FIELD EXERCISE 1: INTRODUCTION TO FLOW RESISTANCE

Field Trip Date: 8 April 2006
Draft Report Due: 20 April 2006 in class
Report Due: 4 May 2006 in class

The objective of this exercise is to analyze channel form, materials, and hydraulic conditions in a "reach" (length scale of 10^0 to 10^1 channel widths) using fundamental field techniques. You will need to collect data and make observations that you can use to describe spatial variation of physical characteristics in the reach and to discuss how these characteristics are related to each other. In particular, your field report will identify and, where feasible, provide quantitative estimates of factors in the reach that generate flow resistance. Overall, you will want to compare and contrast flow resistance in different parts of the reach.

Directions to the Swamp Creek site:
Leave Johnson Hall parking lot @8:00 AM;
Drive north on 15th Ave NE;
Turn right (east) on Lake City Way;
Follow Lake City Way to Kenmore (the north end of Lake Washington);
Turn left (north) on 73rd Ave NE;
Follow 73rd for 0.8 km to access road on right (east) side of 73rd, between the mailboxes numbered 18707 and 18727.

FIELD ACTIVITIES

You will be a part of team collecting data that are to be shared with the class. Each team has four tasks:

1. Draw a sketch map of the portion of the reach where you are working, and of the overall reach;
2. Survey two cross-sections of the channel and floodplain or a long profile of the channel thalweg;
3. Characterize bed material texture at each cross section; and
4. Measure current velocities at each cross-section.

Each person should participate in each task so that you become familiar with all these techniques. None of these activities requires more than three people, so if you are in a larger group you will need to take turns and the group will need to engage in some tasks simultaneously (e.g., two members can survey while two other are doing a pebble count, then switch assignments). Make sure you complete the sketch map and all surveying. Complete a pebble count and current measurement at your first (upstream) cross-section. Do pebble counts and current measurements at subsequent cross-sections as time allows.

Again, the purpose of this exercise is to document spatial patterns in physical characteristics of streams at a reach-scale, relationships among these characteristics, and geomorphic processes accounting for the spatial patterns. While you can only collect one type of data (topographic, hydraulic, sedimentologic) at a time, different types of data can be used together if they are collected in the same place. Make sure you document where data are collected and collect data in places where they can be related to other types of data (e.g., long profiles should indicate location of cross-sections; a pebble count should be done around the area where vertical velocity measurements are made).

Task 1: Sketch map

Familiarize yourself with the general features of the stream by making a sketch map of the channel and bank showing channel pattern; width; cross-section locations; distribution and type of vegetation/organic material in, above, and near channel; bank conditions (slumped, reinforced by roots, armored by large boulders, undercut, recent deposits); channel forms (pools, bars, riffles, bank constrictions and expansions); bank material; textural patches of bed material (silt, sand, gravel, cobble, boulders, bedrock); flow direction and patterns (convergence, divergence, eddies, cross-channel variation); and other features that affect the roughness of the channel). Do not attempt to document everything everywhere. Indicate the approximate location of large features (e.g., the channel, clumps of vegetation). Select representative areas to provide more detail of patterns repeated throughout the reach.

The map should illustrate spatial relationships of geomorphic features and hydraulic conditions such as variation of grain size with channel form, flow patterns near eroding banks or bar deposits, variation in channel form/materials where current velocity changes. These relationships will provide evidence for any conclusions you may have about the geomorphic processes actively forming the channel and floodplain in this reach. Include a scale and orientation.

Once you have completed the sketch map, estimate Manning's roughness coefficient for the reach. Since different factors contribute to flow resistance, Manning's coefficient can be estimated as a composite of the roughness contributed by each type of feature. Use Cowan's formula (in Chow 1959) and Table 1 to estimate Manning's n:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m_5 \qquad (1)$$

The values in Table 1 were developed from a study of 40 to 50 natural streams, floodways, and unlined drainage channels where $R < 5$ m. Which components have the greatest potential influence on roughness?

At some time during the day you should also make a sketch map of the entire reach. Think about what you will want to be describing about the overall site in the introduction to you report—these are the features you should be sure to include!

Task 2: Channel survey

Each group will survey either two cross-sections of the channel or a long profile of the reach of interest. Surveys of channels, provide geometric information needed to calculate discharge, shear stress, roughness as well as summary statistics for characterizing the channel size. Surveying is most efficient when you limit the number of times you move the instrument, so try to locate the level where you have clear line of sight to all points of interest.

a. Cross sections

The cross section of a channel influences the depth and velocity of stream flow at a given discharge. A survey of a cross-section should extend across as much of the channel and floodplain as of interest. Beginning on the left bank (looking downstream), stretch a tape across the channel. The section should be perpendicular to the primary direction of flow for the discharge of interest (e.g., high flow), which may or may not be the same as the direction of the current during the survey.

Record the orientation of the cross section. Survey the cross-section topography using a stadia rod and level. For each point, record the horizontal distance (along the tape), elevation of the channel, and depth of water. Survey the entire width of the channel and, if possible, extend the survey at least a few meters beyond each bank. You are not obligated to pick points at a fixed interval but you do need to represent the topography so make sure to survey topographic breaks, obstructions, and the thalweg (i.e., the lowest point of channel). Note the location/elevation of banks.

b. Long profile

The longitudinal profiles of a stream bed and the water surface indicate channel forms, the energy gradient causing water to flow, and large-scale flow resistance (e.g., a constriction with backwater). A long profile is typically surveyed along the main path of the current, which ideally corresponds to the channel thalweg. One group will make this survey, which can be accomplished by standard surveying techniques or by running a tape along the channel (secure it upstream with a stake/cobbles) following the dominant flow path as best as possible. Record the distance along the tape for each point, the elevation of the channel, and depth of flow. Make sure to capture changes in both topography and water surface slope/elevation. Record where each cross-section crosses the long profile.

Task 3: Bed material texture

Bed material can be characterized quantitatively in terms of the size of grains. Since alluvial deposits normally cover a wide range of particle sizes, the texture of deposits are often characterized in terms of a log-normal distribution (Allen 1965; Folk 1966). The challenge in the field is to draw an adequate sample of grains from the population of all grains in a deposit to characterize the distribution. Furthermore, there are “patches” of bed material with distinct size distributions.

We will use pebble counts (Wolman 1954) to characterize the surface texture of the bed material at the surveyed cross-sections. Pace across the channel in the vicinity of the cross section. With each step, reach down to the stream bed with a single finger and pick up the first grain you touch. Do not look at where you are reaching. Measure the intermediate diameter of the grain (image it as an ellipsoid with three axes). Repeat until you have measured 100 grains. Work systematically sampling across the entire width of the channel. Replace grains (especially large ones) either upstream or downstream where you won't re-sample them. Note that there is a limit to the size of grain that you can sample – most schemes stop at 4 mm.

Record the measurement in the following categories by noting the lower limit of the category. This is equivalent to the mesh size of the sieve that would catch the grain in question:

Categories (in mm)
<4.0
4.0 - 5.6
5.6 - 8.0
8.0 - 11.0
11.0 - 16.0
16.0 - 22.0
22.0 - 32.0
32.0 - 45.0
45.0 - 64.0
64.0 - 90.0
90.0 - 128.0
(etc.)

Task 4: Current velocity

a. Cross-section velocity

Measurement of current velocity is necessary for calculating discharge, a roughness coefficient for uniform flow equations, and local shear stress applied on the stream bed. Since current velocity varies across the channel, the usual approach to calculating discharge is to estimate average velocity of vertical sections across the channel. Review survey data for your first cross section.

Divide the wetted width of the channel into five to 10 subsections of approximately equal length with previously surveyed points defining the boundary between subsections. Calculate the center point of each subsection. You will measure current velocity at the horizontal center of each subsection. Your survey data will allow you to calculate the area of each subsection. Discharge through each subsection is equal to the product of mean velocity and area. For future reference, note that 20 to 30 sections are desirable with no more than 10% of the discharge passing through a single section (Linsley et al. 1982).

Current velocity varies vertically from 0 at the bed to a maximum value near the surface. The mean velocity of each section is best estimated by averaging a series of vertical current measurements. You can apply theoretical principles of turbulent flow to minimize the number of vertical measurements needed. For shallow streams with low relative roughness (i.e., $D_{84} < 0.3$ total depth of flow), stream flow can be represented as a fully developed turbulent boundary layer with a stable velocity profile. In this case, we can approximate the current velocity as a logarthmic function of height above bed according to the Prandtl–von Karman velocity distribution law or "Law of the Wall" (Schlichting, 1979):

$$u(z) = u^*/k \ln(z/z_0) \qquad (2)$$

where u is velocity, z is vertical height up from bed, $u^* = (\tau/\rho)^{0.5}$ is shear velocity, $k \approx 0.4$ is von Karman's constant, and z_0 is a characteristic roughness length scale at which level the velocity is projected to equal zero. By integration of equation (2), you will find that the average velocity of a vertical subsection will be equal to the measured velocity at a height 0.4 y_{max} above the bed (or 0.6 of the depth, depending on your perspective). Flow in shallow gravel bed streams does not always have a stable velocity profile, and the velocity profile may deviate from the Law of the Wall. To limit the error in your estimate of mean velocity, measure velocity at 0.2 and 0.8 of the depth. Use the average of these values as the average velocity for the section.

Current should be measured upstream or to the side of where you are standing. Make sure that no one is working immediately upstream or downstream while you are making current measurements. Orient the meter to the direction of flow. Turbulent fluctuations in stream flow cause its velocity to vary over very short time scales. You should measure velocity at a point for 30 to 60 seconds depending on the magnitude of these fluctuations. Before measuring the current velocity, it may be helpful to construct a table with four columns. The first column will indicate the cross-channel location of the measurement. The second column will be the total depth of the section. The third and fourth columns will be the velocity measured at 0.2 and 0.8 of the depth. This way you will know where to measure velocity rather than having to perform calculations in the middle of the channel.

b. Vertical velocity profile

The vertical variation in velocity can be used to estimate the shear stress of stream flow on the bed. Make a series of detailed vertical velocity measurements at two locations your first cross-section. Record the cross-stream location and depth of each measurement. Make the most measurements at the depths where the velocity gradient (i.e., the change in velocity) is the greatest.

REVIEW OF DATA

It is common to make mistakes when collecting data in the field. The repercussions are trivial if you catch your error while you are still at a site. You may have a major headache if you don't realize your mistake until you are working on your report. We will stop at approximately 3:00 PM so that you can check the quality of your data and identify additional data you need to collect during the remaining time. To facilitate this, your group will need to provide an oral summary of your results including:

1. Bankfull width of each cross-section or reach-average water surface slope;
2. Estimate of median grain size and maximum grain size from your pebble count;
3. Depth of channel at vertical velocity profile, 0.6 depth, velocity at 0.6 depth, and maximum velocity.

With your remaining time, complete pebble counts and vertical velocity profiles at your other cross-sections.

Sharing data

Each group will be responsible for compiling data collected in the field using the supplied spreadsheet. The standardized format is intended to limit the time you spend on data input and reduction. Please review all data you use for obviously spurious values. The deadline for submitting this information to the TA is not flexible.

DATA ANALYSIS

1. Channel geometry and hydraulics

Plot channel cross-sections and long profiles. Compare reach-average and local water surface slopes (change in water surface elevation divided by longitudinal distance). Channel cross-section geometry can be summarized by its hydraulic radius R = area/wetted perimeter. The spreadsheet supplied to you allows convenient calculation of R. Will R increase linearly with (i.e., by a constant multiple of) depth? If flow resistance scales with R, what is the relationship between flow resistance and flow depth?

Compare the cross-sectional area of water in each section. What does variation in cross sectional area tell you about changes in mean velocity at each cross-section (consider $Q = \text{Area}\ U_{mean}$ and will be constant at each cross-section). Does flow accelerate or decelerate? What geomorphic features are associated with these changes? How is water surface slope related to variation in current velocity?

To calculate discharge at a cross-section, you will first need to calculate the area of each vertical subsection where velocity was measured. Again, the supplied spreadsheet will assist you. Calculate the mean velocity of each subsection (a simple average of the two measured values). The product of the area of a subsection and the mean velocity will give you the discharge through each subsection. The sum across the channel is the total discharge of the stream. Do the estimates of discharge vary from cross-section to cross-section? Why?

Calculate mean velocity and hydraulic radius for each cross-section and average values for the reach. Solve Mannings equation for the roughness coefficient for each cross-section and using reach-average values:

$$n = R^{2/3} S^{1/2} / U \qquad (3)$$

Does roughness vary between cross-sections? How do your calculated values compare to your estimate using equation (1)? How does the mean velocity at a cross-section compare to the mean velocity of the more detailed vertical velocity profile? How will roughness change with stage?

2. Bed material texture

Stream bed material spans a large range of grain sizes. The frequency distribution of grain sizes can be approximated by a log normal distribution. Consequently, grain diameters are often transformed into phi units using the equation:

$$\phi = -\log_2 D \text{ or } D = 2^{-\phi} \qquad (4)$$

where D is measured in mm. Describe the texture, location, and extent of bed material. Analyze the characteristics in terms of channel forms, flow patterns, and shear stress. Summarize and compare bed material distributions using the 16th, 50th (median), and 84th percentile grain diameters (i.e., sort all of the phi values and select the 16th, 50th and 84th values). Is the distribution normal ($\phi_{84} - \phi_{50} = \phi_{50} - \phi_{16}$)? Is the variation between textural patches most pronounced for the median grain, the fine fraction, or coarse fraction? Strickler developed an empirical equation for the roughness coefficient using median grain diameter in mm (e.g., in Shen and Julien 1993):

$$n = 0.015 d_{50}^{1/6} \qquad (5)$$

Note that almost any number raised to the 1/6th power approaches one! So grain roughness values are generally <0.03. If your results differ, check your calculations. How do estimates of n based on grain size compare to calculated values at cross-sections?

3. Shear stress and grain roughness

Flowing water imparts a force on sediment. The momentum of the water decreases as a result (i.e. flow resistance) and, if the force is sufficiently large, the sediment will move. Since water is a fluid, this force is typically expressed as a stress (force per unit area). Since the stress is directed parallel to the bed surface, it is a shear stress. Shear stress can be estimated over different spatial scales and using different techniques. Please provide your estimates of shear stress using the following methods:

- Total boundary shear stress for uniform flow using reach-average values and at each cross-section:

  $$\tau_b = \rho g R S. \qquad (6)$$

- Local viscous shear stress using the Law of the Wall (equation 2) and:

  $$\tau_{local} = \rho u^{*2} \qquad (7)$$

To determine local shear stress, first construct a graph of u (x values) versus ln(y) (y values) for each of the vertical velocity profiles. Fit a straight line to your data, particularly values near the bed (this line can be approximate). This line can be described by equation 2. The slope of the line is: $(\ln y_1 - \ln y_2) / (u_1 - u_2) = \kappa / u^*$. Use the slope of the line with equation 7 to calculate a local value of shear stress.

The variable z_0 in the Law of the Wall is equal to the y-intercept of the velocity profiles. Extrapolate your "best fit" lines to the y-axis to determine values of z_0 for each velocity profile.

Whiting and Dietrich (1990) found that z_0 can be approximated by $0.1D_{84}$. Estimate z_0 using data from pebble counts. How do the results (i.e., z_0) of these two methods compare? Fit a line to near-bed velocity data only and re-estimate z_0. How does the near-bed estimate compare to $0.1\ D_{84}$? Does the estimate based on near-bed data suggest more grain roughness than the estimate based on the whole velocity profile?

FIELD REPORT

The report should describe fundamental field techniques and physical conditions of streams at a reach scale. Use your observations and data to demonstrate relationships between basic geomorphic features and processes and hydraulic conditions. Characterize flow patterns. Discuss spatial variability of flow resistance include factors generating flow resistance. Describe how geomorphic features both influence and result from flow patterns. Qualify your observations and results with important information such as their spatial scale (e.g., reach-average or local shear stress) and the validity of assumptions implicit in your methods (e.g., Manning's equation applies to uniform flow, channel banks were formed by the stream). Comment on data quality, reliability of methods, and the concurrence of results. Synthesize what you have measured and observed by comparing and contrasting flow resistance in different parts of the reach.

You do not need to answer all of the questions raised in this handout. Avoid including information that does not help you describe geomorphic features and processes. If you find yourself speculating on why things are the way they are, you may be trying to explain too much or not using all of the information available.

In most cases, you should report summary statistics or calculations in your report referencing an appendix with raw data tables and calculations. You may want to provide figures (i.e., graphs, maps, and illustrations) which should be referenced in the text and provided as attachments. Figures should have titles with all axes labeled.

The body of the report should have seven sections:

- abstract,
- introduction/statement of purpose,
- field and analytical methods,
- results
- discussion,
- conclusions; and
- references.

It should conform in length to be no more than 5 pages (not including the attachments listed below), single spaced, 12-point font, 1-inch margins. **However, please print out the final version as 1.5- or double-spaced text.** Attach your sketch map, figures, and any other data as appendices.

REFERENCES

Allen, J.R.L. 1965. A review of the origin and characteristics of recent alluvial sediments. *Sedimentology* 5: 89-191.

Chow, V.T. *Open-Channel Hydraulics*. McGraw-Hill, New York.

Folk, R.L. 1966. A review of grain-size parameters. *Sedimentology* 6: 73-93.

Linsley, R.K., M.A. Kohler, J.L.H. Paulhus. 1982. *Hydrology for Engineers*. McGraw-Hill, New York.

Schlichting, H. 1979. *Boundary-Layer Theory*. McGraw-Hill, New York.

Shen, H.W. and P. Julien. 1993. Erosion and sediment transport. In D. Maidment ed., *Handbook of Hydrology*. McGraw-Hill, New York.

Whiting, P.J. and W.E. Dietrich. 1990. Boundary shear stress and roughness over mobile alluvial beds. Journal of Hydraulic Engineering 116: 1495-1511.

Wolman, M.G. A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35(6): 951-956.

Table 1: Values for the Computation of the Roughness Coefficient (Chow, 1959)	
Channel material (n0)	
earth	0.02
rock cut	0.025
fine gravel	0.024
coarse gravel	0.028
Degree of surface irregularity (n1)	
Smooth	0
Minor (e.g., dredged channel, slightly eroded side slopes)	0.005
Moderate	0.01
Severe (e.g., extensively sloughed banks of natural channel)	0.02
Variation in channel cross-section size or shape (n2)	
Gradual changes along channel	0
Alternating occasionally between large and small sections or shape such that flow shifts from side to side	0.005
Alternating extensive	0.01 to 0.015
Relative effect of obstructions (extent of water area occupied, degree to which obstructions are streamlined or induce turbulence in flow, position and spacing of obstructions) (n3)	
Negligible	0
Minor	0.010 - 0.015
Appreciable	0.020 - 0.030
Severe	0.040 - 0.060
Vegetation	
Low (e.g., flexible grasses, weeds, or seedlings where depth of flow is 3 times that of vegetation height)	0
Medium (e.g., grasses, weeds, or seedlings where depth of flow 2 times that of vegetation height or brush limited to channel side slopes and hydraulic radius greater than 2 ft)	0.010 - 0.025
High (e.g., emergent vegetation, trees in channel without foliage)	0.025 - 0.050
Very high (e.g., vegetation height 2 times that of flow, bushy willow with foliage)	0.050 - 0.100
Degree of meandering based on sinuousity (ratio of channel length to valley length) (m5)	
Minor (sinuousity < 1.2)	1
Appreciable (sinuousity 1.2 to 1.5)	1.15
Severe (sinuousity > 1.5)	1.3

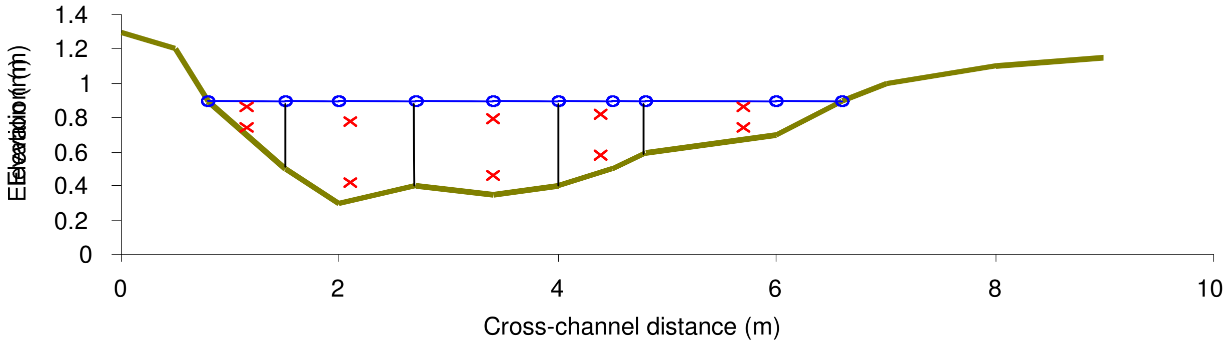

Figure 1: Example of locations for current measurements

SOME METHODS FOR ESTIMATING ROUGHNESS PARAMETERS

I. Visual Estimates of Manning's n:

1. Visual estimate of field conditions using experience, "type" photographs, and published tables. Tables are found in most geomorphology texts. "Type" photos are in Water Supply Paper 1849. Listed below are a few examples (from Richards):

Description	Manning's n
Artificial channel, concrete	0.014
Excavated channel, earth	0.022
Excavated channel, gravel	0.025
Natural channel, < 30 m wide, clean, regular	0.030
Natural channel, < 30 m wide, some weeds, stones	0.035
Mountain stream, cobbles, boulders	0.050
Major stream, > 30 m wide, clean, regular	0.025

2. Estimate from Table 1 (previous page) given by Chow (1959), where n is given by:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m_5$$

II. Back-calculation of *n* or *f* from field data

- Manning's Equation: (n is the roughness coefficient)

$$\bar{v} = \frac{1}{n} R^{2/3} S^{1/2}$$

- Darcy-Weisbach Equation: (f is the friction factor)

$$\bar{v}^2 = \frac{8gRS}{f}$$

f can also be estimated by empirical grain-size data (Leopold et al., 1964):

$$\frac{1}{\sqrt{f}} = 2.0 \log\left(\frac{d}{D84}\right) + 1.0$$

where D_{84} = 84th percentile value from cum. freq. distribution (grain diameter)

Note that:

$$n = \frac{R^{1/6} f^{1/2}}{\sqrt{8g}}$$

ESTIMATION OF LOCAL SHEAR STRESS FROM THE VERTICAL VELOCITY GRADIENT

“Near” to the bed (but for all practical purposes, everywhere in the flow), we expect the velocity profile to follow the “Law of the Wall”:

$$u = \frac{u_*}{k} \ln \frac{z}{z_o}$$

where $u^* = \sqrt{\frac{\tau_b}{\rho}}$, $k = 0.40$ (Von Karmen's Constant), and z_o is the roughness parameter)

However, to determine the correct value for z_o we need to determine whether or not we have hydraulically rough (HRF) or hydraulically smooth (HSF) flow. To do this, we first define the roughness Reynolds number (R_*) as:

$$R_* = \frac{u_* k_s}{\nu}$$

where k_s = the “representative” grain diameter that controls the bed roughness and ν = kinematic viscosity (= 1.514×10^{-2} cm^2/s for typical river temperatures); D_{84} is often assumed to provide a reasonable measure of k_s, although as noted earlier, Whiting and Dietrich (1990) suggest that z_0 can be approximated by $0.1D_{84}$, which for HRF would mean that $k_s = 3D_{84}$ (see below for HRF equation). What value do your data support best?

HSF occurs where $R_* < 3$, and HRF where $R_* > 100$

Case 1. HSF:

$$z_o = \frac{\nu}{9u_*}$$

Case 2. HRF:

$$z_o = \frac{k_s}{30}$$

(If $3 < R_* < 100$, then z_o must be determined from experimental data—the “Nikaradse's diagram”)