EFFECTS OF VEGETATION ON CONTAMINANT TRANSPORT IN SURFACE FLOWS

R. Green[1], L. Roig[3], R.S. Govindaraju[2], and L.E. Erickson[1], [1]Department of Chemical Engineering and [2]Department of Civil Engineering, Kansas State University, Manhattan, KS, 66506, Phone: 913-532-5584, Fax: 913-532-7372, and [3]U.S. Army Corps of Engineers Waterways Experiment Station, 3909 Halls Ferry Road, Vicksburg, MS, 39180, Phone: 601-634-2801, Fax: 601-634-4208

ABSTRACT It is well known that vegetation reduces off-site contamination that would result from surface flows. A significant portion of heavy metal contamination occurs at abandoned mine sites due to sediment movement. The effects of vegetation on sediment transport and surface runoff are reviewed, with an emphasis on factors that can reduce or prevent the movement of such metals in mine tailings. Several mathematical models for sediment transport in surface flows are briefly discussed, including advantages and limitations of the Universal Soil-Loss Equation and CREAMS model. Reported experimental and field data on contaminant transport in surface flows are reviewed and evaluated, as well as studies in treating the bioavailability of heavy metals in attempts to reduce metal phytotoxicity or decreasing the potential for entrance of the metals into the food chain via vegetation.

KEYWORDS: surface water, metal, sediments, vegetation

INTRODUCTION

In southeastern Kansas, as well as many other sites around the nation, heavy metals have been mined with residual piles of tailings being left behind. These tailings, which contain elevated levels of lead, zinc, and cadmium, are considered serious risks to both human health and the environment. Transport of contaminants associated with sediments in surface flows is a significant problem at many sites where tailings remain void of vegetation. This paper reviews the literature on the effects of vegetation on contaminant transport in surface flows [1-55]. Remediation choices available for heavy metal contaminated sites include *ex situ* and *in situ* treatments. *Ex situ* treatments include reprocessing, leaching, segregation by particle size, solidification, vitrification, and washing. *In situ* treatments include solidification and vitrification, but can also include attenuation, encapsulation, volatilization, and phytoremediation [39].

Cunningham and Berti [10] define phytoremediation as the use of green plants to remove, contain, or render harmless environmental contaminants. Four techniques of phytoremediation are in current practice: phytoextraction, phytodegradation, phytostabilization, and rhizofiltration. Phytoextraction employs vegetation to transport or “mine” the metal contaminants from the soil into the plants. Phytodegradation is the chemical transformation of organic contaminants in the soil rhizosphere and in the plants. Rhizofiltration removes metals from water; it is beneficial and has many terrestrial applications, especially within “zero discharge” contexts where NPDES permits are not required. In wetland applications, increased root biomass coincides with increased bacterial biomass and metal adsorption. In phytostabilization, the chief objectives are the stabilization of soil through increased soil organic matter and the prevention of soil erosion and water percolation [45]. Soil amendments such as lime may be added to reduce solubility and bioavailability of metals. Phytostabilization is sufficiently attractive to produce commercial interest in its application to relatively large land areas.

PLANT UPTAKE OF METALS

One of the chief disadvantages, or advantage if the intent is there, in the use of vegetation on contaminated sites is the potential for the plants to take up heavy metals into the root and stem system. If routine harvesting of the plant is desired in order to reclaim the metal, then this process is beneficial. Sometimes, plants are simply used as a means of retaining the soil and hence stopping the spread of contaminant. If heavy metals are being transported into the upper portion of the plant, then the ingestion of heavy metals by indigenous wildlife must be considered. If the bioavailability of the metal can be reduced, then plant uptake and introduction of the heavy metal into the food chain is not as severe.

The soluble or ionic state of metals is most bioavailable to plants. Several factors affect the free metal ion activity such as adsorption to organic matter and the soil matrix, leaching, mineralization, precipitation of solids, soluble inorganic and organic complexes, and plant uptake [39, 49].

Various methods have been reported for decreasing the bioavailability of metals. The use of an unpolluted topsoil cover to reduce plant absorption of metals from lower levels of polluted river sediment is documented [53]. Decreases in both cadmium and zinc concentrations in plant biomass, some to 5% of their original amounts, were reported for a variety of crops, including wheat and barley. Following capping, two pathways exist for metals to be taken up into plants. Roots may penetrate into the contamination layer or contaminants may diffuse into the root zone. An exponential decrease of root density with depth was used as an approximation of the structural distribution of roots in the soil [54]. No detectable migration of the heavy metals between the soil cover layer and polluted soil layer was reported after eleven years [54].

Liming, in order to raise the pH of soil, is reported to decrease the uptake of heavy metals by vegetation. Decreases in dry matter zinc concentrations, by as much as 94%, have been reported with applications of lime in amounts of 1.2 g/kg to soils where barley and ryegrass were established [3]. The application of lime helps to increase soil pH which helps decrease soluble zinc concentrations [33]. As the soil pH rises, metal-mineral complexes, which have low solubility and increased adsorption by negatively-charged soil colloids, reduce the bioavailability of the metal to the plants [48].

In addition to the effects of heavy metals on plants, the interaction of metal contamination and soil microorganisms must be considered. It has been reported that the adherence of metals to microorganisms is related to both organism density and the presence of metals, with lower density colony adherence being impaired by metal presence [6]. At higher densities, it appears the presence of zinc enhances adherence. Additionally, Prahalad and Seenayya [40] report that organisms have some effective regulatory mechanism for zinc uptake. As the zinc concentration in solution increased, the concentration in the cells maintained a constant value, demonstrating the ability to maintain metal concentrations [40].

In contrast to methods that limit plant uptake of metals, the application of chelates will increase metal uptake. Chelating agents have the ability to increase plant uptake of metals by forming complex ions which have increased solubility and uptake. There are also reports of possibly decreased plant toxicity [3].

MODELING METAL MOVEMENT

Metal movement depends on overland flow, flow through soil, sediment transport, and soluble metal transport. Sediment transport depends on the magnitude and turbulence of the overland flow. Models are needed for flow, sediment movement, and soluble metal transport.

In modeling transport of heavy metals, the phenomena to consider are the quantity of metals on soil surfaces, the amount of sediment in overland and stream flows, and the solubility of the metal ions themselves. Although water transport occurs by two main means—surface flow and subsurface flow—it has been reported that surface flow transmits water and solute an average of 100 to 500 times faster than subsurface flow [18]. The majority of metal transport occurs due to transport of soil sediment in which the metal is contained or attached to soil aggregates. Once the aggregates have settled, re-establishment of equilibrium between precipitated and ionic or soluble metals often occurs.

MODELING SURFACE FLOWS

For modeling of stream flow, Govindaraju and Kavvas [19] report that simplified versions of the Saint-Venant equations, considering only the first two terms on the right hand side of the momentum equation, Equation 2 below, are adequate approximations for most situations. The Saint-Venant equations are as follows:

$$V\frac{\partial A}{\partial x} + A\frac{\partial V}{\partial x} + \frac{\partial A}{\partial t} = Q \tag{1}$$

$$S_f = S_0 - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} - \frac{QV}{gA}, \tag{2}$$

where V is the mean water velocity in the channel, A is the area of cross section normal to the stream flow, x is the distance in the horizontal direction, t is time, Q is the inflow per unit length, S_f is the friction slope, S_o is the slope of the channel bed, y is the flow depth normal to the direction of flow (horizontal), and g is gravitational acceleration.

Equally important to stream flow is overland flow. Overland flow is often treated as stream flow for a very wide, shallow rectangular channel [19]. The diffusion wave approximation uses the first two terms on the right hand side of the momentum equation, Equation 2. Govindaraju and Kavvas [19] report the outcome of diffusion wave approximation for overland flow as:

$$\frac{\partial h}{\partial t} + C_{wo}\frac{\partial h}{\partial x} - Q_0 = \alpha_0\left(\frac{\partial^2 h}{\partial x^2} - \frac{\partial S_0}{\partial x}\right) \tag{3}$$

and the overland flow friction law is

$$V_0 = D_0 h^{mo}\left(S_0 - \frac{\partial h}{\partial x}\right)^{jo}, \tag{4}$$

with

$$C_{W0} = V_0(1+mo) \tag{5}$$

$$\alpha_0 = \frac{V_0\, hjo}{S_0 - \frac{\partial h}{\partial x}} \tag{6}$$

where h is the depth of flow, t is time, x is the horizontal direction, Q_o is net lateral inflow to the overland flow section per unit length of flow, and constants are D_o, mo, and jo.

EFFECTS OF VEGETATION ON EROSION

Soil erosion, the means by which the majority of potential heavy metal contamination is spread, is affected by four factors: climate, soil, vegetation, and topography [46]. Physical properties of soil, such as its size, structure, organic matter content, and composition, all influence the ease with which soil can be detached and transported.

While climatic factors, and to some degree the region's topography, are beyond human control, vegetation can be used in a beneficial manner to control erosion. Some benefits of vegetation include interception and subsequent decrease in runoff, providing additional roughness or physical resistance to surface runoff and soil movement, aiding in soil porosity, creating local depression in soil moisture by transpiration processes which allows for greater rainfall infiltration and less runoff, and, finally, the interception of rainfall that reduces the number and velocity of raindrop impacts on the soil surface.

Goldman, *et al.* [17], note that vegetation is a key component of sediment control principles. They make special mention of the benefits of minimizing soil exposure by maintaining existing vegetation and mulching and revegetating barren areas. Additionally, preventing runoff from barren areas as much as possible and developing proper drainage systems can help limit or at least confine sediments to the site. On barren soils, raindrop impacts can destroy the soil matrix. The presence of vegetation can hinder this effect through interception of the raindrops and by creating local soil moisture depressions which increase infiltration and thus delay overland flow. The effectiveness of vegetation in this endeavor is a function of plant form and density, seasonal variations, and management practices.

The effects of vegetation on erosion and sediment transport will be discussed considering the physical processes listed below:

1. raindrop impact,
2. overland flow,
3. sediment transport.

Raindrops impacting the soil surface can mechanically disturb the cohesive bonds between soil particles. Under normal conditions, soil aggregates are bound together and stabilized by electrochemical bonds which increase the effective primary particle size relative to the component mineral particles alone [7]. Aggregation is therefore a desirable quality for mitigating soil loss because larger soil particles are more difficult to detach from the soil surface and require more energy to transport. Furthermore, aggregation normally improves the ability of the soil to absorb water and may delay the onset of overland flow during a rainfall event.

Direct raindrop impact on the soil surface provides sufficient force to destroy soil aggregates, to detach the soil particles from the soil surface, and to transport the soil particles within the splash. The mechanical mixing of the soil particles with ponded water on the soil surface encourages the soil to remain in suspension. The suspended soil is then more likely to be carried away with the flow. The presence of vegetation mitigates these effects by providing a physical barrier to raindrop impact and by effectively increasing the infiltration rate of the soil. Root channels loosen the soil and provide a mechanism by which stem flow (rainfall that is intercepted by the plant and transmitted to the soil surface by running down the stem) can enter the soil. The onset of overland flow on a vegetated hillslope is therefore delayed relative to an unvegetated hillslope.

MATHEMATICAL MODELS FOR SEDIMENT TRANSPORT

Many different models predict the response of watersheds to rainfall events. Most models are based, to some degree, on a mixture of empirical and theoretical relationships. Koelliker and Govindaraju [25] report most models are evaluated on "the basis of the accuracy of the model predictions, the simplicity of the model, the data requirements of the model, the sensitivity of results to parameter changes, the economics and user expertise." Many models monitor surface water flows, including AGNPS, ANSWERS, CREAMS, KINEROS, MIKE11, SWAT, SWRRB, and WASP4. Other models, such as GLEAMS and PESTAN, model unsaturated flow. And still others, like QUAL2E, model surface stream flow [25].

Agricultural engineers have developed several equations to estimate the erosion losses from agricultural fields and hill slopes. One of the most popular, empirical models currently being used is the Universal Soil-Loss Equation, or USLE, which is based on data collected from natural runoff plots and plots under artificial rainfall simulators. The Universal Soil-Loss Equation estimates overland or sheet-rill erosion flow and can be expressed as:

$$A = RKLSCP \tag{7}$$

The soil loss "averaged over the slope length" is a function of the "combined erosivity of rainfall and runoff," which is the major variable of the relation [35]. The universal soil-loss equation relates soil loss per unit area (A) to six major factors affecting erosion. Those factors are rainfall (R), soil erodibility (K), slope length (L), slope gradient (S), crop management or vegetative cover (C), and erosion control practices (P). The rainfall factor of the universal soil-loss equation is a function of the total rainfall, the rainfall intensity, and the seasonal distribution of the rainfall. Total rainfall can provide an indicator of the degree of soil saturation and the amount of total runoff. The rainfall intensity determines the force with which a raindrop impacts the soil and the degree of mechanical mixing. The seasonal distribution of rainfall is important because rainfall occurring when vegetation cover is most dense has a lower erosion potential than rainfall occurring when vegetation is dormant.

The vegetation cover factor of the USLE is determined by the plant form, the plant density, and the ability of the vegetation to provide mechanical protection for the soil. Plant forms vary seasonally, thus it is important to determine the degree of protection that the vegetation provides during periods of heaviest rainfall. In case of cropped lands, the cropping practice may either increase or decrease the erosion potential. For example, inter-tilled crops can actually encourage soil erosion by leaving soil exposed to raindrop impact and providing pathways for unimpeded surface flow.

The erosion control factor of the USLE is most appropriately applied to crop lands. The degree of erosion in a planted field can be controlled by cropping practices such as contour tillage, mulching or grassing between rows of crops, and increasing crop coverage. Similarly, the planting of hill slopes for the mitigation of environmental impacts may require conservation practices such as mulching to reduce soil losses during the period of vegetation establishment.

USLE has several advantages and limitations. The model's chief advantages include its simplicity and readily available parameter values, for which reasons it is used by the USDA for providing soil conservation services. Model disadvantages include inaccuracy for single storm events, no estimation for deposition, and no estimation for channel erosion.

Another commonly employed model is CREAMS [12]. An event-based model, CREAMS, like USLE, uses storm energy and intensity, runoff rates, and runoff volumes. The model represents the watershed under study by an overland flow profile, impoundment, and channel elements. Inexpensive simulation, utilizing USLE parameter data sets, representing complex watersheds with minimal "input details," and having the capabilities of describing a broad range of management practices are some of the advantages of the model. While having several benefits, the model is not as "powerful" as ANSWERS and CSU. CSU [31] is also an event-based model. The model breaks the system under study into grids and channels, and estimates erosion and sediment yield distribution. However, the model does require some calibration. The ANSWERS model [5] also breaks up the watershed into grids and channels. It has separate components for erosion, channel flow, tile flow, and sediment transport. ANSWERS also predicts effects of individual storm events. The model parameters are physically-based, and little or no calibration is required because USLE parameters are utilized.

EFFECTS OF VEGETATION ON OVERLAND FLOW

Overland flow is the primary mechanism for transporting detached soil particles away from the hill slope of origin. Overland flow, which can include sheet flow and rill flow, occurs as water becomes ponded on the soil surface and begins to move down slope under the influence of gravity. Water which accumulates in gullies and channels is referred to as channel flow.

Vegetation on a hill slope has the effect of increasing resistance forces acting to oppose the flow. Increased resistance results in slower velocities. One effect of reducing flow velocity is that sediment particles are permitted to settle onto the bed rather than being carried farther downstream. The presence of vegetation can also have the effect of reducing soil erosion because the shear force exerted by the flow on the soil surface is lowered as the flow velocity is lowered. If the flow is sufficiently slow, it may behave as a laminar flow. Laminar flows have a much lower capacity for keeping particles in suspension than do turbulent flows. In this section, the effects of vegetation on the velocity and depth of overland flow are investigated. It is assumed that overland flow exists and that one wishes to describe the frictional effects of vegetation on the flow. The problem of describing the influence of vegetation on the infiltration rate and the onset of overland flow are deferred to the section which describes the effects of vegetation on infiltration.

Stems of vegetation obstruct the free passage of fluid. The physical mechanisms that dissipate energy within the flow include the following [36]:

Form drag: Flow passing around an obstacle separates at a point upstream of the obstacle boundary. Downstream of the separation point the pressure on the obstacle is lower than the pressure on the upstream side. This hydrodynamic pressure difference is equivalent to a force acting on the obstacle, causing a reactive force to oppose the oncoming flow.

Skin drag: As fluid passes over the surface of the obstacle, a shear stress is applied to the fluid because of friction acting along the boundary.

Wave drag: An obstacle penetrating the free surface of an incompressible fluid will result in a deformation of the fluid surface. When the flow is sub-critical, as it is in tidal marshes, a backwater forms upstream of the obstacle. Downstream of the obstacle a wake forms which may have a depressed water surface [22]. The hydrostatic pressure difference between the upstream and downstream sides of the obstacle is called wave drag.

Viscous effects: Both laminar and turbulent flows experience energy losses due to fluid viscosity. Collisions between molecules generate heat, which is lost to the surrounding environment. Turbulent flows have additional energy losses caused by macroscopic random fluctuations of the velocity field. The scale of these fluctuations is small compared to the overall flow pattern but nonetheless creates local velocity gradients which increase the energy loss. Virtually all open channel flows are turbulent flows. Turbulent energy loss occurring in the boundary layer around the stems of vegetation is normally modeled as part of the skin drag. Turbulent energy loss in the free stream flow field is normally modeled by a turbulent sub-model such as the Boussinesq eddy viscosity formulation.

Hydraulic engineers often describe the combined frictional effects of these different drag mechanisms as a lumped coefficient. Obstructions in the flow field may be characterized by a drag coefficient which describes the net frictional force exerted by each obstruction on the flow. When many obstructions are present, the combined effect of the assembled obstructions are lumped together with the coefficient for bed friction to provide an overland friction coefficient for the flow. The Manning's coefficient or the Chezy coefficient are representative of this type of physical description. For example, let F_B be the combined resistance force due to bed shear and vegetation drag, then $F_B = -\rho g u^2/C^2$ in which C is the Chezy coefficient, ρ is the density of water, g is the acceleration due to gravity, and u is the flow velocity. The minus sign indicates that the direction of the resistance force is opposing the direction of flow. Strictly speaking, the total resistance force, F_B, is the sum of the vegetation resistance force, F_V, and the bed friction force, F_b, i.e. $F_B = F_V + F_b$. Lumped roughness coefficients have been determined in field tests for a wide range of vegetation and flow conditions [2, 4, 16, 32, 52, 55].

When considering drag on an isolated cylinder submerged in a uniform flow field, flow separation is characterized by parameters such as the width of the wake and the point of separation. These parameters describe the deviations of the near field flow from the free stream conditions. Closely spaced obstacles, such as the stems of vegetation, have overlapping wakes and surface deformations. The scale of the fluid turbulence within the stems is of the same order of magnitude as the length of the mean free flow path. Therefore, the loss of energy due to viscous effects cannot be easily separated from the loss of energy due to the form drag and skin drag of the vegetation.

Hsieh [22] performed experiments to determine the resistance of a single row of piers arranged in a line that was perpendicular to the flow direction in a rectangular flume. Although those experiments covered a range of sub-critical and supercritical flow conditions, only the sub-critical flow results are summarized here. Hsieh measured the resistance coefficient $C_R = [F_P / 0.5\rho V^2 hd]$ as a function of the Froude Number $F = [V^2/gh]^{0.5}$ and two length scales, h/d and s/d, in which s = pier spacing, F_p = force acting on the pier, ρ = density of water, V = velocity of the approach flow, h = depth of the approach flow, and d = pier diameter.

Hsieh concluded that both the relative pier spacing and the relative depth of the oncoming flow have a significant effect on C_R in sub-critical flow. Wave drag was an important component of the total resistance when depth was small, but the importance of the surface effect diminished with increasing depth. Therefore, C_R approached a limiting value, C_{RC}, as the Froude number approached zero. The limiting resistance coefficient, C_{RC}, was different for each pier spacing, s/d, and also varied slightly with the non-dimensional flow depth, h/d. The trend was for C_{RC} to increase with decreasing pier spacing.

In several studies, conceptual models of vegetation as cylindrical roughness elements have been proposed. Nnaji and Wu [34] related resistance to the root mean square amplitude of cylindrical roughness elements. Pasche and Rouve [37] used cylindrical wooden dowels to simulate slender tree trunks growing on a flood plain in a physical model of flow in compound channels. The later study utilized the following method to determine the drag coefficient for a single rod in a multi-cylinder arrangement:

1. Assume that the Darcy-Weisbach friction factor can be linearly decomposed into a bed friction component, f_b, and a vegetation friction component, f_v.
2. Assume $f_v = [\ 4hd/a_x a_y\ ]C_{WR}$, in which C_{WR} = drag coefficient for cylindrical rod, h = flow depth, d_p = stem diameter, a_x = dimensional component of the area associated with a single cylinder in the direction of flow, and a_y = dimensional component of the area associated with a single cylinder in the transverse flow direction.
3. Let $C_{WR} = [1 + 1.9\ (d_p/a_y)\ C_\infty][u_n/u_f]^2 + \Delta C_W$, in which C_∞ = drag coefficient of a single cylinder in an idealized two-dimensional flow; u_n = an empirical derived shear velocity for flow among spaced cylinders which is dependent upon the wake length and the wake width; u_f = depth averaged bulk velocity through the cylinders; ΔC_W = correction for flow depth given by $(2/F^2)(1 - z)$; F = Froude number, $(u_f^{\ 2}/gh)^{1/2}$; and z = a depth ratio satisfying $F = [z(z^2 -1)/2\ (z - a_y/(a_y - d_p))]^{0.5}$.

This method was used to compute the flood plain roughness over the portion of the flood plain that was not influenced by the main channel flow.

Petryk and Bosmajian [38] also utilized the idea of a drag coefficient per stem, but they noted that the drag coefficient is difficult to measure for natural vegetation. These researchers used an observed flood profile to calibrate Manning's n in computation of backwater curves. The computed drag coefficient was then correlated with Manning's n for each vegetation type. If one assumes that the overall coefficient of a drag is constant over the flow depth to the top of vegetation, then the computed drag coefficient can be applied to projected flood events.

In each of the studies described above, the assumption was made that the velocities were sufficiently small so that bending of the vegetation was negligible. Kouwen and Unny [30] investigated flexible roughness in open channels. The friction factor and Manning's n were found to be a function of the relative roughness when the flexible roughness was either erect or waving. Relative roughness was defined by the authors as the ratio of the roughness length to the flow depth. When the roughness elements were bent over, Manning's n was a function of the product uR, where u was the cross-sectional average velocity and R was the hydraulic radius.

Later work by Kouwen, *et al.* [28], suggests that the well known n vs. uR method of channel design [42] is not applicable to very small slopes. Kouwen [26] developed a method for determining toe flow resistance of grassed channels with small slopes based on relative roughness, and he outlines field methods for determining the appropriate roughness parameters. The methods developed by Kouwen account for the flexibility of the vegetative material and are most appropriate for open channel flow where submerged roughness elements are subject to bending by the flow. The method was later extended and applied to the design of grassed channels [27].

Surface flows in wetlands can be similar to overland flows because both emergent and submerged vegetation may be present, as well as unvegetated mud flats. Wetlands surface flows may be ponded, sheet flows, rill flows, and/or channel flows. Kadlec, *et al.* [24], were among the first to study the fluid mechanics of wetland ecosystems. Concerned mainly with fresh water systems and constructed wetlands for waste water treatment, these researchers investigated slow overland flow in managed wetlands.

Kadlec [23] introduced the conceptual model of wetland flows as flow through a porous medium. Two porosity scales were identified, a fine-scale porosity through the litter layer and a large-scale porosity through hummocks and channels. Because of the slow velocities and the doubly porous characteristic of the wetlands studied, inertial terms and acceleration terms in the momentum balance were ignored. Hammer and Kadlec [21] cite depth-Reynolds numbers in the range of 1 to 100 for wetlands where this model can be applied.

Burke and Stolzenbach [8] studied the vertical velocity profile that occurs in tidal marsh vegetation. A model was developed to predict three-dimensional velocity structures in tidally-driven and wind-driven flow through marsh vegetation. The k-ϵ turbulence model was employed to capture the turbulence that was characteristic of the flow between the layer of flow through the stems and the layer of flow over the stem tops. The velocity profile in flow through marsh grass was found to be nearly uniform. The model developed by Burke and Stolzenbach was successfully applied to flow through marsh vegetation, a flume study of flow through plastic strips, and air flow through a vegetation canopy. The model relies upon a drag coefficient formulation to account for flow resistance due to vegetation.

The variable resistance to flow with depth due to marsh vegetation has been investigated by Kadlec [23]. Kadlec developed charts for the dependence of flow rate on flow depth for a given slope, stem density, bottom profile, and single cylinder drag coefficient. He notes that both the single-cylinder-drag-coefficients-approach and the overall-friction-factor-approach for expressing resistance to flow due to vegetation have drawbacks. The drag coefficient is dependent on depth and velocity in a system of equations where depth and velocity are unknown. Similarly the friction factor formulation depends upon velocity and slope.

Roig [44] measured the head loss through a flume that was fitted with stems of artificial vegetation. Wooden dowels were used to approximate the behavior of rigid, emergent marsh grasses found in tidal marshes. An expression was developed relating the total vegetation resistance force to some measurable characteristics of the vegetation such as stem diameter, submerged stem length, and stem spacing. The depth-Reynolds number of the flow, the velocity, and the depth also appear in the relationship which describes the vegetation resistance force. This research defines an explicit dependence of vegetation resistance force on the flow properties, indicating that constant coefficient expressions for friction force are not appropriate for describing flow through emergent vegetation.

Rauws [41] studied the resistance to overland flow due to composite roughness elements. The total force opposing the flow was partitioned into flow resistance due to soil particles and microaggregates, and form resistance exerted by macro-roughness elements. The laboratory setup considered hemispherical bed forms with and without sand grains varnished to the bed surface.

EFFECT OF VEGETATION ON SEDIMENT TRANSPORT

The ability of overland flow to erode sediment particles depends upon the effective bed shear stress that the flow exerts upon the soil surface. If the local bed shear stress is sufficient to separate a soil particle from the soil surface, the overland flow may carry that particle downstream as either suspended load or bed load. A review of several widely used sediment entrainment relations is provided by Garcia and Parker [15]. The sediment-carrying capacity of the flow is dependent upon the velocity of the flow, the depth of the water column, and the fall velocity of the sediment particles. The fall velocity of a sediment particle is dependent upon the particle size and particle mass and the turbulent energy of the ambient flow field. Faster and deeper flows tend to be more turbulent, thus keeping sediments in suspension longer and transporting them farther downstream. Slower and shallower flows permit sediment particles to settle to the bed where they may remain at rest, or they may be resuspended at a later time.

In addition to the impacts that the vegetation may have on the capacity of the flow to both erode and carry sediments, the stems of vegetation may act to physically intercept sediment particles. Particles may become trapped on the surface of the stems and leaves, particularly when the vegetation has a pronounced surface texture. Densely-branching plants, plants with spiny projections, and leafy plants provide ample surfaces for sediment particles to deposit and to remain sheltered from the oncoming flow.

Freeman, *et al.* [13], measured flow resistance and sediment retention for bulrushes in a concrete-lined drainage channel. The 15 meter long by 1.2 meter wide flume resides at the Lewisville Aquatic Ecosystem Research Facility in Lewisville, Texas. Hydraulic tests were conducted at two different stages of bulrush development, and the sediment trapping efficiencies of the bulrushes for both silt and clay sediments were measured. An interesting result of these tests was that although sediment was trapped in and among the bulrush stems, even more deposition of sediment was observed upstream of the bulrushes. The presence of the bulrushes caused upstream velocities to slow, and the upstream reach had substantially less turbulence than the reach containing the bulrushes. Consequently the sediment carrying capacity of the upstream reach was reduced relative to the bulrush reach.

The retention of sediment in vegetated stream beds was studied experimentally by Abt, *et al.* [1]. A unique feature of this study was that the experiments were designed to measure both sediment deposition among the vegetation and sediment retention in the vegetation after a flushing event. Thus, the net sediment trapping efficiency of the vegetated channel was evaluated. The laboratory stream channel was approximately 18.9 meters long and 5.5 meters wide, and the channel sinuosity was 1.05. The tests were conducted with stands of Kentucky bluegrass, and the sediment was a fine-grained material with median grain size of 0.09 mm. Net sediment trapping efficiency of the channel was between 30 and 70 percent for the various tests that were conducted.

A study completed by Neuman, *et al.* [33], reported that the use of vegetation decreased the volumetric amounts of both runoff water and sediment. The revegetated zone under study measured only 1.29 liters of runoff and contained 1.28 mg of Zn, as compared to 15.95 l of runoff with 35.8 mg of Zn from the control or barren zone. Similar results were reported for sediment movement in a nearby region of study. In a time span of nine weeks over a 1.3 hectare non-vegetated region, movement of 22.25 cubic meters of sediment with a zinc concentration of 4,983 mg/kg was reported. The vegetated zone, which was a 0.7 hectare region, reported no volumetric movement of sediment and thus no movement of zinc.

EFFECTS OF VEGETATION ON INFILTRATION

Vegetation affects infiltration by removing soil moisture through evapotranspiration, reducing soil crusting by retarding rainfall velocity, reducing overland flow velocity, and enhancing soil porosity and hydraulic conductivity. Several hydrologic models for watersheds include both infiltration and evapotranspiration [43]. The porosity of the soil at and near the soil surface affects infiltration significantly.

One of the reported problems with previous mine land remediation efforts was the impact heavy machinery had on the hydraulic conductivity of the soil. Sharma and Doll [47] report that soil hydraulic conductivity is reduced in the process of returning abandoned mines to their original topography. In the process of reclaiming the lands, the machinery compacts the soil, thus reducing its hydraulic conductivity. In a study performed on western minelands in North Dakota, Sharma and Doll report a decrease in conductivity from 2.39 cm/hr to 0.97 cm/hr for an undisturbed pre-mine site to a post-mine reclaimed site. They also report that using mechanical means to help increase the conductivity of the soil was not an effective solution because as the topsoil was laid out over the site, in accordance with standard EPA procedure, the soil was again compacted. The use of vegetation was recommended as a possible long-term solution. A direct relationship between the soil conductivity and porosity of the soil was established; alfalfa and other vegetation helped increase the porosity of the soil over years of root establishment, growth, and decay [47].

CONCLUSIONS

Four key conclusions can be drawn from the work discussed. First, much of the spread of heavy metal contamination that is occurring at abandoned mine sites is due to sediment movement. The metal, adsorbed to the soil aggregates or precipitated in them, is transported and reestablishes an equilibrium with the ionic or soluble metal state once settlement occurs. Second, vegetation can help decrease movement and runoff by interception of the rainfall, increasing infiltration by decreasing antecedent soil moisture, increasing soil hydraulic conductivity, binding the soil aggregates, and offering physical resistance to overland flow thus slowing the velocity of the water. Third, several models are currently employed in predicting runoff and soil erosion, among them being the Universal Soil-Loss Equation and CREAMS model. Finally, concerns in metal bioavailability can be addressed with proper soil amendments, including the addition of unpolluted topsoil and increasing the pH of the soil via liming.

ACKNOWLEDGMENT

Although this work has been funded in part by the U.S. Environmental Protection Agency under assistance agreement R-819653, through the Great Plains/Rocky Mountain Hazardous Substance Research Center, headquartered at Kansas State University, it has not been subjected to the agency's peer and administrative review and, therefore, may not necessarily reflect the views of the agency. No official endorsement should be inferred. The Center for Hazardous Substance Research provided partial support.

REFERENCES

1. S.R. Abt, W.P. Calry, and C.I. Thornton, Sediment deposition and entrapment in vegetated stream beds, J. of Irrigation and Drainage Engineering, 120 (1994) 1098-111.

2. S.E. Ahmed and M.B. Saad, Prediction of natural channel hydraulic roughness, J. of Irrigation and Drainage Engineering, 118 (1992) 632-639.

3. N. Albasel and A. Cottenie, Heavy metal uptake from contaminated soils as affected by peat, lime and chelates, Soil Science Society American Journal, 49 (1985) 386-390.

4. M.F. Bakry, T.K. Gates, and A.F. Khattab, Field measured hydraulic resistance characteristics in vegetation-infested fields, J. of Irrigation and Drainage Engineering, 118 (1992) 256-274.

5. D.B. Beasley, ANSWERS: A Mathematical Model for Simulating the Effects of Land Use and Management on Water Quality, Ph.D. Dissertation, Purdue University, West Lafayette, IN, 1977.

6. J.W. Bhattacherjee, Effect of cadmium and zinc on microbial adhesion, growth and metal uptake, Bulletin of Environmental Contamination and Toxicology, 36 (1986) 396-400.

7. N.C. Brady, The Nature and Properties of Soils, MacMillan Publishing Company, Inc., New York, 1974, p. 639.

8. R.W. Burke and K.D. Stolzenbach, Free Surface Flow Through Salt Marsh Grass, MIT Sea Grant College Program, MITSG, 83-16, 1983, p. 252.

9. C. Chen, Flow resistance in broad shallow grassed channels, Journal of the

Hydraulic Division, ASCE, 102 (1976) 307-322.

10. S.D. Cunningham and W.R. Berti, Remediation of contaminated soil with green plants: An overview, Invitro Cell Dev. Biol., 29P (1993) 207-212.

11. T. Dunne, W. Zhang, and B.F. Aubry, Effects of rainfall, vegetation and microtopography on infiltration and runoff, Water Resources Research, 27 (1991) 2271-2285.

12. G.R. Foster, L.J. Lane, J.D. Nowlin, J.M. Laflen, and R.A. Young, A model to estimate sediment yield from field sized areas: Development of model, In: CREAMS - A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems, Volume I: Model Documentation, Chapter 3, USDA-Science and Education Administration Conservation Report No. 26, 1980, pp. 36-64.

13. G.E. Freeman, B.R. Hall, and D.D. Abraham, Flow resistance and sediment retention for bulrushes, Proceedings of the ASAE Winter Conference, 1993, pp. 276-285.

14. R.W. Frey and P.B. Basan, Chapter 3: Coastal Salt Marshes, In: R.A. Davis Jr. (Ed.), Coastal Sedimentary Environments, Springer-Verlag, New York, 1978, p. 101-169.

15. M. Garcia and G. Parker, Entrainment of bed sediment into suspension, J. of Hydraulic Engineering, 117 (1991) 414-435.

16. J.E. Gilley and S.C. Finkner, Hydraulic roughness coefficient as affected by random roughness, Transactions of the ASAE, 34 (1991) 897-903.

17. S.J. Goldman, K. Jackson, and T.A. Burszynsky, Erosion and Sediment Control Handbook, McGraw-Hill, New York, 1986, p. 2.1.

18. R.S. Govindaraju and L.E. Erickson, Modeling of overland flow contamination due to heavy metals in shallow soil horizons, In: L.E. Erickson, D.L. Tillison, S.C. Grant, and J.P. McDonald (Eds.), Proceedings of the 10th Annual Conference on Hazardous Waste Research, Kansas State University, Manhattan, KS, 1995, pp. 287-300.

19. R.S. Govindaraju and M.L. Kavvas, Dynamics Hydrology of Variable Source Areas, Encyclopedia of Earth Systems Science, vol. 2, Academic Press Inc., 1992, pp. 93-104.

20. A.Y. Gunter and W.A. Shan, A general correlation of friction factors for various types of surfaces in cross flow, Transactions of the American Society of Mechanical Engineers, 67 (1945) 643-660.

21. D.E. Hammer and R.H. Kadlec, 1986, A model for wetland surface water dynamics, Water Resource Research, 22 (1986) 1951-1958.

22. T.-Y. Hsieh, The Resistance of Piers in High-Velocity Flow, M.S. Thesis, University of Iowa, Iowa City, 1962, p. 50.

23. R. Kadlec, Overland flow in wetlands: Vegetation resistance, Journal of Hydraulic Engineering, ASCE, 26 (1990) 691-706.

24. R.H. Kadlec, D.E. Hammer, I.-S. Nam, and J.O. Wilkes, The hydrology of overland flow in wetlands, Chemical

Engineering Communications, 9 (1981) 331-344.

25. J.K. Koelliker and R.S. Govindaraju, Preliminary Evaluation of Models and Data Collection, FY94 Kansas State University Progress Report to the Division of Water Resources, Kansas State University, 1994.

26. N. Kouwen, Field estimation of the biomechanical properties of grass, Journal of Hydraulic Research, 26 (1988) 559-568.

27. N. Kouwen, Modern approach to design of grassed channels, Journal of Irrigation and Drainage Engineering, 118 (1990) 733-743.

28. N. Kouwen, R.-M. Li, and D.B. Simons, Flow resistance in vegetated waterways, Transactions of the ASAE, 24 (1981) 684-690, 698.

29. N. Kouwen, T.E. Unny, and H.M. Hill, Flow retardance in vegetated channels, Journal of the Irrigation and Drainage Division, ASCE, 95 (1969) 329-342.

30. N. Kouwen and T.E. Unny, Flexible roughness in open channels, J. Hydraulics Div., ASCE, 99 (1973) 713-728.

31. R.M. Li, Water and sediment routing from watersheds, Proc. of River Mechanics Institute, ch. 9, Colorado State University, Fort Collins, CO, 1977.

32. Y. Liong, S. Selvanlingam, and D.K. Brady, Roughness values for overland flow in subcatchments, J. of Irrigation and Drainage Engineering, 115 (1989) 203-214.

33. D.R. Neuman, F.F. Munshower, D.J. Dollhopf, S.R. Jennings, and J.D. Goering, Phytoremediation of Smelter Hill, Anaconda, Montana, Planning, Rehabilitation and Treatment of Disturbed Lands, Billings Symposium, Montana State University, Bozeman, Montana, 1996, pp. 285-296.

34. S. Nnaji and I-P. Wu, Flow resistance for cylindrical roughness, Journal of the Irrigation and Drainage Division, ASCE, 99 (1973) 15-26.

35. H.B. Osborn, L.J. Lane, C.W. Richardson, and M. Molnau, Precipitation, In: Hydrologic Modeling of Small Watersheds, C.T. Haan, H.P. Johnson, and D.L. Brakensiek (Eds.), ASAE Monograph No. 5, American Society of Agricultural Engineers, St. Joseph, MI, 1982, pp. 81-118.

36. R.L. Panton, Incompressible Flow, Wiley, New York, 1984, p. 780.

37. E. Pasche and G. Rouve, Overbank flow with vegetative roughened flood plains, Journal of Hydraulic Engineering, ASCE, 111 (1985) 1262-1278.

38. S. Petryk and G. Bosmajian, Analysis of flow through vegetation, Journal of the Hydraulics Division, ASCE, 101 (1975) 871-884.

39. G.M. Pierzynski, J.L. Schnoor, M.K. Banks, J.C. Tracy, L.A. Licht, and L.E. Erickson, Vegetative remediation at Superfund sites, In: R.E. Hester and R.M. Harrison (Eds.), Mining and its Environmental Impact, Issues in Environmental Science and Technology, Royal Society of Chemistry, 1994, pp. 49-69.

40. A.K. Prahalad and G. Seenayya, Bioavailability of zinc and cadmium and their effect on microbial growth and metal uptake, Bulletin of Environmental Contamination and Toxicology, 41 (1988) 921-927.

41. G. Rauws, Laboratory experiments on resistance to overland flow due to composite roughness, J. of Hydrology, 103 (1988) 37-52.

42. W.O. Ree and V.J. Palmer, Flow of Water in Channels Protected by Vegetated Linings, U.S. Soil Conservation Bulletin, No. 967, 1949, p. 155.

43. K.G. Renard and M.M. Fogel, Currently available models, In: C.T. Haan, L.J. Lane, and D.L. Brakensiek (Eds.), Hydrologic Modeling of Small Watersheds, ASAE Monograph No. 5, American Society of Agricultural Engineers, St. Joseph, MI, 1982, pp. 507-522.

44. L.C. Roig, Hydrodynamic Modeling of Flows in Tidal Wetlands, Ph.D. Dissertation, University of California, Davis, 1994, p. 177.

45. J.L. Schnoor, Stabilization of Contaminated Soils with Hybrid Poplar Trees, Presentation, HSRC/WERC Joint Conference on the Environment, 1996.

46. G.O. Schwab, D.D. Fangmeier, W.J. Elliot, and R.K. Frevert, Soil and Water Conservation Engineering, Wiley, New York, 4th ed., 1992.

47. P.P. Sharma and E.C. Doll, Soil Quality Evaluation for Reclamation Success: An Alternative Mitigation Paradigm, Planning, Rehabilitation and Treatment of Disturbed Lands Billings Symposium, Montana State University, Bozeman, MT, 1996.

48. S.R. Smith, Effect of soil pH on availability to crops of metals in sewage sludge-treated soils. I. Nickel, copper and zinc uptake and toxicity to ryegrass, Environmental Pollution, 85 (1994) 321-327.

49. K. Tanji and L. Valoppi, Groundwater contamination by trace elements, Agriculture, Ecosystems and Environment, 26 (1989) 229-274.

50. Texas Department of Transportation, A Practical Guide to the Establishment of Vegetative Cover on Highway Rights-of-Ways, November 1993.

51. G.T. Thompson and J.A. Roberson, A theory of flow resistance for vegetated channels, Transactions of the American Society of Agricultural Engineers, 19 (1976) 288-293.

52. T.J. Trout, Furrow flow velocity effect on hydraulic roughness, J. of Irrigation and Drainage Engineering, 118 (1992) 981-987.

53. W. van Driel, B. van Luit, K.W. Smilde, and W. Schuurmans, Heavy metal uptake by crops from polluted river sediments covered by non-polluted topsoil, Plant and Soil, 175 (1995) 93-104.

54. M. van Noordwijk, W. van Driel, G. Brouwer, and W. Schuurmans, Heavy metal uptake by crops from polluted river sediments covered by non-polluted topsoil, Plant and Soil, 175 (1995) 105-113.

55. M.A. Weltz, A.B. Arslan, and L.J. Lane, Hydraulic roughness coefficients for

native rangelands, J. of Irrigation and Drainage Engineering, 118 (1992) 776-790.