Hydrokinetic Impacts to Canal Systems

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14. ABSTRACT Hydrokinetic (HK) power technologies have been applied to inland waterways in recent years such as rivers and canal systems. While they advantageously utilize the existing infrastructure and flow conditions of canal systems, impacts to daily operations and canal safety must be considered. A pilot study was done where 10 HK units were installed in Denver Water's South Boulder Canal. Flow and water level measurements were made in the canal for several flow conditions and compared to baseline levels without HK operation. Test results and field experience suggest that safety planning and emergency procedures are imperative. Also, arrays of multiple HK units are not well suited for canals due to increased water levels that may encroach upon freeboard limitations. However, HK units may be advantageous if installed in strategic locations such as offshoot channels or flumes that offer operational flexibility and where altered hydraulic conditions do not compromise operations or safety. Critical design parameters are canal slope, velocity, freeboard, and design discharge when considering applying HK to existing systems.			
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Acronyms and Abbreviations

CFD	Computational Fluid Dynamics
CRADA	Cooperative Research and Development Agreement
EGL	energy grade line
HK	Hydrokinetic
O&M	Operation and Maintenance
Reclamation	Bureau of Reclamation

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Executive Summary

Hydrokinetic (HK) power technologies have been applied to inland waterways in recent years such as rivers and canal systems. While they advantageously utilize the existing infrastructure and flow conditions of canal systems, impacts to daily operations, maintenance, and canal safety must be considered. As part of a Cooperative Research and Development Agreement (CRADA), Reclamation and Denver Water have collaborated on a field study to investigate HK impacts to canal systems. The main objective of this study was to evaluate HK effects to canal hydraulics, operations and maintenance (O&M), and safety by obtaining physical hydraulic measurements as well as practical field experience.

A pilot study was conducted where 10 HK units were installed in Denver Water's South Boulder Canal near Golden, CO. The canal consisted of three test reaches which consisted of both earthen and concrete lining and varied in geometry and slope. Flow and water level measurements were made in the canal for several flow conditions and compared to baseline levels without HK. This comparison helped determine the hydraulic impacts to the canal. Practical field experience was gained by installing, testing, maintaining, and removing 10 HK units over a period of several months.

Based on physical test results and practical field experience, the following conclusions have been made:

- Safety planning and emergency procedures are imperative to monitor and prevent canal overtopping due to debris clogging in the HK unit or other emergencies. HK design concepts or modifications that minimize the amount of HK equipment or superstructure blocking the flow and offer flexibility to remove equipment or otherwise prevent the buildup of debris and ice will help address safety concerns and reduce operational limitations due to increased water levels.
- Arrays of multiple HK units are not well suited for canal mains due to increased water levels that may encroach upon freeboard limitations during normal operation. Head differential across the HK units caused upstream water levels to rise. Water level increases were compounded when multiple units were installed too close together and caused water levels to "stack up", further increasing the water level in the upstream canal. This result opposes the general desire or need to keep HK units closer together to reduce distance required for cable runs and electrical connections. Critical parameters for determining unit spacing and hydraulic impacts include canal slope and velocity, freeboard, and design discharge.
- HK power generation may be advantageous if units are installed in strategic locations such as turnouts, laterals, wasteways, or flumes that may offer greater flow velocities, operational flexibility, and where disrupted hydraulic conditions or increased water levels do not compromise normal operations or safety. Still, these locations should always be evaluated for impacts to safety and hydraulic performance when considering HK installation.

Introduction

Hydrokinetic (HK) power generation utilizes the energy of flowing water to generate power. Since this technology uses the "kinetic energy" of water movement, it is targeted toward open channels that don't require additional storage such as ocean tides, rivers, and man-made water ways. This is different than traditional hydropower that uses "potential energy" from an elevation difference such as a dam and reservoir or a drop structure. A basic HK system consists of a rotor, shaft, generator, and supporting infrastructure. The rotor is submerged and rotates in the flow which enables the generator to produce power (Figure 1). While HK designs vary significantly (Laws & Epps, 2016), the basic concept is the same.

Figure 1 Vertical shaft HK design concepts. Single rotor used in Roza Main Canal, Yakima Project (left) and twin rotor similar to the design used in the current study (right).

To date, HK technologies have mostly been used in the marine industry, harvesting energy from tidal fluctuations. In recent years, efforts have been made to expand this technology inland to rivers, streams, and canal systems (Laws & Epps, 2016). Application to man-made channels such as canals are attractive because factors such as fish passage and debris removal have already been addressed to a large extent by the existing infrastructure. While opportunities may exist to take advantage of existing infrastructure, effects on the hydraulics, operation, and safety of the existing system must be carefully considered.

Background

Efforts to apply HK technologies to inland water conveyance systems has affected Reclamation which owns and operates approximately 8,000 miles of canal systems (Bureau of Reclamation, 2020). Reclamation has been approached a number of times to install and test HK technologies in their canal systems. The first actual test installation occurred at Reclamation's Roza Main Canal in Central Washington. During testing canal hydraulics and operation of a local hydropower plant were affected, but no flow or water level measurements were made and impacts to the canal system could not be quantified. Beginning in 2013, Instream Energy Systems LLC worked with Reclamation's Pacific Northwest Region to install and test a single HK unit in the Roza Main Canal. At that point, Reclamation's Technical Services Center became involved with the testing to quantify hydraulic effects to the canal system and gain practical field experience with HK technologies (Mortensen, 2013).

In 2017, Reclamation entered into a Cooperative Research and Development Agreement (CRADA) with Denver Water who had contracted with Emrgy Inc. to install several HK units in the South Boulder Canal near Golden, CO. The intent of this CRADA was to determine HK effects to canal hydraulics, O&M, and safety as well as to determine the performance of this particular HK design in a canal. At the time, a project to deploy an array of multiple HK units in a single canal had not yet been attempted. Under the CRADA, Denver Water was responsible for providing access to the canal facility, providing up to 10 HK units and their equipment, as well as canal monitoring and safety. Reclamation was responsible for obtaining physical measurements of canal water levels and localized velocities at strategic locations to the extent possible. Data and analysis results from physical measurements or numerical modeling were shared among both parties. This report documents the methods, test results, and conclusions from this collaborative study by Denver Water and Reclamation.

Objectives

The main objective of this study was to evaluate hydraulic, operational, and safety impacts to canal systems from HK power technologies. Secondary objectives include demonstrating HK unit functionality and quantifying unit performance of the design in a field environment.

Approach and Methodology

Field testing in an existing canal was decided upon to reduce complications and uncertainties of scaled hydraulic modeling in a laboratory and to obtain practical experience from a canal system typical in size and function of many open channel conveyance systems in the western United States.

Pilot Field Test

South Boulder Canal Test Site

South Boulder Canal was chosen as the test site and is operated and maintained by Denver Water. It is the final reach of canal that provides water to Ralston Reservoir, which is about 6 miles north of Golden, Colorado. The test site was divided into 3 test reaches, Zones C, B, and A as shown in Figure 2. Zone C is an earthen canal with a cross-section geometry that varies, but typically consists of a rounded section with approximate dimensions of 20-ft bottom width, 40-ft top width and more than 10-ft depth. Zone C begins with a transition from an inverted siphon and runs approximately 0.68 miles (Station 2,050 – 5,664 ft) before the concrete section of Zone B begins. There were no HK units installed in Zone C during this study.

Zone B is a concrete-lined canal and was the focus of this study as most of the HK units were installed in this reach as it had the tightest freeboard restrictions due to its lining, typical of many western canal systems. It is about 0.39 miles long (Station 0 – 2,050 ft) and has a trapezoidal cross-section with a 16-ft bottom width and a 32-ft top width as shown in Figure 2. The downstream end of Zone B transitions into a rectangular section that bifurcates. To the right, water is discharged directly into Ralston Reservoir. To the left, water flows down a steep chute then enters a long flume which is Zone A.

The flume of Zone A is about 100-ft long with a rectangular cross-section 16-ft wide and about 10-ft deep. Downstream from the flume is a steep baffled "dragon tooth" spillway which aids in degassing the water prior to entering Ralston Reservoir. The ability to release into the reservoir through either Zone A or the right leg of the bifurcation offered operational flexibility that allowed installation and modifications to HK units in Zone A without shutting down the South Boulder Canal.

For hydro-kinetic power generation key hydraulic parameters are canal slope, average cross-sectional velocity, and fee-board. These parameters are shown for each zone in Table 1 for the design discharge of 300 ft^3/s. Photos of Zones A, B, and C are shown in the appendices.

Table 1 Physical and hydraulic characteristics of the three zones within the test reach of the canal.

	Zone C	**Zone B**	**Zone A (Flume)**
Geometry & Lining	Trapezoidal - Rounded, earthen and cobbles	Trapezoidal, Concrete	Rectangular, Concrete
Bottom Width (*ft*)	20 ft (varies)	16	16
Top width (*ft*)	40 ft (varies)	32	16
Avg Slope (*ft/ft*)	0.0002 - .00048 (varies)	0.00049	0.00052
Avg Velocity at 300 cfs (*ft/s*)	1.6 – 2.3	4.1	4.9
Flow Depth at 300 cfs (*ft*)	5.3 - 6.8	3.7	3.9

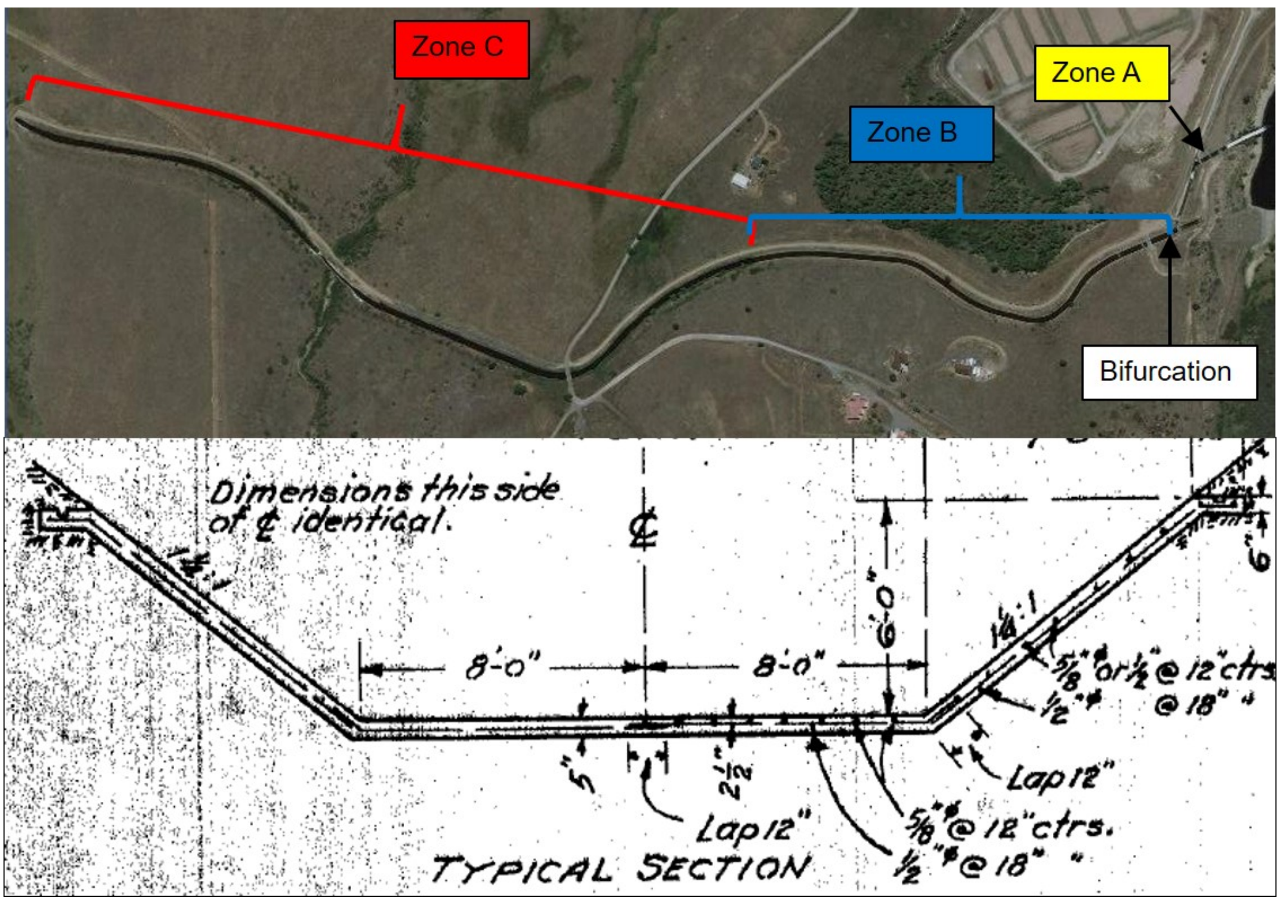

Figure 2 Arial view of South Boulder Canal Test Zones C, B, and A (top – image from Reclamation's Tessel) and typical trapezoidal cross section of Zone B (bottom).

The South Boulder Canal was constructed in the early 1930's and was designed for a maximum discharge of 300 ft^3/s. The freeboard requirement, which is the minimum allowable distance from the water surface to the top of the canal lining (Figure 3), was assumed to be 12 inches (Bureau of

Reclamation, 1978). Zone B was the critical reach in this study as it had about 15 inches of available freeboard while Zones C and A had several feet. The freeboard acts as a safety buffer to prevent water from overtopping the canal lining. Even in areas where the earthen side walls are higher than the concrete lining, there is still a risk of erosion behind the concrete lining which can lead to failure. The freeboard restriction also helps limit the hydrostatic head in the canal to reduce seepage losses or erosion rates. It is especially important for older canals that may be more prone to seepage or failure due to age (Bureau of Reclamation, 1978). The South Boulder Canal falls into this category as do many canal systems throughout Reclamation and the western United States that are approaching 100 years old.

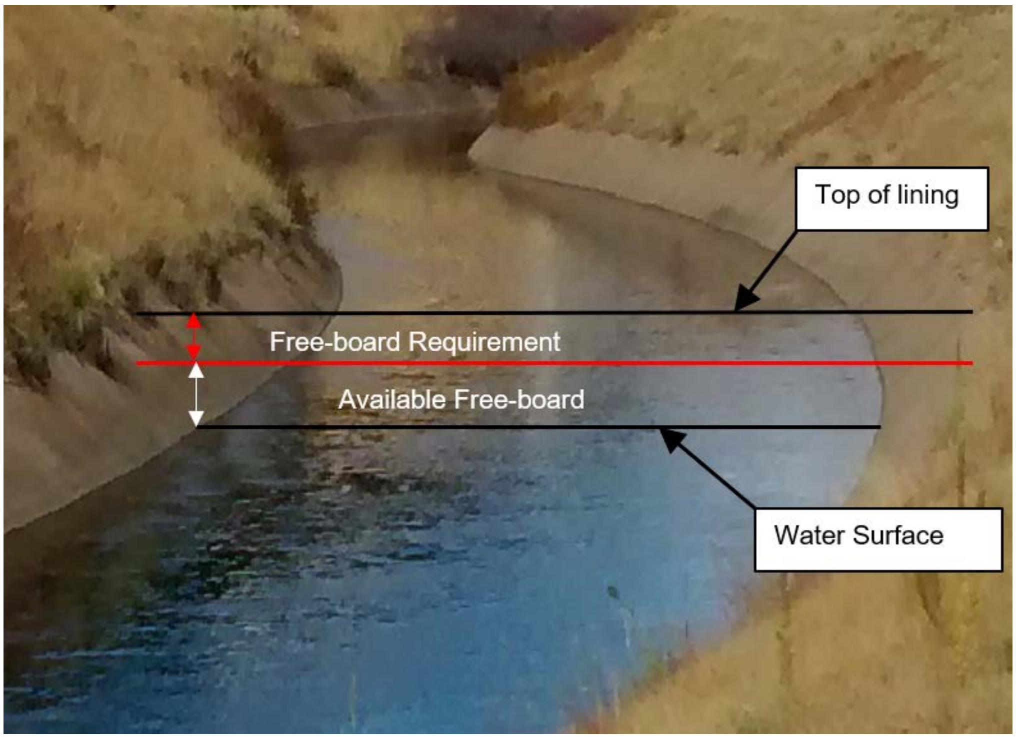

Figure 3 Illustration of freeboard requirement at South Boulder Canal.

Hydrokinetic Power Units

The HK units were designed, by Denver Water's sub-contractor Emrgy Inc and installed and operated by Emrgy and Denver Water staff. They consisted of two rotors supported by a concrete housing with the transmission system and generator, rated at 7.5kW, located on top (Figure 4). The rotors were approximately 4.5 ft in diameter and 4 ft high with three vanes each. The concrete housing was 16 ft wide and could either be anchored to the concrete floor or be supported only by its own weight. For installations in the trapezoidal sections of Zone B temporary wingwall transitions, made with tarps and cables, were installed to concentrate the flow through the rectangular rotor sections to increase velocity and resulting power output (Figure 5). HK units were placed and removed into the canal using a mobile crane. This was not attempted with flow in the canal due to safety concerns and required a flow outage for any HK installations or modifications in Zone B.

For this pilot test, the HK units produced power only one unit at a time since they were not connected to a grid. The rotors were allowed to free spin when not in use. When generating power, the output was sent to a single heat bank which dissipated the HK power output one unit at a time.

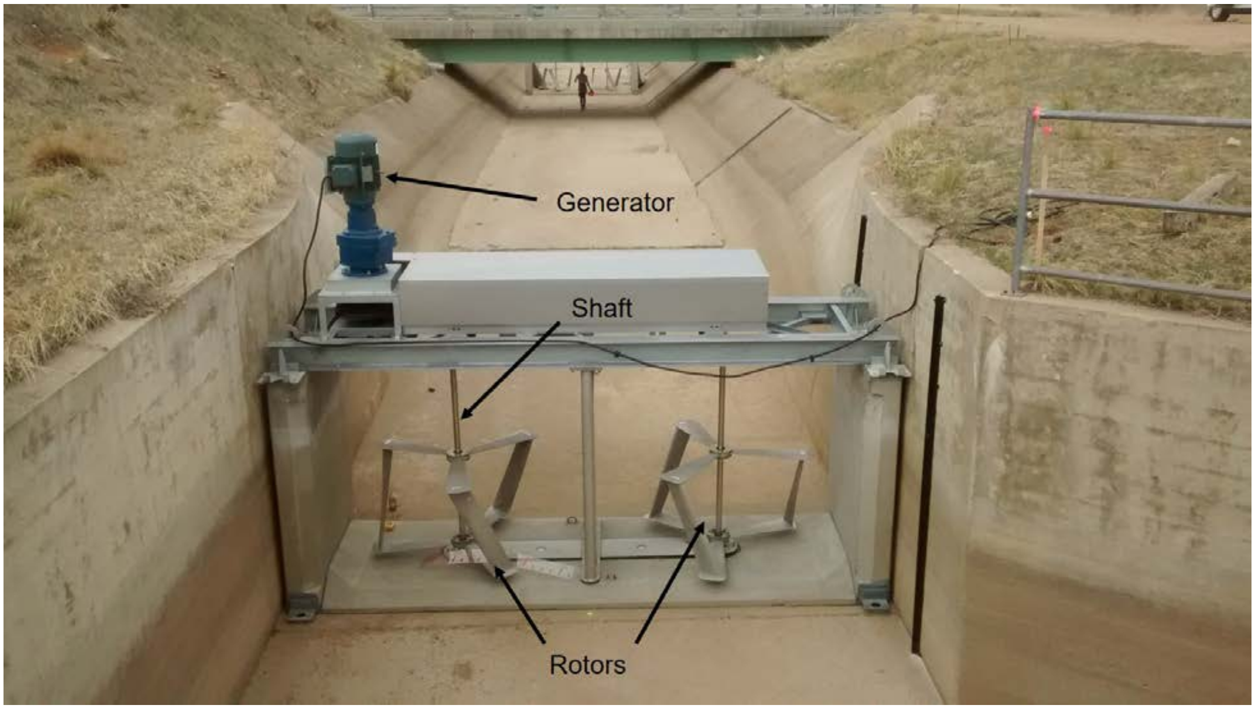

Figure 4 Photo of the dual rotor HK unit installed in the downstream transition of Zone B (looking upstream).


Figure 5 HK unit in operation with temporary upstream transitions made of tarps. Flow is from right to left.

Field testing at South Boulder Canal was conducted in 2017 and 2018. Table 2 shows details of the testing dates, HK configurations, and flow conditions. A baseline test was made in September 2017 without HK installations for a range of discharges. This report focuses on HK operational tests conducted in October 2017 in comparison to baseline conditions. While many tests were conducted throughout 2017 and 2018, the October tests are the focus of this report because they provided the greatest number of HK units installed at one time as well as the greatest envelope of operating test flow conditions.

Table 2 Testing dates, HK unit locations, and range of discharge for 2017 and 2018.

Test Date	Zone A	Zone B	Discharge	Notes
-	*# HK Units*	*# HK Units*	*(ft^3/s)*	-
6/5 – 6/15/2017	1	0	Varies	Preliminary shakedown testing
9/5 – 9/7/2017	0	0	154, 216, 252, 289	Baseline test with no HK Installation
10/11 – 10/12/2017	3	7	226, 266	ADCP Velocity Measurements
4/16 – 4/20/2018	2	3	224	Debris Issues
6/11 – 6/14/2018	2	3	254	

Hydraulic Measurements

Canal water level and velocity were the main hydraulic parameters that were measured. Water levels were measured with Onset HOBO® water level loggers. They were deployed in an angle iron casing anchored to the side walls of the canal (Figure 6). The HOBO loggers contain an internal pressure transducer and memory storage. For each test, loggers were activated and deployed in the canal after which the water surface elevation at each location was surveyed. Pressure measurements from the loggers were corrected for atmospheric pressure variation and tied to surveyed water surface elevations to produce a time series of the water surface elevation at each logger station. Water levels were recorded at 1-minute intervals and averaged over a minimum time period of 2.5 hours at steady state for each test condition. The systematic uncertainty of water level measurements was estimated to be ±0.02-ft (0.25-inch).

Velocity measurements were made using a RD Instruments StreamPro acoustic Doppler current profiler (ADCP) mounted on a tri-hull float that was traversed across the canal using rope taglines (Figure 7). A StreamPro has four separate acoustic beams that measure velocity across the traverse section. Due to difficult in deploying the ADCP, measurements were made only at HK#5 (Zone B) during the October 2017 field tests. Velocity transects were made at one station upstream and five downstream of HK #5 with water level measurements at the same stations.

Several complications limited the quality and usefulness of velocity measurements from the ADCP. These included high shear zones (eddies), turbulence, and air entrainment in the flow downstream from the HK rotors. In addition, the proximity to the HK unit may have compromised the magnetic heading of the transducer possibly due to magnetic interference to the ADCP's internal compass from the proximity to the metal of the HK housing. Point velocity measurements with an acoustic Doppler velocimeter (ADV) would have been preferred but was not attempted because of the difficulty and safety concerns with its deployment.

Figure 6 HOBO® water level logger used for water level measurements (top left). Angle iron installations mounted in Zone A (bottom left) and Zone B (right).

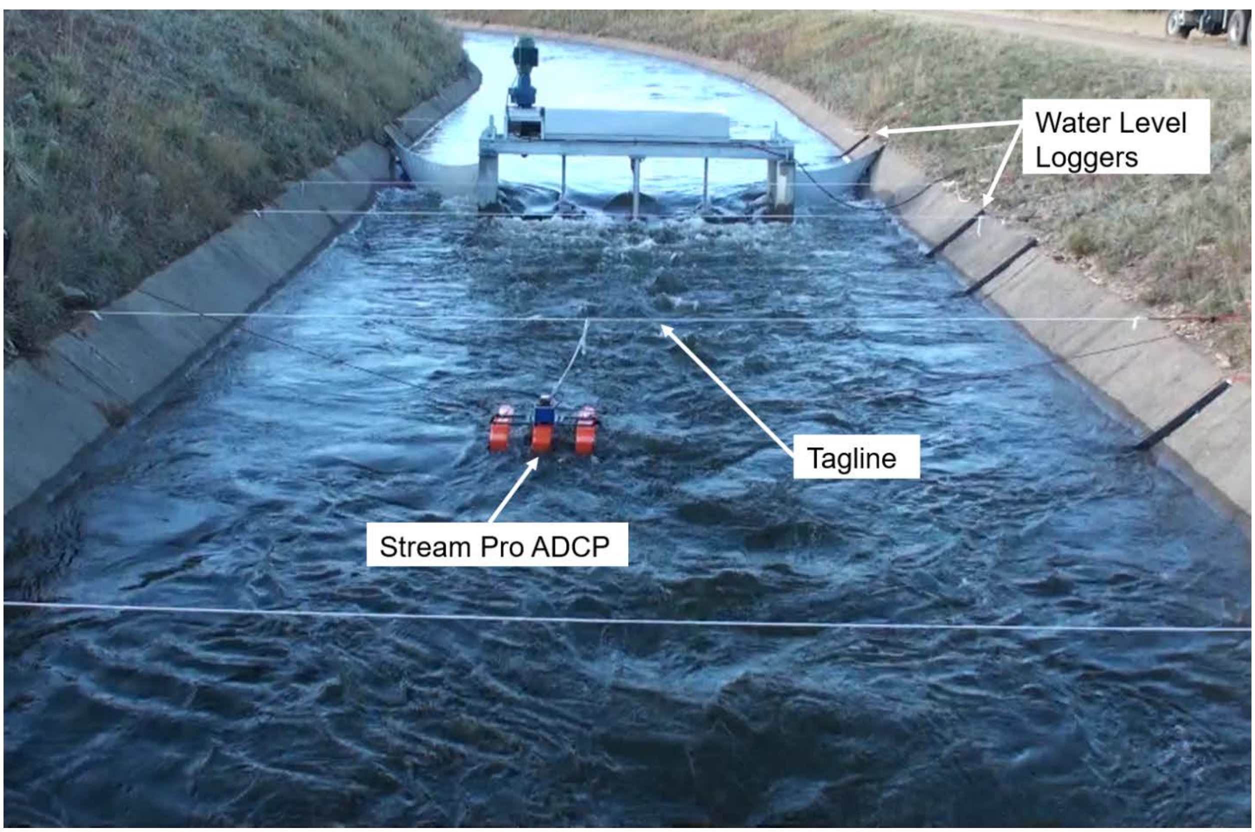

Figure 7 StreamPro ADCP mounted on a tagline for traversing velocity measurements downstream of HK #5.

Numerical Hydraulic Modeling

Numerical hydraulic models were used to provide data that were not possible to obtain from physical field test measurements. A one-dimensional HEC-RAS 5.0.3 model that provides water level and average velocity data (US Army Corps of Engineers, 2020), was used to determine baseline water levels at discharges for HK operational testing that were not directly measured during the baseline test. To directly compare water levels of the October 2017 HK operating tests to baseline results at the same flow conditions, a HEC-RAS model of Zones B and C was developed. The model was calibrated with baseline water level measurements from September 2017 (154 – 289 ft^3/s) and then used to compute baseline water level data at the same measurement locations of the October HK operating tests (226 and 266 ft^3/s) for a direct comparison of baseline and operating conditions.

Flow3D® Version 12.0, a three-dimensional Computational Fluid Dynamics (CFD) software from Flow Science, Inc. (Flow Science, Inc, 2020) was used to evaluate effects from the HK concrete housing structure without rotors. There was not an opportunity to test the housing only in the field to differentiate energy losses due to the HK infrastructure from those of HK power generation. A single concrete housing of the same dimensions of those used in the field test was assumed. Full upstream and downstream transitions that directed all the flow through the housing were assumed to simulate a more permanent configuration, instead of the tarp transitions tested in the field. CFD water level results without the concrete housing were validated with baseline flow conditions at 226 and 266 ft^3/s. Simulations with the housing geometry were then run with the same two flow conditions. The following parameter settings were used for the CFD simulations:

- Volumetric flowrate upstream boundary condition (226 and 266 ft^3/s)
- Pressure downstream boundary condition (fluid elevation from water level measurements)
- Baseline simulations – single mesh block with 0.5-ft cell size
- HK housing simulations – total of 4 nested mesh blocks to refine cell size around housing geometry (0.5, 0.25, 0.125, and 0.0625-ft cell size)
- Renormalized group (RNG) turbulence model

Results

Test results from flow conditions of the October 2017 HK operating tests (226 and 266 ft^3/s) are compared to those at baseline conditions without HK units in the canal. This report focuses on October 2017 test results because they had the greatest number of HK units in the canal system at one time and covered the operational discharge range for all testing conducted throughout the study. Unfortunately, power output data from generating HK units were not available to include with the test results. The October 2017 operating test included a total of 10 HK units, 3 in Zone A and 7 in Zone B. Each HK unit and their location is identified in Table 3.

Table 3 HK unit locations for October 2017 test conditions (226 and 266 ft^3/s)

HK #	Zone	Station	Notes
1	A	25	Rectangular flume
2	A	50	Rectangular flume
3	A	100	Rectangular flume
4	B	0	Rectangular transition, downstream Zone B
5	B	250	Tarp transitions, velocity measurements
6	B	504	Tarp transitions
7	B	750	No transitions
8	B	823	No transitions
9	B	890	Tarp transitions
10	B	2045	No transitions, upstream end of Zone B near transition from Zone C

Baseline Tests

In September 2017, a range of flows were sent through the South Boulder without any HK installations over the period of about 3 days. Discharge was measured at a venturi flume near the upstream end of the South Boulder Canal (~9 miles upstream of the test site). Water level measurements were made at the upstream and downstream end of each zone as well as other strategic locations. A time-series plot of the baseline flow test (154 – 289 ft^3/s) is shown in Figure 8, along with the water surface elevation at the upstream end of Zone B, station 2020. Although the canal was originally designed for a maximum discharge of 300 ft^3/s, the water surface was still more than 6 inches below the freeboard restriction at the highest discharge of 289 ft^3/s.

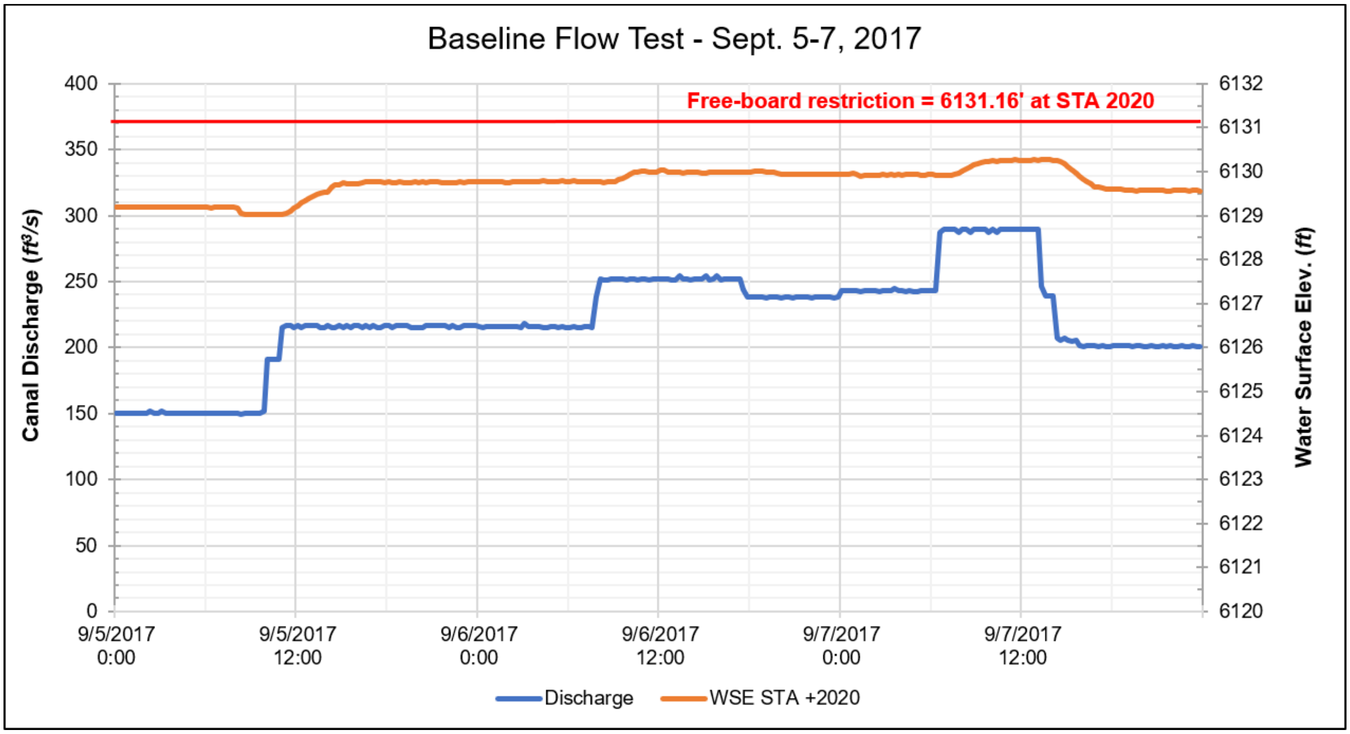

Figure 8 Discharge and water level results (Station 2020, upstream end of Zone B) for the baseline test with no HK installations in the canal.

Water Level Measurements

Following the baseline test, HK units were installed during a canal outage and water level loggers were relocated to upstream and downstream of each HK unit to measure water level changes relative to baseline conditions without HK units in the canal. Additional loggers were placed at five stations downstream of HK #5 in Zone B to match velocity measurement locations. Only two locations were measured in Zone C during operating tests; station 4,000 (downstream of bench flume) and station 5,664 at the siphon outlet.

Zone A

Water surface elevations for 226 and 266 ft^3/s in Zone A are shown in Figure 9. Baseline water levels were not measured so a direct comparison with HK units is not available. However, the normal depth of the channel is 3.9 ft. A head drop is clearly shown for HK #1 and #3, but not for the middle unit #2. This was likely due to the elevated water surface back watered from #1. It is unclear why this backwater effect did not affect the water level immediately downstream of HK #3. The three units did cause irregular and elevated water levels within the flume. However, there was still more than 3.5 ft between the highest water level and top of the flume at the worst-case condition which is well within safe flume operation. Photos of Zone A are shown in Appendix A.

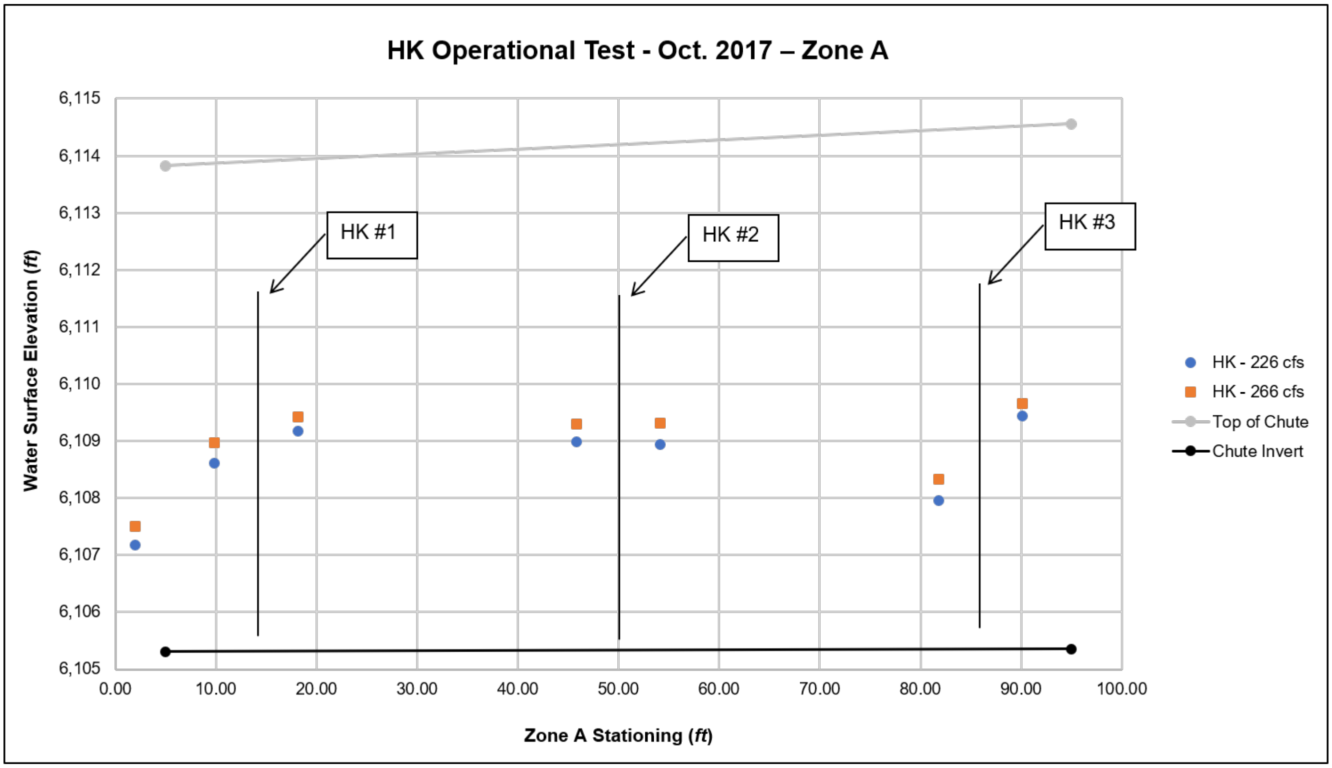

Figure 9 Zone A water level results for the October 2017 HK operational test for 226 and 266 ft^3/s.

Zone B

Water surface elevations in Zone B are compared to baseline conditions and the freeboard restriction for 226 ft^3/s in Figure 10 and 266 ft^3/s in Figure 11. At 226 ft^3/s water levels were increased by varying degrees at each HK location but did not encroach upon the freeboard restriction at any location. At 266 ft^3/s water levels increased further and encroached the freeboard restriction from station 800 near HK #7 to HK #10 at station 2045 at the upstream end, more than half the length of Zone B. Note: the water level logger just upstream from HK #7 failed, as a result, no water level data were available for both test conditions.

The water levels shown in Figures 10 and 11 not only increased, but also exhibited a compounding effect where the water was checked up more near the upstream end due to multiple HK units compared to a water level increase from a single unit near the downstream end. This is also shown in the photos of HK #5 near the downstream end (Figure 12) and HK #10 near the upstream end (Figure 13). Additional photos of Zone B are shown in Appendix B.

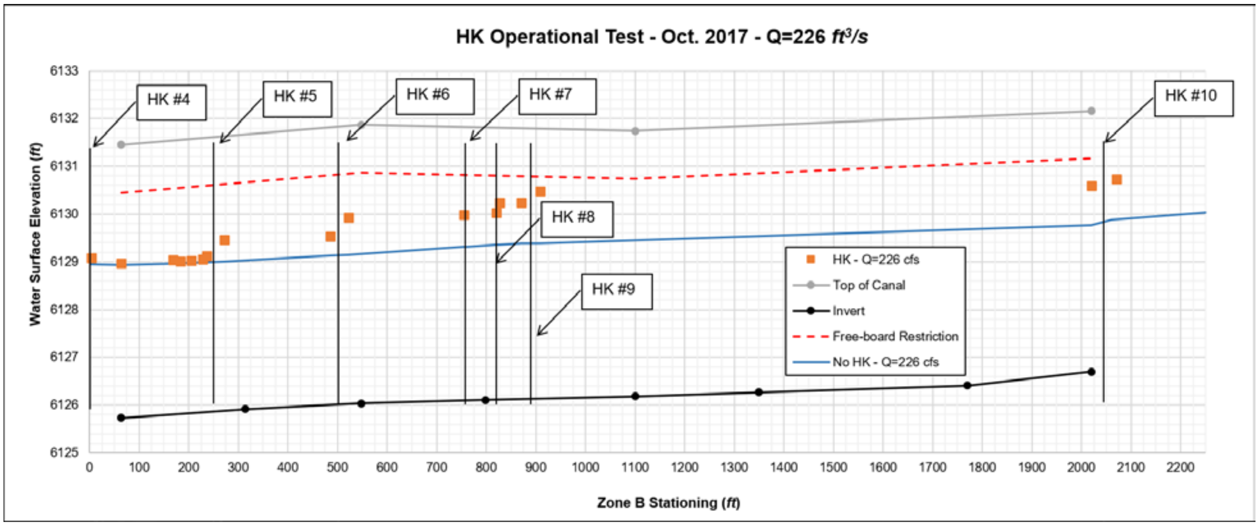

Figure 10 Zone B water level results for the October 2017 HK operational test for 226 ft³/s.

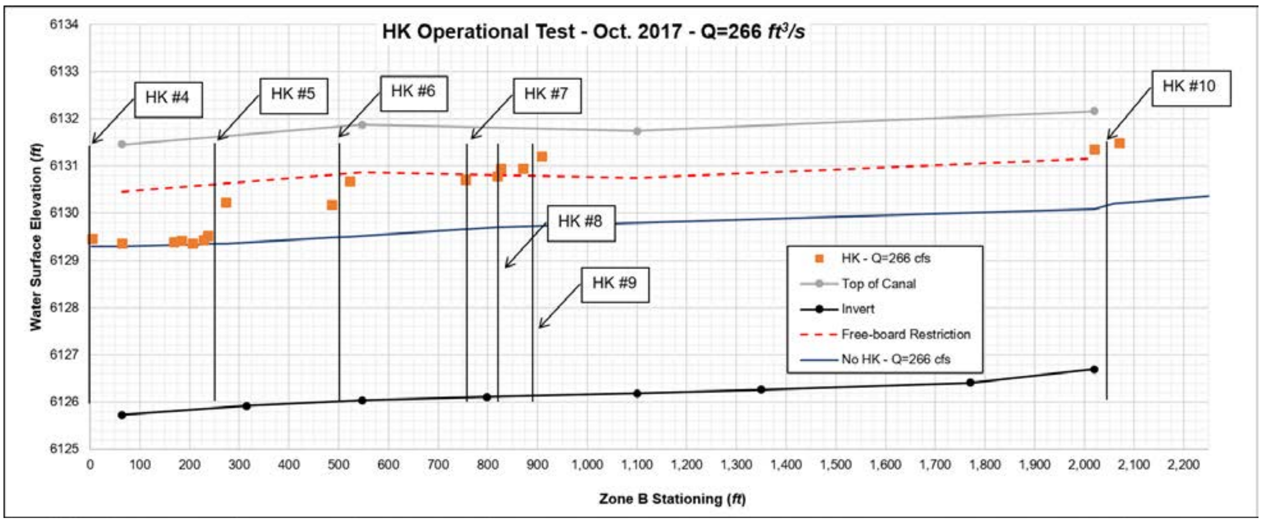

Figure 11 Zone B water level results for the October 2017 HK operational test for 266 ft³/s.

Figure 12 Water level upstream of HK #5 (station 250) at 266 ft^3/s. Flow is from right to left.

Figure 13 Water level near top of lining upstream of HK #9 (station 890) at 266 ft^3/s. Flow is from right to left.

Zone C

Water level results for Zone C are shown in Figure 14 for station 4,000 and 5,664 ft. Although there were no HK installations in Zone C, water levels at station 4,000 ft increased by 0.08 ft at 226 ft^3/s and 0.51 ft at 266 ft^3/s compared to the baseline condition. This was due to a backwater effect from the HK installations in Zone B downstream. Station 4,000 ft is directly downstream of a rectangular bench flume that crosses a ravine. Water levels upstream from the bench flume were unaffected by the HK installations because of super critical flow and hydraulic jump entering the upstream end of the bench flume which caused a change in hydraulic control between upstream and downstream water levels at that location. Due to this shift in hydraulic control the HK units did not affect the operation of the inverted siphon upstream from Zone C but impacts to inverted siphons may be a possibility in other canal systems and should be an important consideration. Photos of Zone C are shown in Appendix C.

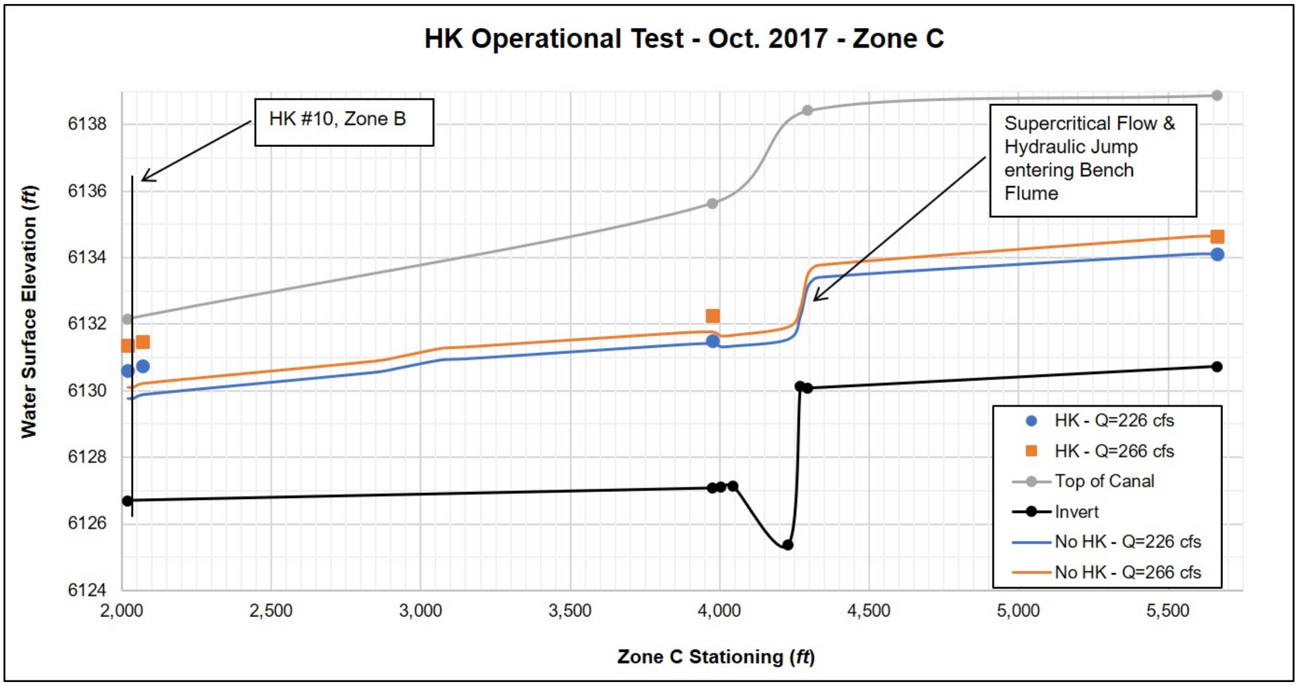

Figure 14 Zone C water level results for the October 2017 HK operational test for 226 and 266 ft^3/s.

Effects of HK Housing

Figure 15 shows changes to water levels from a permanent HK housing with transitions upstream and downstream from the housing. Results are from the Flow3D CFD model that assumed a single HK housing in the canal without influences from other units for 20 rotor diameters (x/d) both upstream and downstream. Water levels are less than baseline downstream of the housing and fluctuate before stabilizing and returning to a baseline condition further downstream. The increase in upstream water levels is less than 0.25 ft for both flow conditions. Water level measurements from the South Boulder Canal did not have sufficient spatial resolution to detect water level fluctuations with distance downstream.

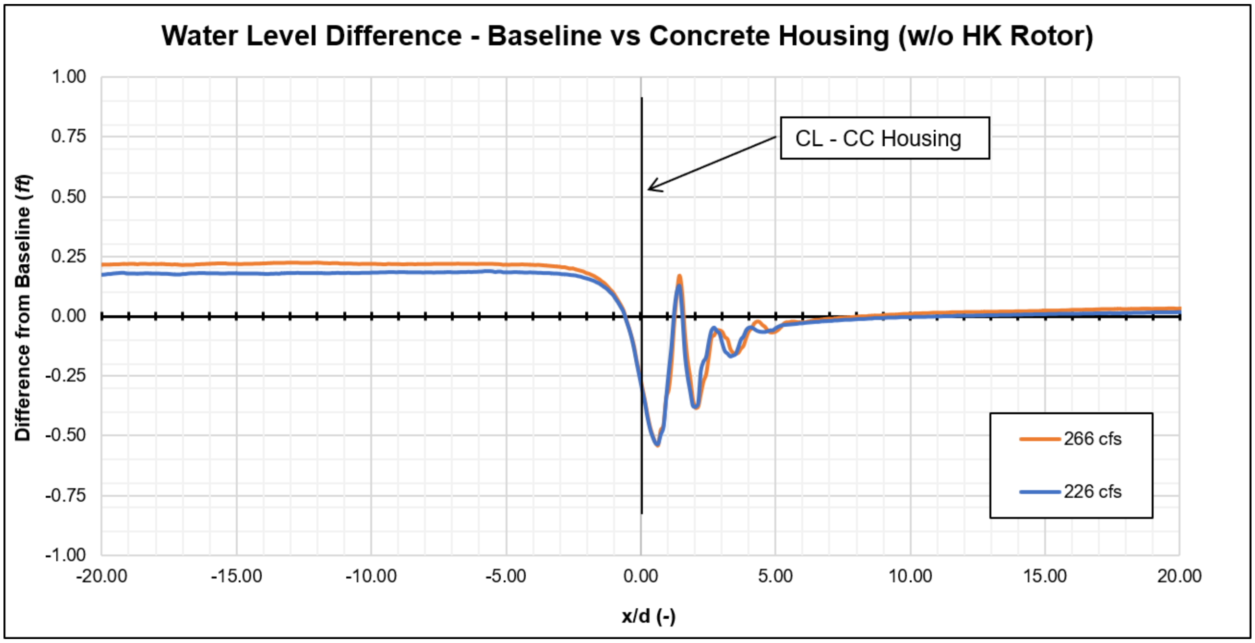

Figure 15 CFD water level differences of the HK housing without rotors compared to the baseline condition for both 226 and 266 ft³/s. Negative x/d indicates upstream.

Figure 16 shows the energy grade line which includes the water surface elevation plus the velocity head ($V^2/2g$). The total energy loss from the HK housing from 5 rotor diameters upstream to 5 downstream is 0.23 ft at 226 ft^3/s and 0.26 ft at 266 ft^3/s. A general view of the 3D velocities of the canal and HK housing is shown Figure 17.

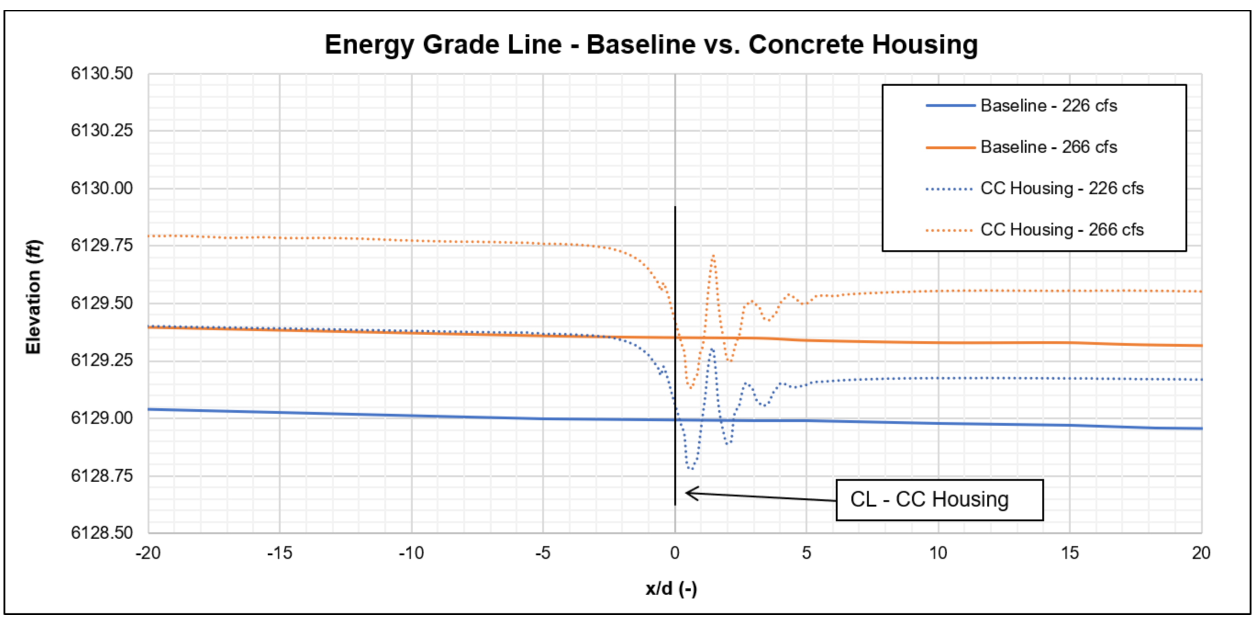

Figure 16 CFD energy grade line of the HK housing without rotors compared to baseline for both 226 and 266 ft³/s. Negative x/d indicates upstream.

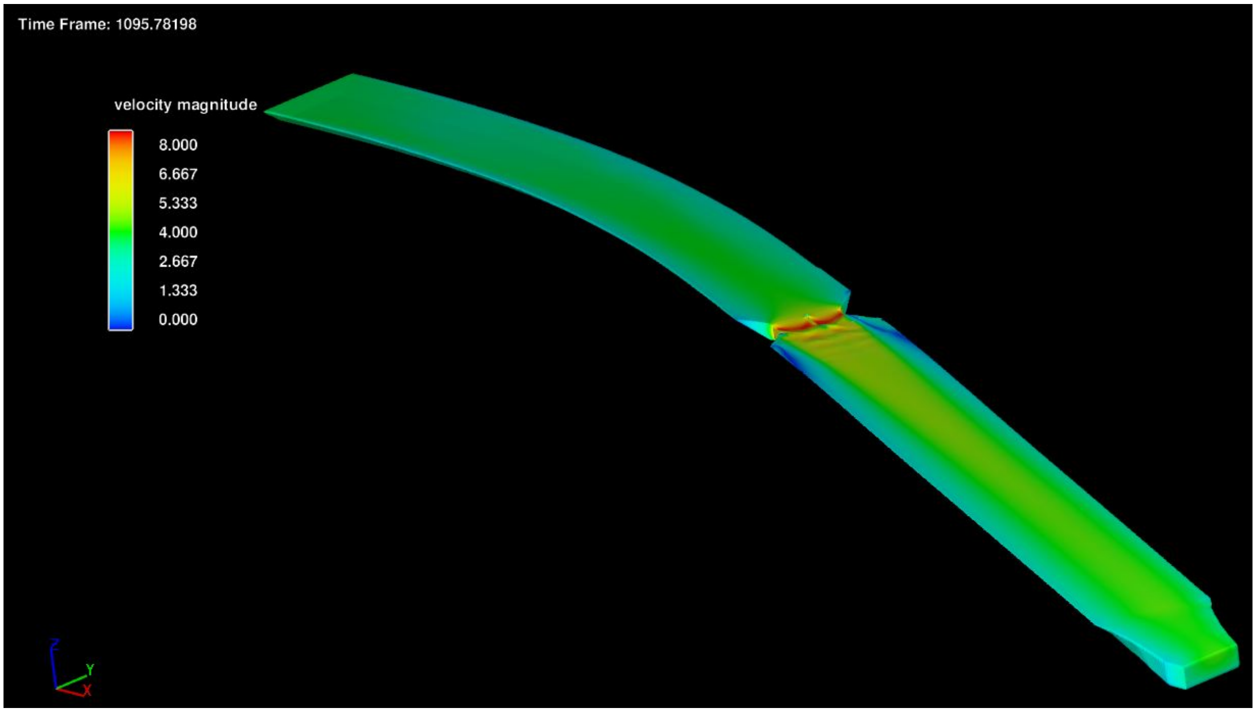

Figure 17 Isometric CFD 3D velocity contour plot of the canal with a single concrete housing without HK rotors at 266 ft^3/s.

Velocity Measurements

Figure 18 shows velocity magnitude distribution at cross-sections from ADCP measurements made near HK #5 at 266 ft^3/s. The six plots represent transects taken at 5 rotor diameters (x/d) upstream and 3, 5, 10, 15, and 18 rotor diameters downstream from HK unit #5. Measurements had to be made at 18 diameters rather than 20 because access was prevented by a bridge across the canal at that location downstream from HK #5.

Portions of the contour plots that are whited out represent locations without data due to excessive turbulence or air entrainment which prevented a return of the acoustic signal. These were most prevalent 3 and 5 diameters downstream from the unit where flow patterns were most turbulent. Still, flow distributions downstream of the HK unit can be seen. Upstream of the HK unit (x/d = -5) flow was mostly uniformly distributed with some flow skewed toward the left bank. Immediately downstream (x/d = 3) the flow was concentrated near the center of the canal due to the transition through the HK housing and the inward rotation of both rotors. Some flow is shown near the banks of the canal indicating leakage through tarp transitions which confirmed the visual observations. Current velocities in excess of 8 ft/s near the center were measured as far as 10 rotor diameters downstream. Velocities dissipated with distance downstream as the flow was distributed more evenly across the canal section. However, most of the flow was still concentrated near the center of the canal at 18 diameters downstream and had not yet recovered to the original flow distribution similar to those measured 5 diameters upstream.

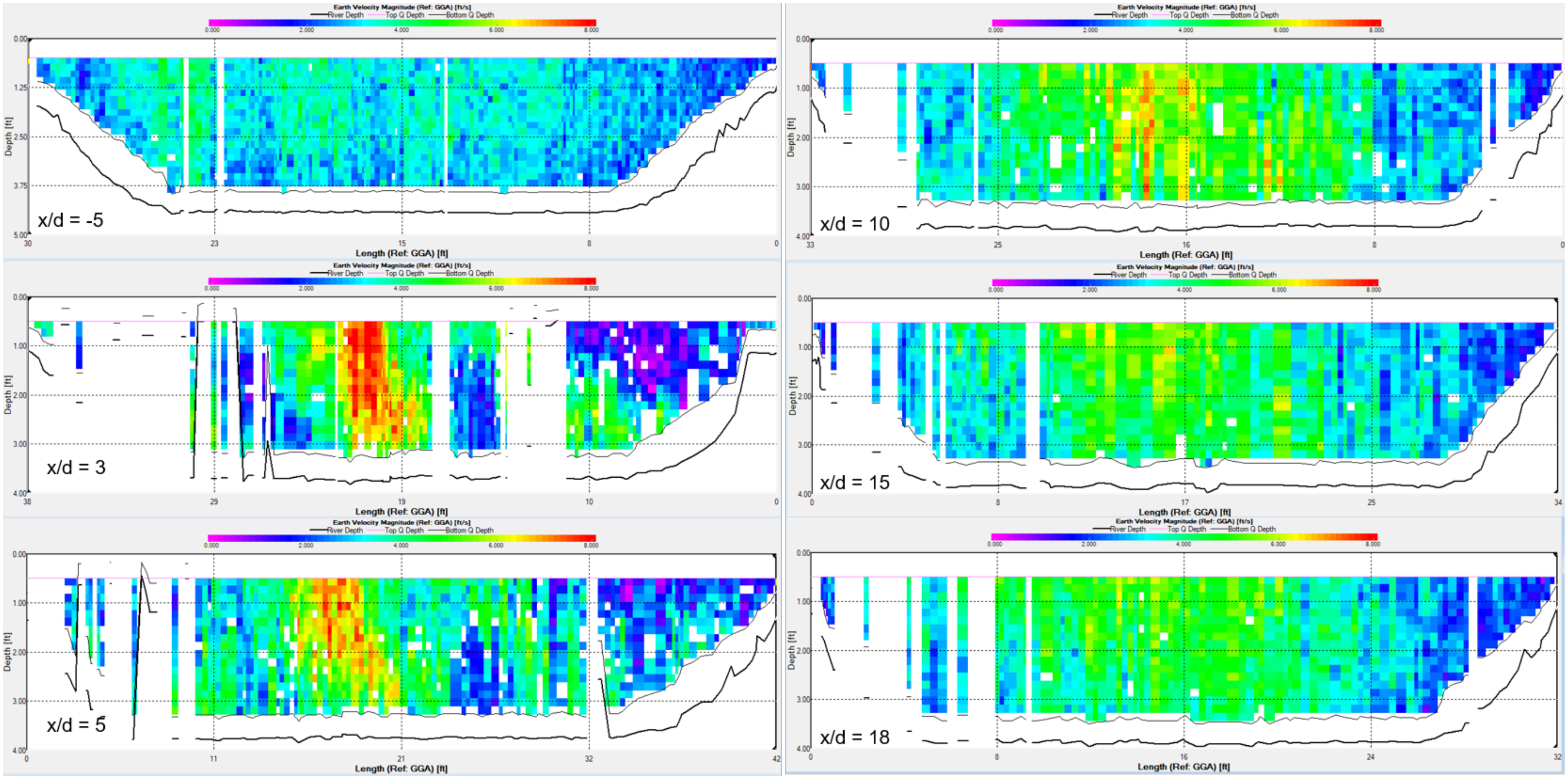

Figure 18 ADCP velocity magnitude distribution looking downstream for 6 stations from x/d = -5 (top left, upstream) to x/d = 18 (bottom right, downstream).

Practical Field Experience

An important element of this pilot study was the practical aspect of operating and maintaining a real canal system with several HK units. Coordination of water schedules, canal outages, and crane availability with HK installation and maintenance was critical. Safety procedures were developed and implemented to monitor the canal system whenever HK units were installed. This included a site inspection from the local facility operator on regular intervals at night or other times when test personnel were not on site.

During the night of April 15th, 2018 debris clogged the rotor and housing of HK #5 in Zone B and checked up the upstream water level (Figures 19 and 20). The problem was identified by the facility operator on his scheduled site visit and was quickly resolved before water over-topped the concrete lining. After attempting to remove the debris utilizing mechanical methods (backhoe) the tarp transitions were sliced to allow flow around the outside of the HK housing and relieve the upstream water level. The debris consisted mainly of tumble weeds blown into the canal from a windstorm during the night. The safety protocols were effective at protecting the canal and personnel, although completely removing the debris and returning the HK unit to service was difficult and time consuming. Water level measurements were not available during this event as it occurred just before the first planned test period of 2018 and water level loggers were not yet installed.

Figure 19 Debris clogged in the HK rotors. Tarp transitions were cut to relieve upstream water levels. Looking downstream.

Figure 20 Debris clogged in the HK rotors. Looking upstream.

Analysis and Discussion

The following sections further explore test results and observations from the South Boulder Canal pilot test with the intent of identifying important factors that should be considered when exploring the possibility of adding HK power generation to existing open channels. Discussions and conclusions are of a technical nature and do not attempt to address economic or financial considerations.

Available Power

The amount of power available in the canal vs. the total power required to spin the rotors against an electrical load and drive the flow across the supporting structure should be considered to determine the rated power output and number of HK units that can be installed. The amount of kinetic power available to the rotors can be estimated by equation 1 (Sandia National Laboratories and Bureau of Reclamation, 2017):

$$P_r = \frac{1}{2}\rho A_r v^3 \tag{1}$$

Where:
P_r = power from kinetic energy (ft-lb/s)
ρ = density of water (1.94 slug/ft^3)
A_r = rotor's flow facing area (assume two rotors, total of 35.7 ft^2)
v = average streamwise velocity approaching rotors (assume 6 ft/s entering rectangular HK housing from wing wall transitions)

Using the South Boulder Canal as an example with the same geometry, HK units, and flow of 266 ft^3/s, the total power available to the HK rotors is 7,480 ft-lb/s, or 13.6 horsepower (10.1 kW). The actual power output from the generator will depend on the efficiency of the HK unit. The efficiencies of the HK units used in the current test were not quantified as part of this study. The power dissipated by the support structure with wingwall transitions can be estimated by equation 2:

$$P_s = \gamma Q \Delta H_s \tag{2}$$

Where:
P_s = power loss across support structure (ft-lb/s)
γ = specific weight of water (62.4 lb/ft^3)
Q = canal discharge (266 ft^3/s)
ΔH_s = total energy loss from structure (ft), obtained by empirical formulas or modeling

With a total energy loss of 0.26 ft from 5 diameters upstream and downstream of the rotor centerline (from Flow3D model) the power dissipated only by the concrete housing structure and wingwall transitions is 7.9 horsepower (5.9 kW). This, combined with the rotor power, gives a total consumption of 21.5 horsepower (16 kW) across each unit which could be compared to the actual power output from the generator to determine net efficiency.

Energy Losses, Spacing, and Location

The total energy of flow in a channel is useful in assessing energy losses from the HK units and their effect on spacing and hydraulic operation of the canal. The energy grade line (EGL) accounts for potential and kinetic energy of the flow at a given location and is defined by equation 3:

$$EGL = \frac{P}{\gamma} + z + \frac{v^2}{2g} \tag{3}$$

Where:
EGL = Energy Grade Line (ft)
P = water pressure at invert (lb/ft^2)
γ = specific weight of water (62.4 lb/ft^3)
z = elevation at invert (ft)
v = average velocity (discharge/flow area, ft/s)
g = gravitational constant (32.2 ft/s^2)

The EGL from test measurements in Zone B is presented in Figure 21 and shows a significant increase compared to the baseline at the same discharges. Although the total energy at the downstream end of Zone B ended up the same for both operating and baseline conditions, the additional energy required to overcome the resistance of the HK housings and rotors produced greater upstream flow depths. While this did reduce the velocity head to some degree, most of the energy grade line with HK consisted of increased potential energy from greater flow depths. In other words, to maintain the same baseline discharge, additional storage upstream was created by increasing the flow depth until the total energy was sufficient to overcome HK unit energy losses. This could become a safety concern if there isn't enough storage in the system and flow depths encroach upon freeboard restrictions. Most canals in the western United States were designed to operate near the freeboard limitation at the design flow and have little wiggle room for additional energy loss. Altered EGL's may also be a concern for specific features like inverted siphons that depend on a specified water level range to maintain discharge through the siphon.

The energy grade line can also be used to approximate the minimum distance between HK units without significantly altering canal hydraulics. Using HK unit #5 as an example with wingwall transitions, the total energy loss measured across the unit was 0.72 ft (which also corresponds to the total power consumption previously estimated in equation 2). The minimum spacing could be approximated by dividing the energy loss by the slope of the energy grade line (0.0049, same as bottom slope assuming normal depth) which results in a spacing of 1,470 ft between unit installations. Of course, spacing could be tighter depending on canal slope and velocity, freeboard and the degree the canal may be overdesigned. However, this demonstrates the potential for limitations of the quantity and spacing of HK units in canal mains and highlights the importance of reducing supporting structures in the flow path if possible. Also, it shows the advantages of installing in strategic locations such as units 1-3 where disrupted hydraulics can be tolerated or unit 4 where energy is already being dissipated by the existing system.

Due to the limited number of configurations that could be tested and differences in HK unit tarp transitions and uneven spacing (as seen in Figure 21), a detailed evaluation of unit spacing was not conducted in this study. Studies of flow recovery and unit spacing have been conducted for other HK designs (Neary, Gunawan, Hill, & Chamorro, 2013). Further investigations to optimize unit spacing for general vertical axis HK configurations would be beneficial.

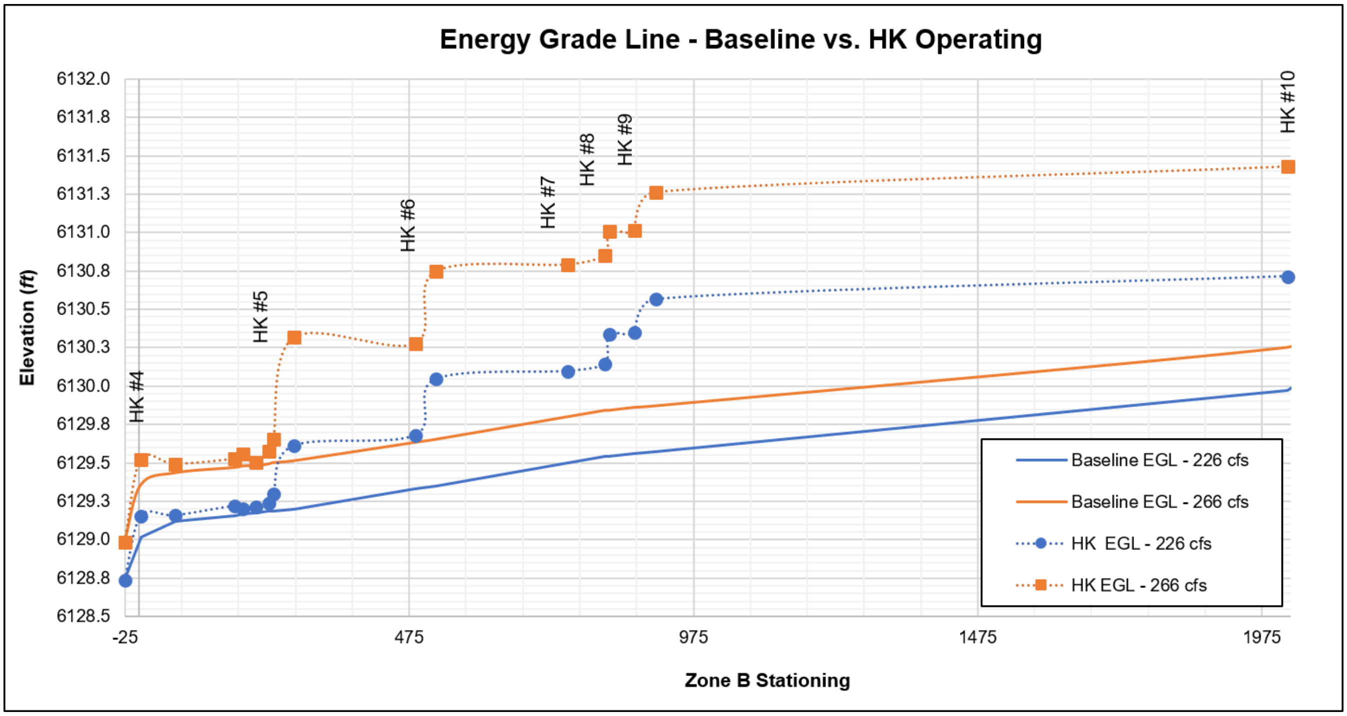

Figure 21 Energy Grade Line for both HK operating and baseline conditions at 226 ft^3/s and 266 ft^3/s.

The extent of increased flow depth is dependent on the canal slope and velocity, design of the HK unit, the number of unit installations, and the spacing of the units from each other. Figure 22 shows the water level changes relative to the baseline condition for Zone B. Effects from individual units varied, probably because tarp transitions were different at each installation, and some didn't have transitions. However, the data suggest that there is a compound or "stacking" effect where water level increases grow with distance upstream. The only exception to this compounding effect is HK #10 where the upstream water level difference was less than that at HK #9. This was likely due to the greater distance between the two units that allowed the flow to recover to some degree before reaching #9.

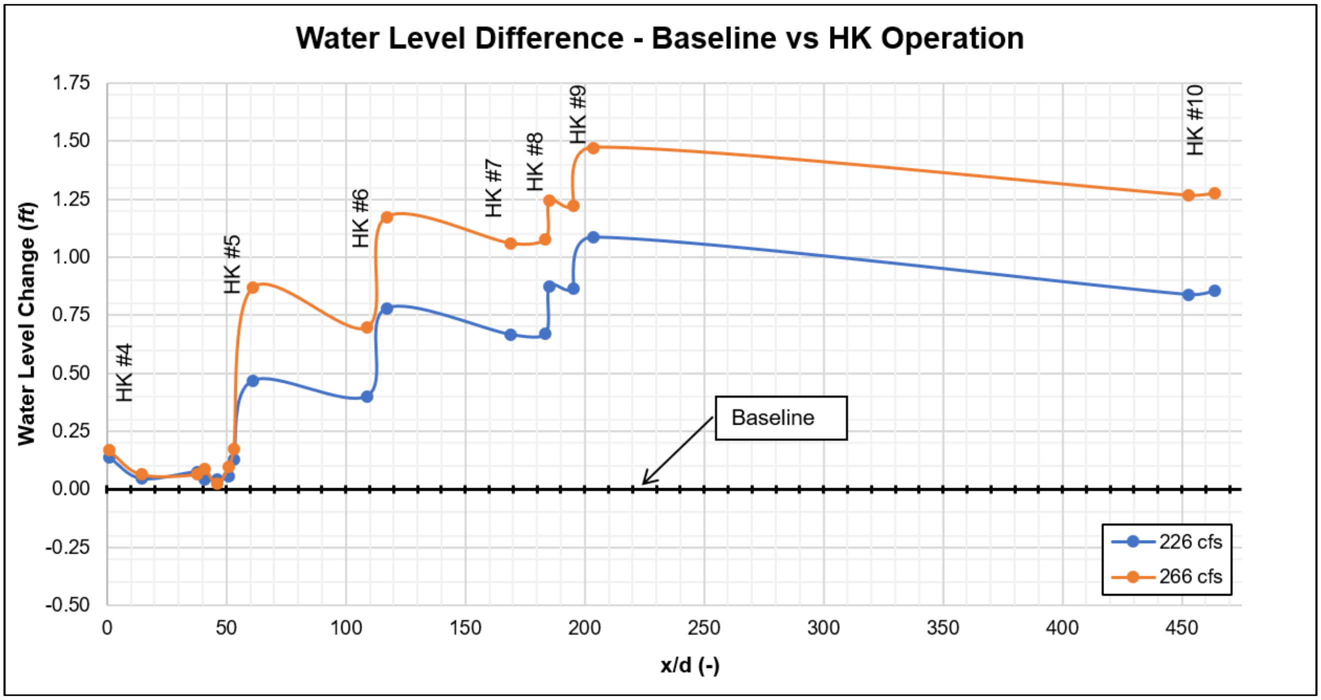

Figure 22 Water level changes from HK operation compared to the baseline condition.

Location and spacing of HK installation is important for both hydraulic operation and distance to an electrical grid connection. Limitations in unit spacing will increase the distance and cabling required for an electrical connection. As previously discussed, canal geometry, slope, velocity, and freeboard are critical parameters that will affect unit spacing.

Turnouts or lateral flumes and channels may be more ideal for HK power generation due to greater velocities, flow depth capacity and operational flexibility. This was shown by tests conducted in Zone A. The short distance of 100 ft (22 rotor diameters) was able to accommodate three HK units without approaching the freeboard restriction. Other benefits included the ability to divert flow from the flume for installations or modifications to the units without shutting down the canal, tighter spacing to reduce distance for electrical grid connections or to a local load, higher flow velocity and power output without channel transitions, and negligible impacts from other disruptions to the hydraulics such as localized turbulence and air entrainment.

HK Capacity vs. Discharge Reduction

Test results from Zone B demonstrate the balance between the number of HK installations in a canal system and maximum discharge before the upstream freeboard is exceeded. The potential of reducing system discharge capacity due to water level constraints from the HK units should be an important consideration. This is especially true for canal systems typical in the western U.S. where water is scarce and urban development has increased around canals making both reliable water delivery and safety top priorities.

For the case of the South Boulder Canal, Zone B included seven HK units in October 2017 with the greatest water level encroachment of the freeboard restriction at station 908 ft, just upstream of HK #9 (see Figure 11). Assuming the head losses from the downstream units are linear with flow, the maximum discharge without violating freeboard is 241 ft^3/s. This would reduce the canal capacity by almost 60 ft^3/s, or 20% from the original maximum design discharge of 300 ft^3/s. This is shown visually in Figure 23.

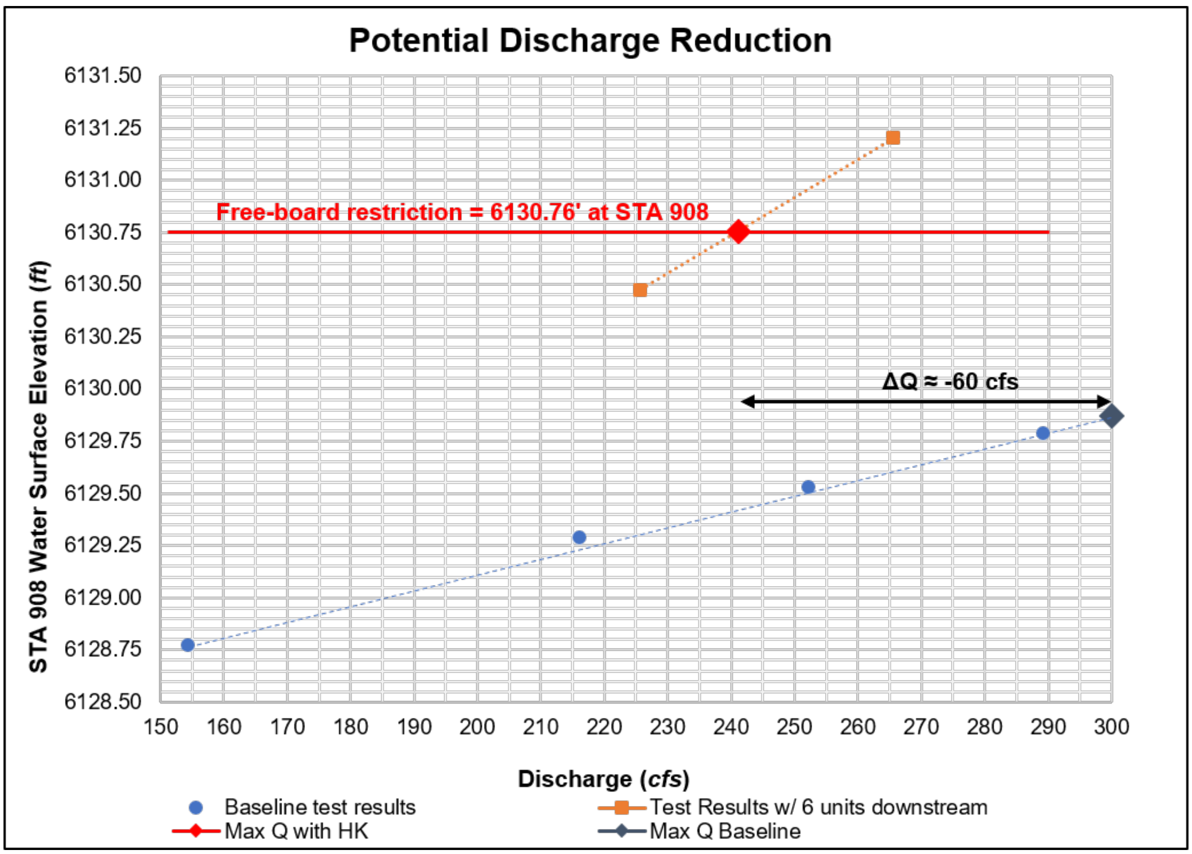

Figure 23 Illustration of potential reduction in discharge assuming 6 HK installations downstream from station 908 in Zone B.

Safety and Emergency Planning

Additional safety and emergency procedures should be considered for HK power generation in canal systems. These include but are not limited to water level and freeboard restrictions, canal shutdown or flow routing procedures, electrical and mechanical safety, and debris and ice handling.

Emergency procedures may require additional water level sensors with real-time data monitoring and alarm systems or regularly scheduled inspections such as were done during the pilot study at South Boulder Canal. In the case of this pilot study, having staff nearby allowed for quick response to any issues that could arise. HK units in more remote locations could present challenges to operators but could be addressed by utilizing remote monitoring technologies. Emergency planning would need to include procedures to either quickly shutdown the canal or divert the flow depending on the severity and location of the emergency.

Warning signs, physical barriers, or other methods may be required to protect personnel and the public from mechanical and electrical hazards. The potential for vandalism to the HK systems may also need to be addressed.

Debris handling may require additional equipment, man-power, or changes to the design of the HK system to reduce debris clogging. Design changes could include debris handling equipment upstream or a configuration that removes or rotates the rotors out of the flow when debris is present. Ice formation in the canal may be a concern for systems in cold weather climates. This was a concern for South Boulder Canal during winter operations and the ability to pass pieces of ice through the HK units became a challenge. While HK units were removed from Zone B, HK units in Zone A were operated during winter due to the ability to immediately divert water from Zone A should freeboard be compromised. Figure 24 is an example of ice forming upstream of an HK unit in Zone A. Mechanical means were employed to break ice into smaller pieces so that they could be passed through the rotors.

In Zone B access to the units for maintenance was limited by the inability to safely access the superstructures while operating. While limited access for maintenance was part of the temporary nature of the HK pilot study, consideration should be given to installing access catwalks or other means of performing maintenance tasks while the units are operating in a canal section that cannot be easily isolated from flow.

Figure 24 Ice upstream of an HK unit in Zone A, looking downstream.

Conclusions

A pilot study was conducted in which 10 Hydrokinetic (HK) power generating units were installed in Denver Water's South Boulder Canal System. Flow and water level measurements were made in the canal for several discharge conditions and compared to baseline levels without HK. Hands-on experience was also gained by installing, operating, maintaining, and removing 10 HK units over a period of several months.

Based on physical test results and practical field experience, the following conclusions have been made:

- Safety planning and emergency procedures are imperative to monitor and prevent canal overtopping due to debris clogging in the HK unit or other emergencies. HK design concepts or modifications that minimize the amount of HK equipment or superstructure blocking the flow and offer flexibility to remove equipment or otherwise prevent the buildup of debris and ice will help address safety concerns and reduce operational limitations due to increased water levels.
- Arrays of multiple HK units are not well suited for canal mains due to increased water levels that may encroach upon freeboard limitations during normal operation. Head differential across the HK units caused upstream water levels to rise. Water level increases were compounded when multiple units were installed too close together and caused water levels to "stack up", further increasing the water level in the upstream canal. This result opposes the general desire or need to keep HK units closer together to reduce distance required for cable runs and electrical connections. Critical parameters for determining unit spacing and hydraulic impacts include canal slope and velocity, freeboard, and design discharge.
- HK power generation may be advantageous if units are installed in strategic locations such as turnouts, laterals, wasteways, or flumes that may offer greater flow velocities, operational flexibility, and where disrupted hydraulic conditions or increased water levels do not compromise normal operations or safety. Still, these locations should always be evaluated for impacts to safety and hydraulic performance when considering HK installation.

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Appendix A – Zone A Photos


Figure 25 Downstream of Zone A flume, looking down the “dragon tooth” spillway that discharges into Ralston Reservoir.


Figure 26 Zone A flume, looking downstream.

Figure 27 Zone A flume and regulating gate, looking upstream.

Figure 28 First HK unit installed near the downstream end of Zone A, looking downstream.

Figure 29 HK #1 in operation near downstream end of Zone A. Looking downstream.

Figure 30 HK #3 operating near the upstream end of Zone A, looking upstream. A radial gate is located just upstream from HK #3.

Appendix B – Zones B Photos


Figure 31 Bifurcation structure at downstream end of Zone B. The left leg goes to the Zone A flume and the right leg (straight) leads directly to Ralston Reservoir.


Figure 32 Trapezoidal to rectangular transition at the downstream end of Zone B, looking downstream.

Figure 33 Zone B canal with trapezoidal cross section. At station 64, looking upstream.

Figure 34 HK #4 (Zone B station 0) operating at 266 ft^3/s, looking downstream.

Figure 35 HK #5 (Zone B station 250 ft) operating at 266 ft^3/s, looking downstream.

Figure 36 HK #6 (Zone B station 504 ft) operating at 266 ft^3/s, looking downstream.

Figure 37 HK #'s 7, 8, and 9 (Zone B stations 750, 823, and 890 ft, respectively) operating at 266 ft^3/s, looking downstream.

Figure 38 HK #10 with no transitions (Zone B station 2,045 ft at connection with Zone C) operating at 266 ft^3/s, looking upstream.

Appendix C – Zone C Photos

Figure 39 Downstream end of Zone C in the dry (station 2,050 ft at connection to Zone B), looking upstream.

Figure 40 Zone C station 4,000 (downstream end of bench flume), looking downstream.

Figure 41 Rectangular Bench flume that crosses a ravine in Zone C (station 4,000 ft), looking upstream.

Figure 42 Supercritical flow and hydraulic jump entering Zone C bench flume at 266 ft^3/s (station 4,300 ft), looking downstream.