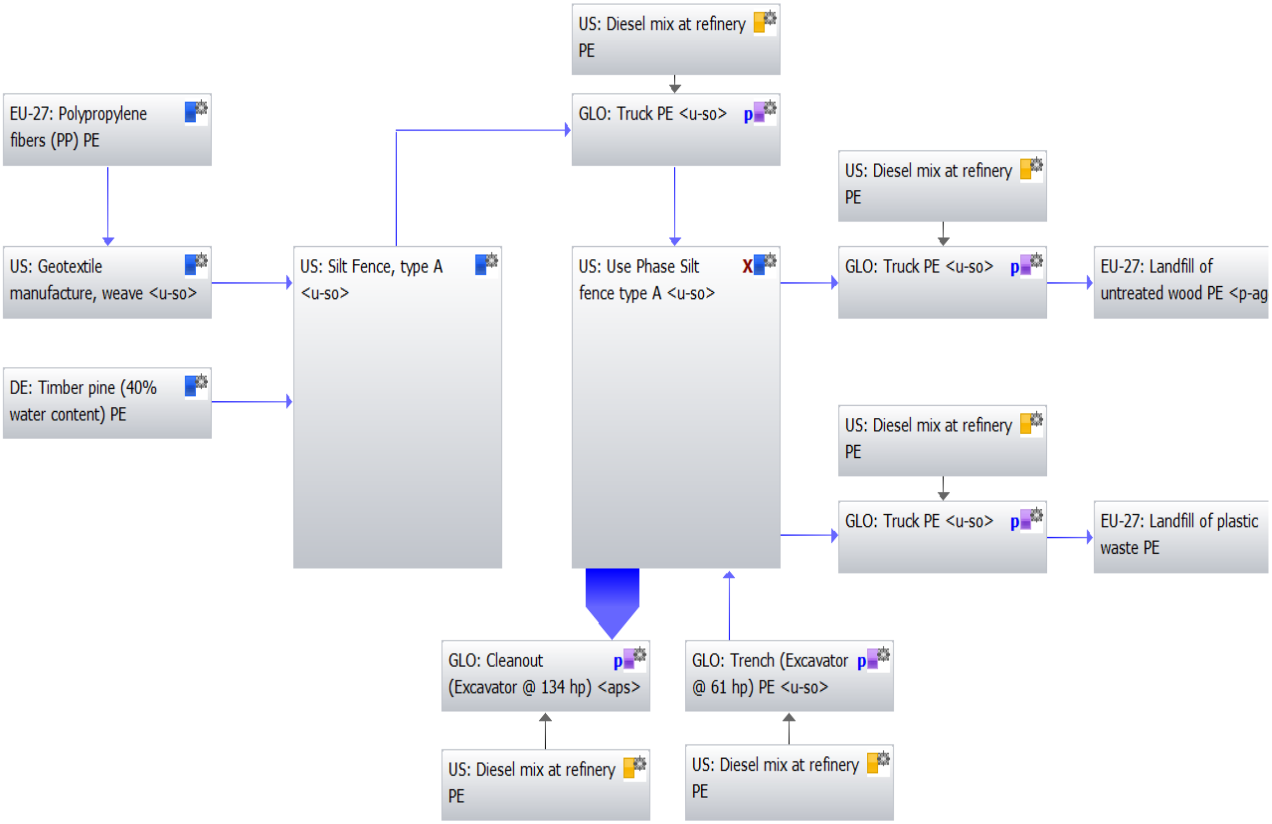

Figure 28 through Figure 32 show life-cycle plans developed for each SCD analyzed.

Table 13: Inputs and outputs from use-phase processes

Use-phase process	Inputs (kg) Material required for installation of 1,000 meter length	Outputs (kg) Combined effluent passing 1,000 meter SCD installation over 1 year
Silt fence – Type A	109 polypropylene geotextile 426 timber (as stakes)	4177 suspended solids 426 wood for landfill 109 plastic for landfill 2.43 NO_2, NO_3, NH_3, PO_4 2.43 Cu, Pb, Zn
Silt fence – Type C	179 polypropylene geotextile 1737 steel sections (as stakes) 325 steel wire rod (as wire mesh)	6265 suspended solids 2062 metal for landfill 179 plastic for landfill 2.14 NO_2, NO_3, NH_3, PO_4 2.14 Cu, Pb, Zn
Compost sock	165 Polypropylene geotextile 65617 wood waste (as compost) 758 timber (as stakes)	18535 suspended solids 758 wood for landfill 165 plastic for landfill 2.32 NO_2 0.2 Cu 1.76 NO_3 0.2 Pb 3.01 NH_3 0.4 Zn 2.32 PO_4
Straw bale	15626 straw 3031 timber (as stakes)	22972 suspended solids 3031 wood for landfill 0.63 NO_2 1.1 Cu 0.20 NO_3 1.1 Pb 3.51 NH_3 1.6 Zn 19.5 PO_4
Mulch berm	74803 wood waste (as mulch)	13053 suspended solids 0.56 NO_2 0.3 Cu 0.80 NO_3 0.3 Pb 1.92 NH_3 0.5 Zn 2.49 PO_4

Table 14: Single-unit processes approximated for this research

Process	Description
Geotextile manufacture	Approximates weaving fibers into geotextile fabric. Assumes 2 kWh/kg power requirements for weaving (Palamutcu 2010). **Inputs**: Polypropylene fibers **Output**: Polypropylene geotextile (100% of input fibers by weight)
Cleanout	Required effort to remove deposited soil mass from behind SCD devices. Assumes cleanout can be performed with 100kW (134 hp) excavator. This is a small hydraulic excavator with 0.7 to 0.8 m^3 (22 – 28 ft^3) bucket capacity. Roughly equivalent to a CAT 318E. **Inputs:** 0.172 kg diesel per 1,000 kg excavated material **Outputs:** Combustion emissions
Mulch	Approximates mulching site coverage. Assumes mulcher is 63 kW (85 hp) tractor or skid-steer with mulch cutting attachment. Roughly equivalent to a Bobcat S-750. **Inputs:** 0.108 kg diesel per 200 kg mulch generated **Outputs:** Wood waste (mulch), combustion emissions
Trench	Required effort for trenching and installation of silt fence material. Modeled as a 46kW (61 hp) small tractor or skid-steer such as a Bobcat S-160. **Inputs:** 0.078 kg diesel per 1000 kg excavated material **Outputs:** Excavated material, combustion emissions
Straw bale creation	Approximates the combined energy required for cultivation and baling straw bales. Assumes fuel usage for cultivation and baling is 0.60 and 0.45 US gallons, respectively (Downs and Hansen 1998). For a density of 6.1 lb/gallon and assuming 25 bales produced per acre, combined fuel consumption is 0.193 kg per m of bale installation. **Inputs:** Straw, diesel fuel as described **Outputs:** Straw bale

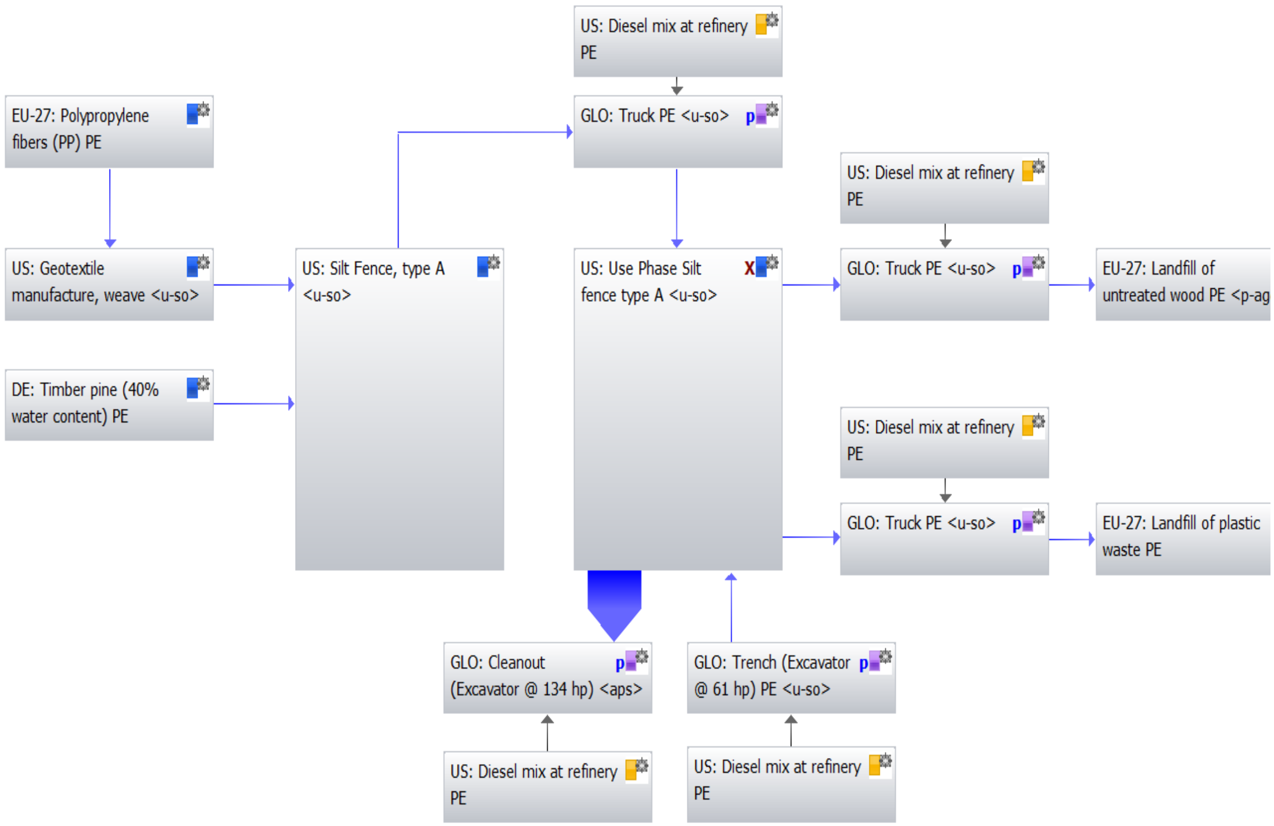

Figure 28: Process plan for silt fence –Type A

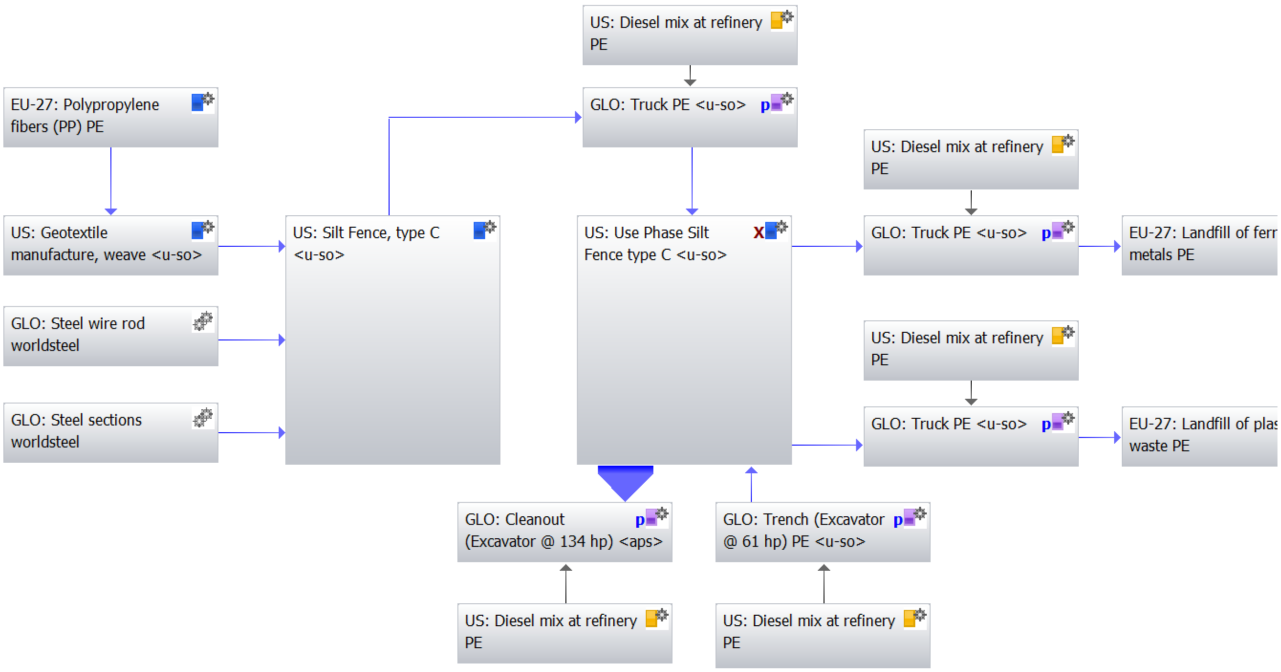

Figure 29: Process plan for silt fence – Type C

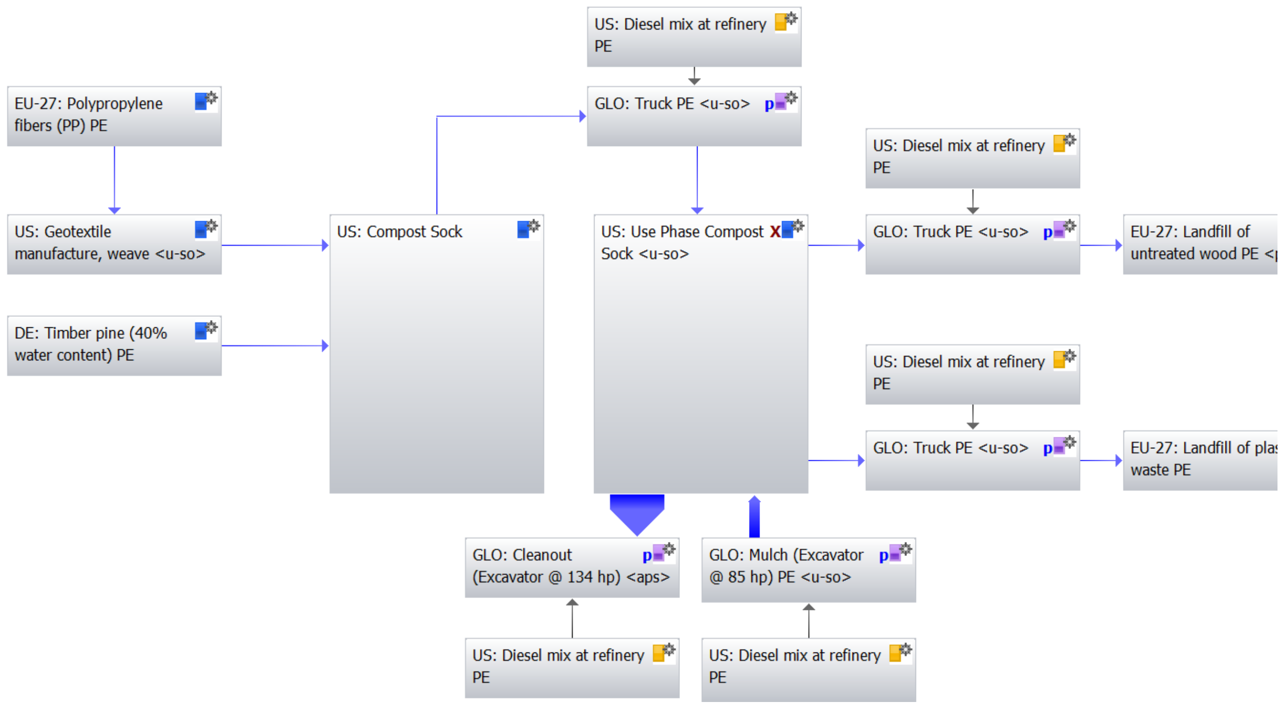

Figure 30: Process plan for compost sock

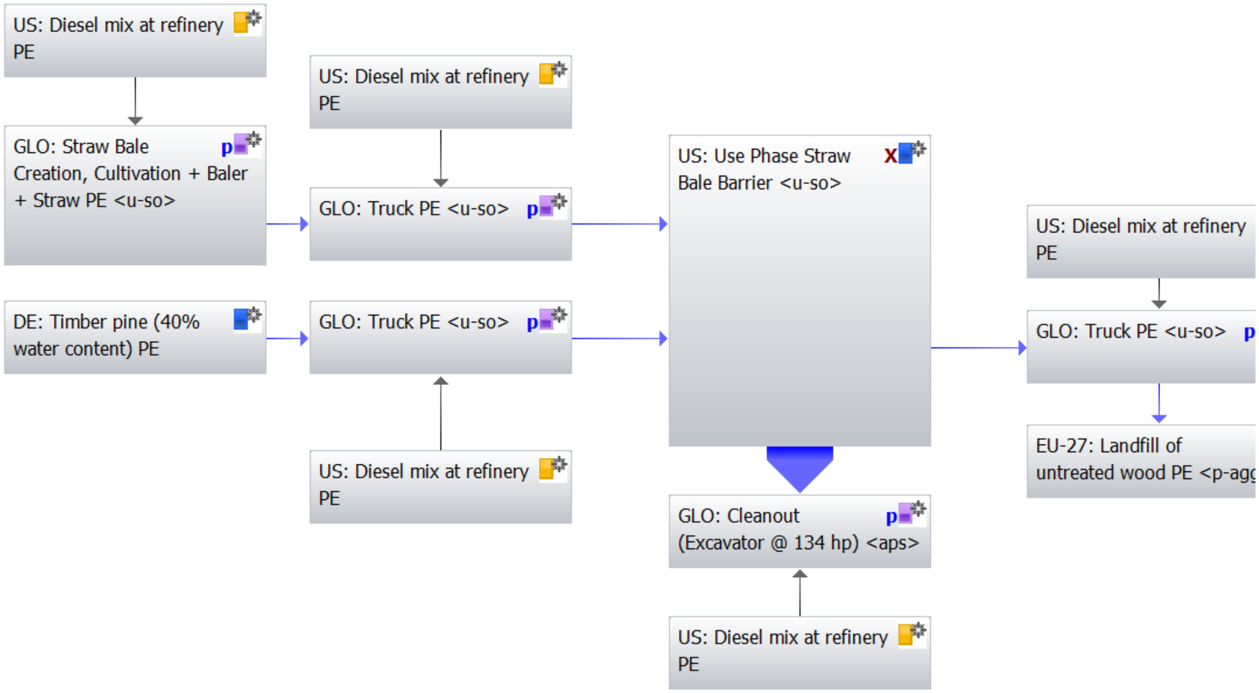

Figure 31: Process plan for straw bale barriers

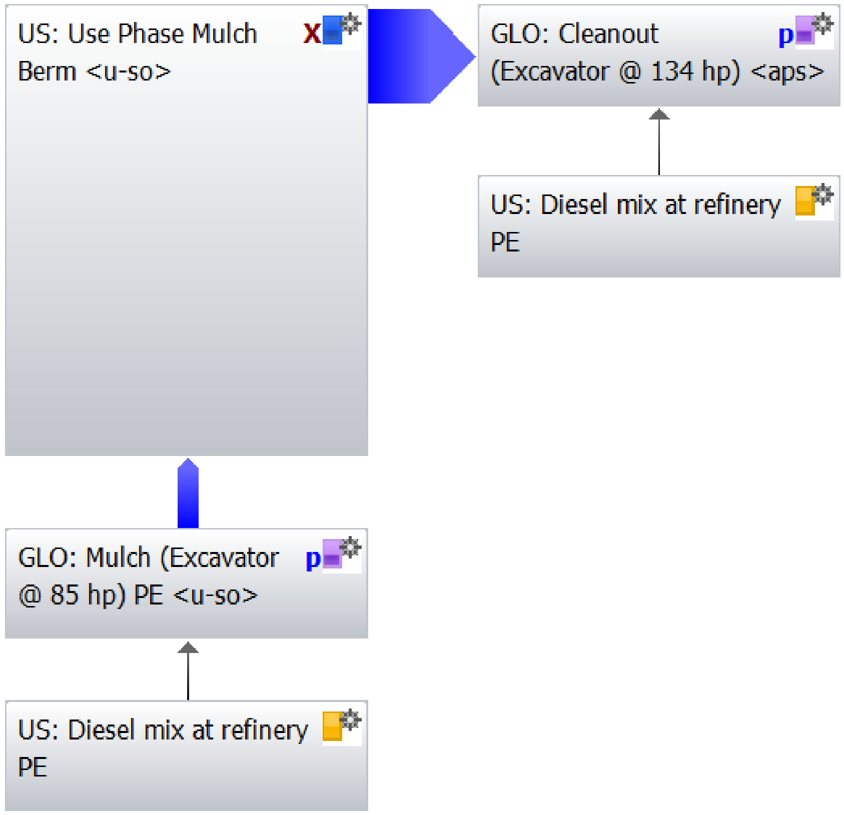

Figure 32: Process plan for mulch berm

3.4.6 Impact analysis

LCA impact analysis was performed using GaBi 6.0 inventory balance functions and grouping and impact categories developed by the EPA Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI). TRACI is previously discussed in Chapter 2. All inventory balances and impact sorting was performed using GaBi 6.0.

RESULTS AND ANALYSIS

4.1 SCD field performance

Seven (7) total large-scale SCD installations were tested using the ASTM D7351 test method during this study. The tests are briefly described in Table 15. The initial test of Type C silt fence (test #2) resulted in a significant undercutting failure at the west installation barrier connection. The fence installation was repaired and retested (test #2b). Testing of 12" compost sock (test #3) resulted in significant undercutting along approximately ½ of the length of the sock installation. Compost sock was retested using a larger, 18" diameter sock (test #6).

Table 15: Summary of ASTM D7351 testing.

Test Number (test date)	Material Tested	Comments
1 (8/6/12)	Silt fence (Type A)	Successful test
2 (9/12/12)	High-flow silt fence (Type C)	SCD failed at 18 minutes from severe undercutting (blow-out)
2b (9/14/12)	Low-flow silt fence (Type C)	Successful retest of low-flow fence
3 (9/21/12)	12" Compost sock	Poor performance, significant under-cutting of SCD installation
4 (9/24/12)	Straw bales	Significant flow between bales
5 (9/26/12)	Mulch berm	Successful test
6 (2/23/13)	18" Compost sock	Successful test with some overtopping

Type A silt fence during and after testing is shown in Figure 33, respectively. Figure 33 shows the significant amount of sediment that settles before reaching the fence installation. At termination, flow through the fence had decreased significantly. Connection of the geotextile fabric to the test barrier wall is by wrapping the fabric upstream and pinching between abutment post and wall with added sealant at post-to-fabric and fabric-to-wall interfaces.

Figure 33: Type A silt fence during (left) and after (right) test.

Low-flow silt fence testing during and the accumulated sediment behind the fence after testing is shown in Figure 34. Figure 34 shows the retest of the Type C fence.

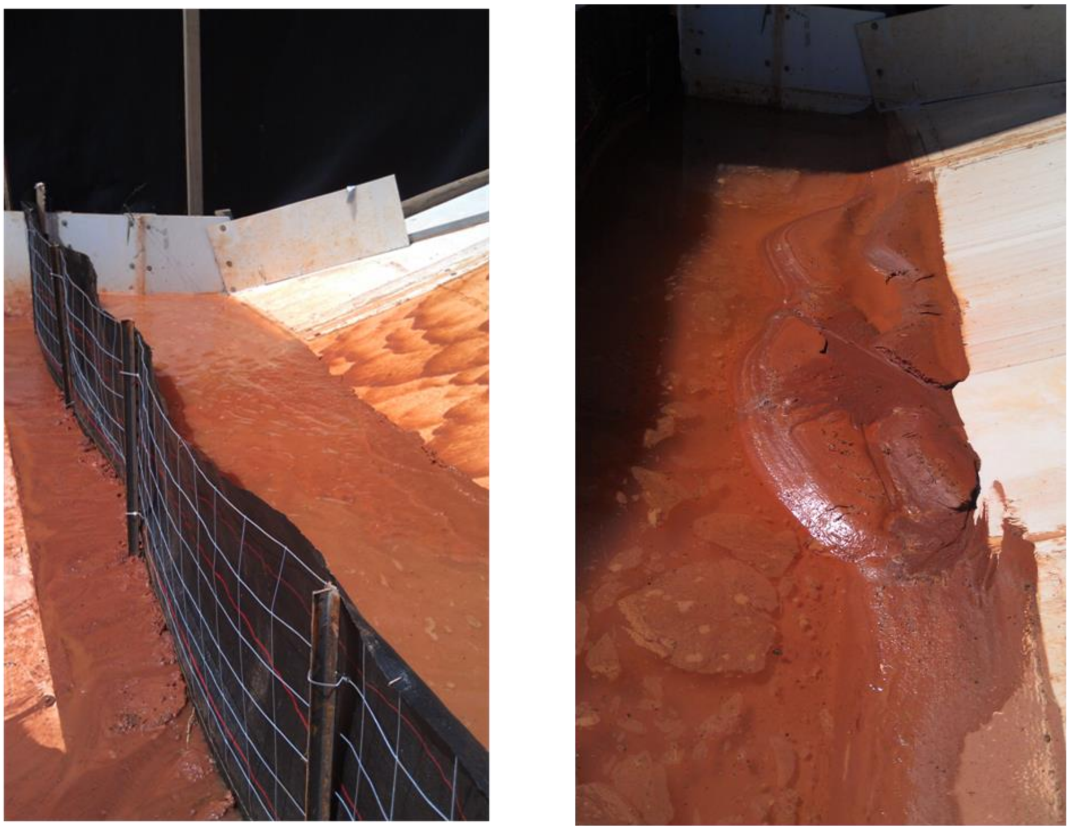

Figure 34: Type C silt fence during (left) and after (right) test.

Twelve (12)-inch compost sock is shown during and after testing in Figure 35. Streaking behind the sock installation is where significant undercutting occurred during testing. No connection was possible between the compost sock and the barrier walls. Flow around the sock at the installation ends was reduced by installing wing-walls with granular bentonite backfill between the sock and wing-wall.

 

Figure 35: 12-inch compost sock during (left) and after (right) test.

The installed line of straw bales is shown before and after testing in Figure 36. Soil present on the upstream and downstream ramps was removed prior to the start of the test. Flow around the bales was limited using wing-wall and granular bentonite barriers.

Figure 36: Straw bales before (left) and after (right) test.

The mulch berm is shown during and after testing in Figure 37. The mulch berm was supported using plywood and small wooden posts. Flow around the berm was limited using wing-walls backfilled with compacted mulch.

Figure 37: Mulch berm before (left) and after (right) test.

The 18-inch compost sock is shown during and after 7351 testing in Figure 38. Flow around the sock was limited using wing-walls backfilled with compacted compost taken from extra sock material. Overtopping of the compost sock occurred at 15 minutes after the start of the test.

Figure 38: 18-inch compost sock before (left) and after (right) test.

4.1.1 Soil and water retention

Weights of the upstream mix tank and downstream collection tanks were recorded at intervals during the ASTM D 7351 testing. The weight of the soil and water mixture retained at the SCD installation is given as the total test weight less the weight of both tanks expressed as:

$$W_{SCD} = 5300lbs - W_{up} - W_{down}$$

Where W_{SCD} is the weight retained at the SCD, W_{up} and W_{down} are the recorded mix and collection tank weights, respectively, and 5,300 lbs is the total soil-water mixture test weight. Recorded tank weights and SCD retention for the seven tests conducted are shown in Figure 39 through Figure 45.

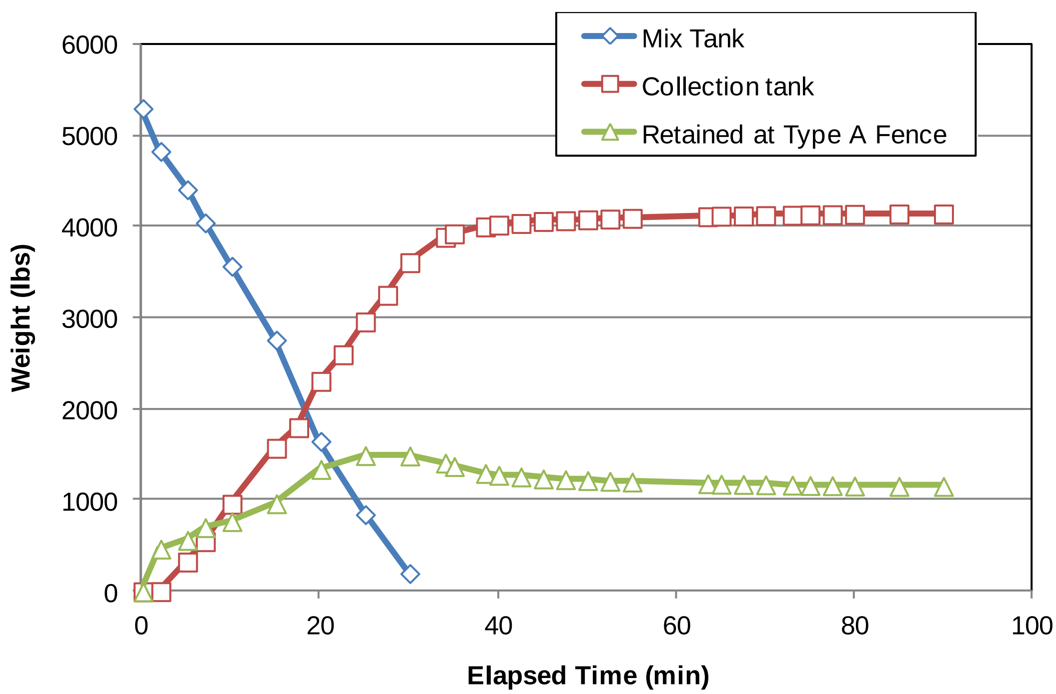

Figure 39: Recorded tank weights and retention of Type A silt fence.

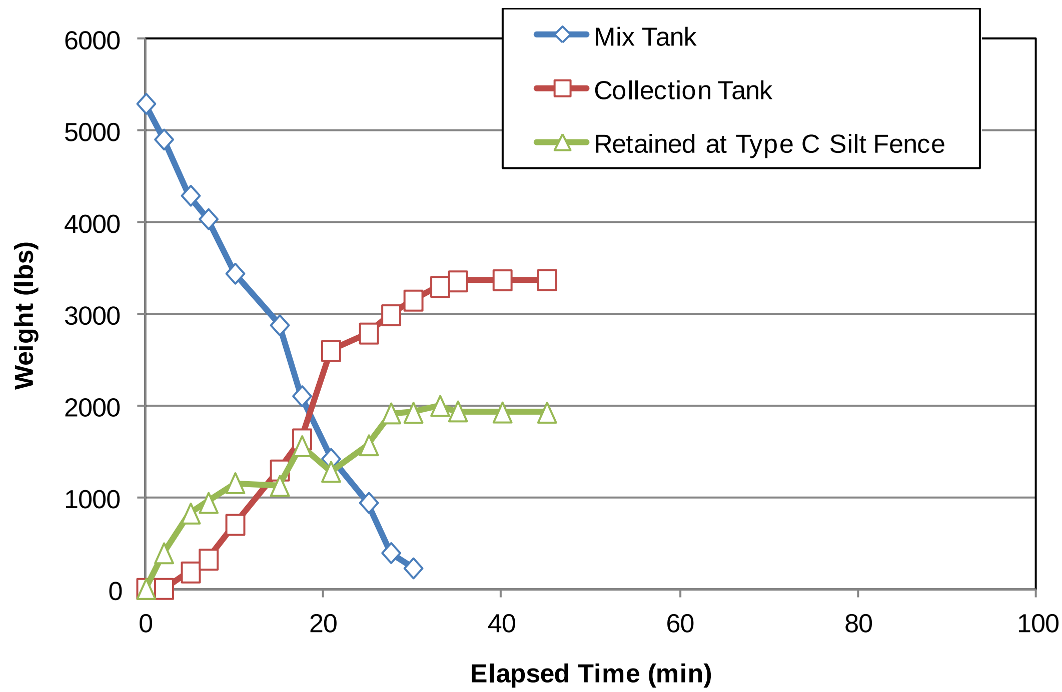

Figure 40: Recorded tank weights and retention of high-flow Type C silt fence with failure from undercutting at 18 minutes.

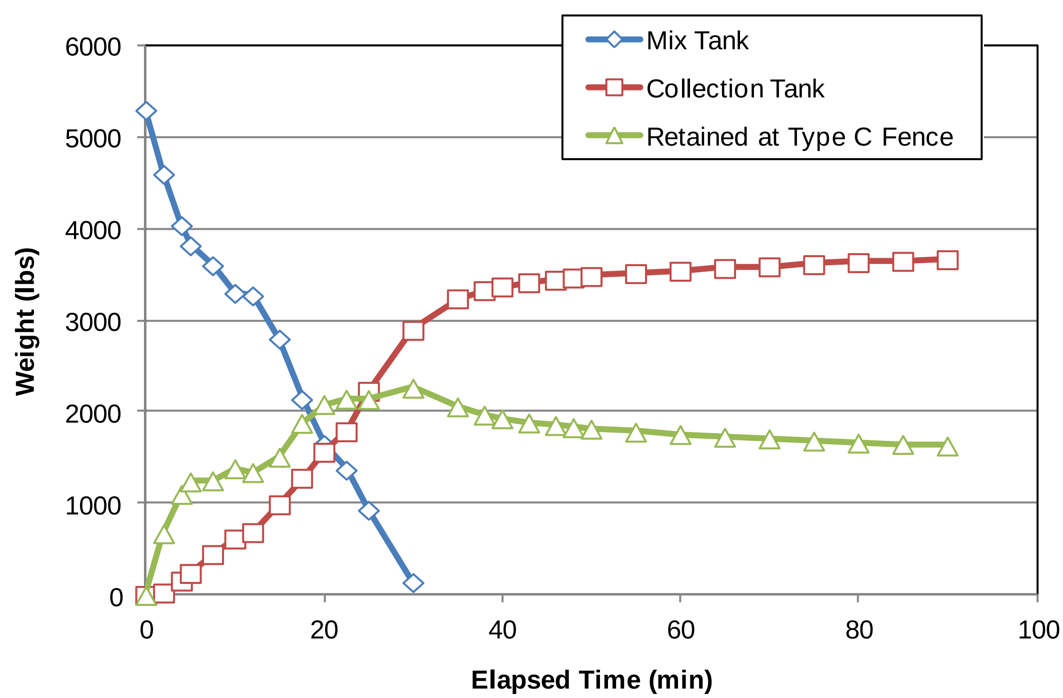

Figure 41: Recorded tank weights and retention of high-flow Type C silt fence.

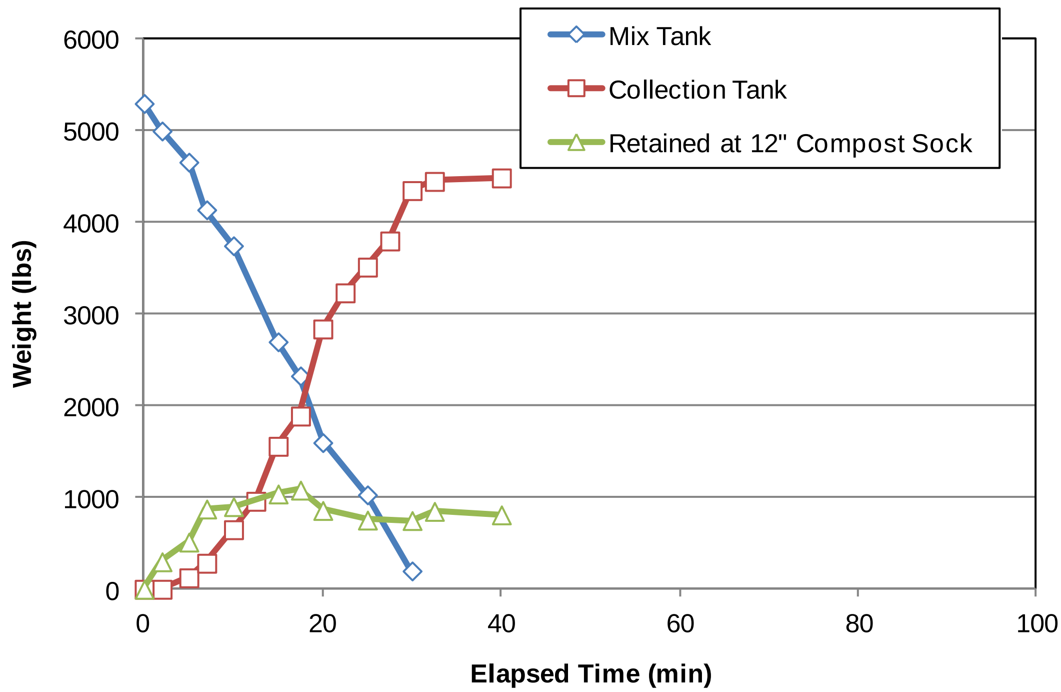

Figure 42: Recorded tank weights and retention of 12-inch compost sock with significant undercutting of beginning at 5 minutes.

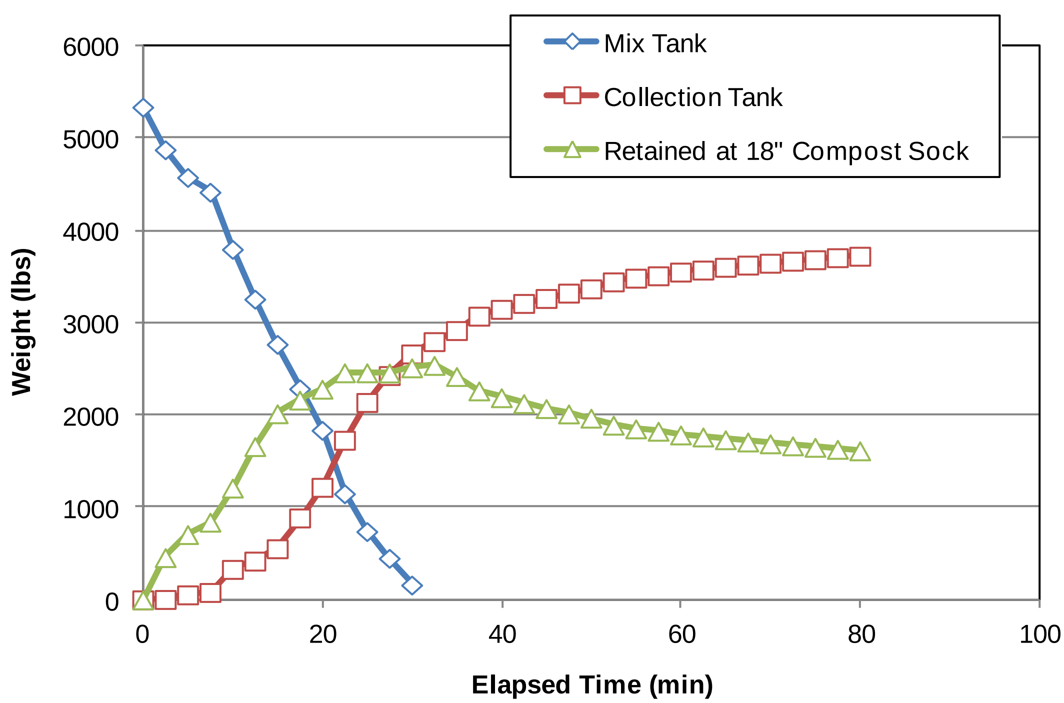

Figure 43: Recorded tank weights and retention of 18-inch compost sock.

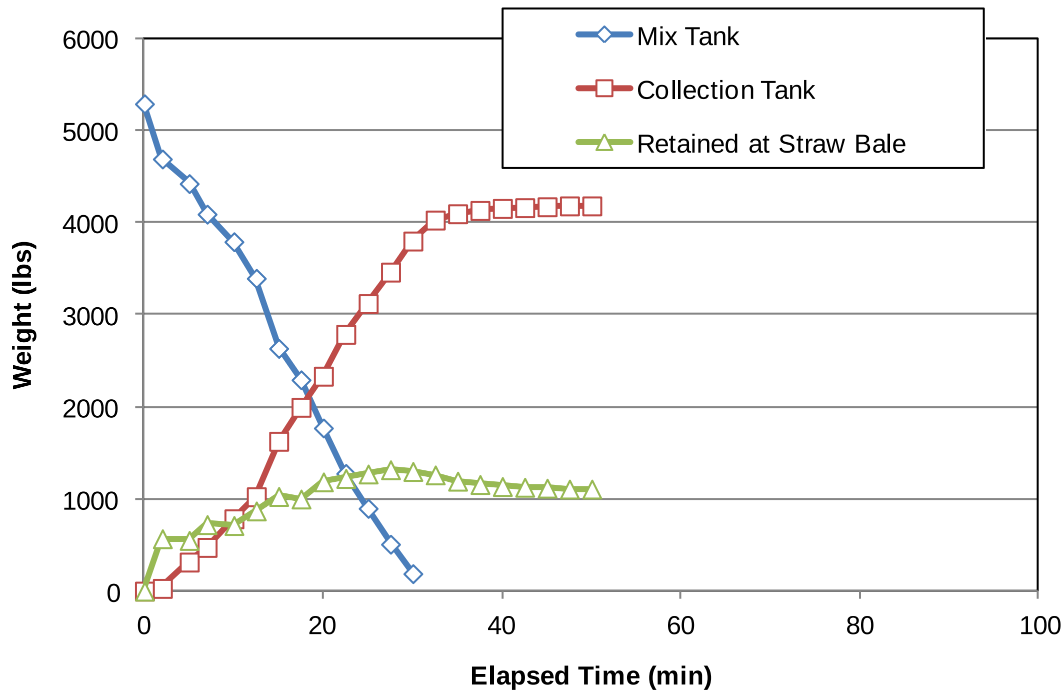

Figure 44: Recorded tank weights and retention of straw bales.

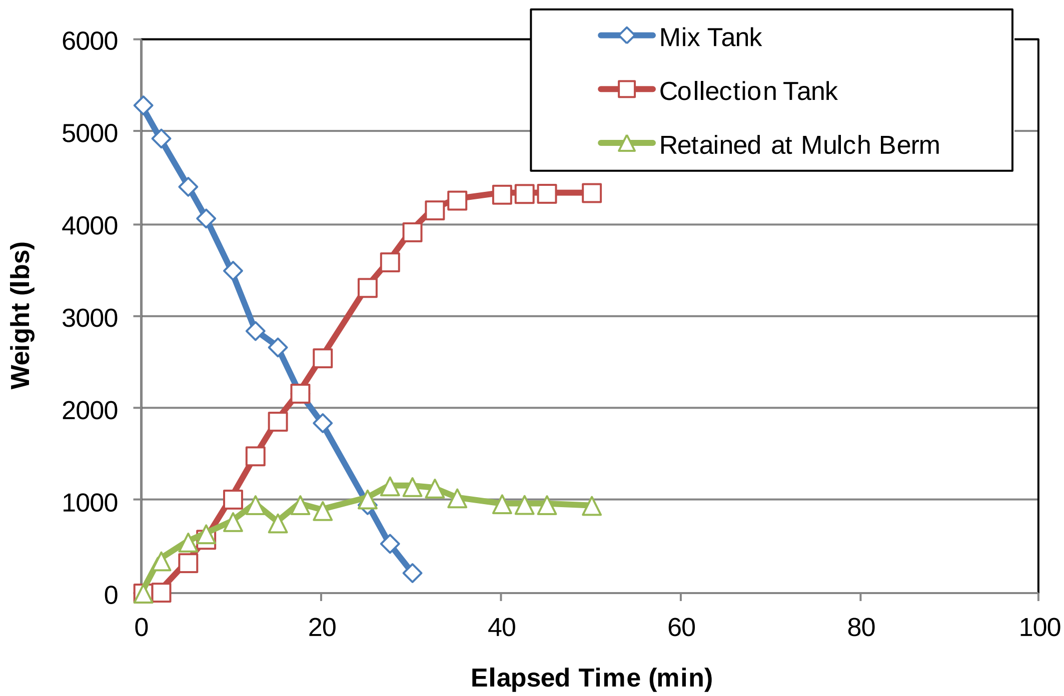

Figure 45: Recorded tank weights and retention of mulch berm.

The flow-through rate or exit flow rate from the SCD installations is approximated as the change of collection tank weight over time intervals between record times expressed as:

$$\frac{\Delta W}{\Delta t} = \frac{W_2 - W_1}{t_2 - t_1}$$

Where $\Delta W/\Delta t$ is the rate of weight increase in the collection tank and W_2 and W_1 are tank weights recorded at times t_1 and t_2, respectively. Maximum exit rates for each test are shown in Figure 46. The highest rates were calculated for the initial test of Type C silt fence and the 12-inch compost sock, both tests failed by undercutting. Successful tests of both silt fence, much berm and 18-inch compost sock experienced maximum exit rates between 177 and 204 lb/min.

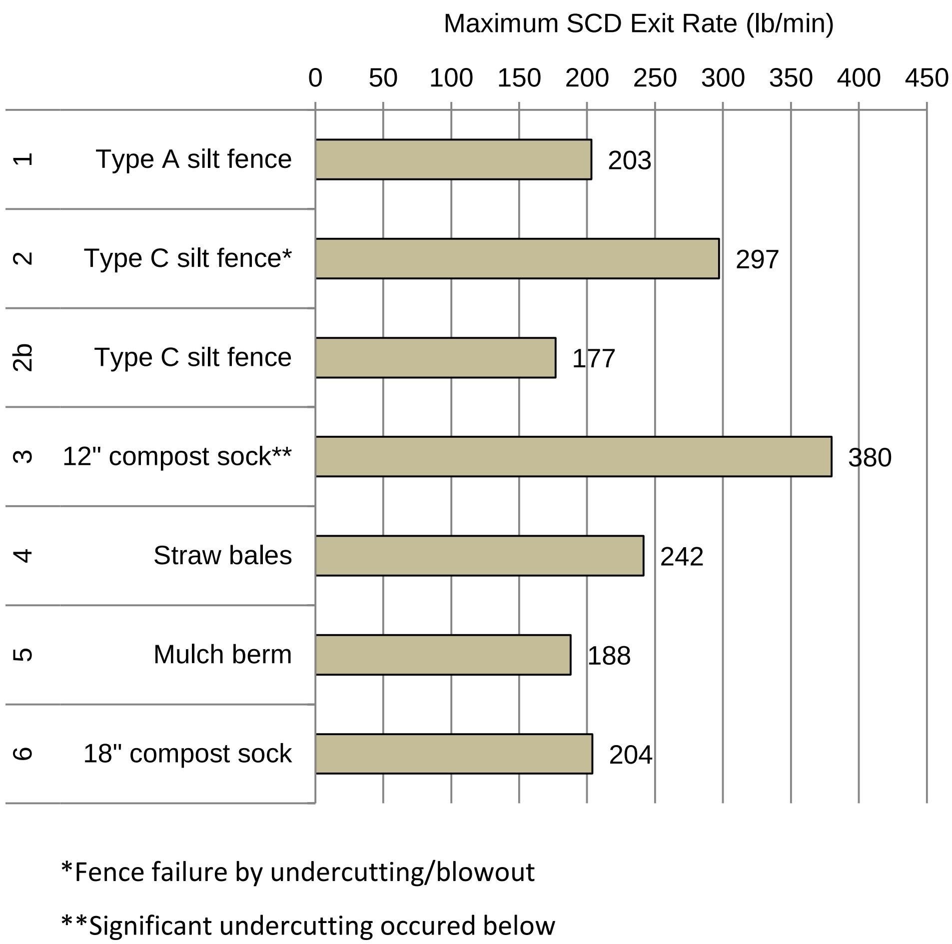

Figure 46: Maximum exit rates for each SCD tested.

4.1.2 TSS reduction

Results summarized in section 4.1.1 show the ability of the SCD installations to retain the test soil and water mixture and do not indicate the amount of solids captured by the devices. To determine the removal capability of each device to remove suspended solids, TSS concentration of water entering the collection tank was determined. Figure 47 through Figure 53 show the TSS results for five minute samples collected during each test. Two TSS tests were performed for each sample. The following bullets discuss some of the trends and irregularities visible in/between the figures.

1. TSS values generally increase during the 30 minute discharge period as soil-laden test water accumulates behind the installations.
2. TSS values decrease substantially after the initial discharge period.
3. Silt fence installations (Figure 47, Figure 48, and Figure 49) show a slight decrease in TSS values during the discharge period. The decrease is due to formation of a filter cake of soil particles at the upstream face of silt fence.
4. The TSS peak at 20 minutes for the 18” compost sock (Figure 51) corresponds to overtopping of the installation.
5. Decreasing TSS in the after 20 minutes for the 18” compost sock (Figure 51) and for the mulch berm (Figure 53) is due to ripening of the filter material.
6. Increased TSS at 15 minutes for the 12” compost sock (Figure 50) and straw bale (Figure 52) correspond to undercutting of the sock and penetration at the bale interfaces.

The following figures show the results for two iterations of TSS filter tests performed with the same samples. The high repeatability of separate TSS tests is not to be confused with iterations of field testing procedures, which would produce charts with higher variability.

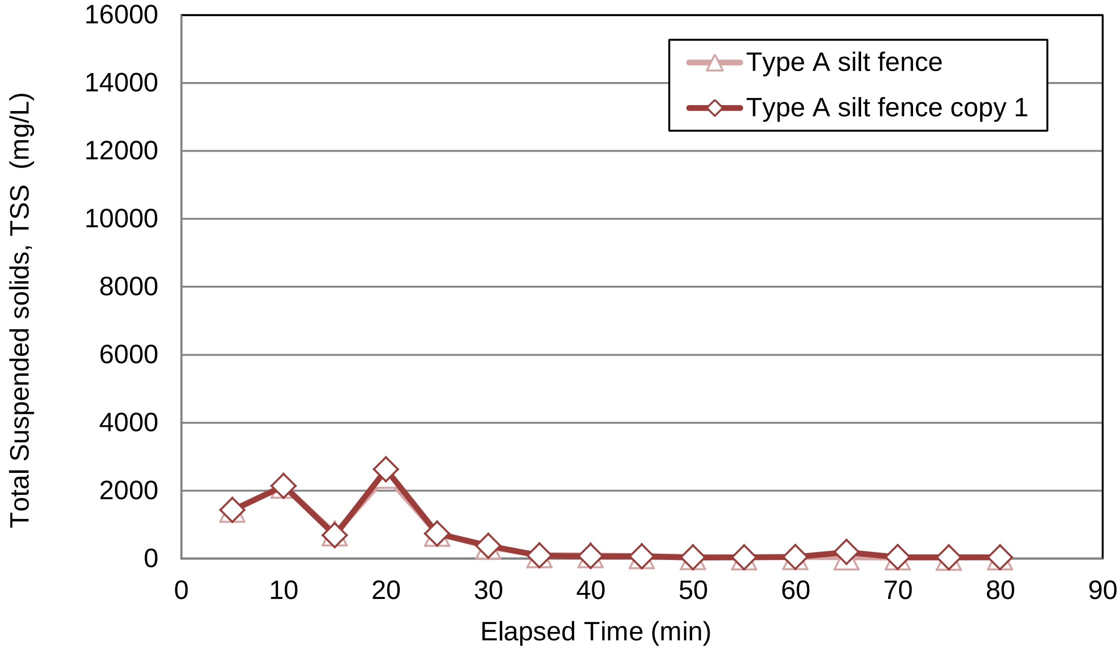

Figure 47: Measured TSS downstream of Type A silt fence, 5-minute samples.

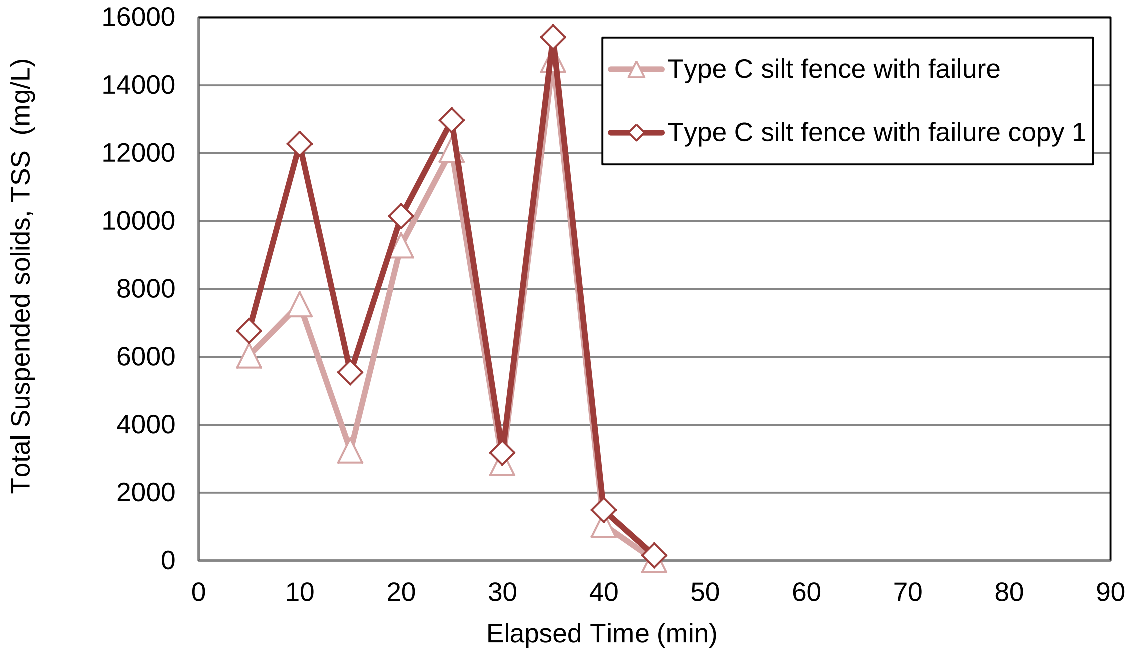

Figure 48: Measured TSS downstream of Type C silt fence, 5-minute samples. Fence failed 18 minutes into test.

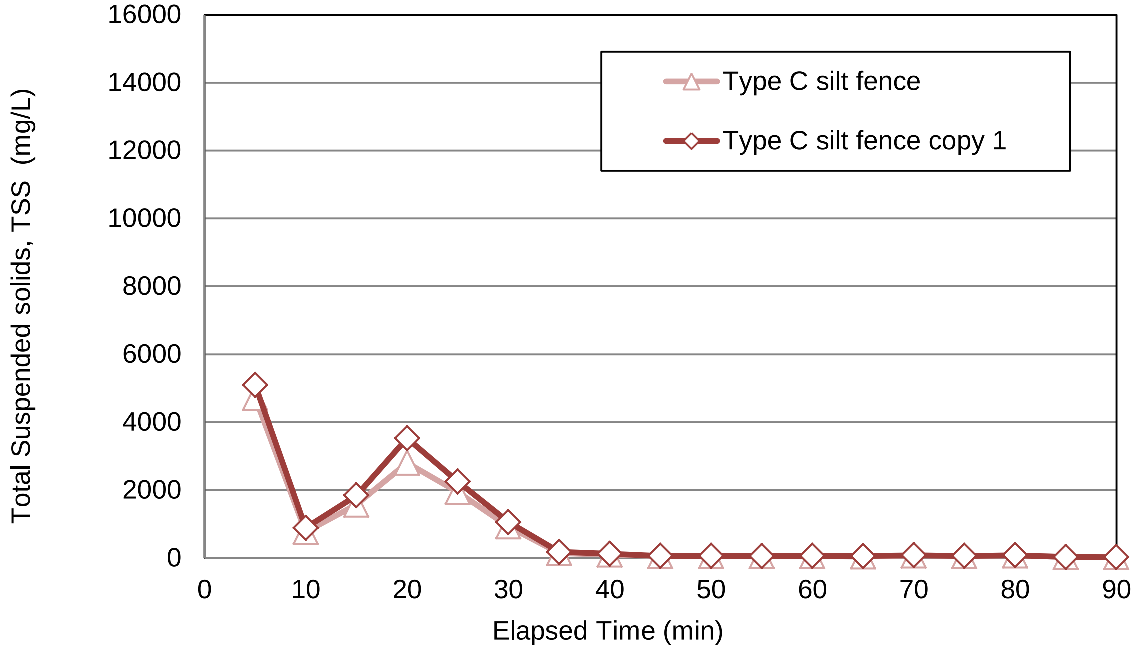

Figure 49: Measured TSS downstream of Type C silt fence retest, 5-minute samples.

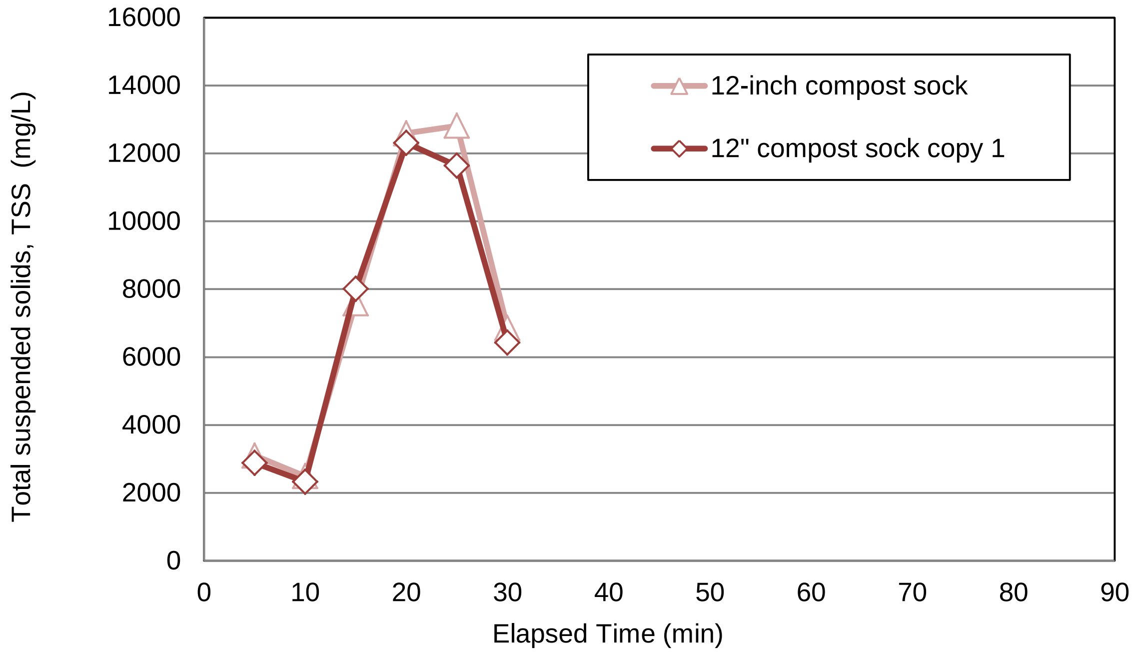

Figure 50: Measured TSS downstream of 12-inch compost sock, 5-minute samples.

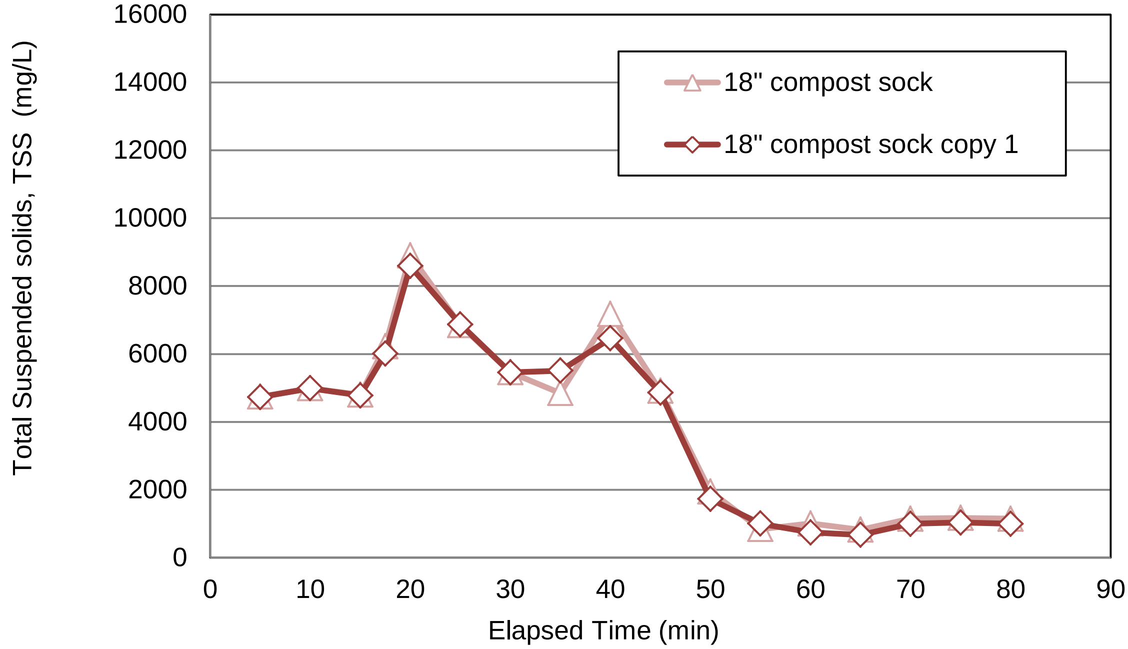

Figure 51: Measured TSS downstream of 18-inch compost sock, 5-minute samples.

Figure 52: Measured TSS downstream of straw bales, 5-minute samples.

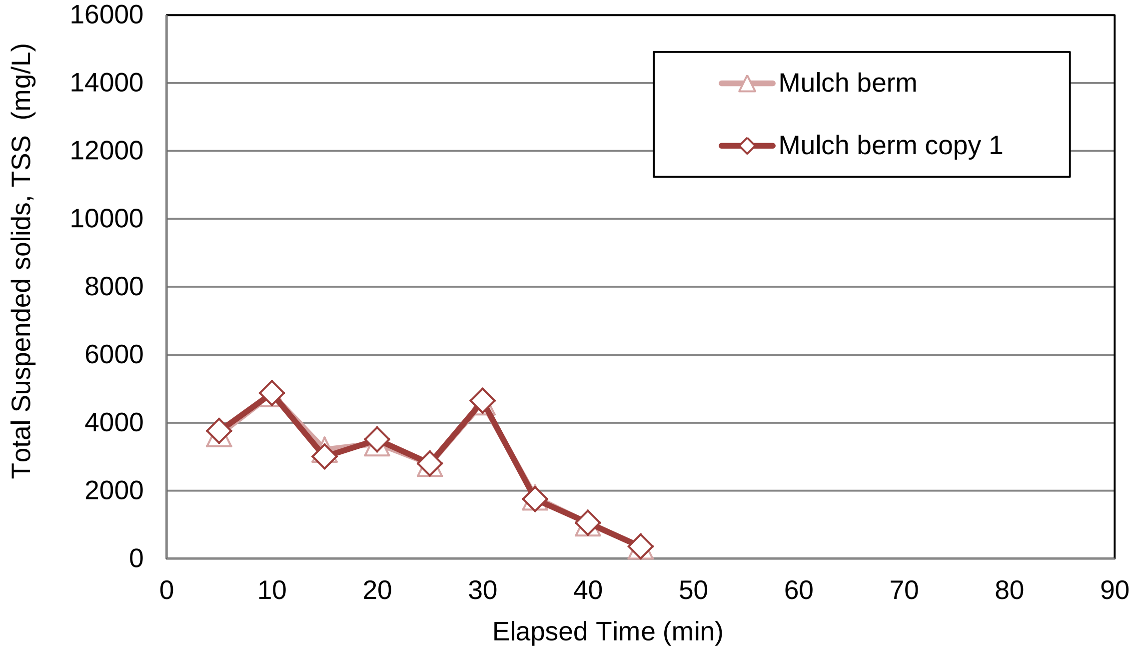

Figure 53: Measured TSS downstream of mulch berm, 5-minute samples.

The minimum, maximum and average value of the averaged TSS test pairs are shown in Table 16. The Type A silt fence installation showed the lowest maximum TSS value. Measured TSS values for each sample collected are included in Appendix B.

Table 16: Range and average TSS for each test.

Test	**Device**	**Measured TSS (mg/L)**		
		Minimum	**Maximum**	**Average**
1	Type A	33	2531	532
2	Type C	80	15078	6261
2b	Type C	25	4911	807
3	12” Sock	2411	12447	7418
4	Straw Bales	316	8675	4195
5	Mulch Berm	354	4857	2856
6	18” Sock	750	8749	4324

4.1.3 SCD removal efficiency

The amount of solids passing each SCD device is a function of the flow rate through the SCD device and the downstream solids concentration. The amount of solids passing the SCD between times t_1 and t_2 is approximated as the volume passing the SCD over the time range multiplied by the average TSS concentration for the same time range and is expressed as:

$$W_s = \Delta V \cdot C = \frac{W_2 - W_1}{\gamma_w} \cdot \frac{C_2 - C_1}{2}$$

Where W_s is the weight of solids passing the SCD, ΔV is volume passing the SCD approximated as the increase of tank weight ($W_2 - W_1$) divided by the unit weight of water (γ_w). W_2 and W_1 are the collection tank weights and C_2 and C_1 are the measured TSS concentrations at times t_1 and t_2, respectively. The assumption that the passing volume is equal to the change in weight over the unit weight of water is validated by showing the negligible increase in unit weight by the maximum measured TSS concentration (15,078 mg/L):

$$\gamma^* = \gamma_w \cdot (1 - V_s) + \gamma_s \cdot V_s$$

$$V_s = \frac{W_s}{\gamma_s} = \frac{C_s \cdot unit\ volume}{SG \cdot \gamma_w}$$

$$\gamma^* = 1\frac{kg}{L} \cdot \left(1 - \frac{15{,}078\frac{mg}{L} \cdot 1L \cdot \frac{1kg}{10^6 mg}}{2.65 \cdot 1\frac{kg}{L}} \right) + 2.65 \cdot 1\frac{kg}{L} \cdot \left(\frac{15{,}078\frac{mg}{L} \cdot 1L \cdot \frac{1kg}{10^6 mg}}{2.65 \cdot 1\frac{kg}{L}} \right)$$

$$\gamma^* = 1.0094\frac{kg}{L} \cong 1\frac{kg}{L}$$

Where γ^* is the corrected unit weight, γ_w and γ_s are the unit weights of water and solid (assumed as $2.65\gamma_w$), V_s and W_s are the solid volume and weight, respectively, and C_s is the maximum measured TSS concentration for downstream samples. Figure 54 shows cumulative solids passing each SCD tested. Incremental TSS passing each SCD is minimal at the end of the test duration except for the failed 12-inch compost sock installation. Additional testing time for the 12-inch sock would yield a significantly higher cumulative downstream TSS value.

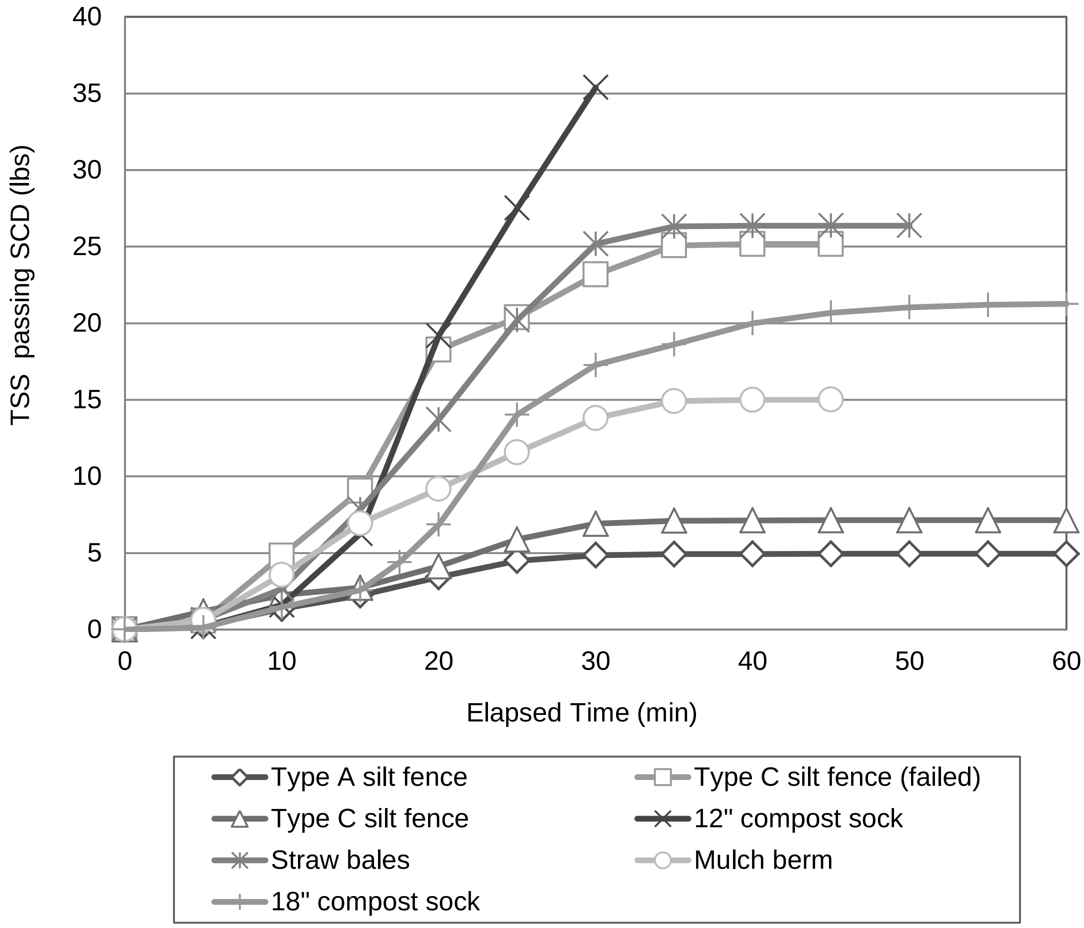

Figure 54: Cumulative solids passing SCDs.

Sediment removal efficiency of each SCD can be approximated as the ratio of solids retained to total solids tested. Removal efficiency for this test is expressed as:

$$EF_s(\%) = 100 - 100 \cdot \frac{W_p}{W_s}$$

Where EF_s is the solids removal efficiency, W_p is the cumulative weight of soil passing the SCD and W_s is the total weight of solids tested, 136.1 kg (300 lbs). Calculated removal efficiencies for each SCD tested are shown in Figure 55.   Additional test time for the 12-inch sock would have resulted in higher downstream TSS; therefore, the removal efficiency shown is not accurate.

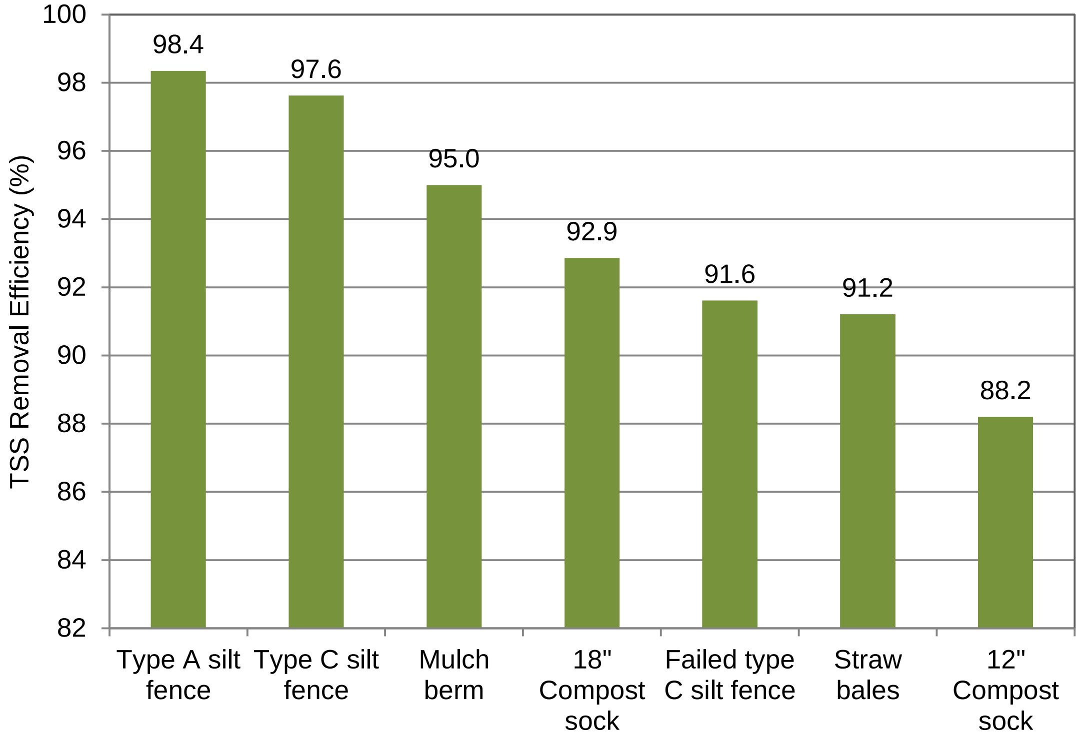

Figure 55: Removal efficiency including solids removed by sedimentation.

4.1.4 Turbidity reduction

Measured turbidity of samples made downstream of the Type A and C silt fence installations is shown in Figure 56. Turbidity of samples taken downstream of the 12 and 18-inch compost sock installations is shown in Figure 57. Turbidity of samples taken downstream of the straw bale and mulch berm installations is shown in Figure 58. Each test shows a decrease in turbidity after the initial 30 minute release period. The failed Type C silt fence installation resulted in the highest downstream turbidity measurements.

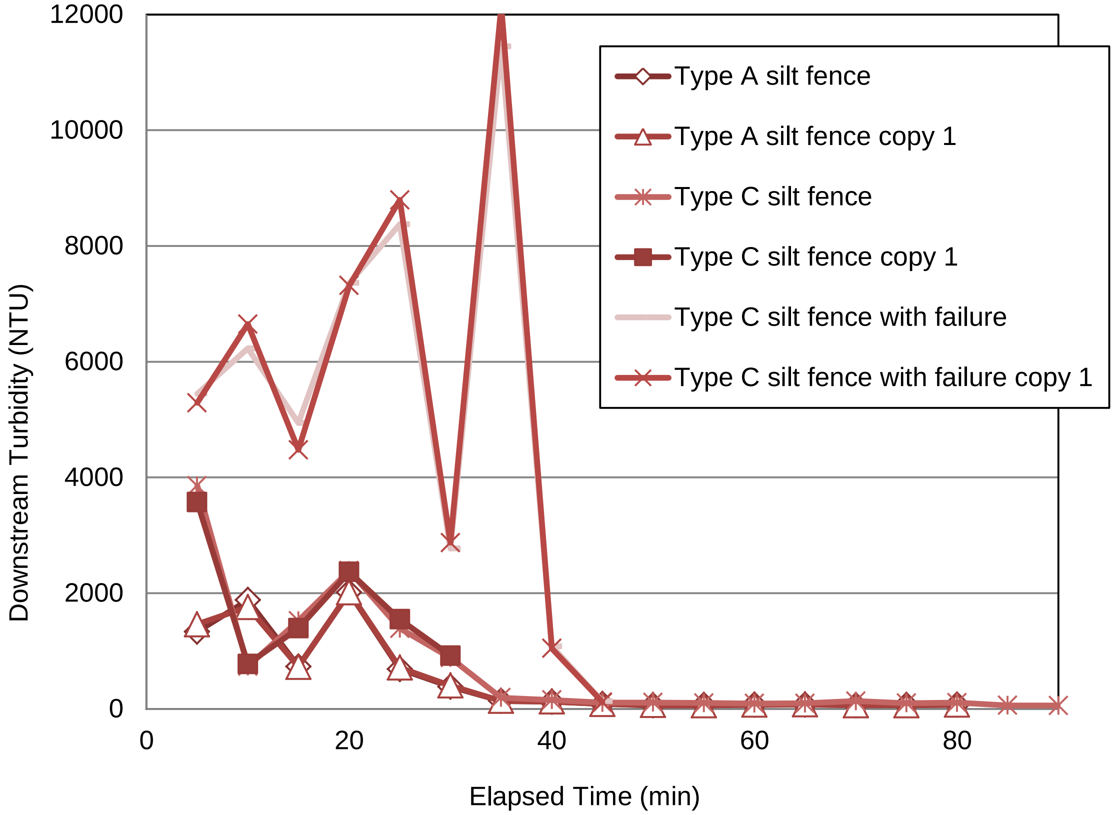

Figure 56: Measured turbidity downstream of Type A and Type C silt fence installations.

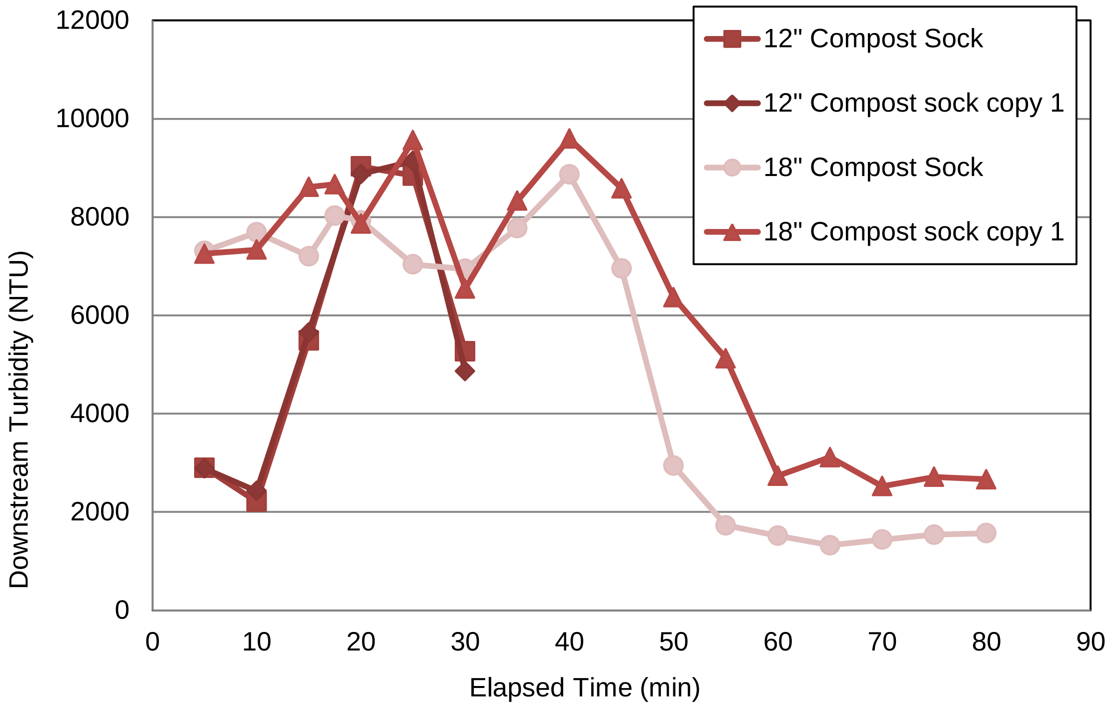

Figure 57: Measured turbidity downstream of 12 and 18 inch compost socks.

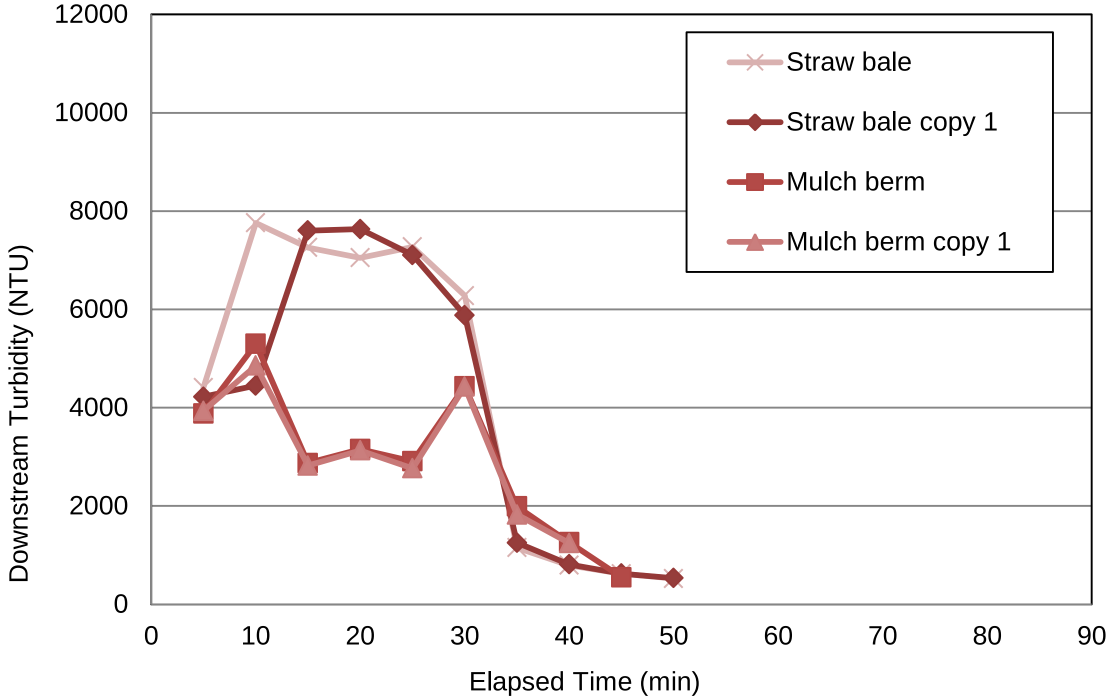

Figure 58: Measured turbidity downstream of mulch berm and straw bales.

Figure 59 shows turbidity measurements of upstream samples collected at the distributor output from the mixing tank. Turbidity of upstream samples generally ranges between 7,500 to 12,500 NTU except for samples taken during the 18” compost sock test. High turbidity of the 18” compost sock test may be a result of greater fines content of the new stockpile soil. Average upstream turbidity was calculated for each test and is shown in Table 17. Measured turbidity values for each sample collected are included in Appendix C.

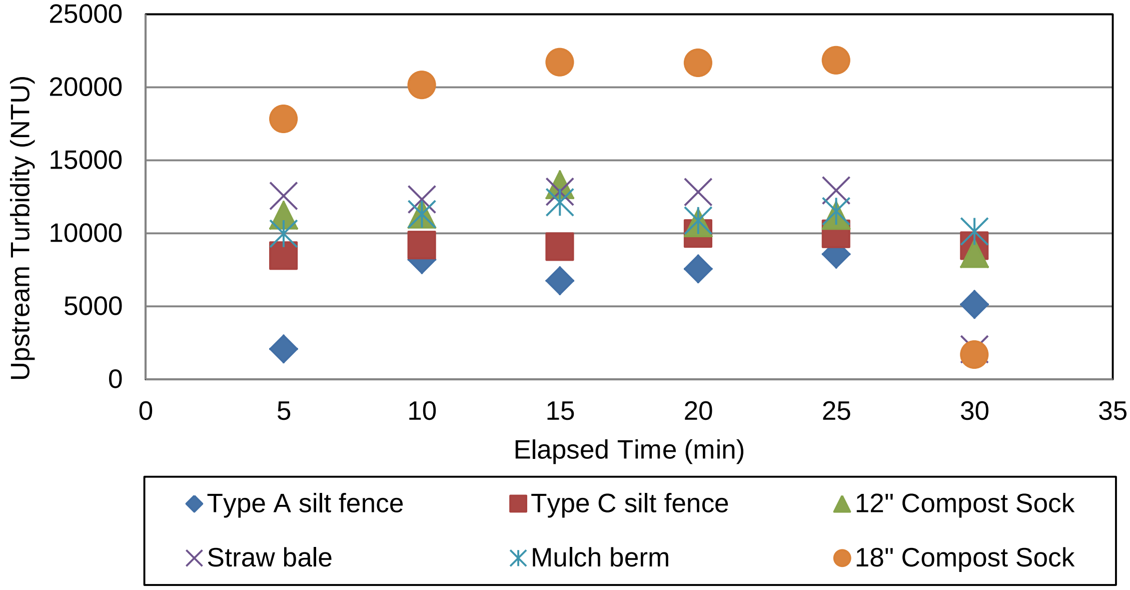

Figure 59: Measure turbidity of upstream samples.

Table 17: Average upstream turbidity measurements.

Test Number	Material	Average Upstream Turbidity (NTU)
1	High-flow silt fence	6,386
2	Low-flow silt fence with failure	Not tested
2b	Low-flow silt fence	9,298
3	12" compost sock	11,077
4	Straw bales	10,932
5	Mulch berm	10,990
6	18" compost sock	17,482

Turbidity reduction as a percentage of upstream average turbidity is show in Figure 60. The figure shows three reductions, the average reduction for all test samples, the average reduction during the initial 30 minute release period and the reduction for the remaining time after the initial release period.

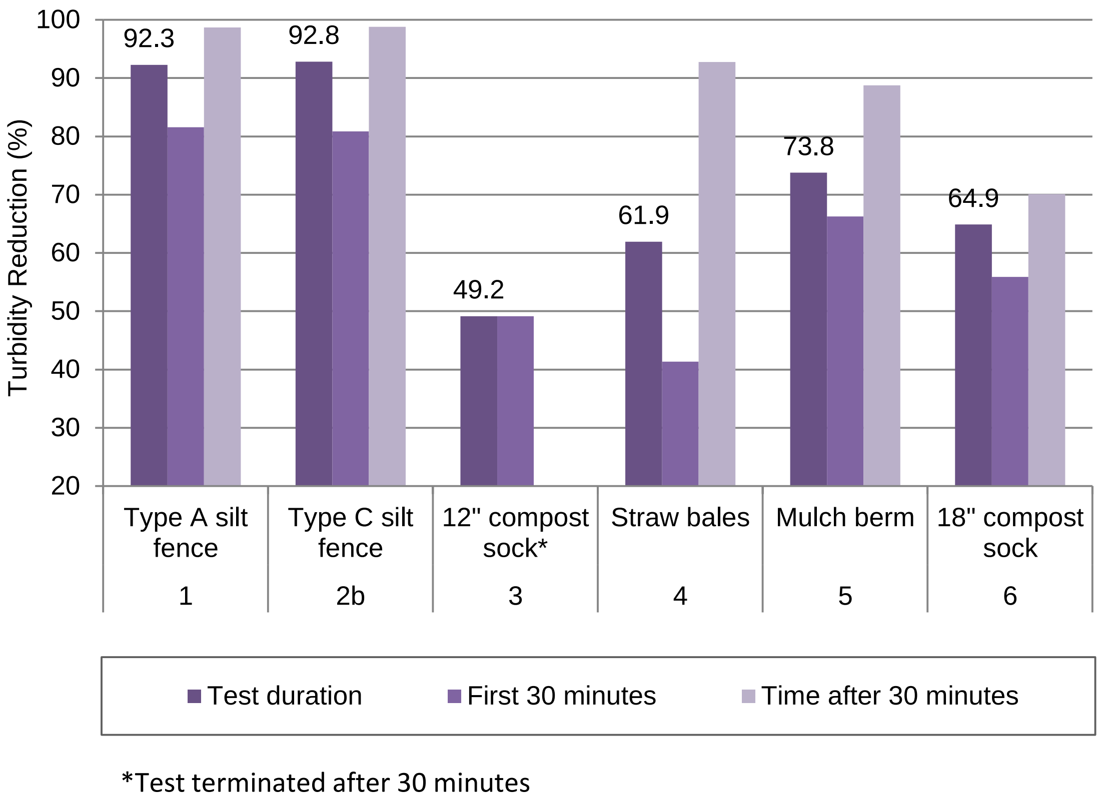

Figure 60: Average turbidity reduction for entire test, first 30 minutes and time after first 30 minutes.

A good agreement between measured turbidity and total suspended solids (TSS) was apparent for tests of silt fence, mulch berm and 18" compost sock and is shown in Figure 61. Measurements taken from samples downstream of the failed Type C silt fence show much higher TSS and turbidity readings than samples downstream of the 18" compost sock, mulch berm, and Type A silt fence. TSS versus turbidity for tests of straw bale and 12" compost sock are shown in Figure 62 with the trend from Figure 61. Samples from the 12" sock with low turbidity and high TSS values were taken between 15 and 30 minutes, after failure of the sock by undercutting. The failure resulted in coarse material passing the installation; coarse material increases TSS but has little affect on turbidity measurements. Four samples downstream of the straw bale installation showed large turbidity values with small TSS. These samples were taken between 35 and 50 minutes. Only a small amount of water passed the straw bale installation after the initial 30 minute discharge period. These samples consist of heavy slurry of fine particles still in suspension, slowly leaking through the straw bale connections.

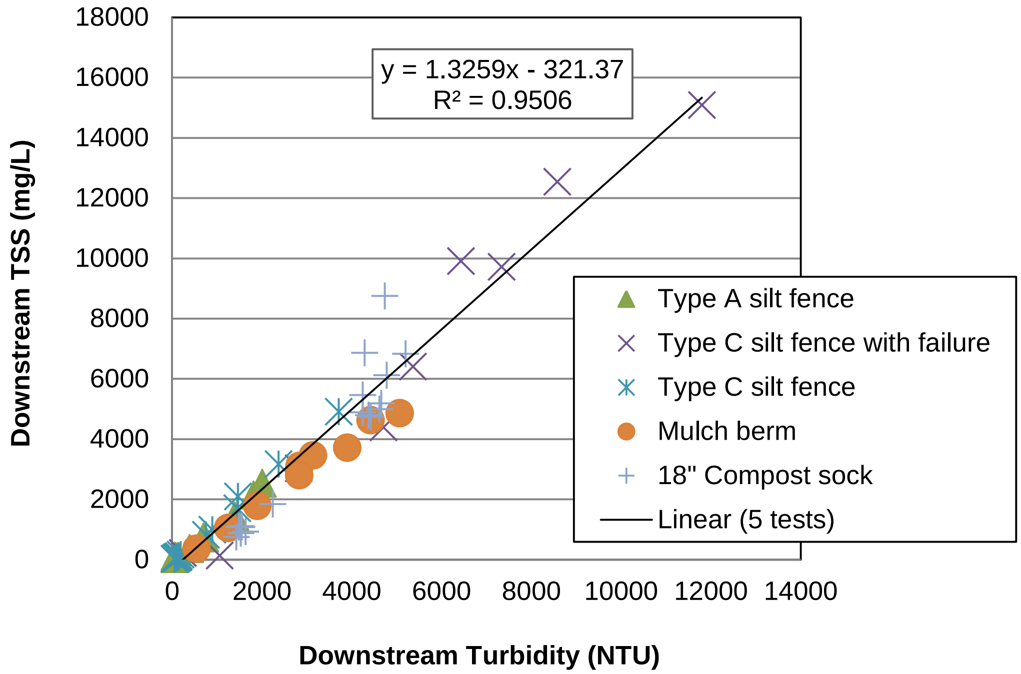

Figure 61: Correlation for turbidity and TSS.

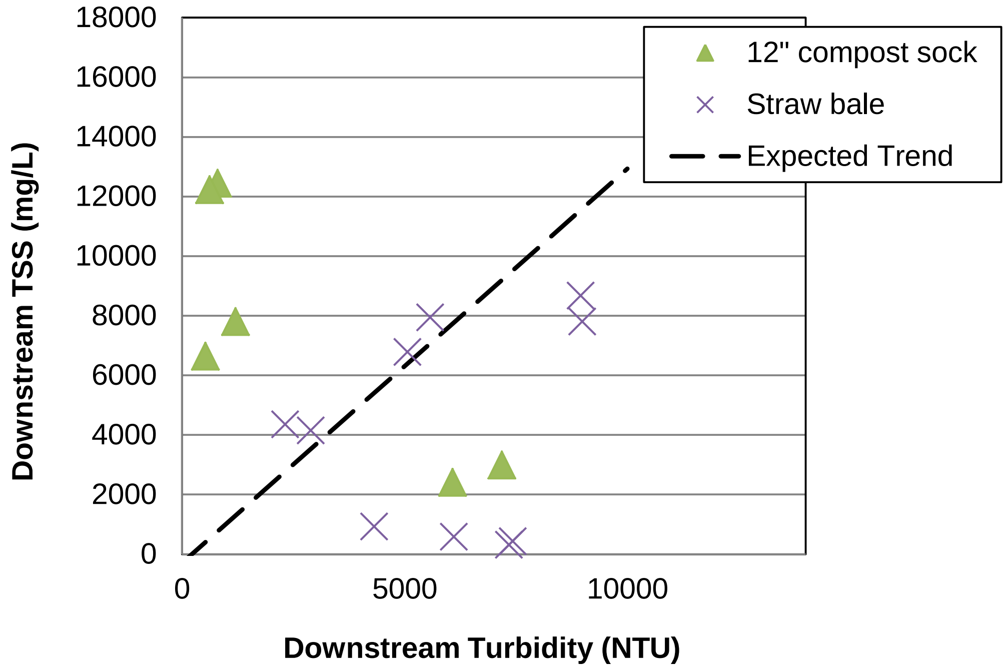

Figure 62: Turbidity vs. TSS for straw bale and 12” compost sock.

4.1.5 Total dissolved solids (TDS) reduction

Calculated TDS values for downstream samples for each SCD tested are shown in Figure 63. TDS values are somewhat erratic; however, an initial decrease in TDS seems to occur for the three-dimensional devices. TDS values for Type A silt fence are fairly uniform over the duration of the test. TDS values for the Type C silt fence generally increase over the duration of the test. No correlation between TDS and TSS or turbidity was apparent.

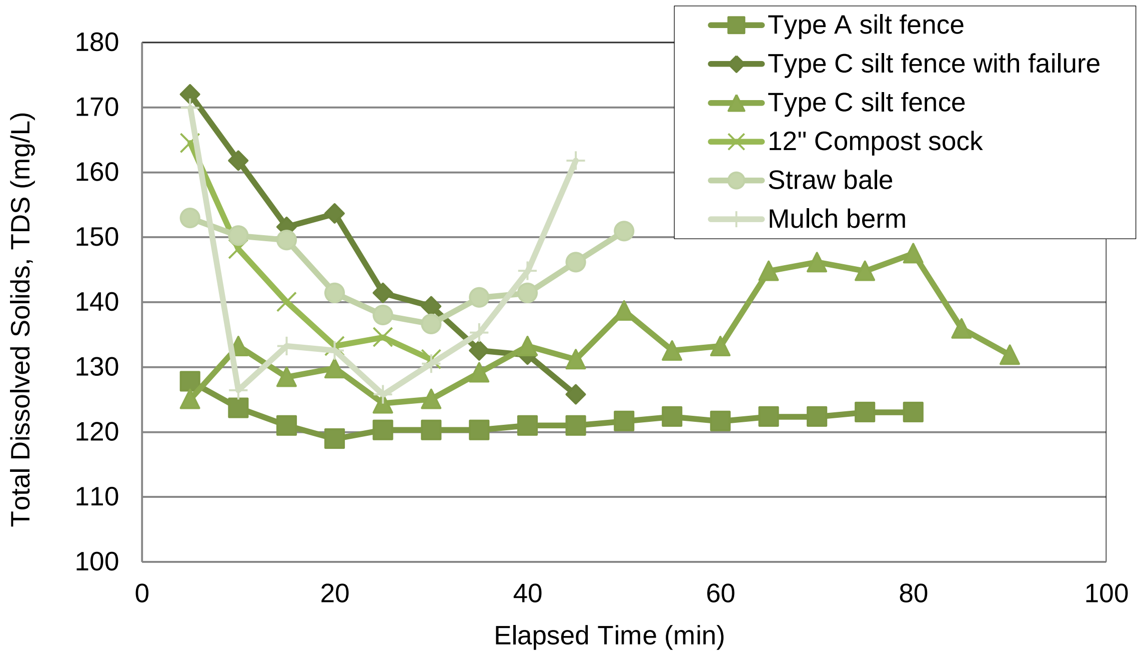

Figure 63: Measured TDS for each SCD tested.

4.1.6 SCD installation

Good performance of sediment control barriers depends on proper installation. Installation procedures of the devices tested were significantly different. The following bullet points are observations of SCD installation made during field testing.

1. Installation of the mulch berm was easy and fast.
2. Mulch was easier to place than compost socks.
3. Compost sock installation was not difficult once the socks were in the soil installation zone; however, moving the socks into the zone was labor intensive, even with help from a forklift and operator.
4. On site filling of compost sock with a compost blower would make installation easier.
5. Straw bale installation was difficult due to the required 4-inch deep trench that had to be excavated.

6. Installation of silt fence required significant trenching. Type C silt fence was slightly more difficult than Type A silt fence due to the metal mesh backing.

No machinery was used during this research; Table 18 lists machinery commonly used for installation of SCDs.

Table 18: Available SCD installation equipment

SCD Material	Available Installation Equipment
Silt fence	Line trencher
Compost sock	Compost blower, fork lift
Straw bales	
Mulch berm	Mulcher, chipper, grading equipment

4.1.7 Discussion

Results from the ASTM 7351 field testing are generally good; however, the test method has multiple shortcomings with regards to this study. The most significant failing is the large soil loading used during testing. The sediment load described in the standard (136 kg soil in 600 gallons water) is approximately 60,000 mg/L. After correcting for soil water content, the actual sediment load tested in this study was approximately 45,000 mg/L. The sediment load is the load from erosion during a 10-year, 6-hour storm event on a 30 meter long slope using the MUSLE. According to the standard, the same size storm is used for sizing detention ponds. The storm choice is adequate for worst-case testing, but is not a good choice for typical conditions over a year. The assumed storm for the LCA study is discussed in detail in section *4.3.4 Discussion*.

Another limitation of the test method is that variable soil gradations will behave differently during the test. Coarse grains will settle faster and fine particles will stay in suspension longer.

Also, fine particles will form a filter cake at the upstream filter. Test method ASTM D7351 includes a gradation for test soil, but there is a large range of acceptable grain sizes. Additionally, the soil selected for the study may not truly represent the soil fraction that would erode during a storm event. Sloping soil bed tests with simulated rainfall performed by Faucette et al. (2009) includes only the eroded fraction of soil and compares results to control plots with no SCDs. These tests require multiple iterations to demonstrate consistent performance of erosion occurring in control plots.

Additional weaknesses of the test method are that edge effects are difficult to overcome using the method as specified and SCD installation will vary between studies. A curved installation zone similar to McFalls et al. (2009) will eliminate edge effects. Adequate installation is difficult to control.

TSS removal efficiency for silt fence measured during this study generally agrees with values determined by Beighley and Valdes (2009) and slightly higher than Barrett et al. (1998). Removal efficiency for compost socks is slightly higher than measured by Faucette et al. (2009). Removal efficiency for straw bales and mulch berm is significantly higher than Faucette et al. (2009). An improvement to the solids retention testing in this study is to perform duplicate field tests for a variety of water and soil loadings (as calculated for different storm events). Test iterations on this scale will take a significant amount of effort.

This study shows that silt fence performed the best with respect to reducing downstream turbidity and TDS. Although the performance of SCDs with regards to turbidity and TDS were measured, no good method to include the results in the LCA was determined.

4.2 SCD laboratory performance

Filter testing of compost, mulch and straw material was performed by passing multiple 1 liter (L) increments of deionized water (DI) or prepared nutrient and metal solutions through the laboratory filter containers. The schedule of filter testing is indicated in Table 19.

Table 19: Schedule of laboratory testing

Test Increment	Description
1	1 L DI – Initial rinse, sample collected
2	1 L DI
3	1 L DI
4	1 L DI
5	1 L DI – Sample collected
6	1 L DI
7	1 L DI
8	1 L DI
9	1 L DI – Sample collected
10	1 L 0.5 ppm NO_2, NO_3, NH_3, PO_4 - Sample collected
11	1 L DI – Sample collected
12	1 L 0.5 ppm Pb, Zn, Cu – Sample collected
13	1 L DI – Sample collected

Nutrient levels of each sample were tested with an initial aliquot sized as needed to decrease turbidity and lower suspected high nutrient concentrations to within testing limits. One repetition was performed for each test. Variance between initial and replicate tests for concentrations up to 2 mg/L is shown in Figure 64. Tests for nitrite and orthophosphate showed good agreement between approximately 0.25 mg/L to 2 mg/L. Nitrite results are more variable at lower concentrations, shown in Figure 65. Potentiometric ammonia measurement shows high variability at all concentrations.

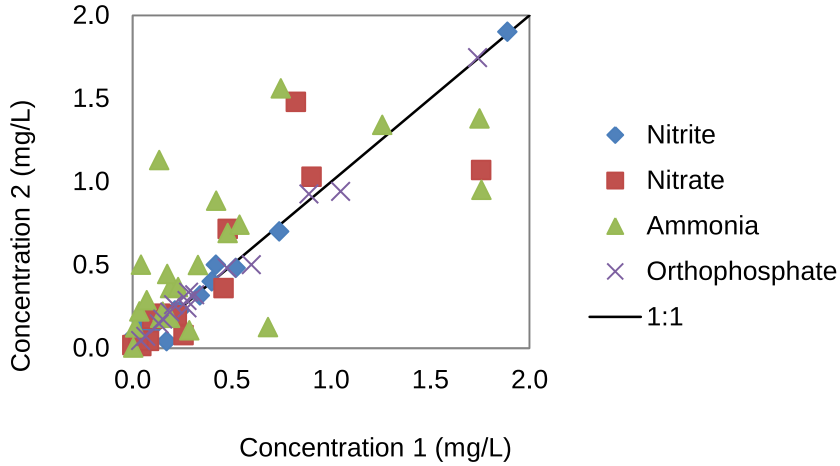

Figure 64: Initial and replicate nutrient results, 0 – 2 mg/L

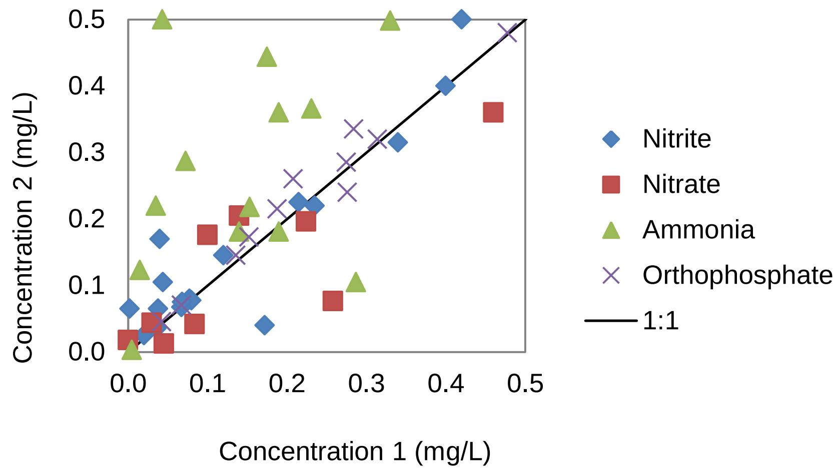

Figure 65: Initial and replicate nutrient results, 0 – 0.5 mg/L

Initial nutrient concentrations measured in the first portion of water passing the filters are shown in Figure 66. Leachate collected from the compost samples generally shows the highest initial nutrient concentrations. The mixed hardwood mulch and straw samples contained very high levels of phosphate. Nutrient concentrations of leachate water after rinsing with a total of 9 L of deionized water are shown in Figure 67. The source of increased nutrient values measured for the 18” compost sample is not clear. For simplicity, data used for characterizing nutrient retention is limited to results from tests with the 12” compost sample. Also, results for both mulch samples are combined to describe a mixed mulch material. Measured nutrient concentrations for each test and material are included in Appendix D.

4.2.1 Nutrient retention

Nutrient retention is determined by filtering water with an initial 0.5 mg/L concentration through each filter container. Concentrations of test water were checked prior to testing; generally, the test water was within 0.025 mg/L of the target 0.5 mg/L concentration. Nutrient retention is calculated as the measured initial nutrient concentration less the nutrients passing the filter container. Results of nutrient retention tests are shown in Figure 68. A negative value indicates nutrients were added to the test water after passing through the filter container. A positive value indicates nutrients were removed from the test water.

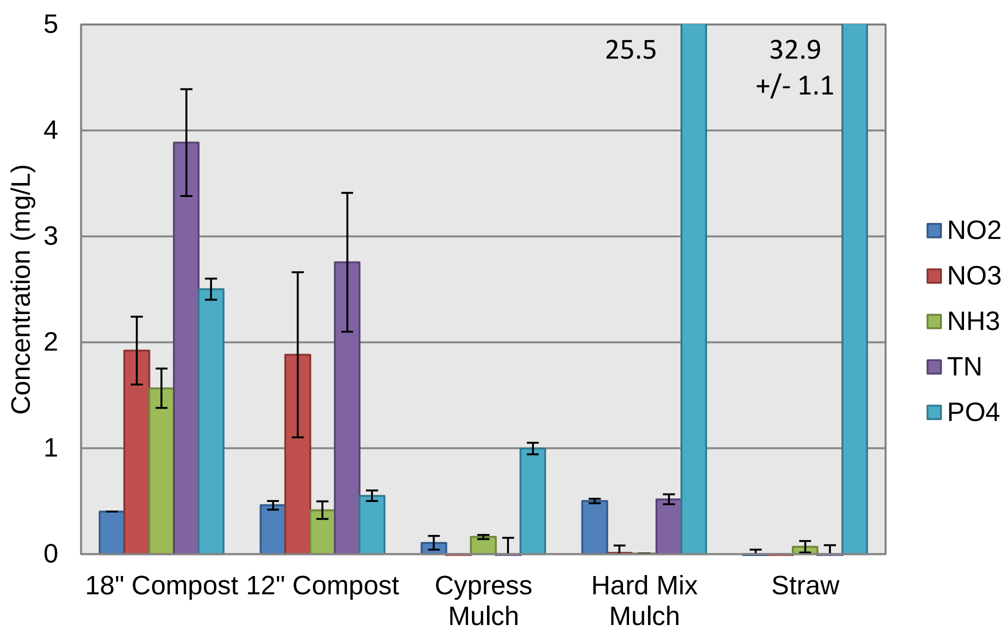

Figure 66: Initial nutrient concentrations (mg/L)

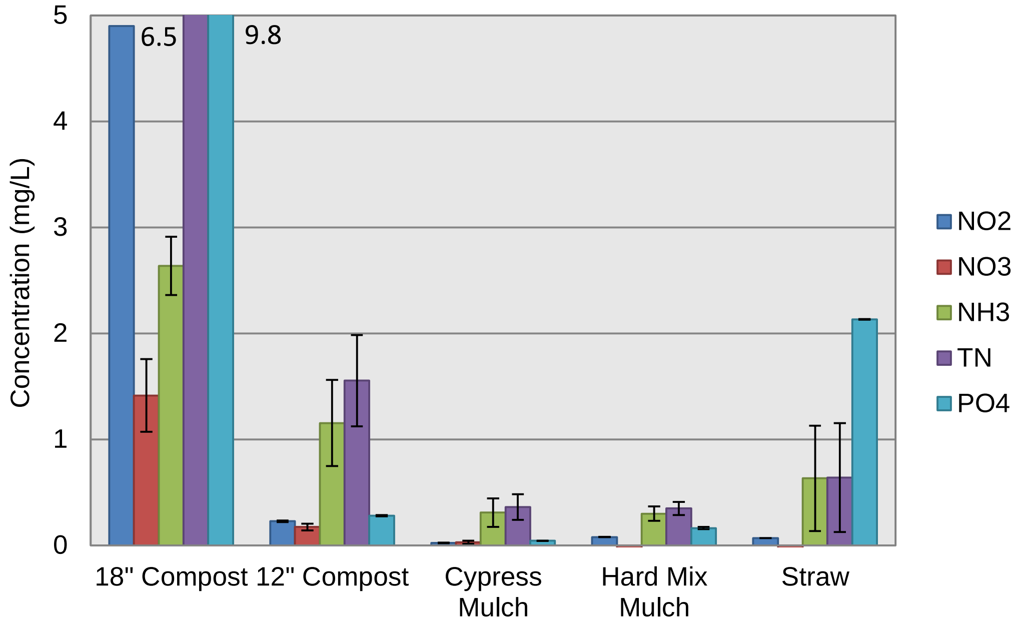

Figure 67: Nutrient concentrations after ninth liter of water

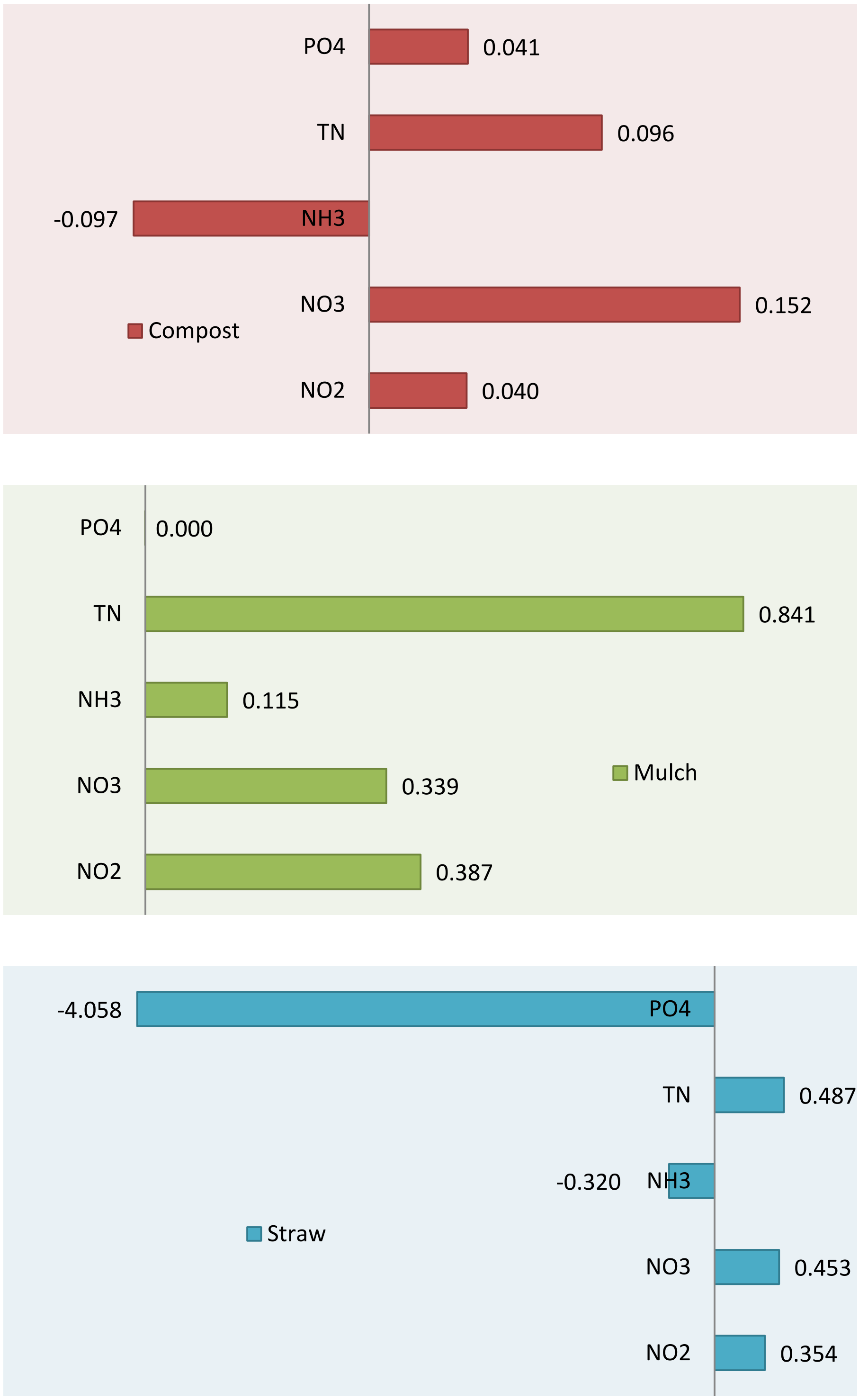

Figure 68: Nutrient retention of compost (upper), mulch (middle) and straw (lower). Negative is nutrient (mg/L) added to stream, positive is nutrient (mg/L) removed from stream.

4.2.2 Metal retention

Metal test water was prepared by mixing deionized water with concentrated metal standards to form approximate 0.5 mg/L concentrations of lead (Pb), copper (Cu) and zinc (Zn). Tests of the initial standard mix indicate metal concentrations of 0.465 mg/L ± 0.01 mg/L. Metal retention is the initial test concentration less the concentration measured in water passing the filter containers. Metal concentrations retained in the containers are shown in Figure 69. Each material retained a significant portion of the test metal. Measured metal concentrations for each test and material are included in Appendix E.

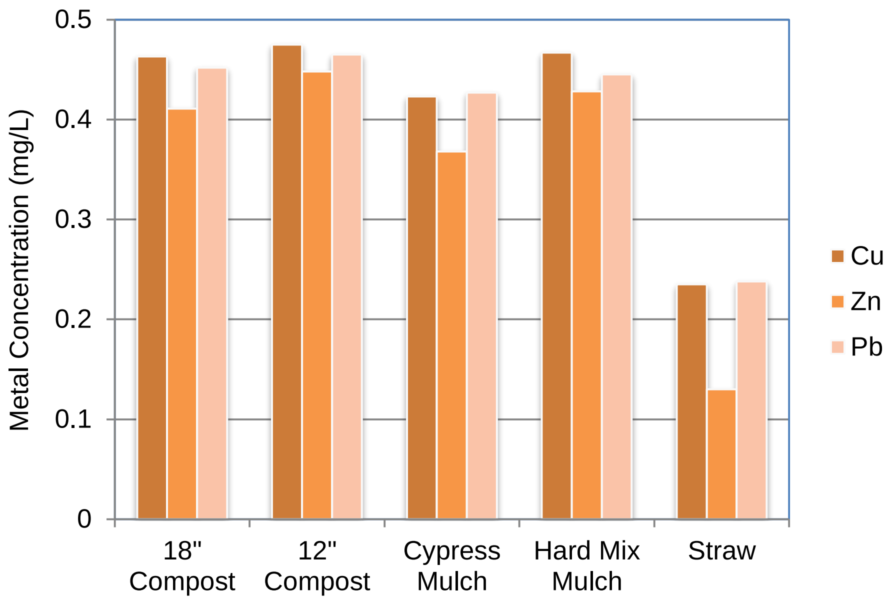

Figure 69: Metals retained in filter material

4.2.3 Discussion

Multiple iterations of nutrient testing were performed in an attempt to eliminate interference from sample turbidity. When included in the life cycle analysis; however, the most important result of the nutrient retention testing is that straw adds a significant amount of phosphorous to the water flow. An improvement to nutrient and metal retention testing would be to include soil particles in the test water and measure nutrient/ metal retention for geotextile silt fence, assumed to be zero in this study.

4.3 Life cycle analysis

4.3.1 Use-phase description

The purpose of the field and laboratory testing was to generate descriptive use phase processes for each SCD. Overall soil, nutrient and metal retention characteristics of the silt fence, compost, mulch and straw tested is summarized in Table 20. Negative values indicate nutrients were added to the water flowing through the material. The retention of soil solids is based on performance during the standard ASTM D7351 test method. Test conditions are as described in Chapter 3.

Table 20: Percentage soil, nutrient or metal retained

Material	Soil	NO_2-N	NO_3-N	NH_3	PO_4-P	Cu	Zn	Pb
Type A	98.4							
Type C	97.6							
Compost	92.9	8.0	30.4	-19.3	-63.9	93.8	85.9	91.7
Mulch	95.0	77.4	67.8	23.0	-0.1	89.0	79.6	87.2
Straw	91.2	70.8	90.6	-63.9	-811.6	47.0	26.0	47.6

Note: Blank cells not tested, assumed as zero

Inputs required for each use-phase process are calculated by multiplying the materials required per unit length listed in Table 9 by the 1,000 meter test length. Outputs over the life of the SCD installation are determined by multiplying the retention values in Table 20 by the expected total runoff approaching the installation for the 1-year test duration. The amount of solids passing each SCD is calculated as:

$$Effluent\ Solids = 136\frac{kg}{storm} \times 11.5\frac{storms}{year} \times \frac{1{,}000\ m}{4.5\ m} \times R(\%)$$

The predetermined solid mass generated per storm event is 136 kg, 11.5 storms per year is the mean precipitation for Macon, Georgia (46”) divided by the storm precipitation (4”), 4.5 m is the length of the test installation and *R* is the solids retention of each SCD. The amount of nutrients and metals passing each SCD is calculated as:

$$Effluent\ Nutrients/Metals = 0.5\frac{mg}{L} \times Q\frac{L}{storm} \times 11.5\frac{storms}{year} \times \frac{1{,}000\ m}{4.5\ m} \times R(\%)$$

The concentration of nutrients and metals in the runoff stream is assumed as 0.5 mg/L, Q is the effluent runoff water passing each SCD and *R* is the nutrient and metal retention. The resulting outputs for the LCA model installation is listed for each SCD and contaminant in Table 21.

Table 21: Solids, nutrients and metals (kg) leaving site over 1 year period.

	Silt fence Type A	**Silt fence Type C**	**Compost**	**Mulch**	**Straw**
Solids	5,575.8	8,363.6	24,742.4	17,424.2	30,666.7
NO_2-N	2.4	2.1	2.3	0.6	0.6
NO_3-N	2.4	2.1	1.8	0.8	0.2
NH_3	2.4	2.1	3.0	1.9	3.5
PO_4-P	2.4	2.1	2.3	2.5	19.5
Cu	2.4	2.1	0.2	0.3	1.1
Zn	2.4	2.1	0.4	0.5	1.6
Pb	2.4	2.1	0.2	0.3	1.1

4.3.2 Inventory balance

The following charts show inventory balances performed using GaBi 6.0 life cycle analysis software. The balances are performed using the life-cycle maps shown in Chapter 3. The software scales required production units (i.e. plastic, metal, and timber) and disposal units (i.e. wood, plastic, and steel waste) to meet inputs required and outputs generated by the use phases developed previously.

The contribution from each SCD to runoff solids is shown in Figure 70. Figure 71 shows energy requirements for each SCD. Figure 72 shows energy requirements for only the production processes. The large amount of timber required for staking straw bales is energy intensive with a majority of the energy being renewable from solar. As expected, production of steel sections is energy intensive and mostly from non-renewable sources. Polypropylene is shown as somewhat energy intensive from mostly non-renewable sources. Figure 73shows non-renewable resources used during production phases. As expected, steel production requires a large amount of non-renewables, generally followed by polypropylene and then timber.

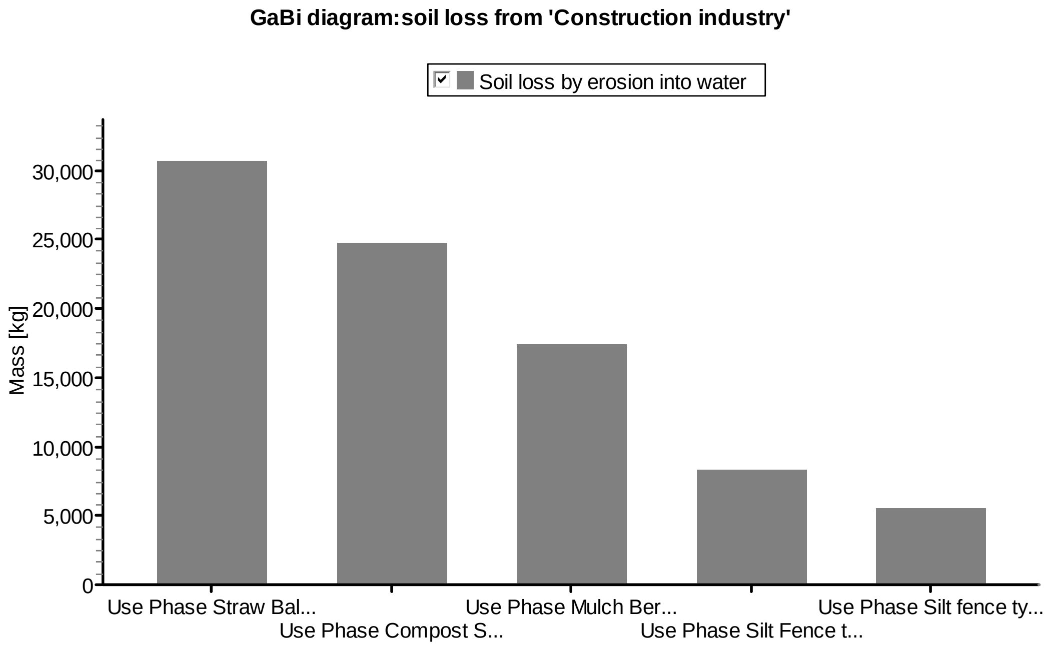

Figure 70: Soil loss balance

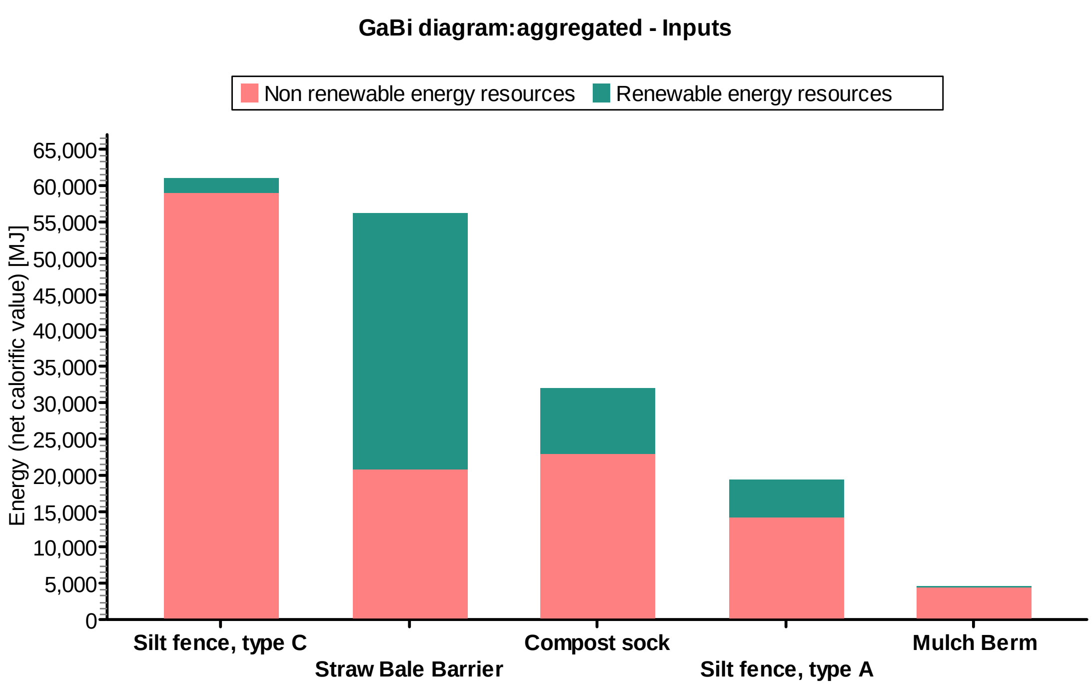

Figure 71: Energy resources by SCD

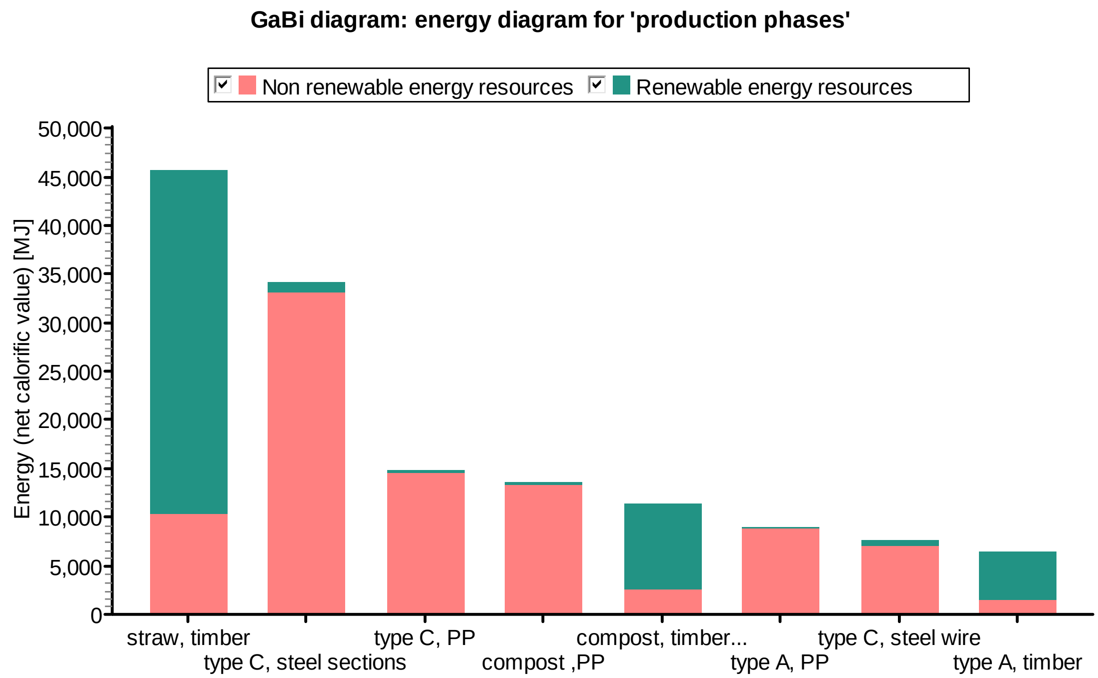

Figure 72: Energy by production phase

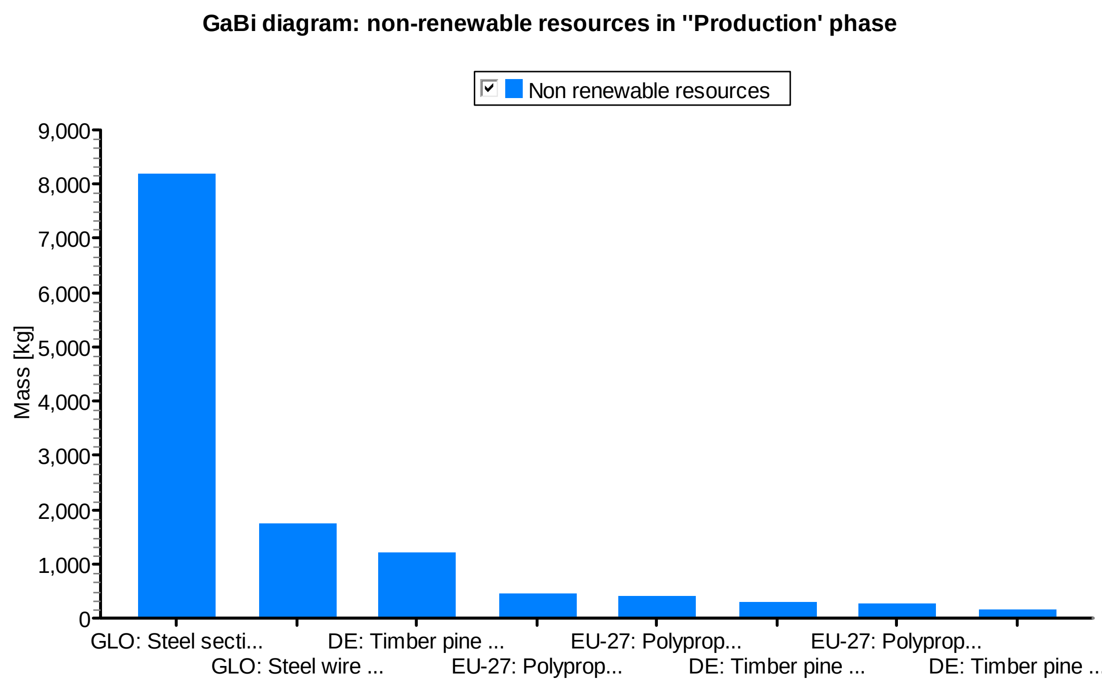

Figure 73: Non-renewable resources

Emissions to freshwater from each SCD not including runoff and waste water from production and manufacturing processes or eroded soil are shown in Figure 74. Figure 75 shows the top six inorganic emissions to fresh water. The large values of phosphorous, nitrate, nitrite and ammonia are due to the nutrient levels in runoff water. Figure 76 shows emissions to air associated with each SCD.

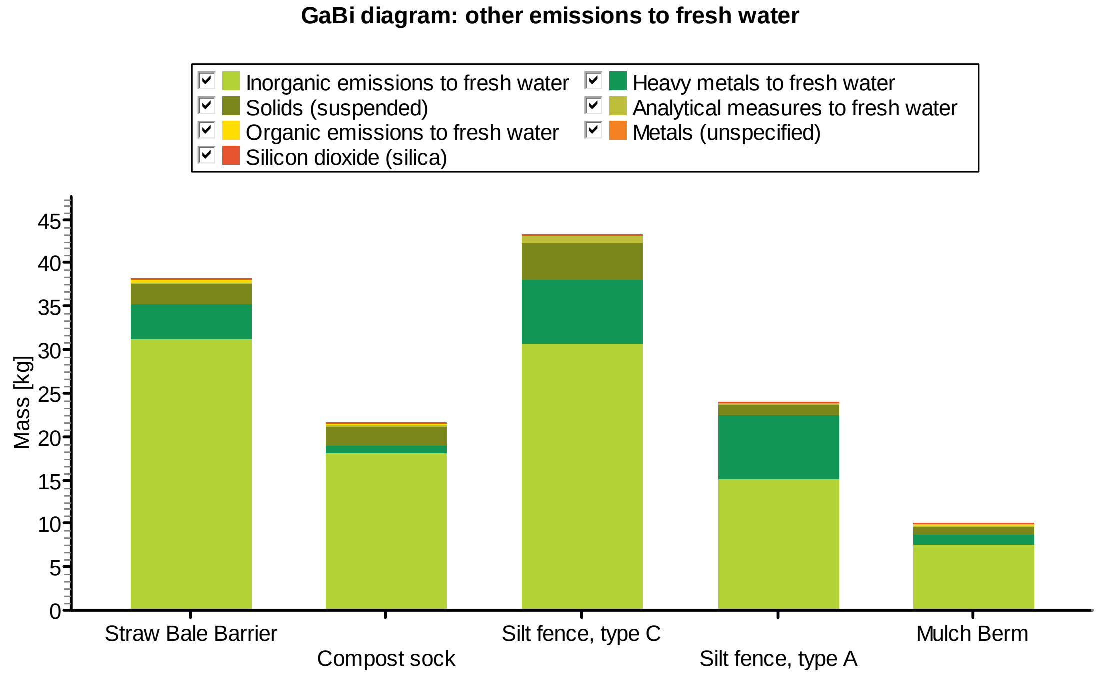

Figure 74: Freshwater emissions. Soil and water (runoff and process) not included

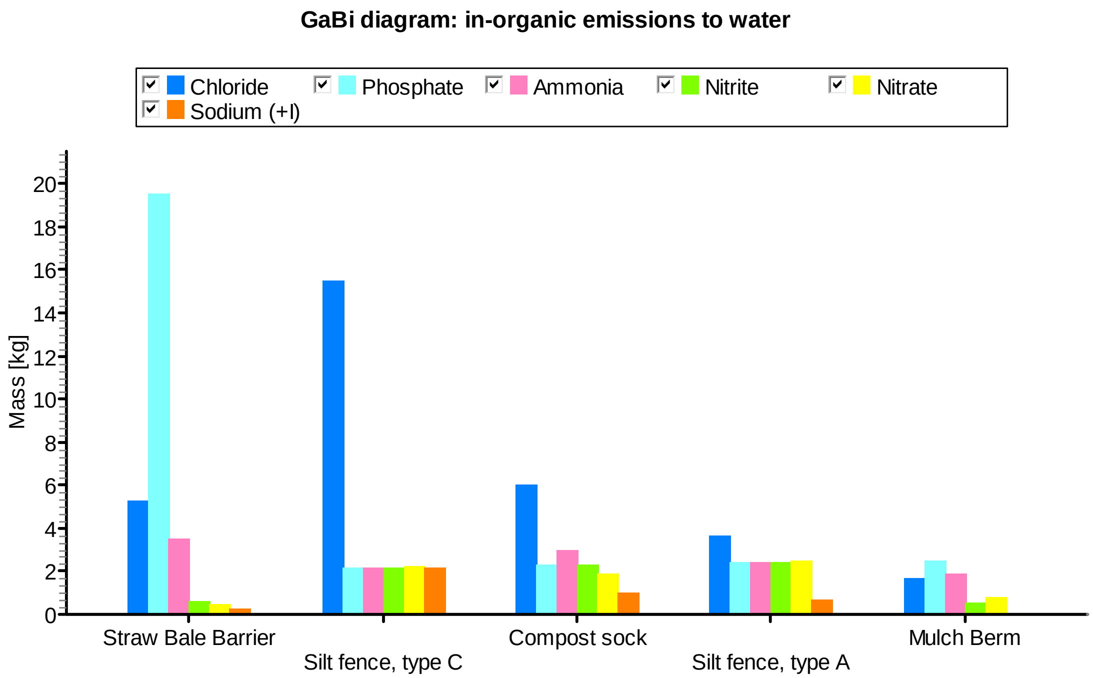

Figure 75: Top 6 in-organic emissions to fresh water

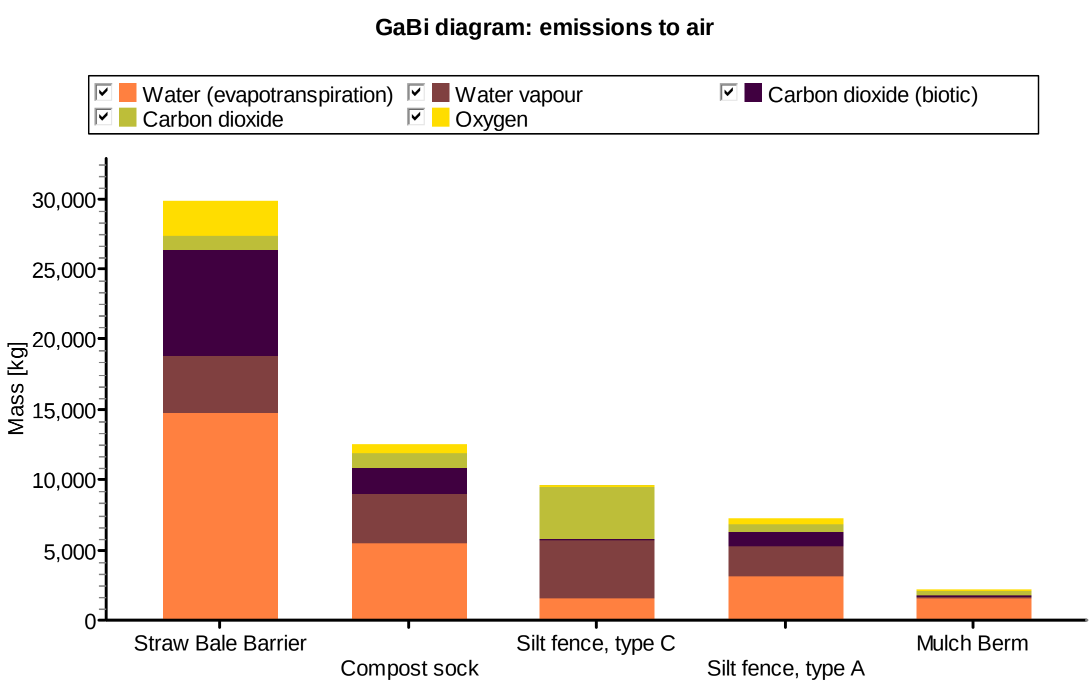

Figure 76: Top 5 emissions to air

4.3.3 Life cycle impact analysis (TRACI)

Results of the impact analysis performed with GaBi 6.0 according to US EPA's TRACI methodology are shown for each SCD in the following figures. Figure 77 shows the global warming potential (GWP) of each SCD in terms of equivalent kg of CO_2. Figure 78 shows acidification potential (AP) of each SCD in terms of equivalent kg of H+ ions. Figure 79 shows eutrophication potential (EP) of each SCD in terms of equivalent kg of nitrogen (N). Figure 80 shows ecotoxicity to water of each SCD in terms of m^3-days per kg potential affected fraction (PAF). Each of these impact categories is described in Chapter 2. For EP and ecotoxicity a baseline value is included. The baseline considers effluent from the model site that would occur with no SCD installed. The baseline has no associated air emissions and is therefore not included in GWP or AP. Key items from the impact analysis are identified for each impact category in the following paragraphs.

Global warming potential associated with straw bale barriers is 26 times greater than that for the mulch berm device. GWP for each SCD is divided into process-Type in Table 22 with values contributing at least 10% of GWP in bold. The large GWP for straw bales is attributed to landfill of the untreated wood waste. Creation of the timber for each SCD using wooden stakes is a sink for greenhouse gases and reduces overall GWP. Steel production for Type C silt fence is a significant source of GWP. GWP associated with combustion emissions from combined transport processes and diesel fuel production is low compared to GWP from production phases. The large amount of material required for straw bale installations increases transport trip required and results in higher GWP. Operation of diesel machinery for SCD cleanout has a much higher GWP than for truck transportation.

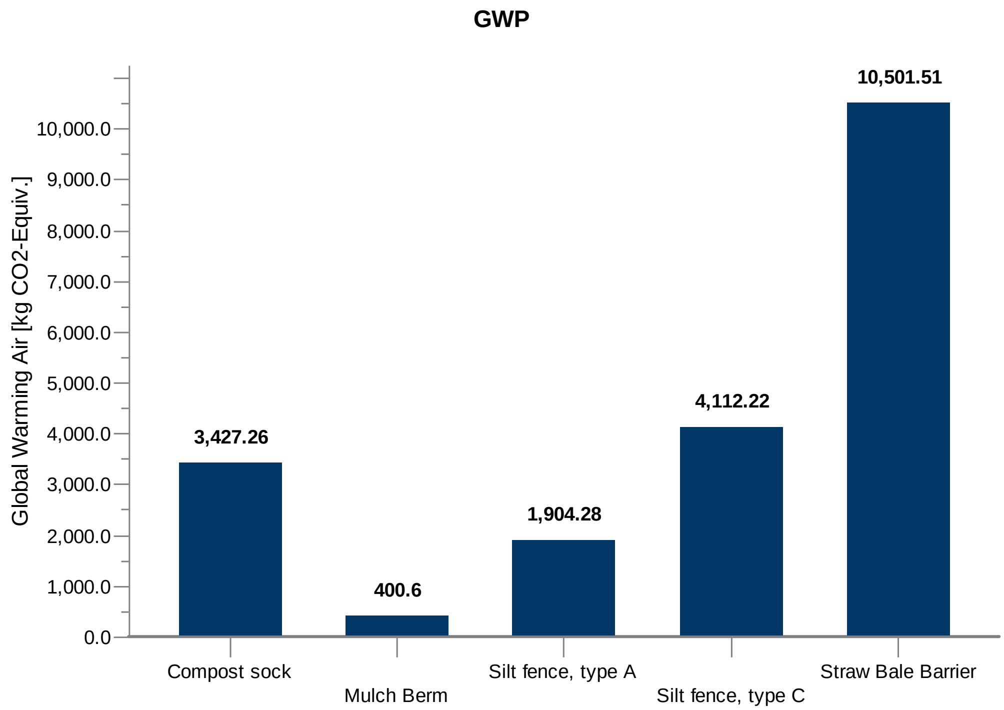

Figure 77: Global warming potential (GWP)

Table 22: Global warming potential (GWP) by process

Global Warming Potential (Equiv. kg CO_2) **Bolded values are >10% of total**		**Geotextile silt fence**		**Compost sock**	**Straw bale**	**Mulch berm**
		Type A	**Type C**			
Production	Steel		**3,417.5**			
	Timber	-422.9		-752.4	-3,008.8	
	Polypropylene	**251.0**	**412.2**	**380.0**		
	Straw				25.1	
	Mulching			285.6		**163.8**
Use	Trenching	12.1	12.1			
	Cleanout	**189.1**	187.5	178.1	174.8	**182.5**
Disposal	Metal		21.3			
	Plastic	7.9	13.0	12.0		
	Timber	**1,827.0**		**3,250.8**	**12,999.1**	
Transport	Transport	2.5	10.3	4.3	228.9	
	Diesel	37.5	38.7	68.9	82.4	**54.4**

Total	**1,904.3**	**4,112.6**	**3,427.3**	**10,501.5**	**400.6**

Acidification potential is similar for all devices except Type C silt fence. Table 23 lists AP by process. The table shows that high AP associated with Type C fence is from production of steel. For the mass of material created, production of polypropylene is comparable to diesel machinery operation. The large amount of wooden stakes required for straw bales installations show a significant amount of AP during production and disposal. Large amounts of bales and wood for straw bale installations increases transport trips resulting in greater AP.

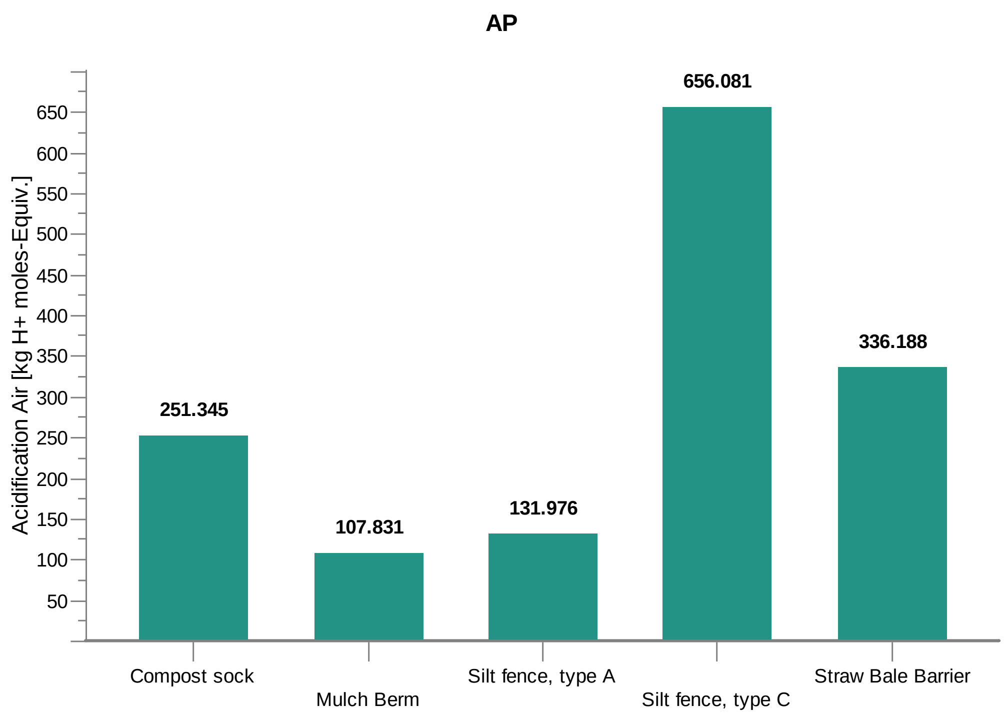

Figure 78: Acidification potential (AP)

Table 23: Acidification potential (AP) by process

Acidification Potential (Equiv. kg H+ moles) Bolded values are >10% of total	Geotextile silt fence		Compost sock	Straw bale	Mulch berm
	Type A	Type C			

Production	Steel		**508.7**			
	Timber	10.2		18.1	**72.4**	
	Polypropylene	**42.6**	**70.0**	**64.5**		
	Straw				6.6	
	Mulching			**74.4**		**42.7**
Use	Trenching	3.2	3.2			
	Cleanout	**49.3**	48.9	**46.4**	45.6	**47.6**
Disposal	Metal		6.3			
	Plastic	1.3	2.2	2.0		
	Timber	12.2		21.8	**87.1**	
Transport	Transport	1.1	4.4	1.8	**97.9**	
	Diesel	12.1	12.5	22.3	26.7	17.6
Total		**132.0**	**656.1**	**251.3**	**336.2**	**107.8**

Eutrophication potential is much higher for straw bales than any other SCD and the baseline. The high EP for straw bale installations is due to the large amount of phosphate that leaches from straw material. Eutrophication is caused by large increases in nitrogen (N) or phosphorus (P). Almost all of EP for each device is due to the performance during the use phase. The use phase accounts for 98, 94, 96, 99 and 99 percent of total EP for the Type A, Type C, compost sock, straw bale and mulch berm devices, respectively. A small amount of EP is due to steel manufacture for the Type C device.

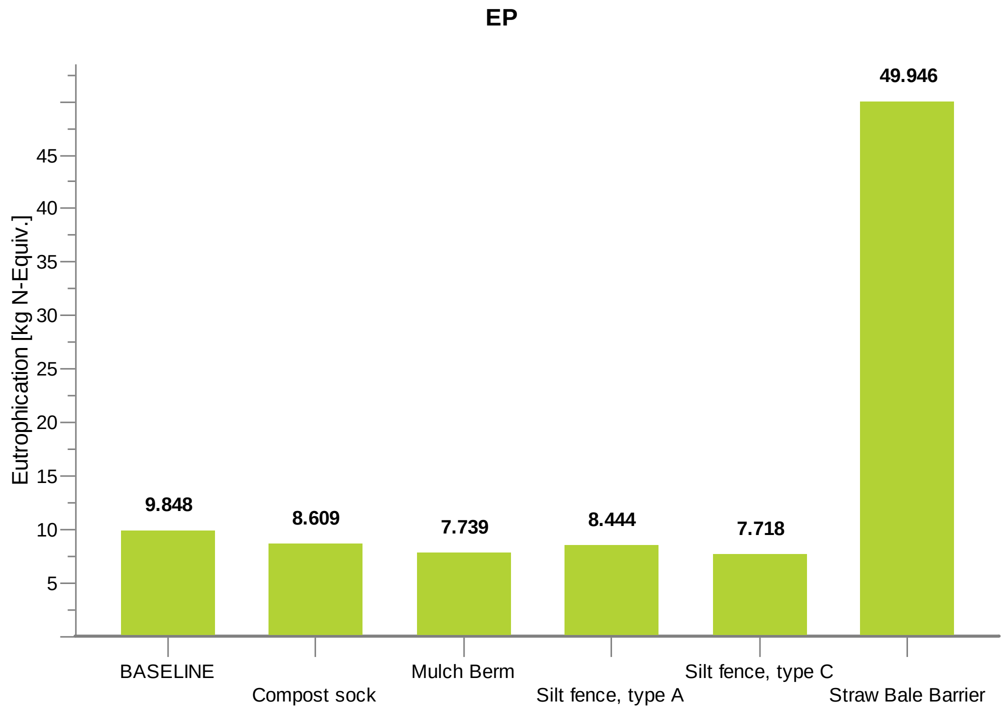

Figure 79: Eutrophication potential (EP)

Ecotoxicity to water shows the most deviation between each device and the baseline. At least 99.8% of contributions to water ecotoxicity are from the use phases of each device. The mulch berm and compost sock show an approximate 90% reduction in ecotoxicity when compared to the baseline value. The straw bale barriers show a 55% reduction. Ecotoxicity reduction in the compost, mulch and straw devices is mostly due to the measured reduction in metals and nutrients from the site effluent. The reduction achieved by both silt fence types is relatively low because the devices were assumed to have no nutrient or metal retaining capabilities. The reduction shown for the silt fence material is due to the detention of runoff water and subsequent retention of nutrients and metal concentrations in the water. Ecotoxicity is shown as the potential affected fraction (PAF). The PAF is area of the local environment affected for a certain time per kg of pollutant.

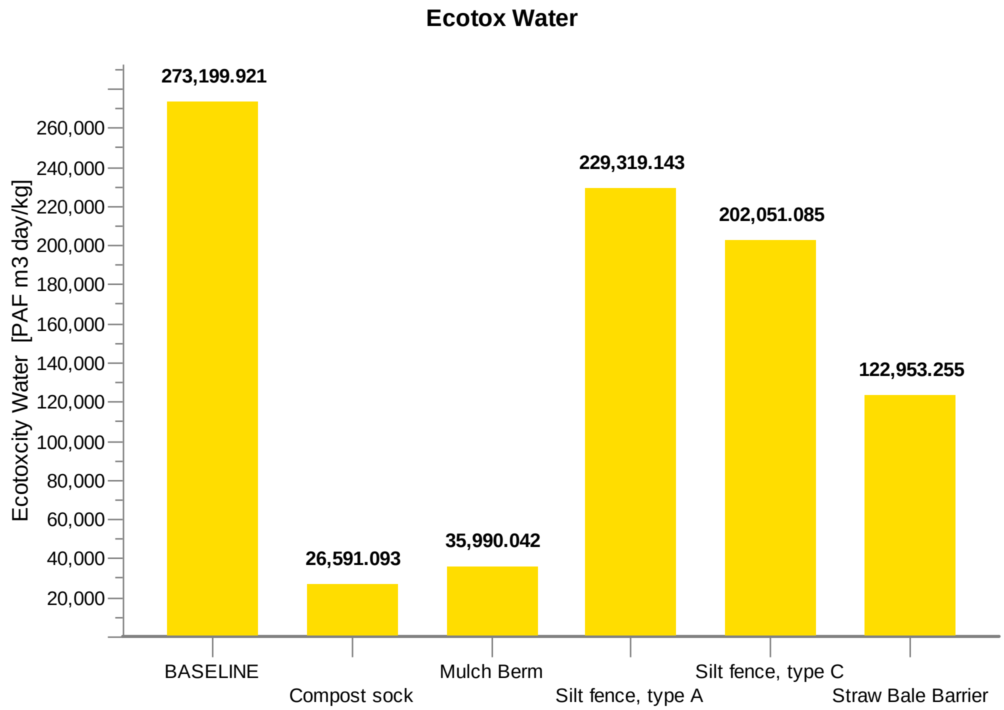

Figure 80: Ecotoxicity to water

GWP and AP for each life cycle phase are shown in Figure 81 and Figure 82, respectively. GWP and AP are mostly by steel production for Type C fence supports. GWP and AP from disposal are dominated by landfill of wood materials.

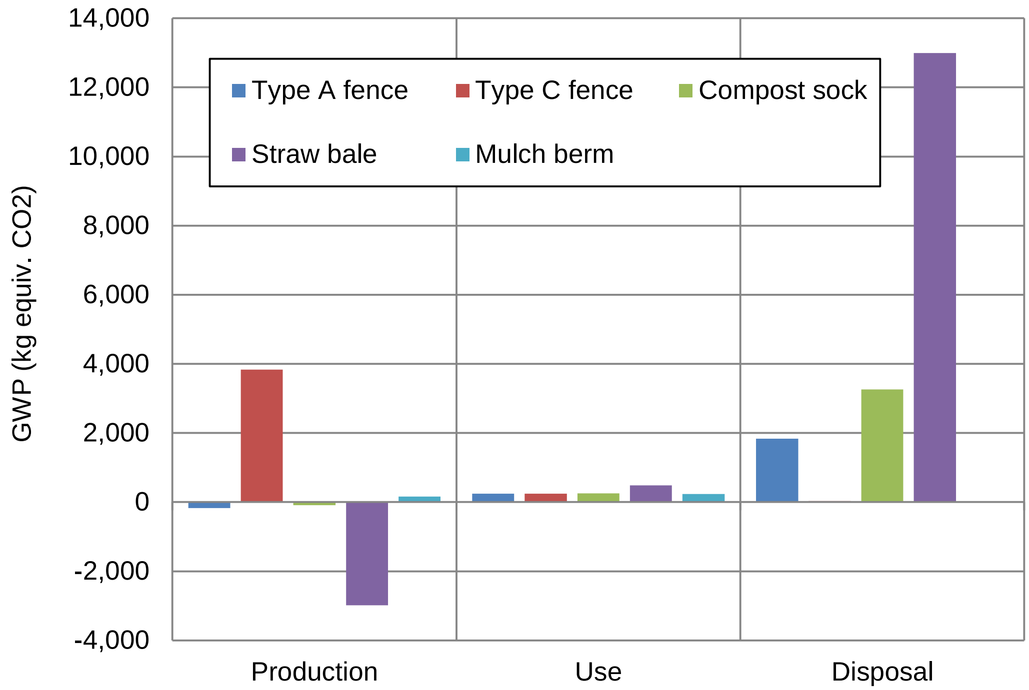

Figure 81: GWP by phase

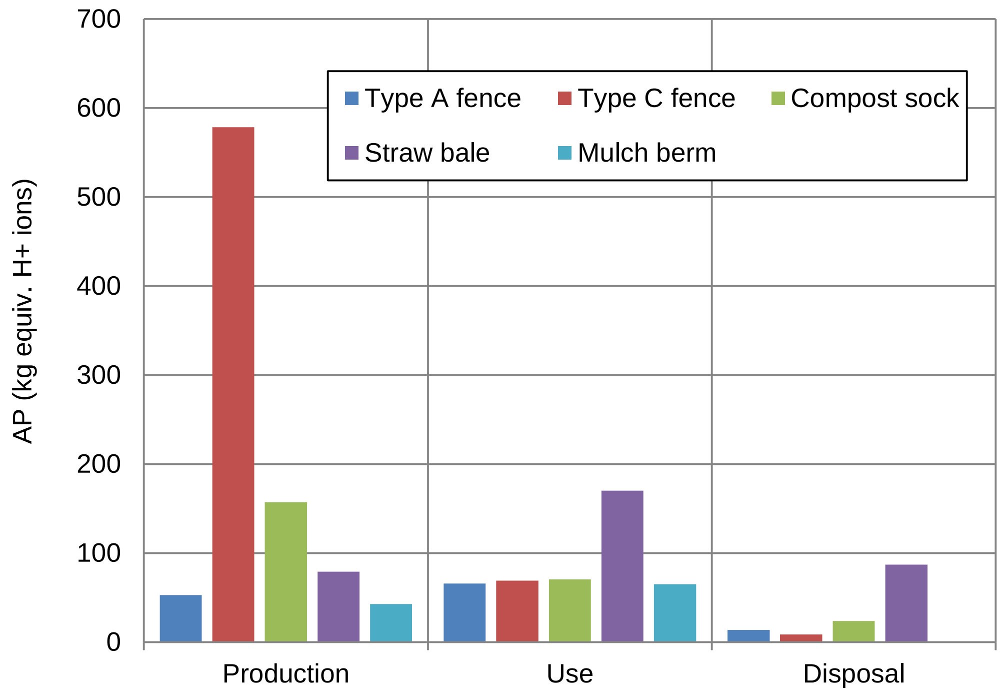

Figure 82: AP by phase

4.3.4 Discussion

The first point of emphasis is that GWP and AP from overall production and disposal phases is much larger than transport and diesel machinery processes (i.e., mulching, clean out). This increases the confidence of the assessment because production and disposal processes included in this study are based on a large amount of data developed by PE INTERNATIONAL whereas distances for transport and power requirements for diesel machinery are only approximations and will vary from site to site. It also suggests greater potential for lowering environmental impact by focusing on reducing SCD production than developing more efficient transport and installation methods.

The results of the life cycle analysis show that differences in GWP and AP for the use phase of SCDs are relatively small and only differ by the amount of diesel machinery operation required for cleanout. Differences in GWP and EP from production phases are due to the high energy requirement during steel production. The production of polypropylene on the scale covered in the model results in GWP and AP on par with operation of diesel equipment for mulch production. A large amount of GWP and AP is derived from landfill of wood waste. This is likely due to the fast degradation of wood that results in gas emissions. Gas collection and reuse is considered as part of the landfill of wood waste process and results in a power source within the product life cycle. Productive reuse of the gas material was not included in this model.

Differences in EP are generally small between different SCDs except for the straw bale installation that generated a large EP due to high levels of phosphate leachate that were encountered during the laboratory testing. EP for the silt fence installations was similar to the compost sock and mulch berm even though no nutrient retention was assumed for the silt fences. This is explained by the relatively low amounts of nutrient concentrations (0.5 mg/L) assumed to be in runoff water from the site. Additional testing with much higher nutrient concentrations (2 – 5 mg/L) should be performed to investigate EP during times of high nutrient loading, such as after grassing and/or fertilizing on site.

Results for ecotoxicity are the best example of beneficial SCD installation. Each device showed a reduction in aquatic ecotoxicity when compared to the control model (baseline). EP due to nutrient loading showed little variation between baseline and SCD values (except straw bales) which suggests that the large variation in ecotoxicity values are due to metal retention. The compost and mulch material each showed very high metal retention capabilities under very short test duration. No metal retention was assumed for the geotextile fences, although retention of runoff water was assumed to reduce metal concentrations in the total effluent volume.

4.3.5 Overall Performance (Valuation)

SCD performance varies significantly between the different impact categories analyzed so that the best environmental option is not easily identified. To determine the SCD with the overall lowest environmental impact, a valuation analysis is performed. The steps in the valuation analysis are as follows:

1. Weighting factors are applied to each impact category,
2. SCD performance in each impact category is normalized relative to the other devices,
3. The product of relative SCD performance and the impact weights is summed for each SCD to determine the overall environmental impact.

As discussed in section *2.3.7 Valuation*, developing proper weighting factors requires significant discussion and one of the available development methods. The Berrittella et al. (2007) report is recommended as a good example of developing weighting factors. The weighting factors assumed for this study are shown in Table 24. The weighting factors are shown as fractions of the final goal, similar to an analytical hierarchy process (AHP) study. The final goal in this evaluation is to determine the SCD with the lowest environmental impact. The primary goal of SCDs is to reduce surface discharges to adjacent waterways, thereby reducing water pollution. This is included in the valuation by rating impact criteria associated with water quality twice as high (0.666) as those for air quality (0.333). Sub-criteria for air and water quality are assumed to be equally important. The total environmental impact is now described as the sum of effects from global warming, acidification, eutrophication, and aquatic toxicity. This relationship is expressed as:

GWP + AP + EP + Toxicity = Environmental Impact

0.1665 + 0.1664 + 0.333 + 0.333 = 0.999

Table 24: Weighting factors for LCIA valuation.

Start:	**Environmental Impact (EI)**			
	1.000			
Criteria:	**Air Quality**		**Water Quality**	
	0.333		0.666	
Sub-criteria:	**GWP**	**AP**	**EP**	**Toxicity**
	0.1665	0.1665	0.333	0.333

Relative performance of SCDs in each impact category is expressed as the fraction of impact from each SCD to the total impact from all the SCDs analyzed. Relative performance values are shown in

Table 25 for air quality and Table 26 for water quality. An example of relative performance calculation for GWP of compost sock is shown below.

$$GWP_{rel-CS} = \frac{GWP_{CS}}{GWP_{TOTAL}} = \frac{3427.26}{0 + 1904.28 + 4112.22 + 3427.26 + 400.6 + 10501.51} = 0.168$$

Table 25: Relative SCD performance, air quality.

	GWP		AP	
	kg CO2-Eq	% of max	kg H+ moles-Eq	% of max
Baseline	0	0.000	0	0.000
Type A Fence	1904.28	0.094	131.976	0.089
Type C Fence	4112.22	0.202	656.081	0.442
Compost Sock	3427.26	0.168	251.345	0.169
Mulch Berm	400.6	0.020	107.831	0.073
Straw Bale	10501.51	0.516	336.188	0.227

Table 26: Relative SCD performance, water quality.

	EP		Toxicity	
	kg N-Eq	% of max	PAF m3 day/kg	% of max
Baseline	9.848	0.107	273199.9	0.307
Type A Fence	8.444	0.091	229319.1	0.258
Type C Fence	7.718	0.084	202051.1	0.227
Compost Sock	8.609	0.093	26591.09	0.030
Mulch Berm	7.739	0.084	35990.04	0.040
Straw Bale	49.946	0.541	122953.3	0.138

Relative SCD performance is multiplied by the corresponding impact category weighting factor to determine the final overall environmental impact. An example for compost sock is included below. Results of the valuation are shown in Figure 83.

$$EI_{CS} = V_{GWP}I_{CS-GWP} + V_{AP}I_{CS-AP} + V_{EP}I_{CS-EP} + V_{TOX}I_{CS-TOX}$$

$$EI_{CS} = 0.1665 * 0.168 + 0.1665 * 0.169 + 0.333 * 0.093 + 0.333 * 0.030 = 0.097$$

Where *EI* is the environmental impact for compost sock, *V* is the weight factor for each impact category, and *I* is the relative performance of compost sock in each impact category.

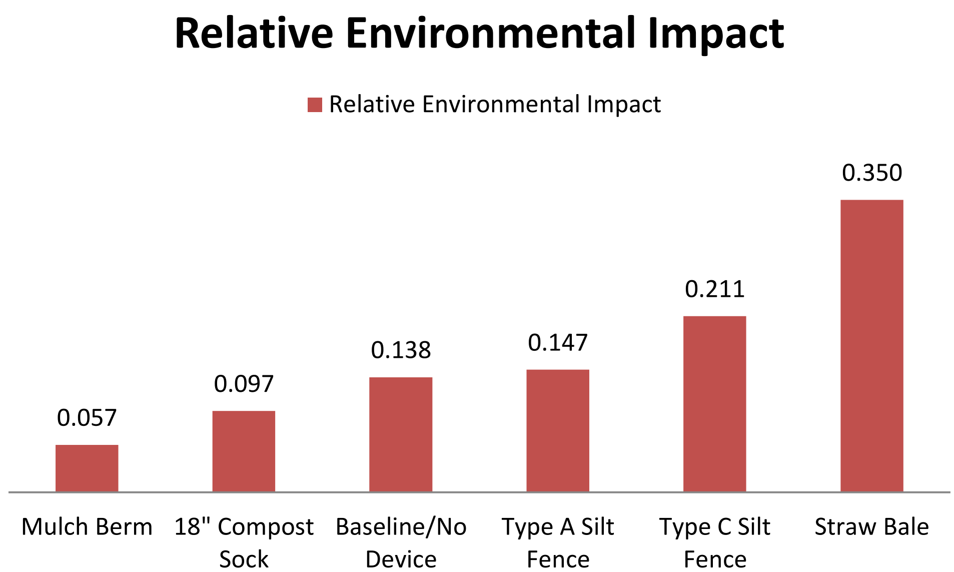

Figure 83: Results of LCIA valuation. SCDs are ranked from lowest to highest relative environmental impact.

Results of the valuation indicate that for the assumed site conditions, the mulch berm has the lowest environmental impact, followed by the compost sock and then no SCD device. For the assumed weighting factors and the field and lab testing performed, the overall impact of silt fence installation is higher than no SCD installation.

An additional valuation was performed using the relative performance of SCD devices for TSS removal and turbidity reduction. The added valuation was performed to compare the typical decision making criteria of lower TSS and turbidity to results from the life-cycle study. For the SCD performance valuation, TSS removal and turbidity reduction are considered to be equally important, as shown by weighting factors in Table 27. Relative SCD performance for

TSS removal and turbidity reduction are shown in Table 28. The baseline (no SCD installation) has no reduction potential. Results of the SCD performance valuation are shown in Figure 84. Results indicate that silt fence is the best option for TSS removal and turbidity reduction, but are only marginally better than each of the other SCD options.

Table 27: Weighting factors for SCD performance valuation.

	SCD Performance	
Start:	1.000	
	TSS Removal	**Turbidity Reduction**
Criteria:	0.500	0.500

Table 28: Relative SCD performance, TSS removal and turbidity reduction.

	TSS Removal		Turbidity Reduction	
	Reduction (%)	% of max	Reduction (%)	% of max
Baseline	0	0.00	0	0.00
Type A Fence	98.4	0.21	92.3	0.24
Type C Fence	97.6	0.21	92.8	0.24
Compost Sock	92.9	0.20	64.9	0.17
Mulch Berm	95	0.20	73.8	0.19
Straw Bale	91.2	0.19	61.9	0.16

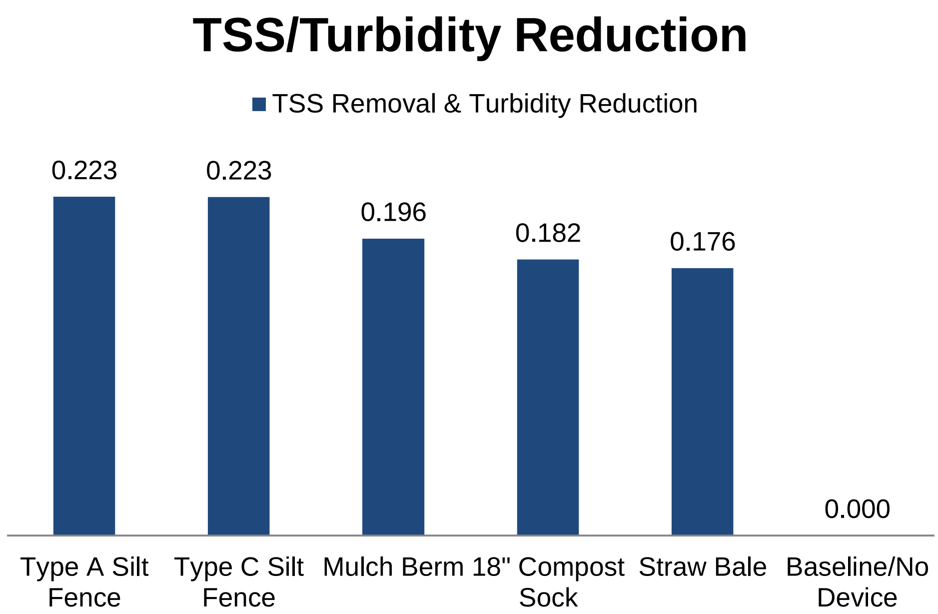

Figure 84: Results of SCD performance valuation. SCDs are ranked from best (highest) to worst (lowest) relative performance.

4.3.5 Implications

Results from the study suggest that straw bale installations may degrade downstream water systems by adding a large amount of phosphate to water leaving construction sites and thus increasing the potential for eutrophication. In addition, although timber production is a sink for greenhouse gasses, the large amount of wood waste from wooden stakes creates a much larger source for harmful emissions. The assumed duration on site of one year is about the usable lifetime of an untreated wooded stake and reuse of the wood stakes to avoid landfill is unlikely. However, emissions from degradation of the wood waste may be used for power generation in order to lower the apparent environmental impact during modeling. Regardless, the poor performance of straw bales as sediment barriers is noted by many state DOTs that currently no not allow bales for use as perimeter barriers.

Another implication from the study is that high flow (Type A) geotextile silt fence performs better than low flow (Type C) silt fence. During field testing the devices, the Type A fence resulted in overall lower sediment downstream of the installation. Type A fence shows slightly more EP and aquatic toxicity due to the higher retention of runoff water of the Type C fence. However, GWP and AP associated with the Type C fence are much higher than those of the Type A fence due to the energy intensive production of steel. The steel support is required for additional support of silt fence, however; during field testing, the Type A fence performed well, if not better than the Type C fence (first test of Type C fence resulted in undercutting failure).

Although polypropylene is the result of the energy intensive process of cracking of hydrocarbons, cumulative GWP and AP associated with the material is on the scale of GWP and AP from operating equipment for mulching and trenching. Although, the use of steel stakes and supporting wire mesh adds environmental load, the impact of polypropylene is not large enough to discourage its use as SCD material.

A single field test of each SCD with total maximum test duration of 90 minutes was performed for this research. Mulch berms and compost socks performed very well during testing; however, the performance of these devices on the scale of the model site duration (1 year) was not measured. All installations modeled are assumed to stay in place without replacement for the entire duration; only maintenance to clean out the SCDs was modeled. Still, the size and weight of compost socks suggests that they would stay in place for long durations. Additionally, the mulch berm tested was much smaller than typical brush barriers formed on sites from slash material during site clearing stage.

Results from the LCIA valuation indicate that the mulch berm is the SCD with the lowest overall environmental impact. Results from the SCD performance indicate that silt fence is the best option to reduce TSS and turbidity. The difference in the results underlines the ability of LCA to identify impacts that were not previously considered. The difference in performance between the worst performing SCD (straw bales) to the best performing SCD (mulch berm) is approximately 83%. The largest difference in performance from the SCD valuation is only 21%, from silt fence to straw bales. The differences suggest that the SCD valuation based on only TSS and turbidity reduction is slight. The valuation based on life-cycle performance is much greater, suggesting the best-option is far better than the worst option.

4.3.6 Limitations

Life cycle analysis provides a holistic approach to comparing the environmental impacts of processes; however, the analysis is still based on a model of a real system and simplification errors are unavoidable. Multiple modeling assumptions and other general shortcomings of the analysis are discussed in this section. Problems associated with the field and laboratory testing are discussed in previous sections.

In this model, steel fence posts are assumed as steel sections and wire mesh is assumed as steel wire rod. A power requirement for weaving textile in Indonesia is assumed as applicable to weaving polypropylene geotextile in the southeast United States. Processes refined in Europe for production of polypropylene fibers and disposal of wood waste, metal and plastic and production of timber in Germany are assumed to be applicable in Georgia. Using foreign processes is generally okay as production phases are not expected to vary spatially as much as power generation; diesel refining processes specific to the United States were used in the study. Inventories for common processes like steel and plastic production are based on a large amount of industry data and analysis. For this model, installation and maintenance requirements are only approximations based on power requirements. Accuracy of the model with increase with additional data on machine emissions, fuel requirement and actual machine hours required for installation and maintenance.

The model developed for this study assumed a 1,000 meter (0.62 mile) long installation operating at a site for 1-year. The site was assumed to be located 10 kilometers (6.2 miles) from SCD supply plants and 25 kilometers (15.5 miles) from landfill facilities. Distances from supply plants may vary for each SCD. Total precipitation on site was assumed as the yearly average for Macon, Georgia (~46"). The rainfall was assumed to occur over 11.5 storms each with the intensity of a 10-year, 6-hour storm. This was the test condition assumed during the field testing of the SCDs, actual performance of the SCD devices is expected to vary significantly with different storm intensities.

Nutrient retention was not considered for silt fence in this study. Slight differences in nutrient retention are realized for the silt fence due to the water retention capabilities. Additional studies of nutrient retention for all devices in the field will increase LCA accuracy.

The LCIA and SCD performance valuations provide insight to SCD selection; however, the valuations are based on assumed weighting factors. Additionally, at the time of this report, it is not clear how the TRACI aquatic eco-toxicity impact category quantifies affects from downstream TSS loads and turbidity.

CONCLUSION

5.1 Sediment Control Device Performance

This study was performed for the Georgia Department of Transportation (GDOT) in order to better understand the environmental impacts associated with sediment control devices currently employed on transportation projects. In this study, current and past methods for testing sediment control devices (SCDs) in the field and laboratory and procedures for conducting a life cycle assessment were reviewed. Extensive field testing was performed in accordance with ASTM D7351. TSS and turbidity reduction performance in the field tests is summarized in Table 29. The table ranks the devices in two columns according to performance. The tests indicate that geotextile silt fence performed the best in both TSS reduction and turbidity reduction. TSS reduction only varied by 7.2% from Type A fence to straw bales. Turbidity varied by 43.6% from the best, Type C fence, to the worst, straw bales.

Table 29: SCD TSS and turbidity removal performance.

TSS Reduction **Device: Removal Efficiency (%)**	Turbidity Reduction **Device: Removal Efficiency (%)**
Type A Fence: 98.4	**Type C Fence: 92.8**
Type C Fence: 97.6	**Type A Fence: 92.3**
Mulch Berm: 95.0	**Mulch Berm: 73.8**
18” Compost Sock: 92.9	**18” Compost Sock: 64.9**
Straw Bales: 91.2	**Straw Bales: 49.2**

A combination of laboratory filter testing was performed to determine the capability of SCD nutrient and metal retention capabilities. Results, summarized in Table 30, indicate that retention of nitrogen in mulch berms is significantly higher than in straw and compost and that removal of phosphorous is generally low. Straw bales are a significant source of additional phosphorous.

Table 30: Nutrient retention results.

Total Nitrogen Reduction **Device: Removal Efficiency (%)**	Phosphorous Reduction **Device: Removal Efficiency (%)**
Mulch: 56.1	**Compost: 8.2**
Straw: 32.5	**Mulch: 0.0**
Compost: 6.4	**Straw: -811.6**

Table 31 ranks compost, mulch, straw according to metal retention capability. Retention in compost and mulch is high. Retention in straw is moderate.

Table 31: Metal retention results.

Copper (Cu) Reduction **Device: Removal Efficiency (%)**	Zinc (Zn) Reduction **Device: Removal Efficiency (%)**	Lead (Pb) Reduction **Device: Removal Efficiency (%)**
Compost:93.8	**Compost: 85.9**	**Compost: 91.7**
Mulch: 89.0	**Mulch: 79.6**	**Mulch: 87.2**
Straw: 47.0	**Straw: 26.0**	**Straw: 47.6**

Overall results of the SCDs indicate that silt fence is the best option for reducing TSS and turbidity in downstream water samples. Mulch is the best option for reducing downstream nutrients. Compost is the best option for retaining metals in runoff water. Taken without performing a LCA, the SCD performance testing suggests that when nutrient and metal concentrations exist in runoff streams, mulch and compost are good modifiers to be used in combination with silt fence. A valuation of the SCD performance indicates that silt fence are the best option to reduce TSS and turbidity, but are only slightly better than other SCD options.

5.2 Life Cycle Analysis of Sediment Control Devices

The field and lab tests were combined to create a use phase process for each SCD. The use phase processes were combined in a life cycle inventory with previously created production and disposal processes included in the GaBi 6.0 professional life cycle database. Additional processes were approximated based on power requirements found in literature. The processes were linked to form a life cycle plan of each SCD. The life cycle model included performance of the SCDs on a 1,000 meter long installation for 1 year under assumed runoff conditions. A life cycle impact analysis was performed using GaBi 6.0 software and USEPA TRACI methodology. An LCIA valuation was performed using assumed weighting factors to determine the overall most environmentally friendly SCD option. Results of the LCA indicate:

1. Straw bale installations significantly increase eutrophication potential in downstream water systems due to high levels of phosphate present in the straw bales,
2. Production of steel sections and wire mesh for support of low-flow (Type C) silt fence result in large increases in global warming and acidification potential,
3. Good performance of Type A silt fence suggests it is a good alternative to Type C fence in extreme conditions,
4. Overall low global warming and acidification potentials as well as low aquatic toxicity levels attributable to mulch berms suggests their use as an alternative SCD to geotextile silt fence is favorable,
5. A preliminary LCIA valuation with assumed impact weighting factors indicates that mulch berm is the SCD with the lowest overall environmental impact.

5.3 Impact/Recommendations

Currently, selection of SCD devices is based on TSS removal and turbidity reduction. The SCD valuation indicates that although silt fence is favorable, it is not significantly better than other SCD devices. The LCIA valuation adds impacts to global warming, acidification, eutrophication, and toxicity that include production and disposal phases. The major re-ordering of SCD performance between the two valuations reveals the significance of previously unconsidered environmental impacts on SCD selection. The following recommendations are derived based on results from this study:

- Mulch berms should be considered favorable for use as perimeter SCDs,
- Evaluation of new and existing sediment control devices should include a life-cycle analysis to compare overall environmental performance, and
- Results from general LCA studies can be tailored to individual construction sites using valuation processes and weighted impact factors determined at the local level.

Life-cycle analysis is beneficial but also costly. As data is accumulated from additional SCD performance testing, as impact categories are refined to include affects from downstream TSS and turbidity, and as energy and material cost for SCD materials are better understood, increasingly accurate LCA studies can be determined. LCA studies for every SCD installation would require significant time and may be too costly to sustain for a long period of time. However, general LCA studies to describe SCD performance in different conditions are beneficial to describe relative performance of devices. Results from the general studies can be modified using weighting factors that reflect the local site conditions (i.e., vicinity to vulnerable waterway, location in urban area with high air quality standards).

5.4 Future Work

On the basis of the results of this study, the following recommendations are presented for future work:

1. Nutrient and metal retention of SCDs should be studied with advanced laboratory procedures and in-field conditions.
2. Field and large-scale testing of SCDs for TSS retention and turbidity reduction should be studied for various sediment and water loads. Additional large-scale testing of SCDs should be done to study the effect of sediment grain size on filtering performance.
3. Advanced studies should be done to identify the mode of filtration of SCDs for sediment, nutrient, and metal reductions.
4. Additional LCAs should be performed to investigate the costs and benefits for recycling SCD components. The feasibility of SCD recycling should be investigated in the field.
5. Additional studies should determine appropriate weighting factors to be used for various on-site conditions.

APPENDIX A: DOT SUMMARY

Sources for DOT search summarized below, general form of data is:

[**State**]

[DOT website]

[Name of E&SC manual]

[Online access]

Alaska

www.dot.state.ak.us

Alaska Storm Water Guide. Alaska Department of Environmental Conservation.

http://dec.alaska.gov/water/wnpspc/stormwater/docs/AKSWGuide.pdf

Arizona

http://www.azdot.gov/

ADOT Erosion and Pollution Control Manual for Highway Design and Construction

http://www.azdot.gov/Highways/Roadway_Engineering/Roadside_Development/Resources.asp

Arkansas

http://www.arkansashighways.com/

2004 Erosion and Sediment Control Design and Construction Manual

http://www.arkansashighways.com/Construc/2004_E&S_Control_Manual/11-04%20E%20SC%20MANUAL%20FINAL.pdf

California

http://www.dot.ca.gov/

Caltrans Storm Water Quality Handbooks
Construction Site Best Management Practices Manual Section 1
March 1, 2003

http://www.dot.ca.gov/hq/construc/stormwater/CSBMPM_303_Final.pdf

Colorado

http://www.coloradodot.info/

CDOT Erosion Control and Stormwater Quality Field Guide

http://www.coloradodot.info/programs/environmental/waterquality/documents/CDOT%20Pocket%20Guide%20122211.pdf

Connecticut

http://www.ct.gov/dot/site/default.asp

2002 Connecticut Guidelines for Soil Erosion and Sediment Control

http://ahhowland.com/regulations/state-of-ct/ct-dep/2002-ct-guidelines-for-sediment-and-erosion-control.pdf

Delaware

http://www.deldot.gov/

E&S Field guide

http://www.deldot.gov/stormwater/pdfs/EandS_fieldguide/III+PerimeterControlsDiversionAndInletProtection.pdf

Florida

http://www.dot.state.fl.us/

State of Florida Erosion and Sediment Control Designer and Reviewer Manual, June 2007

http://www.dot.state.fl.us/rddesign/dr/files/Erosion-Sediment-Control.pdf

Georgia

http://www.dot.ga.gov/Pages/default.aspx

Manual for Erosion and Sediment Control in Georgia

Hawaii

http://hidot.hawaii.gov/

HiDOT - Construction Best Management Practices Field Manual, January 2008

http://www.coralreef.gov/transportation/constructionmanual_022708.pdf

Idaho

http://itd.idaho.gov/

Best Management Practices, Erosion and Sediment Control, ITD, August 2008

http://itd.idaho.gov/manuals/Online_Manuals/Current_Manuals/BMP/BMP%20Manual.pdf

Illinois

http://www.dot.state.il.us/

IDOT Erosion and Sediment Control Field Guide for Construction Inspection, July 1, 2010

http://www.dot.il.gov/desenv/environmental/idot%20field%20guide.pdf

Indiana

http://www.in.gov/indot/

2013 Indiana Design Manual

http://www.in.gov/indot/design_manual/files/Ch205_2013.pdf

Iowa

http://www.iowadot.gov/

Iowa DOT Erosion & Sediment Control Field Guide, April 2012

http://www.iowadot.gov/construction/earthwork_erosion/Erosion_Sediment_Control_Field_Guide.pdf

Kansas

http://www.ksdot.org/

KDOT Temporary Erosion Control Manual, January 2007

http://www.ksdot.org/burconsmain/Connections/ecm.pdf

Kentucky

http://transportation.ky.gov/Pages/default.aspx

Kentucky BMPs for Controlling Erosion, Sediment, and Pollutant runoff from construction Sites

http://transportation.ky.gov/environmentalanalysis/environmental%20resources/ky%20bmp%20manual%20section%201.pdf

Louisiana

http://www.dotd.state.la.us/

http://www.dotd.la.gov/highways/construction/lab/pdf/embankment/temporary%20erosion%20control.pdf

Maine

http://www.maine.gov/mdot/

Erosion and Sediment Control BMP, revised October 2012

http://www.maine.gov/dep/land/erosion/escbmps/

Maryland

http://www.mdot.maryland.gov/

2011 Maryland Standards and Specifications for Soil Erosion and Sediment Control, December 2011

http://www.mde.maryland.gov/programs/Water/StormwaterManagementProgram/SoilErosionandSedimentControl/Documents/2011%20MD%20Standard%20and%20Specifications%20for%20Soil%20Erosion%20and%20Sediment%20Control.pdf

Massachusetts

http://www.massdot.state.ma.us/

Massachusetts Erosion and Sediment Control Guidelines for Urban and Suburban Areas: A Guide for Planners, Designers, and Municipal Officials, reprint May 2003

http://www.mass.gov/dep/water/laws/policies.htm#storm

Michigan

http://michigan.gov/mdot/

MDOT Soil Erosion and Sedimentation Control Manual, April 2006

http://www.michigan.gov/documents/2006_SESC_Manual_165226_7.pdf

Minnesota

http://www.dot.state.mn.us/

MnDOT Erosoin and Sediment Control Pocketbook Guide, June 2009

http://www.dot.state.mn.us/environment/pdf/erosion-sediment-control-handbook.pdf

Mississippi

http://mdot.ms.gov/portal/home.aspx

Field Manual for Erosion and Sediment Control in Mississippi, 2nd edition 2005

http://www.deq.state.ms.us/MDEQ.nsf/pdf/NPS_Field_Manual_For_Erosion_And_Sediment_Control_Version_2/$File/NPS_FieldManualV2.pdf?OpenElement

Missouri

http://www.modot.org/

MoDOT Stormwater Pollution Prevention Plan, June 2012

http://www.modot.org/business/contractor_resources/documents/MoDOTSWPPPJune2012.pdf

Montana

http://www.mdt.mt.gov/

Erosion and sediment control BMPs: Reference Manual, March 2003 (FHWA/MT-03-006/8165)

http://www.mdt.mt.gov/research/projects/env/erosion.shtml

Nebraska

http://www.dor.state.ne.us/

Nebraska Department of Roads Construction Stormwater BMPs

http://www.dor.state.ne.us/environment/guides/Const-Strmwtr-Pocket%20Guide.pdf

Nevada

http://www.nevadadot.com/

Nevada DOT Storm Water Quality Manuals: Construction Site BMPs Manual, January 2006

http://www.nevadadot.com/uploadedFiles/NDOT/About_NDOT/NDOT_Divisions/Engineering/Hydraulics/2006_Storm_Water_Quality_BMP_Manual.pdf

New Hampshire

http://www.nh.gov/dot/

New Hampshire Stormwater Manual: Volume 3, Erosion and Sediment Controls During Construction, December 2008

http://des.nh.gov/organization/commissioner/pip/publications/wd/documents/wd-08-20c.pdf

New Jersey

http://www.state.nj.us/transportation/

New Jersey DOT Soil Erosion and Sediment Control Standards, 2008

http://www.state.nj.us/transportation/eng/documents/SESC/pdf/SESCStandards2008.pdf

New Mexico

http://www.dot.state.nm.us/content/nmdot/en.html

National Pollutant Discharge Elimination System Manual: Storm Water Management Guidelines for Construction and Industrial Activities, August 2012

http://www.dot.state.nm.us/content/dam/nmdot/Infrastructure/NPDESM.pdf

New York

https://www.dot.ny.gov/index?nd=nysdot

New York State Standards and Specifications for Erosion and Sediment Control, August, 2005

http://www.dec.ny.gov/chemical/29066.html

North Carolina

http://www.ncdot.gov/
Erosion and Sediment control Planning and Design Manual, June 2006, updated March 2009

http://portal.ncdenr.org/web/lr/publications#espubs

North Dakota

http://www.dot.nd.gov/

NDDOT Erosion and Sediment Control Handbook, June 2004

http://www.dot.nd.gov/manuals/environmental/escm/escmfinal.pdf

Ohio

http://www.dot.state.oh.us/pages/home.aspx

Ohio DOT Handbook for Sediment and Erosion Control, February 2000

http://www.dot.state.oh.us/Divisions/ConstructionMgt/Admin/Manuals/Erosion%20Control.pdf

Oklahoma

http://www.okladot.state.ok.us/

Oregon

http://www.oregon.gov/odot/pages/index.aspx

Erosion and Sediment Control Manual, April 2005

http://www.deq.state.or.us/wq/stormwater/docs/escmanual/manual.pdf

Pennsylvania

http://www.dot.state.pa.us/

PennDOT Maintenance Field Reference for Erosion and Sediment Controls, 2003

ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%20464.pdf

Rhode Island

http://www.dot.state.ri.us/

Rhode Island Soil Erosion and Sediment Control Handbook, 1989

http://www.dot.ri.gov/documents/enviro/stormwater/Soil_Erosion_Sediment_Control_Handbook.pdf

South Carolina

http://www.dot.state.sc.us/

http://www.scdot.org/doing/stormwater_Erosion.aspx

South Dakota

http://www.sddot.com/

http://sddot.com/business/design/docs/wqep/section3.pdf

Tennessee

http://www.tdot.state.tn.us/

Tennessee Erosion & Sediment Control Handbook, August 2012

http://www.tnepsc.org/TDEC_EandS_Handbook_2012_Edition4/TDEC%20EandS%20Handbook%204th%20Edition.pdf

Texas

http://www.txdot.gov/

Texas DOT Storm Water Field Inspector's Guide, June 2004

http://ftp.dot.state.tx.us/pub/txdot-info/library/pubs/bus/natural/inspectors_guide.pdf

Utah

http://www.udot.utah.gov/main/f?p=100:6:0::::V,T:,1

Utah DOT Erosion and Sediment Control Field Guide, July 2010

http://www.udot.utah.gov/main/uconowner.gf?n=15220806279436191

Vermont

http://www.aot.state.vt.us/

The Vermont Standards and Specifications for Erosion Prevention and Sediment Control, 2006

http://www.anr.state.vt.us/dec/waterq/stormwater/docs/construction/sw_vt_standards_and_specifications_2006_updated_2_20_2008.pdf

Virginia

http://www.virginiadot.org/

Virginia Erosion and Sediment Control Handbook, 1992

http://www.dcr.virginia.gov/stormwater_management/e_and_s-ftp.shtml

Washington

http://www.wsdot.wa.gov/

Highway Runoff Manual, Chapter 6: Temporary Erosion and Sediment Control Design Guidelines and Process, November 2011

http://www.wsdot.wa.gov/publications/manuals/fulltext/M31-16/chapter6.pdf

West Virginia

http://www.transportation.wv.gov/Pages/default.aspx

WV DOT Division of Highways Erosion and Sediment Control Manual, March 2003

http://www.transportation.wv.gov/highways/engineering/files/EROSION/Erosion2003.pdf

Wisconsin

http://www.dot.wisconsin.gov/

Wisconsin Erosion Control Product Acceptability List, July 2012

http://www.dot.wisconsin.gov/business/engrserv/docs/pal.pdf

Wyoming

http://www.dot.state.wy.us/wydot

Wyoming DOT Pollution controls and BMPs for Storm Water During Construction

http://www.dot.state.wy.us/files/content/sites/wydot/files/shared/Construction/WYDOT-field-guide,4-6-11%5B1%5D.pdf

APPENDIX B: TSS/TDS RESULTS

Measured total suspended solids (TSS) and conductivity and corresponding total dissolved solids (TDS) values shown for each sample collected during ASTM D 7351 tests. Conductivity was not measured and therefore TDS not calculated for the initial (failed) test of Type C silt fence, test number 2. Test numbers are as described in Table 15: Summary of ASTM D7351 testing. Values not measured are indicated by *NM*.

Table B-1: Measured TSS, test 1.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	1429.3	1437.0	1433.14
10	2137.3	2144.5	2140.90
15	686.2	741.7	713.93
20	2625.5	2436.4	2530.95
25	734.3	734.9	734.64
30	377.5	354.2	365.85
35	89.7	103.8	96.71
40	70.0	99.4	84.70
45	65.5	73.4	69.43
50	33.8	46.8	40.32
55	36.5	39.5	38.00
60	47.0	45.2	46.07
65	194.5	36.7	115.60
70	42.0	32.4	37.20
75	37.0	29.6	33.30
80	35.5	38.1	36.80

Table B-2: Measured conductivity/TDS, test 1.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	107.83	94.62	101.22	68.81
10	72.04	105.46	88.75	60.33
15	65.47	93.46	79.47	54.02
20	64.35	94.69	79.52	54.06
25	65.35	96.23	80.79	54.92
30	52.18	99.08	75.63	51.41
35	84.46	96.54	90.50	61.52
40	88.31	102.46	95.38	64.84
45	90.85	100.77	95.81	65.13
50	88.15	89.46	88.81	60.37
55	83.85	90.62	87.23	59.30
60	106.15	97.08	101.62	69.08
65	99.23	94.46	96.85	65.84
70	98.23	93.31	95.77	65.10
75	94.62	91.77	93.19	63.35
80	99.00	91.08	95.04	64.61

Table B-3: Measured TSS, test 2.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	6035.0	6767.5	6401.25
10	7547.5	12265.0	9906.25
15	3237.5	5537.5	4387.50
20	9282.5	10137.5	9710.00
25	12100.0	12962.5	12531.25
30	2875.0	3172.5	3023.75
35	14747.5	15407.5	15077.50
40	1055.0	1485.0	1270.00
45	15.0	145.0	80.00

Table B-4: Measured TSS, test 2B.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	4722.6	5100.3	4911.43
10	768.8	883.9	826.33
15	1572.6	1842.5	1707.55
20	2802.1	3524.1	3163.10
25	1944.6	2252.8	2098.68
30	930.2	1053.9	992.03
35	147.6	177.7	162.60
40	100.1	122.8	111.48
45	57.4	61.3	59.33
50	58.0	62.3	60.15
55	52.8	58.8	55.78
60	58.8	60.8	59.82
65	44.1	56.6	50.35
70	73.6	80.2	76.90
75	58.5	60.3	59.38
80	76.3	78.4	77.38
85	26.7	30.3	28.50
90	26.2	24.6	25.45

Table B-5: Measured conductivity/TDS, test 2B.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	86.31	112.00	99.15	67.40
10	94.77	111.31	103.04	70.05
15	99.77	110.00	104.88	71.30
20	110.92	110.92	110.92	75.41
25	101.38	99.62	100.50	68.32
30	111.77	98.15	104.96	71.35
35	71.08	101.54	86.31	58.67
40	96.54	76.15	86.35	58.70
45	91.54	106.46	99.00	67.30
50	110.62	112.85	111.73	75.95
55	107.92	108.92	108.42	73.71
60	112.92	115.31	114.12	77.58
65	119.69	117.46	118.58	80.61
70	125.23	117.08	121.15	82.36
75	120.54	117.00	118.77	80.74
80	125.15	115.38	120.27	81.76
85	114.69	110.77	112.73	76.63

90	114.31	105.85	110.08	74.83

Table B-6: Measured TSS, test 3.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	3101.2	2883.6	2992.38
10	2492.7	2329.7	2411.20
15	7585.9	8006.6	7796.23
20	12589.6	12305.2	12447.40
25	12812.5	11633.8	12223.15
30	6854.5	6420.8	6637.63

Table B-7: Measured conductivity/TDS, test 3.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	176.00	122.00	149.00	101.29
10	135.15	111.43	123.29	83.81
15	113.54	98.07	105.80	71.93
20	139.75	81.64	110.70	75.25
25	116.85	95.71	106.28	72.25
30	110.54	65.94	88.24	59.98

Table B-8: Measured TSS, test 4.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	4114.1	4180.7	4147.38
10	4249.4	4451.7	4350.57
15	7968.3	7908.2	7938.21
20	8652.1	8697.4	8674.73
25	7815.3	7790.4	7802.83
30	6843.5	6725.6	6784.55
35	941.4	907.2	924.28
40	610.5	550.9	580.70
45	455.7	398.4	427.10
50	412.0	219.8	315.90

Table B-9: Measured conductivity/TDS, test 4.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	142.92	142.92	142.92	97.16
10	130.23	130.23	130.23	88.53
15	115.15	115.15	115.15	78.28
20	125.69	125.69	125.69	85.45
25	144.92	144.92	144.92	98.51
30	125.17	125.17	125.17	85.09
35	168.09	168.09	168.09	114.27
40	166.18	166.18	166.18	112.97
45	138.58	138.58	138.58	94.21
50	189.36	189.36	189.36	128.73

Table B-10: Measured TSS, test 5.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	3662.7	3755.75	3709.23
10	4843.5	4869.5	4856.50
15	3205.7	3003	3104.35
20	3394.0	3503.35	3448.68
25	2787.5	2801.2	2794.35
30	4595.6	4643.9	4619.73
35	1798.8	1750.75	1774.78
40	1034.7	1056.6	1045.63
45	357.35	351.55	354.45

Table B-11: Measured conductivity/TDS, test 5.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	129.33	142.50	135.92	92.40
10	130.42	143.00	136.71	92.93
15	115.08	99.00	107.04	72.77
20	124.42	131.42	127.92	86.96
25	113.33	131.92	122.63	83.36
30	129.33	132.75	131.04	89.08
35	128.50	156.18	142.34	96.76
40	138.33	139.67	139.00	94.49
45	147.33	140.08	143.71	97.69

Table B-12: Measured TSS, test 6.

Elapsed Time (min)	Trial 1 TSS (mg/L)	Trial 2 TSS (mg/L)	Average TSS (mg/L)
5	4743.5	4731.67	4737.58
10	4990.0	4990	4990.00
15	4800.0	4780	4790.00
17.5	6231.7	6010	6120.83
20	8908.3	8590	8749.17
25	6845.0	6870	6857.50
30	5463.3	5457.5	5460.42
35	4850.0	5510	5180.00
40	7183.3	6462.5	6822.92
45	4913.3	4860	4886.67
50	1951.7	1730	1840.83
55	843.3	1003.75	923.54
60	1008.3	746.67	877.50
65	825.8	675	750.42
70	1150.8	998.33	1074.58
75	1172.5	1038.33	1105.42
80	1151.7	998.33	1075.00

Table B-13: Measured conductivity/TDS, test 6.

Elapsed Time (min)	Trial 1 Conductivity (us/cm)	Trial 2 Conductivity (us/cm)	Average Conductivity (us/cm)	TDS (mg/L) y=0.6798x x=cond.
5	559.29	NM	559.29	380.20
10	321.39	NM	321.39	218.48
15	283.44	NM	283.44	192.68
17.5	109.60	NM	109.60	74.51
20	94.35	NM	94.35	64.14
25	66.65	NM	66.65	45.31
30	116.76	NM	116.76	79.37
35	105.24	NM	105.24	71.54
40	274.71	NM	274.71	186.75
45	222.23	NM	222.23	151.07
50	236.33	NM	236.33	160.65
55	211.05	NM	211.05	143.47
60	294.00	NM	294.00	199.86
65	261.60	NM	261.60	177.84
70	247.97	NM	247.97	168.57
75	335.23	NM	335.23	227.89
80	282.17	NM	282.17	191.82

APPENDIX C: TURBIDITY RESULTS

Measured turbidity vales for samples collected downstream of SCD installation are shown in following tables. Test numbers are as described in Table 15: Summary of ASTM D7351 testing. Values not measured are indicated by *NM*.

Table C-1: Measured turbidity downstream, test 1.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	442	463	455	331	319	309
10	475	500	494	458	465	465
15	276	307	295	312	285	283
20	537	531	525	528	524	513
25	267	276	273	330	351	339
30	390	377	386	417	392	403
35	139	140	134	139	132	140
40	122	124	125	135	122	127
45	85	85	84	86	85	89
50	60	57	62	66	61	72
55	66	63	66	64	63	59
60	67	71	73	77	71	74
65	71	77	74	79	75	75
70	61	62	65	65	65	64
75	66	65	69	64	65	65
80	70	71	74	71	76	74

Table C-2: Measured turbidity downstream, test 2.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	402	409	387	379	372	400
10	424	444	446	342	328	391
15	410	338	330	430	421	475
20	417	397	392	514	503	462
25	564	563	560	549	537	569
30	224	215	215	244	285	243
35	792	784	778	667	746	659
40	168	162	150	157	157	175

Table C-3: Measured turbidity downstream, test 2b.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	632	590	590	420	416	401
10	416	417	401	288	283	301
15	452	457	450	350	365	358
20	704	720	737	544	570	584
25	392	423	403	515	565	519
30	259	295	268	260	264	264
35	180	197	200	NM	NM	NM
40	151	158	154	NM	NM	NM
45	109	108	109	NM	NM	NM
50	108	112	110	NM	NM	NM
55	99.6	101	103	NM	NM	NM
60	92	89.9	96	NM	NM	NM
65	95.5	96.6	98	NM	NM	NM
70	136	129	137	NM	NM	NM
75	100	101	98.4	NM	NM	NM
80	109	106	111	NM	NM	NM
85	59.7	58.7	62.5	NM	NM	NM
90	54.8	57	60.1	NM	NM	NM

Table C-4: Measured turbidity downstream, test 3.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	233	259	260	289	296	305
10	403	395	399	513	514	555
15	524	506	483	530	581	504
20	624	638	660	599	652	637
25	566	582	615	460	489	503
30	377	382	395	465	487	469

Table C-5: Measured turbidity downstream, test 4.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	617	585	582	415	432	412
10	744	647	719	585	600	588
15	732	737	742	795	813	743
20	836	814	785	739	813	798
25	621	586	653	637	658	618
30	763	766	750	535	541	568
35	489	515	467	382	410	409
40	285	276	277	348	332	349
45	263	270	258	167	170	170
50	524	524	520	528	535	536

Table C-6: Measured turbidity downstream, test 5.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	413	397	391	458	463	468
10	353	376	355	417	424	388
15	455	462	424	528	537	502
20	277	302	293	443	448	473
25	616	562	586	628	586	595
30	751	642	693	724	735	721
35	461	487	495	464	462	478
40	460	431	438	566	552	589

45	556	571	521			

Table C-7: Measured turbidity downstream, test 6.

Elapsed Time (min)	TRIAL 1			TRIAL 2		
	NTU 1	NTU 2	NTU 3	NTU 1	NTU 2	NTU 3
5	702.1	717.4	656.8	659.4	661.7	652.7
10	670.2	671	682.2	619.5	624.7	612.5
15	684.9	700.9	693.1	485.8	477.7	480.9
17.5	565	553.3	546.6	480.3	508.3	537.2
20	528.3	517.2	540.6	569.3	580.7	594.8
25	471.2	461.4	474.9	527.3	509.1	552.5
30	523.7	512.7	523	660.3	641.3	637.7
35	479.2	478.7	474.3	556.8	569.2	566.3
40	844.9	831.2	826.9	617.9	566.5	601.3
45	482.8	492.2	478.5	456.2	478.4	488.7
50	286.8	295.3	291.2	297.6	296.1	291.4
55	272.9	270	280.1	210.4	207.9	204.7
60	239.8	237.9	240.6	334.3	326.8	332
65	269.3	260.2	265.2	251.6	251.7	254.4
70	287.3	286	288.8	358.2	356.5	360.7
75	346.2	348.2	337.3	397.1	402.8	406.3
80	450	447.3	447.6	378.2	374.4	382.2

APPENDIX D: NUTRIENT RESULTS

Nutrient measurements are shown in the following tables. A table is included for each of the four nutrients tested. Measurements are sorted by test number and sample. Test numbers 1, 5 and 9 correspond to nutrients measured after the first, fifth and ninth liter of DI rinse water was passed through the samples, respectively. Test numbers 10 and 11 correspond to filtered test water and one rinse of DI water after the test water, respectively. Test *N* is the prepared test water. Samples A through E are 18” sock compost, 12” sock compost, cypress mulch, hardwood mulch and straw, respectively. Check tests are prepared solutions used to verify the performance and consistency of the nutrient test methods.

Table D-1: Measured Nitrite (NO_2) by sample.

Test #	Sample	Trial 1 Measured NO_2 (ppm)	Trial 2 Measured NO_2 (ppm)	Test #	Sample	Trial 1 Measured NO_2 (ppm)	Trial 2 Measured NO_2 (ppm)
1	A	0.400	0.400	10	A	0.980	2.300
1	B	0.420	0.500	10	B	0.340	0.315
1	C	0.040	0.170	10	C	0.172	0.040
1	D	0.520	0.480	10	D	0.002	0.065
1	E	-0.080	0.040	10	E	0.044	0.105
check1	0.32	0.311		11	A	1.890	1.900
5	A	4.700		11	B	0.120	0.145
5	B	0.740	0.700	11	C	0.036	0.035
5	C	0.035	0.040	11	D	0.038	0.065
5	D	0.215	0.225	11	E	0.068	0.075
5	E	0.078	0.080	check5	0.4	0.378	
check2	0.2	0.184		N	A	0.474	
check6	0.32	0.310		N	B	0.490	
9	A	4.900		N	C	0.480	
9	B	0.235	0.220	N	D	0.490	
9	C	0.020	0.025	N	E	0.500	
9	D	0.080	0.078				
9	E	0.068	0.068				

check3	0.4	0.393					

Table D-2: Measured Ortho-phosphate (P) by sample.

Test #	Sample	Trial 1 Measured P (ppm)	Trial 2 Measured P (ppm)	Test #	Sample	Trial 1 Measured P (ppm)	Trial 2 Measured P (ppm)
1	A	2.600	2.400	10	A	2.280	5.300
1	B	0.600	0.500	10	B	0.276	0.240
1	C	1.050	0.940	10	C	0.314	0.320
1	Db	26.500	24.520	10	D	0.284	0.335
1	Eb	34.000	31.720	10	E	2.856	2.775
check	0.1ppm	0.094		11	A	4.790	24.500
5	A	9.500		11	B	0.188	0.215
5	B	0.890	0.925	11	C	0.136	0.145
5	C	0.068	0.070	11	D	0.208	0.260
5	D	0.478	0.480	11	E	1.740	1.745
5	E	3.025	3.060	check5	0.2ppm	0.174	
check6	0.08ppm	0.055		N	A	0.510	
check	0.05ppm	0.049		N	B	0.525	
9	B	9.800		N	C	0.530	
9	B	0.275	0.285	N	D	0.525	
9	C	0.043	0.045	N	E	0.545	
9	D	0.153	0.173				
9	E	2.130	2.135				
check2	0.2ppm	0.173					

Table D-3: Measured Nitrate (NO_3) by sample.

Test #	Sample	Trial 1 Measured NO3 (ppm)	Trial 2 Measured NO3 (ppm)	Test #	Sample	Trial 1 Measured NO3 (ppm)	Trial 2 Measured NO3 (ppm)
1	A	2.2400	1.6000	10	A	0.4600	0.3600
1	B	2.6600	1.1000	10	B	0.2240	0.1960
1	C	-0.0280	-0.5600	10	C	0.2580	0.0767
1	D	-0.0560	0.0800	10	D	0.0840	0.0420
1	E	-0.1320	-0.0800	10	E	0.0000	0.0180
check	0.4ppm	0.4550	--	check	1ppm	0.8660	--
check	1ppm	--	1.1040	11	A	0.8240	1.4800
5	A	0.9033	1.0300	11	B	0.1000	0.1760
5	B	0.4800	0.7150	11	C	0.0300	0.0440
5	C	0.0200	-0.0500	11	D	-0.0020	0.1120
5	D	-0.0300	-0.0600	11	E	0.1040	-0.0280
5	E	-0.0340	-0.0317	N	A	0.5060	--
check	0.4ppm	0.3500	--	N	B	0.5270	--
check	0.6ppm	--	0.6360	N	C	0.4740	--
9	A	1.7575	1.0700	N	D	0.5260	--
9	B	0.1400	0.2050	N	E	0.4800	--
9	C	0.0450	0.0125				
9	D	-0.0250	-0.0325				
9	E	-0.0775	-0.0438				
check	1ppm	1.0610	--				
check	0.4ppm	--	0.3330				

Table D-4: Measured Ammonia (NH_3) by sample.

Test #	Sample	NH_3-N Ion Rdg #1	NH_3-N Ion Rdg #2	Test #	Sample	NH_3-N Ion Rdg #1	NH_3-N Ion Rdg #2
1	A	1.7500	1.3800	10	A	3.5600	7.3600
1	B	0.3300	0.4980	10	B	0.4220	0.4000
1	C	0.1400	0.1810	10	C	--	--
1	D	0.0048	0.0028	10	D	0.1530	0.2180
1	E	0.0150	0.1230	10	E	0.5400	0.7400
5	A	1.2600	1.3400	11	A	1.7600	0.9510
5	B	0.1900	0.3600	11	B	0.1900	0.1810
5	C	0.4810	0.6900	11	C	0.0431	0.5000
5	D	0.2870	0.1050	11	D	0.0352	0.2200
5	E	0.6840	0.1250	11	E	0.0724	0.2870
9	A	2.3600	2.9100	check1	0.3	0.414	--
9	B	0.7480	1.5600	check2	0.5	0.451	--
9	C	0.1750	0.4440	check3	0.7	0.684	--
9	D	0.2310	0.3660	check4	1	0.74	--
9	E	0.1350	1.1300	check5	2	1.24	--
				check6	2.5	1.88	--
				check7	3	2.35	--
				check8	5	4	--

APPENDIX E: METAL RESULTS

Measured metal concentrations for the prepared metal solution and filtered samples are shown according to test number and filter material. Aliquots prepared for testing included a known concentration of Yttrium. The percent Yttrium recovered during testing is shown for each sample measured. Measured results are corrected for volume reductions (aliquot size). Measurements are an average of three test iterations.

Table E-1: Measure metal concentrations.

Material	M Prepared metal solution (ppm)			Yttrium recovery (%)
	Cu	Zn	Pb	
18" Compost sample	0.479	0.455	0.456	103.6
12" Compost sample	0.467	0.464	0.463	101.4
Cypress mulch	0.468	0.467	0.464	101.8
Hardwood mulch	0.459	0.452	0.459	99.2
Straw	0.481	0.466	0.468	96.9
Material	Test 12 Filtered metal solution (ppm)			Yttrium recovery (%)
	Cu	Zn	Pb	
18" Compost sample	0.002	0.016	0.002	104.3
12" Compost sample	0	0.012	0	105.3
Cypress mulch	0.053	0.095	0.035	103.5
Hardwood mulch	0.002	0.018	0.012	100.8
Straw	0.236	0.314	0.218	104.0
Material	Test 13 1L DI rinse after metal test (ppm)			Yttrium recovery (%)
	Cu	Zn	Pb	
18" Compost sample	0.014	0.028	0.002	103.9
12" Compost sample	-0.008	0.004	-0.002	100.3
Cypress mulch	-0.008	0.004	0.002	102.8
Hardwood mulch	-0.01	0.006	0.002	101.3
Straw	0.01	0.022	0.012	104.8

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Figure 85