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Design and Application of Manufactured All-wood Hillslope Erosion Control Structures

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Abstract. The FlowCheck^{TM} hillslope erosion control structure was developed to make it easier to accomplish erosion control on burned-over lands, graded slopes and other disturbed areas. The scientific basis for sediment storage behind wood hillslope structures was developed by the U.S. Forest Service Rocky Mountain Research Station. Forest Concepts, LLC combined the best available science with disciplined design according to the Appreciative Design methodology. The resulting structures are technically sound, while providing an important use for underutilized small diameter timber. Utilization of smallwood from forest thinning, fuel reduction programs and forest management provides revenues to landowners and new jobs in rural areas. More than 600 of the new structures were deployed in forest and wildlands during the fall of 2001. The paper details the design process and first year performance across a range of applications. A method for estimating sediment storage and specifying the spacing for hillslope erosion control materials is provided.

Keywords. Forestry, wildfire, erosion control, design

Introduction

Hillslope erosion from disturbed lands removes valuable topsoil, alters the micro-topography with rills and gullys, and delivers undesirable sediment to roads, streams and the downslope built environment. Soil erosion from disturbed areas and low-volume roads is a major source of water pollution in all areas of the United States (Dunne and Leopold 1978).

The functional objectives of erosion control methods are two-fold. The first line of erosion control is to prevent mobilization of soil particles due to rain impact or overland water flow. The secondary line of erosion control is to trap sediment already in motion so it does not cause down-slope damage. Primary erosion control includes techniques such as hydraulic mulches, spread straw, scattered pine straw, and rolled-out woven products. Secondary erosion control includes techniques such as straw waddles, check dams, hillslope terracing, silt fences, lines of straw bales, contour-felled logs, retention/detention ponds, biofilters and the like.

Erosion control structures constructed from small diameter poles (particularly those from fuel reduction projects) complete the watershed cycle by using co-products of forest management back in the watershed for restoration and enhancement. Hillslope erosion control materials constructed of smallwood last longer and are more ecologically compatible than straw products. Wood products are inherently free of invasive weed seeds, and are colonized by microorganisms that are indigenous to the area.

Fire rehabilitation products such as the FlowCheck^{TM} structure from Forest Concepts can be easily manufactured year-around and stockpiled at depots for deployment to wildfire sites when needed. Stockpiling of materials enables rapid installation by environmental crews before summer thunderstorms and fall rains arrive.

FlowCheck^{TM} structures from Forest Concepts result from the application of sound science and disciplined product engineering. The erosion control materials are highly functional, easy to install by environmental crews, and readily manufactured by community-based businesses in fire-prone regions of the country.

Existing Hillslope Erosion Control Materials

Contour-felled logs are among the most effective, and most ecologically sound methods to trap and store sediment on wildland hillslopes (Robichaud 2000). Collection of sediment behind logs, rocks and other debris provides a rich germination and early-growth medium for reestablishment of vegetative cover.

Although effective, contour-felled logs have a number of limitations that led Forest Concepts, LLC to search for and design a functional alternative:

1. Many recent fires are reburns of land burned only a few years ago. Reburned land is typically lacking sufficient standing dead trees suitable for contour felling. (Robichaud 2000)

2. Open slopes that were grassy or brushy at the time of a fire require that logs be imported from the surrounding forest or from offsite.
3. Contour-felling requires a high level of chainsaw skill. Typically only “hotshot” crews and specialty contractors are allowed to fell standing fire-killed trees. Such crews are normally not available for rehabilitation work until after the close of the fire season. Even then, the time required to fell and buck enough stems for 180 – 300 m ha^{-1} (250 – 450 ft ac^{-1}) limits the area that can be treated.
4. Once felled logs are placed in the intended location, they must be partially crosscut so the bole conforms to ground topography. Unless the bole is carefully cut to the contour, cross-slope logs may actually concentrate flow and exacerbate erosion. (Boise NF)
5. Felled logs are delimbed on all but the downslope face so the logs do not roll down the hill. If the log is from the lower bole, or limbs are burned off, the logs must be staked in place as can be seen in the opening photograph.

Today, the primary alternatives to contour-felled logs are straw waddles and hay bales. Both can provide effective erosion control when properly installed. However, straw waddles and hay bales have a number of limitations when used in wildlands:

1. Agricultural straw has been implicated as a major source of noxious weeds in forested watersheds and wildlands
2. Agricultural straw (typically from wheat or rice fields) is not an indigenous material, thus not particularly palatable to soil organisms.
3. Small mammals in search of food and shelter readily colonize straw waddles. Small mammal nests and tunnels may compromise the functional integrity of the product within a short time after deployment.
4. Fine dust from shattered agricultural straw is a respiratory irritant and source of allergens to workers who are involved in spreading straw products.

FlowCheck^{TM} Product Development

The development of FlowCheck^{TM} structures resulted from the convergence of 1) the need for ecologically sound alternatives to agricultural straw products; 2) increased prescription of erosion control on intensively burned lands; 3) the national priority to create value-added uses for small diameter poles from fuel-reduction programs; and 4) the regional priority to support forest products enterprises in rural communities. Careful analysis of the four drivers resulted in a product definition that included the following key attributes:

- An all-wood hillslope erosion control material that is ecologically consistent with forested wildlands. A product made primarily from wood species indigenous to local watersheds is preferred.
- A product that performs the function of natural downed logs and contour-felled trees.
- An erosion control material that can be deployed by crews with minimal training and experience.
- A product that is made from roundwood 75 – 150 mm (3-6 inches) in diameter utilizes stems from fuel-reduction programs that have few alternative markets. Thus, purchase of small

poles would provide new markets for forest landowners, new jobs for loggers, and incremental revenue to a local forest economy.

- A product that is designed for manufacture and assembly by small businesses in rural timber communities would readily support rural economic development goals.

Figure 1. Conceptual smallwood erosion control structure is comprised of three poles connected by wood spars with round mortise and tenon joints.

Figure 2. Round mortise and tenon joint uses a round cedar wedge to lock the spar to a pole.

Guided by the set of drivers, a conceptual product was created from three small diameter poles connected together by the ELWd® spar system. The conceptual product was derived from the proven design of Forest Concepts' floating rafts for lake and pond habitat enhancement. The ELWd® spar system is easy to manufacture, fast to assemble in a factory or field environment, and is very durable. The trade name for the new product is FlowCheck™.

Once we had a concept model, the relevant scientific and design questions could be developed:

- What is the minimum and maximum effective diameter (height) for a structure?
- How do we make the structure stable on slopes up to 100%?
- What is the value of shorter or longer lengths?
- How do we connect units end-to-end?
- How should we package the units for easy deployment at fire sites?

Scientific Basis

High intensity wildfires consume much of the canopy and most of the ground litter (Van de Water 1998), leaving forest soils unprotected from erosion by rainfall. Steep slope areas affected by high intensity burns are among the highest priority for post-fire erosion control (Robichaud, Beyers et al. 2000). A study of the 1987 fires totaling 110,000 ha (273,000 acres) across the Klamath National Forest found that the proportion of high intensity fire impact was 12 – 16 percent (13,000 – 17,000 ha) (30,000 – 40,000 acres) (Van de Water 1998). Thus, an effective erosion control material would need to be able to manufactured and delivered in large quantities for rapid response programs.

Sediment delivery from burned lands affected by rainfall events is a function of fire intensity, soil type, slope, micro-topography, and time since the fire. Robichaud and Brown (1999) reported first-year erosion rates of 49 Mg ha^{-1} from a 60 percent slope for a site in Eastern Oregon. Sediment delivery was directly related to slope such that the mean delivery from 30 percent slope was 44 Mg ha^{-1} and the delivery from a 20 percent slope was 21 Mg ha^{-1}. Sediment delivery in subsequent years was substantially reduced from first-year levels.

The dominant natural mechanisms for reducing erosion and storing sediment on hillslopes following an intense fire are rock outcrops, rocky soils and fallen trees. These mechanisms work by increasing surface hydraulic roughness, slowing the velocity of surface flow and thus increasing infiltration opportunity. Lacking sufficient natural erosion control features, a preferred emergency rehabilitation technique is to contour-fell standing dead timber and logs (Robichaud, Beyers et al. 2000). The Burned Area Emergency Stabilization and Rehabilitation Technical Reference "e-book" (http://fire.r9.fws.gov/ifcc/esr/techref/default.htm) recommends that contour-felled logs be 4.5 – 6 m (15 to 20 ft.) long and 100 – 305 mm (4 to 12 in.) diameter.

Recommended application rates are 3 m (10 ft) apart on slopes over 50 percent, 4.5 m (15 ft) apart on slopes of 30 to 50 percent, and 6 m (20 ft) apart for slopes less than 30 percent. The technical reference handbook acknowledges that crews may have difficulty finding enough stems, particularly straight stems, to achieve the treatment guidelines. The guidelines further suggest that contour-felled logs should be placed in a random pattern to provide a more natural appearance than would come from long runs across the slope.

Site-specific application prescriptions can be developed by applying the Water Erosion Prediction Project (WEPP) model (Elliott, Scheele et al. 2000) for disturbed lands to estimate sediment movement on slopes and offsetting erosion with storage calculations for cross-felled and placed logs (Elliot, Robichaud et al. 2001).

Forest Concepts modified the Elliot, et. al., storage equation for the case of two stacked small diameter poles as used in the FlowCheck^{TM} product. In general, the manufactured analog can store more sediment per unit length for equivalent effective height due the stacking of small diameter poles rather than losing the volume contained in a single large diameter pole.

Figure 3. Concept model of hillslope erosion control structure is shown on 60 percent slope. The volume of sediment stored is approximately equal to the area of the triangle minus the cross sectional area of one pole.

A generalized equation for the amount of sediment that can be stored upslope of the erosion control structure is: [*NOTE: This equation and the subsequent discussion is in English units for ease of use by practitioners in the field.]*

$$\text{Storage Capacity per unit length (ft}^3\text{ per ft)} = \frac{(2d)^2}{2\text{slope}} - \frac{\pi d^2}{4}$$

Where *d* is the mean diameter of the poles used to make the structure (ft.) and *slope* is the slope steepness (ft ft^{-1}). To estimate the total potential storage per acre in tons, simply multiply the result from the linear feet of material deployed per acre and by the bulk density of the eroding soil.

The Forest Concepts equation differs from that of Elliott et. al. (2001) in that we assume the volume of soil used to key the structure into the hillslope is approximately equal to the volume of extra soil that is stored upslope of the keel pole.

Actual sediment trap efficiency of cross-felled logs or analogs such as the FlowCheck$^{\text{TM}}$ erosion control structure is a function of how long the log is, and how well the log is installed. Trap efficiencies for solid logs were reported to be approximately 66% (Robichaud (2000).

Interviews by Forest Concepts suggest that a larger loss of efficiency results from improper installation of cross-felled logs. Where logs are placed on the contour, back-cut to ensure they are tight to the ground, and keyed into the ground to prevent underflow, then sediment is stored until the logs are filled to near capacity. However, long logs are frequently either placed off-contour, bridged across micro-topography and rills, or effectively buried by soil pulled downslope against the stem. Thus, the length specification for the FlowCheck$^{\text{TM}}$ erosion control structures was set at 1.8 m (60 in) to make the structures easier to place on the contour, and to follow micro-topography. The effect of excessive backfilling is somewhat mitigated by sediment that overflows the structure being trapped behind the lower “keel” pole.

If we calculate the maximum potential storage for FlowCheck$^{\text{TM}}$ structures made from various diameters of smallwood, then we can create the graphs shown in Figure 4. The graph enables rapid estimation of how many hundred feet of FlowCheck$^{\text{TM}}$ structures to deploy across a burned area to store WEPP-derived estimates of sediment production.

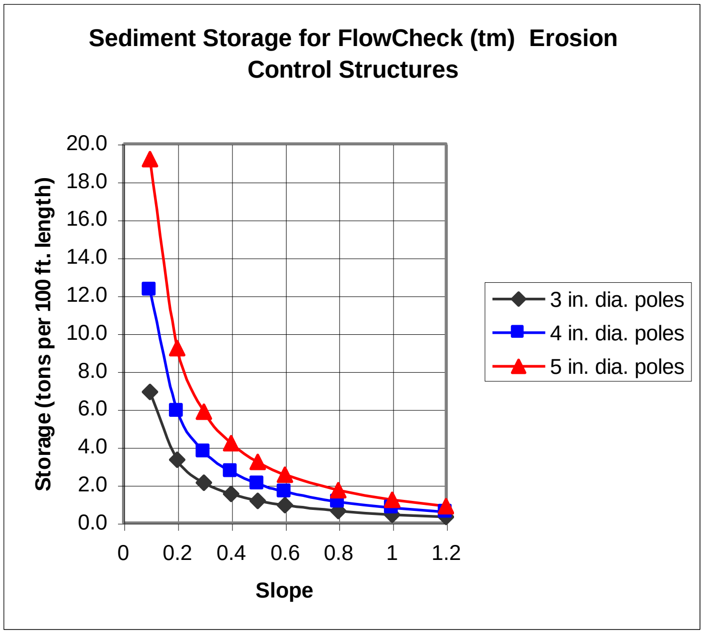

Figure 4. Maximum potential storage of sediment is shown for three smallwood pole diameters in two-pole FlowCheck^{TM} structures versus hillslope (ft ft^{-1}). *[Caution: this data has not been field-verified]*

We can further assist the estimation process by expressing the storage potential in tons per acre for a range of deployment densities of the standard FlowCheck^{TM} 8 to 10 inch tall structures. We assume a predominantly mineral soil with bulk density of 110 lb/ft^3. The storage estimates from Figure 5 should be reduced by an estimate of storage efficiency. For example, a first estimate of how far apart to space FlowCheck^{TM} structures for a 60 percent slope that has an WEPP prediction of 5 tons per acre, and 60 percent trapping efficiency would conclude that spacing the structures about 100 feet apart up the slope would be sufficient.

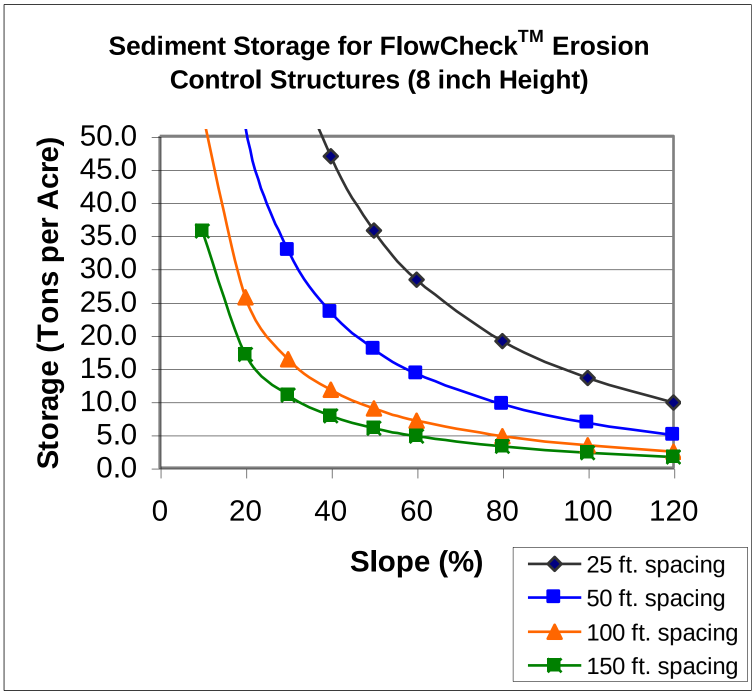

Figure 5. Estimated maximum sediment storage potential for standard FlowCheck^{TM} structures at various spacing versus a range of slopes. *[Caution: this data has not been field-verified]*

Technical Design

Forest Concepts follows a design methodology that brings together sound science and disciplined design processes to guide the definition and development of new products, such as the FlowCheck^{TM} structures. The Appreciative Design method for design of technical works (Dooley and Fridley 1996) is a structured process to search for a best-set solution to technical and design problems. The Appreciative Design method is a significant extension of the hierarchical axiomatic design methodology of Suh (1990; 1995) and includes many features of the Soft Systems Methodology developed by Checkland (1990).

Suh's methods (Suh 1990) (Suh 1995) are particularly well suited for addressing messy problems that are common in the natural resource arena. Suh's approach is based on a set of design rules. Our implementation of Suh's approach adds some important structure and detail, as well as provides an easily followed hierarchical tracking of information, alternatives and decisions. The hierarchical structure allows reviewers, decision-makers and others to easily follow the history of decisions made throughout a project.

Suh's design principles are expressed in terms of a decision logic that includes *functional requirements, design parameters* and *constraints* (Suh 1990). Functional requirements (FRs) are design objectives cast in solution-neutral and independent statements. There is general consensus that problems are best defined when the objectives are framed by what is to be achieved by the project rather than by how needs are to be met (Love 1980).

Design Parameters (DPs) are either brainstormed alternatives or calculated specifications that become features of a solution. Brainstorming, ideation and other methods of creating or searching for alternative solutions are well understood by engineering professionals, educators and students so did not need to be included in the model.

Constraints (Cs) are objective statements and mathematical relationships that set bounds on the range of DPs that are acceptable. Constraints provide limits on the how, what, when, where and why of the design solution. Constraints may be absolute, conditional or preference. Constraints are most often used by designers as criteria to sort alternative DPs into those which are acceptable and those to be discarded or reworked. An initial set of constraints typically is drawn from conversations with the client and all relevant stakeholders. Constraints can also be found through exploration of the laws of nature (e.g., $f = ma$, $\sigma = mc/I$), laws of humankind (e.g. codes, laws and regulations), cultural norms of the organization (e.g., policy and design manuals), and norms of the community (e.g., codes of ethics). In all cases constraints must be linked to a "constraint owner" in order to make them relevant to the problem at hand (McIntyre and Higgins 1989). The constraint-owner linkage provides relevance to a constraint and its source.

FlowCheck^{TM} Design

Functional Requirement: Provide a barrier to downslope overland movement of water and sediment during periods of rainfall on hillslopes impacted by intense wildfires. Achieve sediment storage equivalent to contour-felled trees.

Top Level Constraints:

1. Manufacture the solution from small diameter poles 75 – 150 mm (3 – 6 in) diameter typically collected from fuel reduction and forest health thinning programs.
2. Design such that the product can be manufactured by community-based businesses in traditionally timber-dependent areas.
3. Components must appear to be roundwood so the appearance is consistent with a wildland environment.
4. Wood species should be typical of the region where deployed so product is readily colonized by insects, fungi and other organisms.
5. Decay products should blend with the environment
6. Avoid metal or plastic connectors so end-of-life debris does not pollute the environment
7. Make standard length or lengths that are sufficiently long for efficient transport, but short enough to enable easy installation on uneven ground.
8. Weight of product should be able to be lifted by one person, and carried long distances by two persons (total weight under 45kg (90 lb)).
9. Structure should have a functional life of three to five seasons.
10. Structure should be stable on slopes to 100 percent so it does not tumble downslope.
11. Effective height of structure should be 200 – 250 mm (8 – 10 in) (BAER Handbook recommendation)

12. Package or palletize such that it is easy to connect lifting cables or chokers for helicopter placement on the fire site.

Resulting Design Features and Specifications:

1. Make from poles 100 – 125 mm (4 – 5 in) diameter, two poles high to achieve the 200 – 250 mm (8 – 10 in) working height.
2. Use proven ELWd® spar and round mortise and tenon joint technology.
3. Use bark-on poles to improve aesthetics and minimize unit cost.
4. Make from lodgepole pine, ponderosa pine and/or Douglas fir depending on the region of use.
5. Make three lengths – 0.8, 1.5, and 2.3 m (30, 60 and 90 in) to provide ease of transport and installation. [Note: Assembled FlowCheck™ structures weigh approximately 10 - 15 kg / m (7 - 10 lb / ft) of length.]
6. Use spars with tenons at least 38 mm (1.5 in) diameter. Spars that have tenons at least 38 mm diameter have a typical Westside decay life of 3-6 years.
7. Make the spar length 405 mm (16 in) so the center of gravity remains upslope at slopes of 100 percent.
8. Stack the structures on pallets in vertical stacks and extending past the edges of the pallet so a choker can be threaded down through one stack and up through another for helicopter lifting.

An initial manufacturing run of 25 FlowCheck™ structures was completed to validate the design constraints and specifications. Upon successful testing, the product was released for manufacture at the Cascade Forest Resource Center operated by Forest Concepts in Cascade, ID.

Figure 6. During the summer and fall of 2001, over 500 of the FlowCheck™ erosion control structures were manufactured for use on fire sites and other disturbed lands in the Western United States.

Other benefits of the FlowCheck™ product design became apparent during its initial production and distribution:

- A truckload contains approximately 650 m (2100 lf) of material. This is enough to treat 2 – 3 ha (5 – 7 ac) at typical application rates.
- Unlike straw and hay products, FlowCheck^{TM} structures can be manufactured year around and stored outdoors until needed during the fire season. Year around production enables efficient labor and materials management. Outdoor storage reduces the logistics and expense of creating stockpiles of material at fire depots and regional storage yards.
- Installation can be accomplished by fire crews or environmental contractors with minimal training and supervision.

Application

FlowCheck^{TM} erosion control structures are most frequently applied as an alternative to contour-felled logs in areas lacking in standing dead trees and sites where skilled fallers and chainsaw operators are not available. The FlowCheck^{TM} structures can be placed on the contour, and linked together by nesting the ends as shown in Figure 7.

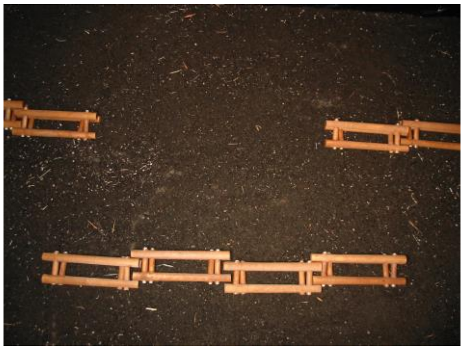

Figure 7. FlowCheck^{TM} model structures are deployed in short runs of 3 – 4 units to be consistent with the recommendations of the BAER handbook. Ends of each unit in a run are interlocked to improve sediment storage and stability on steep slopes.

Where long runs are necessary, the FlowCheck^{TM} structures can be interlocked and/or stair-stepped as shown in Figure 8.

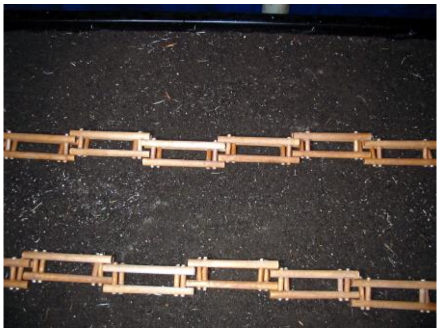

Figure 8. FlowCheck^{TM} model structures are deployed in long runs across slope.

A third method of deployment is to distribute single units across a slope in regular patterns as shown in Figure 9 or in random patterns that total the recommended linear feet per acre.

Recognize that random patterns will be less efficient for sediment storage due to some units being closer or farther apart than the WEPP model results might prescribe.

Figure 9. FlowCheck^{TM} model structures deployed as single units in a regular pattern across the slope. Note that ends slightly overlap to reduce the risk of rill formation.

When a slope is sufficiently steep or unstable that staking is necessary, the preferred method of staking is shown in Figure 10.

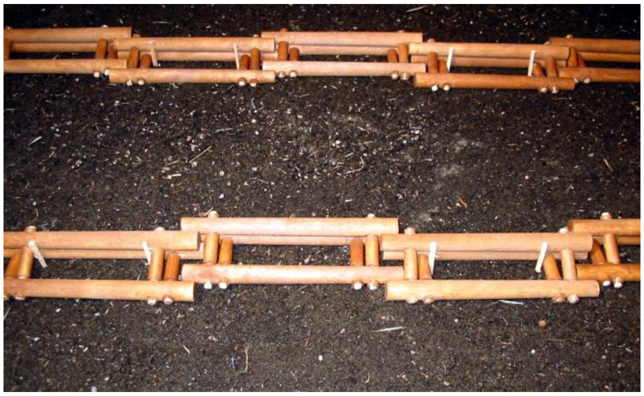

Figure 10. Staking of FlowCheck^{TM} structures can be achieved by driving two stakes behind the upslope face of the lower set of structures in each run. Note that the upslope unit is held from movement by the overlap with lower units on either end.

During the spring and summer of 2002, Forest Concepts will assess the performance of all of the units installed during the 2001 season. Assessments will include how well units were installed, the amount of sediment collected, failures and other observations that suggest improvements to the product or application guidelines.

Conclusions:

An all-roundwood erosion control structure has been developed and manufactured for use on hillslopes disturbed by wildfire. The FlowCheck^{TM} structures were designed to achieve sediment storage functionality equivalent to contour-felled trees. The design was constrained to use smallwood materials from fuel reduction programs, thus supporting the watershed cycle by using materials from a watershed to make restoration and rehabilitation products to go back on the watershed.

The FlowCheck^{TM} structures are currently being manufactured in Cascade, ID by a smallwood business incubator business, thus demonstrating the practicality of local manufacture by a community-based business.

Delivery in truckload quantities proved effective during the year 2001 fire season. Performance assessment is planned for the spring and summer of 2002.

About Forest Concepts:

Forest Concepts, LLC, develops and manufactures specialized roundwood structures and related materials for the erosion control, environmental restoration and landscape markets. The Company's ELWd® ("el-wood") structures make it easier and more practical to restore degraded wetlands and enhance fish and wildlife habitats. The Company's FlowCheck^{TM} erosion control products use readily available small-diameter timber to create functional erosion control materials for burned over lands, construction sites, roadsides and landscapes. A line of roundwood landscape planters offers a desirable rustic feel to residential, municipal and commercial landscapes.

ELWd® brand habitat structures are typically manufactured as kits by regional outsource partners in traditionally timber-dependent communities and delivered to project sites ready for installation. Most products are made from small diameter timber collected as a byproduct of forest health improvement programs and wildland / forest fuel reduction projects. Production of the Company's products supports the economy of rural and timber-dependent communities, as well as contributes to the development of sustainable small businesses and the forestlands of a region. Further, the Company's products are designed for ease of handling and installation by citizen-volunteers and conservation crews. For more information visit the company's web site www.elwdsystems.com .

Acknowledgements:

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