Application of Index Velocity Method in Complex Flow Conditions

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I. Introduction

The collection of accurate and reliable flow records in open channel flow is dependent on several factors of which a stable stage-discharge relationship is crucial.

Flow monitoring site and hydraulic conditions that can impact a stable stage-discharge relationship comprises of unstable section control, sediment transport, debris, vegetation, off-channel storage, variable backwater effects and unsteady flow conditions.

Variable backwater, off-channel storage and unsteady flow conditions are all hydraulic conditions that can have a significant impact on stage-discharge relationship and accurate flow calculations. Flood-wave movement, operation of irrigation canals, tidal effects, stream junctions and flood control measures are some examples of both variable backwater and unsteady flow conditions. The effects of the conditions on stage-discharge rating curves are illustrated in Figure 2.

There are number of established methods in defining a stage-discharge rating curve effected by variable backwater, off-channel storage, and unsteady flow conditions. The methods consist of direct measurements, analytical investigation using simplified approaches, modeling using physical-based approaches, index-velocity method and continuous slope are method. This technical note focuses on the application of the index velocity technique using a bank mounted acoustic doppler velocity meter, SonTek SL1500-3G instrument.

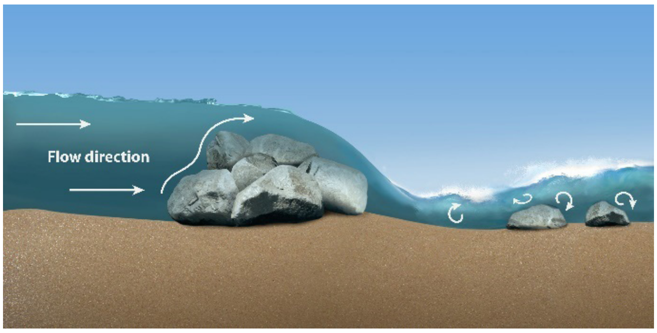

Figure 1. Section Control

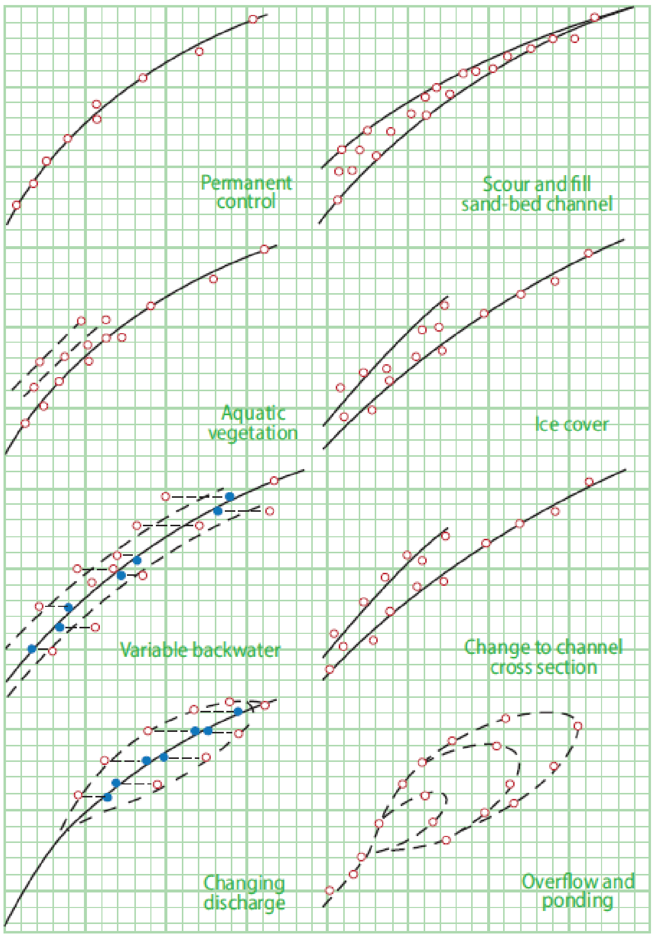

Figure 2. Rating Curves Different Hydraulic Conditions (Adapted from Herschy (2009)

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II. Study Case

The flow monitoring site is situated in a stormwater drain (tributary) shown in Figure 3 for the monitoring of total runoff in the upstream catchment. The tributary discharges into the mainstem of the catchment approximately 1.5km downstream of the flow monitoring site. The site and hydraulic conditions that will affect the development of a traditional stage-discharge relationship at the flow monitoring site consists of variable backwater from the mainstem, off-channel storage on the left bank, backwater due to bridge deck and vegetation.

The conditions present at the flow monitoring site were not suitable for development of a traditional stage-discharge relationship and it was decided to develop an index velocity rating using a SonTek SL1500-3G instrument. The instrument was installed in 2021 on the right bank upstream of the bridge at an elevation of 1.2m above the channel bed.

Figure 3: Flow Monitoring Site

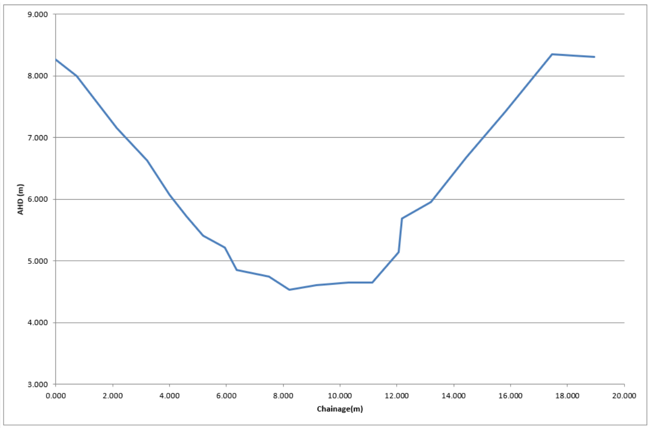

Figure 4: Reference Cross Secaation

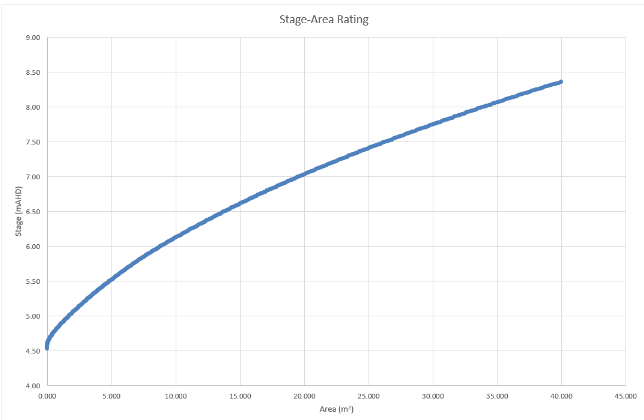

Figure 5: Stage-Area Rating

III. Index Velocity Method

Calculating flow using the index velocity method is different from the traditional stage-discharge rating curve. Index Velocity method consists of two ratings, the index velocity rating and stage-area rating with the output from each rating multiplied to calculate a flow. The index velocity rating is a relationship between the mean-channel velocity and streamwise velocity measured by the SL1500-3G instrument. The stage-area rating is calculated from the cross-section survey of the reference cross section used for the index velocity. The index velocity method is outlined in several published documents listed in the reference section of the tech note.

A. Data Collection

Reference Cross Section: A reference cross section in line with the SL1500-3G instrument was selected for the area calculation. The cross section was surveyed to top of bank, with the left bank starting at chainage 0.000m shown in Figure 4.

Stage-area rating was developed from the reference cross-section surveyed by calculating the area at 1cm intervals for the entire stage range shown in Figure 5.

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Stage: Continuous time series of the stage measurements were recorded from the SonTek SL1500-3G acoustic Doppler velocity meter (ADVM) instrument shown in Figure 6.
The sampling interval of the stage measurements was set to every 15 minutes.

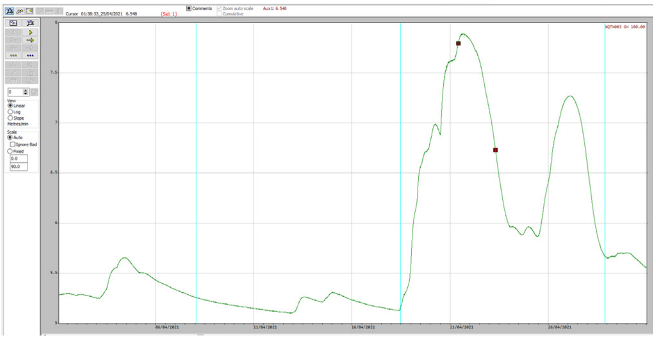

Figure 6: Stage Measurements

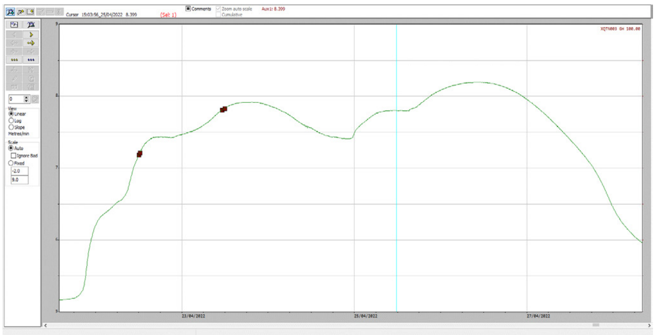

Figure 6: Stage Measurements

Stream Flow Gauging's: A series of stream flow gauging's were performed at the flow monitoring site over a period of 3 years as shown in Table 1.

The stream flow gauging's performed in 2021 was used to develop the initial index velocity rating. Measurements performed in subsequent years were used to analyze and further develop the index velocity rating at the flow monitoring site.

Stream flow gauging's were performed with RiverSurveyor M9, RiverRay and RS5 acoustic Doppler current profilers (ADCP) shown in Figure 8, during the development of index velocity rating. Moving boat technique was used to perform stream flow gauging's and comprised of a series of reciprocal transects (at least 2 transects) and minimum total exposure time of 800 seconds (AUS standard). A loop tagline was used across the channel as this provided increased control over the instrument during stream flow gauging's.

Figure 7: Moving Boat Measurement

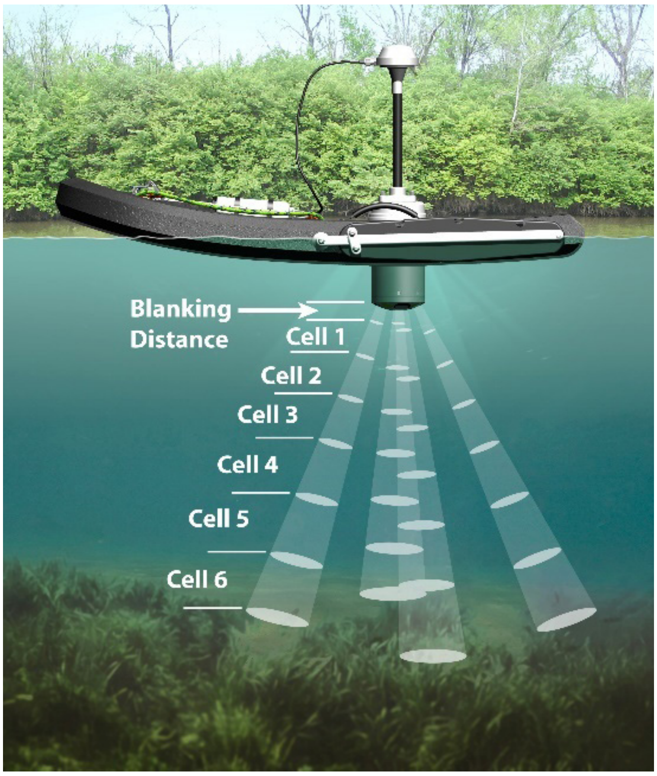

Figure 8: RiverSurveyor M9

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Table 1: Flow Measurements

Date	Time	Flow Measurement (m3/s)	Water Level (mAHD)	Water Level -CTF (m)
29/01/2020	10:12	0.291	5.279	0.649
12/03/2020	09:14	12.349	7.322	2.692
12/03/2020	17:31	5.989	6.791	2.161
13/03/2020	07:23	2.138	6.094	1.464
13/03/2020	12:30	3.932	6.286	1.656
14/03/2020	16:27	1.03	5.595	0.965
17/02/2021	13:20	10.835	7.024	2.394
17/02/2021	13:59	10.963	7.034	2.404
17/02/2021	14:39	10.613	7.035	2.405
18/02/2021	08:42	27.782	8.089	3.459
21/04/2021	09:58	18.685	7.799	3.169
23/04/2021	07:33	5.507	6.732	2.102
22/04/2022	12:01	13.369	7.187	2.557
22/04/2022	12:18	13.613	7.215	2.585
23/04/2022	11:11	8.135	7.81	3.18
23/04/2022	11:57	7.506	7.834	3.204

Index Velocity: Continuous time series of the index velocity measurements were recorded from the SonTek SL1500-3G acoustic Doppler velocity meter (ADVM) instrument shown in Figure 9. The configuration used for the flow monitoring site comprised of the following,

- Sampling duration: 600 seconds
- Sampling interval: 900 seconds
- Number of multi cells: 6
- Multi-cell begin distance: 0.900m
- Multi-cell size: 0.700m

The velocity and stage measurements from the SonTek SL1500-3G instrument were performed concurrently with the stream flow gauging's.

The index velocity types measured by the SonTek SL1500-3G instrument comprised of the following key data sets,

- Velocity (XY).X-MC
- Velocity (XY).Y-MC
- Velocity (XY).X-IVC
- Velocity (XY).Y-IVC
- Velocity Magnitude-MC
- Velocity Magnitude-IVC

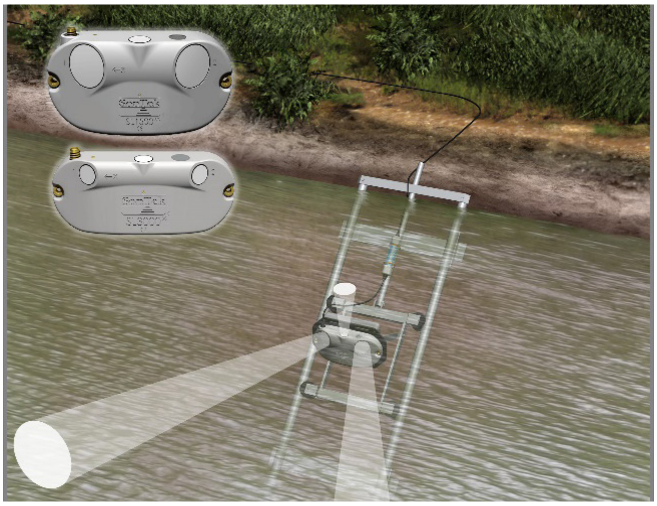
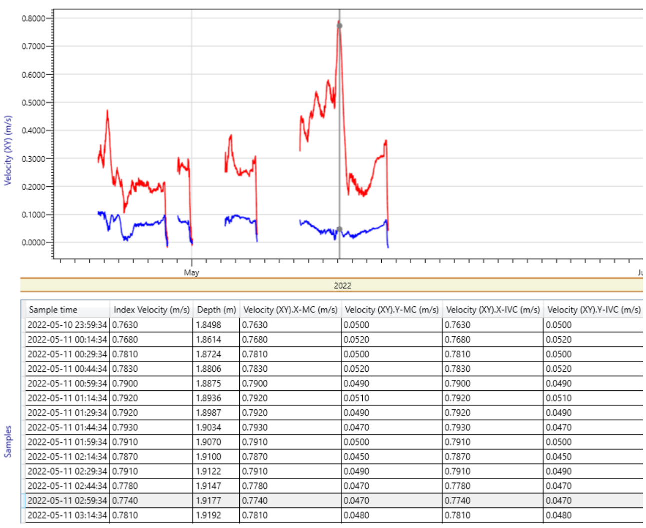


Figure 9: SonTek SL1500-3G



Sample time	Index Velocity (m/s)	Depth (m)	Velocity (XY).X-MC (m/s)	Velocity (XY).Y-MC (m/s)	Velocity (XY).X-IVC (m/s)	Velocity (XY).Y-IVC (m/s)
2022-05-10 23:59:34	0.7630	1.8498	0.7630	0.0500	0.7630	0.0500
2022-05-11 00:14:34	0.7680	1.8614	0.7680	0.0520	0.7680	0.0520
2022-05-11 00:29:34	0.7810	1.8724	0.7810	0.0500	0.7810	0.0500
2022-05-11 00:44:34	0.7830	1.8806	0.7830	0.0520	0.7830	0.0520
2022-05-11 00:59:34	0.7900	1.8875	0.7900	0.0490	0.7900	0.0490
2022-05-11 01:14:34	0.7920	1.8936	0.7920	0.0510	0.7920	0.0510
2022-05-11 01:29:34	0.7920	1.8987	0.7920	0.0490	0.7920	0.0490
2022-05-11 01:44:34	0.7930	1.9034	0.7930	0.0470	0.7930	0.0470
2022-05-11 01:59:34	0.7910	1.9070	0.7910	0.0500	0.7910	0.0500
2022-05-11 02:14:34	0.7870	1.9100	0.7870	0.0450	0.7870	0.0450
2022-05-11 02:29:34	0.7910	1.9122	0.7910	0.0490	0.7910	0.0490
2022-05-11 02:44:34	0.7780	1.9147	0.7780	0.0470	0.7780	0.0470
2022-05-11 02:59:34	0.7740	1.9177	0.7740	0.0470	0.7740	0.0470
2022-05-11 03:14:34	0.7810	1.9192	0.7810	0.0480	0.7810	0.0480

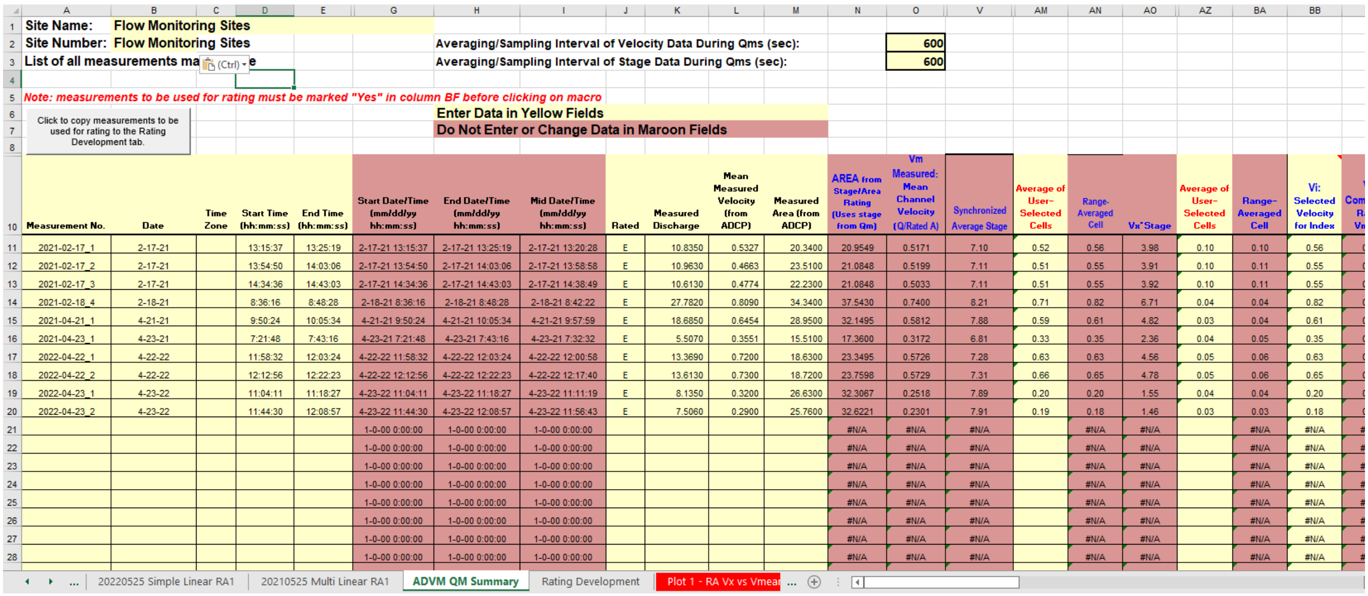
Figure 10: Velocity Measurements

B. Index Velocity Rating

Data Compilation: The velocity and stage time series data recorded during the SonTek SL1500-3G measurements and the calibration data collected at each field visit were compiled into an index velocity spreadsheet shown in Figure 11. The data collected from both the SonTek SL1500-3G instrument and field visits comprise of the following key variables,

- Stream flow gauging's
- Velocity measurements
- Stage measurements
- Stage-Area rating

The stream flow gauging's, velocity measurements and stage measurements were synchronized based on individual time stamps of each measurement. The synchronized timing improves the overall accuracy of the index velocity rating.



Site Name: Flow Monitoring Sites
Site Number: Flow Monitoring Sites
List of all measurements ma (Ctrl) e
Averaging/Sampling Interval of Velocity Data During Qms (sec): 600
Averaging/Sampling Interval of Stage Data During Qms (sec): 600
Note: measurements to be used for rating must be marked "Yes" in column BF before clicking on macro
Click to copy measurements to be used for rating to the Rating Development tab.
Enter Data in Yellow Fields
Do Not Enter or Change Data in Maroon Fields

Row	Measurement No.	Date	Time Zone	Start Time (hh:mm:ss)	End Time (hh:mm:ss)	Start Date/Time (mm/dd/yy hh:mm:ss)	End Date/Time (mm/dd/yy hh:mm:ss)	Mid Date/Time (mm/dd/yy hh:mm:ss)	Rated
11	2021-02-17_1	2-17-21		13:15:37	13:25:19	2-17-21 13:15:37	2-17-21 13:25:19	2-17-21 13:20:28	E
12	2021-02-17_2	2-17-21		13:54:50	14:03:06	2-17-21 13:54:50	2-17-21 14:03:06	2-17-21 13:58:58	E
13	2021-02-17_3	2-17-21		14:34:36	14:43:03	2-17-21 14:34:36	2-17-21 14:43:03	2-17-21 14:38:49	E
14	2021-02-18_4	2-18-21		8:36:16	8:48:28	2-18-21 8:36:16	2-18-21 8:48:28	2-18-21 8:42:22	E
15	2021-04-21_1	4-21-21		9:50:24	10:05:34	4-21-21 9:50:24	4-21-21 10:05:34	4-21-21 9:57:59	E
16	2021-04-23_1	4-23-21		7:21:48	7:43:16	4-23-21 7:21:48	4-23-21 7:43:16	4-23-21 7:32:32	E
17	2022-04-22_1	4-22-22		11:58:32	12:03:24	4-22-22 11:58:32	4-22-22 12:03:24	4-22-22 12:00:58	E
18	2022-04-22_2	4-22-22		12:12:56	12:22:23	4-22-22 12:12:56	4-22-22 12:22:23	4-22-22 12:17:40	E
19	2022-04-23_1	4-23-22		11:04:11	11:18:27	4-23-22 11:04:11	4-23-22 11:18:27	4-23-22 11:11:19	E
20	2022-04-23_2	4-23-22		11:44:30	12:08:57	4-23-22 11:44:30	4-23-22 12:08:57	4-23-22 11:56:43	E
21						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
22						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
23						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
24						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
25						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
26						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
27						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	
28						1-0-00 0:00:00	1-0-00 0:00:00	1-0-00 0:00:00	

Row	Measured Discharge	Mean Measured Velocity (from ADCP)	Measured Area (from ADCP)	AREA from Stage/Area Rating (Uses stage from Qm)	Vm Measured: Mean Channel Velocity (Q/Rated A)	Synchronized Average Stage	Average of User-Selected Cells	Range-Averaged Cell	Vx*Stage	Average of User-Selected Cells	Range-Averaged Cell	Vi: Selected Velocity for Index
11	10.8350	0.5327	20.3400	20.9549	0.5171	7.10	0.52	0.56	3.98	0.10	0.10	0.56
12	10.9630	0.4663	23.5100	21.0848	0.5199	7.11	0.51	0.55	3.91	0.10	0.11	0.55
13	10.6130	0.4774	22.2300	21.0848	0.5033	7.11	0.51	0.55	3.92	0.10	0.11	0.55
14	27.7820	0.8090	34.3400	37.5430	0.7400	8.21	0.71	0.82	6.71	0.04	0.04	0.82
15	18.6850	0.6454	28.9500	32.1495	0.5812	7.88	0.59	0.61	4.82	0.03	0.04	0.61
16	5.5070	0.3551	15.5100	17.3600	0.3172	6.81	0.33	0.35	2.36	0.04	0.05	0.35
17	13.3690	0.7200	18.6300	23.3495	0.5726	7.28	0.63	0.63	4.56	0.05	0.06	0.63
18	13.6130	0.7300	18.7200	23.7598	0.5729	7.31	0.66	0.65	4.78	0.05	0.06	0.65
19	8.1350	0.3200	26.6300	32.3067	0.2518	7.89	0.20	0.20	1.55	0.04	0.04	0.20
20	7.5060	0.2900	25.7600	32.6221	0.2301	7.91	0.19	0.18	1.46	0.03	0.03	0.18
21				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
22				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
23				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
24				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
25				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
26				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
27				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A
28				#N/A	#N/A	#N/A		#N/A	#N/A		#N/A	#N/A

20220525 Simple Linear RA1 | 20210525 Multi Linear RA1 | ADVM QM Summary | Rating Development | Plot 1 - RA Vx vs Vmean

Figure 11: Index Velocity Spreadsheet (provided by USGS)

Rating Development: The index velocity types and stage measured by the SonTek SL1500-3G instrument were analyzed (graphical plots) against the mean channel velocity that was calculated from the stream flow gauging's and reference cross-sectional area (V=Q/A) shown in Figure 12. If patterns are evident in the graphical plot analyses it indicates the index velocity type that provides the best relationship with the mean channel velocity.

A simple linear regression and multi linear regression analyses were performed using the index velocity type with the best relationship with mean channel velocity. In case of the multi linear regression, stage was also included in the analysis because graphical analysis between mean channel velocity and stage also indicated a pattern. The multi linear regression and associated plots are provided in Figure 13.

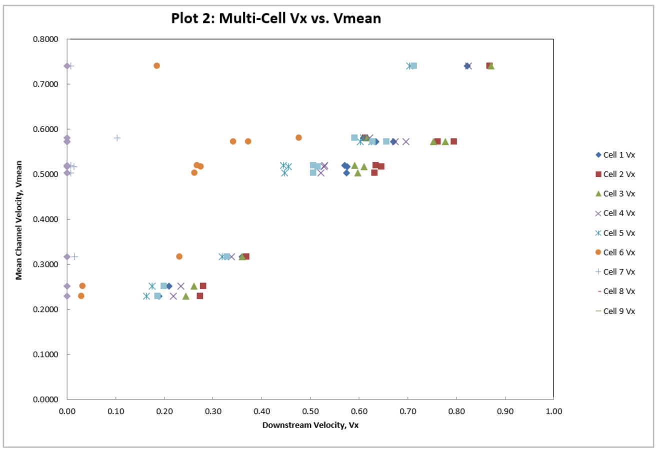


Figure 12: Multi-Cell vs VMean

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SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.99672103
R Square	0.993452811
Adjusted R Square	0.991582185
Standard Error	0.014969485
Observations	10

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.238014884	0.119007442	531.0805468	2.27087E-08
Residual	7	0.001568598	0.000224085		
Total	9	0.239583482			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.085240387	0.013853443	6.153011106	0.000466162	0.0524822	0.117998574	0.0524822	0.117998574
Range-Averaged Cell	0.415444732	0.155051611	2.679396422	0.031566855	0.048805932	0.782083532	0.048805932	0.782083532
Vx*Stage	0.048260098	0.019520934	2.472222775	0.042693722	0.002100424	0.094419772	0.002100424	0.094419772

RESIDUAL OUTPUT

Observation	*Measured: Mean Channel Velocit*	*Residuals*	*Standard Residuals*
1	0.509771585	0.007291496	0.552308888
2	0.502734245	0.01721476	1.303966255
3	0.503565305	-0.000215967	-0.016358842
4	0.748132237	-0.008126851	-0.615584495
5	0.571548985	0.009641833	0.730339791
6	0.343441698	-0.02621783	-1.985921696
7	0.565482121	0.007079301	0.536235703
8	0.587685829	-0.014742331	-1.116687177
9	0.241743012	0.010062419	0.762197931
10	0.232076459	-0.00198683	-0.150496357

PROBABILITY OUTPUT

Percentile	*sured: Mean Channel Velocity (Q/Rated A)*
5	0.23008963
15	0.251805431
25	0.317223868
35	0.503349339
45	0.517063082
55	0.519949006
65	0.572561421
75	0.572943498
85	0.581190818
95	0.740005386

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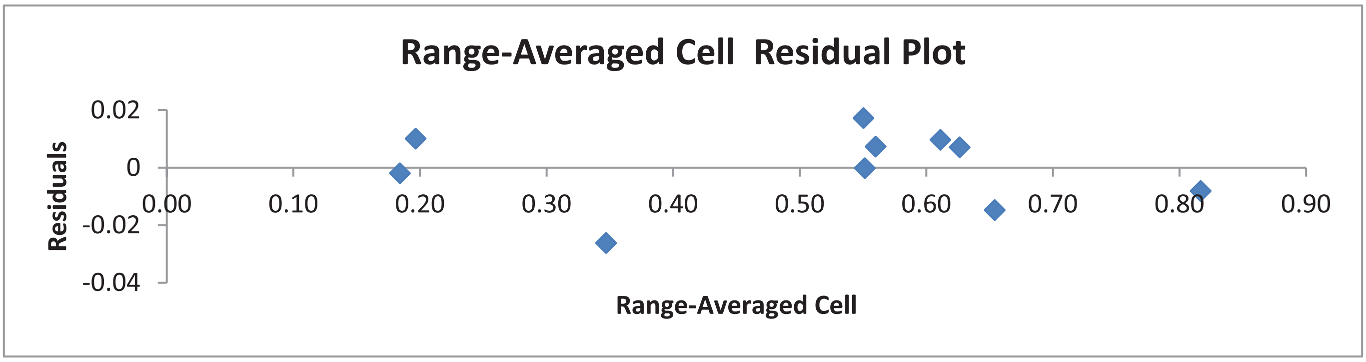
Figure 13: Multi Linear Regression



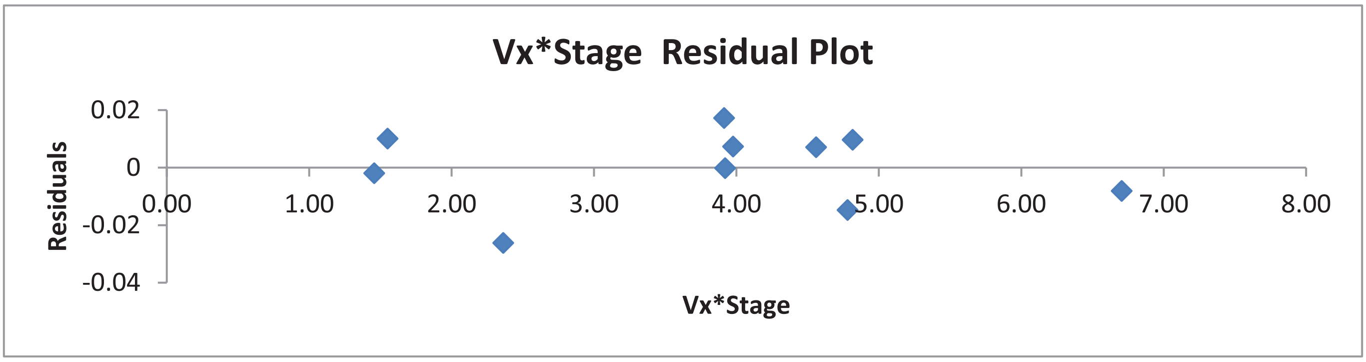
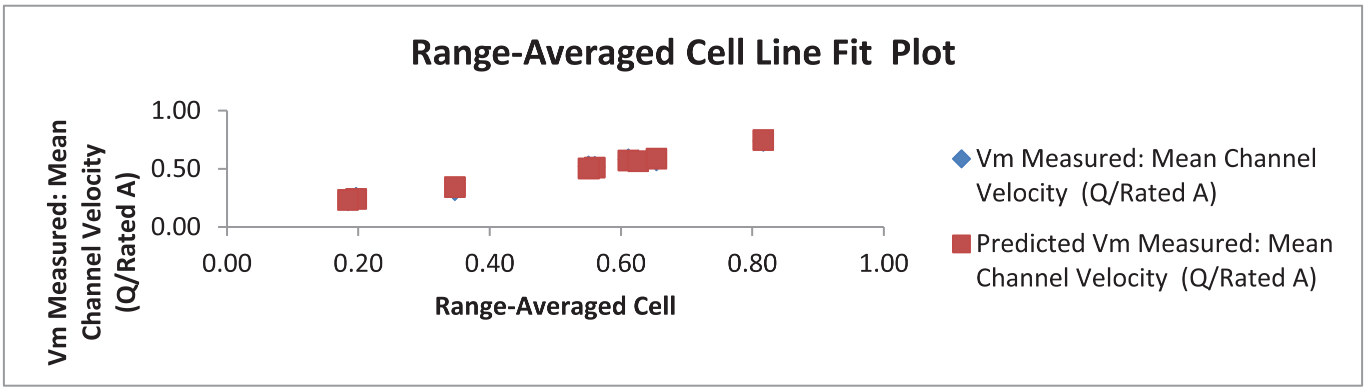
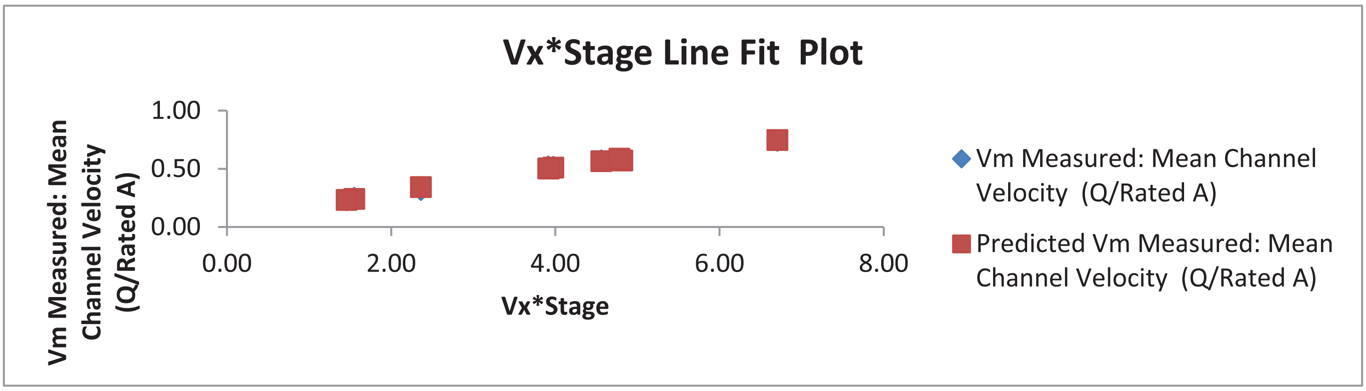


Figure 13: Multi Linear Regression





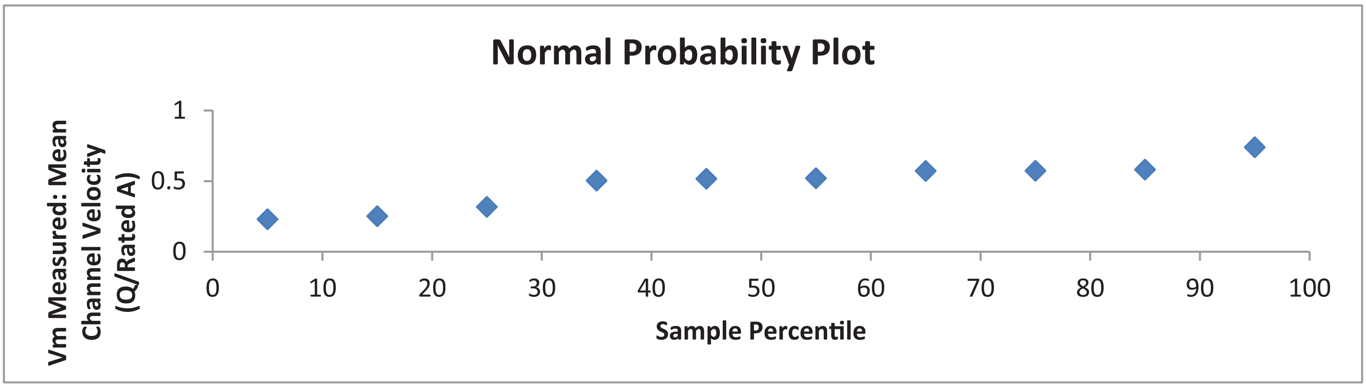


Figure 13: Multi Linear Regression

IV. Traditional Stage-Discharge Rating

Stage-Discharge Rating was developed based on all the stream flow gauging's performed at the flow monitoring site to compare the flow calculations against the index velocity rating. The stage-discharge rating was developed in Hydstra Rating Workbench, Hydrological Information Management System shown in Figure 14.

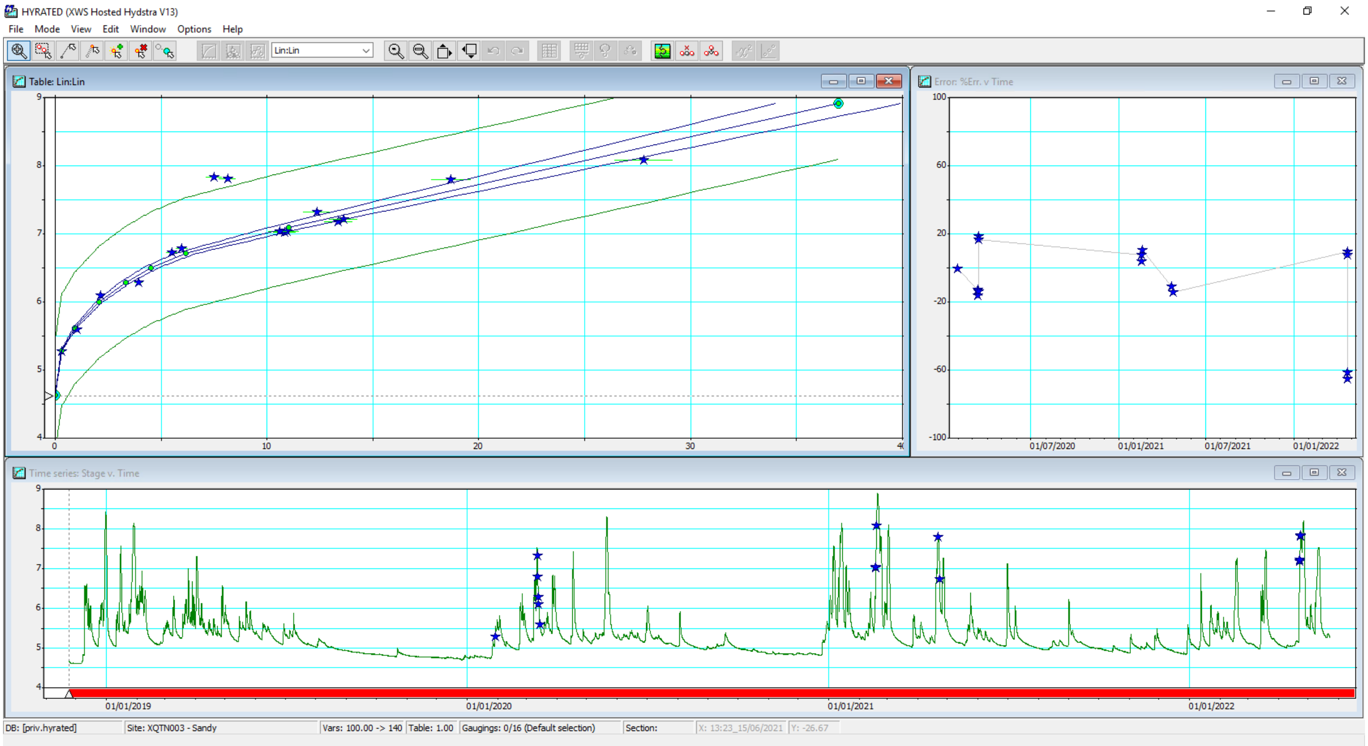


Figure 14: Stage-Discharge Rating

The results of the tests performed on the stage discharge rating developed in Hydstra Rating Workbench is provided in Table 2. The tests and formula used is published in Annexure A, ISO 1100/2, Liquid flow in open channels - Part 2: Determination of the stage-discharge relation.

Table 2: Stage-Discharge Rating Test Results

Test	Result	Statistics	Description
Value Bias	Pass	Mean % errs: -7.116 Confidence -20.312..6.080	Value bias test will fail if the mean of all percentage errors is too far from zero
Sign Bias	Pass	Tot +ve errs: 8 Should be within 3..12	Sign bias test fails if the number of negative errors is too different from half of the total
Time Runs	Pass	Runs: 4 Should be at least 3	Runs tests (sorted by both time and stage) fail if the number of runs of negative or positive errors cannot be explained as random variation
Stage Runs	Pass	Runs: 7 Should be at least 3	
% Within	Fail	31.25% (5 of 16) were within Must be at least 80%	Percentage of gauging's within a percentage of rated discharge" test

The deviation of stream flow gauging's from the stage-discharge rating curve is evident from the % Within test performed. This is direct result of variable backwater conditions present at the flow monitoring site.

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V. Flow Calculation

A. Stage Discharge vs Index Velocity

A comparison between the **stage-discharge** rating and **index velocity** rating flow hydrographs is provided in Figure 15. The first peak of the index velocity flow hydrograph developed shows a much steeper rising and falling limb than the stage-discharge flow hydrograph. The flow directly after the peak of the hydrograph reduces to zero due to backwater influences from the mainstem in the catchment during flood events. The bridge deck at flow monitoring site also effects the flow hydrograph of index velocity compared to stage-discharge.

B. Influences

Bridge Deck: The bottom of the bridge deck is at 7.8mAHD elevation. Flows exceeding 7.8mAHD water elevation will be impacted by the bridge deck shown in Figure 16, resulting in decrease in velocity because of backwater effects caused by orifice / full flow conditions.

This flow condition is clearly visible in Figure 15 where a reduction in flow is reported from the SonTek SL1500 instrument.

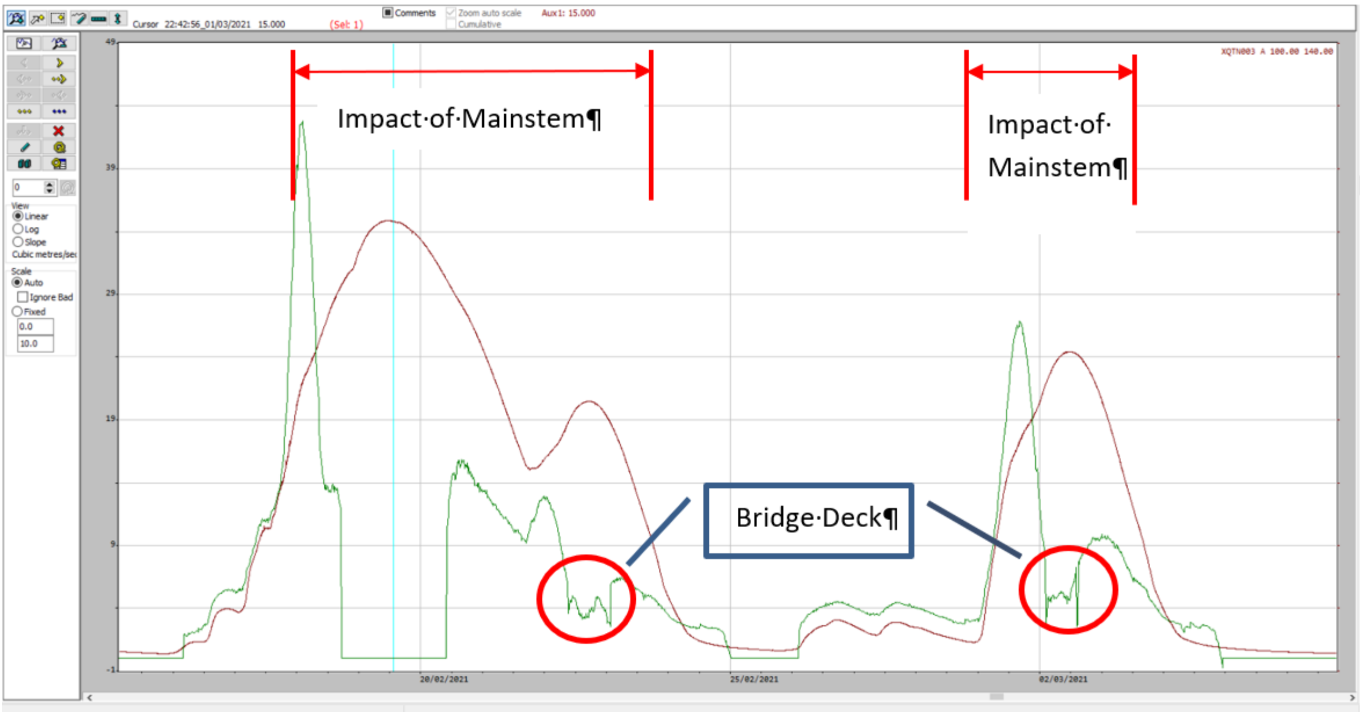

Figure 15: Comparison Stage Discharge vs Index Velocity Flow

Figure 16: Bridge Deck at Tributary

Off-Channel Storage: Off channel storage is occurring on the left bank just upstream of the monitoring site shown in Figure 17. This can result in unsteady flow conditions resulting in a loop rating.
The approach velocity to the monitoring site is also reduced, impacting the stage-discharge relationship.

Mainstem: The mainstem was in flood during the same time the stream flow gauging's were performed at the flow monitoring site.

The confluence of the tributary and mainstem is located close to the flow monitoring site shown in Figure 18. Any runoff occurring in the mainstem will flow upstream into tributary.

The extent of the backwater influence is dependent on the magnitude of the flow hydrograph in both the mainstem and tributary systems. The flood event in February 2021 clearly shows the impact of the mainstem on the flow monitoring site flows in Figure 19.

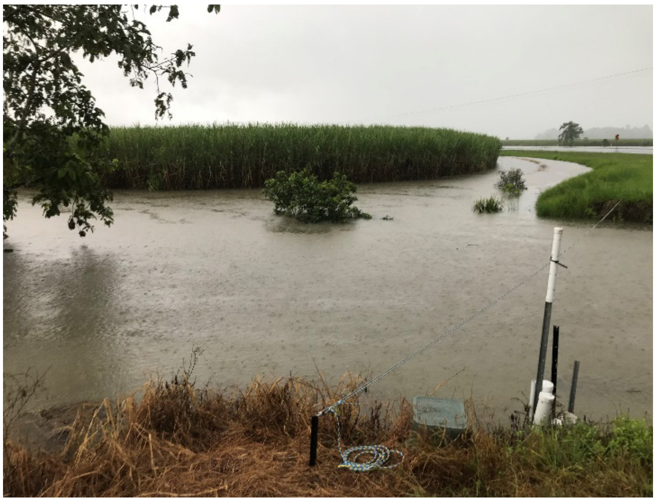

Figure 17: Off-Channel Storage

Figure 18: Mainstem Confluence

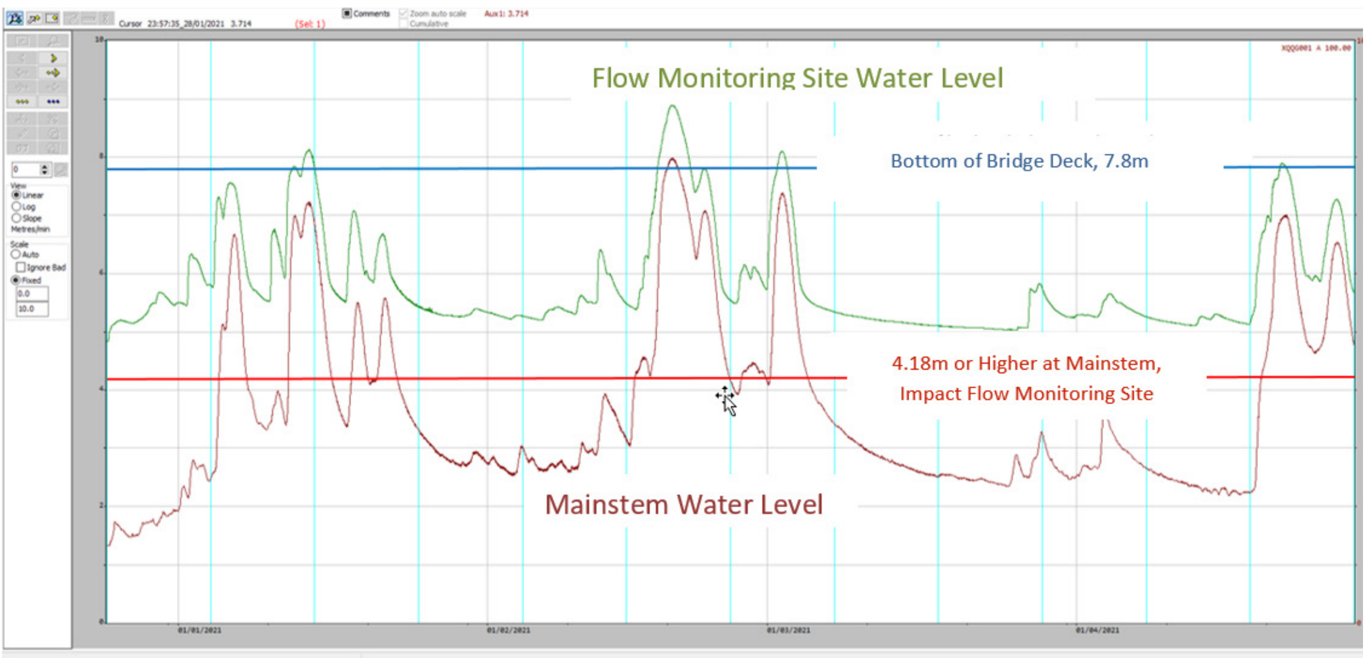

Figure 19: Mainstem Water Level

VI. Conclusion

The proximity of flow monitoring site in relation to the mainstem of the catchment makes it very sensitive to any flow events that may occur in the mainstem. This sensitivity impacts the accuracy of stage-discharge relationship significantly over the entire stage range especially for traditional stage-discharge rating. The flow hydrograph comparison in Figure 15 shows that the traditional stage-discharge rating overestimates the total flow significantly especially during periods of zero velocity when the backwater effects from the mainstem is most significant.

The index velocity method is designed for these type of flow conditions, however the final flow calculations are extremely complex as several factors need to be considered to determine the quality and validity of the flow data.

Acknowledgment

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