RECLAMATION
Managing Water in the West

Hydrokinetic Impact Study – FY16 Closeout

Research and Development Office
Science and Technology Program
Final Report ST-2016-7317-1

HL-2016-06

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 2016

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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14. ABSTRACT
A numerical tool is being developed to predict impacts from hydrokinetic power generation unit installations in canal systems. This tool, which utilizes HEC-RAS, was calibrated using physical measurements from field tests of a hydrokinetic installation on Reclamation's Roza Main Canal near Yakima, WA. Further development of the predictive numerical tool will continue in 2017.

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Acknowledgements

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Introduction

Attention has currently been given to the development of Hydrokinetic Power Generation technologies in in-land waterways. These hydrokinetic (HK) turbines utilize the velocity of flowing water to turn a turbine rotor which is connected through a shaft to a generator to produce power. The end goal of many private developers is to install their HK technologies in rivers and canal systems throughout the United States. Since 2011, Reclamation has received requests from private HK developers to install their technology in Reclamation canal systems for demonstration testing. As the impacts of this technology on existing in-land systems are unknown, a study was initiated in early 2013 to determine the hydraulic impacts of HK devices on existing water delivery and hydropower operations.

The main objective of this study was to determine and predict HK impacts on water delivery systems by developing a numerical prediction tool. Field testing was conducted on the Roza Main Canal near Yakima, WA where Instream Energy Systems Corp. (Instream) installed their vertical axis HK unit. Physical data from this testing were used to verify and calibrate a HEC-RAS model of the canal to quantify hydraulic impacts. Additional physical data and analysis are needed to further develop the HEC-RAS model approach for reliable HK impact predictions. It is anticipated that additional field testing and further numerical model development will continue into 2017.

Research Approach

The purpose of this project is to develop a numerical tool that predicts hydraulic impacts from HK installations that is quick and easy to use. Detailed information of the near field hydrodynamics of the canal flow around the turbine rotor are not needed to determine far field impacts. This tool targets end users who make decisions about HK installations in their systems such as water and irrigation districts, canal operators, or engineers who serve these entities. Information such as HK power output, flow blockage area, and especially water level impacts will be valuable to those decision makers.

The numerical prediction tool uses simple user inputs to model channel hydraulics with and without an HK installation to show impacts. The total energy loss across the HK unit is estimated and input into the HEC-RAS model which accounts for the geometry and hydraulic operating condition of the channel to apply the resulting impacts throughout the entire system. Results are compared to physical field measurements to calibrate the total energy loss calculation and verify far field water level results from the HEC-RAS model.

Results

Field Testing

Field testing was conducted in August 2013 (Mortensen, 2014) which was considered a shakedown trial run, as well as May and August 2014 (Mortensen, 2015). Details of 2014 field test results are shown in the Appendix of this report.

Numerical Modeling

An approximate 5.16 mile reach of the Roza Main Canal was included in the HEC-RAS model (Figure 1). This reach of canal includes both trapezoidal concrete lined and unlined sections (Figure 2) which affect both the depth and velocity of flow (Figure 3). The entire model was calibrated using measurements from the 2014 field test.

Model calibration was initiated using a baseline condition without the HK installation by adjusting the Manning's N roughness values of the canal. This calibration produced good agreement between numerical and physical results (Figure 4). These same roughness values were used for modeling conditions with the HK operating. Ineffective flow areas were added to cross-sections near the test site to simulate the turbine rotor blocking part of the flow. This "brute-force" method was necessary to obtain good agreement between numerical and physical results with the HK installed (Figure 5). While this calibration effectively modeled this HK installation it is limited to a single HK design under a single operating condition.

An improved calibration approach is needed for a more versatile and user friendly numerical model. Further development of this approach is planned to continue in Fiscal Year 2017 by using the power abstracted from the HK unit with an assumed efficiency to estimate the total energy loss in the canal flow across the test site to simulate far field hydraulic impacts in the model. 2014 field test data will again be used for calibration. Additional field testing is planned for 2017 with a wider range of HK designs and operations that will be valuable for further numerical testing and calibration.

Figure 1 Google Earth image of Roza Main Canal that was included in the HEC-RAS model (yellow). Blue lines show an inverted siphon under the Yakima River (top) and the tunnel upstream of the Roza Powerplant (bottom).

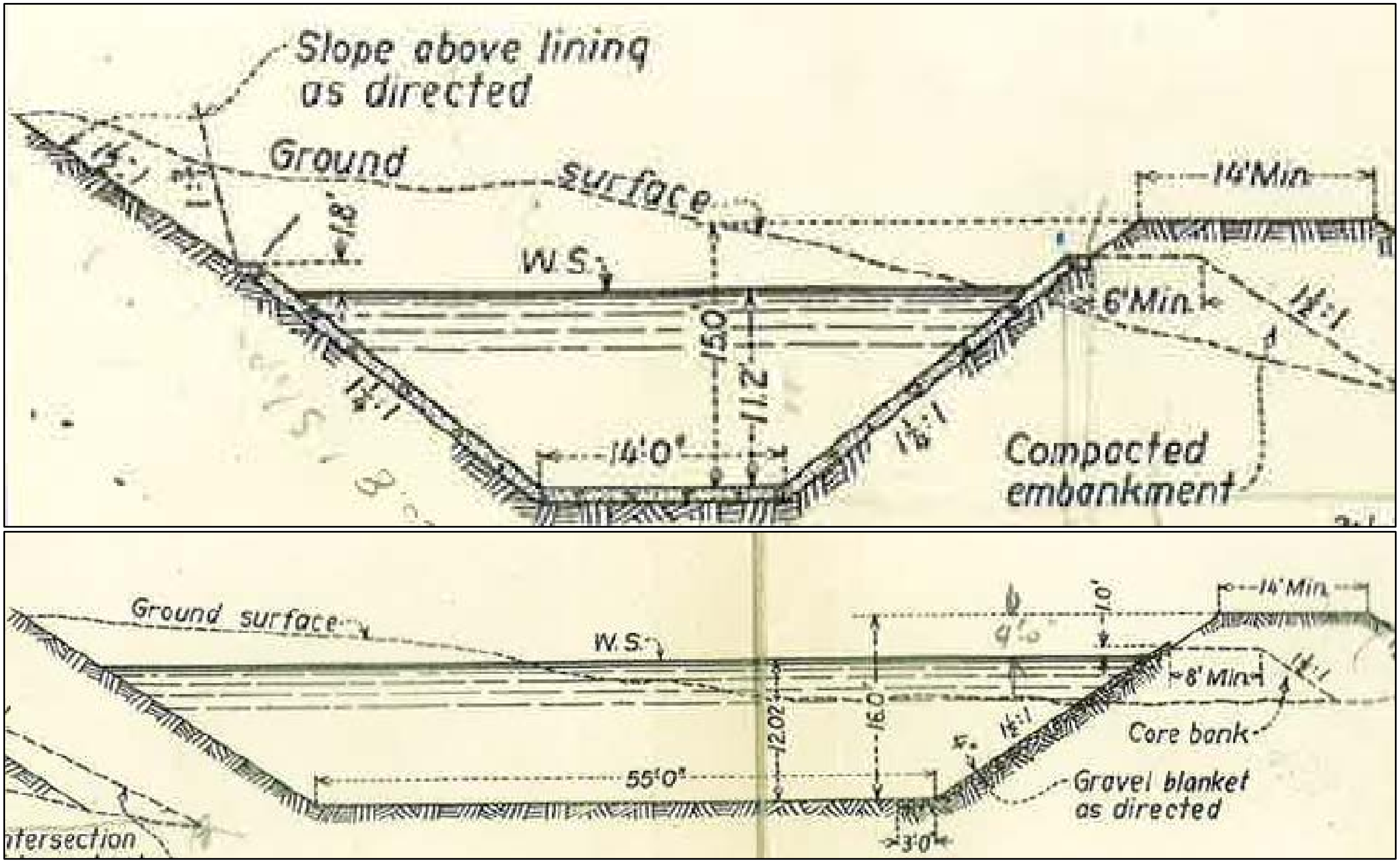

Figure 2 1936 design drawings of the lined canal cross-sections (top) and unlined canal cross-sections (bottom) of the Roza Main Canal.

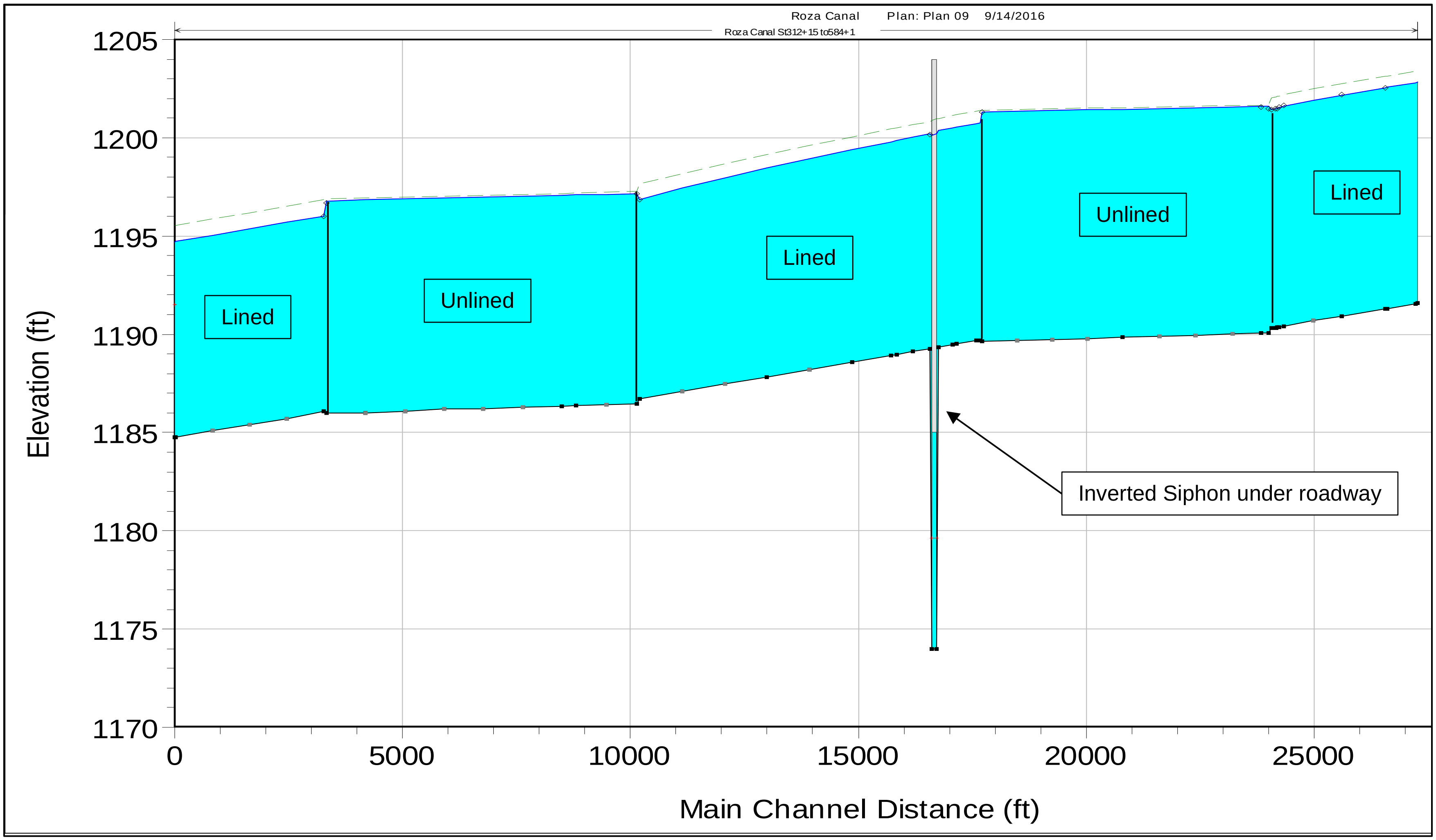

Figure 3 HEC-RAS water level profile plot which shows the entire canal and all features that were included in the model. Flow is from right to left.

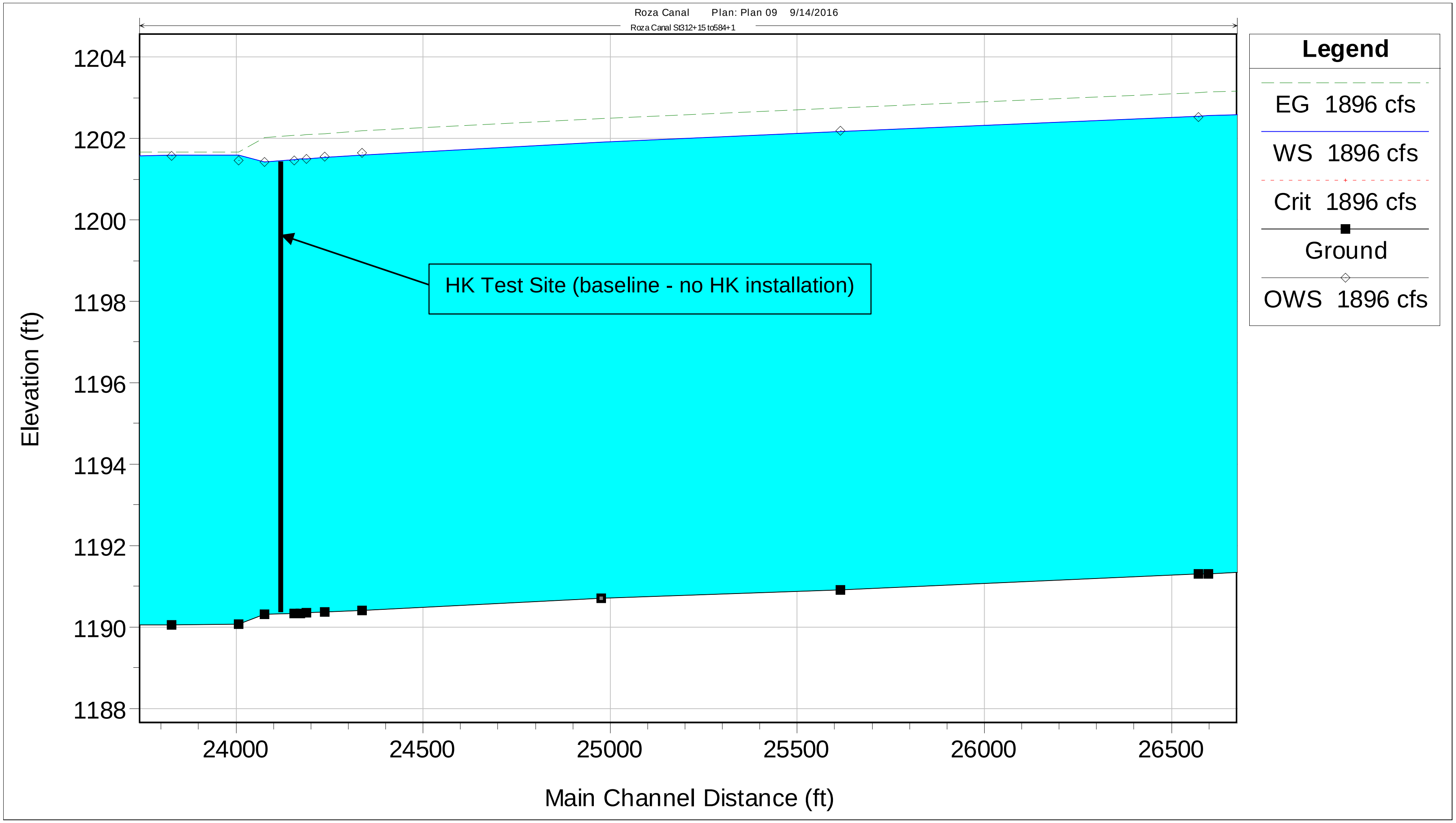

Figure 4 Water level profile plot without the HK installation (baseline) compared to measured data points (◊) near test site. Flow is right to left.

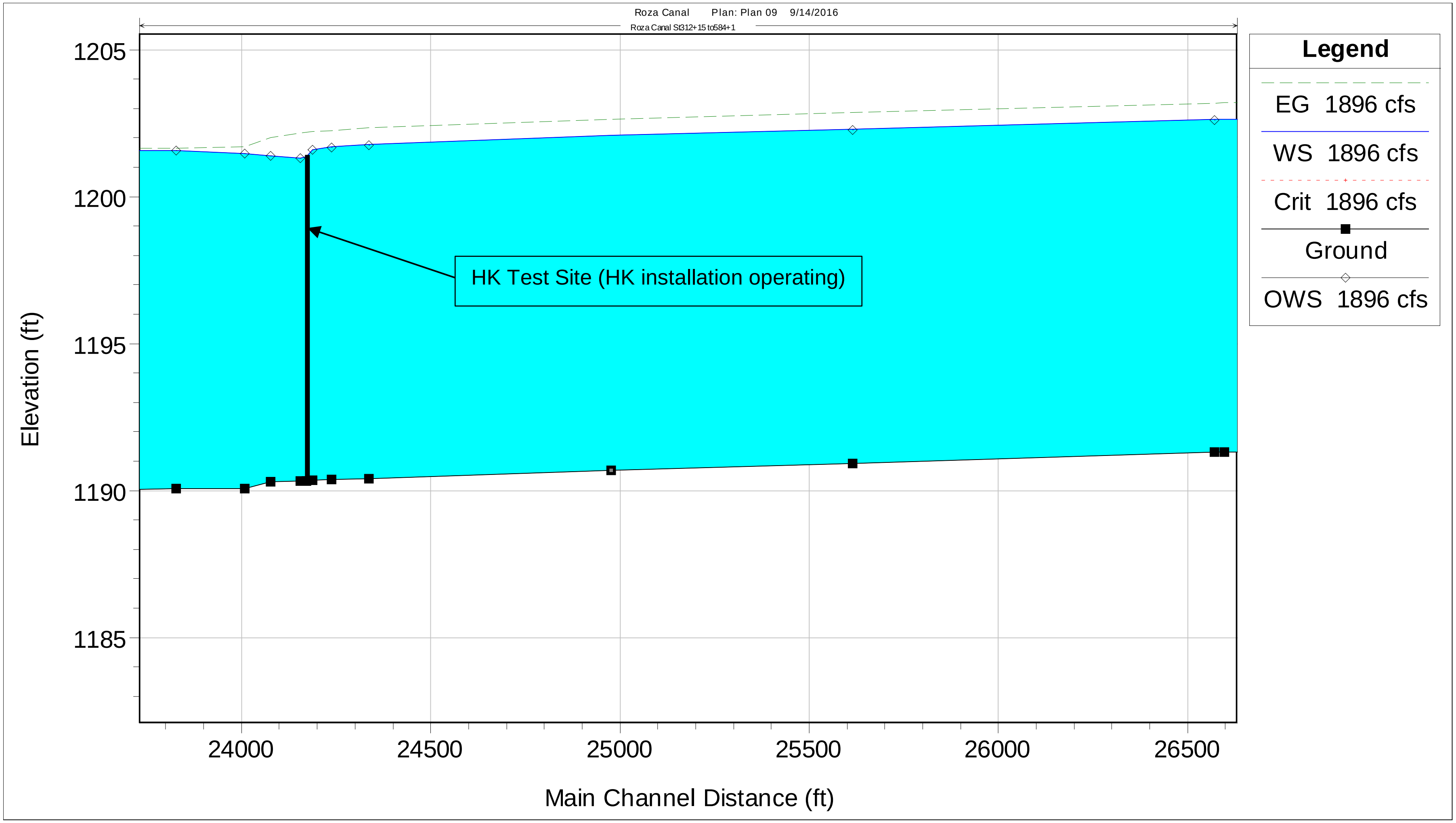

Figure 5 Water level profile plot with the HK installation operating compared to measured data points (◊) near test site. Flow is right to left.

Conclusions

A HEC-RAS numerical model of the Roza Main Canal was built which predicts hydraulic conditions both with and without a HK unit deployed in the canal. Physical data from 2014 field testing were used to calibrate the model. However, the model is not sufficiently robust as it cannot accurately predict HK impacts outside of the hydraulic conditions that were physically measured. Modifications to the numerical model are needed to make it more versatile and user friendly. Additional field data are also needed to support the calibration and verification of the numerical model in a wider range of HK applications. Further field testing at Roza is tentatively planned for 2017 with a newly developed rotor by Instream with a greater power output than the previous one tested in 2013 and 2014. Also, a new collaboration with private developer Emrgy, Inc., is tentatively planned for 2017 which will include testing their HK design for hydraulic impacts in a field installation.

References

Mortensen, J. D. (2014). *Hydrokinetic Impact Study Update - 2013*. PAP-1082, Denver, CO: Bureau of Reclamation.

Mortensen, J. D. (2015). *Hydrokinetic Impact Study Update - 2014 Field Testing*. PAP-1118, Denver, CO: Bureau of Reclamation.

Appendix: 2014 Field Test Report

Hydraulic Laboratory Technical Memorandum PAP-1118

Hydrokinetic Impact Study Update – 2014 Field Testing

Prepared for Reclamation's Power Resources Office and Science & Technology Program

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Disclaimer

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Introduction

Testing was performed on Reclamation's Roza Main Canal to investigate hydraulic impacts from a hydrokinetic turbine. This testing is part of an ongoing study performed by Reclamation in collaboration with Instream Energy Systems Corp. (Instream) and Sandia National Laboratories (SNL). Measurements were taken by all three organizations including ADCP and ADV velocity measurements, power output, speed, and torque measurements on the hydrokinetic unit, as well as water surface elevations at multiple locations along the canal. While these measurements were used to quantify hydrokinetic turbine performance and near-field hydraulics, this report focuses on hydraulic impacts to the existing operation of the canal, which is Reclamation's primary interest. The analysis herein documents water surface impacts related to 2014 testing. These measurements, as well as additional test measurements planned for 2015, are being used to calibrate a numerical model for predicting hydraulic impacts from hydrokinetic turbines under a range of operating conditions.

Field Measurement Results

Testing occurred over two separate weeks (May 12-16 and August 11-15, 2014) to collect data under different canal flow and depth ranges. More detailed information about the test site, hydrokinetic installation, and measurement locations is available in a previous report (Mortensen 2014). Impacts to canal hydraulics were quantified primarily using water surface elevation and hydrokinetic operating measurements for a range of canal flows.

Water surface elevations were measured with Onset HOBO® submersible water level loggers (model U20-001-01) that were deployed and surveyed by Reclamation (Mortensen 2014). Water level data were collected at 30 second intervals and the overall uncertainty was ±0.032 ft for the May test and ±0.023 ft for the August test, based on surveyed water surface elevations. Generator power output, speed, and torque measurements were made with Instream's data acquisition system at a sample rate of 10 Hz. Canal flowrate data were measured at a rated section near the canal headworks and were downloaded from Reclamation's Hydromet database. These data were compared to determine if there is a correlation between operation of the hydrokinetic unit and change in water level in the canal.

Canal flowrate (Figure 1) and generator power output (Figure 2) are displayed with water surface elevations measured at 66 ft (20 m) upstream from the hydrokinetic turbine. Testing in May involved data collection at more than one flowrate which allowed a greater test range but complicated testing because of fluctuating water surface elevations. Also, difficulty surveying lower water surfaces relative to the top of the canal lining added uncertainty to the water surface elevation measurements.

Testing in August provided a steady canal flow that was near the canal capacity of 2,000 cfs. Water surface elevations were significantly higher in August primarily due to the increased canal roughness caused by significant aquatic growth within the two unlined portions of the canal downstream. Increased hydraulic roughness resulted in a water surface elevation very close to the canal's free board limit.

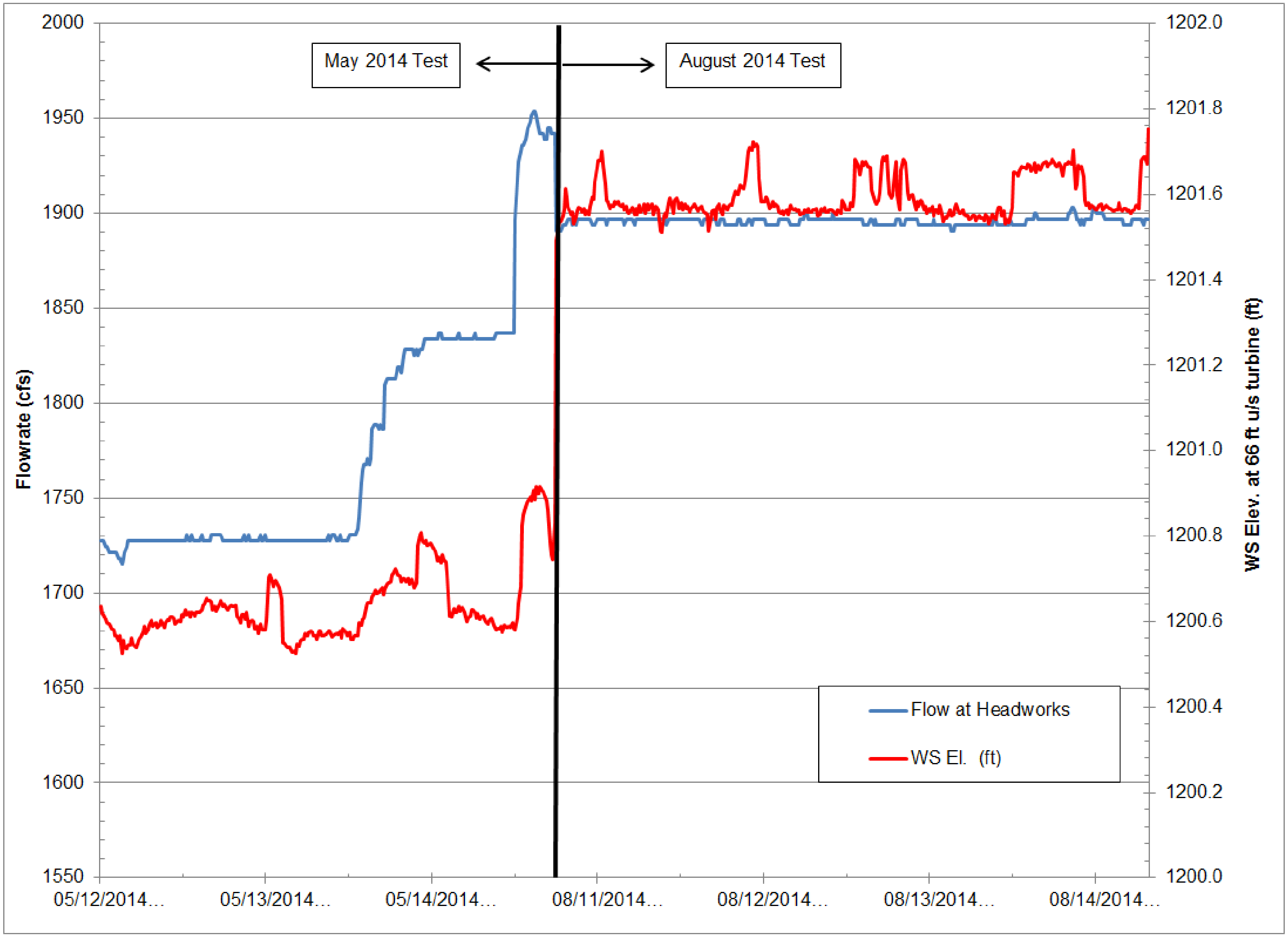

Figure 1. Canal flowrate and water surface elevation data at 66 ft (20 m) upstream from the turbine for both May and August tests.

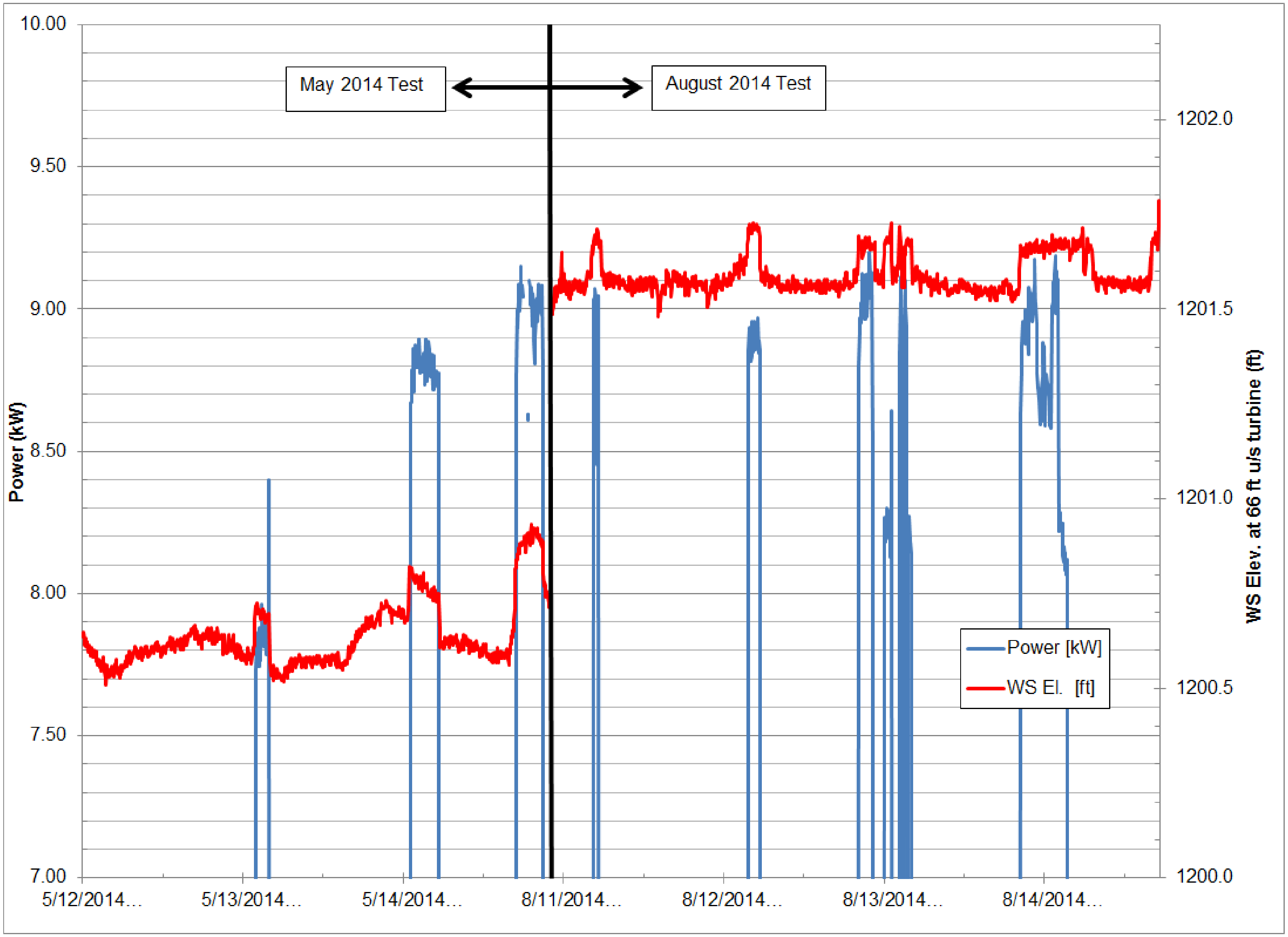

Figure 2. Power and water surface elevation data (5 minute average) at 66 ft (20 m) upstream from the turbine for both May and August tests.

Analysis and Discussion

Test results were analyzed by organizing measurement data into eight different test cases, each with a baseline water surface elevation followed by data with the hydrokinetic turbine operating after at least ½ hour for conditions to stabilize (Table 1). Water surface elevation data for each test case were compared to determine if there was any correlation with hydrokinetic operation. Three of these test cases were performed on 8/14/2014 which compared three operating settings to a single baseline.

Table 1. Test case data sets used to compare water surface elevation changes with hydrokinetic operation.

Test Case	**Condition**	**Pacific Time**		**Average Power**	**Power Standard Deviation**	**Average Canal Flow**
		Start	*End*	*kW*	*kW*	*cfs*
5/13/2014	Baseline	12:51	16:00	-	-	1,728
	HK Operating	16:32	18:22	7.84	0.06	
5/14/2014	Baseline	11:51	15:00	-	-	1,829
	HK Operating	15:36	19:46	8.79	0.06	
5/15/2014 *	Baseline	0:00	7:17	-	-	1,888 *
	HK Operating	8:27	12:22	8.99	0.12	
8/12/2014	Baseline	05:37	15:27	-	-	1,896
	HK Operating	17:44	19:24	8.88	0.05	
8/13/2014	Baseline	00:00	09:21	-	-	1,897
	HK Operating	10:15	12:20	9.01	0.15	
8/14/2014	Baseline	03:42	10:00	-	-	
	HK Operating - a	10:27	13:17	8.93	0.17	1,896
	HK Operating - b	15:27	16:22	9.08	0.05	1,896
	HK Operating - c	16:32	17:47	8.17	0.07	1,896

* 5/15 HK Operating results were biased due to a significant flow increase (1,836 to 1,945 cfs) at about the same time operation began.

The average change in water surface elevations at multiple locations upstream and downstream from the hydrokinetic turbine are compared in Figure 3 for each test case. For the upstream data, the water surface elevation increased by 0.05 to 0.15 ft with an average of 0.11 ft for distances less than 200 ft upstream (Table 2). The increase is slightly less for measurements made further away at 1,444 and 2,400 ft upstream which would be expected due to the backwater effect. Still, this is a small variation in water surface increase with distance upstream from the turbine, which may be due to the mild canal slope (0.0004 ft/ft). The water surface increase at 2,400 ft upstream from the turbine was 0.03 ft on average in May and 0.08 ft in August. These results indicate that the spacing between measurement locations could potentially be increased for testing in 2015.

There is some variability in upstream water surface results but it is not significant (with the exception of results from 5/15/2014). This variability may be due to differences in canal flows from May to August, as well as unsteady flows and additional water surface elevation uncertainty in May.

Table 2. 2014 average water surface elevation changes (ft) at 8 different locations upstream from the hydrokinetic turbine.

Location - Distance u/s from Turbine (ft)	**5/13**	**5/14**	**5/15** *	**8/12**	**8/13**	**8/14 - a**	**8/14 - b**	**8/14 - c**	**Location Average**
-2,400	0.05	0.02	0.23	0.10	0.07	0.07	0.09	0.09	**0.07**
-1,444	0.05	0.04	0.24	0.10	0.08	0.09	0.11	0.11	**0.08**
-164	0.10	0.07	0.27	0.14	0.10	0.12	0.13	0.13	**0.11**
-131	0.09	0.07	0.27	0.14	0.10	0.11	0.13	0.12	**0.11**
-98	0.10	0.07	0.26	0.14	0.10	0.11	0.12	0.12	**0.11**
-66	0.10	0.07	0.27	0.15	0.11	0.11	0.12	0.13	**0.11**
-33	0.10	0.07	0.26	0.14	0.10	0.11	0.13	0.13	**0.11**
-16	0.08	0.06	0.26	0.13	0.09	0.10	0.11	0.11	**0.10**
Test Case Average	**0.08**	**0.06**	**0.26**	**0.13**	**0.09**	**0.10**	**0.12**	**0.12**	

* Water surface elevation changes on 5/15/2014 are not used in the location average calculation as they were biased by a flowrate increase at the time of the test.

For water surface elevations downstream of the turbine, there was a significant difference in the May and August data (Figure 3). Most water surface elevations in August returned to the baseline condition within 200 ft downstream from the turbine while those from May required a greater distance to recover. This may be due to the difference in submergence of the turbine rotor which was almost one foot greater in August due to the higher water surface elevation. In theory, a higher water surface elevation would increase the total flow area and decrease the percentage of effective area that is blocked by the turbine rotor, reducing the head drop across the rotor as a result. While there is insufficient data in this report to support this conclusion, further analysis of velocity data collected by SNL may shed some light on the differences in downstream water level results.

The recovery of the downstream water surface elevation may have been influenced by the canal expansion at that location which naturally raises the water surface. It is likely that the downstream water surface would require a greater distance to recover in a constant canal section. This would be important to determine in the future, if testing at a different test site further upstream becomes possible.

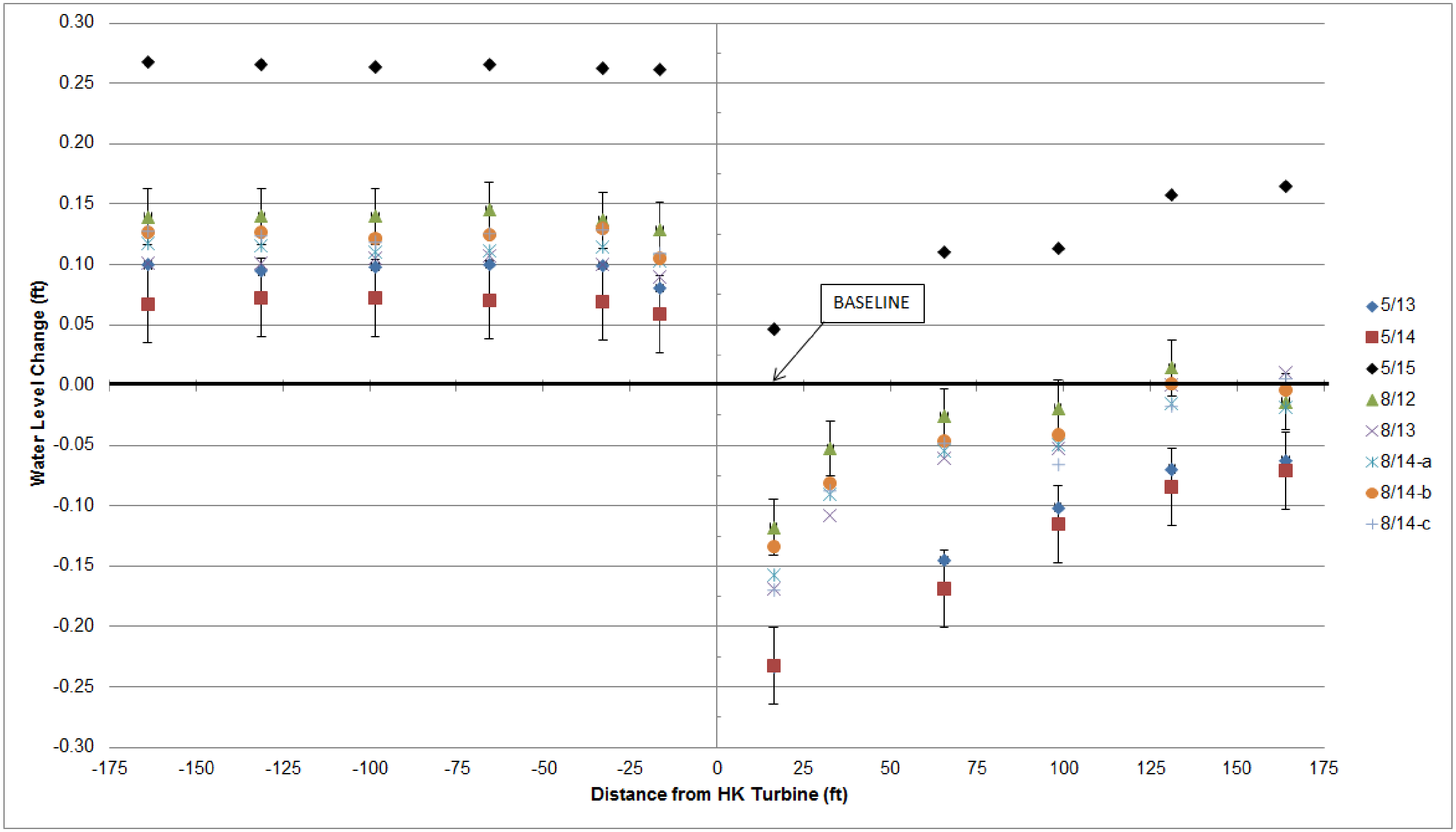

Figure 3. Plot of change in water surface elevation caused by hydrokinetic turbine operation. Negative distance is upstream and positive is downstream from the turbine. Error bars indicate the water level measurement uncertainty for two representative data sets.

Changes in the water surface elevation were compared with hydrokinetic operating data to determine the hydraulic impact to the canal. Test results obviously show that the hydrokinetic turbine does have an effect on both the upstream and downstream water surface elevation. This was previously shown by the increase in upstream and decrease in downstream water levels when the unit was operating. However, data in Figure 4 indicate that generator power output, within a range of 7.5 to 9.5 kW, has no impact on upstream water surface elevation. This was the full power output range of the hydrokinetic unit. Table 3 shows correlation coefficients of the water surface time-series data with power and turbine speed data which show there is no correlation between these variables. This may be due to the large variation in power output for each case (Figure 4). In Figure 5 average torque and turbine rotational speed data for each test case were compared to water surface changes upstream which also suggest that there is no correlation between the upstream water surface and hydrokinetic operation within the test range.

Table 3. Correlation coefficients of water surface elevation data at 66 ft (20 m) u/s from the turbine compared to power and turbine speed data over the same time period.

	5/13	**5/14**	**5/15**	**8/12**	**8/13**
Power	-0.085	-0.066	-0.026	0.212	-0.093
Turbine Speed	-0.100	-0.065	-0.083	0.207	-0.089
Correlation of time series data at 30 second time intervals.					
Power and turbine speed data (10 Hz) averaged over 30 second intervals.					

Finding a correlation between the hydrokinetic unit operation and hydraulic impacts is important to accurately predict the impacts of other installations and to calibrate the numerical model. Additional testing is planned in 2015 with a larger turbine rotor installed at the existing test site. The new rotor is designed to produce 25 kW which will likely cause a greater change to the water surface elevation than the unit tested in 2014. It is anticipated that a change in power output would have the strongest correlation to a change in water surface elevation since that will likely have the greatest impact to the energy grade line of the canal flow. A larger range of power output data will hopefully allow this correlation to be determined. Additional analyses that include the velocity data will help determine the kinetic energy loss across the turbine which may have a significant effect on the correlation between hydrokinetic operation and hydraulic impacts. Other hydrokinetic variables that may influence canal hydraulics include torque, turbine rotation speed and the submerged cross-sectional area of the rotor which will also be tested and analyzed using the larger rotor in 2015.

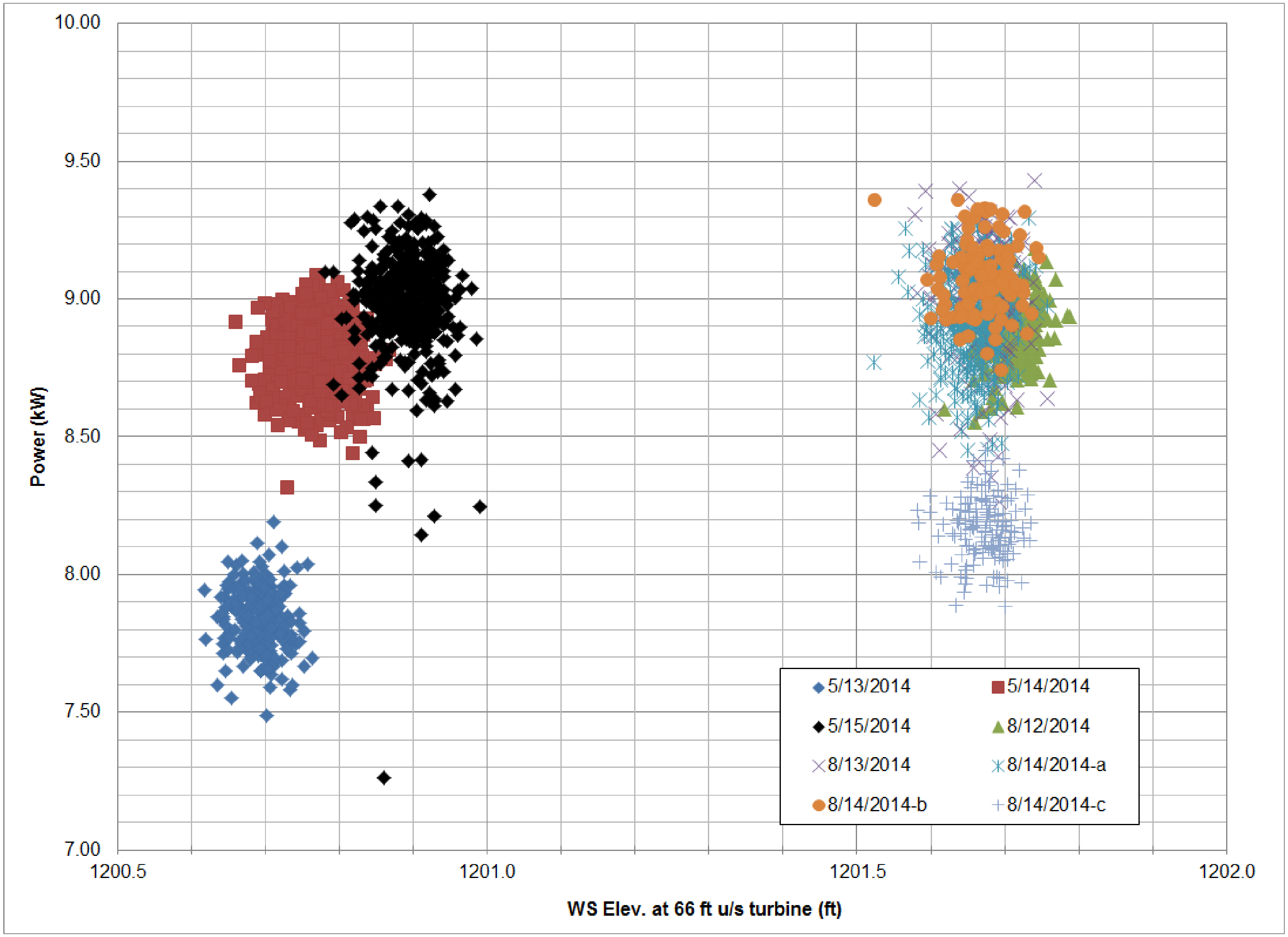

Figure 4. Power output data averaged over 30 second intervals versus water surface elevation data at 66 ft (20 m) upstream from the turbine.

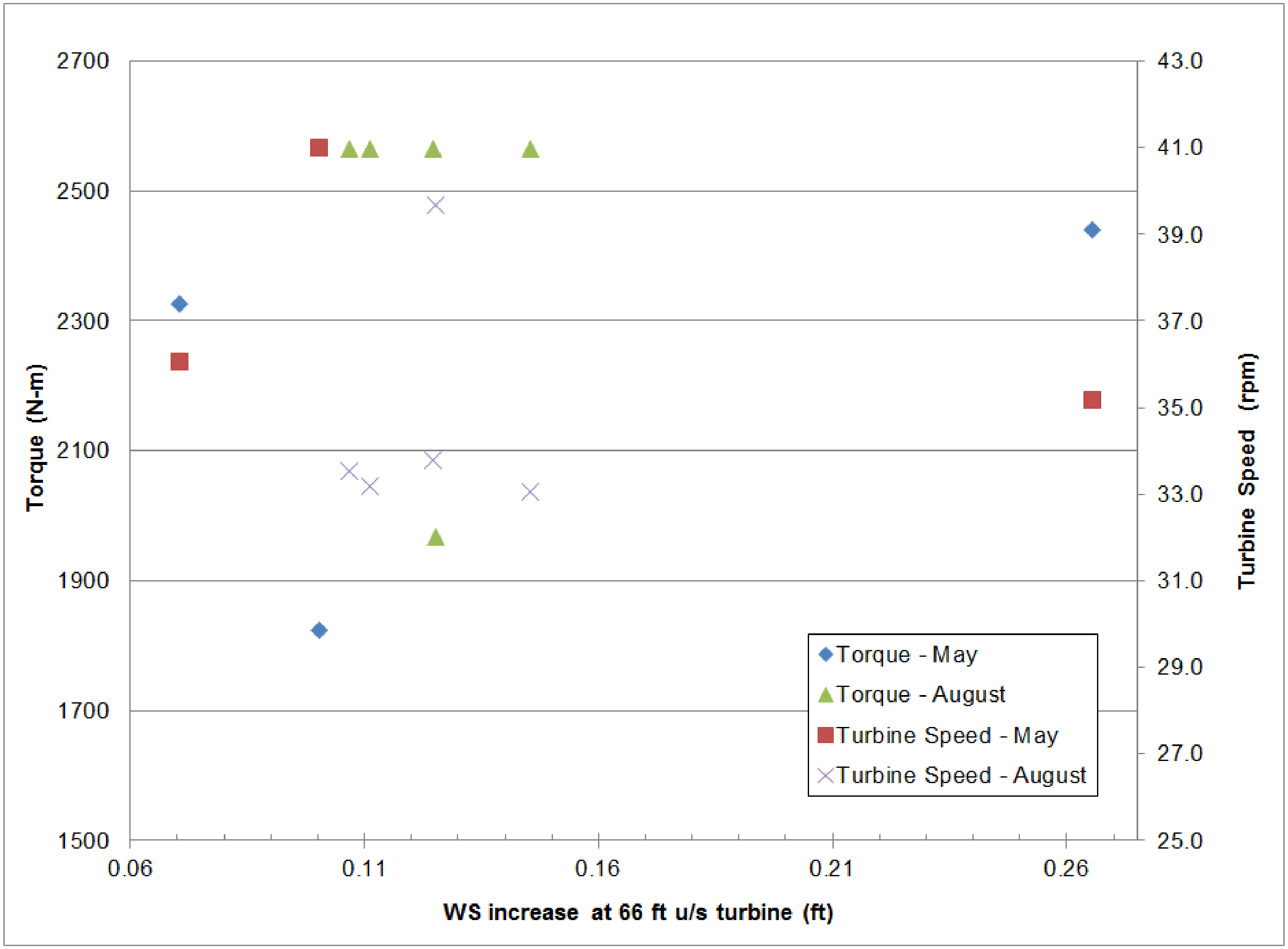

Figure 5. 2014 average torque and turbine speed output versus water level increases at 66 ft (20 m) upstream from the turbine.

Conclusions

Measurements taken during two separate weeks of testing in 2014 were used to identify hydraulic impacts to the Roza Main Canal from a hydrokinetic turbine. Water surface elevation and hydrokinetic operating data from eight different test cases were analyzed. Measurements showed a difference in downstream water surface elevations for the May and August tests which may be due to the difference in submergence of the turbine rotor during the two test periods. Most downstream water levels recovered within about 200 ft of the turbine to match baseline water surface elevations. Upstream water surfaces increased by about 0.10 ft and were similar for all distances from 16 to 165 ft upstream from the turbine and decreased only slightly at distances up to 2,400 ft upstream. There was no correlation between water surface elevation increases and the power outputs within a range of 7.5 to 9.4 kW. Additional testing is planned in 2015 using a larger hydrokinetic turbine rotor capable of producing 25 kW.

It is anticipated that the larger rotor will cause greater changes to canal water surface elevations which could help identify a correlation between canal hydraulics and hydrokinetic operations. The final analysis will include velocity results to identify the total energy loss across the turbine which may help determine the correlation between hydrokinetic operation and hydraulic impacts. This correlation is necessary for numeric model calibration in order for it to be used as a predictive tool for hydraulic impacts. Once this correlation is determined with additional field measurements, a more accurate calibration of the numerical model can be made.

Reference

Mortensen, J. D. (2014). Evaluation of Hydro-Kinetic Impacts to Existing Water Delivery & Hydropower Systems. *HydroVision 2014 Conference Proceedings.* Nashville, TN July 22-25, 2014.