PREDICTION OF EFFECTS OF WOODY DEBRIS REMOVAL ON FLOW RESISTANCE

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ABSTRACT: A simple technique for predicting the Darcy-Weisbach friction factor for river channels with varying amounts of large woody debris was developed. First, debris density is determined based on measurement or visual estimation of cross-sectional areas of debris formations in the plane perpendicular to flow. The Darcy-Weisbach friction factor is then computed using debris density, channel geometry, and the debris drag coefficient. The debris drag coefficient may be computed from a power function with experimentally determined coefficients. For verification of the proposed procedure, debris density and friction factors were measured in river reaches in western Tennessee, and southeastern New South Wales, Australia. Friction factors computed using the procedure were within 30% of measured values for straight, sand-bed reaches and within 38% of measured values for sinuous, gravel-bed reaches. The computational procedure explained 84% of the variance in observed values.

INTRODUCTION

Removal of large woody debris from stream channels (also termed "clearing and snagging," "desnagging," or "snagging") is widely practiced to increase conveyance (Young 1991), eliminate navigation hazards, and control erosion. Large woody debris (debris) influences stream morphology and fluvial processes (Bilby 1984; Cherry and Beschta 1989; Gregory et al. 1985) as well as ecosystem dynamics (Harmon et al. 1986). Debris formations influence sediment storage and channel morphology (Smith et al. 1993). Debris accumulations and the detritus they trap provide substrate for much of the invertebrate biomass in sand-bed rivers (Benke et al. 1985). Cover, depth, and velocity patterns associated with debris formations are essential elements of fish habitats (Angermeier and Karr 1984; Hortle and Lake 1983).

Guidelines for selective removal of debris formations (International 1983; Shields and Nunnally 1984; Jordan 1984; McConnell et al. 1980) have been proposed to reduce adverse effects of debris removal on stream habitats, but little information is available to facilitate prediction of selective debris removal effects on physical habitat or channel conveyance (Gippel 1995, in press). Published friction factors for badly obstructed channels are three to four times larger than for those free of significant debris (Shields and Nunnally 1984). The few observations of Manning's n before and after debris removal are given in Table 1, with increases in conveyance ranging from 12% to 1,000%.

At present, engineers typically estimate the effects of debris removal on stage by manipulating the resistance factor (Manning's n or Darcy-Weisbach f) in the uniform flow equation. Equations are available for computing resistance due to roughness elements that are small relative to flow depth (grain roughness), but not large-scale roughness elements. Flume studies of large-scale roughness have considered boulders (Bathurst 1985), cylinders (Li and Shen 1973; Young 1991; Gippel et al. 1992), artificial strips (Knight and MacDonald 1979), and vertical vegetation (Dawson 1988), but have not produced generally applicable equations for debris. Thus, selection of resistance factor values for complex natural channels with debris is an art based on judgment and experience (Chow 1959; Fasken 1963). Reliable, yet inexpensive, methods for predicting the variation of channel friction factor with debris density are needed for planning-level hydraulic analyses.

The present paper shows a method for computing incremental effects of debris removal on hydraulic roughness of river channels. The method is based on the assumption that flow around woody debris can be evaluated on a reach level and assumed to be uniform. This method is useful for generating first-order approximations, but is a gross simplification of the complex nonuniform flow that often occurs around and through debris formations. To use the method, debris density in a given river reach is computed based on visual estimates, and Darcy-Weisbach friction factors are determined using the debris density values. Effects of debris removal may be predicted by adjusting debris density values.

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TABLE 1. Reported Changes in Manning's *n* Following Removal of Woody Debris or Vegetation or Following Seasonal Regrowth of Vegetation

		Channel		Manning's *n* Values for				
Treatment (1)	Location (2)	Width (m) (3)	Depth (m) (4)	Clear (5)	Obstructed (6)	Percent decrease in *n* (7)	Percent increase in conveyance ($K = AR^{2/3}n^{-1}$) (8)	Reference (9)
Clear and snag-obstructed reaches of river, clear bank vegetation	East Fork Tombigbee River, Miss.	—	—	0.024–0.026	0.038–0.053	37–51	58–104	U.S. Engineer Office (1940)
Clearance of debris dams in headwater stream at low flow	Highland Water, Hampshire, U.K.	—	—	0.292	0.516	43	77	Gregory et al. (1985)
Clear and snag-obstructed reaches of river	Wannon River, Victoria, Australia	25	0.7	0.036	0.079	54	119	State (1981)
Channel clearing	Ovens River, Victoria, Australia	30	3	0.035	0.045	22	29	"Analysis" (1981)
Debris removal	River Murray, Hume-Yarrawonga, Australia	—	—	0.033	0.037	11	12	Murray-Darling Basin Commission (unpublished report)
Debris removal	Deep Fork River, Okla.	80	4	0.04	0.15	73	275	Taylor and Barclay (1985)
Comparison of reaches with forested (obstructed) and riprapped (cleared) banks	Pajaro River, Calif.	—	—	0.039–0.058	0.042–0.095	7–39	8–64	Hecht and Woyshner (1987)
Vegetation growth in channelized creek	Hanging Moss Creek, Miss.	15	3.7	0.022	0.045–0.070	51–69	105–218	Wilson (1973)
Seasonal vegetation growth in river	Lincolnshire River, U.K.	—	—	0.04–0.021	0.25	84–92	525–1,090	Powell (1978)
Seasonal vegetation growth in river	River Frome, U.K.	10	0.5–1.5	0.02–0.04	0.06–0.11	64–67	175–200	Dawson and Robinson (1984)
Seasonal vegetation growth in river	River Yare, Norfolk, U.K.	9	0.35	0.02	0.15	87–100	650	Watts and Watts (1990)
Plant removal from river	River Ebble, Wiltshire, U.K.	—	—	0.02–0.17	0.03–0.41	35–59	50–141	Watson (1987)
Weeds and willows to 1.2 m cleared from ditches	Illinois drainage ditches	5–17	—	0.032	0.05	36	56	Pickles (1931)
Eradication of dense trees from river	Gila River, Ariz.	25–35	2	0.024	0.08	70	233	Burkham (1976)

Constants in an empirical relationship between debris formation geometry and drag coefficient were evaluated using data from a series of flume experiments conducted by Gippel et al. (1992, 1994). These constants were then used to test the procedure previously described for computing channel friction factor using field data collected by independent efforts on the Obion River in western Tennessee (Shields and Smith 1992; Smith et al. 1992) and on the Tumut River in southeastern New South Wales, Australia (Gippel et al. 1992).

DERIVATION OF FORMULA

A relationship is derived below between the Darcy-Weisbach friction factor for a river reach and the density of debris within the reach. The formula may be used to estimate effects of debris and its removal on channel hydraulics. The approach taken here assumes that the cumulative effect of debris within a river reach may be treated as boundary roughness uniformly distributed along the reach. For a control volume corresponding to the fluid in an arbitrary river reach of length L and low sinuosity, the streamwise component of the equation for conservation of linear momentum may be approximated by:

$$\sum F_s = \rho\beta Q \Delta V_s \tag{1}$$

where F_s = forces acting on control volume in streamwise direction (N); ρ = density of water (kg m^{-3}); β = momentum correction factor, assumed = 1.05 for reaches with simple cross sections (Henderson 1966); Q = discharge (m^{3}s^{-1}); and ΔV_s = difference between mean velocity in streamwise direction at upstream and downstream ends of the reach (ms^{-1}).

For reaches with flow that may be assumed uniform, the right side of (1) is zero. The left side of (1) may be expressed as difference between the streamwise components of the gravity force and resistance force acting on the fluid. Resistance force may be partitioned into various components:

$$\sum F_s = \text{force of gravity} - \text{resistance force due to bed (grain and bar resistance)}$$

$$- \text{resistance force due to bends} - \text{drag forces on debris} = 0 \quad (2)$$

$$\text{force of gravity} = \gamma A_{av} L S_0 \quad (3)$$

where γ = specific weight of water (N m^{-3}); A_{av} = fluid volume divided by reach length L (m^2); L = length of control volume (m); and S_0 = average bed slope.

$$\text{resistance force due to the bed} = \tau_b P_{av} L \quad (4)$$

where τ_b = shear on boundaries (N m^{-2}); P_{av} = wetted perimeter (m) = A_{av}/R_{av}, where R_{av} = mean hydraulic radius (m). Head loss coefficients may be used to compute the resistance force due to bends. In a river with large width to depth ratio ($>\sim 10$) and low Froude number (<0.5), the head loss coefficient for the ith bend in a reach C_{L_i} may be approximated by (Henderson 1966; Rouse 1965)

$$C_{L_i} = 2B_i/r_{c_i} \quad (5)$$

where B_i = ith bend water surface width (m); and r_{c_i} = ith bend radius of curvature (m). Therefore the resistance force due to bends ΣF_{b_i} in a given reach with steady, uniform flow is approximated by

$$\sum F_{b_i} = \sum \rho A_{av}[B_i/r_{c_i}]\alpha V_{av}^2 \quad (6)$$

where α = kinetic energy correction factor, assumed = 1.15 (Henderson 1966). Woody debris in a stream occurs in more or less discrete clusters or formations. If the drag force on each formation is D_i, then, for the reach

$$\text{resistance force due to debris} = \sum D_i \quad (7)$$

By substituting (3), (4), (6), and (7) into (2) and solving for the gravity force

$$\gamma A_{av} L S_0 = \tau_b P_{av} L + \sum \rho A_{av}[B_i/r_{c_i}]\alpha V_{av}^2 + \sum D_i \quad (8)$$

Eq. (8) can be converted to dimensionless form by dividing each term by the weight of the control volume $\gamma A_{av} L$ to obtain

$$S_0 = \frac{\tau_b}{\gamma R_{av}} + \frac{\sum [B_i/r_{c_i}]\alpha V_{av}^2}{gL} + \frac{\sum D_i}{\gamma A_{av} L} \quad (9)$$

The Darcy-Weisbach equation for uniform flow in an open channel is

$$S_e = S_0 = \frac{f\alpha V_{av}^2}{8gR_{av}} \quad (10)$$

where f = Darcy-Weisbach friction factor representing total flow resistance of reach; V_{av} = mean velocity of flow (m s^{-1}); and g = acceleration of gravity (m s^{-2}).

It is customary to express flow resistance (or energy loss) of a river reach as the sum of two or more components (Einstein and Barbarossa 1952; Richards 1982; Bathurst 1982). Flow resistance due to stiff vegetation can be partitioned just as resistance due to other processes (Petryk and Bosmajian 1975; Rouve and Schroder 1993). In the present paper, we have chosen to partition total resistance into four components: $f = f_{\text{grain}} + f_{\text{bedform and bar}} + f_{\text{bends}} + f_{\text{debris}}$. Each term of (9) may be expressed in a form similar to those in (10). If S_d represents the head loss per unit length due to debris drag, the fourth term of (9) can be expressed

$$\frac{\sum D_i}{\gamma A_{av} L} = \frac{f_d \alpha V_{av}^2}{8gR_{av}} \quad (11)$$

where f_d = Darcy-Weisbach friction factor for resistance due to debris. Using the relationship for the form drag of a solid object in fluid

$$D_i = \frac{C_{d_i}\gamma V_i^2 A_i}{2g} \quad (12)$$

where C_{d_i} = drag coefficient of ith debris formation; A_i = projected area of ith debris formation on plane normal to flow (m^2); and V_i = approach velocity to ith debris formation (m s^{-1}).

This equation treats debris formations as solid objects rather than permeable clusters of stems and branches. Flume experiments with rows and clusters of cylinders have shown that this approach is appropriate (Young 1991; Gippel et al. 1992). Field observations of debris formations indicate that spaces between branches are often filled with leaves and sediment, especially on the upstream face of formations.

If we assume that channel roughness is uniformly distributed along the reach, then $V_i = V_{av}$. Noting that $R_{av} = A_{av}/B$, where B is the reach-mean water surface width in meters, then (11) and (12) may be combined and solved for f_d

$$f_d = \frac{4}{\alpha}\chi \tag{13}$$

where

$$\chi = \frac{\sum_{i=1}^{n} C_{d_i} A_i}{BL} \tag{14}$$

The symbol χ is referred to herein as the debris density, and is dimensionless.

To use (14), drag coefficients C_{d_i} for debris formations are needed. The drag coefficient for a vertical cylinder of diameter d in a flume of width B is given by an equation of the form [Rana 1980 in Ranga Raju et al. (1983)]

$$C_d = \frac{C'_d}{a\left[1 - \frac{d}{B}\right]^b} \tag{15}$$

where C'_d = drag coefficient in flow of infinite extent (no boundary effects); and a and b = experimentally determined coefficients. Although debris formations are not vertical cylinders, a series of flume tests on model debris (briefly described in the following) verified the form of this equation for debris formations, and provided values for coefficients a and b.

LABORATORY EXPERIMENTS

By reasoning that the drag for debris is governed by the same factors that control drag of a cylinder, Gippel et al. (1992) postulated that the drag coefficient is dependent on the Reynolds number, the Froude number, the geometry and orientation of the debris formation, its location relative to the channel bottom, and its proximity to other debris formations. The relative importance of all of these factors except for Reynolds number was evaluated in a series of towing carriage (pool 2-m wide × 2-m deep) and flume (0.6-m wide) experiments conducted at the Centre for Environmental Applied Hydrology, University of Melbourne, using model debris made from polyvinyl chloride (PVC) pipes and wooden dowels. Details of experiments are given in the original report and a companion paper (Gippel et al. 1992, 1994). Individual cylinders of various diameters (0.0254, 0.0484, and 0.0755 m) and lengths (0.33, 0.5, and 1.0 m) and groups of cylinders arranged in cylindrical arrays with variable separation were used for tests. A branching model ("snag"-shaped) was also tested in the towing carriage. Effects of proximity to other debris was further examined by arranging cylinders horizontally in line and stacked vertically at various separation distances. Flume experiments were conducted for three Froude numbers (0.35, 0.47, and 0.63), at orientation angles to approach flow ranging from 0–180°, velocities ranging from 0.45–0.6 m s^{-1} and at blockage ratios (A_i/BR) ranging from 0.03 to 0.4.

All experiments were conducted within a range of subcritical Reynolds numbers (10^4–10^5), where drag coefficient for a cylinder is relatively constant. Higher Reynolds numbers occur in rivers, but work by White (1979) shows that the drop in drag coefficient at the transition to a turbulent boundary layer is not large for rough-surfaced cylinders (like woody debris). Furthermore, as Reynolds number increases past transition, drag coefficient tends to return to its pretransition value.

Experiments for single cylinders have shown that the drag coefficient is a weak function of cylinder geometry (ratio of cylinder length to diameter), but a strong function of the angle to the flow. However, for more complex shapes (i.e., the branching model debris) C'_d showed less variation with orientation angle as shown in Fig. 1. When oriented perpendicular to the flow, C'_d was equal to 0.7. In small streams where channel width is less than debris length, the flow does not greatly influence the arrangement of debris, and median angles of orientation are close to perpendicular (Cherry and Beschta 1989, figure 3, p. 1035). In lowland streams, like the Obion and Tumut Rivers, debris orientation is strongly conditioned by the flow, and surveys in the Thompson River, Victoria (Gippel et al. 1992) found a median angle of 27° to the flow, with the branching end downstream. From Fig. 1, 0.6 is an appropriate value for C'_d in (15) when applied to lowland rivers.

At conditions typical of lowland rivers with significant debris loading, the blockage ratio was the most important factor controlling drag coefficients of single cylinders and groups of horizontal

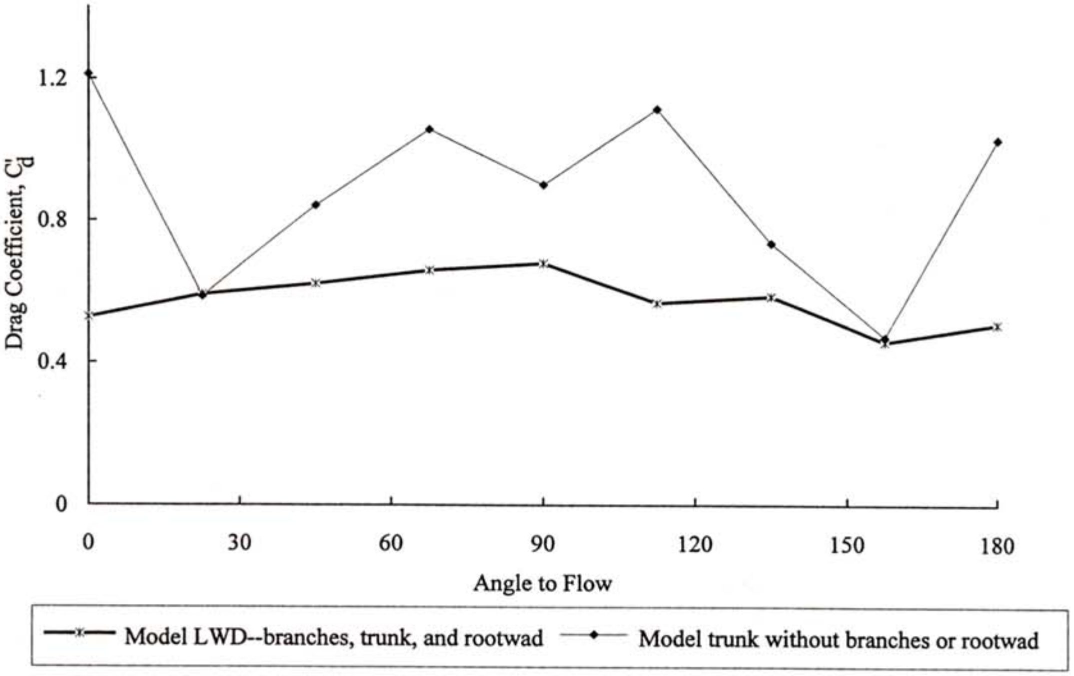

FIG. 1. Variation of Drag Coefficient of PVC Model Debris with Angle of Rotation to Flow (Angle = 0° Implies Object Is Aligned with Flow (Branches Downstream); Angle = 90° Implies Object Is Aligned Perpendicular to Flow)

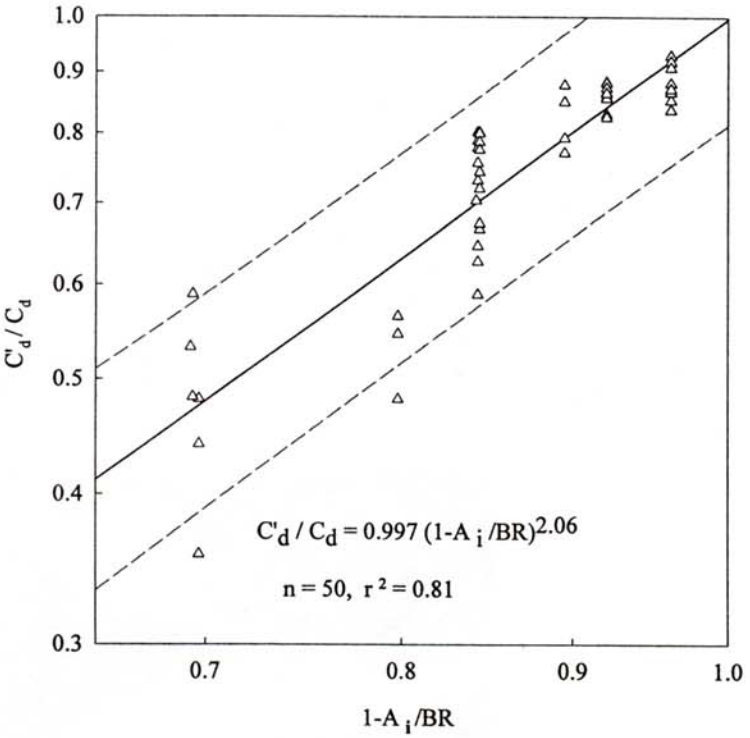

FIG. 2. Relationship of Measured Drag Coefficient and Blockage Ratio for 50 Flume Experiments

cylinders of varying lengths at right angles to the flow in the flume test section. Regression of results from 50 flume experiments conducted with single and vertically stacked cylinders placed normal to the flow, a Froude number of 0.35, and blockage ratios ranging from 0.03 to 0.3, resulted in coefficients for (15) of a = 0.997 and b = 2.06 (Fig. 2). Dashed lines in Fig. 2 show the interval where individual predicted values will fall 95% of the time. The vertical scatter is due to the change in C_d with vertical position of the cylindrical obstructions within the water column [for additional details see Gippel et al. (1992, 1994)]. Thus, the expression for the drag coefficient of a given debris formation is

$$C_d = \frac{0.6}{0.997\left[1 - \frac{A_t}{BR}\right]^{2.06}} \tag{16}$$

Drag coefficients for formations rotated away from normal to the flow direction would be slightly smaller (Fig. 1).

FIELD STUDIES

Independent field studies were conducted in rivers in western Tennessee, and southeastern New South Wales, Australia in order to measure effects of debris removal on stream channel roughness. Furthermore, field data were used to develop and test procedures for rapidly quantifying debris density for a river reach. Visual observations of debris formation geometry and (16) were used along with (13) and (14) to compute the contribution of debris to channel roughness.

Obion River Study

The South Fork Obion River is part of an agricultural watershed that is a tributary to the left descending bank of the Mississippi River in western Tennessee. Regional geology is characterized by unconsolidated and highly erosive Quaternary formations. Wisconsin loess dominates surficial geology, and there are no bedrock controls of stream base level. Watershed relief is low, and prior to initial channelization the narrow floodplains were wetlands traversed by sinuous channels of low gradient. Straightening and dredging of channels throughout the basin has occurred periodically since about 1900 (Simon 1989; Simon and Hupp 1986).

Drainage area upstream of the study reaches was about 927 km^2. The sand-bed channel was straight, and cross sections were trapezoidal and uniform with top widths ranging from 18 to 23 m and maximum depths from 4 to 5 m. Mean bed slope was about 0.0006, and median bed sediment size was about 0.50 mm. At the outset of the study banks were steep, but stable, and were composed of clay and silt. At base flow, water surface widths were 12–17 m, and mid-channel depths ranged from 0.6 to 1.5 m. Large woody debris formations occupying more than one-fifth of the cross section were common (Fig. 3). Test reaches were free of major tributary inflows. Flow conditions were nearly steady during each test because flow and stage fluctuations were damped by ponding upstream of a major debris dam above the study area. Emergent bars and riffles were not observed during dye tests. Photographs of the study area are presented by Smith et al. (1992).

A debris removal project was in progress within the study area while data were being collected. Project design and construction were according to the environmental guidelines (International 1983). Work was limited to removal of trees and debris from the bottom and banks of the channel. Logs embedded in the channel were not removed if they were aligned with the flow. No channel excavation (i.e., sediment removal) was performed.

Debris densities were obtained for three straight reaches, each approximately 1.5-km long (Fig. 4). Methods for estimating debris were simple, and were designed to allow rapid development of estimates for reaches of medium-sized rivers 1–10 km long. Data were obtained at

FIG. 3. Typical Large Woody Debris Formation, Obion River

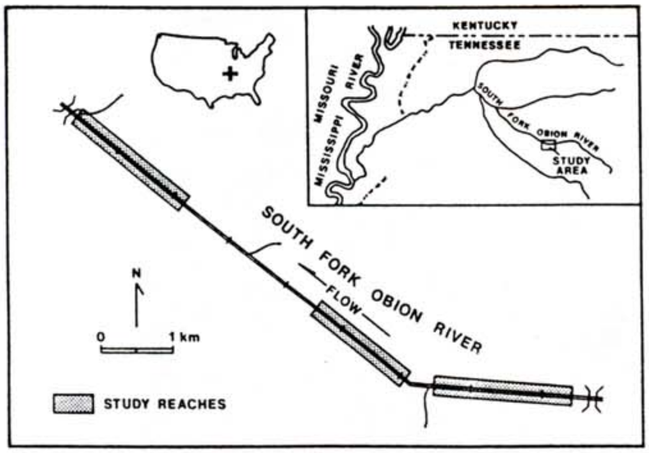

FIG. 4. Location of Obion River Study Reaches, Numbered 1, 2, and 3 from Downstream to Upstream

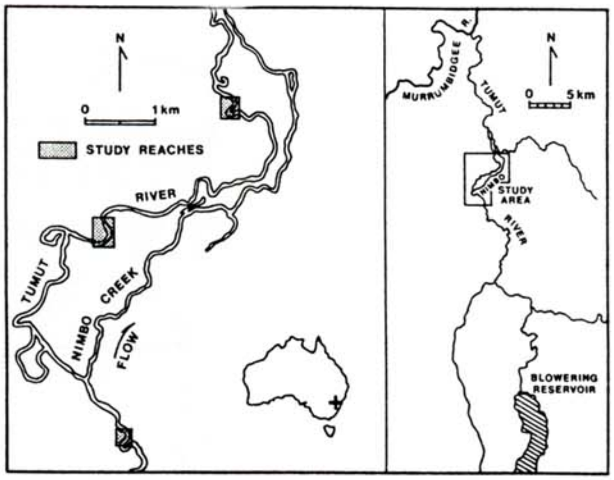

FIG. 5. Location of Tumut River Study Reaches, Numbered 1, 2, and 3 from Upstream to Downstream

low, midbank, and near-bank-top conditions, and for natural and cleared conditions. Debris formations and trees and stumps that were projecting into the flow from the banks were counted and classified according to their size. The maximum dimension of each debris formation in the direction perpendicular to the primary flow direction ("formation width") was visually estimated. Debris formation widths were recorded relative to the average water surface width at the time of inspection: classes were less than one-quarter width, between a quarter-width and a half-width, or more than half of the width. These data were used to compute debris density (as defined earlier). For simplicity, the vertical dimension of the submerged portion of each debris formation was assumed equal to the reach mean depth. Although this was a simplification, detailed depth measurements collected at 0.9-m intervals along five to eight transects spaced one channel width apart (Shields and Smith 1992) indicated that depth variation in reaches with debris was not extreme even at lower stages (means were 0.8 to 1.3 m, coefficients of variation were 20–44%). Debris formations and the matter they trapped generally extended from the surface to the bed.

Slug-injection fluorescent dye tests were conducted at a range of flows for each of the three study reaches. An appropriate volume of Rhodamine WT dye was instantaneously released at the upper end of each reach from a small boat. A flow-through fluorometer was set up at the lower end of the reach and used to measure dye concentration with time. Dosage requirements, preparation of the dye standards, and procedures for calibration of the fluorometer were determined using standard procedures (Hubbard et al. 1982). Tests were conducted at the downstream reach first and then proceeded upstream. During each dye test, water surface elevations were recorded using temporary staff gauges that were installed at the upstream and downstream ends of each reach, and water surface widths were measured at five to 12 regularly spaced cross sections. Dye curves were used to compute discharge, and mean depth was computed by dividing the discharge by mean width times mean velocity. Mean velocity was computed by dividing reach length by mean dye travel time. Water surface slope was determined from gauge readings and reach length.

Tumut River Study

The Tumut River is a north-flowing tributary to the Murrumbidgee River in New South Wales, Australia (Fig 5). Prior to 1959, mean discharge at the Tumut gauge was 41 m^3s^{-1}. Interbasin transfer, which began in 1959, increased mean discharge to 53 m^3s^{-1}. A major dam was constructed in 1969 to regulate the flow to serve downstream irrigation water demands. Since that time mean discharge had averaged 62 m^3s^{-1}. River regulation has reversed the seasonal flow pattern, causing low flows in winter and near-bank-top flows throughout summer. Extensive debris removal occurred between 1958 and 1960 and continued at a reduced rate between 1960 and 1967. Additional debris and bank vegetation removal was performed in 1972–78, and debris removal continues as ongoing maintenance. The main objective of debris removal is to maximize summer flow conveyance, but major bank erosion hazards have also been removed.

The Tumut River channel in the study area flows through Quaternary alluvial deposits. It was a sinuous, fast-flowing river with a bed composed of sand (~15%), gravel (~75%), and cobbles (~10%). In cross section the channel was variable but roughly trapezoidal. Bank-top-flow water-surface widths ranged from 30 to 50 m, and water depths at this flow were about 2.5 m. At the bank-top discharge of about 110 m^3s^{-1}, water surface slope was about 0.001. Flows were largely controlled by the aforementioned dam, with only one major unregulated

FIG. 6. Typical Large Woody Debris Formation, Tumut River

tributary entering between the dam and the study site. Trees on banks were large (up to 15-m high, and on the order of 1-m diameter) river red gums (*Eucalyptus camaldulensis*) and river oaks (*Causarina cunninghamiana*), and they regularly fell into the river as banks eroded. Debris formations occupying 5–40% of the channel cross section were observed (Fig. 6). Photographs of the study area are presented by Gippel et al. (1992).

For safety reasons, debris is normally removed only during the low-flow period. However, in 1989 a brief period of maintenance works at the dam required cessation of flow at the outlet and the river authority organized removal of seven debris formations at three sites. This allowed the opportunity to conduct hydraulic measurements at bank-top flow immediately before and after debris removal. Therefore, any observed change in the flow characteristics could be attributed solely to debris removal. The dimensions, orientations, and positions of the debris formations were surveyed using an electronic distance-measuring system. These data were used to compute debris densities for the three reaches, each approximately 400-m long (Fig. 5). Bank-top water-surface profiles were surveyed using an electronic distance-measuring system before and after debris removal. The river was gauged at cross sections just downstream of debris formations using a current meter suspended form a dinghy, with velocity being measured at 40–50 points in each cross section.

Data Analysis

Data from both field studies were analyzed in a similar fashion. Darcy-Weisbach friction factors were determined using hydraulic data [water surface slope, reach means of velocity, and hydraulic radius (depth)] and the uniform flow equation. Since these values of f were based on measured data, they are referred to in the following as measured friction factors. Measured friction factors were compared with computed values that were the sums of estimated values of friction factors for bed, bend, and debris resistance.

Friction factors for bed resistance f_b comprised both grain and bar resistance and were computed using equations presented by Brownlie (1983) for the sand-bedded Obion River and by Griffiths (1981) for the gravel-bedded Tumut River. To apply Brownlie's approach, the grain Froude number was compared with the criteria suggested by Brownlie to verify that flow was in the lower regime region

$$\frac{V_{av}}{\sqrt{\frac{gD_{50}(\rho_s - \rho)}{\rho}}} \leq 1.74S_e^{1/3} \tag{17}$$

Equation 35a in Brownlie (1983) was used to compute a hydraulic radius. This value was then placed in the Darcy-Weisbach equation solved for f_b.

For the Tumut River, the criteria suggested by Griffiths (1981) ($D_{50} < 11RS$) led to selection of the following equation for resistance in gravel-bedded streams with bed forms and bed material transport:

$$\frac{1}{\sqrt{f_b}} = 2.21\left(\frac{V_{av}}{\sqrt{gD_{50}}}\right)^{0.340} \tag{18}$$

Since Obion River study reaches were straight, no resistance was computed for bends. For the Tumut reaches, a friction factor representing bend resistance was computed by setting the third term of (9) equal to a term similar to the right side to (10)

$$\frac{\sum [B_i/r_{c_i}]\alpha V_{av}^2}{gL} = \frac{f_{\mathrm{bends}}\alpha V_{av}^2}{8gR_{av}} \tag{19}$$

and solving for f_{bends} to obtain

$$f_{\mathrm{bends}} = \frac{8R_{av}}{L}\sum \frac{B_i}{r_{c_i}} \tag{20}$$

A friction factor corresponding to flow resistance by debris formations was computed using (13), (14), and (16). Measurements and estimates of debris formation dimensions were used in (14) and (16) to compute debris drag coefficients and densities.

RESULTS

Debris Density

Nine debris surveys were performed on Obion River reaches over a wide range of discharges prior to debris removal, yielding debris density values that ranged from 0.005 to 0.054 and that averaged 0.024. Six surveys were performed after debris removal; debris densities ranged from 0.000 to 0.015 and averaged 0.005. Post–debris removal values for the upper and middle reaches were higher than for the lower reach, primarily due to midchannel debris formations exposed by bed scour following construction. Debris density varied with stage, generally decreasing as stage increased from low to midbank elevation, but remained relatively constant from midbank to near bank top. However, debris formations that were submerged deeply enough to be invisible were not counted. Therefore, debris density may have been underestimated. Debris densities for the Tumut River reaches were 0.006, 0.007, and 0.0003 before debris removal, and were zero after debris removal.

Measured Friction Factor

Measured total Darcy-Weisbach friction factors f ranged from 0.07 to 0.44 for the Obion River as shown in Table 2. Obion River friction factors decreased with increasing discharge, and friction factors for cleared and uncleared reaches converged. At flows >10 m^{3}s^{-1}, the mean value of f for cleared reaches (four observations) was 0.10, and the mean value for uncleared reaches (six observations) was 0.15. Assuming bed slope remained constant after debris removal, the difference in mean friction factors implies that debris removal increased the amount of discharge conveyed by the channel at bank top by about 22%.

Removal of debris formations from the Tumut River study reaches lowered upstream water-surface elevations (corrected for discharge variation) 0–0.23 m. Friction factors for the three

TABLE 2. Results of Field Studies

Study (1)	Reach (2)	Q (m^3 s^{-1}) (3)	V (m s^{-1}) (4)	R (m) (5)	B (m) (6)	Slope (m km^{-1}) (7)	D_{50} (mm) (8)	Froude number (9)	f_{bed} (10)	f_{debris} (11)	f_{bends} (12)	Computed f_{total} (13)	Measured f (14)	Error (15)
Obion River (debris)	3	3.9	0.29	0.9	16	0.63	0.27	0.10	0.22	0.20	0.00	0.42	0.44	−5%
Obion River (debris)	2	4.0	0.33	0.7	17	0.61	0.44	0.12	0.16	0.18	0.00	0.34	0.29	19%
Obion River (debris)	2	9.0	0.46	1.1	17	0.78	0.44	0.14	0.17	0.17	0.00	0.34	0.29	19%
Obion River (debris)	3	16.2	0.53	1.6	19	0.45	0.27	0.13	0.11	0.04	0.00	0.16	0.18	−11%
Obion River (debris)	2	16.9	0.65	1.4	18	0.51	0.44	0.17	0.09	0.02	0.00	0.11	0.12	−12%
Obion River (debris)	3	36.9	0.72	2.7	19	0.46	0.27	0.14	0.11	0.07	0.00	0.18	0.16	9%
Obion River (debris)	2	40.5	0.86	2.5	19	0.60	0.44	0.17	0.10	0.03	0.00	0.13	0.14	−8%
Obion River (debris)	3	40.9	0.77	2.7	19	0.49	0.27	0.15	0.10	0.07	0.00	0.17	0.15	15%
Obion River (debris)	2	41.3	0.86	2.5	19	0.59	0.44	0.17	0.10	0.03	0.00	0.13	0.14	−8%
Obion River (cleared)	2	3.6	0.46	0.5	15	0.42	0.44	0.21	0.06	0.03	0.00	0.11	0.10	8%
Obion River (cleared)	1	4.2	0.45	0.6	15	0.54	0.57	0.18	0.09	0.00	0.00	0.09	0.12	−23%
Obion River (cleared)	1	10.7	0.57	1.2	16	0.42	0.57	0.17	0.08	0.06	0.00	0.14	0.11	30%
Obion River (cleared)	1	22.2	0.84	1.6	17	0.46	0.57	0.22	0.06	0.01	0.00	0.07	0.07	−1%
Obion River (cleared)	1	47.9	0.91	2.7	19	0.52	0.57	0.18	0.09	0.01	0.00	0.10	0.12	−15%
Obion River (cleared)	1	53.2	0.98	2.8	19	0.54	0.57	0.19	0.08	0.01	0.00	0.10	0.11	−12%
Tumut River (debris)	1	112	1.01	2.8	39	1.10	16.0	0.19	0.11	0.02	0.04	0.17	0.21	−20%
Tumut River (debris)	2	96	0.90	2.9	38	1.00	22.0	0.17	0.13	0.03	0.07	0.22	0.24	−7%
Tumut River (debris)	3	96	0.90	2.9	38	1.50	28.0	0.17	0.14	0.00	0.12	0.26	0.36	−28%
Tumut River (cleared)	1	125	1.08	3.0	39	1.30	16.0	0.20	0.10	0.00	0.04	0.14	0.23	−38%
Tumut River (cleared)	2	92	0.93	2.6	38	0.90	22.0	0.18	0.13	0.00	0.06	0.19	0.19	1%
Tumut River (cleared)	3	92	0.93	2.6	38	1.50	28.0	0.18	0.14	0.00	0.11	0.25	0.31	−20%

[illegible]

Computed Friction Factors

[illegible]

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DISCUSSION

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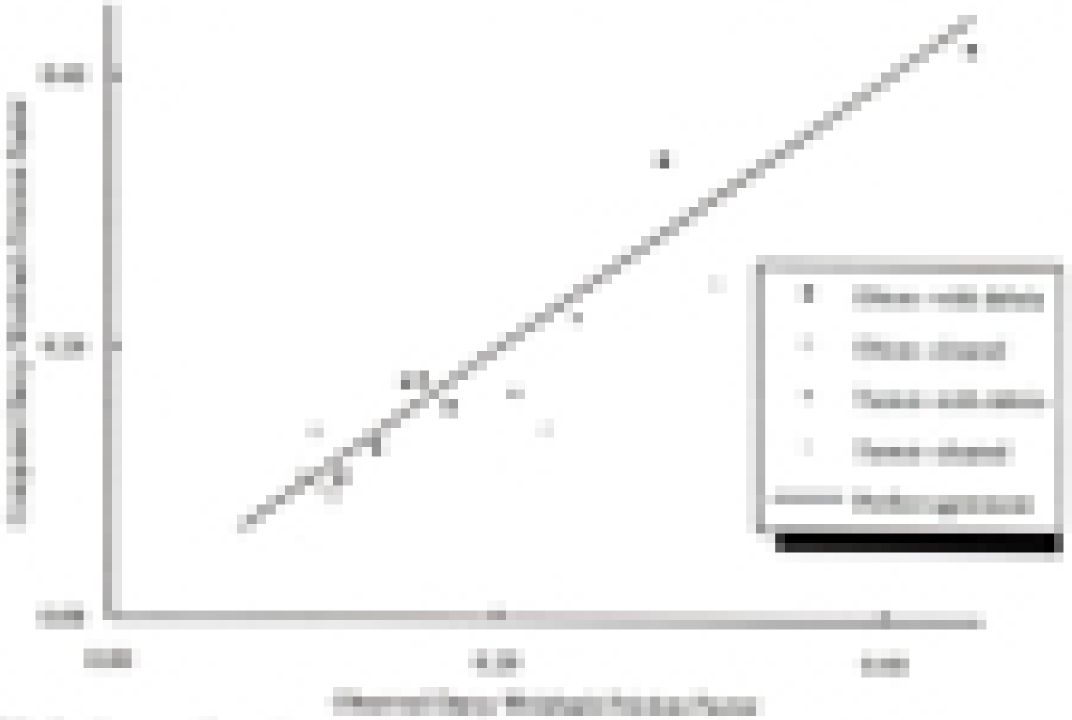

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bends reduced the accuracy for the Tumut reaches. The formula used to estimate bed resistance for the Tumut gravel bed reaches contains empirically determined coefficients generated with stepwise regression with an r^2 of only 0.384 (Griffiths 1981), which compares with a similar value of 0.984 for the Brownlie (1983) lower-regime equation used to estimate sand-bed resistance for the Obion.

Measured friction factors for uncleared Obion reaches were lower for higher discharges. A 10-fold increase in discharge resulted in values of *f* that were two to three times lower. Evidently debris promoted energy dissipation through flow-contraction and pool-formation processes that were gradually eliminated as flows increased. Additionally, flexible branches may have been forced prone at higher flows (Kouwen and Unny 1973). Decreasing flow resistance with increasing stage and discharge (within-bank flows) is in agreement with observations of Manning's *n* for larger sand-bed rivers (Chow 1959), an ephemeral sand-bed stream (Coleman 1962), similar channels in the Southeastern United States (Fasken 1963), and other channels with significant debris (Gippel 1989; Gregory et al. 1985). Jarrett (1984) reported a similar trend for Manning's *n* in high-gradient streams, but noted that the trend reversed at highest stages when dense bank vegetation was partially submerged. Coleman (1962) and Beven et al. (1979) reported decreases in Darcy-Weisbach *f* with increasing stage and discharge in small streams.

Friction factors for cleared and uncleared Obion River reaches converged at higher flows, but were still lower for cleared reaches. Hecht and Woyshner (1987) reported converging Manning's *n* values for riprapped and forested reaches of the Pajaro River in California.

Although the literature contains observations of large increases in conveyance following debris removal from badly blocked channels (Table 1), selective debris removal had only modest effects (increases of 6% and 22%) on conveyance in the two rivers studied. Furthermore, effects of debris removal on friction factor of sand-bed channels may decline with time. Inspection of cleared reaches of the Obion following storms revealed additional debris either from riparian trees falling into the channel or becoming exposed in the bed as a result of scour.

Debris removal may trigger complex response in fluvial systems that is difficult to predict. Although investigation of effects of debris on channel stability was beyond the scope of the present study, visual observation of bank erosion following debris removal combined with evidence of headward-progressing degradation suggested that debris removal may have triggered or exacerbated bed lowering through the upper portion of the Obion River study area. Similar observations are reported by others [Gippel et al. 1992; Bilby 1984; Strom 1950 in Gippel (1989)]. These results suggest that flood-control benefits of debris removal may be extremely limited in channels similar to the Obion River. Smith et al. (1993) found that removal of debris from a small, gravel-bed stream increased flow resistance by allowing alternate bar formation. On the other hand, historical cross-section surveys of the gravel-bed Tumut River suggested that removal of debris had not been a significant factor in promoting channel change. In this case, large floods and regulation of the flow appear to have been more important in increasing the cross-sectional area of the channel (Gippel et al. 1992). Removal of debris from the Tumut River to gain a hydraulic benefit can only be justified in reaches that have resisted expansion by erosion, and which act to limit the maximum regulated flow that can be contained within the channel.

Benefits of proposed debris-removal projects should be carefully analyzed in light of costs and environmental impacts. Even selective removal of debris with small equipment and manual tools can have measurable impact on aquatic habitat quality (Shields and Smith 1992). Complex response of fluvial systems (here taken to include riparian forests) can render improvements in channel conveyance limited and transient. In certain cases reach channel stability may be adversely affected by debris removal. However, local scour near debris formations is often alleviated.

CONCLUSIONS

Removal of debris from the two rivers studied decreased Darcy-Weisbach friction factor for near-bank-top conditions by roughly 20–30% and increased bank-top flow capacity by roughly 5–20%. The simple procedure developed in this study for quantifying debris density and its effect on channel resistance allowed estimation of friction factors for near–bank-full flows in a straight, sand-bed, debris-choked channel that were within 15% of measured values. Estimated friction factors for a more sinuous gravel-bed channel were less accurate, but were within 38% of measured values. Site-specific adaptation of the procedure is necessary to account for resistance components not considered (e.g., bridges).

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_{av} = fluid volume divided by reach length L (m^2);
A_i = projected area of ith debris formation on plane normal to flow (m^2);
a and b = experimentally determined coefficients;
B = reach-mean water surface width (m);
B_i = mean water surface width in ith bend (m);
C'_d = drag coefficient in infinite flow;
C_{d_i} = drag coefficient of ith debris formation;
C_{L_i} = head loss coefficient for ith bend;
D_i = drag on ith debris formation (N);
D_{50} = median bed material size;
d = diameter of cylinder;
F_{b_i} = resistance force due to ith bend (N);
F_s = forces acting on control volume in streamwise direction (N);
f = Darcy-Weisbach friction factor representing total flow resistance of reach;
f_b = Darcy-Weisbach friction factor for resistance due to grain and bar resistance (bar resistance includes all types of bedforms and bed irregularities);
$f_{\text{bedform and bar}}$ = Darcy-Weisbach friction factor for resistance bedforms and bars;
f_{bends} = Darcy-Weisbach friction factor for resistance due to flow through bends;
f_d = Darcy-Weisbach friction factor for resistance due to debris;
f_{grain} = Darcy-Weisbach friction factor for resistance due grain roughness of bed sediment;
g = acceleration of gravity (m s^{-2});
h_{Ld} = head loss due to debris (m);
L = length of control volume (m);

P_{av} = wetted perimeter (m) = A_{av}/R_{av};
Q = discharge (m^3s^{-1});
R_{av} = reach mean hydraulic radius (m);
r_{c_i} = ith bend radius of curvature (m);
S_d = head loss per unit length due to debris drag;
S_e = slope of energy grade line;
S_0 = average bed slope;
V_{av} = mean velocity of flow (m s^{-1});
V_i = approach velocity to ith debris formation (m s^{-1});
ΔV_s = difference between mean velocity in streamwise direction at upstream and downstream ends of reach;
α = kinetic energy correction factor, assumed = 1.15;
β = momentum correction factor, assumed = 1.05 for reaches with simple cross sections (Henderson 1966);
γ = specific weight of water (N m^{-3});
ρ = density of water (kg m^{-3});
ρ_s = density of sediment (kg m^{-3});
τ_b = shear on boundaries (N m^{-2}); and
χ = dimensionless debris density.