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HYDRODYNAMIC EFFECTS OF HYDROKINETIC TURBINE DEPLOYMENT IN AN IRRIGATION CANAL

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BACKGROUND

The primary goal of the Department of Energy's Water Power Program is to efficiently develop and utilize the country's marine hydrokinetic (MHK) and conventional hydropower (CH) resources. The program has recently identified the need to better understand the potential for hydrokinetic energy development within existing canal systems that may already have integrated CH plants. Hydrokinetic (HK) turbine operation can alter water surface elevations and modify the flow in a canal. Significant water level alterations and hydrodynamic energy losses are generally undesirable not only for CH plan operations, but also for irrigation and flood management operations.

The overarching goal of this study is to better understand the effect of operating individual and arrays of devices on local water operations through field measurements and numerical modeling. This study is conducted at Roza Canal, Yakima, WA, where a developer has been testing its vertical axis hydrokinetic turbine for nearly two years. Sandia National Laboratories (SNL) has been working together with Instream Energy Systems (IES) and US Bureau of Reclamation (USBR) to conduct comprehensive field measurements at the site, which include hydrodynamic and turbine performance measurements. These measurements are currently being used to develop hydrodynamic models for simulating the effects of one or more turbines in the canal. The work presented here focuses on the analysis of preliminary measurement results for studying the effects of turbine deployment on the site's hydrodynamics.

SITE DESCRIPTION

Roza Canal is a ten of kilometers long canal that diverts water from the Yakima River between Ellensburg, WA and Yakima, WA. Roza Canal provides irrigation water to nearly 300 km^2 of farmland in the Yakima Valley, a major agricultural land in Washington state. The Roza Hydropower Plant, located 18 kilometers downstream of the diversion dam diverts the water from the canal to supply a 13 kW Francis turbine that generates 65 GWh of electricity on average annually.

Since 2013, IES has tested a 25 kW 3-blade vertical axis Darrieus turbine at the Roza Canal, near Selah, WA, approximately 8 kilometers upstream of the Roza Power Plant. The turbine's rotor diameter (D_T) and rotor height (H_T) are 3 m and 1.5 m. The rotor was located between 1.5 and 3 m above the canal bed. The turbine was mounted on a large cylindrical platform that can rotate by 90 degrees, enabling the turbine to be taken completely out of the water when not operating (Figure 1).

The turbine was deployed on a straight trapezoidal section of the canal, with a longitudinal bed slope of 0.0004. Both canal sidewalls have a slope of 1.25:1 (or 39 degrees from horizontal). The canal bed and sidewalls are made from concrete up to 50 m downstream of the deployment site, where the bed becomes unlined and the channel enlarges. At the turbine location, the water surface width was typically around 12.5 m and the depth was typically 3.3 m (Figure 2), with a turbine blockage ratio of ~16%.

During the site visits, the typical mean velocity in the canal was around 2 m/s, and flow discharge was 50-55 m^3/s. The Reynolds Number (Re) was 4 x 10^6, and the Froude Number (Fr) was 0.4.

The canal flow is significantly reduced in the winter periods and is not suitable for HK turbine operation. The canal flows are of interest for testing between the spring and fall due to the high flows typically occur during this period.

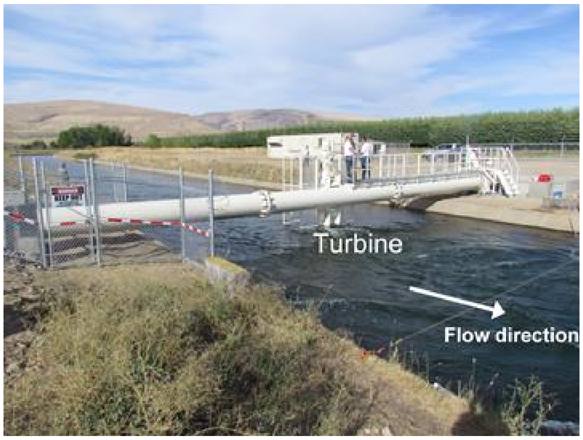

FIGURE 1. THE INSTREAM ENERGY SYSTEM'S TURBINE, IN OPERATIONAL CONDITION.

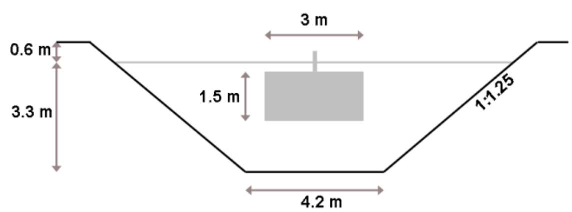

FIGURE 2. A SCHEMATIC VIEW OF THE CROSS-SECTION, SHOWING THE ROTOR SWEPT AREA.

INSTRUMENTATION AND METHODOLOGY

In order to achieve the project objectives, a suite of high-resolution flow and water level measurements were obtained. Hobo water level pressure transducers monitored water level, every 0.5 minute, near the bank of twelve cross-sections located nearby the turbine. The locations of these cross-sections (T1-T12) are shown in Figure 3. While the near bank water level may differ from the centerline water level, the bank water level is of primary interest for the USBR because spillways, which release water into neighboring fields, are located at the bank of the canal. Current management practice also prohibits modifying the Roza Canal channel bed, which is required to deploy the Hobo sensors for centerline measurements. In addition, Hobo sensors were also deployed at various locations further upstream and downstream of the turbine for quantifying HK impact over a larger region.

Two 1200 KHz RDI Rio Grande ADCPs were used for measuring velocity, which can be done simultaneously upstream and downstream of the turbine. The water profiling accuracy of the ADCPs is +/- 2mm/s +/- 0.25% of the water velocity relative to the ADCP [1]. Due to blanking distance and transducers' submersion, the first velocity cell is typically located at 0.7 m below the water surface. The first ADCP, primarily used for measuring inflow velocity, was mounted to an OceanScience Tethered Riverboat [2]. The Riverboat was equipped with a single-channel Hydrolink radio modem that enables wireless communication with an onshore PC, from which the measurement was controlled.

The second ADCP, primarily used for wake flow velocity measurements, was mounted to an OceanScience Remotely-Operated Survey Boat Z-boat 1800. The ADCP position was tracked using a dGPS system which consisted of two Hemisphere A325 antennas. One of the antennae was mounted on the boat while the other was mounted stationary on a tripod on-shore. This rover-base system allows a real-time kinematic (RTK) correction, resulted in a positional accuracy of a few centimeters. The manufacturer's software WinRiver 2 was used for operation and data collection.

Moving vessel (MV) cross-section (CS) ADCP measurements were collected at several cross-sections upstream and downstream of the turbine to investigate flow structure changes between cross-sections (i.e. determine changes to flow entering and exiting the turbine) as well as monitor flow discharge (Figure 4). Inflow velocity contours were measured using the first ADCP at cross-section T1 (Figure 3). Wake flow velocity contours were measured using the second ADCP at CS T8 -T10. During the MV-CS measurements, the ADCPs were tethered across the channel using a tagline. The ADCPs were mounted to a second tagline, anchored to both channel banks, to constrain its movement from the large hydrodynamic force created by the canal's typical 2 m/s current speed. The second tagline provided stability, which is critical for guiding the ADCP through a straight path.

Two ADCPs were used throughout the field measurement campaign for collecting simultaneous measurements. The mean discharge data measured using both ADCPs agree to within 2%.

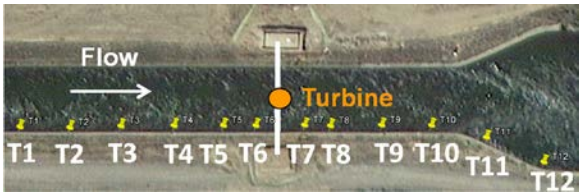

FIGURE 3. LOCATIONS OF WATER LEVEL MEASUREMENTS.


FIGURE 4. SNL STAFF CONDUCTED CROSS-SECTION VELOCITY MEASUREMENT USING AN ADCP AT THE DOWNSTREAM OF THE IES TURBINE

PRELIMINARY RESULTS

Water level

One of the most important concerns for impact assessment is whether the HK turbine deployment would cause flooding by raising the water level over the canal's banks. Analysis from the water measurements indicates that this was not the case at Roza Canal, even when the turbine in place and water level reached its near seasonal maximum during the summer months.

The raw bank water level measurements, i.e., taken once every 30 seconds, fluctuate significantly. In order to better analyze the data, a 21-sample moving window averaging scheme was applied to the raw data for reducing the fluctuation. Figure 5 illustrates the post-processed water level measurements for the August 2014 site visit. The figure shows that deploying the IES turbine slightly raised the water levels upstream of the turbine and decreased the water levels downstream of the turbine.

Operating the IES HK turbine raised the water levels within 50 m upstream of the turbine up to 0.04 m. At 700 m upstream of the turbine, the water level was raised by 0.02 m. In both HK deployments in May and August 2014 the water levels 50 meters from the turbine were still lower than the canal's banks, by 0.45 m or more. The water level downstream of the turbine, on the other hand, showed a local decrease when the turbine was in the water that quickly recovered to its natural state. As seen in the plot of water level difference between the HK-operation and baseline condition in Figure 6 the water level differences upstream of the turbine (negative distance from the turbine) remained constant at around +0.04 m. The turbine's presence caused a water level drop of 0.08 m at the bank of the canal, within 5 meters upstream and downstream of the turbine location. The water level variation decreases to within ~0.01 m at 20 m downstream of the turbine and further.

The canal width starts expanding at 30 m downstream of the turbine, from approximately 15 m to 30 m wide. The widening introduces higher turbulence levels, which accelerates flow recovery, and slows the mean canal velocity downstream of the site. These effects help negate the hydrodynamic changes downstream of the site due to the HK turbine. At ten other sensor locations downstream of the turbine, between the HK turbine site and the Roza Power Plant, water levels were not affected by the HK turbine deployment.

As there were no significant hydrodynamic changes downstream of the HK site, the production rate at the Roza Hydropower Plant was unaffected – this was confirmed by comparing the plant's power production when the HK turbine was in and out of water [3] .

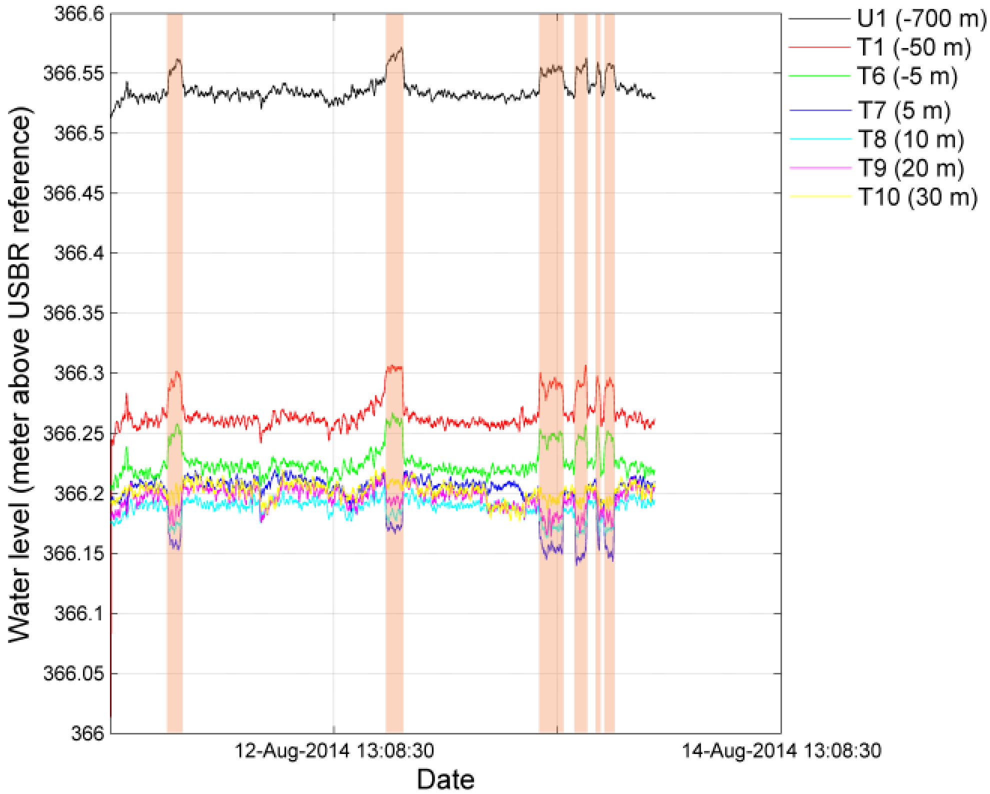

FIGURE 5. WATER LEVEL TIME SERIES AT DIFFERENT LOCATIONS DURING THE AUGUST 2014 SITE VISIT. ORANGE COLORS INDICATE THE PERIODS OF HK TURBINE OPERATION.

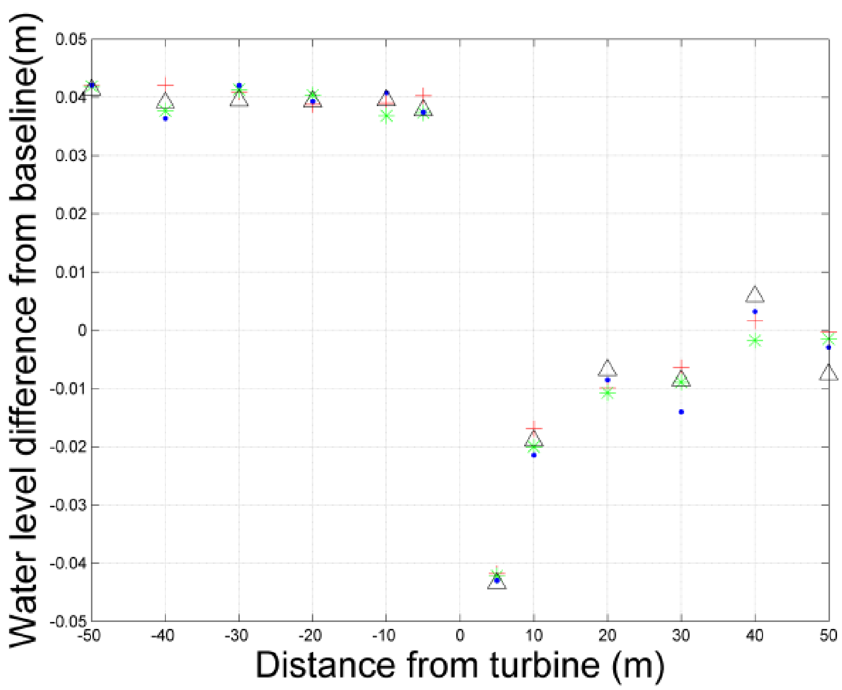

FIGURE 6. WATER LEVEL DIFFERENCES AT THE 12 CROSS-SECTIONS (HK OPERATION – BASELINE), DURING THE 12 AUGUST 2014 MEASUREMENTS. THE FOUR DIFFERENT DATASETS SHOWN WERE MEASURED WITHIN 15 MINUTES TIMEFRAME.

Water velocity

During the August 2014 site visit the turbine (rotor) RPM was varied to study the effect of turbine RPM to power production and wake flow dynamics. The turbine RPM was set to: 1) optimal RPM, ~33 RPM, where the generator produced maximum power; and 2) high turbine RPM, ~40 RPM, the highest RPM that can be achieved with a safe turbine operation. SNL and USBR conducted ADCP MV cross section measurements at the inflow and wake flow cross-sections. Measurement for three or four different cross-sections typically last for several hours, within which the flow conditions may have changed. The stationarity of the flow within this period can be evaluated using the flow discharge values, which can be derived from the MV-CS ADCP measurements. During the two sets of testing the ADCP-derived flow discharge varied by less than 11%, i.e., from 52.5 to 56.9 m3/s during the first set of measurements and from 51.3 to 55.4 m3/s during the second set of measurement. These variations were mainly caused by variation of canal's flow discharge with time.

During the earlier measurements and testing in August 2013, the turbine's presence appeared to have little effect on velocity upstream as the upstream cross sections have similar velocity distributions whether or not the turbine is deployed. The first set of the August 2014 measurements also resembles the same characteristics as shown in the upstream velocity contours, which did not appear to be affected by the turbine's presence (Figure 7, T1 and T5).

These sets of measurements also showed that the ADCP was able to quantify the velocity deficit in the near-wake region and the local velocity increase between the turbine and the canal banks, which is observed downstream of the turbine at 10 m and 20 m (Figure 7, T8 and T9). This information is extremely useful for calibrating and validating numerical models of hydrokinetic turbines. The turbine's presence caused a local flow acceleration to the sides of it, which can be observed by comparing the upstream and downstream (of the turbine) velocity contours (Figure 7).

Similar to the first set of measurements, the second set of measurements also show a velocity dip behind the turbine and high velocity regions on the sides of where it is located (Figure 8). The further from the turbine the lesser the magnitude of both the velocity dip and high velocity regions. Visually, the velocity dip on the downstream cross-sections appears to be more pronounced for the cases with higher turbine RPM values. In order to better quantify the current speed differences for these two cases the ADCP data will be post-processed and smoothed according to the methodology presented in [4].

It is interesting to note that, for all cases, a high velocity core existed at the right part of the cross sections. This high velocity core was caused by the canal's geometry at the upstream of the site; at the upstream of the site the canal curves to the left (looking downstream), which causes super elevation of the water surface on the right side at the measurement location and shifts the high velocity core to the right side downstream of the bend. This finding can be useful for optimizing the turbine layout for future deployment at the site, i.e., moving the turbine to the right of its current location may significantly increase the rate of power generation. Moving the turbine, however, may not be feasible, because the high velocity region has a shallower depth than the current turbine location, which might result in inadequate clearance between the turbine and channel bottom. Nonetheless, it is important to conduct site-specific full-cross-section velocity measurement, such as the moving-boat ADCP measurement, to identify local hot spots, when designing the deployment strategy for a hydrokinetic turbine.

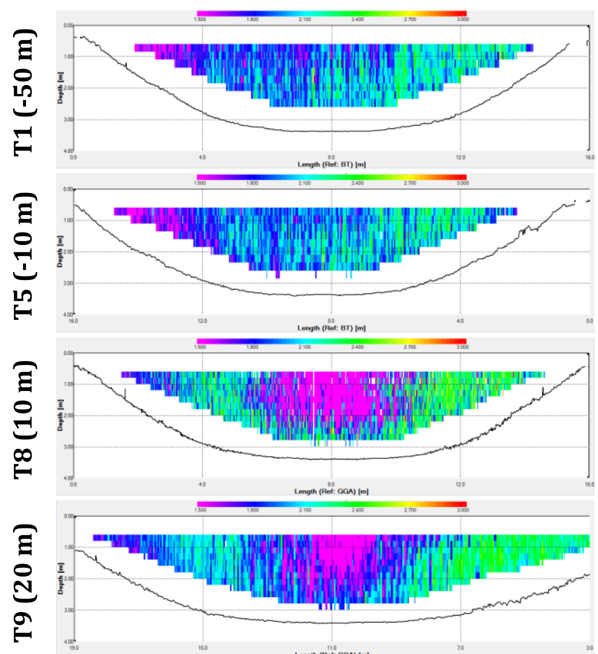

FIGURE 7. STREAMWISE VELOCITY CONTOURS AT VARIOUS LOCATIONS UPSTREAM AND DOWNSTREAM OF THE TURBINE. TURBINE WAS OPERATED AT THE OPTIMAL POWER PRODUCTION CONDITION (TURBINE RPM ~33).

T8 (10 m)

T9 (20 m)

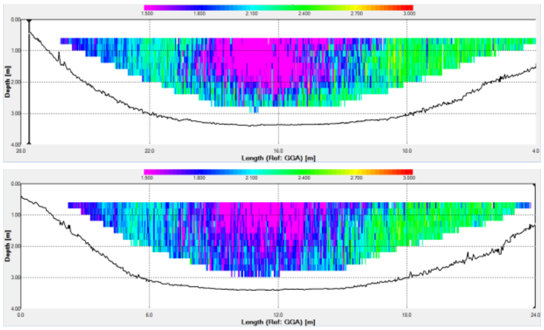

FIGURE 8. STREAMWISE VELOCITY CONTOURS AT THE DOWNSTREAM OF THE TURBINE (TURBINE RPM ~40).

RESULTS SUMMARY

A comprehensive field measurement campaign has been conducted to investigate the effect of hydrokinetic turbine deployment in a canal test site. Deploying the turbine at the canal raised the water upstream of the turbine by a relatively small margin and did not appear to have a significant effect on water operations. The turbine deployment also decreased the water level at the downstream of the turbine. However, the water level quickly recovered due to strong turbulence mixing, partly due to the enlargement of the channel's width. The presence of the turbine did not affect the power production at a hydropower plant located 8 kilometers downstream of the site.

Velocity measurements were able to capture the velocity deficit in the wake of the turbine, important information that can be used to identify optimal turbine spacing when considering deployment of multiple turbines and for validating numerical hydrodynamic models of hydrokinetic turbines. It is also interesting to note that a high velocity core existed at the right part of the cross sections, due to the canal's curving at the upstream of the turbine. This information can help determine the optimal turbine location for future deployment at the site.

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