FEASIBILITY FOR APPLICATION OF

SOIL BIOENGINEERING TECHNIQUES

TO

NATURAL WASTEWATER TREATMENT SYSTEMS

BY

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Soil Bioengineering and natural treatment systems, two surprisingly similar technologies, each have their "roots" in Europe in the 1500's, were both refined in the 19th century, and were both redeveloped scientifically in the middle of the 20th century. Yet for all these parallels in principles and historical development, apparently no one has attempted to integrate these two technologies. Without the profound influence of two highly competent professionals, the thought of using Soil Bioengineering for natural treatment systems would have never occurred to me:

• Dr. Raymond Loehr has been a superb teacher, a true mentor, and a good friend. His adroit mastery of the environmental discipline will forever be a model to strive for in my profession.

• Robbin B. Sotir is a catalytic entrepreneur and a premier champion of Soil Bioengineering in this country. Her motivating insights and our exciting work experience together are what brought me to this research topic to begin with. Her assistance in developing this report has been priceless.

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I. EXECUTIVE SUMMARY

This report examines the general feasibility for application of Soil Bioengineering techniques in construction, operation, and management of natural wastewater treatment systems.

Soil Bioengineering is an applied science that combines structural, biological, and ecological concepts to construct living structures for erosion, sediment, and flood control (Sotir and Gray, 1989). Using live plant parts as major structural components to reinforce the soil mantle, Soil Bioengineering offers natural and effective solutions to land instability problems along streams and rivers, transportation and utilities transmission corridors, and in forest and wetlands sites.

Natural treatment systems are wastewater treatment processes which use the soil-water-plant matrix as a "natural reactor" for physically, chemically, and biologically stabilizing applied wastes . Recognized natural treatment systems currently include constructed and natural wetlands, aquatic plant systems (aquaculture), wastewater stabilization ponds, and land application of wastes, termed "land treatment".

As a result of renewed interest in this technology, natural treatment systems design and performance has been considerably improved over the last two decades, but there are still several limitations, such as slope restriction, flow distribution, short-circuiting caused by erosion, and limited availability of suitable land area. Since these are mainly limitations to soil-based systems, this report focuses on application of Soil Bioengineering to overland flow (OF) and slow rate (SR) non-crop and forest irrigation land treatment systems.

Slow rate (SR) land treatment is the application of wastewater at a controlled rate to vegetated land by spray or surface irrigation (WPCF, 1990). Wastewater is treated as it percolates vertically through the soil profile, removing pollutants by microbial activity, adsorption, and vegetative uptake. While capable of the highest degree of wastewater treatment of any natural system, SR sites are limited by slope erosion and low nitrogen removal in established forests.

Overland flow (OF) is a land treatment process in which wastewater is treated as it flows down carefully graded slopes of low permeability soil (Reed, et al , 1988). Vegetative stems, surface roots, litter and the soil surface itself serve as microbial attached-growth strata and adsorptive sites to renovate wastewater flowing past. OF sites are also limited by excess slope and unevenly distributed flow across the slope, leading to surface erosion and "channeling" of wastewater flow, consequently short-circuiting treatment.

The Soil Bioengineering approach essentially uses live woody plants or plant cuttings, taken during their dormant season, and emplaces them in a soil slope in various configurations ("living systems") to provide immediate mechanical soil reinforcement and stabilization. During the growing season, "adventitious" rootings develop along the buried length of the plant cuttings, creating a measure of apparent cohesion, which biologically reinforces the soil mantle beyond mechanical stabilization capability (Gray and Ohashi, 1983).

Natural treatment systems are a cost-effective method for renovating wastewater, but are limited by land availability and suitability. Variations to the original slow rate irrigation process have overcome many of these limitations, except for the limitation of excessive slope. Restriction of slopes to 2 to 15% was subjectively developed based on irrigation standards used to combat surface erosion and mass instability. If surface erosion and mass instability can be controlled, steeper sloped land and sites with significant topographic relief could be considered as candidates for land treatment sites. An immediate benefit is that steeper sloped and high relief sites are typically less expensive to acquire.

Nutter (1975) confirmed earlier research (Hewlett and Hibbert, 1963) showing that under draining conditions water in the vadose zone will move *parallel to the slope surface* down the slope rather than simply infiltrate vertically. Nutter, et al. (1979) validated this conclusion in the field at an operational SR land treatment site. Reed and Bastian (1990) also confirmed lateral water movement on a forest SR site. Given that SR land treatment systems essentially act as an attached-growth bioreactor under a first order plug flow kinetics model (Eckenfelder, 1966), dependence of removal efficiency on travel distance through the media means that a steeper sloped site with lateral flow will achieve a much higher performance than a conventional "flat" SR system.

Operating under similar first order plug flow kinetics, OF sites rely on large travel distances (45 - 60 m) downslope to boost wastewater detention time, the critical controlling factor for treatment efficiency. Martel and co-workers (1982), in developing a first order model based on detention time to describe OF performance, noted that vegetation density and pattern significantly affected slope detention time. Peters, et al.(1981) confirmed this conclusion, observing that dense vegetation on an 8% slope actually gave it a longer detention time than a poorly vegetated 2% slope.

The wastewater treatment benefits of lateral slope flow for SR sites and vegetation density and pattern for OF sites are inherently achieved by the two basic objectives of Soil Bioengineering living systems considered in this report: mass stabilization and surface erosion prevention. Of the 32 currently developed living systems (Schiechtl, 1980), five were considered as most applicable for use at natural treatment sites. Brushlayer, live cribwall and branchpacking are predominantly mass stabilization techniques, while live fascine and brushmattress are designed primarily for surface erosion prevention.

Brushlayering consists of placing woody species such as willow (Salix spp.) or cottonwood (Populous spp.) in prepared terraces, called "benches", along slope contours. The most prevalent

Soil Bioengineering technique, brushlayer may be used for reinforcing fill slopes during construction or for rehabilitation of an eroded or failed cut slope. A live cribwall is a hollow, box-like interlocking arrangement of untreated logs or timbers, the inside of which is filled with suitable soil. Live branches extend through the box and into the slope behind. A very site-specific technique, live cribwall is useful in areas where space is limited and a very steep slope must be instantly stabilized, such as adjacent to a drop structure or at the toe of a slope of terrace face. Branchpacking consists of alternating layers of live branch cuttings and soil, secured vertically with "dead stout stakes" of wood or metal. Like live cribwall, this is also a specialized Soil Bioengineering system used typically for earth reinforcement and mass stability of small earthen fill sites. The system produces a filter barrier, reducing scour and erosion and providing immediate stabilization.

Live fascine is a sausage-like bundle of live plant material, usually woody herbaceous cuttings. Placed horizontally (on slope contour), these structures will root along their entire length and create a "mini-dam", preventing soil loss and increasing sedimentation and organic texture in a poor soil. Live fascines also act as soil moisture "regulators", first channeling water laterally from the slope, and, after rooting, removing ground water through transpiration. Brushmattress, or brush matting, is essentially a mulch of hardwood brush cuttings fastened down with stakes and wire. It is primarily used as a surface erosion control technique, providing shallow soil protection against the impact of heavy rains and running water.

As adventitious rooting develops, brushlayer, branchpacking and live cribwall will not only prevent mass instability but create an outstanding aerobic and organic soil-plant matrix through which wastewater will laterally flow in a steeper sloped SR site. These constructions are also effective at surface erosion prevention, but live fascine and brushmattress are specifically tailored to this task by bringing a large amount of biomass to bear at certain points in the water flow path.

This dense foliage, coupled with the shallow planting depth, make live fascine and brushmattress very effective for OF systems on steeper slopes.

A review of Soil Bioengineering woody vegetation performance characteristics revealed that many of the woody species employed in Soil Bioengineering are known to be effective in renovating wastewater. Species with high water, sediment, and salt tolerances, such as black willow (Salix nigra) and eastern cottonwood (Populus deltoides) are ideal for Soil Bioengineering systems employed in OF and SR sites.

Live fascines and brushmattress will overcome critical slope-related problems for OF sites by preventing surface erosion and ensuring uniform distribution of wastewater across the slope. Live cribwall and branchpacking techniques should be useful in terracing of OF sites, potentially serving as an active "vertical filtration" treatment component. Brushlayer is not recommended for OF sites because of the tendency to increase infiltration. Brushlayer will be effective on steeper sloped SR sites, however, along with live fascines, and perhaps live cribwall or branchpacking if terracing is required. Combining these techniques with lateral slope flow to the fullest extent can result in an alternative method of treatment similar to a soil-based version of a subsurface flow constructed wetland -- the "Constructed Brushland".

Further research is vital to validate and confirm the feasibility of Soil Bioengineering techniques in natural wastewater treamtne systems. Results from pilot and field studies could yield ground-breaking advances in land treatment methods.

It is readily apparent that these two technologies are compatible and will greatly benefit each other in both preserving the landscape and cleaning the environment. Extremely effective low-cost wastewater treatment on previously unsuitable land is highly feasible by teaming with nature's strengths rather than fighting to overcome them.

II. STATEMENT OF OBJECTIVES

A. INTRODUCTION

This report examines the general feasibility for application of Soil Bioengineering techniques in construction, operation, and management of natural wastewater treatment systems.

Soil Bioengineering is an applied science that combines structural, biological, and ecological concepts to construct living structures for erosion, sediment, and flood control (Sotir and Gray, 1989). Using live plant parts as major structural components to reinforce the soil mantle, Soil Bioengineering offers natural and effective solutions to land instability problems along streams and rivers, transportation and utilities transmission corridors, and in forest and wetlands sites.

Though relatively unknown in the United States today, this rapidly re-emerging European technology dates back to the 1500's. Broad advances in concrete and steel technology at the turn of the century led to the abandonment in America of vegetative structures in favor of rigid, inert construction materials. Increased use of Soil Bioengineering is occurring in North America today due to renewed research showing that plant systems are more permanent, flexible, and environmentally responsible than concrete revetments, steel retaining walls and other "hard" systems.

Another re-emerging technology is the use of natural systems for treatment of wastewater. Natural treatment systems are wastewater treatment processes which use the soil-water-plant matrix as a "natural reactor" for physically, chemically, and biologically stabilizing applied wastes . Recognized natural treatment systems currently include constructed and natural wetlands, aquatic plant systems (aquaculture), wastewater stabilization ponds, and land application of wastes, termed "land treatment".

In the nineteenth century, land application of wastewater had been the only acceptable method for waste treatment, but it gradually slipped from use with the invention of modern devices such as the Imhoff tank, sedimentation basins, and the activated sludge process (Reed, et al., 1988). Renewed interest in land treatment and other natural treatment systems followed passage of the 1972 Amendments to the Federal Water Pollution Control Act (the Clean Water Act) as a result of the need to use innovative and less costly treatment systems. Studies at that time and subsequent research showed that natural treatment could realize the statutory goal of "zero discharge" of pollutants.

The use of bioengineering construction for water renovation has been suggested (Schiechtl, 1980), but little if any research has been done in the area of wastewater treatment using these methods. Natural treatment systems design and performance has been considerably improved over the last two decades, but there are still several limitations in design and operation, such as slope limitations, flow distribution, short circuiting, and limited availability of suitable land area.

B. OBJECTIVES

The primary objective for this report is to indicate how natural treatment system limitations can be managed by applying Soil Bioengineering principles and techniques. Since no experimental research has been done for this specific report, methodology for achieving this objective will be an engineering interpretation of the compatibility of the two technologies.

The ultimate goal of this report is to stimulate further research and experimentation to verify potential performance, benefits, and drawbacks to suggested systems. All types of natural treatment systems might conceivably benefit from Soil Bioengineering techniques, but the unique aspects of this science are most applicable to non-aquatic, or "soil-based" systems, namely land treatment. This report will focus on applications of Soil Bioengineering to land treatment systems.

One type of natural treatment system not listed above is sludge application to land for treatment and disposal or for renovation of drastically disturbed land. This area has already been shown in the literature to benefit from Soil Bioengineering techniques (Schiechtl, 1980: Gray and Leiser, 1982). Since this technology has been fairly well established, it will not be explored in this report.

Specific objectives for this report include:

1. Define Soil Bioengineering, including aspects of the science and constructions that are of potential benefit to the environmental engineering field in general.

2. Determine the general feasibility of Soil Bioengineering techniques in:

   a. Overland Flow Land Treatment systems.

   b. Non-crop and Forest Slow Rate Irrigation Land Treatment systems.

   c. other potential applications for pollution and waste management.

3. Evaluate the potential performance of Soil Bioengineering techniques for enhancement of biodegradation, adsorption, and vegetative uptake of wastewater constituents in the land treatment systems.

Analysis, evaluation and conclusions will follow a general description of Soil Bioengineering and the specific natural treatment systems mentioned above.

III. DESCRIPTION OF NATURAL TREATMENT SYSTEMS

A. NON-CROP/FOREST SLOW RATE IRRIGATION LAND TREATMENT

1. Description.

Slow rate irrigation (SR) land treatment is the application of wastewater at a controlled rate to a vegetated land surface (WPCF, 1990). Wastewater is applied by spray or surface irrigation and is treated as it infiltrates through the soil-plant matrix. A portion of the flow percolates to ground water, with the remainder taken offsite by evapotranspiration, as shown in Figure 1. Offsite surface runoff is avoided in design, so that this system typically results in "zero discharge" of pollutants, as defined by the Clean Water Act (EPA, 1981).

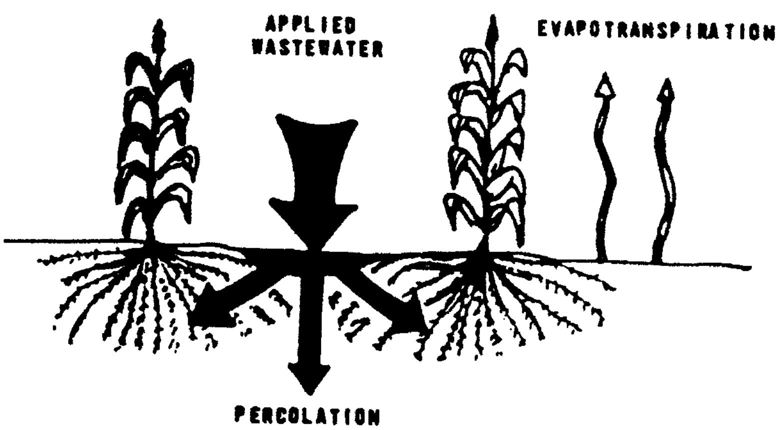


FIGURE 1. SLOW RATE LAND TREATMENT PROCESS
(adapted from EPA, 1981)

The treatment process occurs physically, chemically, and biologically as the wastewater percolates vertically through the soil. Organics are degraded within the first few feet of the soil profile by carbonaceous and nitrifying bacteria. Mineralized nitrogen is removed primarily through vegetative uptake. Degraded organics and other nutrients (e.g., phosphorus) in the wastewater are taken up by vegetation or are adsorbed or precipitated in the soil matrix. Heavy metals and refractory organics are removed by adsorption and precipitation mechanisms. Intermittent application cycles and moderate to highly permeable soil maintains an aerobic environment for enhanced biological activity.

SR was the first type of land treatment system to be developed, dating back to a "sewage irrigation farm" devised in Brunslaw, Germany, in 1531(Jewell and Seabrook, 1979). The practice was refined extensively in the 1800's in England and the United States. After losing favor in the early 1900's, it regained prominence in the '70's and '80's and has evolved into a well-defined, controlled system.

The two basic types of SR systems are defined by their design objectives. A Type 1 system has the principal objective of wastewater treatment - the wastewater application rate is not controlled by crop water requirements, but by the land's ability to assimilate each particular constituent in the waste. Type 2 systems establish water reuse through crop production as the primary objective, and are designed to apply sufficient wastewater to meet crop irrigation requirements for optimum production (WPCF, 1990).

Due to the intensive agricultural maintenance, restriction to relatively flat slopes for crop cultivation, and specific land shaping requirements (furrowing), Type 2 systems have been excluded in this report as candidates for Soil Bioengineering techniques.

Type 1 systems may be further classified by the type of vegetation used, either non-crop herbaceous systems (e.g., forage grasses) or forest systems. Temporary wastewater storage may be required during the nongrowing season for grass systems, while forest systems may be irrigated all year around.

2. <u>System Performance and Applicability.</u>

Annual hydraulic loading of a typical slow rate site ranges from 0.5 to 6.0 m^3/m^2-yr (10 to 150 gal/sq ft/yr), which is the lowest of all types of land treatment (EPA, 1981). The slow rate method is applicable in the widest range of acceptable soil permeabilities, soil conditions, and vegetation selection, making it the most flexible and potentially useful system. This flexibility leads to the highest degree of wastewater treatment of any natural treatment system, with total nitrogen, phosphorus, biochemical oxygen demand (BOD) and suspended solids each less than 3.0 mg/L in the percolate reaching ground water or surface waters (EPA, 1981).

3. <u>SR Limitations</u>.

Forest and non-crop SR systems (Type 1) offer several advantages over agricultural (Type 2) systems, including higher infiltration rates, lower site acquisition costs, higher cold weather soil temperatures, and suitability of forest sites on steeper grades than agricultural sites. These systems, however, have some pronounced limitations in their design and operation (EPA, 1981):

- Water needs and tolerances of some existing tree species may be low,

- Nitrogen removals in established forest systems are relatively low, requiring larger land areas for equivalent hydraulic loading.

- Forage grass sites are limited to grades similar to agricultural sites (2% to 8%, generally) due to surface erosion and excess runoff, causing short circuiting of treatment.

- Forest soils may be rocky, very shallow, and non-uniform in contour, creating channeling, erosion, and increased runoff and short circuiting.

B. OVERLAND FLOW LAND TREATMENT

1. Description.

Overland Flow (OF) is a land treatment process in which wastewater is treated as it flows down carefully graded slopes (Reed, et. al., 1988). Wastewater is either spray- or surface-applied to the top of a slope, called a "terrace", and flows in a thin uniform sheet across the vegetated surface to runoff collection ditches, called "drainage channels". Figure 2 shows a typical OF system. The effluent collected may be either recycled to the top of the slope for further treatment or discharged as a point source (EPA, 1984).

Overland flow was originally developed to overcome the limitations of low permeability, poorly drained soils imposed on the slow rate process. With a SR system, these soils require extremely low hydraulic loading rates (hence large land areas for assimilation of a given volume of wastewater) and make crop management difficult (WPCF, 1990).

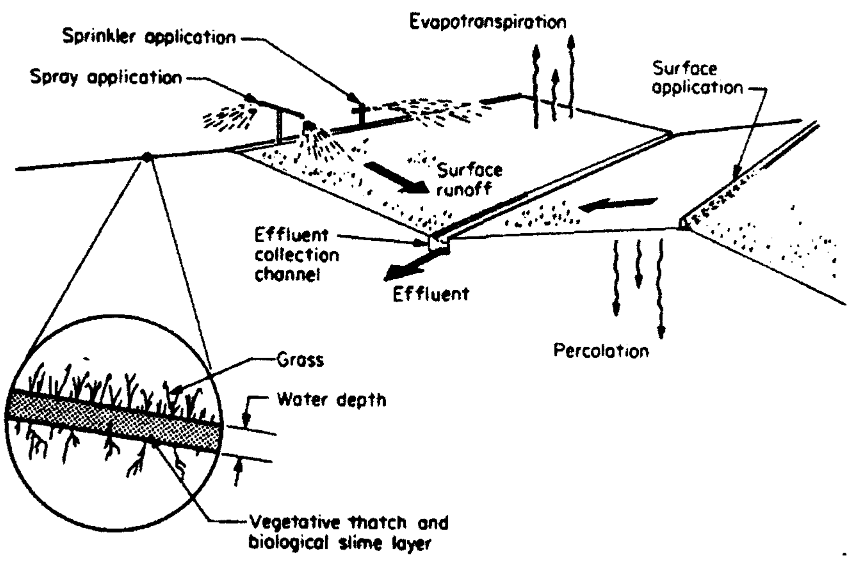


FIGURE 2. OVERLAND FLOW LAND TREATMENT SYSTEM
(adapted from Reed, et al., 1988)

With permeabilities of less than 0.15 cm/hr, infiltration is limited, so most treatment occurs as the wastewater passes through the stems, surface roots, vegetative litter and along the soil surface itself. This matrix, when loaded and unloaded intermittently, develops a "biological slime layer" on available microsites resulting in biodegradation of the organics passing through it. The matrix itself also acts physically as a sediment trap and chemically as a filtration (adsorption) mechanism to remove suspended solids, metals, and refractory organics. Nitrogen removal occurs by plant uptake, denitrification and volatilization of ammonia. Phosphorus removals are relatively low for OF systems because of limited contact with soil adsorption sites, although research on pretreatment of wastewater with a precipitating agent (alum) prior to application indicated some control of this problem (Lee, 1976).

2. System Performance and Applicability.

Performance of an OF system with untreated wastewater is typically equivalent to or better than secondary treatment. Nitrogen removals are equivalent to an SR system. Like SR systems, vegetation is a primary component of treatment, but selection is limited in current design methods to perennial water tolerant grasses and other "thatch" producing vegetation. Higher "thatch permeability" means that hydraulic loading rates are typically higher than in SR systems, ranging from 3.0 to 20.0 m^3/m^2-yr (75 to 500 gal/sq ft/yr). Hydraulic loading rate and application rate (expressed as volume of wastewater applied per unit time per unit width of terrace, m^3/m-hr) are key design parameters in order to attain adequate residence times of wastewater on the terrace.

Applicability is limited to sites with low permeability soils, although OF can be designed successfully on sites where surface permeability is greater than 0.5 cm/hr (EPA, 1984). Compaction can be used on OF sites to decrease permeability in the soil surface layers. Clogging of soil pores by solids and the biological slime layer also ensures a lower permeability (WPCF, 1990).

3. <u>OF Limitations</u>.

Although basically defined by a limited soil permeability, there are several advantages to OF treatment:

- Higher loading rates generally mean less land area is required than SR systems.

- The runoff collection and recycling system allows greater control over effluent quality.

There are, however, several limitations in the construction and operation of the system:

- Slopes have been limited to between 1 to 12% due to problems with adequate residence time and channeling and erosion. Erosion causes severe short circuiting in this type of system.

- Extremely careful land preparation and grading are required to ensure a uniformly distributed "sheet" flow over the terrace area. Maintenance operations (vehicular traffic) may contribute to disruption of uniform flow by inducing channeling, reducing uniform flow area on the terrace.

- The effect of sedimentation and filtration causes a uneven deposition of nutrients along the slope, resulting in variable growth and development of the grass-matting structure along the slope. Grass will be much thicker at the top of the terrace compared to the bottom. This contributes to erosion on the lower portions of the slope, increasing suspended solids in the runoff and decreasing residence time of the wastewater on the terrace.

- Since the system operates as a point source discharge system, design and construction of this runoff collection system is often critical to final effluent quality.

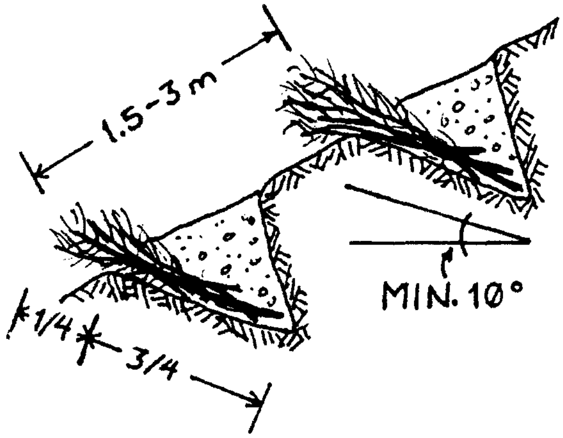
IV. DESCRIPTION OF SOIL BIOENGINEERING

A. GENERAL DESCRIPTION

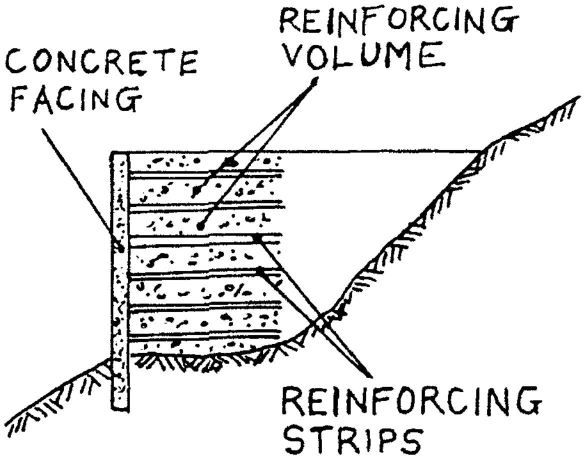
1. Stabilization Mechanisms.

The Soil Bioengineering approach essentially uses live woody plants or plant cuttings, taken during their dormant season, and emplaces them in a soil slope in various configurations to provide immediate soil reinforcement and stabilization. Figure 3 shows how, initially, unrooted live woody herbaceous cuttings provide mechanical protection against surface erosion and mass movement, similar to the "Reinforced Earth®" system of alternative soil layers and reinforcing strips (Gray and Leiser, 1982). Development of roots and shoots during the growing season begins the biological stabilization process, which strengthens with time. Stems and foliage intercept rainfall erosion, filter out sediments and enrich the soil, inviting other native species to invade and establish a stable ecosystem. "Adventitious" rootings develop along the buried length of the plant cuttings, creating a measure of apparent cohesion, which consolidates and reinforces the soil mantle (Gray and Ohashi, 1983). Roots also act to increase infiltration rates and aerobic conditions, encouraging further vegetation of the site. Well developed root systems also provide greater mass stability by establishing natural arching and buttressing structures, and greater moisture removal through increased transpiration (Sotir and Gray, 1989).

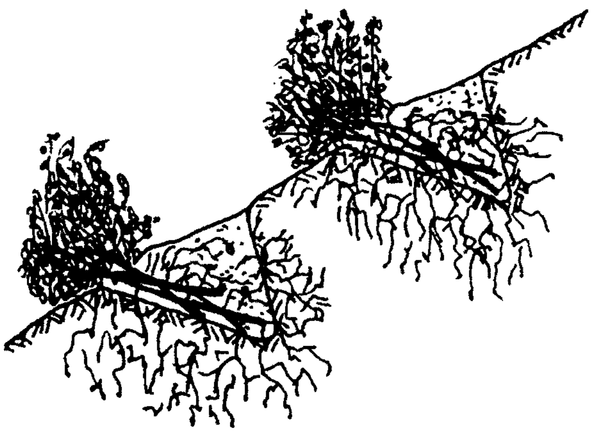
While use of live plants and supporting dead materials alone may be sufficient for stabilization of shallow seated mass erosion, typically these "living systems" are constructed together with conventional systems of concrete, wood, stone, or steel such as riprap, drop structures, diversion channels, etc. These biological and conventional systems, when designed to function together in an integrated and complementary manner (Gray and Leiser, 1982), offer a more permanent and complete approach to land reclamation than conventional techniques alone.



(a) Unrooted condition of typical Soil Bioengineering system (brushlayer), showing mechanical stabilization aspects. (adapted from a drawing by Robbin B. Sotir and Associates)



(b) Reinforced Earth structure showing principal elements. (Reinforced Earth is a registered trademark of The Reinforced Earth Company.) (after Gray and Leiser, 1982)



(c) Rooted, sprouted Soil Bioengineering system showing "biological reinforcement" (adapted from a drawing by Robbin B. Sotir and Associates)

FIGURE 3. SOIL BIOENGINEERING STABILIZATION MECHANISMS

2. Development of Soil Bioengineering Systems.

Although its roots can be traced back to the 1500's, much of what is today known as "Soil Bioengineering" grew out of pioneering work done in the 1930' to 1950's. In 1937 Eduard Keller of Austria undertook experiments using willows as live construction elements and coined the phrase "Living Construction". During this same time period, Charles J. Kraebel was installing similar works on mountain fill slopes in southern California (Sotir, 1992).

Development of current Soil Bioengineering methods largely began in 1934 when an Austrian construction supervisor, Wilhelm Hassenteufel, used willow cuttings obtained free of charge from nearby sites to provide mountain stream and avalanche protection works. Using live cuttings to reinforce a conventional rock paving system led to a considerable reduction in the amount of stone required, reducing construction costs by 85% (Sotir, 1992: Schiechtl, 1980).

A critical period of technique advancement and standardization followed World War II, with investigators such as Schiechtl, Pruekner, Kruedner, and Bittman developing specific techniques for specific objectives (Sotir, 1992). In 1990 the U.S. D. A.- Soil Conservation Service (SCS) formally adopted the term "Soil Bioengineering" to define this technology and is, at the time of this report, offering its first Engineering Field Handbook chapter on the subject (USDA-SCS, 1992).

3. System Objectives and Applications.

The ultimate goal of a Soil Bioengineering project is to allow the indigenous plant community nearby to overtake the site with a "climax" growth which permanently stabilizes and reclaims the site. Toward that end, most Soil Bioengineering installations use "pioneer" species of plants specifically selected for their immediate stabilization and soil-water matrix reconditioning properties. As the climax growth begins to invade, it is expected that many of the pioneer species may fail to compete and thus die back. This period of change, however, usually takes several years (Schiechtl, 1980).

Gray and Leiser (1982) list several advantages for Soil Bioengineering systems, discussed in Table 1, and suggest several generic applications, shown in Table 2. Soil Bioengineering cannot be used to control all erosion problems. Particular techniques, or "living systems", that are employed will depend on a variety of factors, including availability of labor and suitable plant materials, site access for equipment unique to the bioengineering process, site restriction to equipment unique to the conventional process, and timing of the project. Plant material can ONLY be harvested and installed during the dormant season, usually September through March or April (Sotir, 1989).

TABLE 1. ADVANTAGES OF SOIL BIOENGINEERING[a]

• **Cost Effectiveness** -- White (1979) showed that Soil Bioengineering is considerably more cost effective at control than concrete construction or vegetative construction measures alone over the total life cycle.

• **Environmental Compatibility** -- systems "blend" into the landscape without visual intrusion and do not deteriorate over time.

• **Use of Indigenous Natural Materials** -- locally available materials offer more resistance to deterioration, greater chance of success (survival) and lower cost of installation than exotic materials.

• **Labor Intensity .vs. Capital Intensity** -- the nature of Soil Bioengineering makes it labor-intensive, as opposed to the capital/energy-intensive conventional methods. With enhanced techniques, a proper design, and a well-supervised workforce, however, this should greatly reduce project costs.

[a]adapted from Gray and Leiser, 1982

Schiecthl (1980) lists over 32 living systems using woody plant species. Each living system is specifically designed for certain situations and project objectives. Of these, the brushlayer, live fascine with live staking. live cribwall, branchpacking, and brushmattress systems will be directly investigated in this report for applicability.

TABLE 2. GENERAL APPLICATIONS FOR SOIL BIOENGINEERING[a]

- **Stabilization of Cut and Fill Slopes_**-- in transportation corridors and along utilities rights-of-way (e.g., power lines).

- **Coastal Zone Backshore Slope Protection.**

- **Waterway Embankments and Channel Protection**

- **Housing Development and Construction Sites -- erosion protection.**

- **Rehabilitation of Severely Damaged Lands** -- and upland watersheds from mining, timber harvesting, etc.

- **Gully Erosion Control.**

[a]adapted from Gray and Leiser, 1982

B. BRUSHLAYER.

1. Technique Description.

Developed by Schiechtl in 1949, brushlayering consists of placing woody herbaceous species such as willow (Salix spp.) or cottonwood (Populous spp.) in prepared terraces, called "benches", along slope contours. The most prevalent Soil Bioengineering technique, brushlayer may be used for reinforcing fill slopes during construction (see Figure 4), or for rehabilitation of an eroded or failed cut slope (see Figure 5).

On cut slopes, benches are prepared at a slight angle to the horizontal slope contour, with the angle increasing with slope wetness (Schiechtl, 1980). Fill slope benches are constructed horizontally, along slope contour. Either rooted plants or live cuttings may be used, with about 20 branches per lineal meter installed in a criss-crossing fashion. Cuttings are installed perpendicular to the face of the slope, as shown in Figures 4 and 5. This arrangement allows the best penetration effect of all Soil Bioengineering techniques, and serves to stabilize and improve the soil structure and microclimate (Scheichtl, 1980).

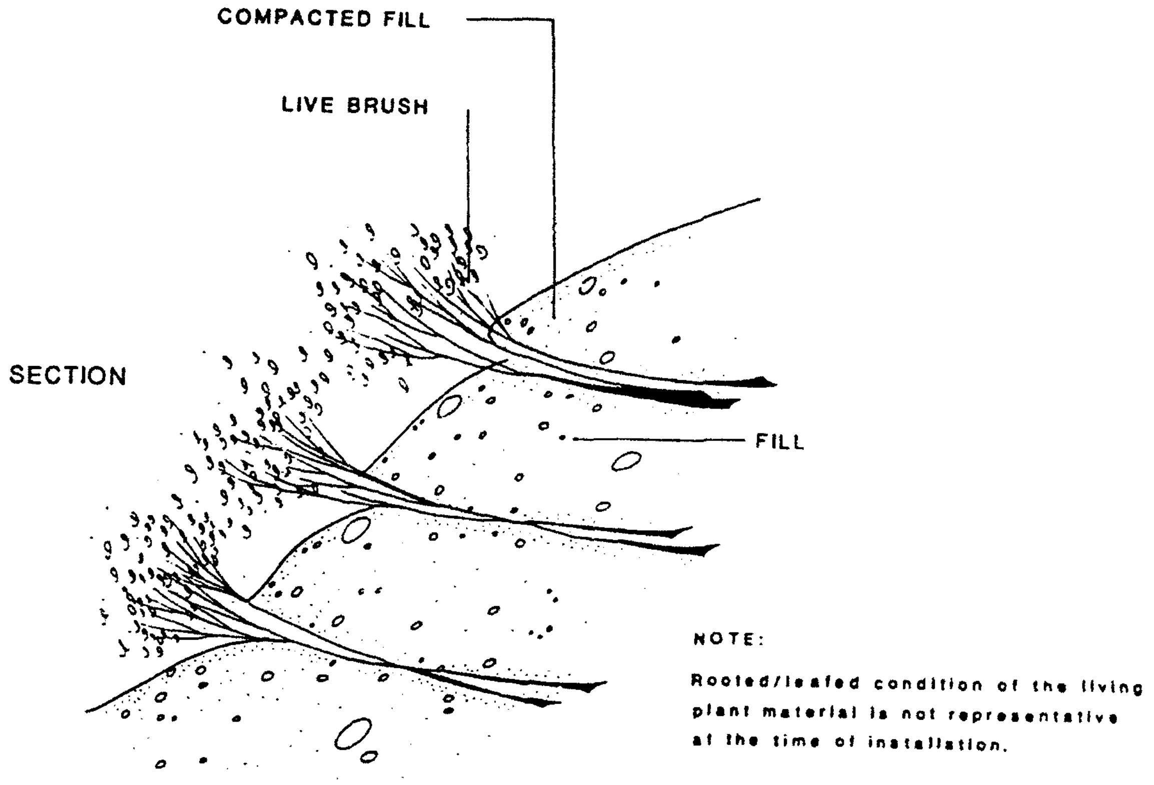


FIGURE 4. BRUSHLAYER INSTALLED ON FILL SLOPE.
(drawing by Robbin B. Sotir and Associates)

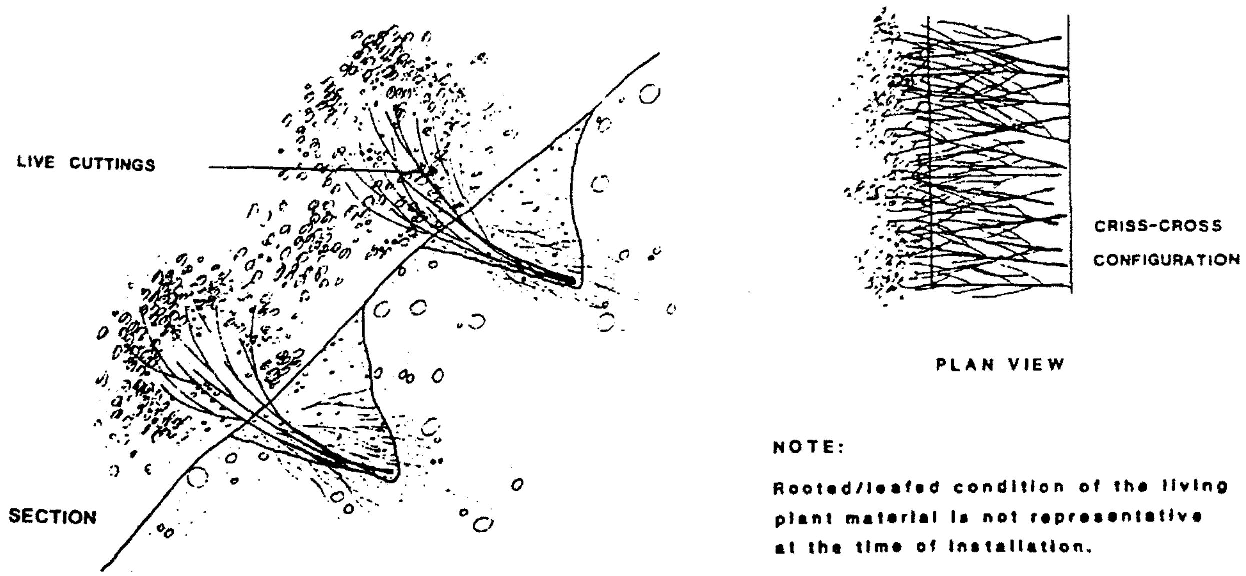


FIGURE 5. BRUSHLAYER INSTALLED ON CUT SLOPE
(drawing by Robbin B. Sotir and Associates)

A distinct advantage of brushlayering is the ability to rapidly install systems, using mechanized equipment to prepare and backfill benches, along with the simple criss-cross configuration of the plant materials on the bench. Rapid installation makes this system the most inexpensive and widely used technique. This system must be used in conjunction with seeding of herbaceous species between layers, however, to protect against localized topsoil erosion.

2. Application Within Soil Bioengineering.

Brushlayer is primarily used for rapid stabilization of cuts on extreme sites, as well as on fill slopes where the danger of erosion and slides is high (see Figure 6). The system effectively breaks up the slope length into a series of shorter slopes, allowing vegetative cover to establish. It is also used for waterway embankment protection, as shown in Figure 7.

A variation of brushlayer, called "hedge brushlayer", uses one rooted woody climax specimen placed vertically into the bench every meter. This method is more expensive, but may have lower life cycle costs, since it serves to establish an effective soil matrix, along with the climax community, much faster than brushlayer alone.

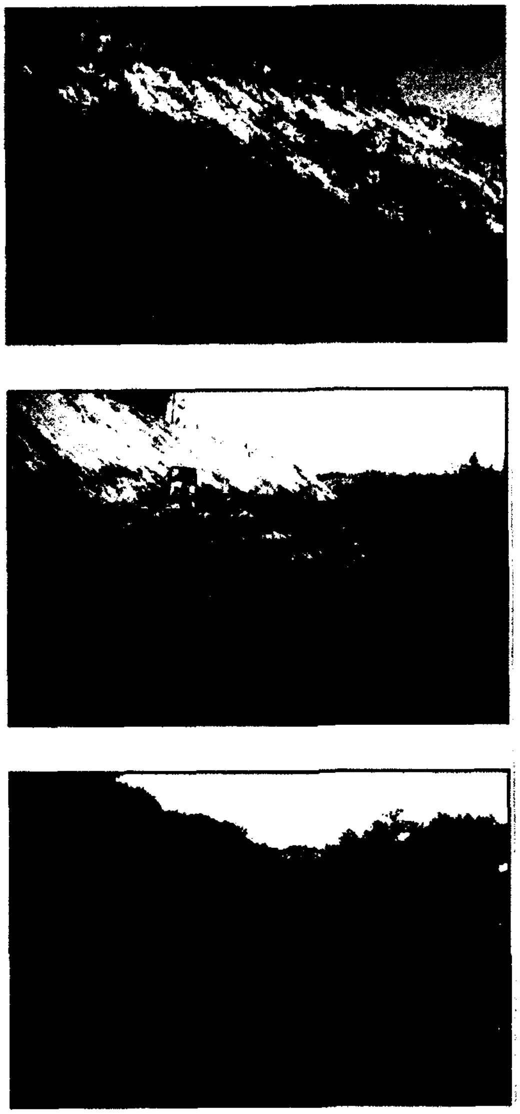


FIGURE 6. FILL SLOPE BRUSHLAYER

(TOP) Badly eroded embankment along NC Route 126

(MIDDLE) During brushlayer construction. Brushlayer can be placed and covered in a fairly mechanized process, saving time and costs. Note installation taking place during winter (dormant season).

(BOTTOM) Brushlayer installation 6 months after construction.

(all photos by Robbin B. Sotir and Associates)

(a) Waterway brushlayer installation during construction. Note use of Soil Bioengineering techniques with conventional sheet pile drop structure. (Robbin B. Sotir and Associates photo).

(b) Waterway brushlayer 3 months after installation. Site is a large intermittent flow drainage channel, OLF Silverhill, Baldwin County, Alabama. (Robbin B. Sotir and Associates photo).

FIGURE 7. BRUSHLAYER USED IN WATERWAY CONSTRUCTION.

C. LIVE FASCINE

1. Technique Description.

A "fascine", from the Latin "fasciare", meaning bundling, is a sausage-like bundle of live plant material, usually woody herbaceous cuttings. Developed independently by both Kraebel and Hofmann in 1936 (Schiechtl, 1980), this technique can serve a variety of soil conditions and objectives.

Placed horizontally on contour, as shown in Figure 8, these structures will root along their entire length and create a "mini-dam", preventing soil loss and increasing sedimentation and organic texture in a poor soil. Placed at an angle to the contours, fascines can act as soil moisture "regulators", first channeling water laterally from the slope, and, after rooting, removing ground water through transpiration. Placed perpendicular to the contours and using phreatophytic species, fascines can act as "living pumps" to drain an entire slope where soil moisture may be a cause of failure (Schiechtl, 1980). As Figure 8 shows, live fascines are secured on slopes by a combination of lumber stakes, called "dead stout stakes", and live stakes of woody species cuttings. "Live Staking" is a system by itself that is used for shallow reinforcement in uncomplicated site conditions, but is addressed here as part of the live fascine system. Rooted, sprouted live staking assists the fascine in reinforcement, soil conditioning and moisture control.

2. Applications Within Soil Bioengineering.

Fascines have been used in conjunction with brushlayer (see Figure 9), placed between layers to secure sections where extra rooting is desirable to increase permeability and a strong tensile configuration is required to reduce head cutting up the slope face (Sotir, 1991). They are useful for preventing surface erosion and rilling at specific locations on a slope, and can be used to drain slopes in moderately permeable soils.

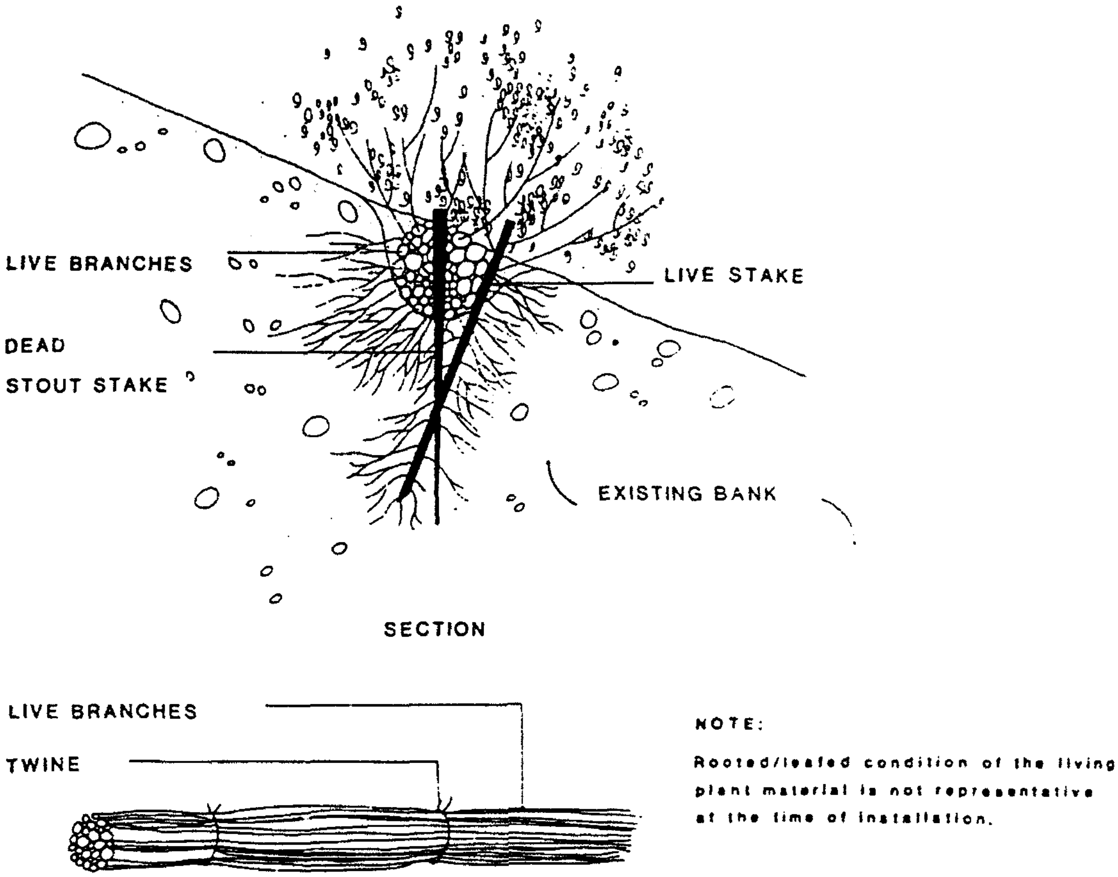
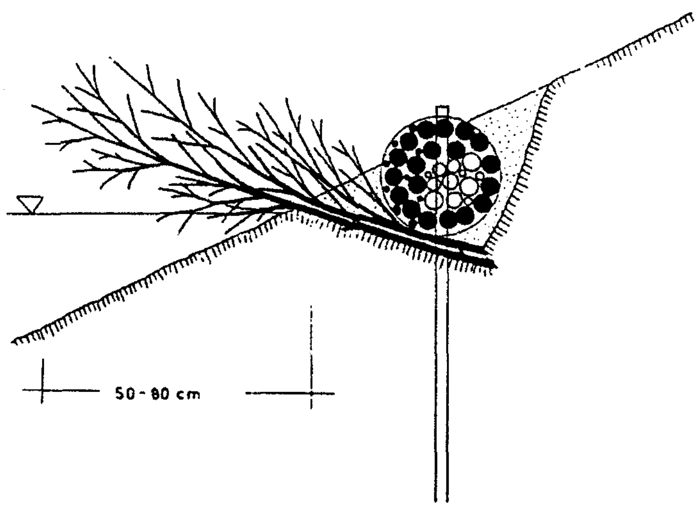


FIGURE 8. LIVE FASCINE
(drawing by Robbin B. Sotir and Associates)



(NOTE: application shown is used in waterway construction. System can also be used on dry slopes, either emplacing live fascine in same trench as brushlayer or in separate trench.

FIGURE 9. LIVE FASCINE USED IN CONJUNCTION WITH BRUSHLAYER.
(after Schiechtl, 1980)

D. LIVE CRIBWALL

1. Technique Description.

Developed by Hassenteufel in 1934 (Schiechtl, 1980), a live cribwall is a hollow, box-like interlocking arrangement of untreated logs or timbers, the inside of which is filled with suitable soil. Live branches extend through the box and into the slope behind, as shown in Figure 10. A live cribwall is a very site-specific technique, useful in areas where space is limited and a very steep slope must be instantly stabilized, such as adjacent to a drop structure or at the toe of a slope of terrace face.

Untreated timber is used to avoid effects of leached pressure treatment process constituents on plant establishment and growth, and to allow the live system to eventually take over. As the live cuttings root, the root systems gradually strengthen as the wooden timber rots and weakens (Schiechtl, 1980).

2. Applications Within Soil Bioengineering.

Not designed to resist large lateral stresses, the live cribwall is usually limited to a height of six feet unless concrete members are substituted for the dead wooden materials (Schiechtl, 1980; Gray and Leiser, 1982). The system is applicable where small slopes of loose material must be held against surface erosion down the slope, or against flowing water in a waterway (see Figure 11). It may also be useful in a terracing arrangement, with successive cribwalls above one another, in a stair-step fashion.

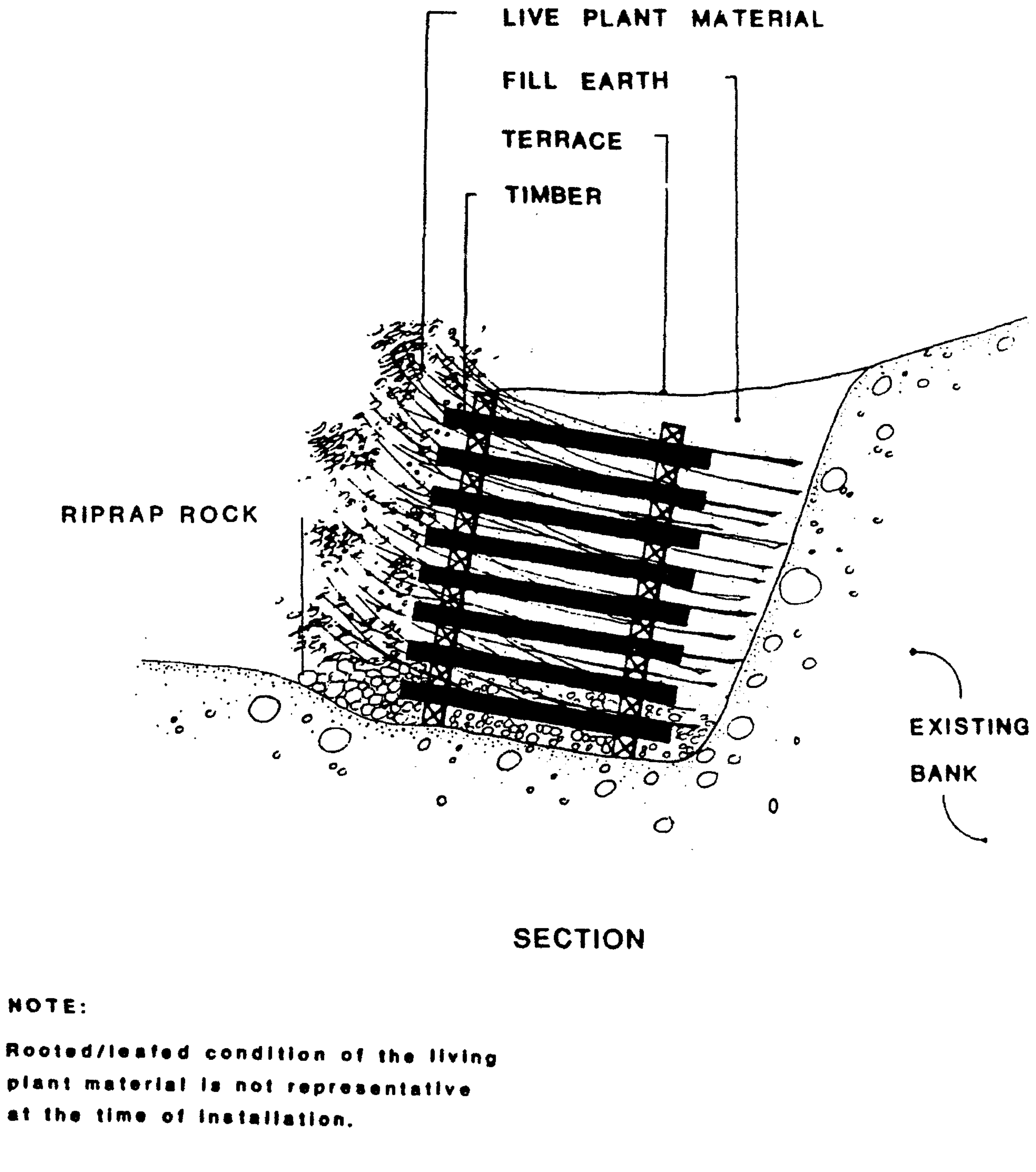


FIGURE 10. LIVE CRIBWALL
(drawing by Robbin B. Sotir and Associates)

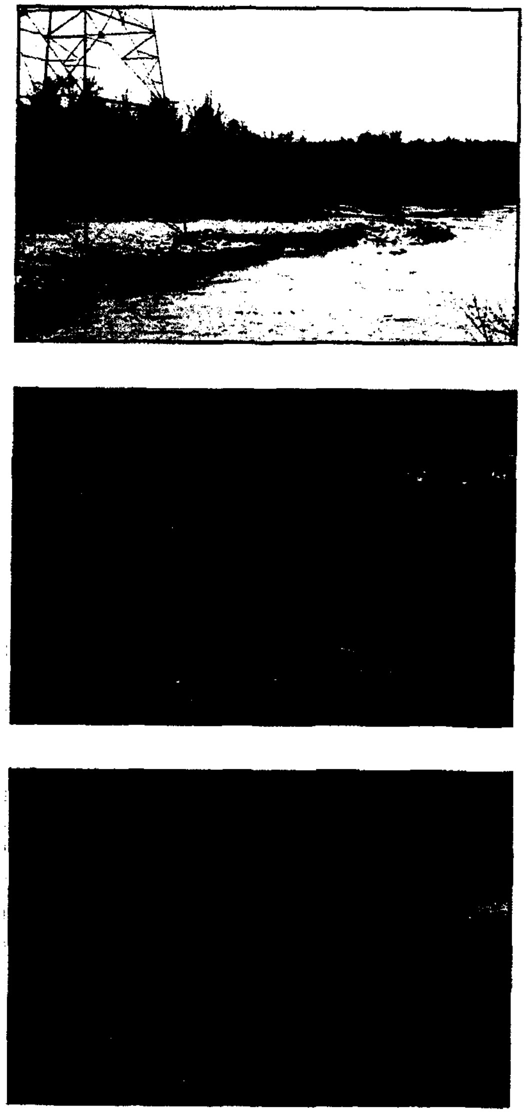


FIGURE 11. LIVE CRIBWALL INSTALLATION.

(TOP) Badly eroded bulkhead foundation for 120 KV towers near meandering stream.

(MIDDLE) Soil Bioengineering system of live cribwall "groins" connected by embankment branchpacking.

(BOTTOM) Stabilized site during a spring high flow event.

(all photos by Robbin B. Sotir and Associates)

E. BRANCHPACKING

1. Technique Description.

Branchpacking consists of alternating layers of live branch cuttings and soil fill, secured vertically with "dead stout stakes" of wood or metal, as shown in Figure 12. Like live cribwall, this is also a specialized Soil Bioengineering system used typically for earth reinforcement and mass stability of small earthen fill sites. The system produces a filter barrier, reducing scour and erosion and providing immediate stabilization.

2. Applications Within Soil Bioengineering.

Developed mostly for use as a bank stabilization technique along rivers (see Figure 11), this technique is also effective at gully repair and stabilization. It is also used to "tie in" conventional structures such as riprap or sheet pile walls to general Soil Bioengineering techniques such as brushlayer and fascines (Sotir, 1991). It acts to slow water movement at critical flow points such as the top of a drop structure, or a live cribwall (when used as a drop structure).

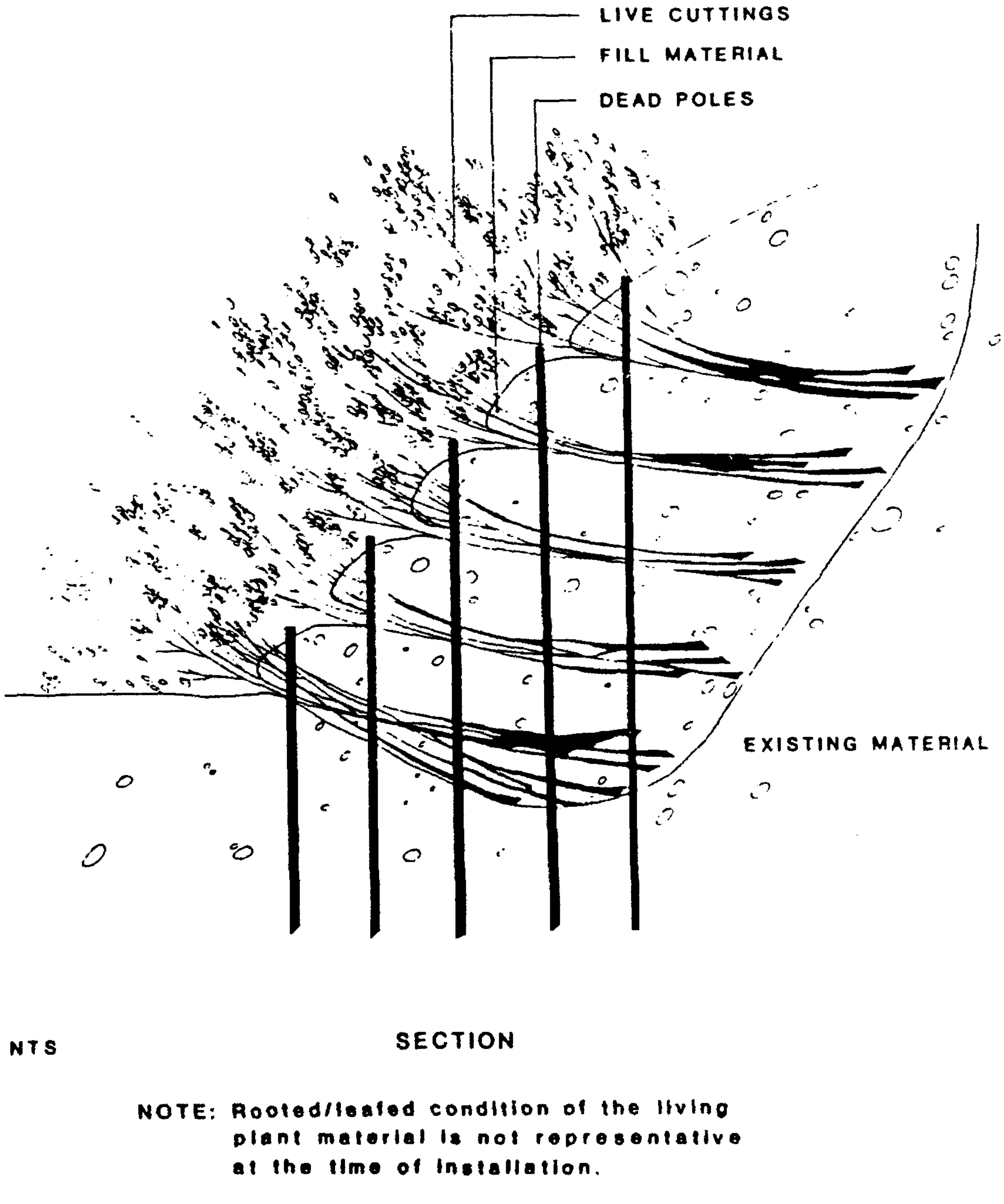


FIGURE 12. BRANCHPACKING
(drawing by Robbin B. Sotir and Associates)

F. BRUSHMATTRESS

1. Technique Description.

Brushmattress, or brush matting, is essentially a mulch of hardwood brush cuttings fastened down with stakes and wire (Gray and Leiser, 1982). It is primarily used as a surface erosion control technique, providing shallow soil protection against the impact of heavy rains and running water (Schiechtl, 1980). Figure 13 shows a typical brushmattress used as streambank protection. Live fascines are sometimes used along the lower edge to help anchor butt ends of the brush cuttings into the soil and provide washout protection as the system becomes established.

2. Applications Within Soil Bioengineering.

Brushmattress can be used to stabilize either dry slopes or waterway embankments, and acts immediately to stabilize the site against scouring by running water and wave action (Schiechtl, 1980; Gray and Leiser, 1982). As Figure 13 shows, a very dense matrix of roots and shoots develops quickly, providing a very enriched, aerobic climate to allow fast climax species establishment. Due to the "mat" orientation root systems (and therefore soil stabilization) will be shallow for this type of installation.

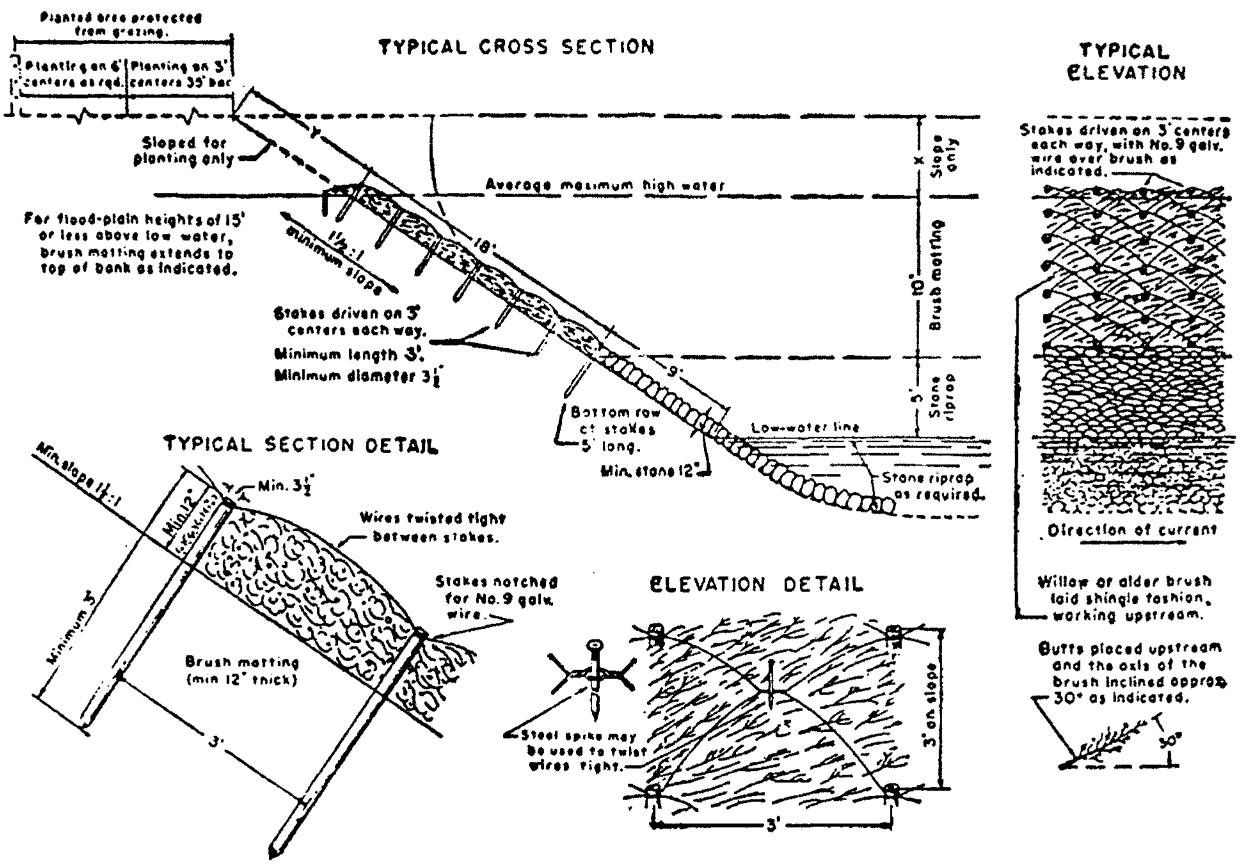


FIGURE 13. BRUSHMATTRESS
(after Gray and Leiser, 1982)

V. FEASIBILITY FOR APPLICATIONS OF SOIL BIOENGINEERING TO NATURAL WASTEWATER TREATMENT PROCESSES

A. TREATING WASTEWATER ON SLOPES

1. An Introduction to the Problem of Slopes.

In comparison to mechanical- and energy- intensive conventional wastewater treatment systems such as the activated sludge process, natural land treatment systems require fewer operational personnel, consume less energy, and produce very little, if any, sludge (WPCF, 1990). Natural treatment is often more cost-effective than conventional treatment, provided that there is sufficient land of suitable character to utilize as a "natural bioreactor".

The availability of suitable land can be a fairly serious factor. In addition to "wetted field area" for actual application of wastewater, most situations require additional land for storage and preapplication treatment, buffer zones, etc. Land availability tends to limit the application of natural systems for many urban areas, where regional wastewater flows can exceed 100 million gallons per day (MGD). Generally, there is simply not enough land within a radius of these urban areas where it is economically feasible to transport the waste for application. A typical slow rate treatment system, for example, can require 70 - 140 ha (133 - 346 acres) of wetted field area to treat 1.0 MGD (Reed, et al., 1988).

Fortunately, over 81% of municipal wastewater treatment facilities operating today are less than 1.0 MGD, with a substantial portion of this number belonging to small, rural communities where land may be readily available (Tchobanoglous, 1991; EPA, 1981). The requirement for suitable land for a natural treatment, however, further restricts the treatment system designer. Specific soil, hydrologic, and topographic site conditions all serve to limit land where natural treatment systems may be sited.

There have been many successful innovations that deal with the variability in these site conditions. Different land treatment system concepts, for instance, have evolved to adapt to the range of soil permeabilities from rapid ("Rapid Infiltration" systems) to slow ("Overland Flow" systems). Hydrologic variabilities are also addressed in a limited fashion by choice of treatment system, with wetlands systems potentially applicable in areas of high ground water that are otherwise unsuitable for land application of wastewater. The case of site topography, however, is an interesting exception.

Virtually all natural treatment systems require flat to gently sloping land for application. While this requirement is obvious for some aquatic-based systems such as stabilization ponds, aquaculture systems and wetland, it is less obvious for soil-based systems. Both slow rate and overland flow land treatment are restricted to slopes of 2 - 15% (WPCF,1990; EPA, 1981; Reed, et al., 1988). Although slow rate systems operated in forests have been shown to be successful on slopes up to 40% (Sepp, 1973), recommended slope ranges for forest application are 15 - 30% (Asano and Pettygrove, 1985). Overland flow sites are generally restricted to slopes of 2 - 8% (EPA, 1981; WPCF, 1990).

In many mountainous or foothills areas with high degrees of topographic relief, this narrow range of slopes significantly restricts the selection of a natural treatment system site. Much of the suitable land (gently sloping) within these regions is already utilized as agricultural land or is well populated and developed. While agricultural land is always an option for land treatment, its use is generally restricted to crops other than those grown for direct human consumption and it usually requires higher levels of preapplication treatment, which increases site acquisition costs.

In contrast, sites with medium grade slopes (30% - 50%) and land with significant topographic relief within a single site are usually lower in land cost and often underutilized from a land use perspective. Less desirability for development and agriculture uses also means that public acceptance (critical for municipal systems) of wastewater treatment systems may easier to obtain for these sites. (Note: this report will define a "medium grade slope" as 30 - 50%, and will limit the term "steeper slopes" to 50%, based on the proven ability of Soil Bioengineering using natural materials alone to stabilize sites up to this level.)

Unlike soil and hydrologic site conditions, little if any research has been conducted to suggest alternatives or techniques to deal with slope limitations. In light of the possible economic and social benefits discussed above, analysis of the development of land treatment slope ranges and factors related to slope limitations should be investigated.

2. Development of Recommended Slope Ranges.

Actual slope limitations of 2%, 8%, 15%, etc., were not calculated based on quantitative measurement, but were derived from logical "rules of thumb" observed in the field (S.C. Reed, personal interview with author, 1992). Generally accepted slope limits for land treatment systems, such as those shown in Table 3, were originally based on empirical irrigation standards such as the "Ten States Standards" for the Great Lakes Upper Mississippi River Basin (Loehr, et al., 1979; Sanks and Asano, 1976).

TABLE 3. ORIGINALLY RECOMMENDED SLOPE RANGES FOR LAND TREATMENT SYSTEMS[a]

Type of Slope	Slope Limit
• Unsodded Slopes	≤ 4 %
• Sodded Slopes	≤ 8 %
• Forest, Year Round Application	≤ 8 %
• Forest, Seasonal Application	≤ 14 %

[a] adapted from Loehr, et al., 1979

This lack of a quantitative basis for recommendations of slope in land treatment systems suggests that treatment on steeper slopes may be possible if factors related to slope limitations can be analyzed and protective measures considered.

3. <u>Factors Related to Slope Limitations.</u>

The primary reason for avoiding steeper slopes in land treatment systems is the increased potential for erosion and runoff. Other reasons cited are soil instability under saturated conditions, difficulty of crop cultivation and increased irrigation expense (WPCF, 1990; Asano and Pettygrove, 1985). For OF systems, "excessive" slope is thought to lead to inadequate detention time of the wastewater on the slope and create channeling down the slope, causing short-circuiting of treatment (WPCF, 1990).

To enhance microbial degradation, land treatment systems must operate under aerobic, or unsaturated, conditions. To ensure unsaturated conditions, proper drainage and depth to ground water are prime considerations in selecting and screening potential land treatment sites. Moderately well- to well-drained soils are preferred for slow rate land treatment, and preferred minimum depths to ground water are 0.9 to 1.2m (3 to 4 ft) (WPCF, 1990; EPA, 1981). Site evaluation determines the ability of the site to accept the applied wastewater load while maintaining the minimum distance to ground water. Design of an application rate for a site also ensures that applied water will percolate and soils will not remain saturated for prolonged periods. If these design considerations are properly addressed, soil mass instability due to saturation by application of wastewater alone should not prohibit land treatment on slopes. Instability of sloped soils due to saturation can, however, be a serious problem during significant or prolonged rainfall events and/or periods of low evapotranspiration rates.

Surface erosion and runoff are perhaps the most substantial deterrents to use of steeper slopes for wastewater treatment. Although surface erosion can be caused by water, wind, or ice action, it most often results from applications of water to the slope in excess of the infiltration rate (runoff), due to either high intensity (large volume per unit area per unit time) applications or prolonged saturated conditions. During intense applications, localized mass wasting in loose, shallow topsoils can form a network of rills across the soils surface, developing into gullies (Gray and Leiser, 1982). Under saturated or near saturated conditions, as gully depth increases the ability of water in the gully to infiltrate decreases, leaving most of the water applied per unit area to drain off as "channel flow".

In the case of applied wastewater, channeling causes inadequate contact time between the waste constituents in the water and the treatment media (the soil and plant matrix), which "short-circuits" the waste removal process. While this situation can be somewhat controlled by proper design of the application rate when wastewater alone is applied, serious problems can result during significant rainfall events.

B. POTENTIAL BENEFITS OF TREATING WASTEWATER ON SLOPES

1. Nature of Subsurface Flow on Permeable Slopes.

If the limitations of mass instability and surface erosion can be controlled adequately, an immediate benefit realized is the ability to consider steeper sloped land and sites with significant topographic relief as candidates for land treatment sites. As the following analysis will show, there is also evidence that if erosion and mass movement can be controlled, sloping land may actually yield greater performance per acre, dramatically reducing the amount of land required for treatment of a given wastewater flow.

To a varying extent, all natural treatment systems act as fixed film or attached growth bioreactors, with soil and vegetation components acting as strata for microorganism attachment and as adsorption and filtration surfaces. In OF systems these "microsites" for biological activity and sorption processes are limited to the vegetative thatch and the soil surface. In SR systems the soil profile itself provides a much larger surface area for adsorption and microbial activity, and the added absorption of nutrients and metals by vegetation combines with microsite action to produce much higher renovation of wastewater.

In attached-growth bioreactors, travel distance and specific surface area of the filtering media are prime independent variables affecting pollutant removal efficiencies and system performance (Tchobanoglous, 1991). Eckenfelder's trickling filter model has become the "standard" design equation for this type of system, and is typical of attached-growth theory (Eckenfelder, 1966).

$$\frac{C}{C_o} = \exp\left[-\frac{C' K A_v^{m+1} D A^n}{Q^n}\right] \tag{1}$$

where,

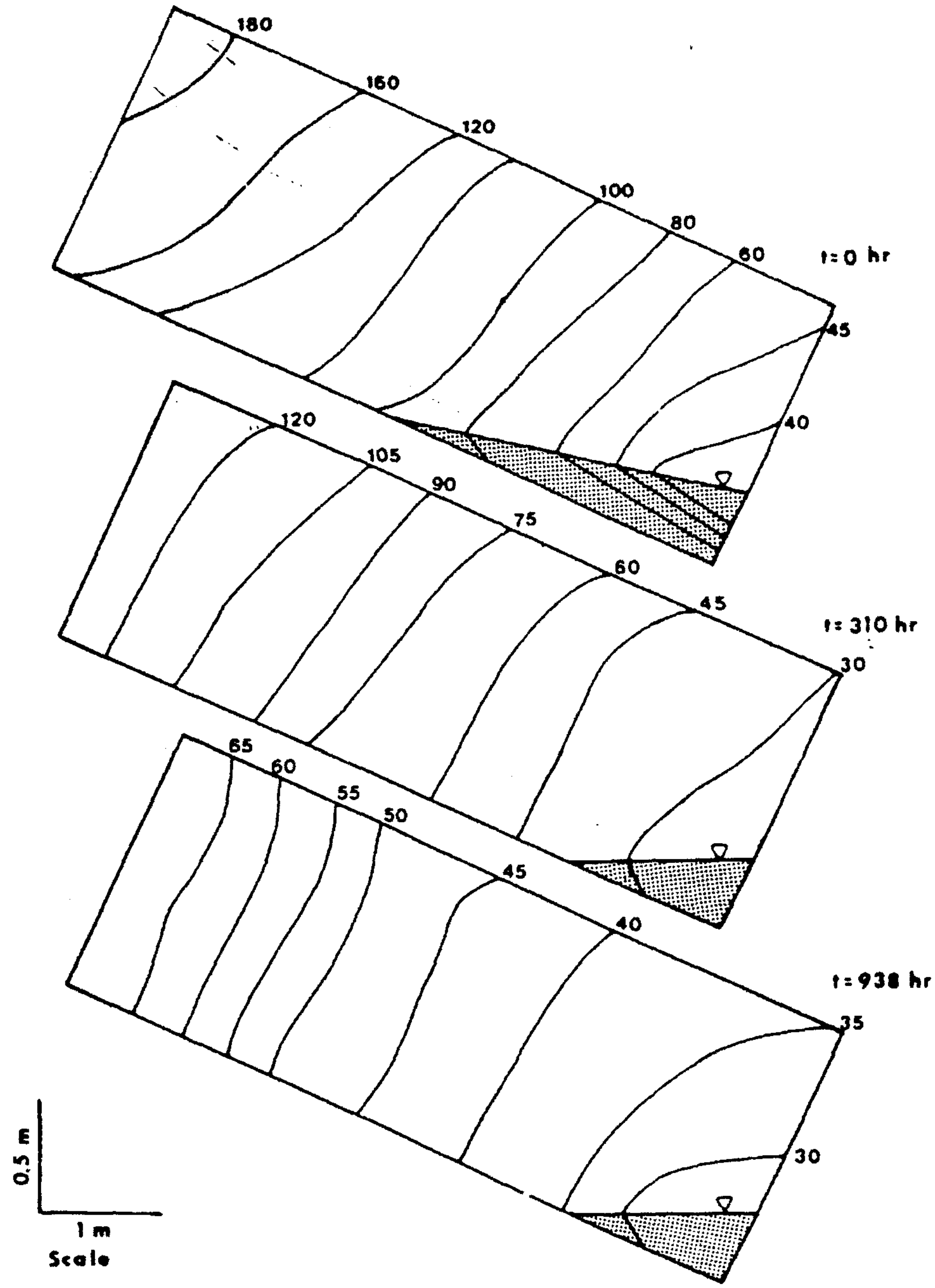
- C = Effluent concentration of pollutant from system, mg/L
- C_0 = Influent concentration to system, mg/L
- C' = Characteristic of the filter media
- K = Rate constant, m/hr
- A_v = Specific surface area of the media, m^2/m^3
- A = Cross-sectional area of media, m^2
- D = Trickling Filter media depth, m
- Q = Hydraulic loading rate, $m^3/hr\text{-}m^2$
- m,n = Empirical constants related to media composition

The first attempts at modeling the OF land treatment process, and subsequent model developments by Martel (1982) and Smith and Schroeder (1985), closely resemble the Eckenfelder model and focus on the effect of travel distance along the slope for removal efficiency of pollutants from applied wastewaters (Tedaldi, 1990). The empirical design approach for OF systems (EPA, 1981) is patterned after the design method for SR systems. The SR system design is adapted from conventional agricultural irrigation technology, and does not address travel distance as a variable in treatment efficiency.

It appears that one of the reasons that removal models similar to equation (1) have not generally been proposed for SR systems is because of the basis in irrigation technology, which relies on the vertical infiltration of applied water. The Eckenfelder model, however, could be used to describe the slow rate process, where the wastewater travels vertically through the media (identical to the trickling filter) and the point of effluent from the system is taken as the ground water table itself. Using equation (1), the relatively shallow "active zone of treatment" depth, D (typically considered as 5 ft from the soil surface), is compensated for by the wide cross-sectional area (A) over which the waste is applied and the relatively low hydraulic loading rate, Q. (See Section III for comparison of hydraulic loading rates.)

On sloped sites, however, the concept of vertical infiltration must be modified. Nutter (1975) confirmed earlier research (Hewlett and Hibbert, 1963) showing that under draining conditions water in the vadose zone will move *parallel to the slope surface* down the slope rather than simply infiltrate vertically. A laboratory model of an isotropic soil mass was constructed on a mechanism which allowed the mass to be adjusted from zero to 27 degrees of slope. A tensiometer grid built into the model recorded moisture levels along the slope depth and length during drainage trials at various slope angles and depths.

Although initial water vertically infiltrated the soil profile, Figure 14 shows that as drainage continued the equipotential lines of hydraulic head slowly oriented toward a position normal to the surface of the slope. Under the orthogonal relationship of equipotential lines to streamlines in an isotropic porous medium, Nutter concluded that water movement within the soil mass was clearly lateral to the slope. Water content gradients were also measured and confirmed an active zone of water movement lateral to the slope, migrating downslope during drainage. As slope angle



Hydraulic head in cm at time=0, 310 hrs., and 938 hrs. for a 25 degree slope. (Vertical exaggeration 2X for clarity)

FIGURE 14. HYDRAULIC HEAD EQUIPOTENTIALS IN A DRAINING SLOPE (adapted from Nutter, 1975)

decreased, the equipotential lines diverged from normal to the surface back toward horizontal. In other words, the steeper the slope, the more closely parallel to the slope infiltrated water would travel.

As soil moisture content increases, flow generally became more downward oriented, but net flow was still laterally downslope. Moreover, the effect of vegetation tended to offset this vertical tendency somewhat, effectively "suspending" water flow in a nearly parallel course of drainage (Hewlett and Hibbert, 1963). This measured phenomenon not only confirmed Hewlett and Hibbert's (1963) observations, but also confirmed earlier qualitative observations by Hoover and Hursh (1943) who described subsurface drainage down a slope as "unsaturated pipeflow supported by the root mass". (Nutter, 1975).

Nutter's conclusions were supported by his 1979 work at a steeply sloped forest site at Unicoi, Georgia, receiving municipal wastewater. A suction lysimeter field similar to the laboratory tensiometer grid was installed at depths of 60, 120 and 200 cm, evenly spaced along 100 m slopes of 30%. Chloride from the irrigant used as a tracer combined with lysimeter water data to clearly confirm that "relatively rapid and extensive lateral movement of water occurs down the slope [after infiltration]." (Nutter, et al., 1979). Reed and Bastian (1990) also confirmed lateral movement of water on forested slopes in a Clayton County, Georgia slow rate system. They found that "Some of the applied wastewater percolates vertically and reaches the native ground water table, but most of the applied wastewater infiltrates to a relatively shallow depth and percolates laterally through the soil, and emerges as surface or subflow in the sites drainage network..." (Reed and Bastian, 1990).

The implication for wastewater treatment of Nutter's demonstration and field confirmations is that, considering the dependence on length of travel, D, shown in equation (1), renovation of wastewater may be considerably higher on steeper slopes. Applied wastewater will travel a considerably longer way down the slope rather than through the slope, and this pathway will be mostly through the organically richer "A" and "B1" horizons, which are by far the most efficient soil layers for wastewater treatment. Nutter, et al., (1979) confirmed this hypothesis with removal data from the Unicoi site, shown in Table 4. (Nitrogen removals were monitored under a separate format in the study and are therefore not reported here.)

Other studies on wastewater treatment using slopes have also shown excellent results (Sepp, 1973; Itoyama, et al., 1990). Another implication for parallel slope flow may be that removals to permit limitations can be obtained using much shorter slope lengths. This means that less land would be potentially required to treat wastewater to the same levels as flatter land requires under "traditional" land treatment designs.

TABLE 4. MEAN ANNUAL INFLUENT AND SOIL PERCOLATE CONCENTRATIONS FROM A STEEPLY SLOPED FOREST SITE[a]

Location and Depth of Percolate	Wastewater Concentration (mg/L)							
	Total P		Ca		K		Cl	
	Infl	Effl	Infl	Effl	Infl	Effl	Infl	Effl
• Irrigated Area	13.5		10.3		12.5		29.6	
60 cm		0.18		0.28		1.40		24.06
120 cm		0.17		0.14		1.15		23.10
• Base of Slope	13.5		10.3		12.5		29.6	
60 cm		0.17		0.09		0.89		14.25
120 cm		0.14		0.08		0.71		17.47
• Non-irrigated Area (Control)								
60 cm		0.16		0.23		0.36		1.35
120 cm		0.20		0.23		0.38		1.41
• Nearby Stream (Background)		0.22		0.59		0.49		1.08

[a] adapted from Nutter, et al., 1979.

A final aspect of the parallel slope flow concept is that faster percolation will take place if flow is mainly through the relatively permeable A and B1 horizon. This means that generally higher hydraulic loading rates can be used, which helps to "minimize land area required by maximizing hydraulic loading rate" (EPA, 1981).

2. Wastewater Renovation on Overland Flow Slopes.

a. Effect of Water Flow Path on Treatment Efficiency. As discussed above, the original OF treatment systems were empirically designed, based on experience with existing successful OF systems (EPA, 1984). This was a logical first approach, following that of the empirical design approach of the SR system. Since OF systems are an innovation to overcome low permeability soils, their performance is not dependent on infiltration but instead relies on the vegetative thatch layer and the surface of the soil itself for renovation microsites (EPA, 1984; WPCF, 1990).

Taking this microscopic view of treatment, it is obvious that there is much less surface area for attachment of biological growth in the vegetative thatch of an OF system than in particles of a moderately permeable soil used in the Slow Rate process. In terms of the attached-growth model (equation (1)) the value of A, specific surface of the media, is smaller for an OF system than an SR system, yielding a higher percentage of the pollutant remaining (as the equation is written) and a corresponding lower removal. However, given that most OF systems have been shown to be capable of treatment to at least secondary treatment standards or higher (EPA, 1984; Tedaldi, 1990), there must be a factor which compensates for this smaller value. Hydraulic loading rate, Q, is not a compensating factor since Of systems are typically loaded to much higher loading rates than SR systems (see Section III for a comparison of loading rates). The cross-sectional area, A, figures into the higher loading rate and is usually constricted by the depth of flow on the slope and the width of the slope necessary to achieve thin "sheet flow" of water across the surface (EPA, 1984; WPCF, 1990).

It appears, therefore, that the largest compensating variable must be some combination of the the characteristic C', the rate constant K and the depth of media, D. In the case of overland flow, D equates to the distance downslope. Typical slope lengths on an OF system are 45 - 60 m (WPCF, 1990), which are significantly greater than the 1 to 3 m treatment depths that most SR systems employ.

Longer slope length for an OF site translates to a longer detention time since the time that the water remains on the slope is given by a portion of equation (1) as:

$$t = \frac{DA^n}{Q^n} \cong \frac{\text{Volume}}{Q} \quad (2)$$

(all terms defined previously).

Thus detention time on the slope is the critical controlling factor in OF treatment efficiency. An investigation of rational design methods for OF systems bears out that this is the case.

b. Overland Flow Design Models. Observations of slope length and detention time effects formed the basis for two rational approaches to OF design. Smith and Schroeder (1985) working at the University of California, Davis, developed a design model which is a function of application rate and slope length:

$$\frac{C_z - C_r}{C_0} = A \exp\left[-\frac{Kz}{q^n}\right] \quad (3)$$

where,

C_z = Effluent concentration at distance z down the slope, mg/L
C_r = Residual concentration at the base of the slope, mg/L
C_0 = Influent concentration, mg/L
A = Empirically determined coefficient
K = Rate constant, m/hr
z = Slope length, m
q = Application rate, m^3/hr-m
n = Empirical constant

Although equation (3) is now the most commonly accepted method for rational design of OF systems, another more interesting one, particularly for applying wastewater to steeper slopes, is the U. S. Army Cold Regions Research and Engineering Laboratory CRREL model developed by Martel and co-workers (1982):

$$\frac{C}{C_0} = A\exp\left[-\frac{0.078KLW}{S^{1/3}Q}\right] \tag{4}$$

where,

C =	Concentration at base of slope, mg/L
C_0 =	Influent concentration, mg/L
A =	Fraction of applied BOD that is not settleable in the first few meters of flow, = 0.52
K =	Rate constant, day^{-1}
L =	Length of flow path (slope), m
W =	Width of treatment area, m
S =	Slope, as a decimal fraction
Q =	Average flow into the system, m^3/day

These two models were developed concurrently under separate research and are quite similar in comparison (EPA, 1981). Both models consider length of slope as a direct, independent variable of removal efficiency. The principal difference, aside from coefficients and exponent usage, is the use of slope in the CRREL model. Slope is used as a component of detention time, taken from the standard form of a first-order plug flow kinetics model:

$$\frac{C}{C_0} = \exp[-Kt] \tag{5}$$

where,

t = Detention time (or residence time)

(other terms defined previously)

In the case of the CRREL model, detention time t is given by:

$$t = \frac{0.078LW}{S^{1/3}Q} \qquad (6)$$

(all terms defined previously)

Equation (6) was developed from an equation for average velocity of flow on an overland slope, which was derived from the Reynolds Number in a laminar flow regime (Nakano, 1978; Martel, et al.,1982). It has been shown that overland flow systems under empirical design operate in the laminar flow regime, with Reynolds Numbers less than 500 (Kirby, 1978). Reynolds Numbers for the CRREL pilot OF facility ranged from 38 to 226, well within the laminar flow range (Martel, et al.,1982).

Tedaldi (1990) challenged the CRREL model because "the equation is completely empirical and was developed entirely from data collected at one pilot test facility...[and...i]n addition, it is dimensionally incorrect". He further suggests that another dimensionally incorrect formula, the Chezy-Manning equation for velocity, might be more applicable for determining detention time in OF systems when rearranged to read:

$$t = \frac{6.95z^{0.5}n^{0.5}}{S^{1/3}L^{0.4}} \qquad (7)$$

where,

n = Manning's roughness coefficient
L = hydraulic loading rate, mm/hr
(other terms defined previously)

Tedaldi's challenge is somewhat unfounded. The detailed theoretical development of detention time (Martel, et al., 1982) in the CRREL model was, upon examination, not very empirical at all. Model results were validated with data from the Utica, Miss. and UC, Davis operating OF systems (EPA,1981; Peters, et al., 1981). The model was also validated for SF wetland systems (which present similar biological treatment conditions to OF) at Listowel, Ontario and Arcata, California (Reed, et al., 1988). In addition, the Chezy-Manning equation is invalid for use in an OF system since the Manning's roughness coefficient, n, was developed solely for use in fully turbulent (not laminar) flow regimes (Kadlec, 1990; Martel, et al., 1982).

Tedaldi (1990) compared his results of observed detention times on a established OF site at Paris, Texas to both equations (5) and (6), but equation (6) surprisingly followed the results more closely. Tedaldi still discounted the CRREL detention time model, equation (4), in favor of the Smith and Schroeder model, equation (3), but actual differences between the CRREL model and observed results were not able to be determined significant due to the qualitative nature of his study (Tedaldi, 1990). Detention time can therefore be considered as the controlling factor for OF treatment, and the CRREL model is a viable approach, particularly as slopes become steeper.

c. The Effect of Vegetation on Slope Detention Time. As discussed in Section III, the main limitations to steeper slopes in OF are surface erosion, channeling, and decrease in detention time. Field validations of the CRREL model, however, showed some interesting results. Martel and co-workers (1982), in determining the experimental constant value of 0.078 for equation (6), noted high variability in the data, due to a change in the 1979 growing season over 1978. Detention times were considerably higher in 1979, due to an increase in vegetation density, which caused an increase in resistance to flow (Martel, et al., 1982). This explanation was confirmed by higher grass yields recorded for 1979 over 1978. Martel and co-workers (1982) concluded that "construction techniques, patterns of vegetative growth and harvesting operations are also factors [other than slope] which can affect detention times".

Peters and co-workers (1981) confirmed the CRREL conclusions of vegetative effects on detention time. A series of OF slopes (2, 4, and 8%) were used to calculate detention times at different application rates. Results indicated no significant difference in detention times due to slope. Factors which accounted for this were the effect of channeling, vehicle travel and vegetation density. The 8% slope, which should have shown the highest flow velocity and therefore the shortest detention time, was the most densely vegetated. Because of the degree of vegetative establishment, the steepest slope in the study also achieved the highest nutrient removals (N and P) (Peters, et al., 1981).

It is clear from this analysis that detention time is related to both vegetation density and slope angle, and the density of vegetation can work to overcome the negative effects of an increase in slope. Since detention time on the slope, and not just slope length and application rate alone, has been shown to be critical to controlling OF slope treatment efficiency, it follows that applied vegetative patterns and Bioengineering technology will have high potential for ensuring effective treatment on steeper slopes.

C. BIOTECHNICAL SLOPE STABILIZATION AS A WASTEWATER TREATMENT COMPONENT

1. Current Stabilization Practices.

To combat surface erosion, non-crop land treatment systems have relied upon standard vegetative techniques such as establishment of uniform, vigorous herbaceous growth. While such efforts work well on gentle slopes, they are typically ineffective when used alone on steeper slopes. Herbaceous cover used alone cannot achieve resistance to mass-wasting caused by soil saturation, and is also limited in preventing even surficial erosion where slopes are very steep.

Forest systems show much greater resistance to erosion and mass movement, due primarily to the extensive woody root systems and the large buildup of litter and detritus material on the forest floor (McKim, et al., 1982). This litter buildup, however, detracts from nitrogen removals. Herbaceous cover has been shown to improve nitrogen removal in forests, but survival is low once a full canopy is closed over the site (McKim, et al., 1982).

For OF systems, most stabilization approaches have been "conventional" in nature, involving step-back terracing of steeper sites and attention to "proper" runoff channel design (EPA, 1984; WPCF, 1990). While these solutions have been generally effective, they involve intensive groundwork during system construction (EPA, 1984).

The use of woody species in Soil Bioengineering may enhance these traditional stabilization approaches. In analyzing Soil Bioengineering for wastewater treatment potential, living systems are divided into two groups: mass stability and root matrix systems (brushlayer, branchpacking, and live cribwall) and surface erosion control systems (live fascine and brushmattress). These five individual techniques can be used differently for specific purposes in wastewater treatment (discussed in Section VI, VII, and VIII), but each essentially provides the same stabilization mechanisms within its group.

2. Mass Stabilization Techniques: Brushlayer, Branchpacking and Live Cribwall.

a. *Shallow-Seated Mass Stability*. Brushlayer, branchpacking, and live cribwall all involve the placement of substantial portions of dormant woody cuttings into the soil profile of a slope such that 75 - 100% of the cutting is beneath the soil surface at an angle to the slope (Scheichtl, 1980) See Figures 4, 5, 10 and 12. Woody species placed in these configurations provide mass stability by:

- Root Reinforcement -- cuttings and later the roots themselves reinforce a soil by transfer of shear stresses in the soil to tensile stress resistance in the roots.

- Soil Moisture Modification -- Evapotranspiration and interception in the foliage limit buildup of soil moisture stress. This is an especially important feature for wastewater treatment systems.

- Buttressing and Arching -- anchored or embedded stems and cuttings can act as buttress piles or arch abutments to counteract shear stresses in a slope.

• Surcharge -- the weight of vegetation on a slope exerts both a downslope (destabilizing) stress and a stress component perpendicular to the slope which increases resistance to sliding (Gray and Leiser, 1982).

b. Adventitious Roots as a Treatment Medium. As shown above, flow of wastewater in a moderately permeable soil will eventually become lateral down the slope (Nutter, et al., 1979). This flow will pass directly through the root systems of the brushlayer, branchpacking or live cribwall, where full renovation capability of the adventitious roots can be realized. In addition, the root system improves the aerobic and organic condition of the soil structure (Schiechtl, 1980) which greatly increases the biological activity and adsorption capacity needed for pollutant removal.

c. Surface Erosion Protection. Branchpacking and live cribwall form a very dense foliage network after shoots develop, effectively eliminating surface erosion through the mechanisms of:

• Interception -- foliage and plant litter absorb rainfall (or applied wastewater spray) energy and prevent soil compaction from droplets.

• Restraint -- stems, shallow roots, and plant litter physically bind and filter sediments out of any developing runoff or shallow lateral percolation.

• Retardation -- vegetative thatch increases surface roughness and resistance to flow, slowing runoff velocity.

• Infiltration -- roots maintain soil porosity and permeability.

• Transpiration -- depletion of soil moisture by plants delays onset of saturation and subsequent runoff.

Brushlayer, when used in conjunction with herbaceous grasses and forbs, can also provide substantial surface erosion protection by effectively separating a slope into a series of shorter, slightly less severe slopes (Sotir and Gray, 1989).

3. Surface Erosion Techniques: Live Fascine and Brushmattress.

a. Surface Erosion. Although brushlayer and associated constructions are effective at surface erosion protection, live fascine and brushmattress are specifically tailored to this task by bringing a large amount of biomass to bear at specific points in the wastewater flow path. Planted perpendicular to the flow path down a slope, as seen in Figure 8, live fascine forms an extremely dense stand of foliage. The fascine acts as a "living filter fence" to restrain sediments and retard runoff velocity. At the same time, a very thick matting of roots sprouts just beneath the soil surface, further reinforcing soil cohesion and transpiring water out of the system.

Brushmattress acts as an intensely thick zone of vegetation which is highly effective at removing suspended solids and sediments from the flow stream. It can also be used at wastewater application points as an energy interception and dissipation structure which can simultaneously actively remove nutrients.

b. Flow Regulation and Distribution. While filling a role as a "biologically active energy dissipation mat" at application points, the brushmattress can also evenly distribute the flow of wastewater to the slope treatment zone. Live fascines can also be used as a means of regulating flow distribution throughout a sloped wastewater treatment system. The longitudinal arrangement of woody fibers in the fascine can act to convey runoff laterally on a slope and can regulate subsurface flow in a lateral direction by acting as a "natural pump" to uptake and laterally redistibute wastewater.

D. SOIL BIOENGINEERING VEGETATION PERFORMANCE CHARACTERISTICS FOR WASTEWATER TREATMENT

An analysis of Soil Bioengineering techniques for treatment systems should naturally focus on vegetative characteristics, since Soil Bioengineering is essentially the unique application of vegetation into the land matrix which treats the wastewater. Most removal mechanisms particular to the soil, such as organics adsorption, will not likely be altered by Soil Bioengineering, other than to be enhanced by the soil conditioning attributes of the vegetation itself. The interest here, then, is mainly survival and flourishing of Soil Bioengineering species in a waste loading environment.

1. Vegetation Requirements for Wastewater Treatment.

Most texts do not provide specific characteristics for plants in wastewater treatment systems, but some generic requirements that have been put forward are:

- High nutrient (mainly nitrogen) uptake capacity
- High moisture tolerance
- High consumptive water use (evapotranspiration demand)
- Long growing season
- High wastewater constituent tolerance (for municipal wastewaters this usually equates to a high salinity tolerance)

(EPA, 1981; WPCF, 1990; Reed, et al., 1988)

Revenue potential is also listed, although for Type 1 SR and OF systems revenue is not a major factor. Limited species lists and performance information are available, and are presented are presented below according to plant type, herbaceous or woody.

a. Herbaceous Species. Grasses and forbs possessing characteristics outlined above include certain perennial forage grasses and turf grasses. Species that have been used successfully are shown as Table 5.

All herbaceous species listed in Table 5 have high consumptive water use and moisture tolerances (EPA, 1981). These perennial grasses also are excellent at nutrient uptake, with most ranging 200 - 500 kg/ha-yr of nitrogen uptake (Reed, et al., 1988). Perennial forage grasses are the only alternative given for OF systems because their shallow widespread fibrous root networks ensure a low permeability is maintained (WPCF, 1990; Palazzo, et al., 1982). Essentially, plant characteristics for OF sites include plants which establish rapidly, grow well on tight, moist soils, have a long growing season and are hardy for the climate of OF operation (Palazzo, et al., 1982).

TABLE 5. VEGETATION SUCCESSFUL IN WASTEWATER TREATMENT[a]

Herbaceous Species	Woody Species
Reed Canarygrass	Cottonwood
Tall Fescue	Sycamore
Bermudagrass	Green Ash
Perennial Ryegrass	Black Cherry
Italian Ryegrass	Red Bud
Orchardgrass	Black Locust
Johnsongrass	Catalpa
Bahiagrass	Chinese Elm
Californiagrass	White Pine
Bromegrass	Eucalyptus
Clover	Willows
Timothy	Hybrid Poplars

[a] adapted from Reed, et al., 1988; WPCF, 1990; EPA, 1981)

Herbaceous species are also well suited for SR systems, with species shown in Table 5 showing the best results in the field.

b. Woody Species. SR systems also use woody species, primarily trees in either tree farming or forest system applications. Tree crops provide a good potential for revenue when sold as firewood or biomass fuel, but they must be harvested whole (trunk, branches, and leaves) to fully remove nitrogen from the site. (WPCF, 1990). Tree species best suited to forest and non-crop SR systems have a high growth response to wastewater (hence a high nutrient uptake value) (WPCF, 1990). Species which have been successful in renovating wastewater are shown in Table 5.

2. Vegetation Used in Soil Bioengineering.

As discussed in Section IV, the technology of Soil Bioengineering does not deal solely with woody species, although woody species-dominating systems have been the focus of this report. The ability to regulate soil water content and provide widespread surface erosion protection on a slope is almost exclusively the function of herbaceous grasses and forbs incorporated into a Soil Bioengineering system. Schiechtl (1980), in fact, goes into great detail in providing applied uses and applicable mixtures lists for herbaceous species. His mixture lists contain many of the species identified in Table 5, such as reed canarygrass, bermudagrass, and others.

A new and rather comprehensive list of woody species commonly used in Soil Bioengineering has recently been published (SCS, 1992), providing an excellent comparison to the list of species used in natural treatment systems, and is adapted for this report as Appendix A. There are several species of cottonwood (Populus spp.), willow (Salix spp.) and black locust (Robinia pseudoacacia) contained in this list which are already identified as candidates for a natural treatment system. Schiechtl (1980) list several other species such as ash (Fraxinus spp.) and elm (Ulmus spp.) for Soil Bioengineering which are effective wastewater renovator species. A brief examination of these selected woody species should point out the best Soil Bioengineering materials for natural treatment.

3. Performance of Woody Species for Wastewater Treatment.

Extensive research has been conducted on the ability of adventitious rooting woody species to provide waste treatment and assimilation, but unfortunately most published papers are case histories of regional systems such as forests, and do not provide specific information on renovation capability of particular species. Many studies on particular woody species have shown survival and growth rates in biomass farming and sludge-amended mine spoil reclamation, but little has been published on wastewater treatment performance.

Lee and co-workers (1976) conducted experiments on the ability of woody and wetland species to filter, dewater, and remove contaminants from dredge material, with the goal of water quality restoration of leachate from spoil piles. Since the process investigated is essentially the same as in a steeply sloping natural treatment system, characteristics determined to be useful in this study provide a good summary of vegetation attributes for wastewater treatment:

- tall, sturdy stems resistant to damage
- strong anchoring root/ rhizomal systems
- dense stem and leaf growth for maximum filter surface area
- development of adventitious from buried aerial parts (e.g., stems)
- rapid growth and elongation of new and old shoots above the soil surface
- root storage organs
- ability to survive anaerobically for extended periods of time.

The study found that, in particular, water willow (Justica americana), eastern cottonwood (Populus deltoides), black willow (Salix nigra), salt cedar (Tamarix gallica), and marsh elder (Iva frutescens) possessed all these characteristics and were excellent at renovating water from dredge operations. Eastern cottonwood and black willow were singled out for their "amazing regenerative powers" after their ability to survive accumulations of up to 6 m of sediment was observed.

b. Water tolerance. Whitlow and Harris (1979) provide an extensive summary of woody species tolerant to flooding and saturated soils and discuss the metabolic and anatomic adaptations of many water tolerant species in transferring oxygen to their root and rhizomes under these conditions. A region-by-region analysis of hundreds of woody species across the U.S. showed that those listed in Table 6 were able to survive flooded conditions for up to one year without damage.

TABLE 6. MOST WATER TOLERANT SPECIES[a]

Buttonbush	(Cephalanthus occidentalis)
Water Tupelo	(Nyssa aquatica)
Black Willow	(Salix nigra)
Bald Cypress	(Taxodium distichium)
Eastern cottonwood	(Populus deltoides)
Red-osier Dogwood	(Cornus stolonifera)

[a] adapted from Whitlow and Harris (1979)

c. Nutrient and Metals Uptake. Very little information is available on nutrient uptake of selected woody species. Most studies of performance of plants for wastewater treatment are focused on the ability of a forest system to perform and thus rarely publish information on specific species. Those species shown in Table 5 were selected based on a high growth response to wastewater applications which is caused by high nutient uptake (EPA, 1981). Svoboda (1979) reported excellent ability of silver maple (Acer saccharinum) and green ash (Fraxinus pennsylvanica) to take up heavy metals in sludge amended mine spoils. Metals uptake by plants is not usually a parameter of concern for municipal wastewater streams.

d. Selected Species for Soil Bioengineering Application to Natural Treatment Systems. Based upon a review of available literature and cross-referencing with species identified in Tables 5 and 6 and Appendix A, the woody species which show the greatest potential for success in a natural treatment system are shown in Table 7.

TABLE 7. BEST CANDIDATE SPECIES FOR SOIL BIOENGINEERING APPLICATION TO NATURAL TREATMENT SYSTEMS

Eastern cottonwood (Populus deltoides)	Red-osier Dogwood (Cornus Stolonifera)
Sandbar Willow (Salix interior)	Black willow (Salix nigra)
Peachleaf willow (Salix amygdaloides)	Red willow (Salix discolor)
Hooker willow (Salix hookeriana)	Black locust (Robinia pseudoacacia)

Of the species in Table 7, the black willow (Salix nigra) and eastern cottonwood (Populus deltoides) appear by far the best choice for use in a natural treatment system, if available. Both species are very common in the eastern part of the U.S., have excellent adventitious rooting capability, are highly resistant to most aspects of wastewater treatment such as salinity and heavy hydraulic loading, and have a documented history of wastewater treatment capability.

4. Harvesting Considerations.

The principal function of vegetation in a SR system is uptake of nutrients, primarily nitrogen (EPA, 1981). OF system vegetative uptake accounts for up to 30% of total nitrogen removal (WPCF, 1990). Mineralized nitrogen which is transformed into plant tissue, however, is stored "on-site" and must be physically removed from the site by harvesting in order to prevent nitrogen recycling back to the soil.

Established Soil Bioengineering practices for living system maintenance are compatible with the harvesting objectives of these land treatment sytems. Schiechtl (1980) recommended regular pruning of woody species to promote growth and further adventitious root development. In particular, certain Salix species should be pruned close to the base (ground surface) every several years to reduce shading (Schiechtl, 1980). All harvesting operations in this "whole-tree" manner must be done during the dormant season (winter) of the woody species (Schiechtl, 1980).

Herbaceous species used for surface erosion protection in between Soil Bioengineering constructions such as brushlayer or live fascine should be harvested at least annually by mowing (Schiechtl, 1980). Most Soil Bioengineering systems are placed at spacings of 1.5 to 3.0 m (see Figure 3) which allows smaller conventional harvesting equipment to be used.

VI. APPLICATIONS OF SOIL BIOENGINEERING TECHNIQUES IN OVERLAND FLOW SYSTEMS

A. GENERAL APPLICATIONS

As discussed in Section V, the most beneficial application of Soil Bioengineering to Overland Flow slopes is the ability of live systems to rapidly establish a vegetative layer on the slope. These vegetative benefits, however, must be examined in light of their impact on other aspects of the OF system, such as soil permeability.

1. Vegetative Effects.

Vegetative pattern and density were shown above to be primary factors for controlling detention time (Martel, et al., 1982; Peters, et al., 1981. Vegetation actually dampens the effect of an increase in slope, but this dampening effect has been documented in the literature only within the "recommended", or "rule of thumb" ranges of 2 - 8%, and only using herbaceous perennial grasses and some legumes (D'Itri, 1982). No research could be found on how herbaceous vegetation functioned on steeper OF slopes, or on any attempts to use woody vegetative erosion controls for steeper OF wastewater treatment.

The EPA (1981) cautions that slope grades greater than 8% may produce significant channeling and erosion, particularly in the first 3 - 5 years of operation while herbaceous vegetation is becoming established.

Even at OF sites with slopes within the "recommended" range, channeling is quite common during the first three years due to slow establishment of the vegetative mat (Martel, et al., 1982; Palazzo, et al., 1982). Conversely, Tedaldi (1990), found that at a well established (20 year old) OF site at Paris, Texas, vegetation density seemed to overcome the negative effect of channeling completely. With a flourishing, dense crop of tall fescue and reed canarygrass, no significant effects on performance were observed, even though "channeling laterally [to flow] and shallow erosion gullies were very ubiquitous" (Tedaldi, 1990).

The obvious solution to these vegetative limitations is to select rapidly establishing, yet dense and well rooted vegetation that will persist. Soil Bioengineering techniques were designed for precisely these objectives. Additionally, the increased growth stage of Soil Bioengineering vegetation (relative to herbaceous species) and the larger aerial foliage surface area on woody plants may mean higher level of treatment in OF systems, particularly those with spray application methods. Tedaldi (1990) noted significant removal action appeared to be occurring as wastewater from spray irrigation traveled down leaves and stems of vegetation. He further noted that dense vegetation could attenuate the resuspension of settled solids caused by droplet impact.

2. Effect on Permeability.

An obvious concern for use of Soil Bioengineering techniques in OF systems is their ability to increase the infiltration rate and permeability of the topsoil. Most texts still specify that only perennial grasses should be used on OF slopes to minimize infiltration (WPCF, 1990; Palazzo, et al., 1982; EPA, 1981). This is mainly due to early research results suggesting that only soils with permeabilities of less than 0.5 cm/hr could be used effectively for OF systems (EPA, 1981). Most designers and regulators used this guidance as an inflexible limit, however, resulting in elimination of both potential vegetation and sites (EPA, 1984). The EPA (1984) now discourages this inflexible view by stating that OF systems can be designed successfully of more permeable soils. The OF system at Paris, Texas, for example, loses approximately 20% of applied wastewater to deep percolation. Percolate collected as ground water showed no contaminants in amounts of concern, and percolation did not affect the quality of the surface effluent from the system (Tedaldi, 1990). Of course, the effect of percolate on ground water is very site specific, and should be analyzed thoroughly in designing an OF system with appreciable permeability.

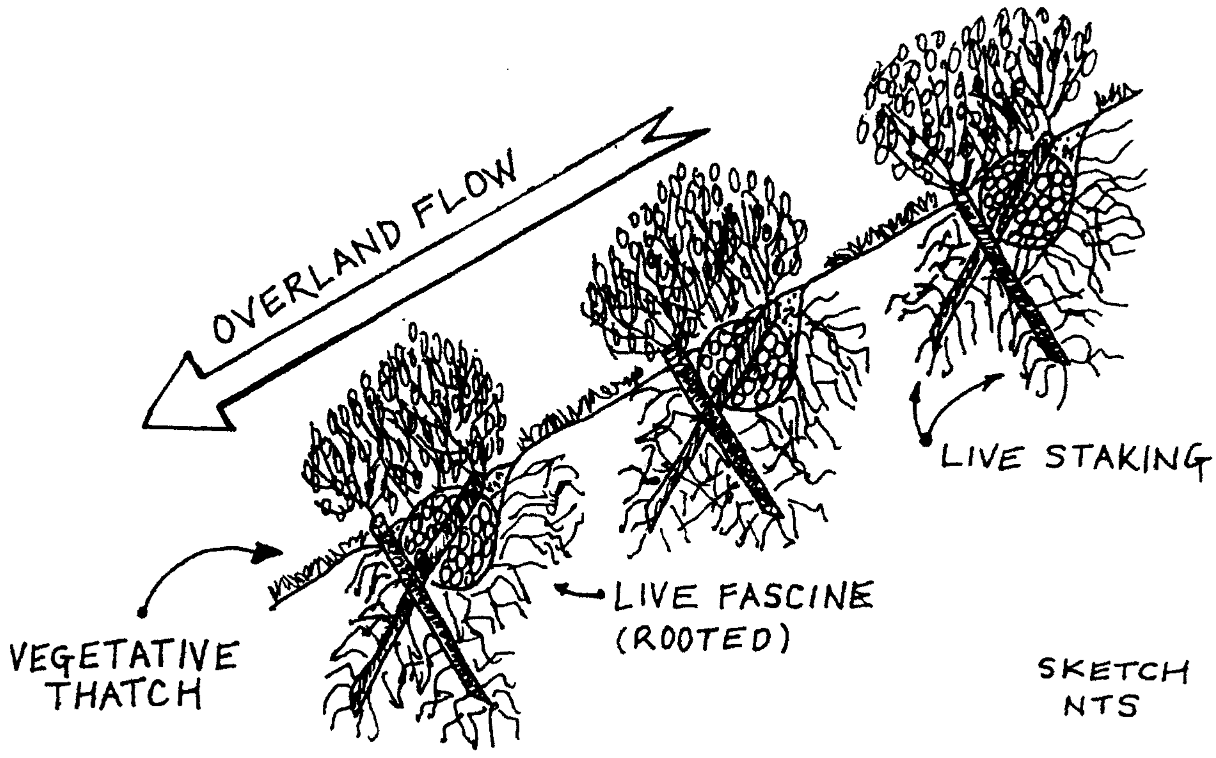
Given this flexibility, Soil Bioengineering structures such as live fascine, brushmattress and live cribwall are highly feasible for OF sites. Several specific applications are recommended below.

B. USE OF LIVE FASCINE FOR EROSION AND UNIFORM FLOW CONTROL ON STEEPER SLOPES.

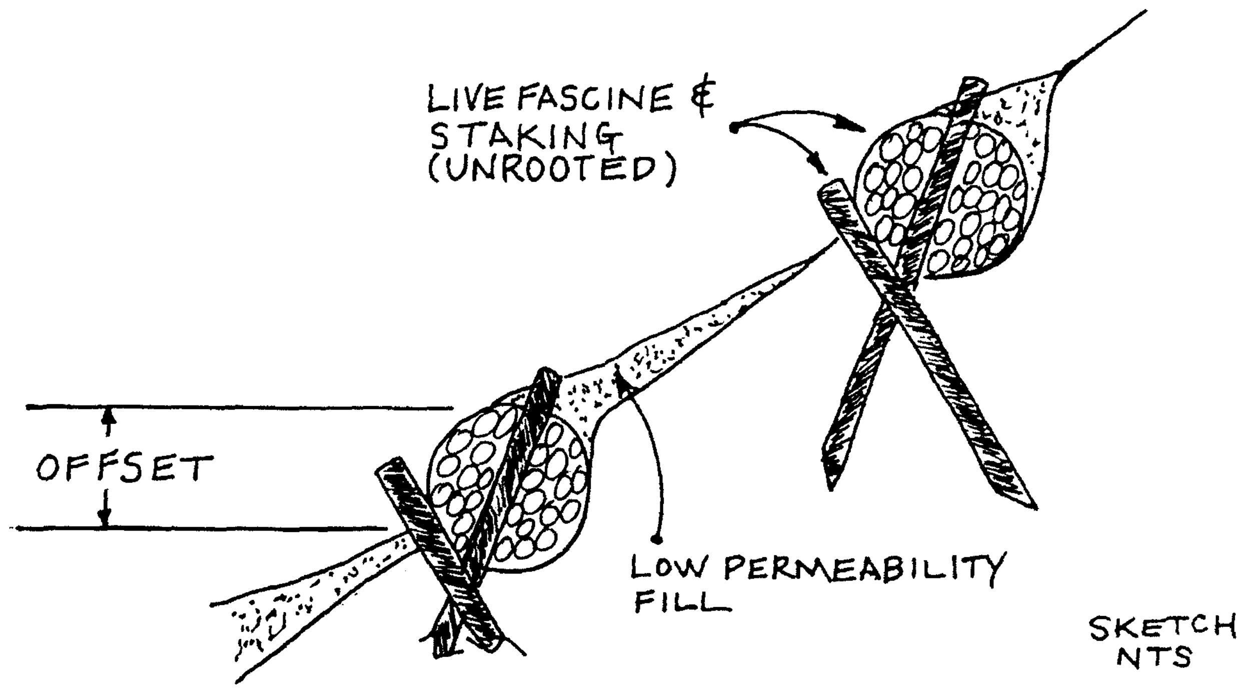
Although some permeability is allowable on OF slopes, it should be still be limited in order to avoid an overly-complex design situation, particularly in the calculation of design slope detention time. To limit the permeability yet retain most of the benefits of Soil Bioengineering on OF slopes, deep penetration methods such as brushlayer should be generally excluded. (Live cribwall and branchpacking may be an interesting exception to this, as noted below.) Brushlayer will also be hard to establish on tight soils because of the depth at which adventitious rooting must take place. Live fascines, therefore, are a good candidate for OF sites, and may be employed in several uses.

The most feasible application of live fascine is in the "normal" configuration, perpendicular to the direction of flow (see Figure 8). Using this arrangement, the system can mechanically act as a sediment screen and roots and shoots can provide a large amount of surface area for microbial growth and adsorption. The proliferation of root growth within and below the fascine will also increase the removal of pollutants by plant uptake, particularly if fascines are used in a series down the slope, as shown in Figure 15(a).

A series of fascines will also significantly slow the velocity of water on steeper slopes and, through sediment deposition, actually develop the site into a series of smaller, less steep slopes (Sotir and Gray, 1989; Gray and Leiser, 1982). Uniform "sheet" flow will not be disrupted by this construction (as one might suspect) because of the ability of the fascine to laterally distribute the hydraulic load. This, coupled with the shorter travel length per "mini-terrace", will dissipate



(a) Live fascines used in series in an overland flow slope.



(b) Live fascines installed with an offset to establish "mini-terraces" and prevent infiltration.

FIGURE 15. LIVE FASCINES ON OVERLAND FLOW SLOPES.

flow momentum and ensure smooth laminar flow and adequate detention time on steeper sloped sites.

Slowing down the flow on the slope, however, also sets the stage for increased infiltration, especially around the highly permeable fascine itself. Gray and Leiser (1982) suggest that this can be controlled by positioning the fascine higher out of the ground, using live stakes to secure the fascine, and packing soil firmly around the fascine. This variation on the regular fascine installation, shown in Figure 15(b), has the added benefit of reaeration of the wastewater as it "trickles" down the fascine to the next "mini-terrace", encouraging enhanced organics degradation and nitrification.

C. USE OF BRUSHMATTRESS FOR INITIAL FILTRATION AND UNIFORM DISTRIBUTION

Surface distribution methods for OF slopes, such as gated pipe or bubbling orifices are favored by many regulators and designers because they offer lower operating costs and require less aerosol land buffer area than sprinkler distribution methods (EPA, 1984). The disadvantages of gated pipe are the potential for erosion and uneven distribution of flow on the slope. EPA (1984) recommends a thick vegetative crop to ensure distribution (consistent with the key features of the fascine mentioned above) and use of gravel pads or splash blocks to guard against erosion. Solids deposition at the top of the slope can smother grasses before they become well established (Palazzo, et al., 1982), decreasing system performance. Gravel pads can clog easily under solids deposition at the application point, also decreasing performance and creating maintenance problems.

Brushmattress may be an effective method of distributing flow and protecting against surface erosion from concentrated pipe gate discharge points. The two-directional aspect of the brushmattress' stem and root matrix, shown in Figure 16, will eliminate surface erosion and will

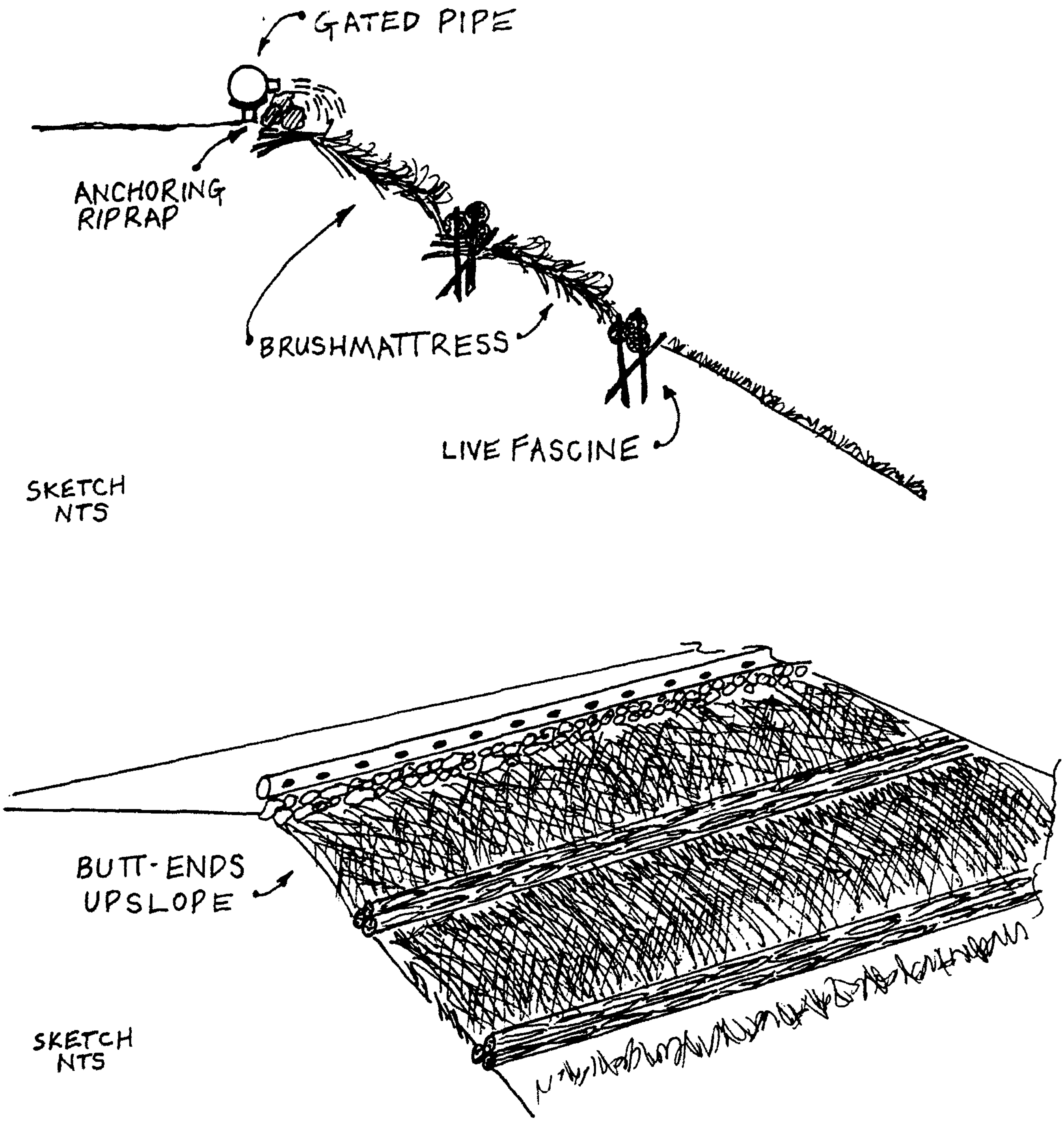


FIGURE 16. BRUSHMATTRESS ON AN OVERLAND FLOW SLOPE.

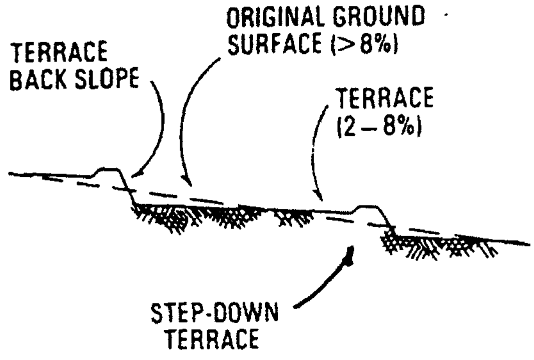
provide a very evenly distributed flow to the OF slope. Designed for surface erosion protection against flowing waterways (Schiechtl, 1980), the woody brushmattress forms an intensely thick layer of vegetation which is mechanically sturdy and resistant to smothering. Sedimentation of organics is, in fact, beneficial for growth and establishment of the woody species used. Given the "amazing regenerative powers" and water, salt and sedimentation tolerances of the black willow (Salix nigra), Eastern cotttonwood (Populus deltoides) and related species listed in Table 8, brushmattress should flourish under normal OF wastewater loading conditions.

D. USE OF LIVE CRIBWALL FOR ACTIVE TERRACE FILTRATION.

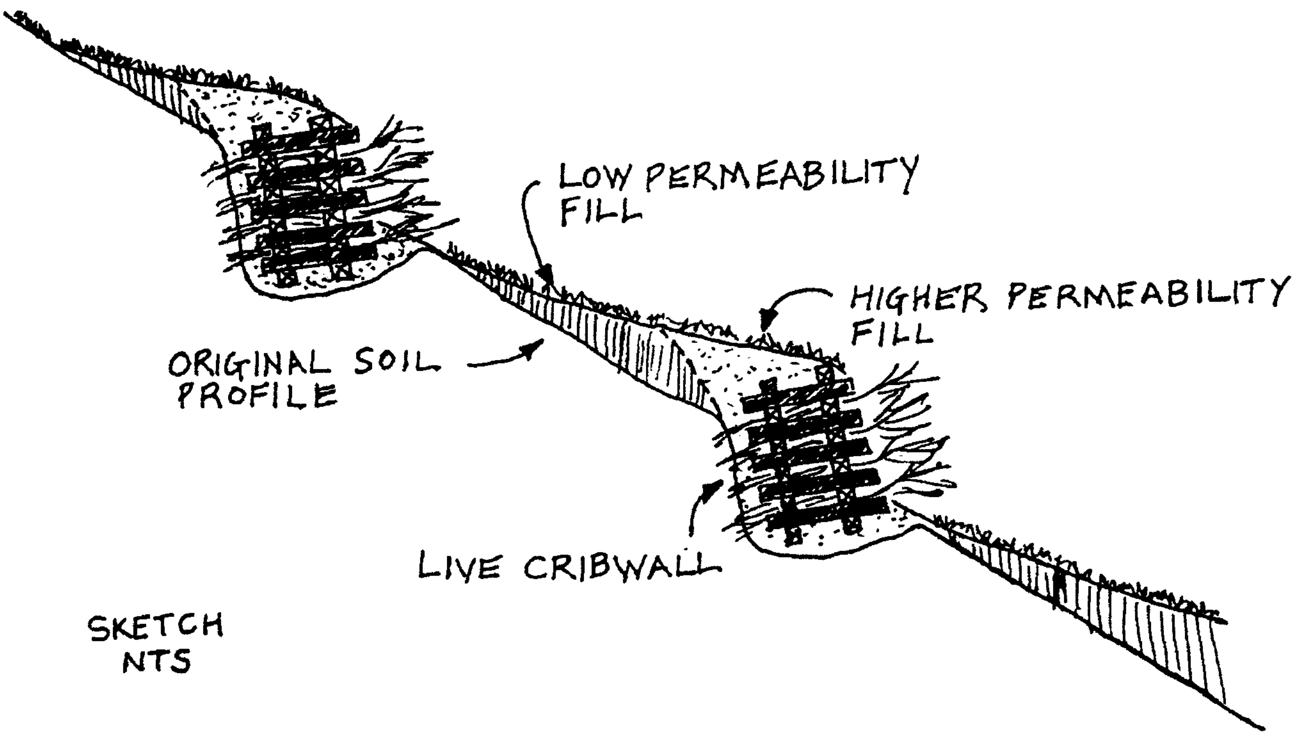
The EPA manual (1981; 1984) suggests several alternatives to reshape a potential OF site so that slopes conform to the "recommended" 2 - 8% range. For sites with greater than 8% slopes, "step-down terraces", shown in Figure 17(a), are recommended to reduce the terrace grade to 8% (EPA, 1984). Through the discussion of live fascines and brushmattress above, it has been established that OF slopes beyond 8 - 12% are certainly feasible. On sites with extremely steep grades (50 - 100%), however, the effect of gravity may overwhelm the capacity of Soil Bioengineering systems to slow down and evenly distribute flow in OF treatment.

In these cases, a modification to the step-down terrace is suggested. Incorporating live cribwall or branchpacking systems in a "stair-stepping" fashion (Gray and Leiser, 1982; SCS, 1992) into the OF flow path will not only reduce the overall slope of the site to a manageable grade (e.g., 30%), but could conceivably provide much higher treatment levels per unit area of slope.

As shown in Figure 17(b), branchpacking or live cribwall systems can be constructed with a more permeable soil fill than the surrounding site so that as the sheet flow reaches the system, most flow will be <u>through</u> the system rather than <u>over</u> it. Surface flow over the top of the system,



(a) Step-down terraces on a conventional overland flow slope.
(adapted from EPA, 1984)



(b). Active step-down terracing using live cribwall as a "vertical filtration" unit.

FIGURE 17. USE OF LIVE CRIBWALL FOR ACTIVE TERRACE FILTRATION.

however, should not present a problem because the cribwall/branchpack type of construction has the abundant mechanical reinforcement of the timbers and branches to protect against surface erosion. These two constructions are, in fact, often deployed along the bottoms of active drainage channels as "natural check dams" (Schiechtl, 1980). Using the gravel bed of the cribwall for uniform water collection and redistribution on the next terrace, the overall travel distance of water flow on the site may be increased, which, as noted in section V, should substantially improve removal efficiency.

As an alternative approach, removal of pollutants to a certain permit limitation may be realized with lower land area overall. In any event, land costs would be lowered since the "step-down" function, performed by a live cribwall or branchpacking construction typically 2 - 4 m thick, will replace the expansive 4:1 terrace backslope grade the EPA (1984) recommends (see Figure 17(a)). On steeper sloped sites, less overall earthwork will be required this type of system layout compared to an 8% terrace and 25% (4:1) terrace backslope.

E. USE OF SOIL BIOENGINEERING IN RUNOFF COLLECTION CHANNEL DESIGN.

The EPA (1984) indicates many operating OF systems suffer erosion in drainage (runoff collection) channels at the base of terraces. Causes cited were misaligned inverts at the junction of tributary and main collection channels and excessive velocity in the channel before vegetation (i.e., grass) becomes established (EPA, 1984).

The EPA manual (1984) suggests "conventional" remedies to these problems, including "staked down jute or nylon matting with wood fiber... [c]oncrete lined channels, riprap, and straw or hay mulch using an injected asphaltic or other binder". Pipe drains are also recommended as "land efficient" where steeper slopes exist and step-down terraces must be used (EPA, 1984).

In addition to the classic drawbacks of using "hard" constructions in drainage channels, which fight against the land rather than utilitizing its natural restorative properties, most the EPA's recommendations will actually degrade effluent quality! Concrete flumes and pipes will promote turbulent flow and algae growth, driving up Total Suspended Solids (TSS) levels, and require extensive maintenance to remove growth (WPCF, 1990).

Erosion problems in drainage channels can be more effectively controlled by Soil Bioengineering techniques such as brushmattress, live fascines, and live siltation (essentially an in-line channel bottom variation of brushlayer). Established Soil Bioengineering texts recommend several other techniques specifically designed to immediately and effectively prevent erosion in drainage channels. (Schiechtl, 1980; Gray and Leiser, 1982).

Moreover, vegetative Soil Bioengineering techniques will continue to "polish" the slope effluent from an OF system as it drains to the final point discharge. Tedaldi (1990) documented that well established channel vegetation acted as a very effective water polishing technique at the Paris, Texas OF site.

VII. APPLICATIONS OF SOIL BIOENGINEERING TECHNIQUES IN NON-CROP AND FOREST SLOW RATE SYSTEMS.

A. GENERAL APPLICATIONS.

In contrast to the design-oriented applications of Soil Bioengineering techniques to OF systems, applications for SR systems will provide the most benefit to the operation and management of SR sites. The treatment process itself (i.e., the flow path), will still largely be a matter of percolation through the applied surface to the ground water table. Using Soil Bioengineering erosion and mass wasting control measures on steeper permeable slopes, however, may mean that percolation can be considered lateral to the slope (see section V) rather than just vertically. An interesting variation of an SR system could capitalize on this flow path, and is presented in part D of this section. There are several other applications of Soil Bioengineering which can benefit forage grass and forest SR systems operation and management.

B. EROSION CONTROL ON FORAGE NON-CROP SR SYSTEMS

Non-crop sites using herbaceous forage grasses as primary vegetation on moderately permeable soils offer perennial nutrient uptake capabilities as high or higher than all other natural treatment systems. These systems, however, suffer serious limitations on steeper slopes due to erosion, as discussed in previous sections. Most herbaceous vegetation will fail to some degree on steeper slopes under increased loading, such as storm events. The EPA manual (1981), suggests several conventional erosion control techniques, such as "contour plowing, no-till farming, and grass border strips" on steeper sites, but these techniques are mainly prescribed in connection with agricultural practice using row crops. Some of these measures also require a substantial amount of preparatory earthwork and site reshaping.

An improved solution for forage non-crop SR sites on steeper slopes would be a combination of brushlayer and live fascines, as shown in Figure 18. This "classic" Soil

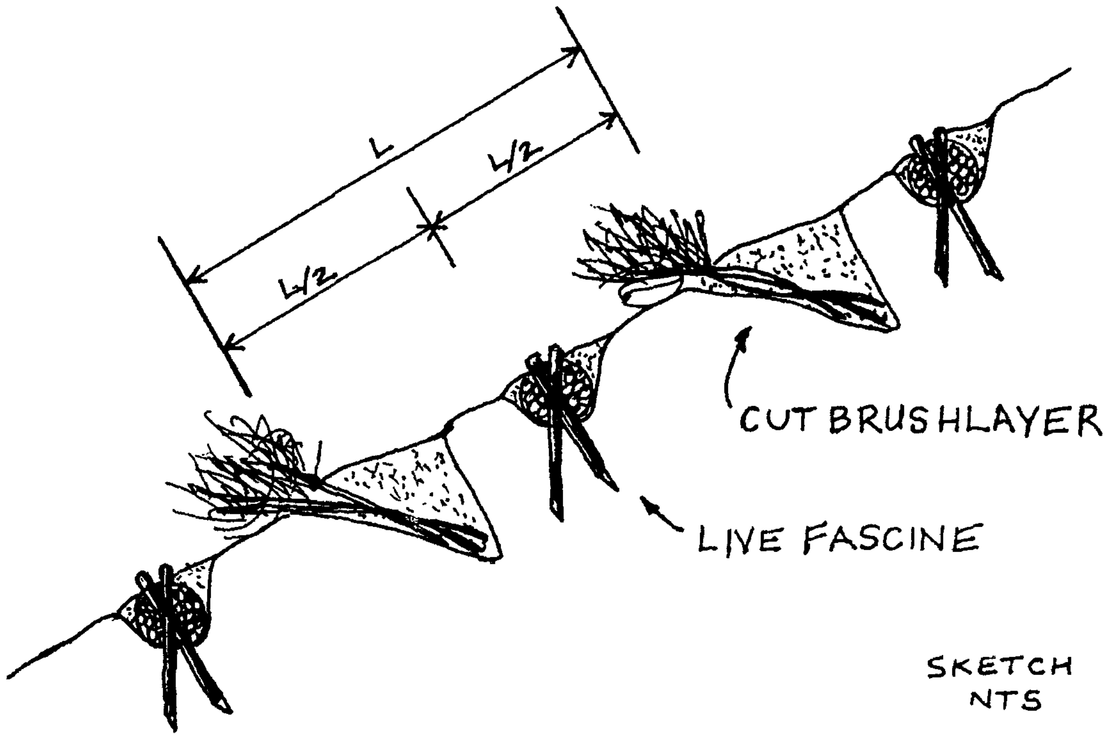


FIGURE 18. BRUSHLAYER - LIVE FASCINE TANDEM COMBINATION FOR FORAGE GRASS SR SYSTEM.

Bioengineering arrangement can function both to resist mass movement and to prevent surface erosion during high hydraulic loading where surface runoff is produced. These systems will also encourage much faster establishment of new herbaceous vegetation (increasing site nitrogen uptake) and produce a much more organically rich soil, with higher adsorption and microbial activity than herbaceous vegetation alone (Schiechtl, 1980).

On extremely steep sites, augmenting this system of brushlayer and fascines with step-down live cribwall terracing is recommended.

C. APPLICATIONS OF SOIL BIOENGINEERING TO FOREST SR SYSTEMS.

Forest SR systems have already demonstrated the capacity to function in the field at considerable slope grades (Nutter, et al., 1979; Sepp, 1973). Because of the relatively well established root network and organic litter on the floor of most forests, the necessity to employ Soil Bioengineering erosion controls is limited. Low sunlight availability, along with high competition for adventitious rooting development will generally result in poor survival of Soil Bioengineering constructions in a full-canopy forest. There are, however, several operation and management oriented applications for Soil Bioengineering, including new forest establishment and post-harvesting reforestation.

1. Applications for New Forest Establishment.

Wastewater irrigation has been shown to be useful to establish forests on barren land, clear cut areas, and abandoned farmland (McKim, et al., 1982). Newly established forests irrigated with wastewater have a generally much higher nutrient and constituent uptake than older, mature forest systems, particularly where herbaceous ground cover is present (McKim, et al., 1982). This phenomenon is attributed to a variety of factors, including the faster storage rates of rapidly reproducing woody seedling tissue, the lack of nitrogen storage capacity of the new forest floor (typically lower in organic content than older forests), and the presence of high uptake herbaceous vegetation.

Because of the less developed root structure of woody seedlings and herbaceous species and low organic content of the forest floor, establishing a new forest on a steeper slope taces significant erosion problems. For this reason "new forest" SR systems have been generally limited to sites less than 8% (McKim, et al., 1982). Until the protective organic layer establishes, the hydraulic loading rate for these gently sloping systems must also be reduced. Organic layer development has been shown to require 3 to 10 years to establish in most new forest SR systems (McKim, et al., 1982).

Soil Bioengineering techniques will be especially useful in establishing new forests using wastewater treatment. The use of indigenous woody species that are normally part of a forest understory (such as red-osier dogwood (Cornus stolonifera) and American elderberry (Sambucus canadensis)) in live fascine, brushlayer and other techniques will actively prevent erosion, protect herbaceous vegetation used for initial uptake, and encourage seedling development. Erosion protection will also allow a higher initial hydraulic loading rate, and rapidly developing shoots of the woody understory shrubs will further augment the systems nutrient uptake capability during the first three years of establishment. For a given wastewater flow, a higher hydraulic loading rate will mean less land area to irrigate. Understory species may also persist at the site after canopy closure, enhancing long term performance.

2. Applications for Post-Harvesting Reforestation.

Similar Soil Bioengineering techniques will be useful for reforestation of an SR site following harvest. "Whole tree" harvesting is essential for forest SR systems in order to permanently remove nitrogen and other wastewater constituents stored in the woody tissue of vegetation (EPA, 1981; WPCF, 1990; McKim, et al., 1982). Trees shrubs and other vegetation not removed periodically will return to the soil as litter-fall, and be "recycled" into forms such as nitrate (NO_3^-) which may migrate to ground water (EPA, 1981).

Whole-tree harvesting may be accomplished by thinning, selective harvest, or clear-cutting (EPA, 1981). Even-aged forests are usually clear-cut, and many uneven-aged forests are also clear-cut by "blocks" of land on a rotational basis in order to minimize the labor costs on selective harvesting and thinning (Reed and Bastian, 1991). While clear-cutting allows the maximum removal of nitrogen per unit of land area, significant erosion problems can result, particularly on sloping sites (Reed and Bastian, 1991). To combat this, many sites will curtail application of wastewater to the site or significantly reduce hydraulic loading (EPA, 1981).

Herbaceous vegetation has been successfully used as an interim cover at harvested forest SR sites (McKim, et al., 1982), but the application rate must be reduced or controlled so that erosion does not occur during herbaceous establishment or "choke out" the reforesting woody seedlings (EPA, 1981).

On steeper sloped sites under reforestation, brushlayer and line fascine can again fill the dual role of actively protecting against erosion and buffering the site against loss of nitrogen removal capability. One specific application, hedge brushlayer, may be optimal at reforesting sloped sites. Described in Section IV, this technique inserts a rooted woody seedling in an upright position into the brushlayer "bench" at one meter intervals. Hedge brushlayer establishes the climax species much faster (Schiechtl, 1980). The concentration of cuttings per lineal meter is reduced, especially in the vicinity of the rooted seedling, to allow some room for seedling roots to compete with the brushlayer species.

Woody shrub and herbaceous species used in Soil Bioengineering applications may not only protect the sloped site from erosion and reduce wastewater curtailments, they may actually "restore" overloaded nitrogen conditions in the soil. Sopper and Kerr (1979) found that "pioneer" herbaceous and woody shrub species invading a SR site following clearcutting of a red pine (Pinus resinosa) stand were "extremely efficient" at renovating wastewater and reducing soil nitrate nitrogen (NO_3^--N). Soil NO_3^--N had accumulated to 24.2 mg/L just prior to clear-cutting the trees. Although wastewater applications continued at the same rate as before the clear-cutting, the invading pioneer vegetation reduced the NO_3^--N level in the soil from 24.2 mg/L to 8.3 mg/L one year later and 2.9 mg/L two years later (Sopper and Kerr, 1979).

This phenomenal performance from a random growth of the same types of vegetation which Soil Bioengineering employs suggests that even higher renovation potential exists through the systematic use of Soil Bioengineering techniques.

D. PROPOSAL FOR AN ALTERNATIVE NATURAL TREATMENT SYSTEM -- THE CONSTRUCTED BRUSHLAND.

Fully integrating the Soil Bioengineering techniques, parallel slope flow concepts, overland flow mechanics and attached-growth reactor efficiencies discussed in this report creates the possibility of an alternative form of natural treatment system. The "Constructed Brushland" (CB) may be a feasible alternative to forage grass SR systems or OF systems on steeper sloping sites. Depicted in Figure 19, the system will essentially be a hybrid of the OF and SR land treatment systems, although flow kinetics for design may more closely resemble the subsurface flow (SF) constructed wetland.

1. General Description.

As shown in Figure 19, the CB will treat wastewater on steeper slopes by capitalizing on the concept of flow parallel to the slope surface. Soil Bioengineering techniques placed as shown will perform integral treatment functions in addition to their land mass stability and erosion prevention roles.

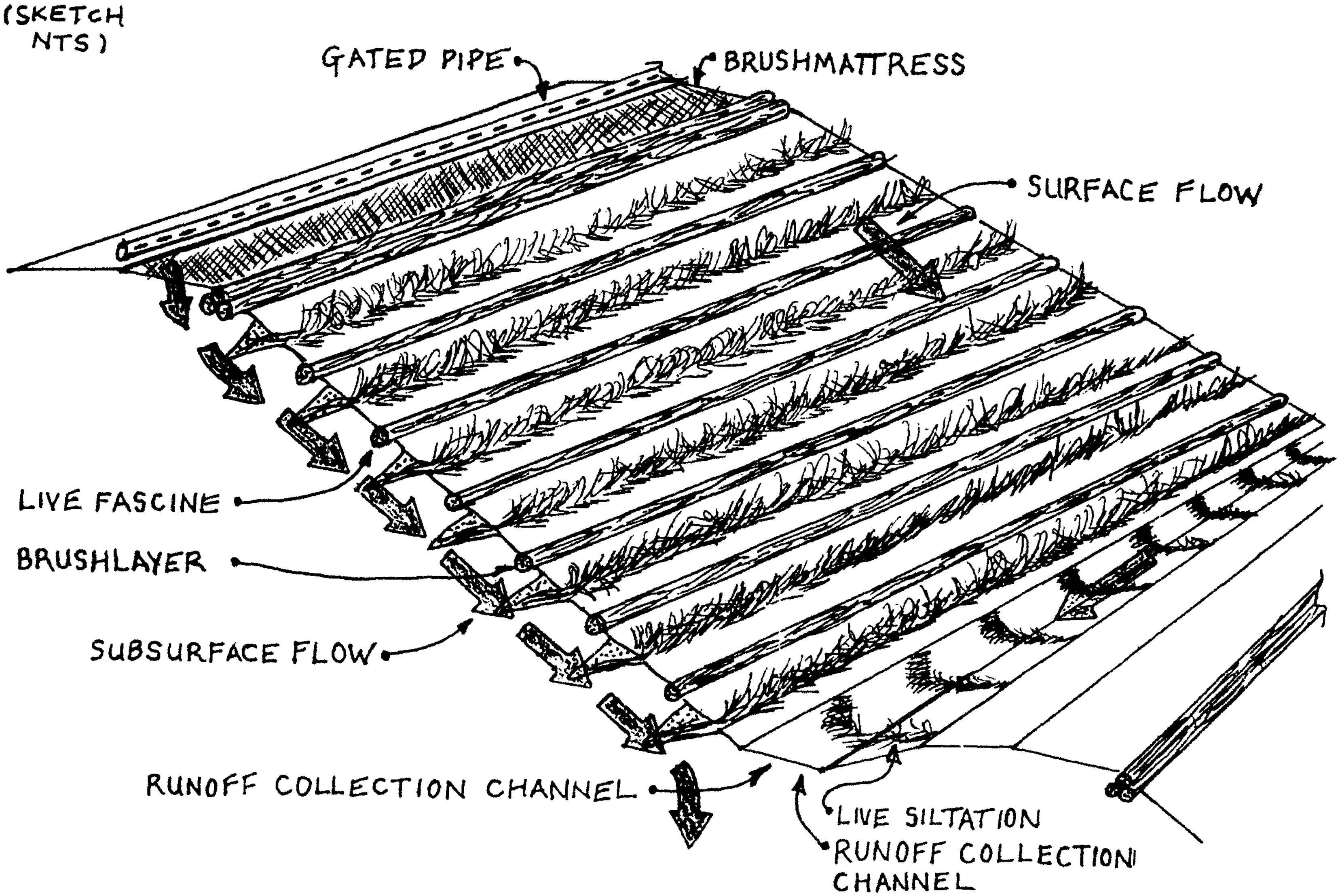


FIGURE 19. CONSTRUCTED BRUSHLAND.

a. Land Treatment Performance Characteristics. Soil selected for this application should be relatively isotropic, moderately well drained to well drained with a moderate (1.5 to 5.1 cm/hr) to moderately rapid (5.1 to 15.2 cm/hr) permeability (SCS, 1992). Position of the ground water table should be considered in design of this system to preclude any short-circuiting of lateral flow through the entire slope. Shallow vadose soil depths may adversely affect the ability of the soil to laterally transfer applied wastewater to the base of the slope (Nutter, 1975).

Flow application by surface or low-pressure distribution methods at the top of the slope would, in a manner similar to OF, ensure the maximum travel distance for the wastewater down the slope. Consistent with EPA guidelines to prevent clogging in these systems, a preapplication treatment to primary standards should be incorporated. As in "normal" SR systems, a facultative storage lagoon may provide primary sedimentation in addition to storage for periods when application is not feasible, such as inclement weather (EPA, 1981).

Effluent from the system would likely be a mixture of surface runoff at the base of the slope and subsurface drainage to the water table at or near the base of the slope, as experienced at other sloping land treatment sites (Nutter, et al., 1979; Reed and Bastian, 1991). Provision should be made for a surface runoff collection system. This system should incorporate Soil Bioengineering techniques for "active polishing" of collected runoff as discussed in Section VI. A tailwater return system to recycle collected runoff back to the top of the slope may be necessary if action of the vegetation in the collection channels is insufficient to meet a permitted discharge level (e.g., to a nearby stream or lake).

b. Soil Bioengineering Performance Characteristics. The performance of a CB will rely upon Soil Bioengineering techniques to preserve the mass stability of the site and eliminate surface erosion caused by large hydraulic loading to the site. A combination of alternating brushlayer and live fascine would fill these roles. Brushlayer will provide slope mass stability through a deep adventitious rooting network. Live fascine will prevent surface erosion through distribution of wastewater perpendicular to the slope and shallow adventitious rooting networks. These two subsurface "layers" of roots will also maximize the amount of biomass exposed to the flow path down the slope. Soil conditioning properties of these systems will quickly and effectively establish soil microsites for adsorption and microbial activity. Spacing of the brushlayers should be 1.5 to 3.0 m apart for optimum biomass concentration, with live fascines placed halfway between brushlayers. (Schiechtl, 1980).

Initial distribution at the top of the slope should be through a brushmattress network, similar to the arrangement discussed for OF systems in section VI. This technique should provide for removal of substantial solids (and associated BOD_5) and aerate the applied wastewater to some degree.

Woody species such as those in Table 8 are recommended for the system, particularly black willow (Salix nigra) and eastern cottonwood (Populus deltoides). Herbaceous vegetation shown in Table 5, such as Bahiagrass and Johnsongrass, should also be incorporated into the site to provide maximum nutrient uptake capability.

2. Construction Details.

The Constructed Brushland is feasible on either appropriate native (in-situ) soils, as discussed above, or on suitable permeable fill hauled to the site. Obviously, hauling in fill will increase site construction costs, but this may be offset by other factors such as proximity of the site to the collection and primary treatment points and acquisition costs of land. If fill is used, the fill brushlayer technique is applicable. The length of fill brushlayer will be proportional to the amount of fill, based on the cross-sectional area required for a given hydraulic loading. Most conventional Soil Bioengineering applications use fill brushlayer of up to 7 m in length (Schiechtl, 1980). Cut brushlayer should be used if the system will be constructed on in-situ soil. While most conventional Soil Bioengineering techniques use 1 to 2 m long cut brushlayer (Schiechtl, 1980), a longer brushlayer should be used in the CB to ensure an adequate amount of rooted biomass is established throughout the "active treatment zone".

If in-situ soils are permeable enough to use, preliminary rough grading at the site should be limited to that sufficient to reduce slope cross-grade so that flow is uniform in one direction. If sites are extremely steep (50 - 100%), some terracing may be required to reduce slopes down to 50%. The use of live cribwall is recommended in this regard (see Figure 17(b) for similar application for OF systems).

A low permeability layer, such as a clay lens, may be an option for areas with a high ground water table along the slope. This layer could exist either in-situ or be placed as an initial lift in a fill CB.

3. System Design -- Flow Kinetics and Land Area Requirements.

The Constructed Brushland is, like other soil-based natural treatment systems, essentially an attached-growth bioreactor, and can be described by a first order plug flow kinetics model for contaminant removal, equation (5). The lateral plug flow movement of wastewater down the slope through the root and soil matrix is most analogous to the submerged flow (SF) constructed wetland process.

The SF wetland is a natural treatment system consisting of a lined basin of gravel or soil and emergent macrophytes such as cattails (Typha spp.), reeds (Phragmites spp.), or bulrushes (Scirpus spp.). The soil and plant roots and rhizomes act as attached-growth strata for microbial activity and as adsorption sites for contaminants in the water flowing past. These "rock-plant beds", usually 0.5 to 1.0 m deep, are loaded with a wastewater flow which is less than the bed depth (hence "subsurface flow"), and are described by the kinetics model (Reed, et al., 1988):

$$\frac{C_e}{C_o} = \exp\left[-\frac{K_T A_s dn}{Q}\right] \quad (8)$$

where,

C_e = Effluent concentration, mg/L
C_o = Influent concentration, mg/L
K_T = First order rate constant, $days^{-1}$
A_s = Surface area of the system, m^2
= LW (length X width of system)
n = Bed porosity (as a decimal fraction)
d = Depth of flow, m
Q = Average flow through system, m^3/day

This equation is analogous to the Eckenfelder trickling filter model, equation (1). The K_T term for SF wetlands has been defined in terms directly related to $C'KA_v^{m+1}$ in equation (1) (Reed, et al., 1988).

Reed, et al., (1988) suggests a model for OF and free water surface wetlands (a type of constructed wetland where water flows freely over the soil and through emergent vegetation, virtually identical to the OF process) which combines the Eckenfelder model, equation (1), with the CRREL model developed for OF systems:

$$\frac{C}{C_o} = A\exp\left[-\frac{C'KA_v^{m+1}LWdn}{4.63S^{1/3}Q}\right] \quad (9)$$

where,

A = Fraction of pollutant not removed as settleable solids near headworks of the system (expressed as a decimal fraction)
C' = Characteristic constant of the medium
K = First order rate constant, $days^{-1}$
A_v = Specific surface area of the media, m^2/m^3
L = Length of the system (parallel to flow path), m
W = Width of the system (perpendicular to flow path), m
d = Depth of applied wastewater flow, m
n = Porosity of the media (as a decimal fraction)
S = Slope of the system, m/m
Q = Average flow through system, m^3/day
m = empirical constant

Since equation (9) contains variables applicable to the performance of the Constructed Brushland, namely slope, and the rate constant in equation (8) can be defined in terms of the variables given in equation (9), the CB should be designed based on the kinetics model given by equation (9).

Using this model, the land required for a CB can be calculated by rearranging terms to yield:

$$A_s = \frac{6.61S^{1/3}Q\left[\ln C_o - \ln C_e - 0.,6539\right]}{KA_v^{1.75}dn} \qquad (10)$$

and detention time on the slope can be expressed as:

$$t = \frac{6.61S^{1/3}\left[\ln C_o - \ln C_e - 0.,6539\right]}{KA_v^{1.75}} \qquad (11)$$

(NOTE: See Appendix B for derivation of these equations (10) and (11) and comments.

4. <u>Comparison to Other Systems</u>.

A fair comparison between this new natural treatment system and established systems such as SR, OF and SF wetlands is not feasible at present due to the differing site conditions for each of these systems, the need to evaluate empirical constants for individual cases, the difficulty of determining specific surface area, A_v, for a permeable soil (Reed, et al., 1988), and the need to evaluate rate constants through bench-scale or pilot studies.

Intuitively, however, the use of moderately permeable soil as the treatment medium will mean a much higher specific surface area, A_v, and porosity, n, for the Constructed Brushland compared to the OF or SF wetland system. This translates in equation (10) to a greatly reduced area required for the same removal efficiency. Furthermore, the depth of flow in a CB will be many times larger than OF or SF wetlands, also acting in equation (10) to reduce land areas required. The effect of increased slope will offset these reductions, but its effect is smaller (a cube root exponent) compared to the effect of increased specific surface area (a 1.75 power exponent).

Qualitatively, then, the Constructed Brushland system appears to be a viable and feasible alternative which could be a considerably more efficient option for natural wastewater treatment.

VIII. CONCLUSIONS

Natural treatment systems are a cost-effective method for renovating wastewater, but are limited by land availability and suitability. Variations to the original slow rate irrigation process have overcome many of these limitations, except for the limitation of excessive slope. There has been some success with irrigation of wastewater on relatively steep established forest slopes (Nutter, 1979; Reed and Bastian, 1990), but established forests have a limited nitrogen removal capacity due to internal recycling. With high nitrogen concentrations found in municipal wastewaters, forests will typically require larger land areas to counter lower assimilative capacity.

Newly established forests and forage grass slow rate systems are much better renovators of nitrogen, but are limited to sites with gentle slopes because of erosion concerns. OF systems, relying on herbaceous species for vegetative cover, are subject to similar slope limitations.

Land characterized by steeper slopes and high degree of topographic relief is generally less expensive to acquire. The concept of lateral subsurface flow of infiltrated water on slopes should allow a higher degree of treatment for a given land area, or a smaller land requirement for a given removal efficiency. Vegetation density can work to maximize detention time on steeper slopes using the overland flow method. The only obstacle to realizing the significant benefits of treating wastewater on steeper slopes is surface erosion and mass movement.

Soil Bioengineering techniques are designed specifically to combat surface erosion and shallow-seated mass movement using live plant materials. Many of the woody species employed in Soil Bioengineering are known to be effective in renovating wastewater. Species with high water, sediment, and salt tolerances, such as black willow (Salix nigra) and eastern cottonwood (Populus deltoides) are ideal for Soil Bioengineering systems employed in OF and SR sites.

Live fascines and brushmattress living systems will overcome critical slope-related problems for OF sites by preventing surface erosion and ensuring uniform distribution of wastewater across the slope. Live cribwall and branchpacking techniques should be useful in terracing of OF sites, potentially serving as an active "vertical filtration" treatment component. Brushlayer is not recommended for OF sites because of the tendency to increase infiltration. Brushlayer will be effective on steeper sloped SR sites, however, along with live fascines, and perhaps live cribwall or branchpacking if terracing is required.

Combining these techniques with lateral slope flow to the fullest extent can result in an alternative method of treatment similar to a soil-based version of a subsurface flow constructed wetland -- the "Constructed Brushland".

Further research is vital to validate and confirm the feasibility of Soil Bioengineering techniques in natural wastewater treatment systems. Pilot-scale studies utilizing a physical model similar to that of Nutter (1975) and Peters, et al.(1981) could confirm treatment mechanisms, performance and proposed kinetic models suggested in this report. Results from pilot and field studies could yield ground-breaking advances in land treatment methods.

Integration of the Soil Bioengineering technology into natural wastewater treatment theory could also foster improvements in treatment of non-point source pollution from overland runoff, landfill cap runoff and leachate return treatment systems, and runoff containment and treatment at hazardous waste remediation sites.

It is readily apparent that these two technologies are compatible and will greatly benefit each other in both preserving the landscape and cleaning the environment. Extremely effective low-cost wastewater treatment on previously unsuitable land is highly feasible by teaming with nature's strengths rather than fighting to overcome them.

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X. VITA

LIEUTENANT ANTHONY J. COX
CIVIL ENGINEER CORPS
UNITED STATES NAVY

Lieutenant Anthony J. Cox is assigned to the Marine Corps Air Station, Beaufort, South Carolina as Environmental Officer.

Lieutenant Cox was born in Greer, South Carolina on July 12, 1961. He graduated Cum Laude from Clemson University in May, 1983 with a Bachelor of Science degree in Civil Engineering, and received his commission in July 1983. He is currently a candidate for the degree of Master of Science in Environmental Health Engineering at the University of Texas at Austin. He is a member of Tau Beta Pi and Chi Epsilon honorary engineering societies, Phi Eta Sigma and Alpha Lambda Delta honor societies, the American Society of Civil Engineers and the Society of American Military Engineers.

Prior to earning his Master's degree and reporting to MCAS Beaufort, Lieutenant Cox served as Public Works Operations Officer at NAS Point Mugu, California. Previous tours include Instructor in Public Works Management at the Civil Engineer Corps Officer School, Assistant Resident Officer in Charge of Construction for the Southern Division Contracts Office in Pensacola, Florida, and Staff Civil Engineer for the Public Works Center, Pensacola, Florida.

Lieutenant Cox's decorations include the Navy Commendation Medal and two Navy Achievement Medals. He is a Registered Professional Engineer in the state of Florida.

He is married to the former Lisa Denise Hewitt of Hickory, North Carolina. He and Lisa have a two-year old daughter, Emilee, and are expecting their second child in June, 1993.

APPENDIX A. SOIL BIOENGINEERING PLANT SPECIES[a]

Name	Location	Availability	Habitat Value	Size/ Form	Root Type	Adventitious Rooting Ability	Tolerances: Deposition	Tolerances: Flood	Tolerances: Salt
Acer Negundo Boxelder	N, NE	Common	Excellent	Small Tree	Mod. deep spreading	Poor-fair	H	H	M
Alnus rubra Red alder	NW	Very Common	Excellent	Large tree	Shallow spreading	Poor	H	M	L
Baccharis glutinosa Water wally	W	Common	Very good	Medium shrub	Fibrous	Good	M	H	L
B. halimifolia Eastern baccharis	S, SE	Common	Very poor	Small/ med. shrub	Fibrous	Fair-good	H	H	M
B. pilularis Coyote brush	W	Very common	Good	Medium shrub	Fibrous	Good	M	M	M
B. viminea Mule fat	W	Very common	Very good	Medium shrub	Fibrous	Good	H	H	M
Betula papyrifera Paper birch	N, E, W	Common	Good	Tree	Fibrous shallow	Poor	M	M	M
B. pumila Low birch	N, E, W	Common	Very good	Medium shrub	Fibrous	Poor	L	*	L
Cornus amonum Silky dogwood	N, SE	Very common	Very good	Small shrub	Shallow fibrous	Very good	L	M	L
C. racemosa Gray dogwood	NE	Common	Very good	Med./ small shrub	Shallow	Good	M	M	L
C. rugosa Roundleaf dogwood	NE	Common	Very good	Med./ small shrub	Shallow fibrous	Fair-good	*	*	*
C. stolonifera Red osier dogwood	N, NE, & W	Very common	Very good	Med./ small shrub	Shallow	Very good	L	H	L

APPENDIX A. SOIL BIOENGINEERING PLANT SPECIES (Continued)[a]

Name	Location	Availability	Habitat Value	Size/ Form	Root Type	Adventitious Rooting Ability	Tolerances Deposition	Tolerances Flood	Tolerances Salt
Crateagus Sp. Hawthorn	SE	Uncommon	Good	Small dense tree	Top root	Fair	M	L	L
Elaeagnus commutata Silverberry	N	Very common	Poor	Medium shrub	Shallow	Fair - good	H	L	M
Ligustrum sinense Chinese privet	S, SE	Common	Fair - good	Small/ med. shrub	Shallow fibrous	Good	H	M	L
Lonicera involucrata Black twinberry	E	Common	Poor - fair	Small shrub	Shallow	Good	M	M	L
Physocarpus capitatus Pacific ninebark	NW, W	Common	Fair	Small	Fibrous	Good	L	M	L
P. opulifolius Common ninebark	NE	Common	Good	Med./ high shrub	Shallow lateral	Fair - good	L	M	M
Populus angustifolia Arrowleaf cottonwood	W	Common	Good	Tree	Shallow	Very good	M	M	M
P. trichocarpa Black cottonwood	NW	Common	Good	Tree	Shallow fibrous	Very good	M	M	M
P. deltoides Eastern cottonwood	MW, E	Very common	Good	Large tree	Shallow	Very good	M	H	H
P. fremontii Fremont cottonwood	SW	Very common	Good	Tree	Shallow	Very good	M	M	M
P. tremuloides Trembling aspen	NW	Very common	Good	Large tree	Shallow	Fair	M	L	M
Robinia pseudoacacia Black locust	NE	Common	Very poor	Tree	Shallow	Good	M	H	H

APPENDIX A. SOIL BIOENGINEERING PLANT SPECIES (Continued)[a]

Name	Location	Availability	Habitat Value	Size/ Form	Root Type	Adventitious Rooting Ability	Tolerances Deposition	Flood	Salt
Rubus alleghenensis Allegheny blackberry	NE	Very common	Very good	Small shrub	Fibrous	Good	M	M	L
R. spectabilis Salmonberry	SW	Very common	Good	Small shrub	Fibrous	Fair - good	M	M	L
R. strigosus Red raspberry	N, NE, & W	Very common	Very good	Small shrub	Fibrous	Good	M	L	L
Salix exigua Coyote willow	NW	Fairly common	Good	Medium shrub	Shallow suckering	Good	H	H	L
S. interior Sandbar willow	N, SE	Common	Good	Large shrub	Shallow to deep	Fair - good	H	H	H
S. amygdaloides Peachleaf willow	N, S	Common	Good	Very large shrub	Shallow to deep	Very good	H	H	H
S. bonplandiana Pussy willow	W	Very common	Good	Medium shrub	Fibrous	Very good	M	M	*
S. ligulifolia Erect willow	NW	Common	Good	Large shrub	Fibrous	Very good	H	H	L
S. gooddingii Goodding willow	SW	Very common	Good	Large shrub/ small tree	Shallow to deep	Excellent	H	M	L
S. hookeriana Hooker willow	NW	Common	Good	Large tree	Fibrous/ dense	Very good	H	H	M
S. humilis Prairie willow	N, NE	Very common	Good	Medium shrub	Fibrous	Good	M	M	L
S. lasiolepis Arroya willow	W	Common	Good	Medium shrub	Fibrous	Good	H	H	L

APPENDIX A. SOIL BIOENGINEERING PLANT SPECIES (Continued)[a]

Name	Location	Availability	Habitat Value	Size/ Form	Root Type	Adventitious Rooting Ability	Tolerances Deposition	Tolerances Flood	Tolerances Salt
S. lemmonii Lemmon willow	W	Common	Good	Medium shrub	Fibrous	Very good	H	H	L
S. lucida Shining willow	N, NE	Very common	Good	Med./ large shrub	Fibrous	Very good	M	M	L
S. lasiandra Pacific willow	NW	Very common	Good	Large shrub/ small tree	Fibrous	Very good	H	H	L
S. lutea Yellow willow	W	Very common	Good	Med.- large shrub	Fibrous	Very good	M	M	L
S. nigra Black willow	N, SE	Very common	Good	Large shrub/ small tree	Shallow to deep	Excellent	H	H	M
S. purpurea Streamco	N. S, E, & W	Very common	Very good	Medium shrub	Shallow	Very good	H	H	L
S. scouleriana Scoulers willow	NE	Very common	Good	Large shrub/ small tree	Shallow	Very good	H	H	L
S. sitchensis Sitka willow	NW	Common	Good	Very large shrub	*	Very good	H	M	L
S. discolor Red willow	N, NE	Very common	Good	Large shrub	Shallow	Very good	H	H	M
Sambucus canadensis American elderberry	NE, SE	Very common	Very good	Medium shrub	Fibrous	Good	H	M	L
S. racemosa Red elderberry	NW	Common	Good	Medium shrub	*	Good	M	L	L
S. pubens Scarlet elderberry	NE	Common	Very good	Medium shrub	Deep laterals	Fair - good	M	M	L

APPENDIX A. SOIL BIOENGINEERING PLANT SPECIES (Continued)[a]

Name	Location	Availability	Habitat Value	Size/ Form	Root Type	Adventitious Rooting Ability	Tolerances Deposition	Tolerances Flood	Tolerances Salt
Spirea alba Meadowsweet spirea	N, E	Common	Good	Small dense tree	Dense shallow laterals	Fair - good	L	M	*
S. douglasii Douglas spirea	NW	Common	Fair	Dense shrub	Fibrous suckering	Good	M	M	L
S. tomentosa Hardback spirea	NE	Common	Good	Small shrub	Dense shallow	Fair	M	M	M
Symphoricarpos albus Snowberry	N, NW, & E	Common	Good	Small shrub	Shallow fibrous	Good	L	L	H
Viburnum dentatum Arrowood viburnum	E	Common	Good	Medium shrub	Shallow fibrous	Good	M	M	L
V. lentago Nannyberry viburnum	S, SE	Fairly Common	Good	Large shrub	Shallow	Fair - good	M	L	L

* No data available.

[a] adapted from SCS, 1992

APPENDIX B DERIVATION OF CONSTRUCTED BRUSHLAND DESIGN EQUATIONS

From Equation (9),

$$\frac{C}{C_o} = A\exp\left[-\frac{C'KA_v^{m+1}LWdn}{4.63S^{1/3}Q}\right]$$

substituting A_s for LW,

$$\frac{C_e}{C_o} = A\exp\left[-\frac{C'KA_v^{m+1}A_sdn}{4.63S^{1/3}Q}\right]$$

taking the natural logarithm of both sides,

$$\ln C_e - \ln C_o = \ln A + \ln\left[\exp\left[-\frac{C'KA_v^{m+1}A_sdn}{4.63S^{1/3}Q}\right]\right]$$

$$\ln C_e - \ln C_o = \ln A - \frac{C'KA_v^{m+1}A_sdn}{4.63S^{1/3}Q}$$

$$\frac{C'KA_v^{m+1}A_sdn}{4.63S^{1/3}Q} = \ln A + \ln C_o - \ln C_e$$

and therefore,

$$A_s = \frac{4.63S^{1/3}Q}{C'KA_v^{m+1}dn}\left[\ln A + \ln C_o - \ln C_e\right]$$

For a broad range of trickling filter (attached-growth), typical values have been found to be A=0.52, m=0.75, and C'=0.7, so:

$$A_s = \frac{4.63S^{1/3}Q}{0.7KA_v^{1.75}dn}\left[\ln C_o - \ln C_e - 0.6539\right]$$

or,

$$A_s = \frac{6.61S^{1/3}Q}{KA_v^{1.75}dn}\left[\ln C_o - \ln C_e - 0.6539\right]$$

similarly,

$$t = \frac{A_s dn}{Q} = \frac{6.61S^{1/3}}{KA_v^{1.75}}\left[\ln C_o - \ln C_e - 0.6539\right]$$