Index-Velocity Rating Development for Rapidly Changing Flows in an Irrigation Canal Using Broadband StreamPro ADCP and ChannelMaster H-ADCP

HENING HUANG, *RD Instruments, 9855 Businesspark Avenue, San Diego, CA 92127, USA*

ABSTRACT

Field data collection and regression analysis were conducted to develop Index-velocity rating for rapidly changing flows in an irrigation canal at Imperial Irrigation District, California. Discharges were measured using a RD Instruments broadband StreamPro ADCP on December 9, 2003. Index-velocities were measured concurrently with the discharge measurements using a RD Instruments 600 kHz broadband ChannelMaster H-ADCP. Because of using broadband technology, the StreamPro ADCP and ChannelMaster H-ADCP were able to measure discharge and index-velocity accurately at short time span or intervals to accommodate rapidly changing flows. A total of 31 pairs of mean velocity and Index-velocity data were obtained for velocities ranging from 0.02 m/s to 0.42 m/s. The data were best fit with a linear regression equation with a correlation coefficient of 0.998. The developed Index-velocity rating can be used to accurately monitoring discharge in real-time at this site.

1 Introduction

Index-velocity method was developed and used by United States Geological Survey (USGS) for discharge (flow rate) monitoring or recording at streamflow-gaging stations where flow conditions may make the use of conventional "stage-discharge rating" method impractical or impossible. These flow conditions include flow reversals, backwater effects, hysteresis effects (different stage-discharge relations for rising and falling stages), and channel-roughness changes (Morlock et. al. 2002).

The principle of the Index-velocity method is to develop a regression equation (or rating curve) that relates the channel mean velocity to an Index-velocity. The Index-velocity is a time and range averaged velocity measured by a velocity meter or current profiler. The development of an Index-velocity rating involves two steps. The first step is to collect data for discharge and Index-velocity. The data collection needs to be conducted for a range of discharge. A set of data for channel mean velocity derived from measured discharge data and Index-velocity will be obtained. The second step is to perform regression analysis for the data set. A regression equation or rating curve is to be developed from the regression analysis.

For a rapidly changing flow, discharge and Index-velocity measurements must be conducted concurrently and rapidly. The concurrent requires the timing for discharge measurement matches the timing for Index-velocity measurement. The rapidity requires a discharge measurement and corresponding Index-velocity measurement is to be completed within a short time span. Apparently, the use of mechanic meters by conventional means such as cableway, wading, or bridge is not suitable for discharge measurement in rapidly changing flows because it usually takes an order of one hour to complete a measurement. High precision and resolution ADCP (acoustic Doppler current profiler) such as RD Instruments Broadband Rio Grande ADCP or StreamPro ADCP that can make rapid and accurate discharge measurements is suitable for rapidly changing flows.

Acoustic Doppler velocity meters (ADVM) are commonly used for Index-velocity measurements. However, an ADVM based on narrowband Doppler technology has a limitation in precision due to its relatively high short-term random error (i.e., high variance in velocity measurement). Therefore, a narrowband ADVM needs a long sampling/averaging interval to achieve a desired Index-velocity measurement accuracy. Obviously, the narrowband ADVM may not be suitable for Index-velocity measurement in rapidly changing flows.

Recently, RD Instruments introduced a ChannelMaster H-ADCP (Horizontal acoustic Doppler profiler). ChannelMaster H-ADCP is based on the patented broadband Doppler technology. Because of its much lower short-term random error as compared to a narrowband ADVM, the broadband ChannelMaster H-ADCP can provide accurate velocity measurement at a short sampling/averaging interval.

This report describes field data collection and regression analysis to develop Index-velocity rating for rapidly changing flows in the Westside Main Canal at Imperial Irrigation District, California. Discharges were measured using a RD Instruments broadband StreamPro ADCP. Index-velocities were measured concurrently with the discharge measurements using a RD Instruments 600 kHz broadband ChannelMaster H-ADCP. Because of using broadband technology, the StreamPro ADCP and ChannelMaster H-ADCP were able to measure discharge and index-velocity accurately at short time span or intervals to accommodate rapidly changing flows at this site.

2 Field Data Collection

Field data collections were conducted on December 9, 2003 in the Westside Main Canal near the Trifolium 13 Check site (Figure 1). The check structure consisted of three drop-leaf gates that were controlled by an on site auto-control system. There were two turnouts at the right bank upstream the check structure. One was located at 4.9 meters (16 feet) and the other was at 25.9 meters (85 feet) upstream the check structure. The one at 4.9 meters from the structure was kept closed during the test period. However, the one at 25.9 meters from the check structure was kept open during the test period.

The trapezoidal concrete lining canal had a bottom width of 3.05 meters (10 feet) and a slope of 1:1.5. The mean water depth over the canal bottom was around 1.4 meters (4.5 feet) during the test day. The canal served as a flow diversion structure for the Westside Main Canal system. Its flow could change dramatically during a day from near zero to over 3 m^3/s (106 cfs).

To facilitate discharge measurements, a pulley system was set up and the StreamPro ADCP was attached to the pulley. The pulley system was at 57 meters (187 feet) upstream the check structure (Figure 2).

A temporary mounting, modified from a steel shelf, was used to mount the 600 kHz ChannelMaster H-ADCP (Figure3). The mounting location was at 7.6 meters (25 feet) upstream the StreamPro ADCP pulley (Figure 2). It was placed on the right bank slope of the canal, about two meters from the wet line. Two steel bars were attached to the front legs of the shelf to accommodate the bank slope.

Figure 1 Trifolium 13 Check structure.

Figure 2 StreamPro ADCP attached to a pulley system 57 meters (187 feet) upstream Trifolium 13 Check structure; ChannelMaster H-ADCP mounted 7.6 meters (25 feet) upstream the pulley.

Figure 3 ChannelMaster H-ADCP prior to deployment.

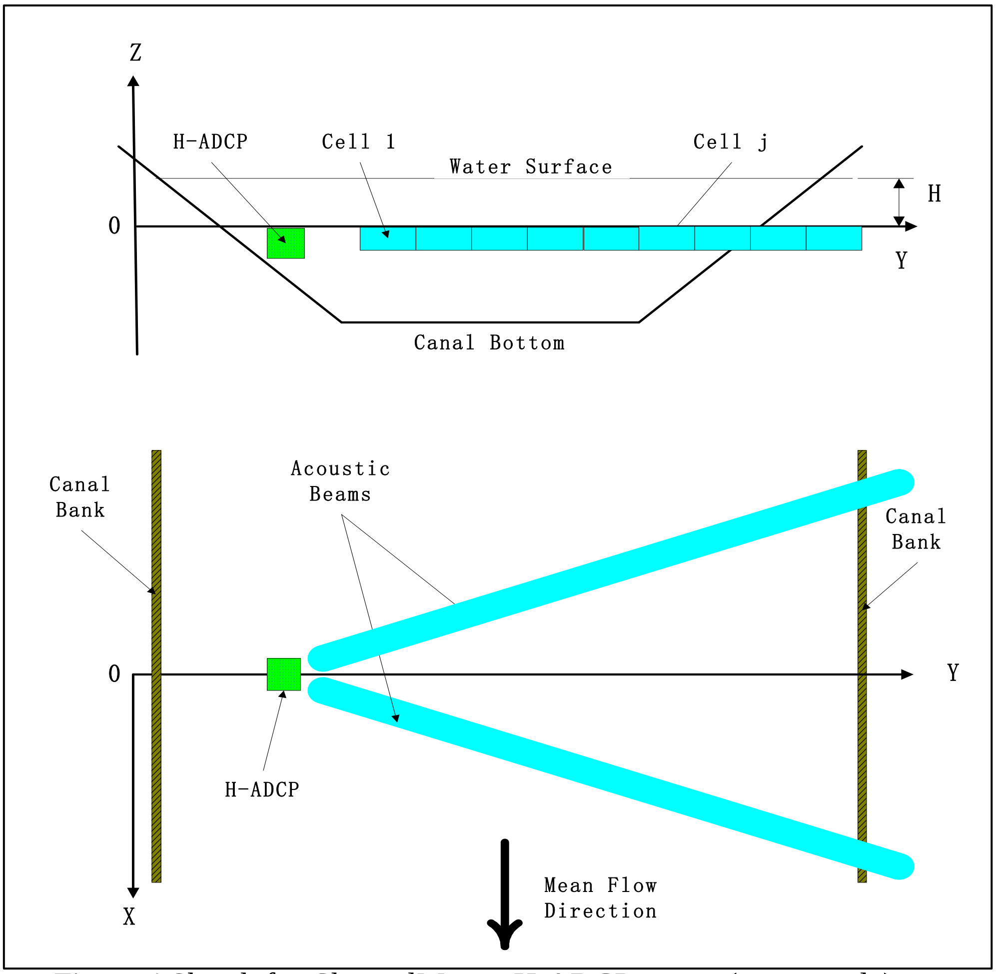

Figure 4 Sketch for ChannelMaster H-ADCP set-up (not to scale).

Figure 4 shows a sketch for the ChannelMaster H-ADCP set-up. The H-ADCP, mounted on the right bank of the canal, had its orientation perpendicular to the mean flow direction. That is, its instrument coordinate X was parallel to the mean flow and Y to the cross-section direction.

The StreamPro ADCP was configured using its software running on iPAQ pocket PC. The parameter settings are summarized as follows:

- Transducer depth: 3.5 cm
- Cell size: 10 cm
- Number of cells: 20

StreamPro ADCP transects were made from 12:30 to 16:30. The float speed was kept around 3 to 5 cm/s. Each transaction took about 2.5 to 4 minutes to complete. A total of 31 transect data files were obtained. Depending on transect time span, each transect usually include 150 to 240 ensembles. The ensemble data include water velocity profile, bottom tracking velocity, water depth, acoustic intensity, etc. Discharges were calculated from ensemble data in real-time by the StreamPro software and in playback by the WinRiver software.

The ChannelMaster H-ADCP was configured using the Windows based WinHADCP software. In order to measure the rapidly changing flows at this site, the H-ADCP was configured at an averaging interval of 37.4 seconds. The sampling interval was set to be the same as the averaging interval so that, if needed, further time averaging in post processing can be made. Below is the summary of the ChannelMaster H-ADCP settings:

- Cell size: 0.5 meter
- Number of cells: 20
- Blank distance: 0.5 meter
- Averaging Interval: 37.4 seconds
- Sampling Interval:37.4 seconds

During the averaging interval of 37.4 seconds, the H-ADCP sent 60 water velocity measurement pings and 3 surface tracking pings.

After setting the parameters, the H-ADCP was disconnected from the PC. It then worked in a self-contained mode and recorded data to its internal memory. The ChannelMaster H-ADCP was continuously collecting data from 12:34:20 to 16:18:43 at the 37.4-second sampling/averaging interval. A total of 361 ensemble data sets for velocity profile, water level, pitch and roll, acoustic intensity, etc. were obtained.

3 Data and Analysis

3.1 Data Playback and Display

Transect data files collected by the StreamPro ADCP were played back and displayed with WinRiver software. Figure 5 shows a screenshot from WinRiver when playing back a data file. The top plot shows the velocity magnitude contour as well as water depth along the float track. The bottom plot shows the float track (red line) as well as depth-averaged velocity vector (blue sticks) along the track. The StreamPro outputs the velocity vectors (and all other data) at 1 Hz, i.e., one vector per second (StreamPro pings at a fixed rate of 48 Hz).

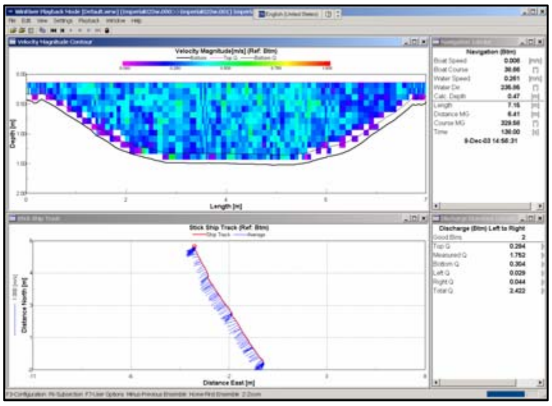

Figure 5 Screenshot from WinRiver software when playing back a StreamPro data file.

After all of the 31 transects data files were played back in WinRiver, a discharge summary table was generated by WinRiver. The summary table then was copied and imported into an Excel spreadsheet for regression analysis.

The data file collected by the H-ADCP was played back with WinHADCP. The payback displayed velocity and acoustic intensity on a PC screen. It was found from the intensity profiles that the acoustic beams were hitting the left bank at the Cell 6 location. Therefore, velocity data at Cells 1 through 5 were valid and to be used in the rating development.

A range averaging of V_x for Cells 1 through 4 was made in WinHADCP post-processing mode. A report file in ASCII format was generated during the processing. The report file was then imported into an Excel spreadsheet. Figure 6 shows time series of the range averaged velocity data imported into the Excel spreadsheet. The time series data for water level (H), referencing to the H-ADCP vertical transducer surface, are also show in the figure.

It is noted from Figure 6 that the velocity variation is significant, from 0.02 m/s to 0.45 m/s. However, the water level variation is less significant, from 0.38 m to 0.54 m. Also note that the velocity data exhibit some "noise". The "noise" is believed to be mainly due to the turbulence of the flow, not the system noise. This is particularly true for high velocities. The system noise, in terms of standard deviation (error), was estimated to be less than 1 cm/s for the sampling volume of 2 meters (Cell 1 through Cell 4) with the averaging interval of 37.4 seconds.

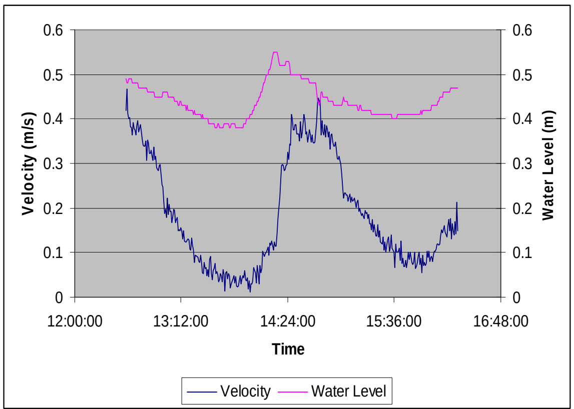

Figure 6 Time series of range averaged V_x for Cells 1 through 4 and water level at the sampling/averaging interval of 37.4 seconds

3.2 Organizing Data for Regression Analysis

The data from the StreamPro ADCP and ChannelMaster H-ADCP were organized to obtain data sets for Index-velocity, stage, canal cross-section area, and canal mean velocity.

3.2.1 Index-Velocity

Proper time averaging interval and range averaging length for Index-velocity first need to be determined. In order to match the average transect time span (in average, 3 minutes) of the StreamPro ADCP discharge measurements, the time averaging interval was chosen to be 187 seconds. Note that the original ensemble data were collected at a sampling/averaging interval of 37.4 seconds. Therefore, the velocities for five ensembles collected within 187 seconds were averaged.

The multiple-cell setting of the ChannelMaster H-ADCP allowed several alternatives for range averaging length for Index-velocity sampling volume (a group of cells) and sampling volume location. An alternative that results in the best Index-velocity rating should be selected. In general, the averaging for a group of cells located near the middle of canal may provide a better rating than a single cell or a group of cells located near canal edges. Two range averaging alternatives were tested. The first alternative was to group the first two cells, ranging from a distance of 0.96 m to 1.96 m from the H-ADCP. The second alternative was to group the first four cells, ranging from 0.96 m to 2.96 m from the H-ADCP. The regression analysis was conducted for the two alternatives and the result indicated that the second alternative resulted in a better rating (higher correlation coefficient). Therefore, the second alternative was chosen so that the Index-velocity range averaging length was 2 meters and the sampling volume was located at the middle portion of the canal.

Both of the time and range averaging was made using the WinHADCP post-processing mode. Below is the formula for calculating the Index-velocity from the H-ADCP output velocity data:

$$V_{I,k} = \frac{1}{5}\sum_{i=k}^{i=k+4}\left[\frac{1}{4}\sum_{j=1}^{j=4}(V_x)_j\right]_i \qquad k = 1, 2, 3\ldots.. \quad (1)$$

where, j is the index for cell number, k is the index for ensemble number, $V_{I,k}$ is the Index-velocity at time t (corresponding to k), $(V_x)_j$ is the Cell j x-component of velocity.

3.2.2 Stage

The H-ADCP used its vertical acoustic beam to measure the distance from the transducer surface to the water surface. The transducer surface was assumed to be the stage reference level (datum). Therefore, the water level measured by the H-ADCP was taken as stage.

3.2.3 Cross-section area

The cross-section area at time t was a function of water level (or stage). It was calculated from the following equation for a trapezoidal canal:

$$A = [\frac{H - Z_{bottom}}{s} + W_{bottom}] \times (H - Z_{bottom}) \qquad (2)$$

where, A is the canal cross-section area, H is the water level (or stage), s is the canal bank slope, W_{bottom} is the canal bottom width, and Z_{bottom} is the canal bottom elevation. For the canal: s = 1/1.5, W_{bottom} = 3.05 meters, and Z_{bottom} = -1.06 meters.

3.2.4 Canal Mean Velocity

The canal mean velocity was calculated by dividing the StreamPro ADCP measured discharge by the cross-section area:

$$V_{mean} = \frac{Q_{measured}}{A} \qquad (3)$$

where V_{mean} is the canal mean velocity, and $Q_{measured}$ is the StreamPro ADCP measured discharge.

Table 1 summarizes the organized StreamPro ADCP and ChannelMaster H-ADCP data for the Index-velocity rating development.

Table 1 Summary of Organized StreamPro ADCP and ChannelMaster H-ADCP Data for Index-Velocity Rating Development.

StreamPro ADCP Measurement			**ChannelMaster H-ADCP Measurement**			
Transect Start Time	Measured Discharge ($Q_{measured}$) [m³/s]	Canal Mean Velocity (V_{mean}) [m/s]	Sample Start Time	Water Level (H) [m]	Index-Velocity (V_I) [m/s]	Cross-Section Area (A) [m²]
12:44:56	2.482	0.304	12:44:56	0.470	0.351	8.175
12:49:03	2.264	0.280	12:49:18	0.460	0.336	8.098
12:57:01	1.914	0.239	12:57:24	0.453	0.274	8.041
13:01:31	1.391	0.172	13:01:46	0.455	0.199	8.060
13:11:05	0.954	0.120	13:11:07	0.435	0.146	7.909
13:14:41	0.783	0.099	13:14:51	0.425	0.127	7.834
13:21:01	0.574	0.074	13:21:05	0.413	0.088	7.740
13:24:57	0.474	0.061	13:24:49	0.405	0.069	7.684
13:36:20	0.256	0.034	13:36:03	0.385	0.045	7.536
13:40:36	0.247	0.033	13:40:24	0.388	0.045	7.555

13:53:28	0.235	0.031	13:50:23	0.380	0.035	7.499
13:58:47	0.312	0.040	13:58:29	0.413	0.027	7.740
14:21:01	2.062	0.241	14:20:55	0.523	0.291	8.580
14:24:55	2.551	0.304	14:24:40	0.513	0.351	8.502
14:43:16	3.036	0.368	14:43:22	0.443	0.429	7.966
14:47:41	2.511	0.313	14:47:44	0.450	0.370	8.022
14:51:30	2.502	0.315	14:51:28	0.440	0.356	7.947
14:54:13	2.422	0.305	14:54:35	0.433	0.343	7.890
14:57:20	2.109	0.268	14:57:42	0.430	0.309	7.871
15:00:27	1.582	0.199	15:00:49	0.443	0.234	7.966
15:09:00	1.44	0.183	15:08:55	0.430	0.212	7.871
15:15:39	1.271	0.163	15:15:47	0.420	0.187	7.796
15:19:05	1.085	0.139	15:18:54	0.418	0.167	7.778
15:23:11	0.974	0.126	15:23:15	0.410	0.143	7.722
15:27:17	0.871	0.113	15:27:00	0.410	0.120	7.722
15:31:24	0.782	0.101	15:31:22	0.410	0.119	7.722
15:36:06	0.737	0.096	15:36:21	0.403	0.097	7.666
15:42:25	0.591	0.077	15:42:35	0.410	0.072	7.722
16:06:45	0.934	0.118	16:06:53	0.450	0.138	8.022
16:11:38	1.069	0.132	16:11:53	0.463	0.165	8.117
16:15:24	1.077	0.132	16:15:37	0.470	0.150	8.175

3.3 Regression Analysis Results

All of the 31 data pairs for measured mean velocity vs. Index-velocity are plotted in Figure 7. It can be seen from the plot that the data can be well fitted by a straight line passing through the zero velocity point, indicating a linear relationship between the mean velocity and Index-velocity. Using the Excel built-in regression analysis tool, we obtain the regression coefficient and correlation coefficient. The following is the resulting regression equation:

$$V_{mean} = 0.8606 \times V_I \qquad (4)$$

with a correlation coefficient of 0.998.

Note that the regression does not include stage as a parameter. This was because the stage variation at this site was insignificant as compared to the mean water depth.

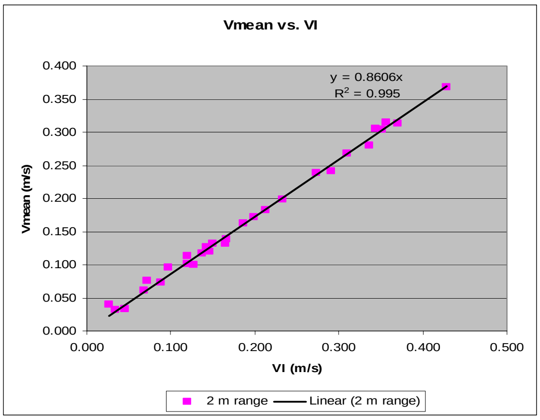

Figure 7 Measured mean velocity vs. Index-velocity: all data.

As a comparison to the regression results from all of the 31 data pairs, Figure 8 shows a plot for the first 12 data pairs for measured mean velocity vs. Index-velocity. These 12 data pairs covered a whole range of flow, from low to high. The regression equation from the partial data is obtained as follows:

$$V_{mean} = 0.8515 \times V_I \qquad (5)$$

with a correlation coefficient of 0.998.

The coefficient (0.8515) derived from the partial data is only 1.1% different from that (0.8606) derived from all of the data, indicating the rating is stable and not sensitive to data amount. However, large data set is always preferred because confidence level for regression results will be increasing with increasing data amount.

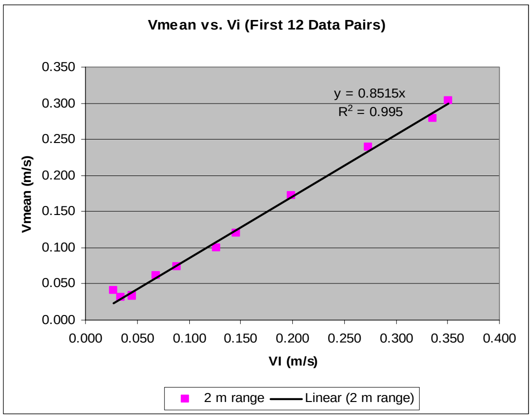

Figure 8 Measured mean velocity vs. Index-velocity: first 12 data.

As a comparison to the Index-velocity rating, Figure 9 shows a plot of StreamPro measured ADCP discharge vs. stage (water level). It can be seen that the data are scattering and it is impossible to create a meaningful stage-discharge rating for this site. This is because the flow at this site is regulated by the check structure and upstream structures. The hydraulic conditions that permit a stage-discharge rating do not exist at this site.

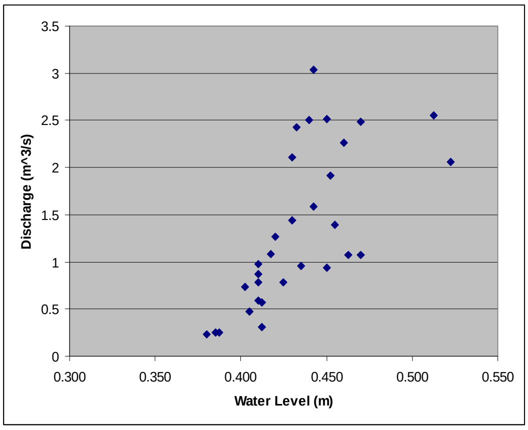

Figure 9 StreamPro ADCP measured discharge vs. stage (water level), indicating a stage-discharge rating cannot be created at this site.

4 Implementing the Index-Velocity Rating

With the developed Index-velocity rating, the discharge in the Westside Main Canal near the Trifolium 13 Check site can be calculated from the following:

$$Q = 0.8606 \times V_I \times A \qquad (6)$$

where Q is the rated discharge, and A is the canal cross-section area that is to be calculated from Equation 2.

It is important to note that the Index-velocity in Equation 6 must have the same range averaging length as that used in the rating development. That is, the same cells need to be grouped to ensure that the sampling volume will be the same. In addition, the H-ADCP mounting location should remain the same and the mounting should be stable over time. This is because the regression coefficient is specific for the sampling volume and its location. Changing size of the sampling volume and/or its location will result in coefficient changing, which will require re-development of rating.

However, the time averaging interval for the Index-Velocity in Equation 5 may not be necessarily the same as that used in the rating development. A short time averaging interval may be used so that flow fluctuation details can be revealed and fast data update can be achieved.

Figure 10 shows the rated discharge time series by applying the rating equation (Equation 6) to all of the ChannelMaster data collected on December 9, 2003. Note that the Index-velocity was calculated with original averaging interval of 37.4 seconds. The StreamPro ADCP measured discharges are also shown in Figure 10. It can be seen that the rated discharges agree very well with the measured discharges.

Note that, in addition to rapidly changing nature of the flow, the discharge also exhibit significant fluctuation. The fluctuation is mainly due to turbulence of the flow, particularly at high flows.

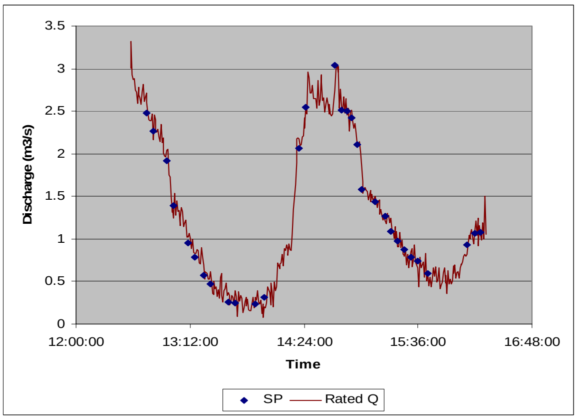

Figure 10 Time series of rated discharges by applying Equation 6 to ChannelMaster H-ADCP data and StreamPro ADCP measured discharges on December 9, 2003.

5 Conclusion

A total of 31 pairs of mean velocity and Index-velocity data were collected and an Index-velocity rating was developed for rapidly changing flows in the Westside Main Canal near the Trifolium 13 Check site at Imperial Irrigation District, California.

Results indicated that, because of using broadband technology, the StreamPro and ChannelMaster were able to measure discharge and index-velocity accurately at short time intervals to accommodate rapidly changing flows at this site. The data for canal mean velocity and Index-velocity were best fit with a linear regression equation with a correlation coefficient of 0.998. The developed Index-velocity rating can be used in conjunction with a ChannelMaster H-ADCP to accurately monitoring discharge in real-time at this site.

References

1. Morlock, S.E., Nguyen, H.T., and Ross, J.H. (2002). Feasibility of acoustic Doppler velocity meters for the production of discharge records from U.S. Geological Survey streamflow-gaging stations. U.S. Geological Survey, Water-Resources Investigations Report 01-4157.