Measuring Water and Sediment Discharge from a Bordered Road Plot using a Settling Basin and Tipping Bucket

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Abstract

Although fine sediment production from forest roads has been a major water quality concern to land managers, the methods for quantifying local rates have been complicated and costly. A simple empirical method for quantifying sediment production from the forest road surface is presented. Bordered plots are installed on existing insloped road segments. Coarse sediment production is measured on an annual basis using a settling tank. Water and fine sediment production can also be measured using a tipping bucket gauge and a flow splitting device. This system allows for the collection of both coarse and fine sediment as well as a continuous discharge record. The tipping bucket is a practical tool for measuring flow and is widely used in rain gauges. A simple and inexpensive tipping bucket design, installation and implementation are described here for measuring plot discharge up to 35 gallons (132 liters) per minute. A system for measuring a complete sediment budget for the plot is described, including the necessary time and equipment.

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Introduction

Runoff and fine sediment production from forest roads are widely acknowledged as some of the more serious consequences of forest management for aquatic ecosystems (Lee et al.1997, Luce and Wemple 2002). Roads have been shown to influence a variety of watershed processes including sediment production (Megahan and Kidd 1972, Reid and Dunne 1984, Bilby 1985, Luce and Black 1999, 2001 MacDonald et al. 2001), hydrologic event timing (Wemple et al. 1996, Jones and Grant, 1996), and slope stability (Sessions et al. 1987, Montgomery 1994). As a consequence water quality regulations and the modeling of cumulative impacts of forest management have frequently focused on forest roads.

One of the limitations facing land managers and aquatic resource specialists attempting to predict runoff and erosion from forest roads is a general paucity of data on which to base decisions. The R1-R4 method (Cline et al., 1984) is an empirical model that is widely used to predict sediment production in the western United States. This model and its derivatives rely on a data set from the Idaho Batholith measured in the 1960s and 1970s. Developments since that time have utilized results from other studies to parameterize the effects of various road treatments (Washington Department of Natural Resources 1994, Dube et al. 2002). However, interpolation to new areas with unique geology, precipitation, and design standards still relies on professional judgment.

Physically based models are another approach for interpolating to novel conditions outside the range of existing data. WEPP (Elliot et. al.1999) and DHSVM (Doten et. al. 2006) are two physically based models that have been used to predict sediment and water output from forest roads. While the general intention is to improve estimates, even physically based models rely on calibration (e.g. Luce and Cundy, 1994 Tysdal et. al.1999) and require observations to validate their application in new environments. As a consequence the greatest precision and accuracy in estimating erosion from forest roads can only be achieved with local observations as a means of calibrating one of the various modeling tools available.

While the need for local observations has been clear to many watershed specialists for years, questions and concerns exist about appropriate methods, costs, and data quality. This manual has been prepared to clarify methods for collecting high quality road erosion and runoff data at a reasonable cost. One of the benefits of a rich literature on road erosion, is that a variety of methods have been used, and much has been learned (Megahan and Kidd 1972, Reid and Dunne 1984, Ice 1986, Bilby et. al 1989, Kahklen 1993, Foltz and Trube 1995, Luce and Black 1999, MacDonald et al. 2001). This manual derives from 12 years experience using sediment trap based systems (Luce and Black 1999, 2001a, 2001b, Turaski 2004, Toth 200?, Alto , Sugden 2004, NOAA -CA).

The manual provides detailed designs, material lists and costs for the construction of plots, sediment traps, tipping bucket devices, and the associated suspended sediment samplers. It also provides information on measurement and maintenance after installation has been completed. This document will be of interest to the watershed professional, student or scientist planning to gather data on road sediment production, road hydrology or attempting to validate a model.

Available methods

Sediment

The quantification of sediment production from roads in the western Unites States has evolved considerably through the yeats, but generally began with the work of Megahan and Kidd (1972). They collected sediment data below newly constructed roads using settling ponds in the Zena Creek study in the 1960s. A large rain on snow event in April 1964 produced a sizeable road fill failure, which generated the majority of the sediment during the study period. It was concluded that 30% of the 6,030 cubic feet (171 cubic meters) measured in one watershed was due to road related surface erosion and that overall erosion increased 770 times as compared to a reference watershed. This study provides the base data for the R1-R4 model (Cline 1984). Several large paired basin studies measuring sediment accumulation in settling ponds after a watershed was first roaded and logged reached similar results of substantial treatment effects (Friedrickson 1970, Beschta 1979). These paired basin studies compared small watersheds with various treatments to undisturbed reference watersheds. Even so the signal form roads was not always easily resolved from the background rate and only coarse sediment could be captured by in stream settling basins.
One of the limitations of the settling pond approach was resolved by moving the settling basin close to the road by using a tank(Ice 1986). This allowed for the sampling of only road sediment and runoff. Fine sediment sampling was also made possible with fractional flow splitting devices such as the Conshocton wheel and automated pump samplers such as the ISCO. Sediment sampling systems have the advantage of collecting all of the sediment in transport but require an accurate flow record to calculate the total mass of sediment in transport.

Reid and Dunne used manual flow and sediment concentration measurements below culverts paired with precipitation measurements to construct unit hydrographs and sedigraphs for road segments. This technique yielded valuable data on the large impact of heavy vehicle traffic, but requires a substantial investment in field sampling during peak flows to calibrate the sedigraph for the expected range of discharge. This technique is useful to document the impact of short term transient impacts such as traffic loading but requires a significant number of sediment concentration measurements to produce hydrographs and sedigraphs that can be correlated with precipitation measurements to predict sediment production

Several investigators have monitored sediment concentrations in channels above and below contributing road segments as a way of indirectly measuring road sediment inputs. (Bilby 1985, Sulivan 1985, Anderson and Potts 1987). The Johnson Creek study from southern Washington utilized pump samplers installed above and below a road crossing to monitor suspended sediment and turbidity. Samples were collected four times daily and composited from sample sites located 100 meters apart, near the channel bottom. The channel gravels were sampled using a freeze coring device to determine weather sediment was being stored or mobilized between the samplers. Although the road contributed 20.4 tons of fine sediment to the reach, no significant storage was detected in the channel bed.

Sullivan (1985) documents nine years of sediment concentration and turbot measurements on the Middle Fork of the Santiam river in the Oregon Cascades, in an 8000 ha watershed. Suspended sediment was sampled every six hours from the fifth order channel above and below an area of active road building and timber harvest. Discharge was measured at a USGS gauging station below the study reach and flow measurements were estimated at the upper station by correlating mean daily discharge. No significant difference in fine sediment yields were detected at the two sample locations

Other researchers have mapped sediment accumulations above filter fabric dams and obstructions to record sediment transport from roads (Megehan and Ketcheson 1996, Brake 1999).

Discharge

Once it was demonstrated that roads play a pivotal role in generating fine sediment, the next logical steps was to examine the hydrology of the road system. Our understanding of runoff from forest roads is derived from methods developed to measure open channel flow. Early road plot studies relied on manual flow and sediment measurements collected at road drainage points (Reid and Dunne 1984). Other investigators have used weirs and flumes to constrict discharge to a known cross section so that a stage to discharge relationship may be established and recorded by mechanical or electronic means (Ackers et al. 1978, USDA Agriculture handbook 224 1979, Replogle and Clemmens 1981, Kahklen 1993, Foltz 1996). Stage may be measured with a pressure transducer, magnetostrictive rod, or float and pulley system and recorded with a data logger. The stage based systems are often paired with continuous samplers for collecting suspended sediment so that a relationship between discharge and suspended sediment may be developed. When appreciable quantities of coarse sediment are in transport in traction or as bedload, then a settling basin or pit trap may be used upstream of the sampling location (Ice 1986, MacDonald et al. 2001). Difficulties may be encountered in measuring flows with appreciable coarse sediment load with a weir due to sediment and debris deposition, unsteady calibration and plugging of the inlet to the stilling well or weir (Grant 1988). Widespread deployment of these systems is limited by the cost of stage recorders, and flume equipment, and the availability of trained personal

These early studies have helped to parameterize the effects of major variables for different regions and treatments (Reid and Dunne 1984, Burroughs and King 1989, Washington Department of Natural Resources 1994, Dube SEDMODL 2 2002) and to quantify the role of fine sediment from road surfaces.

Overview

In order to make erosion plot measurements more accessible to the watershed professional we have developed a simple and low cost method for quantifying road sediment and water discharge. The system that we have developed consists of a bordered road plot, ditch inlet and steel settling tank to capture sediment. Runoff and fine sediment may be measured at they exit the settling tank with a tipping bucket and a fractional sampler. The equipment can be installed by a small crew in a few days, requires some periodic maintenance and data retrieval. The cost of installation and one year of data collection is about $1,000 for a coarse sediment settling tank plot and an additional $600 to capture fine sediment and flow.

Sediment Plot Construction

A gravel surfaced forest road can be instrumented in order to determine the total discharge of water and sediment from the road cut-slope, road running surface and ditch. In order to ensure that all of the flow is captured, the road surface can be insloped if necessary to drain flow to an inboard ditch. In the following examples plots were sized to represent typical flow path lengths for gravel surfaced roads in the Oregon Coast Range. A plot length of 80 meters was selected based on typical culvert spacing and uniformity of road variables such as road slope and cutslope height. The factors of rainfall intensity, groundwater interception, road construction variables, and road surfacing were considered when selecting the capacity of the settling tanks and tipping buckets for the installation (Luce and Black 2001b). The plots produced flows that were well within the calibrated range of 0-35 gallons (132 liters) per minute.

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Figure 1.
Downslope end of road runoff plot with ditch diversion inlet in foreground for collection pipe.

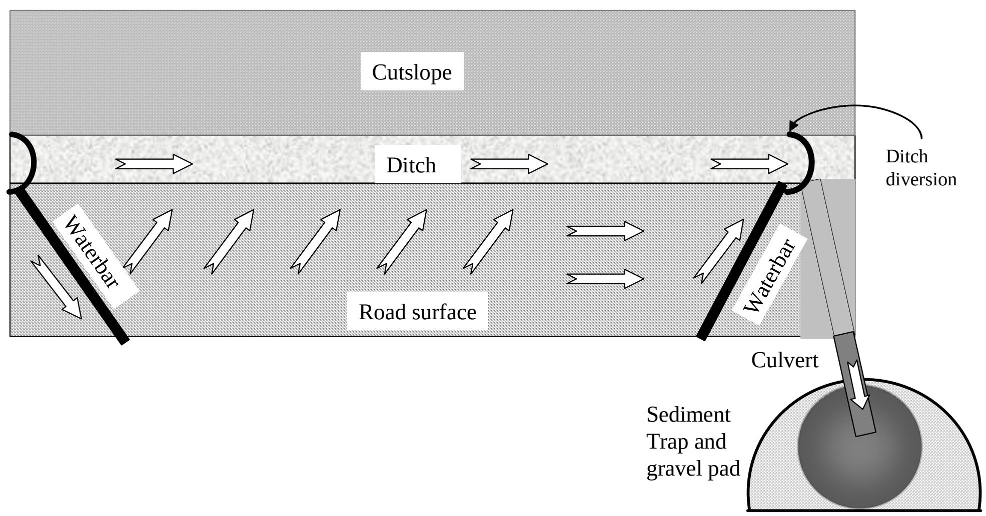


Figure 2.
Runoff plot schematic showing flow directions plot boundaries and sediment tank

Water bars were installed to divert flow coming down the road towards the ditch at the lower end of the plot (figures 1 and 2).
Water bars were constructed of a 9.25" (23.5 cm) wide by .38" (1 cm) thick segment of fabric reinforced conveyor belt bolted between two pressure treated 2" (5.1 cm) x 6" (15.2 cm) boards (figure 3). These were installed at a 35-degree angle to the roadway in a narrow trench cut into the roadway with the aid of a mechanical trenching tool. Secure the ends of the water bars into the roadbed using reinforcing bar hooks driven through eyebolts attached to the water bar. The waterbar is installed with the top of the wood positioned at grade level, backfilled with gravel and mechanically compacted in place. This installation allows traffic to move across the plots unimpeded at normal forest road speed. A similar waterbar is installed at the upslope end of the plot to divert flow off of the road segment.

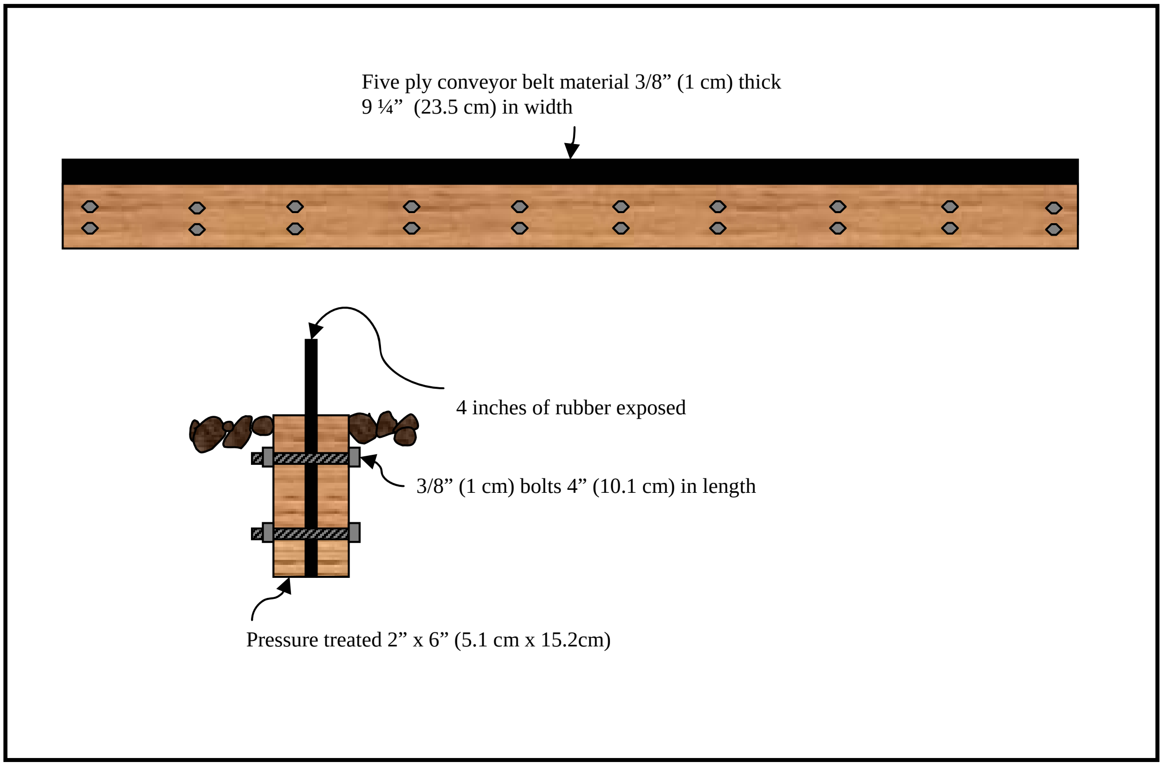


Figure3.
Detail of waterbar fabricated from rubber and fabric conveyor belt material

The ditch at the top of the plot is dammed and drained to the cutslope through a 6” (15 cm) inside diameter pipe. Flow accumulated in the ditch at the lower end of the plot is diverted into a similar pipe with the aid of a corrugated steel half round inlet structure with a concrete footing (figure 4). The pipe is placed beneath the road with the aid of a riding trencher. The pipe exits the road on the fillslope where it enters a 307 gallon (1.16 m^3) steel settling tank (figures 5 and 6). The tank is placed in an excavated alcove cut into the fillslope of the road. The alcove may be floored with compacted gravel or concrete in wet environments to allow for winter access.

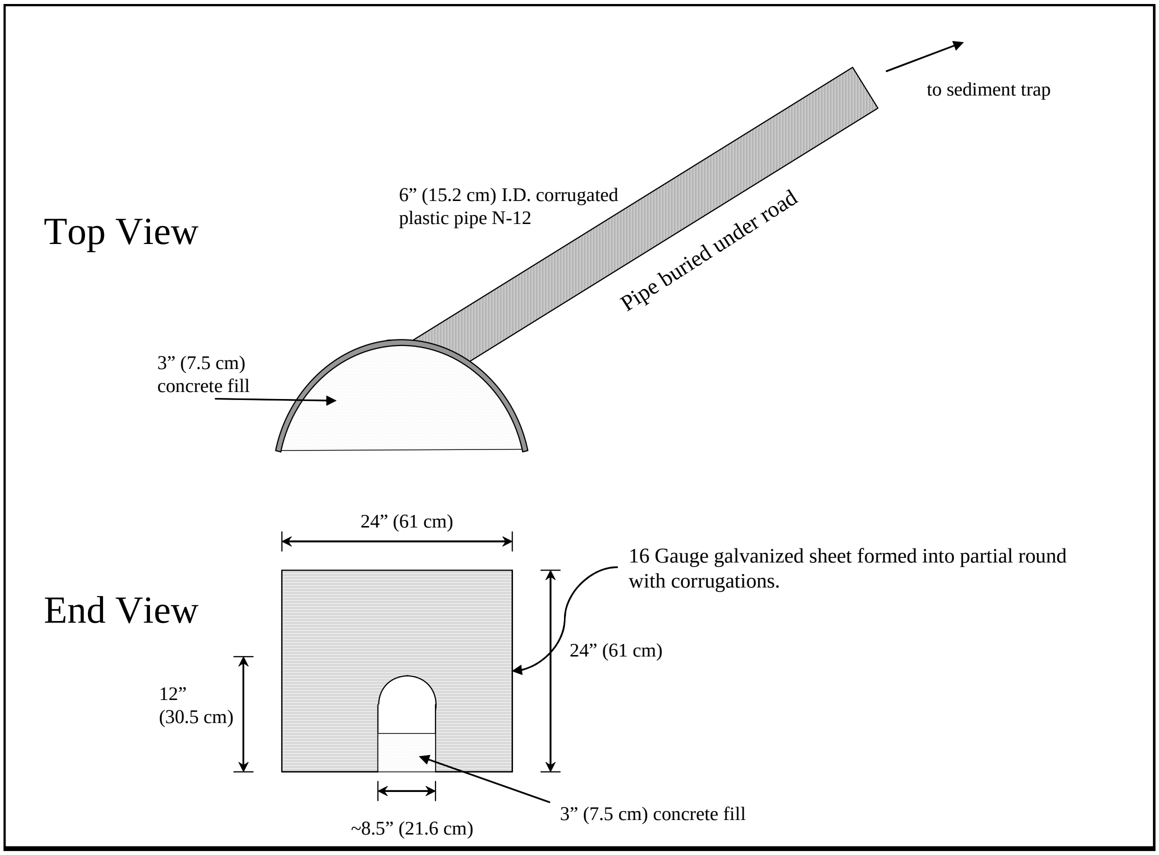


Figure 4
Ditch inlet structure that collects water and diverts it to the settling basin

Figure 5
Settling tank located on concrete pad behind steel retaining wall

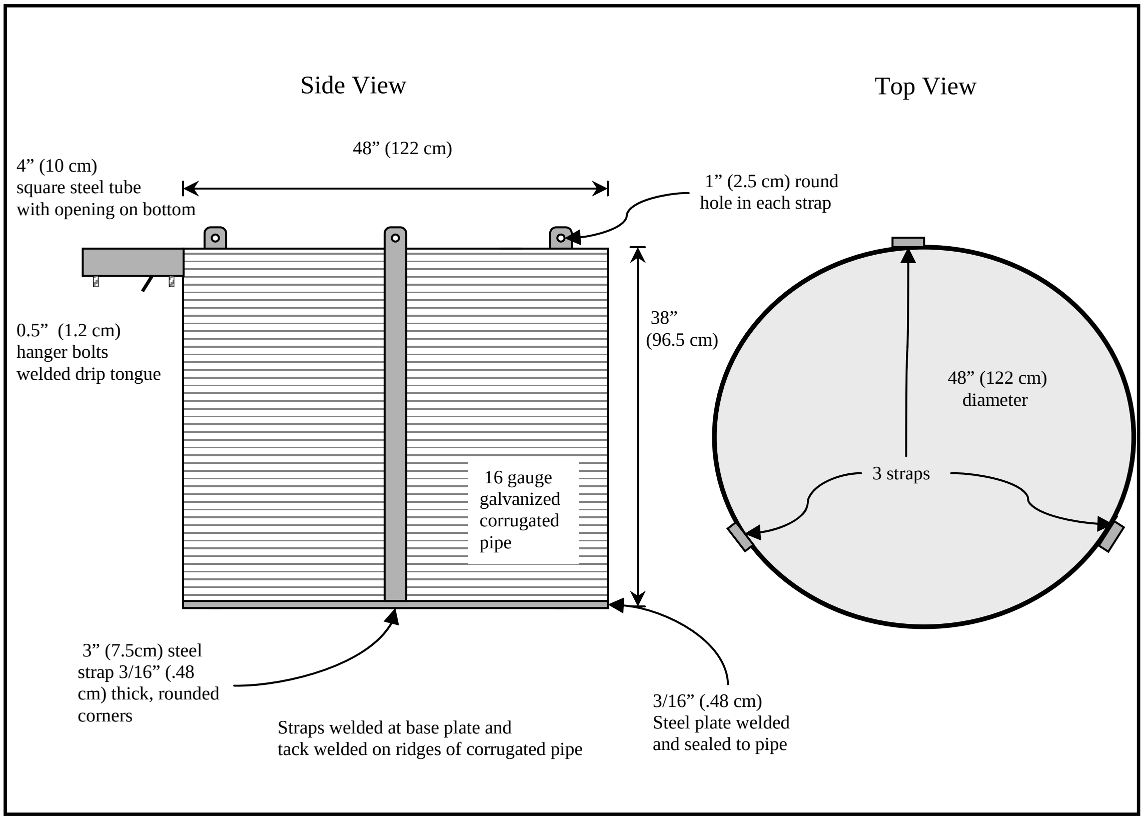


Figure 6
Detail of steel sediment settling tank with outlet for discharge measurements and lifting points for crane rigging.

Runoff and sediment enters the open system settling basin during precipitation events, where the coarse sediment settles from suspension. The tank continuously fills and overflows through the outlet that routes the flow to the optional tipping bucket. Appendix A contains a list of the equipment and hardware required to install 5 typical road sediment plots and the cost in 2004.

Plot Maintenance
Carefully installed sediment measurement plots will perform as designed for many years with periodic maintenance. Heavy traffic and large runoff events may cause road surface rutting. This may generate coarse sediment accumulation at the waterbars and ditch inlet where the flow velocity is reduced. These locations should be inspected monthly throughout the runoff season and after large events to ensure that flow does not escape the plot boundaries and that the settling tanks do not fill beyond half their designed capacity. As the tanks fill substantially their settling efficiency declines and subsequent events will not be equally collected. The conveyor belt material used in the waterbars has

performed well for up to five years depending on the traffic loading. In the case of heavy truck traffic waterbars will need to be replaced or refurbished periodically.

Sediment Measurement Methods

Tripod Method

Several options are available to measure the sediment accumulated in the settling tanks. Previous studies have attempted to collect the entire volume of sediment in sealed containers and transport to a facility where it can be oven dried and weighed (Foltz and Truebe 1995). In other settling basin based studies, volumes have been estimated using surveying techniques and converted to mass using a density conversion factor (Megahan and Kidd 1972). When the sediment masses large and the plots are numerous, it becomes quite cumbersome to handle and transport the sediment. Two methods were developed that use the difference between the wet sediment and container mass and the mass of the container full of water, adjusted by the particle density to yield a measure of the dry mass of sediment.

When the expected sediment sample size is less than 100 lbs (45 kg) and there are fewer than 12 replicates, we found it is most efficient to determine the mass of the sample by using battery powered load cell suspended from a surveying tripod. This portable scale system is inexpensive to operate and does not require transporting the accumulated sediment to a lab facility for oven drying. A general equipment list for the tripod weighing procedure can be found in appendix B. The mass of sediment collected in settling tanks was measured and sampled twice a year. Observations about the site condition, maintenance needs and sediment weights are recorded on the field form (Appendix E).

To access the sediment in the tank carefully siphon the excess water from the sediment tanks close to the level of the sediment surface. Care must be taken to avoid disturbing the sediment with the siphon hose. Before removing the sediment from the tank, a measurement of the depth of the sediment is made. This number should reflect an average depth and if all of the mass is in a pile below the inlet pipe, an approximation should be made. A representative sample of the sediment is collected for particle density, and optional particle size or composition analysis.

The material in the tank is then shoveled into plastic buckets and the tank is then scraped with a plastic trowel or brush to remove any material adhering to the tank. After the tank is shoveled out, tip it on edge and use water to collect all the material into a corner where it may be more easily sampled. The sediment is transferred to plastic buckets and carried to the road where the measurements are taken.

The weight is determined with a 100 lb (45. kg) capacity digital load cell hanging from a portable tripod. An Intercomp CS 200 scale was used in this study with a reported accuracy of .1% of full-scale range. A heavy-duty survey style tripod is fitted with a hook made from threaded rod. The load cell hangs from a hook attached to the tripod at a height so that the suspended weighing bucket clears the ground (figure 7). The sediment weighing container is a 5 gallon (22 liter) steel bucket with three evenly spaced lifting point rings located equidistantly around the upper rim. Three turnbuckles are attached to rings on the lower end and are joined to a central lifting ring at the upper end for easy attachment to the load cell. The tripod is set up on the road above the tank. The load cell is turned on, allowed to warm up for ten minutes and zeroed before installation.

Figure 7
The tripod sediment determination system shown using a 100lb (45 kg) capacity load cell and a fiberglass survey tripod.

These turnbuckles are used to precisely level the bucket. The first measurement is made to determine the mass of clean water that the bucket will hold. The bucket is filled with water to obtain the weight of water and the container (Mtw). The bucket is filled until water begins to spill and then the turnbuckles are adjusted until water spills out in equal volumes from between each of the three quadrants defined by the attachment points. When the bucket is close to level, a half turn adjustment of the turnbuckle is sufficient to make an appreciable difference in height. It is generally easier to raise the lowest of the three sides (the one with the most flow) rather than lowering the two that have the least flow.

To check the level of the water surface, a small volume of water is poured in to the bucket slowly using a cup. Observe in which of the three areas the water spills over. When water is spilling evenly within the three quadrants the bucket is repeatable leveled. Carefully add a small additional volume of water. After five seconds record the measurement. This is the $M2$ value that represents the mass of water and bucket. This measurement should be taken at the start of each sampling day to check the scale and the precision of the system, and should not vary significantly over the course of a day unless the water temperature changes significantly.

The weighing of sediment is done in the same fashion except that the weighing bucket is filled with the excavated sediment to a level close to full and then clean water is added to reach the full level as defined above. The container is re-leveled and topped with a small volume of water until it spills evenly. Wait five seconds for the scale to stabilize before recording the reading $M1$. Repeat the process until the entire sample is measured. The weighing container is carefully cleaned between measurements to prevent carry over.

The mass of the sediment is calculated from the difference between $M1$ and $M2$. The temperature of the water is recorded so that the appropriate value for water density may be used. See appendix D for water density values. A sub-sample of the sediment is collected to measure the particle density using a picnometer (Blake and Hartage, 1986).

The equation for determining the mass of the sediment is derived using the following terms.

Mt	is the mass of the sediment tank, kg
Mw	is the mass of the water, kg
Mtw	is the mass of the sediment kg
ρs	is the particle density of sediment in kg/m^3
ρw	is the density of water at the observed temperature kg/m^3
$M1$	is the observed mass of the tank, water and sediment
$M2$	is the observed mass of the tank filled with water

The observed mass of the full tank of sediment is composed of the mass of the tank, sediment and water.

$$M1 = Mt + Mw + Ms \quad (1)$$

The observed mass of the tank full of water is composed of the mass of the tank and the mass of the water.

$$M2 = Mt + Mw \quad (2)$$

The masses of the sediment and water are the product of the densities and volumes.

$$Mw = \rho wVw \quad (3)$$
$$Ms = \rho sVs \quad (4)$$

The mass of the total system can be written using equations three and four.

$$M1 = Mt + \rho wVw + \rho sVs \quad (5)$$

The mass of the tank with water can be written using equation three.

$$M2 = Mt + \rho wVt \quad (6)$$

The volume of the tank can be described in terms of the sediment and water.

$$Vt = Vw + Vs \quad (7)$$

Substituting equation 7 into equation 6 yields

$$M2 = Mt + \rho w(Vw + Vs) \quad (8)$$

Taking the difference between equation 8 and 5 removes the term for the tank mass.

$$M1 - M2 = \rho wVw + \rho sVs - \rho w(Vw + Vs) \quad (9)$$

$$M1 - M2 = \rho wVw + \rho sVs - \rho wVw - \rho wVs \quad (10)$$

$$M1 - M2 = Vs(\rho s - \rho w) \quad (11)$$

Expressed in terms of the volume of sediment

$$Vs = \frac{M1 - M2}{(\rho s - \rho w)} \quad (12)$$

Substituting equation 4 to rewrite in terms of the mass of sediment.

$$Ms = \rho s \frac{M1 - M2}{(\rho s - \rho w)} \quad (13)$$

Mass of sediment is determined using equation 13 for both the crane method and the tripod method.

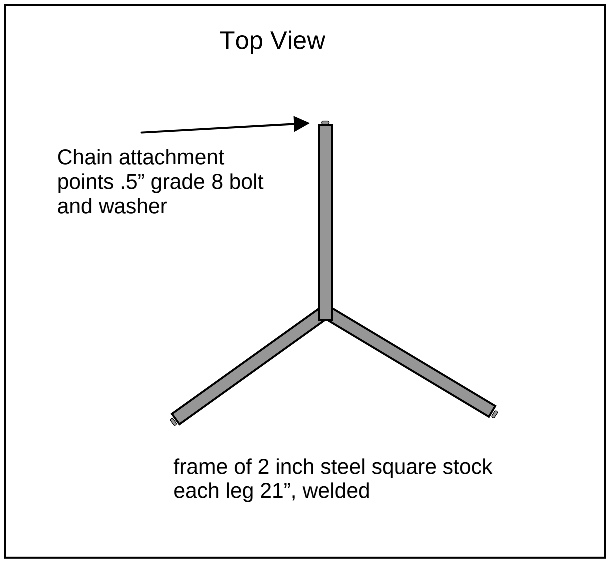
The tank weighing procedure has proven to be repeatable and sufficiently accurate when tested in the field. An experiment was performed to verify the ability of the system to measure the mass of a known amount of sediment Ms. The test was performed using 300 pounds (136.1 kgs) of clean graded quartz sand with a particle density of 2.65 g/cm^3. The initial mass of tank plus water and sand was 2987 pounds (1354.9 kgs). The mass of the tank and water was 2804.9 lbs (1272.3 kgs). In this case the calculated mass of the quartz sand was 300.5 lbs (136.3 kg). The .5 lb (.2 kg) error includes the uncertainty from the load cell, meter, and imperfect tank leveling.

The precision of the full water tank measurement $M2$ was tested by making repeated measurements of the mass of water under the same conditions. The median of the 7 observations was 47.15 lbs (21.4 kg) and the values varied over a range of .35 lbs (.16 kg).

Measuring large sediment masses using a crane

If the sediment mass is expected to exceed 200 pounds per sampler or there are a large number of samples to be taken, a more efficient means of moving and measuring the sample is required. We found that a truck mounted crane is a suitable tool for lifting, moving and weighing sediment tanks weighing as much as 5,000 pounds (2268 kg). A crane based system was used on disturbed road plots that producing as much as 2 tons per plot year. In this case a 10,000 lb (5,000 kg) capacity battery powered S-beam load cell (Dillon model ED 2000) with a reported accuracy of .1% of full-scale range was selected. A 12-ton truck mounted crane was used to lift, manipulate and empty the sediment tanks (figure 8). Tanks are lifted from their top edge using three welded lifting points (Figure 6). The load hook on the crane cable connects an alloy ring to the load cell via a shackle. Below the load cell are attached a roller bearing swivel, spreader bars between the three chain legs and a turn buckle in line with each chain leg. The turnbuckles allow the tank to be precisely leveled under load (figure 8, 9). A large supply of water is required to fill and cleanse the tanks. We used an 800 gallon (3028-liter) tank mounted on the bed of the crane truck and transferred too and from settling basins with a portable gas powered pump. A general equipment list for the crane weighing procedure can be found in appendix C.

Figure 8.
Crane and load cell system used to weigh large sediment samples. Water supply tank is mounted on the bed of the crane



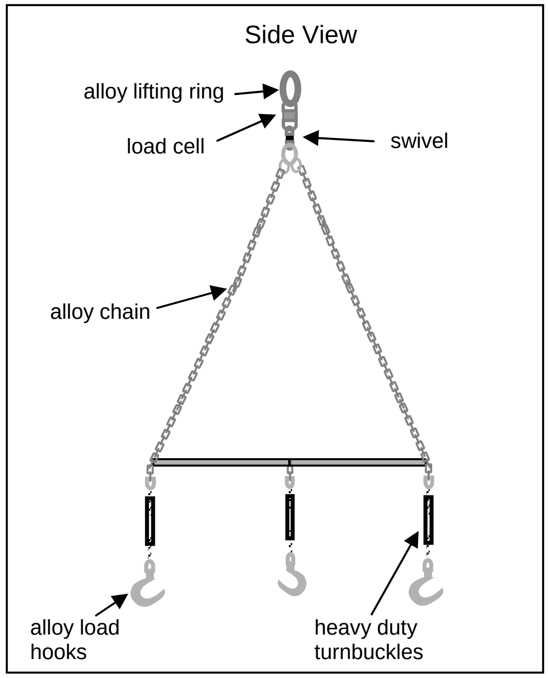


Figure. 9. Detail of tank lifting, leveling and weighing apparatus used with the crane.

Figure 10. Sediment collection tank suspended from crane by radio linked load cell. Notice the load distribution frame, turnbuckles used to level the water surface and steel tipping bars below tank.

The weighing process begins with the calibration and checking of the load cell and meter system. A 1000 lb. (453.6 kg) steel test weight was used for calibration at the start and end of each day’s sampling. Move the crane into position as close to the collector as possible. Stabilize and level the crane in a solid location on the road surface paying attention to areas of soft fill. We used railroad ties to build solid footings and a level platform to spread the load applied by the hydraulic outriggers mounted to the chassis of the crane. Level the bed of the crane to within 1% of level in all directions or as recommended by the manufacturer. Attach the tank lifting assembly to the crane hook and zero the weighing system and lifting mechanism. A signal person aids the crane operator in lifting the sediment-laden tanks from the retaining wall enclosure to the roadway where the measurements are made. The sediment containing tank is topped off with water and leveled using the turnbuckles until water spills evenly across the top edge of the tank, as was described in the tripod method. The mass of the tank, water and sediment is recorded from the calibrated load cell. The tank is lowered onto a pair of steel C-channel brackets that are used to aid in the controlled spilling of the tank. The sediment tank tipping supports are composed of two pieces of 3 inch (7.6 cm) c-channel welded into an L shape with heavy duty lifting eye bolts attached to each of the horizontal legs of the L (figure 11). These eye bolts are attached to crane using the hooks on the spreader frame and the tank is slowly lifted on one side. The vertical side of the L supports the tank as it rotates and gently spills the water and sediment out of the tank and onto the road shoulder vegetation (figure 12). The hooks must have safety retainers that close under spring tension so that the hooks do not slip from the lifting eye bolts as the load shifts. A composite sample of sediment is collected from various depths in the homogenized mass at the bottom of collector. This sample is used to determine the sediment particle density so that the true dry mass of the sample can be determined. The tank is then cleaned out with a shovel and a fire hose driven by a small gasoline powered impeller pump. Use blocks or railroad ties to prevent the tank from rolling on a steep road when it is being cleaned. Care must be taken when emptying the tanks located close to stream channels to avoid unplanned sediment additions.

Sediment Tank Tipping Support

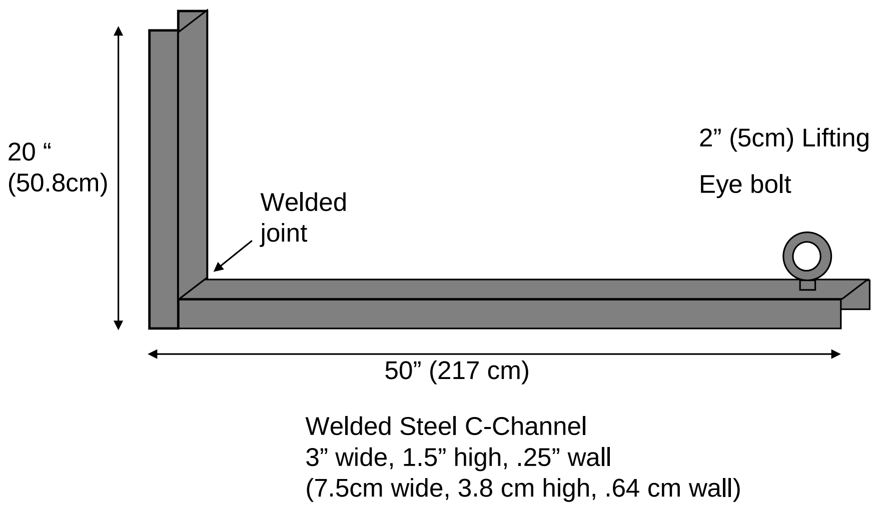


Figure 11.
Sediment tank tipping support dimensions.

Figure 12.
Sediment tank being tipped over for sediment sampling. Note the L shaped tipper bars supporting the tank

The tank is then lifted upright again and refilled by gravity flow with water from the reservoir on the crane bed. The tank is lifted and leveled once again and a second reading is observed from the load cell meter for the mass of the tank and water. Lift the sediment tank above the crane and siphon the 307 gallons (1162 l) of water back into the reservoir using a large diameter rubber suction hose. The water is recycled at the end of the weighing process to reduce the time spent acquiring clean water from the nearest water supply. The empty tank is then lowered and replaced on the pad.
Extreme caution must be exercised when lifting, moving and emptying the tanks as they are extremely heavy and can easily injure a person who is in their path. Always obtain the proper training before operating heavy equipment and use the recommended safety equipment.

Trap Efficiency
The trap efficiency of the settling basin system alone is sensitive to several factors including particle size, sediment supply and the flow rate through the tank. The particle size available for transport may be the most easily addressed variable. Clay size particles have very slow settling velocities once suspended and will produce low trap efficiencies

in a small settling tank system. When there is minimal ground disturbance on a plot overall production of coarse sediment will like wise be low. In these situations a fine sediment capture system is recommended.

Comparisons were made of trap efficiency under various intensities of road traffic and grading under natural rainfall on a silty clay-loam soil. Ditch grading mobilized a substantial supply of sand sized aggregated material that was trapped by the settling basin. Heavy truck traffic produced finer sediment sizes that were not caught in the settling basin but were observed in the suspended sediment splitter. The range of trap efficiency for the traffic example show a low of 21%of total sediment retained for light traffic and no grading to a high of 68% for light traffic and grading of the ditch. These results support the use of a fine sediment sampler and flow monitoring on fine textured soils to ensure the entire sediment stream is being accounted for.

Measuring flow with a tipping bucket system

In many cases a settling tank system will address the immediate need to quantify the coarse sediment generation from a forest road system. However, with a small additional investment a great deal more hydrologic information may be gathered. In order to understand the fine sediment budget of plots, and the timing of that sediment generation we modified the sediment trap system to include the measurement of flow and suspended sediment. The minor incremental increase in cost increases the utility of the system to cover a broad range of problems and environments. When the soil textures are predominantly fine and the plot receives little disturbance, the sediment in transport may be principally fine. In this case the use of the tipping bucket and sediment splitter is also recommended.

The tipping bucket uses a container divided into two equal volumes that are balanced about an axle. Incoming water enters one side of the container or bucket at a time. As the bucket fills, the system becomes unbalanced and the heavier side tips and empties (figure 13). As the bucket rotates to empty a magnetically actuated reed switch records that passage of a magnet that is attached to the side of the container (figures 13-15). The opposing side is now in position to collect incoming flow and the process repeats itself.

Figure 13.
Tipping bucket and flow splitter in operation. The 20 gpm (66 lpm) design is shown.

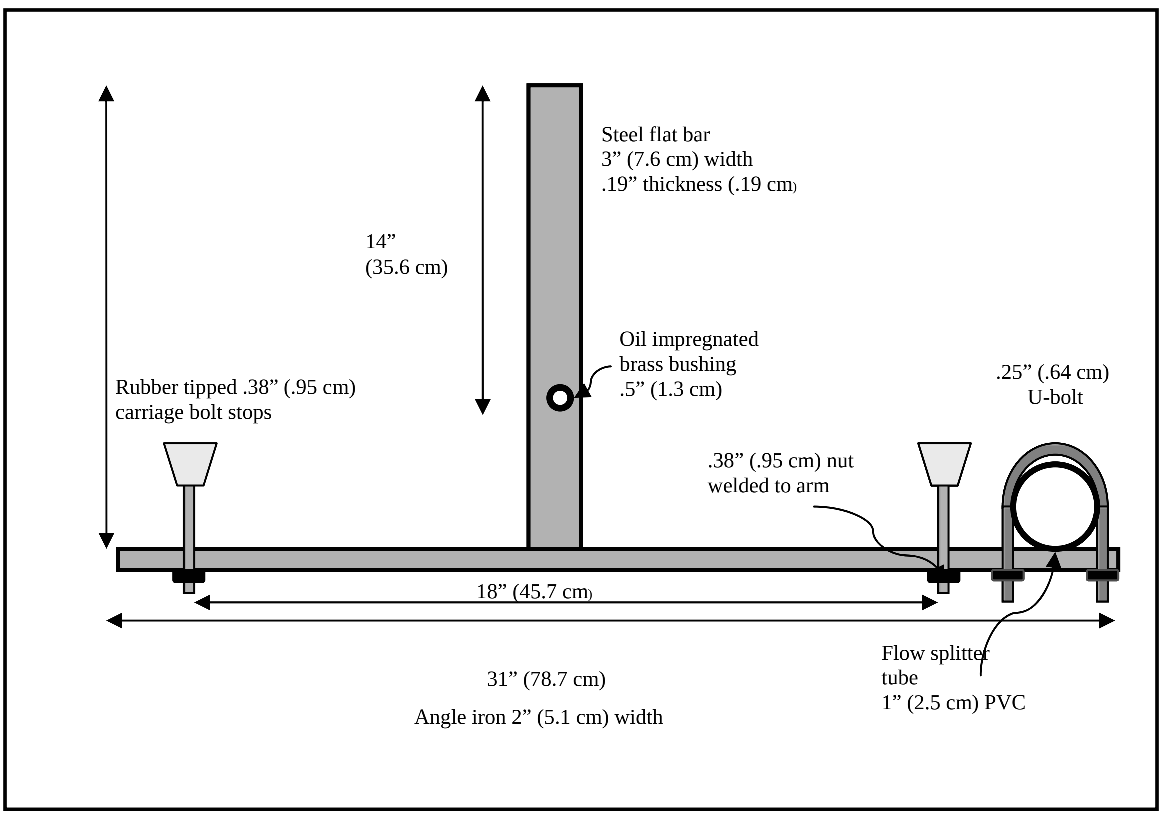


Figure 14. Hanger assembly and sediment splitter for tipping bucket

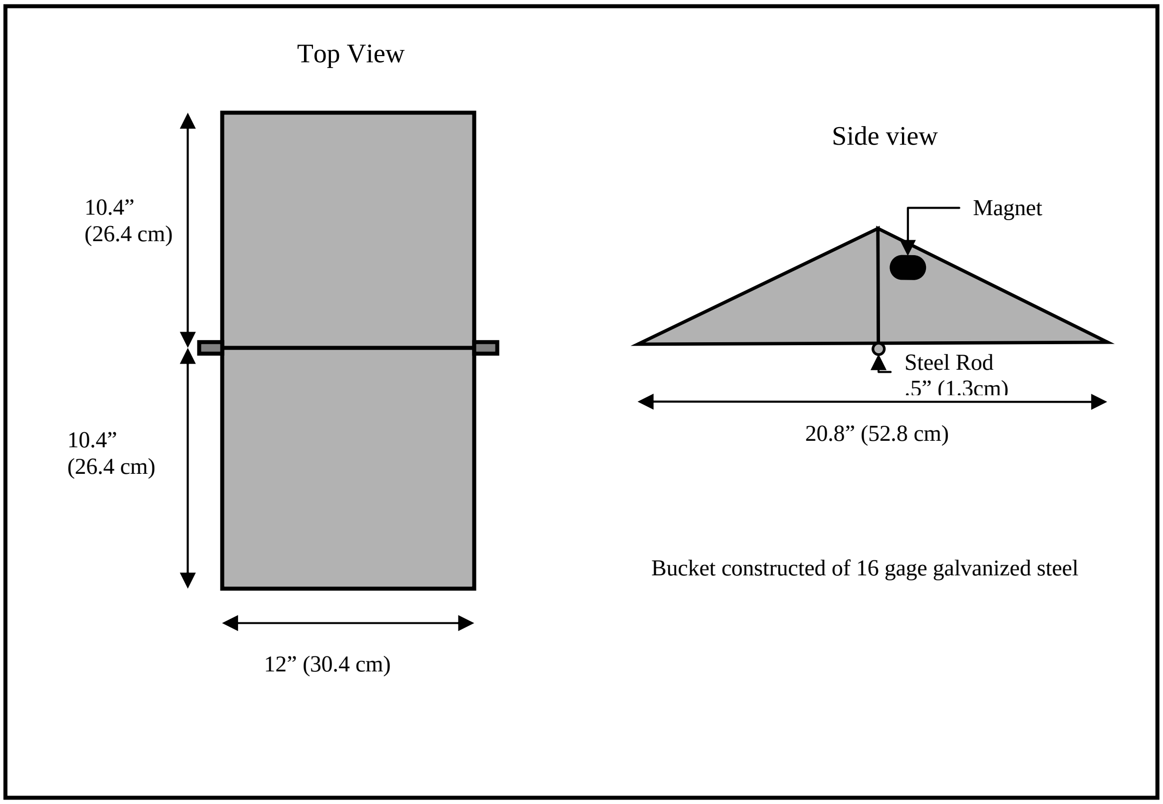


Figure 15. Small tipping bucket container for measuring flows less than 20 gpm (66 lpm)

A data-logging device located in a waterproof case is connected to the reed switch. In this case, an Onset Hobo Event data logger was used. Each time the magnet passes the reed switch a circuit closes causing the data logger to collect a time stamp. The time stamp file allows the user to calculate the time interval required to fill the bucket volume. The device is calibrated to determine the relationship between discharge and switch closures because the relationship is somewhat dependant on setup and leveling of the device. The calibration is applied to the record and a high resolution continuous hydrograph can be created.

Tipping bucket design

The devices are designed to be durable and sufficiently adjustable to accommodate a variety of field installations while minimizing complexity and cost. At the time of writing large size tipping buckets such as those described here were not available on the market so it was necessary to have them fabricated by a machine shop. The costs ranged from less than $100 for the 20 gpm (76 lpm) to $300 for the large 35 gpm (132 lpm) size. Three basic designs are described in this document. The small (figure 13) and medium sizes (figures 16-18) are suspended from the tank outlet. The largest size tipping bucket (figures 19 and 20) is free standing and more durable as a result.

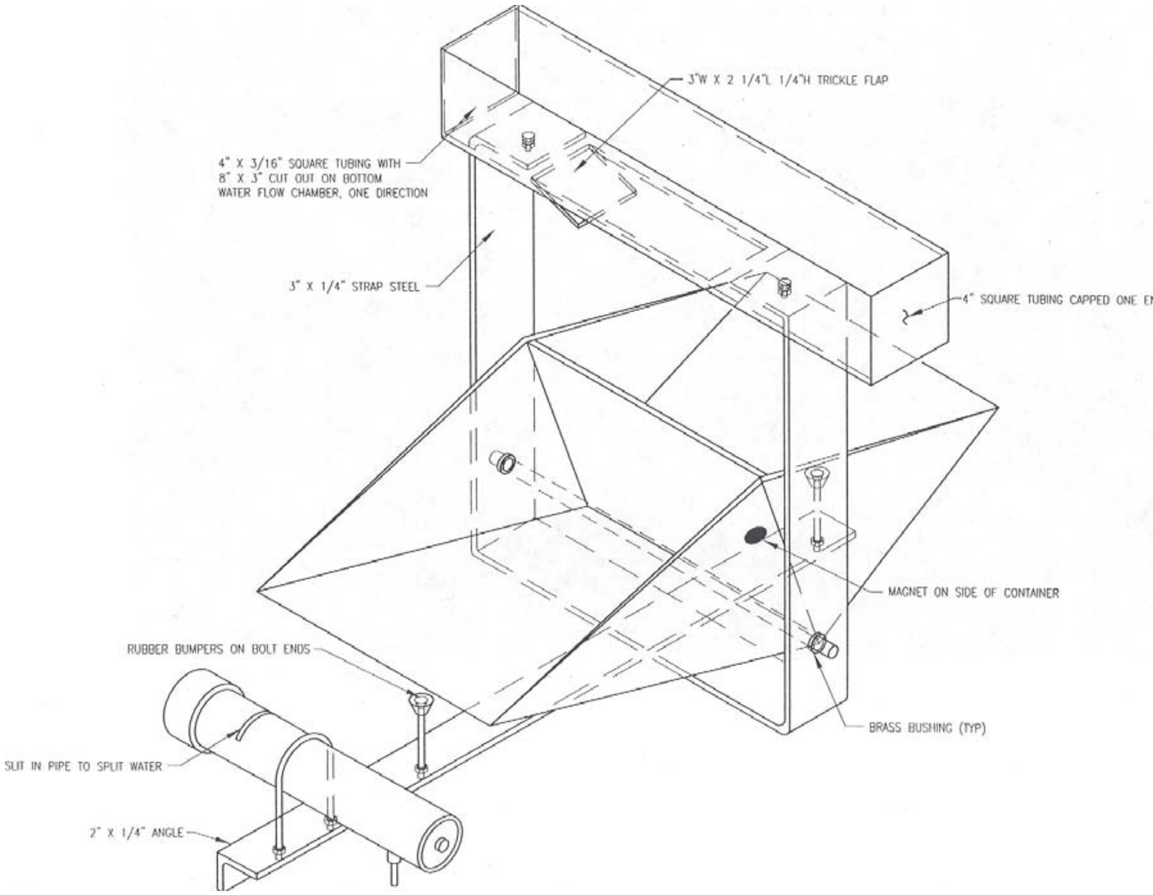


Figure 16
Isometric view of the medium size tipping bucket and attachment to tank outlet.

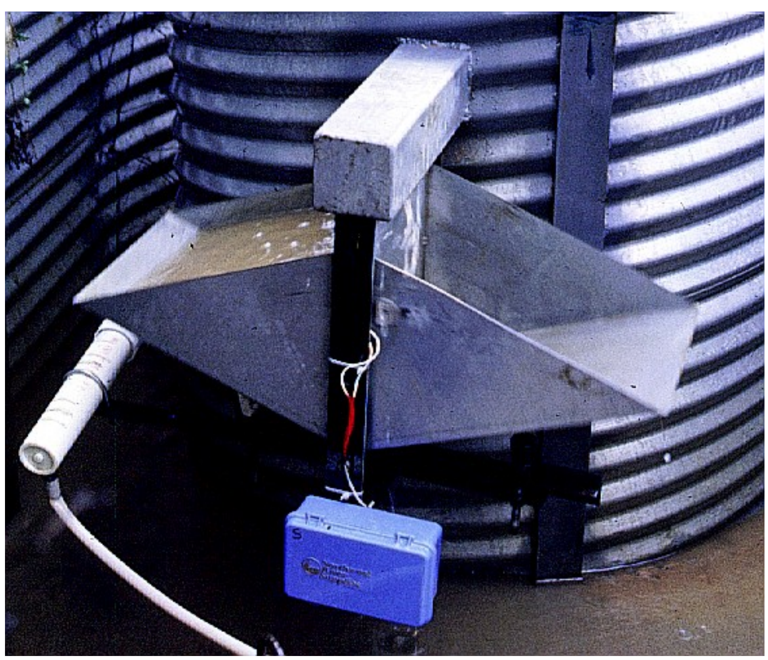


Figure 17.
Medium capacity tipping bucket and flow splitter in mid-cycle

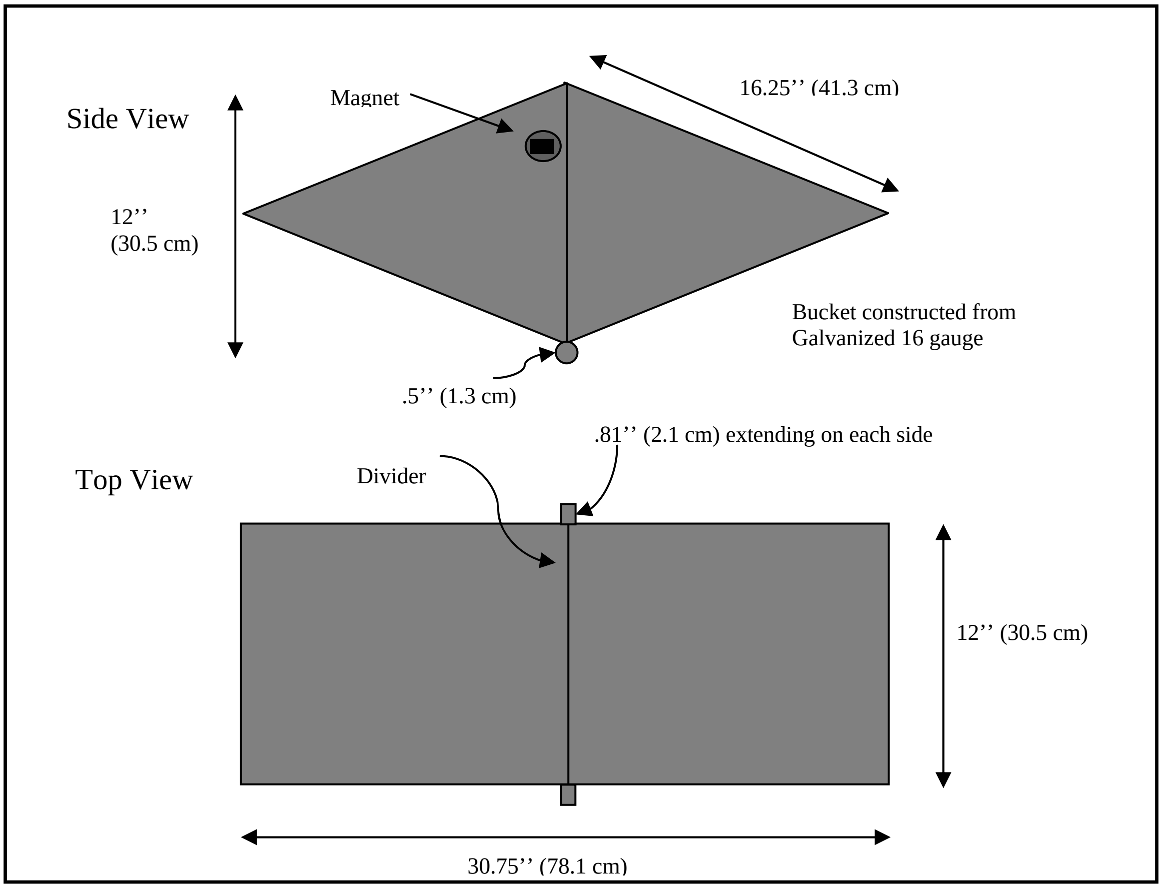
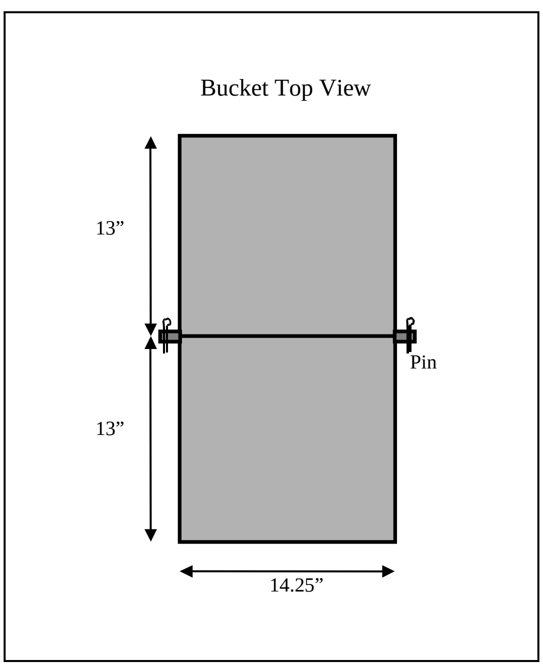
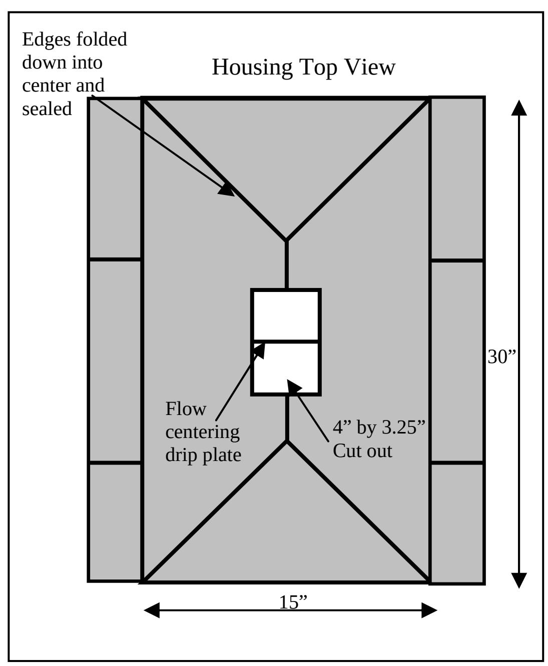
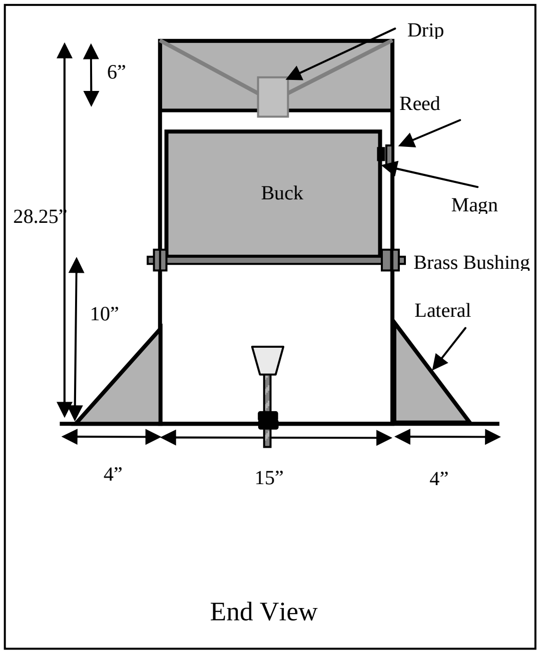


Figure 18.
Medium capacity bucket specifications.

Figure 19. Large free standing tipping bucket with pipe directing flow to inlet.







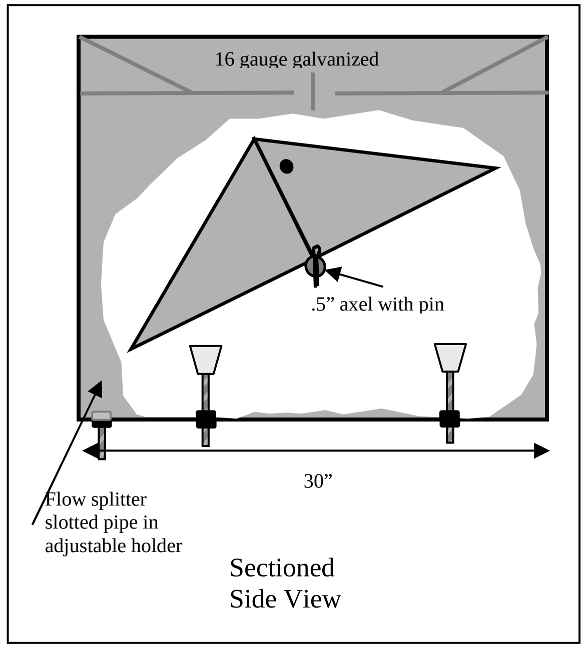


Figure 20.
Large size free standing tipping bucket specifications.

The support frame from which the small and medium buckets are suspended is constructed from steel flat bar. The frame hangs from the tank outlet suspended from two .5” (1.2 cm) bolts. The buckets are constructed of welded 16 gauge galvanized sheet metal sealed at the seams. The pan is welded to a half inch (1.3 cm) rod that acts as an axle. The buckets are connected to the frame by inserting the rod through a brass bushing in the frame before the frame assembly is hung from the bolts on the outlet of the tank. There are adjustable rubber stops on the frame that are used to set the travel of the tipping bucket pan. The stops are constructed from carriage bolts with a rubber crutch tip glued to the round head of the bolt. The stops attach to a transverse arm on the frame by a nut welted in place, and are secured by a second nut.

There are a variety of data loggers available on the market and new models appear each year. At the time of this design the Hobo Event logger was selected for ease of use, durability and value. The Hobo Event logger has a memory capacity of up to 8000 switch closure events. This translates to roughly 6,000 gallons (26,430 liters) of discharge with the small size bucket at .75 gallons (2.8 liters) per tip and 24,000 gallons (90,720 liters) for the medium size bucket holding approximately 3 gallons (11.3 liters). The small bucket size can be used to measure discharge of up to 20 gallons (76 liters) per minute and the larger size is suitable for flows up to 35 gallons (113 liters) per minute. The large free standing model supporting higher flow rates was tested at flow rates as high as 60 gallons per minute (227 l/min).

To select the appropriate size device consider both the expected peak flow rate and the desired low flow rate. The interval at which the data will be downloaded from the field and the size of the data logger memory are also considerations. The ideal size bucket can be determined for the desired application based on the three existing designed sizes. It is conservative to select a larger volume bucket to ensure that peak flows are within the recordable range. Low flow resolution may be compromised if the bucket size is excessively large.

The reed switch is a critical component of the system that registers the motion of the bucket. A high quality reed switch is available from Texas Electronics (S1-128) (appendix A). This device is less prone to errors associated with the passage of the magnet. Inexpensive but low quality reed switches were found to be prone to switch flutter which resulted in rapid multiple closures from a single magnet pass. This situation can occur with any reed switch depending on the proximity of the magnet, but can be rectified by setting a tolerance in the data logger. A filter setting that ignored signals closer together than two seconds was used. The switch and wiring assembly is epoxied to the inside of the frame and the magnate is epoxied to the side of the bucket in such a way that it passes directly across the switch (within a millimeter) when the bucket spills.

The data logger is connected to the leads of the reed switch and sealed into a watertight container. A gasketed dry box container purchased from a white water outfitter was used with a watertight cable entry. A desiccant package and humidity indicator were used in the dry box to keep the electronics dry. The dry box assembly is attached with Velcro to the front of the tipping bucket frame (Figure 19).

Tipping bucket installation

The bucket and the frame that make up the tipping bucket device are assembled in the field. Insert the axle of the pan assembly into the brass bushings with the proper number of spacer washers to position the magnet and the reed switch within one millimeter of each other. Use thin brass spacer washers to fine tune the switch to magnet location. The fine tuning is accomplished by trial and error. Verify the magnet to switch location by attaching a voltmeter to the plug for the data logger and checking for a single signal with each pass of the magnet. Once installed, test the device with the data logger in place to verify that a single time stamp is generated from each pass of the magnet.

Use nylon lock nuts to secure the frame to the tank outlet hanger bolts.

Adjust the level of the device across the two sides of the bucket by using the adjustable bumpers so that each side holds approximately the same volume of water. Level the bucket in the opposite direction by placing spacer washers on the hanger bolts. When the lock nuts are tightened onto the hanger bolts, the bucket should operate freely without contacting the frame.

Tipping bucket calibration

As each field installation is unique and the leveling of the device influences the capacity of the bucket, calibrate each device in place. Create a calibration curve for each tipping bucket gauge by running a known discharge through the system and recording the observed number of cycles of the bucket. Verify manual observations of tips against the data logger record.   A fire truck may provide a convenient water source and an industrial water meter can be used to measure the volume of water. Use a stopwatch to measure the time. Create the calibration curve from three discharge measurements within the range of expected flows for the site. It was noted that for the smaller capacity tipping buckets, flows above 20 g/m (76 l/m) sometimes caused erratic behavior of the bucket due to the force of the falling water. The devices were calibrated at the beginning and end of the measurement period. This calibration is recommended to account for any changes in the adjustment of the system and variation in the friction on the axle.

Maintenance and data collection

Download the data logger frequently so that the memory does not fill during storm events In order to ensure data integrity in previous studies, the data were collected twice monthly and after large events and maintenance was performed at the same interval. The data were downloaded to a Hobo Shuttle logger in the field or directly to a laptop. Change desiccant packages at each visit and check the operation of the tipping bucket mechanism for freedom of motion. Use a dry lubricant such as graphite on the bushing as necessary.

During the two years of data collection the system operated well but a few problems were encountered.

Initially, moisture was encountered in some data logger enclosures despite the double gasket sealed enclosures. A 50 gram charge of desiccant was kept in the dry box enclosure and a charge sized to fit inside the case of the data logger itself was used. Frequent desiccant changes and the use of an umbrella when opening the enclosure in the rain reduced the humidity related problems. Humidity indicator paper was kept in the enclosure.

Several of the medium size tipping buckets were damaged during a high intensity runoff event. Initially, .38 inch (one cm) diameter bolts were used to secure the frame but they did not provide enough resistance to hold the larger devices in place when the flow reached high rates. It was found that many of the large capacity devices had become loose on their support bolts during a large event. When the hanger bolt size was upgraded to .5 inch (1.3 cm) and secured by nylon lock nuts the problem did not reoccur.

Fine sediment collection

A flow splitter was used to collect a sub-sample of the discharge from one side of the tipping bucket. A 1.5 inch (3.75 cm) diameter segment of PVC pipe was attached to the cross arm of the tipping bucket frame below the lower edge of the bucket (figures 16 and 17). The ends of the pipe were capped and a plastic barbed hose fitting was epoxied to the lowest point. A single narrow slit was cut in the pipe with a hacksaw blade so that when the bucket discharged water across the pipe, a 5 ml sample of water and suspended sediment were collected. This water and fine sediment were routed through the inclined pipe and into a piece of rubber tubing and collected in a sealed bucket 5 gallon (19 l) bucket with an air vent.

The sub-sample water reservoir was examined each time the discharge data were collected (figure 17). If more than a gallon of water had accumulated then a sub-sample was taken and the reservoir cleaned. The fine sediment in the water reservoir was homogenized with an impeller driven by a portable drill for a period of three minutes. A .3 gallon (one-liter) sample was immediately taken from near the bottom of the bucket using a wide mouth container. The sediment concentration of these samples was determined by filtration through a Buchner funnel apparatus (Eaton et al 1995). The sediment concentration may also be determined by oven drying the sample at 105 degrees

C when dissolved solid do not constitute an appreciable portion of the mass in transport (Eaton et al 1995).

Conclusions

Settling basins provide a simple and reliable system for monitoring road derived sediment production. The installation, maintenance and measurement of five plots can be accomplished by a technician in less than a month. The tipping bucket system provides a simple and inexpensive method to monitor discharge and sediment production from road surface plots. The tipping bucket devices described herein provides a detailed and reliable record of discharge up to132 liters per minute when properly calibrated and maintained. The system provided a complete sediment and discharge record when used with a settling basin and a flow splitter for the determination of fine sediment. On newly constructed roads and on coarse textured soils settling basins alone provide an adequate measurement of sediment leaving the road. On undisturbed plots and in conditions of traffic without ditch disturbance the tipping bucket and sediment splitter are recommended to adequately characterize the sediment production.

References:

Ackers, P. White, W. R., Perkins, J.A. and Harrison, A.J.M. 1978 *Weirs and Flumes for Flow Measurement*, John Wiley and Sons. New York, NY.

Bilby, R.E., Sullivan, K.O. and S.H. Duncan 1989. The generation and fate of road surface sediment in forested watersheds in Southwestern Washington. Forest Science 35(2):453-468

Blake G. R.and K. H. Hartage 1986 . Particle Density. In Methods of Soil Analysis, Part 1 Physical and Mineralogical Methods-Agronomy Monographs no. 9. pp377-379.

Black, Thomas A. Luce, Charles H. 1999. Changes in erosion from gravel surfaced forest roads through time. Sessions, John; Chung, Woodam, eds. Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium; 1999 March 28- April 1, Corvallis, OR; Corvallis, Oregon. Oregon State University and International Union of Forestry Research Organizations: 204-218.

Cederholm, C.J. Ried, L. M. and Salo, E. O. 1981. Cumulative effects of logging and road sediment on Salmonid populations in the Clearwater River, Jefferson County, Washinton. Pp38-74 in Proceedings the conference Salmon Spawning Gravel: A renewable Resource in the Pacific Northwest?, Water Research Center, Washington State University, Pullman, Washington.

Cline, R.G. Cole, W. Megahan, R. Patten, and J. Potyondy. Guide for predicting sediment yield from forested watersheds. USDA Forest Service Northern Region and Intermountain Region, Missoula MT and Ogden Utah, 1984

Coker, R. J. Fahey, B. D. and Payne, J.J. 1993. Fine sediment production from Truck Traffic, Queen Charlotte Forest, Marlbough Sounds, New Zealand. Journal of Hydrology (N.Z.) 312 (1), 56-64.

NCASI, 2003. Technical Documentation for SEDMODL Version 2.0, Road Erosion/Delivery Model. Report prepared for National Council for Air and Stream Improvement. http://www.ncasi.org

Eaton, D. A., Clesceri, L. S., Greenberg, A. E., 2540-D in Standard Methods for the Examination of water and Wastewater 19th edition. American Public Health Association 1995

Elliot, W.J.; Hall, D.E.; Graves, S.R. 1999. Predicting sedimentation from forest roads. Journal of Forestry, August 1999, 97(8):23-29.

Foltz R. B. and M. A. Truebe. 1995 Effect of Aggregate Quality on Sediment Production from a Forest Road. Proceedings of the Sixth Annual Conference on Low-Volume

Roads, Minneapolis Minnesota. Transportation Research Board, National Research Council.

Grant, D. 1988. *ISCO Open Channel Flow Measurement Handbook* Second Edition. ISCO Corporation, Lincoln Nebraska 227p

Ice, George G. 1986 A study of the Effectiveness of Sediment Traps for the Collection of Sediment from Small forest Plot Studies. NCASI technical bulletin #483

Jones J. A. and G. E. Grant, 1996 Peak flow responses to clear-cutting and road in small basin, Western Cascades, Oregon. Water Resources Research 32(4) 959-974

Kahklen, Keith 1993, Surface Erosion from Forest Roads, Polk Inlet, Prince of Wales Island Alaska. Masters thesis, Oregon state University

Lamarche, J. and D.P. Lettenmaier, 2001, Effects of forest roads on flood flows in the Deschutes River Basin, Washington, Earth Surface Processes and Landforms, 26(2): 115-134.

Lee, D.; Sedell, J.; Rieman, B.; Thurow, R; Williams, J, and others. 1997. A broad-scale assessment of aquatic species and habitats. *in* T. Quigley and S. Arbelbide. tech. ed. An assessment of ecosystem components of the interior Columbia River Basin and portions of the Klamath and Great Basins. General technical report PNW-GTR-405. Portland, OR: USDA Forest Service, Pacific Northwest Research Station

Linde, David R. 2001. The Handbook of Chemistry and Physics 82nd Edition. CRC Press, Boca Raton, Florida.

Luce, Charles H. 2002. Hydrological processes and pathways affected by forest roads: what do we still need to learn? Hydrological Processes. 16: 2901-2904.

Luce, C. H. and T. A. Black, 1999. Sediment production from forest roads in western Oregon. Water Resources Research. 35(8): 2561-2570.

Luce, C. H. and T. Black, Thomas A. 2001a. Effects of traffic and ditch maintenance on forest road sediment production. Proceedings of the Seventh Federal Interagency Sedimentation Conference; 2001 March 25-29, Reno, NV. Washington, DC: Federal Interagency Sedimentation Committee: V-67-74.

Luce, C. H. and T. A. Black. 2001b. Erosion over time from gravel-surfaced forest roads in western Oregon. Proceedings of the Forest Sedimentation Conference; 1999 April 14-15, Tigard, OR. Northwest Forest Soils Council and Western Forestry and Conservation Association: 135-139.

Luce, C. H. and T. A. Black. 2001c. Spatial and temporal patterns in erosion from forest roads. Wigmosta, M. S. and S. J. Burges, eds. Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas – Water Science and Application 2. Washington, DC: American Geophysical Union: 165-178.

Luce, C. H and T.W. Cundy. 1994. Parameter identification for a runoff model for forest roads, Water Resources Research 30(4), 1057-1069

McDonald, L. K, Sampson, R. W. and Anderson, D. M. 2001. Runoff and Road erosion of the Plot and Segment Scales, St John, US Virgin Islands. Earth Surface Processes and landforms, 26, 251-272.

Megahan, W.F and Kidd, W. J 1972. Effects of Logging Roads on Sediment Production Rates in the Idaho Batholith. USDA Forest Service Research Paper INT-123.

Montgomery, David R. 1994 Road Surface drainage, channel initiation and slope instability. Water Resources Research 30(6) 1925-1932
Reid, L. M. and Dunne, T 1984. Sediment Production from Forest Road Surfaces. Water Resources Research V. 20(11) pp1753-1761

Reid, L. M. and T. Dunne. *Rapid Evaluation of Sediment Budgets*. Springer Verlag Reiskitchen, Germany. 164 pp. 1996

Replogle, J. A. and A. J. Clemmens. 1981. Measuring flumes of simplified construction. Transactions of the American Society of Agricultural Engineers 24(2) 362-266

Thurow, R.F.; Burns, D.C. 1992. Fish response to fine sediment deposition in the Idaho batholith. Pp-130 *in* Sommarstrom, ed. Proceedings of the Conference on Decomposed Granitic Soils: Problems and Solutions. Davis, CA: University Extension. University of California.

Tysdal, L. M., Elliot, W. J., Luce, C. H. and T. A. Black. 1999. Modeling erosion from insloping low-volume roads with WEPP watershed model. Transportation Research Record no. 1652. 250-256. Proceedings of the Seventh International Conference on Low-Volume Roads, Batton Rouge, LA. Transportation Research Board, National Research Council.

United States Department of Agriculture. Field Manual for Research in Agricultural Hydrology Handbook #224. Brakensiek, D. L., H. B. Osborn, and W. W. Rawls editors. US Government Printing Office WA. DC. 547 pp 1979

Washington Forest Practices Board. 1993. Standard methodology for conducting watershed analysis under Chapter 222-22 WAC. Version 2.0. Department of Natural Resources Forest Practices Division, Olympia, WA.

Wemple, B. C., Jones, J. A. and G. E. Grant, 1996. Channel network extension by logging roads in two basins, western Cascades, Oregon. Water Resources Bulletin, 32(6) 1195-1207.

Wigmosta, M.S. and W.A. Perkins, 2001. Simulating the effects of forest roads on watershed hydrology, in *Land Use and Watersheds: Human Influence on Hydrology and Geomorphology in Urban and Forest Areas*, M.S. Wigmosta and S.J. Burges, eds., AGU Water Science and Application Volume 2, p. 127-143.

Appendix A Cost for Installation of 5 Road Sediment Plots

Cost to install 5 road sediment plots

Materials	Units	Quantity	Cost per	Extended Cost
Sediment Tank, 330 gallon galvanized steel [a]	piece	5	$150	$750
Pipe, 6 inch plastic N12 pipe, each plot 90 feet	feet	450	$2	$675
Waterbars, conveyor belt [b, c]	piece	10	$110	$1,100
Ditch inlet structure, steel half round [a]	piece	10	$28	$280
Gravel for tank pad	cubic yards	5	$8	$40
Gravel delivery	trip		$200	$200
Load cell scale		1	$200	$200
Construction Equipment Rental				
Mini excavator	days	1	$225	$225
Riding trencher	days	2	$250	$500
Gravel packer	days	2	$100	$200
Labor				
Construction 3 person days per plot (@$18/hr)	days	3	$144	$300
Periodic plot maintenance (one year)	days	3	$144	$432
Sediment tank weighing	days	1.5	$144	$216
Sub-total				**$5,118**
Additions for tipping bucket system				
Tipping bucket and sediment collector [d]	5		$200	$1,000
Data loggers [e]	5		$89	$445
Reed switches [f]	5		$30	$150
Magnets [g]	5		$7	$35
Dry box enclosure	5		$18	$90
Labor $18/hr	days	2	$144	$288
Operational Costs				
Downloading flow data device and maintenance (one year)	days	8	$145	$1,160
Total				**$8,286**

Vendor	Email	Address	Phone
[a] Pacific Corrugated Pipe	www.pcpipe.com	89822 Highway 99 North, Eugene, OR 97402	(541) 461-0990
[b] Fabreeka International	www.fabreeka.com/	696 West Amity Road, Boise Idaho	(208) 342-4681
[c] Goodyear Rubber and Supply	www.goodyear-rubber.com/	765 Conger St. Eugene OR. 97402	(541) 686-9554
[d] Smitty-Bilt Industrial Fans, Inc		32060 Herman Rd. Eugene OR 97408	(541) 343-7584
[e] Onset Computer Corporation	www.onsetcomp.com	P.O. Box 3450 Pocasset, MA 02559-4377	(508) 759-9500
[f] Hermetic Switch Inc.	www.hermeticswitch.com	P.O. Box 2220 Chickasha, OK, 73023	(405) 224-4040
[g] Texas Electronics Inc.	www.texaselectronics.com	P.O.. Box 7225 Dallas TX, 75209	(214) 631-2490

Appendix B _Tripod Weighing Equipment list

Battery operated load cell 100-pound (45 kg) capacity and spare
Load cell battery and spare
Survey tripod
Load cell hanger hook
Steel leveling bucket
Plastic buckets three gallon (11 l) and five gallon (19 l.) sizes
Plastic scoops, 2 large
Plastic cup
Squirt bottle
Hand trowel
Shovel, short handle flat blade
Brush to clean inside of tank
Water supply (55 gallon (208 l) drum or other)
Pump, portable gasoline powered
Hoses for pump, suction and discharge
Hose for water supply container
Pump fuel container
Tool box
Tape measure
Field book with data sheets
Sample bags, plastic 1 gallon (4 l) size
Sharpies
Pencils
Gloves
Rubber Boots
Digital camera

Appendix C _Crane Weighing Equipment list
Radio linked load cell 10,000-pound (5000kg) capacity
Spare batteries for load cell and receiver
Rigging and spreader bars for crane
Plastic buckets five gallon (19 l.) sizes
Plastic scoops, 2 large
Plastic cup
Shovels, long and short handled with flat blade and spade
Pulaski
Brush to clean inside of tank
Water tank
Pump, portable gasoline powered
Hoses for pump, suction and discharge
Hose for water supply container

Pump fuel container
Tipper bars
Railroad ties, 16
Tool box
Tape measure
Field book with data sheets
Sample bags, plastic 1 gallon (4 l) size
Sharpies
Pencils
Leather and rubber gloves
Hard hats
Rubber Boots
Eye protection
Digital camera

Appendix D
Density of Pure water at 101325 Pa (Linde 2001)

Degrees C	kg/m^3	Degrees C	kg/m^3
1	999.902	16	998.945
2	999.943	17	998.777
3	999.967	18	998.598
4	999.975	19	998.407
5	999.967	20	998.206
6	999.943	21	997.995
7	999.904	22	997.773
8	999.851	23	997.541
9	999.783	24	997.299
10	999.702	25	997.048
11	999.607	26	996.787
12	999.500	27	996.517
13	999.379	28	996.237
14	999.246	29	995.949
15	999.102	30	995.651

Appendix E.

Road Sediment Plot Field Sheet

Field Area:

Plot #: Date:

Crew:

Depth of Sediment (in):

Texture of Sediment (in):

Color of sediment:

Tare of bucket+water (lbs):

Tare water temp (F): Sample water temp (F):

Sample #	Sediment + bucket (lbs)
#1	
#2	
#3	
#4	
#5	
#6	
#7	
#8	

Sample #	Sediment + bucket (lbs)
#9	
#10	
#11	
#12	
#13	
#14	
#15	
#16	

Sub-sample taken?

Plot Condition:

Remarks: