



## *extrap*: Software to assist the selection of extrapolation methods for moving-boat ADCP streamflow measurements



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### ABSTRACT

Selection of the appropriate extrapolation methods for computing the discharge in the unmeasured top and bottom parts of a moving-boat acoustic Doppler current profiler (ADCP) streamflow measurement is critical to the total discharge computation. The software tool, *extrap*, combines normalized velocity profiles from the entire cross section and multiple transects to determine a mean profile for the measurement. The use of an exponent derived from normalized data from the entire cross section is shown to be valid for application of the power velocity distribution law in the computation of the unmeasured discharge in a cross section. Selected statistics are combined with empirically derived criteria to automatically select the appropriate extrapolation methods. A graphical user interface (GUI) provides the user tools to visually evaluate the automatically selected extrapolation methods and manually change them, as necessary. The sensitivity of the total discharge to available extrapolation methods is presented in the GUI. Use of *extrap* by field hydrographers has demonstrated that *extrap* is a more accurate and efficient method of determining the appropriate extrapolation methods compared with tools currently (2012) provided in the ADCP manufacturers' software.

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### 1. Introduction

The U.S. Geological Survey (USGS) operates more than 7800 streamgages nationwide. The streamflow data from these gages are used for flood and streamflow forecasting by the National Weather Service and other Federal agencies; design of bridges, roads, culverts, and reservoirs; habitat assessments and preservation; water supply planning; and regulatory development and enforcement. To maintain accurate ratings of streamflow versus stage (Kennedy, 1983) or index velocity (Levesque and Oberg, 2012) at these gages, physical measurements of the streamflow are typically made every 6 to 8 weeks at each gage and more often during extreme events, such as floods (Blanchard, 2007). On average, the USGS makes more than 70,000 streamflow measurements each year. Approximately 25% of streamflow measurements made in the last 4 years (2009–2012) have been made using the moving-boat acoustic Doppler current profiler (ADCP) technique (Mueller and Wagner, 2009).

#### 1.1. Use of ADCPs for measuring discharge

The USGS and other agencies around the world began using ADCPs to measure streamflow in the early 1990s and the use of

this technique has grown substantially. An ADCP deployed on a moving boat can compute the discharge in real time while traversing the stream and continually measuring the water velocity, boat velocity, and depth (Fig. 1). Each traverse of the stream is commonly called a transect. A USGS moving-boat ADCP streamflow measurement is typically the average discharge computed from an even number of transects with a total sampling duration of greater than 720 s (Mason, 2011). Unfortunately, the ADCP is unable to measure the entire water column. An unmeasured zone near the water surface is caused by the immersion of the ADCP into the water, the blanking distance (distance below the transducer where data are unreliable due to ringing of the ceramic transducers), and an additional unmeasured range that is dependent on the instrument configuration settings. The ADCP also cannot measure velocities near the streambed due to the potential for side-lobe interference (Teledyne RD Instruments, 2011). As the ADCP approaches a streambank, the depth will eventually become too shallow for valid data collection, leaving unmeasured zones near each bank. Therefore, the total discharge is the sum of the discharge in the measured part of the cross section, computed using the cross product of the boat velocity and water velocity; the discharge computed using extrapolation methods in the unmeasured top and bottom parts of the cross section; and the discharge computed using extrapolation methods for the unmeasured edges of the cross section (Simpson and Oltmann, 1993; Mueller and Wagner, 2009). The process of computing a final discharge

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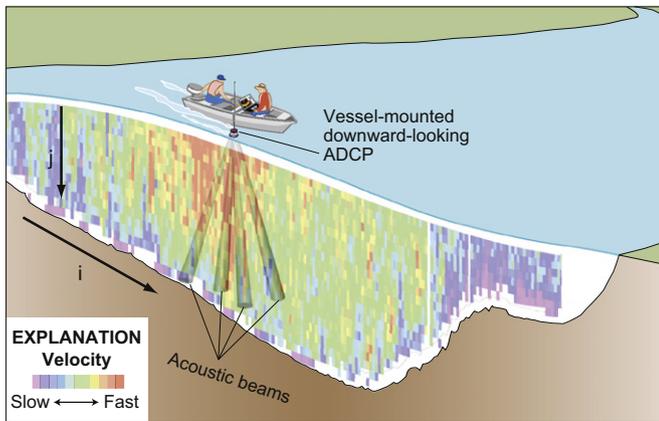


Fig. 1. Illustration of data collected from a moving-boat ADCP streamflow measurement. Each vertical stripe represents a measured profile indexed by  $i$  and each depth cell is indexed by  $j$ .

requires the user to determine and select an appropriate method for computing the discharge in the unmeasured top and bottom and left and right edges of the cross section. The focus of this paper is on selecting the appropriate extrapolation methods for computing the discharge in the unmeasured top and bottom parts of the water profile.

Simpson and Oltmann (1993) investigated use of the two widely accepted general velocity distribution laws for open channels, namely, the logarithmic velocity-distribution law, commonly known as the Prandtl-von Karman velocity-distribution formula and the power velocity-distribution law. A method to fit these two velocity-distribution laws to the measured data using a least-squares approach was developed and the results examined. Simpson and Oltmann (1993) ultimately selected the 1/6th power law (Chen, 1989) because of its robust noise rejection capability during most streamflow conditions (Simpson, 2001). This power law method is an approximation only and Chen (1989) demonstrated the commonly used Manning's equation was equivalent to the power law with an exponent of 1/6th. Different exponents can be used to adjust the shape of the curve to fit the profiles resulting from various types and sizes of bed and bank roughness. An exponent for the power law different from 1/6th is analogous to a Manning's  $n$  that varies with relative roughness (Chen, 1989). Simpson (2001) acknowledged that in the case of bidirectional flow the power method would not work. In addition, the presence of the free surface, friction along the channel boundaries, and/or the presence of wind shear can result in a velocity profile that departs from the typical logarithmic and power velocity-distribution curves (Chow, 1959; Yang et al., 2004; Guo and Julien, 2008). Commercially available software supporting the computation of discharge using an ADCP from a moving boat have followed Simpson and Oltmann (1993) approach, but also provide methods (constant and no slip) that allow the fitting of nonstandard velocity profiles that may result from bidirectional flow and wind driven currents. Typical methods include:

- Top constant: Assumes the velocity or discharge is constant from the uppermost depth cell to the water surface.
- Top 3-point: Uses a linear least squares extrapolation through the uppermost three depth cells to the water surface.
- Bottom no slip: Uses the assumption that the water velocity (and hence the discharge) should be zero at the solid boundary and fits a power curve through zero at the bottom and through depth cells in the lower 20% of the flow or the last valid depth cell, if no valid bins are in the bottom 20% of the water column (specific details may vary among manufacturers).

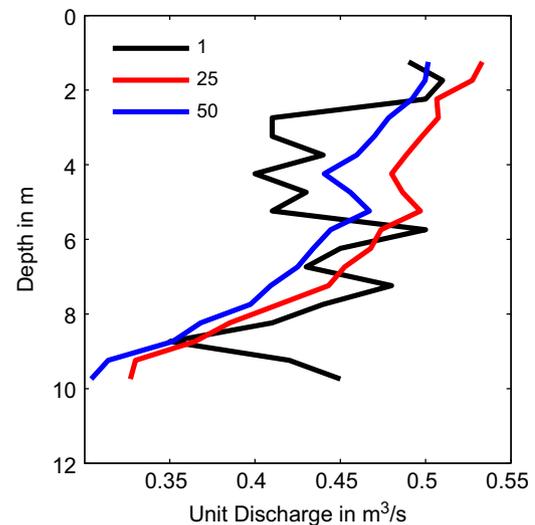
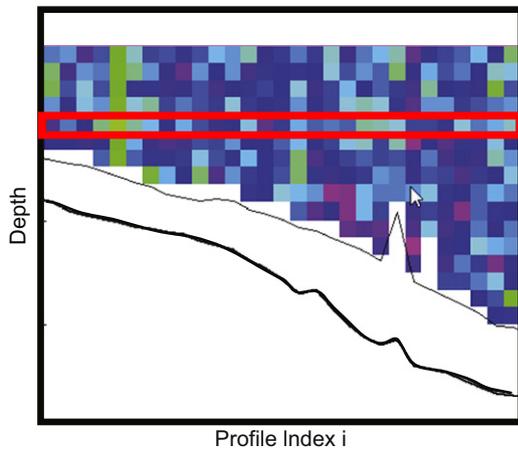


Fig. 2. Plot showing effect of averaging multiple profiles (1, 25, and 50) to obtain a better representation of the profile shape. [Note: A profile returned from an ADCP may represent one or more samples of the velocity profile, but is the rawest form of the data provided to the user].

The user is responsible for evaluating the profile and selecting the appropriate method for the top and bottom extrapolations. Currently (2012), the manufacturers' software assumes the selected extrapolation methods are valid for the entire transect. In other words, the extrapolation methods cannot be changed for different parts of the cross section. Most streamflow measurements include multiple transects and are less than 30 min in duration. During this period it is rare (tidal and transient flow conditions excepted) that channel roughness, channel shape, flow conditions, and weather would change enough to affect the mean profile from one transect to another. Observed variation in the mean profile among transects comprising a streamflow measurement is likely due to natural turbulence and instrument noise that has not been sampled sufficiently to achieve a stable average. Therefore, it is generally the best practice to determine the best top and bottom extrapolation method for the combined transects and apply it to all transects comprising the measurement.

## 1.2. Problem and scope

The previous approach for determining the appropriate extrapolation methods was for the user to evaluate the velocity or discharge profiles in the manufacturers' software. There are two issues with this approach. First, ADCP measured velocity profiles represent about 1 s of averaged data, or less, and due to turbulence and instrument noise the profiles are noisy. The noise in individual profiles makes identification of the mean profile shape difficult. The obvious solution to noisy profiles is to average. However, the amount of data that has to be averaged to obtain an accurate mean profile varies by instrument setup and natural turbulence in the stream (Fig. 2). Second, the averaging algorithms employed do not properly average across varying depths, rather they simply average across the depth cells. In other words, the averaging is at fixed ranges from the water surface and independent of depth. While this approach is acceptable if the depth is constant throughout the average, if the depth changes the resulting profile could become unnaturally distorted. Therefore, using the simple approach in the manufacturers' software could result in averaging velocities that are very near the streambed in shallow areas with velocities that are much further from the streambed in deeper areas (Fig. 3). The vertical velocity distribution laws (logarithmic or power) are based on range from the streambed, not range from the water surface.



**Fig. 3.** Screen capture from WinRiver II (Teledyne RD Instruments, 2012) illustrating the problem with averaging across depth cells when the depth changes across the averaged profiles.

This paper describes a Matlab<sup>®</sup>1 (Mathworks, 2012) program, *extrap*, which provides the ADCP user a technically correct and efficient method to determine the best extrapolation method to use for computing discharge in the unmeasured top and bottom parts of an ADCP discharge measurement. The use of normalized profiles for averaging will be shown to be consistent with the velocity distribution laws and the application of the extrapolation methods in the manufacturers' software. Although other extrapolation methods could be employed, such as the modified log-wake law (Guo and Julien, 2008) or varying the profile fit across the cross section, this version of *extrap* was intentionally limited to the methods that are currently (2012) available in the manufacturers' software. *extrap* is designed to be a tool for the field hydrographer who is actively using the ADCP and supporting software to make discharge measurements in an operational streamgaging program. Future development may investigate new and improved methods for computing the unmeasured top and bottom parts of the water column that are beyond those currently available in manufacturers' software.

## 2. Method development

The methods used in *extrap* are based on the use of normalized data that allow use of data from the entire cross section to determine a mean profile. Use of normalized data necessitates the development of the power law equation for use with these data. The selection of the appropriate extrapolation method is accomplished computationally by a combination of statistics and empirical logic and visually by the user through the use of the graphical tools present in the graphical user interface (GUI) of *extrap*.

### 2.1. Normalized data

The use of normalized data provides the capability of compressing the entire measurement (whole cross section and multiple transects) into a single profile and maintains consistency with the dimensionless power law. Averaging data for the entire measurement minimizes the effect of potentially noisy data and is consistent with the current (2012) application of the top and

bottom extrapolation methods. The use of normalized data ensures that data are plotted in the correct position along the discharge profile relative to the streambed. The following discussion develops the use of a normalized profile in determining the appropriate exponent for the power law.

The general form of the power law subscribed for ADCP profiles is:

$$\frac{u_{i,j}}{u_{*i}} = a_i \left( \frac{z_{i,j}}{z_{oi}} \right)^m \quad (1)$$

where  $u_{i,j}$  is the velocity at distance  $z_{i,j}$  from the streambed;  $u_{*i}$  is the shear velocity;  $a_i$  is a coefficient;  $z_{oi}$  is a value based on roughness;  $m$  is an exponent;  $i$  is the index for the profile; and  $j$  is the index for the depth cell in a profile  $i$ . Chen (1989) showed that by setting the coefficient to 9.5 and the exponent to 1/6 (0.1667) the power law was equivalent to Manning's formula for open channel flow. Simpson and Oltmann (1993) consolidated terms not available from the ADCP measured data and assigned them to a coefficient ( $a'_i$ ) that is determined by fitting the equation to each profile ( $i$ ) collected by the ADCP.

$$u_{i,j} = \left( \frac{a_i u_{*i}}{z_{oi}^m} \right) z_{i,j}^m = a'_i z_{i,j}^m \quad (2)$$

Therefore,  $m$  is constant for the whole cross section but  $a'_i$  changes for each measured profile. For a moving-boat ADCP streamflow measurement, the discharge is not computed directly from the water velocity but rather from the cross product of the water velocity and boat velocity.

$$\chi_{i,j} = (W_{x(i,j)} \times B_{y(i)}) - (W_{y(i,j)} \times B_{x(i)}) \quad (3)$$

where  $\chi$  is the cross product and  $W$  is the water velocity and  $B$  is the boat velocity in the  $x$  and  $y$  directions. Simpson and Oltmann (1993) showed that the shape of the velocity profile and the shape of the cross product or discharge profile are identical. Thus, we can write Eq. (2) as,

$$\chi_{i,j} = \left( \frac{a_i u_{*i}}{z_{oi}^m} \right) z_{i,j}^m = a''_i z_{i,j}^m \quad (4)$$

where  $a''_i$  is a coefficient to be calculated for values of the cross product,  $\chi$ , rather than  $u$ . Recent advances in ADCP technology have produced ADCPs that vary depth cell sizes both within a profile and among profiles. By using the raw cross product and not including the depth cell sizes, the effect of varying depth cell size is removed from the profile, except in regards to where the cross product is located vertically along the profile.

Because the value of  $m$  is applied to the whole cross section, it is desirable to composite all of the data in the cross section to obtain a mean profile and use this mean profile to obtain the most representative value of  $m$ . In order to obtain a mean profile, the data must be normalized so that data from shallow parts of the cross section can be combined with data from deeper parts of the cross section. The cross product term is normalized by dividing the cross product in each depth cell of a profile by the mean of the cross products in that profile.

$$\hat{\chi}_{i,j} = \frac{\chi_{i,j}}{(1/J_i) \sum_{j=1}^{J_i} \chi_{i,j}} \quad (5)$$

where  $\hat{\chi}_{i,j}$  is the normalized cross product (referred to in *extrap* as the unit discharge). The range from the streambed is normalized by dividing by the depth to the streambed for that the profile.

$$\hat{z}_{i,j} = \frac{z_{i,j}}{D_i} \quad (6)$$

where  $\hat{z}_{i,j}$  is the normalized range from the streambed to the center of each depth cell and  $D_i$  is the depth from the water surface to the streambed for each profile. Applying Eqs. (5) and (6)

<sup>1</sup> **Disclaimer.** Use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

to Eq. (4) yields,

$$\hat{\chi}_{i,j} = \frac{a_i'' D_i^m}{(1/J_i) \sum_{j=1}^{J_i} \chi_{i,j}} \hat{z}_{i,j}^m = a_i'' \alpha_i \hat{z}_{i,j}^m \quad (7)$$

where  $\alpha_i$  is a coefficient created for each profile from the normalization process. Since  $a_i''$  and  $\alpha_i$  are variable for each profile we can combine them into a single coefficient for each profile and Eq. (7) becomes,

$$\hat{\chi}_{i,j} = \alpha_i' \hat{z}_{i,j}^m \quad (8)$$

where  $\alpha_i'$  is a coefficient that varies with each profile.

## 2.2. Determining the appropriate extrapolation method

Plotting the normalized cross product and range from the streambed for a typical streamflow measurement produces a cloud of points (Fig. 4). Although the exponent,  $m$ , for a power fit could be computed from a least squares fit of all of the data, it would be difficult to visually assess the appropriateness of the fit and the fit could be influenced by outliers in the data. To provide a visual reference and to improve the method's robustness to outliers, the profile is subdivided into 5% increments of normalized depth and the mean normalized distance from streambed and median and interquartile range of normalized unit cross product for each increment are computed. The median of the unit cross products was selected to represent the mean profile, rather than the mean, because of its robustness to the influence of outliers. The median values of the unit cross product and their associated normalized distance from the streambed are used in both the visual and computation approaches to determine the appropriate extrapolation methods. The interquartile range plotted as whiskers about the median value provides a visual representation of the noise or uncertainty associated with the composite profile in each 5% increment.

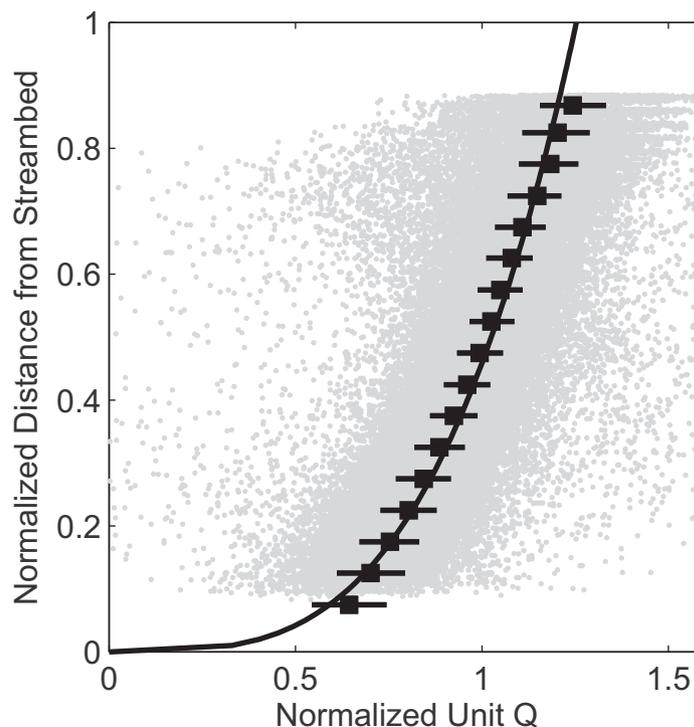
*extrap* provides both an automatic and manual approach to selecting the appropriate extrapolation methods. The manual

approach relies on the user's visual analysis of the data, while the automatic approach uses linear least squares regression and several empirically developed criteria for selecting the appropriate extrapolation method. The automated method will attempt to select the best from among the following extrapolation methods:

- Power fit through the whole profile with an exponent of 0.1667 (default);
- Power fit through the whole profile with a linear least squares fit exponent;
- Constant fit at the top and a no slip fit at the bottom with an exponent of 0.1667; and
- Constant fit at the top and a no slip fit at the bottom with a linear least squares fit exponent.

The approach used in the automatic fit algorithm is that the data follow the power law with an exponent of 0.1667 unless the measured data are sufficient to prove otherwise. The following steps are used to automatically select the appropriate extrapolation method:

1. The automatic method first determines which of the 5% profile increments should be used in the analysis. Often the profile increments near the top and the bottom of the profile have substantially fewer data points contained in them. Data near the surface and particularly near the streambed are often noisier, so with fewer data points in the medians, the medians of these increments may not be a good representation of the profile shape in these locations. The combination of these factors could adversely influence the evaluation of how well the proposed method fits the profile because all medians are given equal weight in the linear least squares regression. In addition, any median of a profile increment that does not contain more than 20% (default value, but user selectable) of



**Fig. 4.** Plot of normalized data from a streamflow measurement showing cloud of points from depth cells (gray dots), the composite median values for each increment (black squares), interquartile range for each increment (black whiskers), and the power fit for these data (black line).

- the median number of points for all of the profile increments is marked invalid and is not used in the automatic analysis.
- If the number of valid medians is less than 7, the data are considered to be insufficient to reject the default assumption that the profile follows a power fit with an exponent of 0.1667 and the power fit with an exponent of 0.1667 is automatically selected. These criteria were determined through analysis of many data sets by multiple persons experienced in the application of ADCPs for discharge measurements.
  - If there are more than 6 valid medians, linear least squares regression is used to determine an optimized exponent for Eq. (8). An exponent 0.1667 is assumed until the data prove a different exponent is appropriate. The 95% confidence intervals about the optimized exponent are used to determine if there is sufficient support from the data to change the exponent. The optimized exponent is considered the appropriate exponent for the power fit of the profile, if the computed coefficient of determination ( $r^2$ ) from the regression is equal to or greater than 0.8 and the default exponent of 0.1667 is not contained within the 95% confidence intervals of the optimized exponent. If either of these conditions is not met then the default 0.1667 exponent is retained.
  - Linear least squares regression is used to compute the exponent for the no slip fit. The bottom third of the medians are used in the regression rather than just 20% as is used for application of the no slip method in the discharge computations in manufacturers' software. The additional data provided by using the bottom third of the profile help provide a smooth trend from the no slip extrapolation, with an optimized exponent determined from regression, to the measured data.
  - Using logic and specific criteria, developed empirically from review of many profiles, the best power fit is evaluated on how well it fits the top and bottom parts of the measured data. If the best power fit does not meet the prescribed criteria, a constant fit at the top and no slip fit at the bottom is selected.
  - If the  $r^2$  from the linear regression in step 4 is greater than 0.8, the no slip exponent computed from the regression is selected, if not, the no slip exponent defaults to 0.1667.

The total discharges computed using the extrapolation methods selected by the automatic algorithm, the 1/6th power fit, and a fit consisting of constant at the top and no slip at the bottom were compared to the total discharges computed using extrapolation methods selected by five experienced ADCP users for measurements collected in various regions of the United States and Canada. Almost 90% of the discharges computed using the automatic algorithm were within 1% of the discharge computed by the experienced user. Only about 65% using the 1/6th power fit and about 70% using a constant fit at the top and a no slip at the bottom were within 1% of the discharge computed by the experienced user. Thus, proper evaluation and selection of the extrapolation methods for each measurement is important. Although the automated algorithms have been shown to be useful and accurate, they failed to meet the 1% standard in about 10% of the measurements evaluated. Therefore, the user must still visually evaluate the automatically selected methods, as the responsibility for selecting the appropriate extrapolation methods remains with the user, *extrap* is simply a tool to make the selection potentially more accurate, and the process more efficient and reproducible.

### 3. Software description

Most of the field hydrographers using ADCPs to measure discharge are not familiar with Matlab<sup>®</sup>, so *extrap* is typically distributed as an executable with a GUI compiled using the Matlab<sup>®</sup> compiler. The GUI for *extrap* (Fig. 5) provides the user with the ability to load files, save results, configure and explore the profile graph, evaluate and change the appropriate increment threshold, change the fit method and exponent, and assess the effect of the fit methods on the computed discharge.

*extrap* allows loading of all transects that comprise a measurement. For Teledyne RD Instrument (TRDI) manufactured ADCPs (Rio Grande, StreamPro, and RiverRay) the \*.mmt, \*.pd0, and \*.r.000 files are supported. If the \*.mmt file is loaded, *extrap* will determine which transects have been marked as being used in the

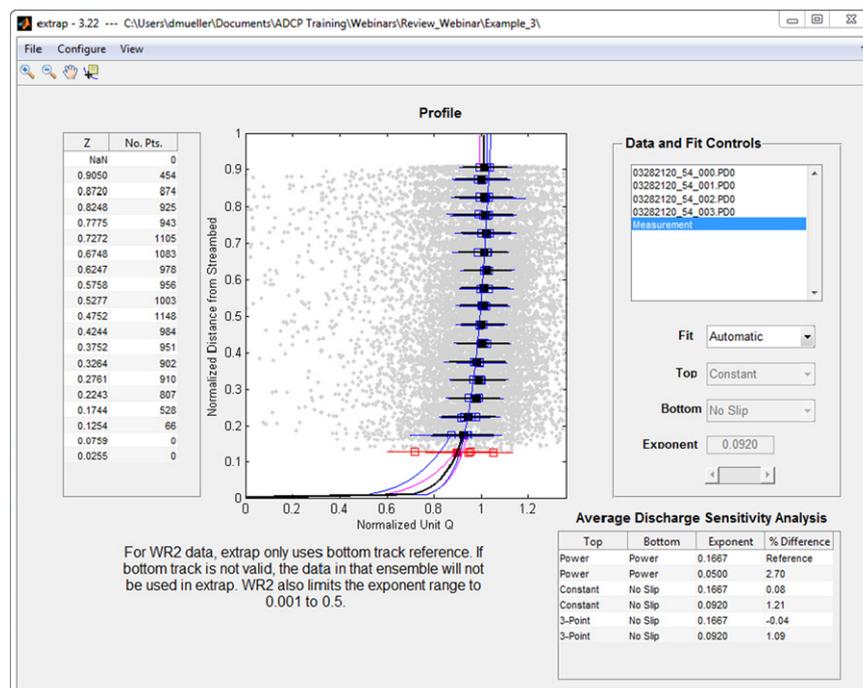


Fig. 5. User interface for *extrap* showing example data.

discharge measurement and read the associated raw data files and supporting data (transducer depth). If TRDI raw data files (\*.pd0 or \*.000) are used independently from the \*.mmt file, the user will be prompted for the transducer depth for each file, as this information is not contained in the raw data files. *extrap* is not compatible with ASCII output files from WinRiver II (Teledyne RD Instruments, 2012). To use *extrap* with SonTek RiverSurveyor data, the data must first be loaded into RiverSurveyor Live (SonTek, 2012) and Matlab® files created. All the necessary data are contained in the Matlab® files generated by RiverSurveyor Live.

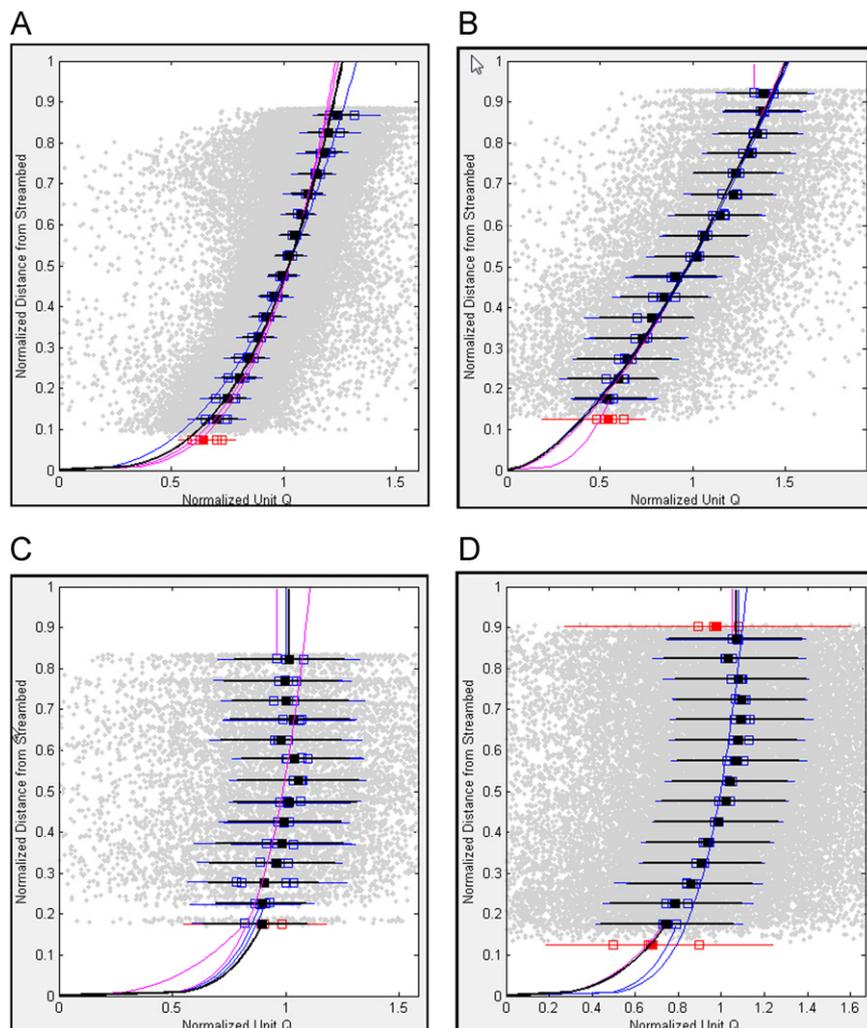
The main feature of the GUI is the Profile graph. The gray points are the normalized data for each depth cell in the cross section. The blue open boxes and whiskers are the median unit cross product (referred to as unit discharge) and interquartile range for each transect. The black solid boxes and whiskers are the median unit cross product and interquartile range for the composite of all transects. Magenta and blue lines along the profile show the extrapolation fit for each transect with the colors indicating the starting bank of the transect. The heavy black line shows the extrapolation fit for the composite of all transects comprising the measurement. Squares and whiskers plotted in red in the Profile graph identify medians that did not meet the minimum threshold for number of points. The user can turn on

and off the display of these features through the Configure menu and use of the Data and Fit Controls panel.

The Data and Fit Controls panel allows the user to select what data are displayed and change the extrapolation method and exponent. The name of each of the transects loaded is displayed in a list box. The final entry in the list box is “Measurement,” which represents the composite of all of the transects. The user can display in the Profile graph individual transects by selecting the desired transect from the list box or display all the data by selecting the “Measurement” (this is the default). The Fit, Top, Bottom, and Exponent controls can be used to change the extrapolation method displayed in the Profile graph for the selected data.

The table at the left of the Profile graph displays the normalized distance from the streambed and the number of points contained in each 5% profile increment. These data are used to determine if the threshold for marking an increment invalid should be changed.

To aid the user in assessing the effect of extrapolation methods on the total discharge, a discharge sensitivity analysis is displayed in a table in the lower right section of the GUI. The discharge sensitivity computes the discharge for six combinations of top and bottom extrapolation methods and compares the differences to the default power law with an exponent of 0.1667. From this



**Fig. 6.** Examples of streamflow data with various profile shapes as presented in the profile plot from *extrap*. (A) Typical power profile, (B) power profile with lower exponent—may due to smooth streambed or channel configuration, (C) near vertical profile requiring constant fit for the top and no slip fit at the bottom—may be caused by channel configuration, (D) profile with lower velocities at the surface—may be caused by upstream wind.

analysis the user can determine how sensitive the final discharge is to changes in extrapolation methods and also obtain a qualitative estimate of the uncertainty in the total discharge resulting from the unmeasured top and bottom parts of the water column.

#### 4. Application

The following is a generalized description of the steps for using *extrap* to evaluate and select the appropriate extrapolation method for a measurement.

1. Load the appropriate data file(s). For TRDI data collected with WinRiver II it is recommended that the user load the \*.mmt file that has been saved with the transects marked that comprise the discharge measurement. For SonTek RiverSurveyor data, the data should be loaded into RiverSurveyor Live and the Matlab® files generated. The Matlab® files generated from RiverSurveyor Live for all of the transects comprising the discharge measurement should be loaded at one time. Moving-bed tests or other transects not used in the computation of the final discharge should not be loaded into *extrap*, as they would affect the reported discharge sensitivity analysis.
2. Visually assess the automated fit generated by *extrap*.
3. Look at the average discharge sensitivity analysis table to determine how sensitive the final discharge is to the selected extrapolation. If the computed discharge is sensitive to the extrapolation method, extra care should be taken and perhaps documentation recorded as to why a particular extrapolation was selected. If the discharge is not sensitive to the extrapolation method, the best extrapolation method should be selected without unnecessary effort spent on detailed evaluation and documentation.
4. If the automatically selected extrapolation is not satisfactory after steps 2 and 3, change the Fit option to Manual and adjust the Top, Bottom, and Exponent to achieve the best fit.
5. A good practice is to save the summary of the fit analysis to an ASCII file and store it with the measurement. The save summary feature will allow the user to enter comments. This is a good place to document any considerations regarding the selection of the extrapolation methods.
6. Manually enter the selected extrapolation method and exponent(s) into WinRiver II or RiverSurveyor Live and reprocess the data to achieve the final discharge. Do not use the percent difference in the discharge sensitivity analysis table to simply correct the final discharge.

A sample of the types of data and profiles evaluated using *extrap* are shown in Fig. 6. The selection of the best extrapolation method often is influenced by hydraulic and environmental conditions experienced during the measurement such as streambed roughness variations, channel configuration, and surface winds.

#### 5. Future enhancements

*extrap* was designed to support the computation of discharge and was thus limited to the extrapolation methods that are supported in the current (2012) manufacturers' software. However, *extrap*'s approach to using normalized data provides the foundation to explore other hydraulically valid extrapolation methods to fit profiles that do not follow the power law. Research into the variation of profile shape within a cross section could result in an applied approach to varying the extrapolation for

different parts of the cross section. Additional and improved logic may allow *extrap* to achieve better performance regarding the automatic selection of the appropriate extrapolation method.

#### 6. Summary and conclusions

*extrap* is a Matlab® program to aid in the selection of the appropriate top and bottom discharge extrapolation methods for moving-boat ADCP streamflow measurements. Prior to *extrap*, the approach was to average multiple ensembles to reduce noise in the discharge profile, visually evaluate the discharge profile, and select an appropriate extrapolation method for the top and bottom discharges. Current (2012) manufacturers' software either does not provide an averaging option or it averages across depth cells, which could result in a distorted mean profile. *extrap* uses normalized profiles, which allow data from the entire measurement to be used in the determination of the mean profile, while ensuring that data from deep and shallow parts of the channel are represented at the appropriate location on the profile. *extrap* provides both automated and manual methods for selecting the extrapolation method. The user interface provides the user with the ability to load files, configure and explore the profile graph, evaluate and change the threshold for number of points required in an increment for a valid median, change the fit method and exponent, assess the effect of the fit methods on the computed discharge, and save results. There is no interaction between *extrap* and manufacturers' software so the user must manually enter the selected extrapolation methods into the manufacturers' software to compute the final discharge for the measurement. Use and testing of *extrap* by field hydrographers have demonstrated that *extrap* is a more accurate and efficient method of determining the appropriate extrapolation methods compared with tools provided in the manufacturers' software.

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#### References

- Blanchard, S.F., 2007. Recent Improvements to the U.S. Geological Survey Stream-gaging Program. Fact Sheet 2007-3080, U.S. Geological Survey, Reston, Virginia, 6 p.
- Chen, Cheng-Lung, 1989. Power law of flow resistance in open channels—Manning's formula revisited. In: Proceedings of the International Conference on Channel Flow and Catchment Runoff: Centennial of Manning's Formula and Kuichling's Rational Formula, Charlottesville, Virginia, May 22–29, 1989, p. 818–848.
- Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill, New York 680 p.
- Guo, Junke, Julien, P.Y., 2008. Application of the modified log-wake law in open-channels. Journal of Applied Fluid Mechanics 1 (2), 17–23.
- Kennedy, E.J., 1983. Computation of continuous records of streamflow. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, Chapter A13. Denver, Colorado 53 p.
- Levesque, V.A., Oberg, K.A., 2012. Computing Discharge Using the Index Velocity Method. Techniques and Methods Report, Book 3, Chapter A23, U.S. Geological Survey, Reston, Virginia, 148 p.
- Mason, R.R., 2011. Exposure time for ADCP moving-boat discharge measurements during steady flow conditions. U.S. Geological Survey, Office of Surface Water Technical Memorandum 2011.08, <<http://water.usgs.gov/admin/memo/SW/sw11.08.pdf>> [accessed September 21, 2012].
- Mathworks, 2012. Matlab, Version 7.14.0.739, Natick, Massachusetts, <<http://www.mathworks.com/products/matlab/>> [accessed September 20, 2012].
- Mueller, D.S., Wagner, C.R., 2009. Measuring Discharge with Acoustic Doppler Current Profilers from a Moving Boat. Techniques and Methods Report, Book 3, Chapter A22, U.S. Geological Survey, Reston, Virginia, 72 p.

- Simpson, M.R., 2001. Discharge Measurements Using a Broad-Band Acoustic Doppler Current Profiler. Open-File Report 01-1, U.S. Geological Survey, Sacramento, California, 123 p.
- Simpson, M.R., Oltmann, R.N., 1993. Discharge Measurement Using an Acoustic Doppler Current Profiler. Water-Supply Paper 2395, U.S. Geological Survey, Denver, Colorado, 34 p.
- SonTek, 2012, RiverSurveyor Live. Version 3.5, San Diego, California, <<http://www.sontek.com/sw/riversurveyor-live.php>> [accessed September 20, 2012].
- Teledyne RD Instruments, 2011, Acoustic Doppler Current Profiler Principles of Operation a Practical Primer. P/N 951-6069-00, San Diego, California, 54 p.
- Teledyne RD Instruments, 2012, WinRiver II. Version 2.09, San Diego, California, <[http://www.rdinstruments.com/support/softwarefirmware/downloadSoftware.aspx?software=WinRiver\\_II\\_v2.09\\_Setup.EXE](http://www.rdinstruments.com/support/softwarefirmware/downloadSoftware.aspx?software=WinRiver_II_v2.09_Setup.EXE)> [accessed September 20, 2012].
- Yang, Shu-Qing, Tan, Soon-Keat, Lim, Siow-Yong, 2004. Velocity distribution and dip-phenomenon in smooth uniform open channel flows. *Journal of Hydraulic Engineering, American Society of Civil Engineers* 103 (12), 1179–1186.