Riparian Vegetation Bending and Washout in the Southwestern U.S.

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ABSTRACT

Encroachment of vegetation is a severe water resources management problem in canals, streams, and rivers in the American West. Hydraulic engineers have traditionally viewed vegetation as part of a maintenance program and hence, have not accounted for long-term impacts if left unchecked. As a result of increasing recognition of ecological benefits, existing flood reduction systems must often be reanalyzed to allow for vegetation as a source of habitat for various aquatic and riparian species. The allowance of aquatic and riparian vegetation in older projects results in increased roughness which affects hydraulic conveyance. The end effect is an increase in hydraulic roughness (and water surface elevation) for a given flow event. It is known that a portion of the vegetation may be washed out during high flow events, which could potentially increase conveyance – and possibly induce a debris hazard downstream; however, both the bending and amount of washout for a given discharge and plant community is not well studied. The objective of this study is to develop predictive relationships for the bending and washout of select woody vegetation species in the Southwestern United States. This was accomplished through a series of field tests to quantify bending, uprooting and breaking conditions under an applied force. The results will be helpful for supporting bioengineering installation, management of invasive species through washout, and investigation of riparian forest stability in large wind events.

INTRODUCTION

Whether it is an abundance of vegetation inducing flood control issues or a lack of vegetation influencing channel stability, riparian vegetation is of critical concern in channel design and maintenance. Vegetation growth and management is generally a result of several competing factors including riparian habitat requirements, aesthetics, and maintenance budgets, and alteration of hydraulic conditions.

The frictional resistance of channel boundaries on flow (i.e. hydraulic roughness or hydraulic resistance) is notoriously difficult to quantify, especially in vegetation, and significant literature addresses the topic (e.g. Fischenich, 2000; Freeman et al., 2000; Yen, 2002; Baptist et al., 2007; Wilson et al., 2008). Given minimal knowledge of hydraulic roughness for shrubs and woody vegetation, accurate estimation of channel capacity and water surface elevation is difficult, particularly because hydraulic roughness is not only a function of individual plant characteristics and community composition, but varies with water depth and velocity as plants deform with flow (Vollsinger et al., 2005).

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Therefore, the ability to predict how a plant bends in the presence of flow permits more accurate prediction of hydraulic roughness and depth.

Moreover, vegetation in channels and floodplains is often scoured or washed out during high flow events and does not fully contribute to resistance. To our knowledge, studies investigating vegetation washout in riparian areas are scant. Groeneveld and French (1995) investigated flow conditions necessary for inducing bending stress capable of lodging (washing out) nuisance tule plants in the Owens River, California. Duan et al. (2002, 2006) presented a theoretical method for lodging of a single stem fully exposed to flow, with the assumption that drag force was the sole failure-inducing force. Conversely, a significant body of literature has examined tree windthrow in managed coniferous forests (e.g. Peltola et al., 2006; Nicoll et al., 2006; Lundström et al. 2007).

An extensive body of literature has addressed the influence of vegetation on fluid dynamics (e.g. increased flood stage) as well as the impact of fluid flow on plants (e.g. bending of vegetation); however, at present, there are no comprehensive techniques for predicting hydraulic roughness, bending, and removal of vegetation. The purpose of this study is to address two impacts of fluid flow on woody vegetation through controlled "tree pulling" experiments. First, we seek to quantify bending of woody riparian species as a function of hydraulic drag force. Second, we will quantify mechanical stability and removal of vegetation under static hydraulic force. This study will focus on key riparian species of the Arid Southwestern United States; however, techniques are generic in nature and analogous data may be collected for additional riparian and terrestrial species.

THEORY

Vegetation-flow interaction is a complex, highly dynamic process that depends upon many parameters varying from flow steadiness to seasonal condition of the plant. To simplify this multifaceted problem, we narrow our examination to leaf-on vegetation under static loading (steady, uniform flow). Following Peltola (2006), we coarsely divide forces into those applied to overthrow vegetation (fluid drag and gravitational force) and those resisting failure (stem and root-soil resistance) (Figure 1a). When assessing vegetation stability, we define a tree as "failed" or "overthrown" when the applied bending moment of fluid and gravitational forces has exceeded the maximum resistive moment of the tree which may be surpassed in either the stem (i.e. stem break/ rupture) or the root-soil matrix (i.e. uprooting/ overturning) with the relative resistance of these forces determining the mechanism of failure (Peltola, 2006). Because of the generic applicability of results, we apply the term "overthrow" in lieu of the fluid specific terms "washout", "lodging", "windthrow", and "blowdown".

Applied Forces

Under steady, uniform flow, the drag induced moment may be expressed functionally as:

$$M_{drag} = f\left(h, \rho, \mu, g, C_d(h), A_{veg}(h), V(h)\right) \qquad \textit{Equation 1}$$

Where M_{drag} is the moment induced by hydraulic drag force $\left(F_{drag} = \frac{1}{2}\rho C_d A_{veg} V^2\right)$, h is flow depth, ρ is the fluid density, μ is dynamic viscosity of the fluid, g is gravitational acceleration, $C_d(h)$ is the drag coefficient, $A_{veg}(h)$ is the area of vegetation exposed to fluid drag, and $V(h)$ is the approach velocity of the fluid.

Net gravitational moment (weight minus buoyancy) varies with the force of gravity acting on the tree as it bends. Thus, net gravitational moment may be summarized as:

$$M_{gravity} = f\left(m_{tree}(h,\alpha), g, \alpha, \gamma_{tree}\right) \qquad \textit{Equation 2}$$

Where $M_{gravity}$ is moment induced by net gravitational force, m_{tree} is the mass the tree at height h and angle α, α is the angle of departure from vertical the tree is bent (Figure 1b), and γ_{tree} is the specific gravity of the wood.

If the total applied moment is expressed as Equation 3, then net gravitational and drag forces may be expressed as a single force applied to a given point (Figure 1b).

$$M_{drag} + M_{gravity} = M_{applied} \qquad \textit{Equation 3}$$

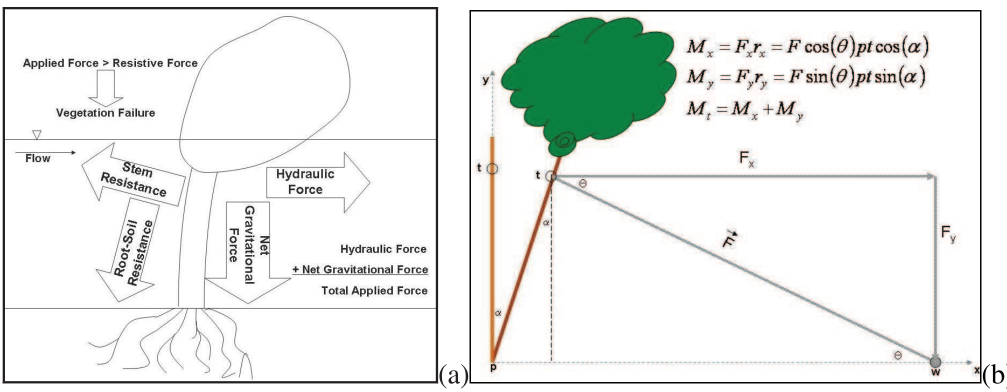


Figure 1. (a) Vegetation-flow static force balance (after Peltola, 2006) (b) Schematic of force decomposition and reference angles

Resistive Force

Stem resistance refers to properties of a plant associated with stem bending and rupture (breaking) which are established by examining the material properties. Application of elastic beam theory leads to the following functional form of stem resistive moment for bending and rupture, Equations 4a and 4b, respectively:

$$M_{stem} = f\left(y, \alpha, d_{tree}(y), h_{tree}, E_y\right) \qquad \textit{Equation 4a}$$

$$M_{stem,break} = f\left(h_{break}, \alpha_{break}, d_{tree}(h_{break}), h_{tree}, E_{break}\right) \qquad \textit{Equation 4b}$$

Where M_{stem} is moment of stem resistance, y is any distance up the tree, $d_{tree}(y)$ is stem diameter at y, h_{tree} is total tree height, E_y is modulus of elasticity of the tree at point y under F_{app} $\left(E_y = \dfrac{F_{app}\, y}{6 I_y \tan(\alpha)}\left(3h_{pull} - y\right)\right)$, I_y is moment of inertia at y $\left(I_y \approx {\pi d_{stem,y}}^4 / 64\right)$, F_{app} is the total applied force, and subscript *break* denotes previously specified variables at the yielding/rupture point.

Root-soil resistance is dependent upon the physical characteristics of the site surrounding the plant and the below-ground plant morphology (roots). Site character influencing overturning includes local topography and slope (S_{local}), soil properties such as texture (e.g. $\%_{coarse}$, $\%_{fine}$), bulk density (ρ_{bd}), and soil moisture (θ_v), and the condition of scour around the individual which is assumed to impact root-soil resistance through changes in local topography as a function of flow. In addition to site character, rooting character is critical to account for root-soil resistance. Tensile strength of roots (σ_{root}) as well as the combined root-soil tensile strength contributes significantly to this resistive force (Norris et al., 2008). Additionally, rooting shape and depth are thought to govern overturning resistance, all of which are highly variable even within a single species (Coutts, 1983). For the purpose of this discussion we assume that rooting depth (h_{root}) alone is the driving factor. As such, root-soil resistive moment (M_{root}) may be expressed functionally as:

$$M_{uproot} = f\left(h, S_{local}, \%_{fine}, \%_{coarse}, \rho_{bd}, X, \sigma_{root}, h_{root}\right) \quad \textit{Equation 5}$$

<u>Dimensional Analysis</u>

As previously indicated, if the applied moment exceeds the resistive moment, vegetation fails; this may be represented mathematically by the ratio of two moments. By nondimensionalizing and removing redundancies from the preceding discussion, this "critical moment ratio" may be resolved by the following functional form:

$$\frac{M_{drag} + M_{gravity}}{M_{resistive}} = f\begin{pmatrix} C_d(h), \dfrac{A_{veg}(h)}{h^2}, R_e, F_r, \dfrac{m_{tree}(h,\alpha)}{\rho h^3}, \gamma_{tree}, \dfrac{d_{tree}(h)}{h_{tree}}, \dfrac{h_{tree}}{h} \\ \dfrac{Eh^2}{\rho v^2}, S_{local}, \%_{fine}, \dfrac{\rho_{bd}}{\rho}, \dfrac{\sigma_{root} h^2}{\rho v^2}, \dfrac{h_{root}}{h} \end{pmatrix} \quad \textit{Equation 6}$$

Where R_e is the Reynolds number and F_r is the Froude number.

Although two applied forces have been discussed thus far (hydraulic and net gravitational), in riparian environments, net gravitational forces (plant weight – buoyancy) are often insignificant because many riparian plants are young and do not have considerable crown mass and submerged portions provide negligible moment. As such, gravitational forces are neglected in this analysis. Furthermore, for our riverine application, flow may be assumed to be turbulent and subcritical, and water and vegetation are interacting so soil moisture must be saturated. Although not rigorously accurate due to complexities in adaptive growth and parasitism, within a given species, mechanical properties of plants are assumed not to vary dramatically and are thus assumed to be isotropic above- and below-ground. Neglecting scour effects and combining terms, Equation 6 may be reduced to a more manageable range of variables for experimentation:

$$\frac{M_{drag}}{M_{resistive}} = f\left(\frac{C_d(h) A_{veg}(h)}{h_{tree}^{\ 2}}, \frac{d_{tree}(h)}{h_{tree}}, \frac{\%_{fine}\,\rho_{bd}}{\rho}, \frac{h_{root}}{h_{tree}}\right) \qquad \textit{Equation 7}$$

In addition to determining the critical moment for failure of a given individual, it is also beneficial to examine the mechanism of failure to determine local impacts (e.g. available large woody debris with stem rupture or large scour hole associated with uprooting). To do so, the ratio of stem to root-soil resistive moment provides a relevant response variable. If this ratio is greater than 1 the stem breaks and if it is less than 1 the plant is bent until uprooted. This ratio may be used to examine the changes in failure mechanism with plant and environmental conditions for a single flow rate. With consideration of a single flow condition, the functional form may be further reduced to:

$$\frac{M_{stem,break}}{M_{uproot}} = f\left(\frac{d_{tree}}{h_{tree}}, \frac{\%_{fine}\,\rho_{bd}}{\rho}, \frac{h_{root}}{h_{tree}}\right) \qquad \textit{Equation 8}$$

These functional forms (Equations 7 and 8) may be used to isolate relevant processes, target field data collection, and develop scaleable predictive models. For instance, through dimensional analysis, vegetation washout has been simplified to a single functional expression (Equation 7) which presents washout in four non-dimensional terms representing fluid-vegetation interaction, relative aboveground size, soil texture and density, and relative rooting size.

METHODS

Vegetation failure was induced by exerting force via an anchored "tree pulling" apparatus (see Figures 2bc). Testing protocols were adapted to riparian environments from methods used in tree stability testing in silvicultural forests (Nicoll et al., 2006). For ease of transport, the experimental design used a ¾-ton truck and mounted ATV winch for applying the force. A strain gage was used to measure the applied force and digital inclinometers collected pulling and bending angles (θ and α, respectively). Force was applied at approximately one-fourth to one-third of total tree height for all specimens in order to provide consistent scaling between tests. Profile videography of the individual was recorded throughout the test. Prior to and following a test, a suite of parameters was collected, including: individual vegetation characterization, site properties, test conditions (height of pull point and winch, etc.), and details of failure mechanisms (stem diameter at break, root structure, disturbance area, etc.).

Figure 2. Tree pulling experimental setup: (a) Collection of frontal area, (b) Connection to tree, (c) Force application, and (d) Uprooting failure.

Site Selection

Detailed investigation of applied and resistive forces associated with various riparian species and environmental conditions is needed throughout the United States to create a robust understanding of intra- and inter- species and site variability; however, to isolate mechanistic drivers and robustly determine the magnitude of resistive and applied forces associated with vegetation washout, this study examined a subset of riparian species specific to the arid Southwestern United States. Based on vegetation surveys previously conducted throughout the region (Fischenich, unpublished data), the following taxa were deemed relevant to a larger array of riparian communities of the region: willow (*Salix spp.*), cottonwood (*Populus spp.*), and salt cedar (*Tamarix spp.*). Experimental sites were selected with the objective of maintaining similar riparian community composition (containing the specified taxa) while collecting a breadth of environmental conditions. Sites were required to be accessible by the needed experimental equipment as well as acceptable from social and regulatory viewpoints. Test sites included the Las Vegas Wash near Las Vegas, NV, Lake Mead National Recreational Area near Boulder City, NV, the San Luis Rey in Oceanside, CA, and the Rio Grande in Albuquerque, NM.

PRELIMINARY RESULTS

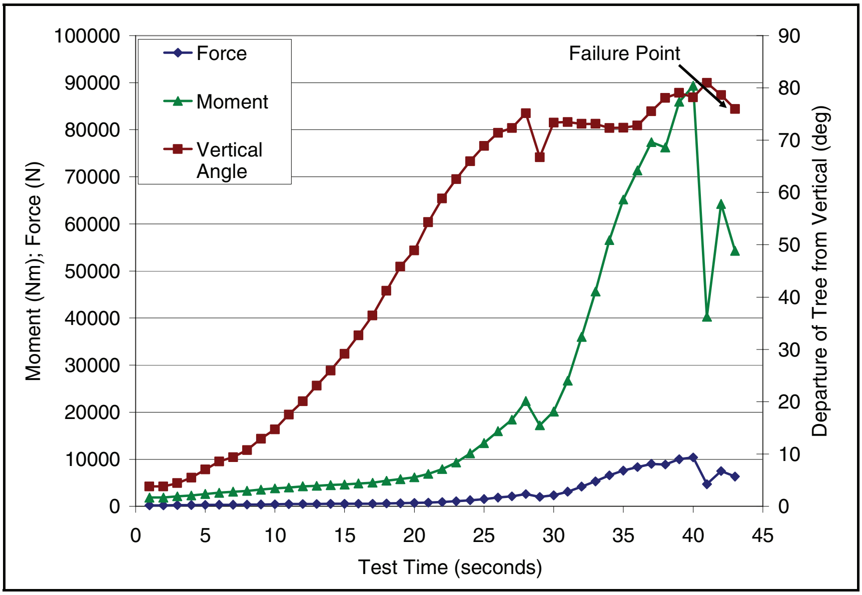
As specified, testing has occurred for greater than 30 trees at four sites. Based on these results, a variety of hypotheses may be tested regarding bending and overthrow of vegetation. As such, the following discussion presents the type of data generated and will not test a specific hypothesis, but instead present a single willow specimen from the San Luis Rey in Riverside, California and discuss data analyses in a general context. This specimen is a “representative” willow in that it is multi-stemmed (3 major stems), relatively small compared to silvicultural species examined by previous researchers (basal diameter of all stems < 5.5 cm), and resides in a dense riparian zone with many surrounding plants of a similar age/size.

Time series data of this specimen (Figure 4a) demonstrates the bending response of the tree as a moment is applied. This data demonstrates a peak in the applied moment as the tree “fails”. This peak in moment may be used to examine the critical moment required to overthrow the plant either by stem rupture or uproot.

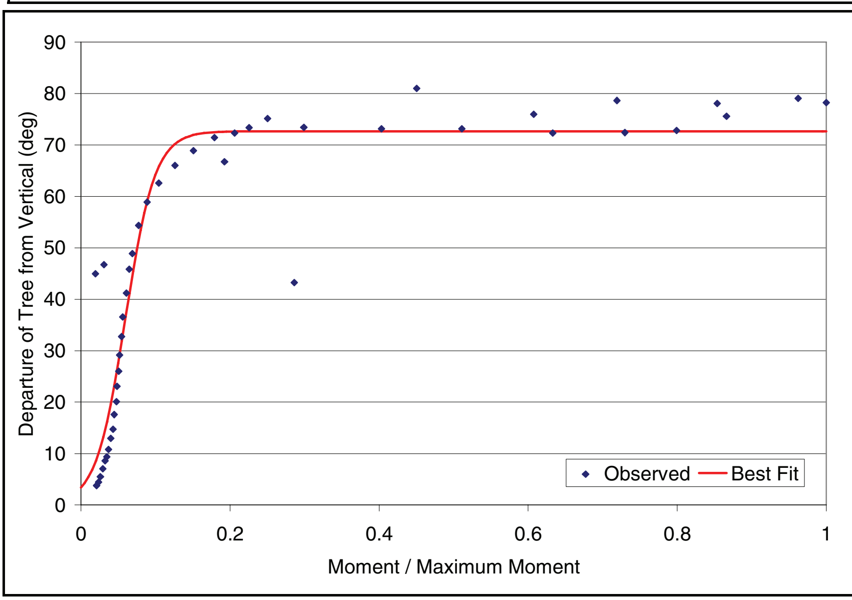
In addition to the single critical point of failure, moment application and resultant bending may be examined in an effort to understand the streamlining of vegetation under vary levels of drag. Figure 4b presents tree bending as a function of the relative applied moment. For consistency in comparison with trees of varying size, the applied moment has been normalized by the critical failure moment. For purpose of discussion, a logistic function has been fit to the data to demonstrate how bending may become predictive based on knowledge of a particular species. Intra- and inter-species differences and changes in bending response with tree size are likely to prove critical in further examination of the bending, streamlining, and resultant changes to hydraulic roughness.

CONCLUSIONS

Flow-vegetation interaction is an important determinant of both hydraulic conditions (e.g. roughness, flood stage) and riparian ecosystem structure and function. Results and techniques developed in this study represent an incremental step forward in advancing understanding of two complex processes associated with flow-vegetation interaction, bending and overthrow. Due to the plethora of riparian species and environmental conditions, collection of data for all species and conditions was infeasible and impractical; however, the results of this effort demonstrate the utility of the approach, and data collection protocols are in place for application to other riparian environments.



(a)



(b)

Figure 4. (a) Time series (b) Bending (logistic function fit).

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REFERENCES

Baptist, M.J., V. Babovic, J. Rodriguez-Uthurburu, M. Keijzer, A. Mynett, and A. Verwey. 2007. On Inducing Equations for Vegetation Resistance. *Journal of Hydraulic Research*. International Association of Hydraulic Engineering and Research , Vol. 45 (4), pp. 435-450.

Coutts, M.P. 1983. Root Architecture and Tree Stability. *Plant and Soil*, Vol. 71, pp. 171-188.

Duan, J. G., R.H. French, and J. Miller. 2002. The lodging velocity for emergent aquatic plants in open channels. *Journal of the American Water Resources Association*. AWRA, Vol. 38 (1), pp. 255-263.

Duan, J.G., B. Barkdoll, and R. French. 2006. Lodging Velocity for an Emergent Aquatic Plant in Open Channels. *Journal of Hydraulic Engineering*. American Society of Civil Engineers, Vol. 132 (10).

Fischenich, J.C. 2000. Resistance Due to Vegetation. *ERDC TN-EMRRP-SR-07*. Engineer Research and Development Center, Vicksburg, Mississippi.

Freeman, G.E., W.H. Rahmeyer, and R.R. Copeland. 2000. Determination of Resistance Due to Shrubs and Woody Vegetation. *ERDC/CHL TR-00-25*. U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi.

Groeneveld, D.P. and R.H. French. 1995. Hydrodynamic control of an emergent aquatic plant (*Scirpus acutus*) in open channels. *Water Resources Bulletin*. American Water Resources Association, Vol. 31 (3), pp. 505-514.

Lundström, T., T. Jonas, V. Stöckli, and W. Ammann. 2007. Anchorage of mature conifers: resistive turning moment, root-soil plate geometry and root growth orientation. *Tree Physiology*. Heron, Vol. 27 (9), pp.1217-27.

Nicoll, B.C., B.A. Gardiner, B. Rayner, and A.J. Peace. 2006. Anchorage of Coniferous Tress in Relation to Species, Soil Type, and Rooting Depth. *Canadian Journal of Forest Research*. NRC Canada, Vol. 36 (7), pp. 1871-1883.

Norris, J.E., A. Stokes, S.B. Mickovski, E. Cammeraat, R. van Beek, B.C. Nicoll, and A. Achim. (2008). Slope Stability and Erosion Control: Ecotechnological Solutions. Springer, Dordrecht, The Netherlands.

Peltola, H.M. 2006. Mechanical Stability of Trees Under Static Loads. *American Journal of Botany*. Botanical Society of America, Vol. 93 (10), pp. 1501-1511.

Wilson, C.A.M.E., J. Hoyt, and I. Schnauder. 2008. Impact of Foilage on the Drag Force of Vegetation in Aquatic Flows. *Journal of Hydraulic Engineering*. American Society of Civil Engineers, Vol. 134 (7), pp. 885-891.

Vollsinger, S., S.J. Mitchell, K.E. Byrne, M.D. Novak, and M. Rudnicki. (2005). "Wind Tunnel Measurements of Crown Streamlining and Drag Relationships for Several Hardwood Species." *Canadian Journal of Forest Research*, Vol. 35, pp. 1238-1249.

Yen, B.C. 2002. Open Channel Flow Resistance. *Journal of Hydraulic Engineering*. American Society of Civil Engineers, Vol. 128 (1), pp. 20-39.