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SAND2011-9305
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Printed November 2011

Reference Model MHK Turbine Array Optimization Study within a Generic River System

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Abstract

Increasing interest in marine hydrokinetic (MHK) energy has spurred to significant research on optimal placement of emerging technologies to maximize energy conversion and minimize potential effects on the environment. However, these devices will be deployed as an array in order to reduce the cost of energy and little work has been done to understand the impact these arrays will have on the flow dynamics, sediment-bed transport and benthic habitats and how best to optimize these arrays for both performance and environmental considerations. An "MHK-friendly" routine has been developed and implemented by Sandia National Laboratories (SNL) into the flow, sediment dynamics and water-quality code, SNL-EFDC. This routine has been verified and validated against three separate sets of experimental data. With SNL-EFDC, water quality and array optimization studies can be carried out to optimize an MHK array in a resource and study its effects on the environment. The present study examines the effect streamwise and spanwise spacing has on the array performance. Various hypothetical MHK array configurations are simulated within a trapezoidal river channel. Results show a non-linear increase in array-power efficiency as turbine spacing is increased in each direction, which matches the trends seen experimentally. While the sediment transport routines were not used in these simulations, the flow acceleration seen around the MHK arrays has the potential to significantly affect the sediment transport characteristics and benthic habitat of a resource.

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FIGURES

TABLE

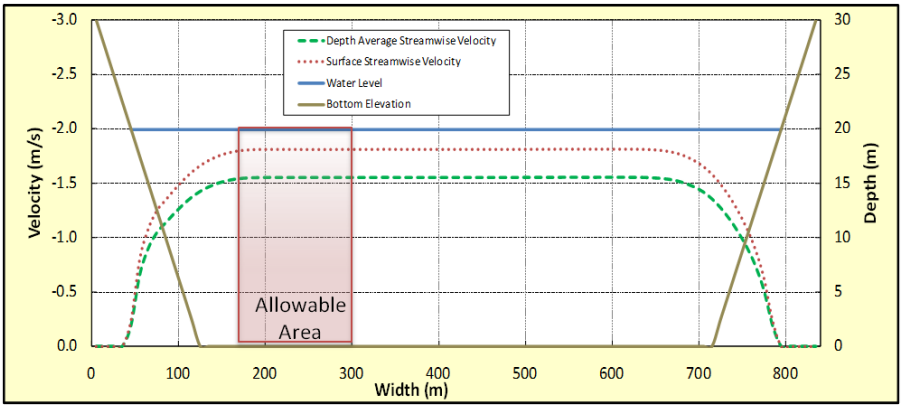
1. BACKGROUND

Sandia National Laboratories (SNL) has developed and implemented "Marine Hydrokinetic (MHK) friendly" modifications to an existing flow, sediment-dynamics, and water-quality code (SNL-EFDC). This provides a tool to qualify, quantify, and visualize the interaction and influence of MHK-turbine operation at a representative site after appropriately representing momentum/energy extraction and turbulent wake generation. Changes to EFDC result in a reduction in momentum in the model cell where the device is situated along with commensurate changes to turbulent kinetic energy and the turbulent kinetic energy dissipation rate. In addition to the effects from the MHK device, the effects of affiliated support structures are also considered. The theoretical details of the implementation of these terms into SNL-EFDC are detailed in Reference 1.

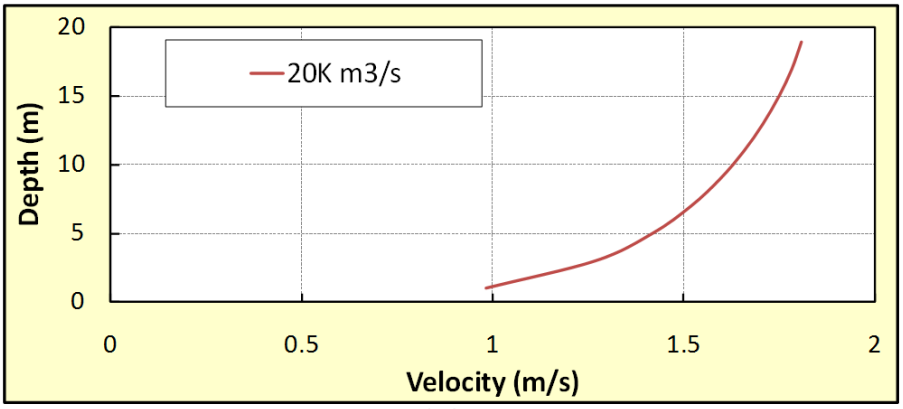
Previously, model validation was performed and included both a parameterization and a grid sensitivity study. The simulated velocity deficits were compared against two sets of published data [2,3] and a third set provided from a recent study by the University of Minnesota [4] that measured the velocity deficits in MHK wakes. The velocity deficits behind the MHK devices, at various flow and turbulence conditions, showed good agreement between the experimental data sets, which allows multiple simulation setups to be compared against a general deficit curve instead of being restricted to experiment-specific models.

The parameterization study was completed using the PEST (Parameter ESTimation) tool, though SNL's DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) was also used, with results presented in Reference 5. The study optimized model parameters to determine how the modeled MHK devices would alter the momentum and turbulence to match the experimental data. After the parameterization study was performed, SNL-EFDC was able to predict the far-field-wake recovery at 10 and more turbine diameters downstream of the MHK device. Corrections have recently been made to the SNL-EFDC code, which are presently being evaluated, to capture accurate velocity-deficits as close as 3 device diameters, where similar parameterization studies will be used to tune the code. The grid-independence study showed no sensitivity to the mesh resolution, which will allow coarser grids to solve the same domain in less time with a similar level of accuracy.

For the River Turbine Reference Model, SNL-EFDC was used to study the effects of spanwise (across the width of the river) and streamwise (in the direction of river flow) spacing of MHK turbine arrays within a simplified channel defined in Figure 1(a). Sediment transport was not included in these simulations. However, simulating array layouts within a simplified channel is a necessary first step to fully understand their effect on the flow before adding increased levels of detail. Results show that the array power efficiency improved, nonlinearly, as turbine spacing was increased in both the spanwise and streamwise directions. Also, changes in flow around and over/under an array of turbines are readily apparent and can be used to address affects of altered flow on the environment (e.g., altered sediment bed transport may affect bank stability and benthic habitat). Additionally, the benefits of increasing array spacing need to be constrained by cost and environmental effects. This work demonstrates a tool that can be used in optimizing MHK array layouts that maximize energy capture while also minimizing environmental effects.



(a)



(b)

Figure 1. Characterization of the simplified channel.
(a) Cross-section of the channel with the depth-averaged (green) and surface (red) velocities. The Allowable Area is a restricted footprint for Scenario 2.
(b) The velocity profile in the flow direction.

2. EFFECTS OF SPANWISE AND STREAMWISE SPACING ON MHK ARRAY PERFORMANCE IN A TRAPEZOIDAL RIVER CHANNEL

2.1 Model Channel and Flow Description

SNL-EFDC was used to model the effect of MHK array spacing, in both the spanwise and streamwise directions, on the effective power captured and initial investigations to visualize and quantify environmental change. The simulations were performed in a straight, trapezoidal channel that was designed to represent a "large" river. The channel was 4,200 m in length and had cross-sectional widths of 600 m at the bottom and 840 m at the top. A constant flow of 20,000 m^3/s was supplied at the inlet, yielding a depth averaged velocity of 1.6 m/s, near surface velocity of 1.8 m/s, and water depth of 20 m. Figure 1(a) shows a cross-section of the channel with the depth-averaged and surface velocities plotted as a function of the width. The velocity profile in the direction of flow compares well with anticipated boundaries in a river flow, and is shown in Figure 1(b). To simulate the resource, grid cells of 10×30 m^2 were used, with 10 vertical layers.

2.2 MHK River Model Device Description

The MHK device for the River Turbine Reference Model is a 20-m-wide floating platform that supports two 6.45-m-diameter crossflow turbines with blade spans of 4.85 m, as shown in Figure 2. The top of the rotor is 2.5 m below the water surface and has a coefficient of thrust, $C_T = 0.35$, and coefficient of drag, $C_D = 1.2$. The floating platform was chosen because the largest velocities are at the surface of the river, as seen in Figure 1, and thus provide the most available power.

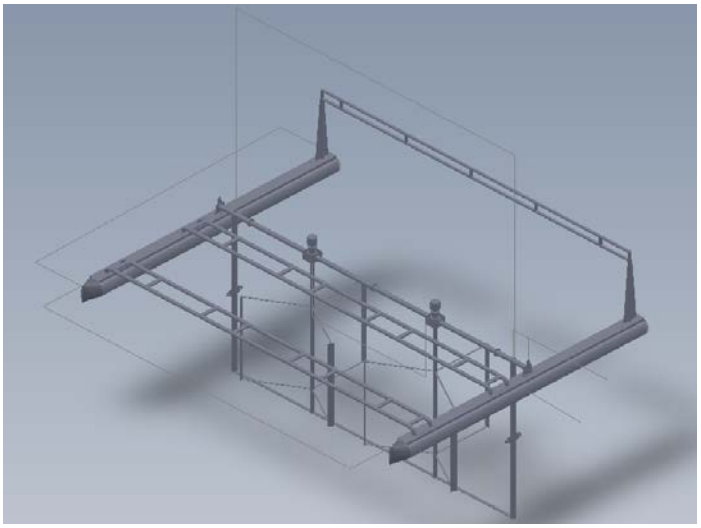


Figure 2. Two crossflow turbines attached to a floating platform that is modeled in the SNL-EFDC simulations.

2.3 Simulation Setup

Two scenarios were simulated to analyze the effect of MHK array spacing on the power captured: (1) a single row with changing spanwise spacing and (2) four rows (staggered and inline) with changing streamwise and spanwise spacing, while constrained by an allowable footprint. In each scenario the spacing was increased by a multiple of the platform width. Figure 3 shows two staggered platform arrangements with each platform spanning two grid cells and streamwise spacing of 4.5 and 9 platforms between the rows.

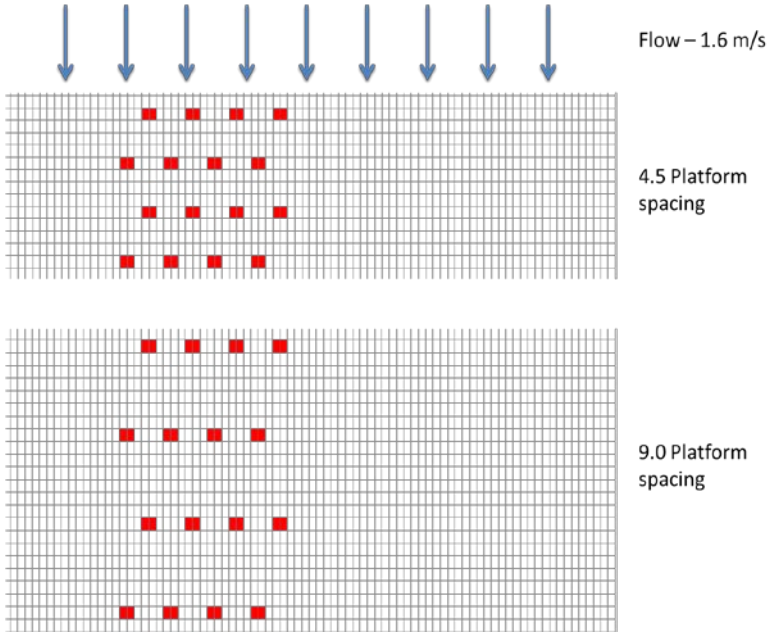


Figure 3. Two arrangements used in Scenario 2, a staggered layout with a streamwise spacing of 4.5 platforms (top) and 9 platforms (bottom).

Scenario 1 increased the spanwise spacing from 0.5 platform widths to 3 platforms. Scenario 2 varied the streamwise spacing from 4.5 platforms to 37.5 platforms for spanwise spacings of 0, 1, and 2 platforms. This was selected to demonstrate a potential case where river traffic and other factors would restrict the allowable space for an MHK array deployment. The placement of the MHK platforms is limited to a hypothetical footprint placed within the trapezoidal channel and power capture is maximized within the footprint. To minimize the number of changing variables, the footprint for the MHK platforms stayed within the constant depth and constant velocity portion of the river, as shown in Figure 1(a). As the streamwise and spanwise spacing of the array is increased, the number of devices that can fit within the footprint decreases. This scenario is presented in Figure 4.

2.4 Simulation Results

Results from both scenarios show that the array power efficiency increased, nonlinearly, as turbine spacing was increased in both the spanwise and streamwise directions. As seen in Figure 5, spanwise spacing (Scenario 1) can have a significant influence on the power captured, where the power of each platform has been normalized by the power captured by a lone platform in the center of the channel

(within the hypothetical line formed by row 1). The increased efficiency of the right-most platform over the left-most can be attributed to the acceleration of the flow around the MHK array due to blockage and shore effects. An important note is that the power efficiency is a comparison of the power captured between single devices and does not imply a generation of more power than is available in the channel. Results also show that flow increases around and over/under the array, leading to elevated velocities in the main channel near the bank, and near the sediment bed, which may have potential implications for bank and bottom erosion, navigation, and acoustic characteristics within the channel.

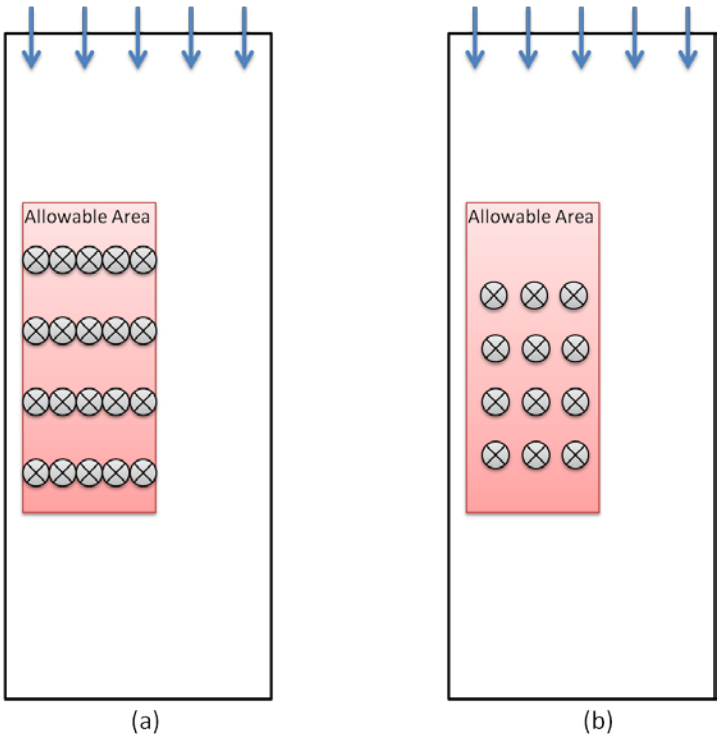


Figure 4. Scenario 2 with a restriction on array deployment, where increasing spanwise spacing limits the number of devices from (a) 20 to (b) 12.

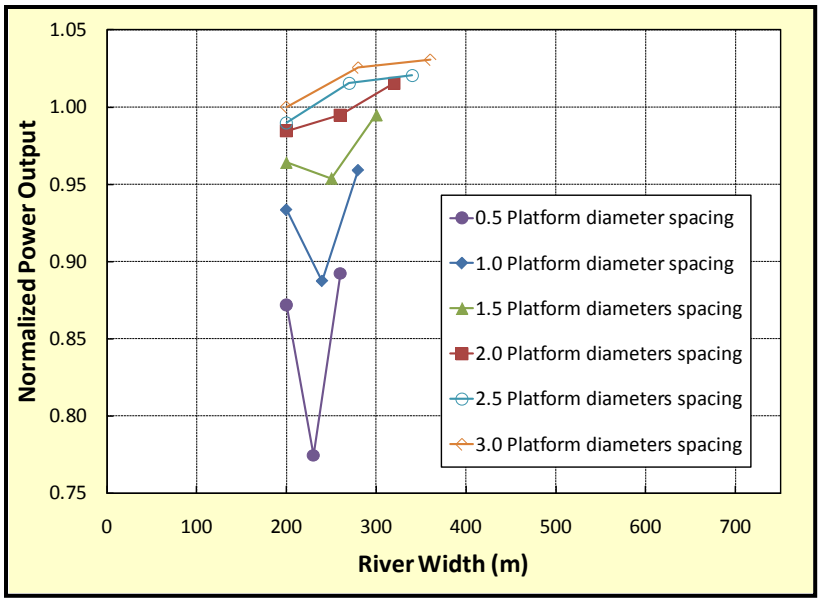


Figure 5. Results of normalized power for increasing spanwise spacing (Scenario 1).

The results for streamwise spacing match the trend seen in the experimental data, which shows a minimum of 10 device diameters are required to recover 90% of the velocity. Spacing devices closer than this will significantly decrease the power captured. Additionally, there is a large drop in power captured between the first and second row, but there is a negligible difference between each subsequent row, as seen in Figure 6. This means one device could be optimized for the first row and a second device optimized for the remaining downstream rows. While the second row of the staggered array outperformed the second row of the in-line array, there was little difference between rows 3 and 4.

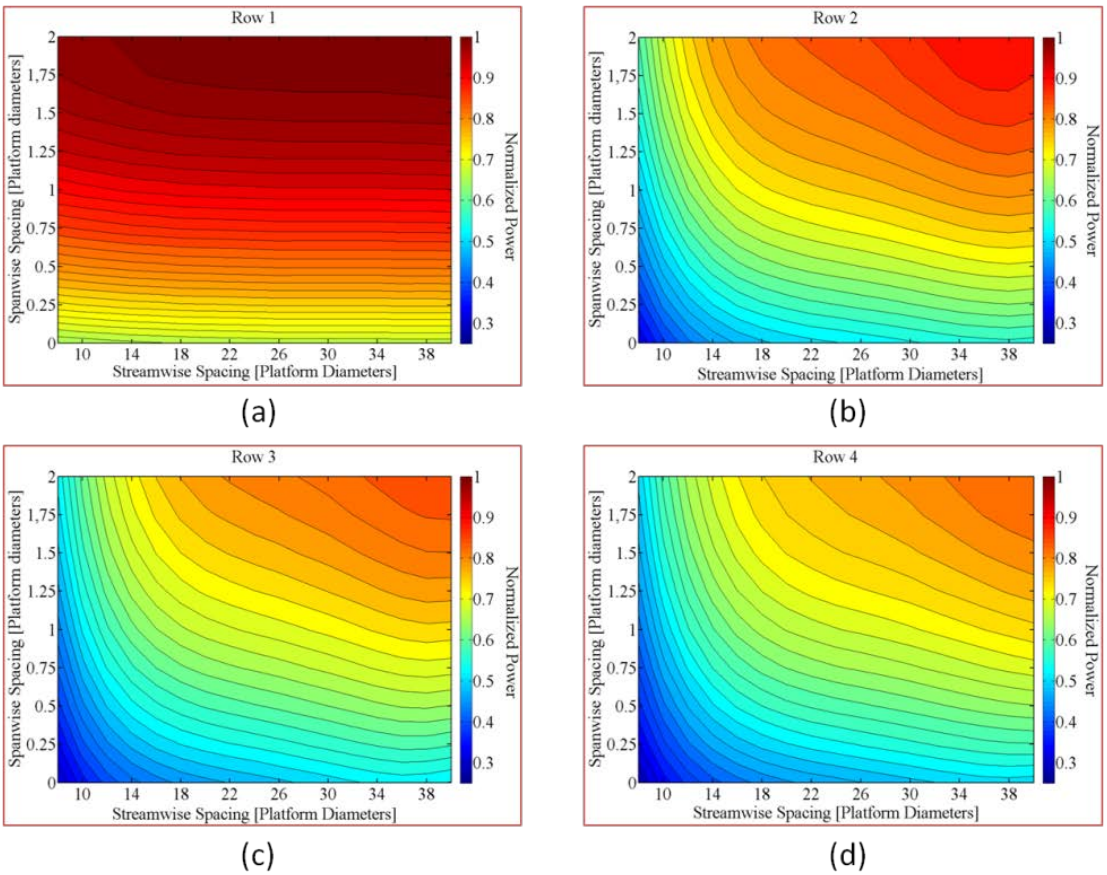


Figure 6. Normalized power with changing streamwise and spanwise spacing for (a) row 1, (b) row 2, (c) row 3, and (d) row 4.

Scenario 2 also shows that even with a loss in the total number of turbines as the spanwise spacing increases there is not an equal decrease in power captured. Results for the relative effect of spanwise spacing are shown in Table 1, and Figure 7 shows the expected increase in the average platform power as both the streamwise and spanwise spacing are increased. As seen in Table 1, when comparing a decrease in the spanwise spacing from 1 platform to 0 platforms, doubling the number of platforms in the array only increases the overall power captured by 27%, while decreasing the average power captured by each platform by 31%.

Table 1. Effect of Spanwise Spacing on Array Performance for Scenario 2. The second percentage, in red, is the relative increase in number of turbines.

Spanwise Spacing	Number of platforms in array	Increase in power per row relative to spanwise spacing		Increase in average platform power relative to spanwise spacing	
		1 Platform	2 Platforms	0 Platforms	1 Platform
0 Platforms	48	27%, 100%	44%, 200%		
1 Platform	24		23%, 50%	31%, -50%	
2 Platforms	16			40%, -66%	13%, -33%

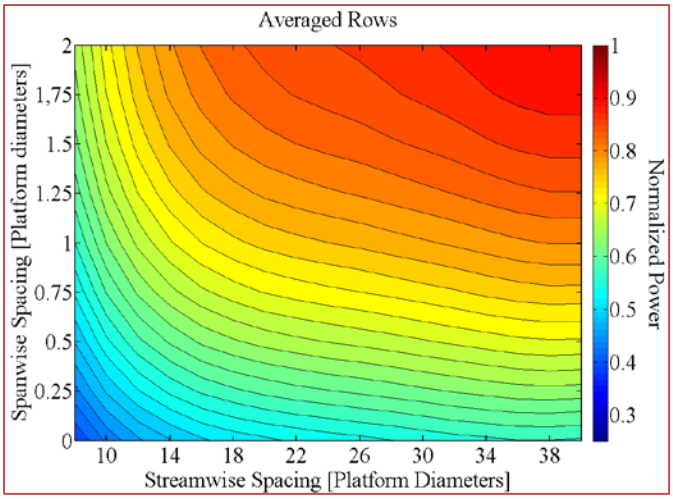


Figure 7. The average of the power captured by all four rows in Scenario 2 as a function of spanwise and streamwise spacing.

3. ENVIRONMENTAL EFFECTS

In addition to optimizing for power captured, there are other considerations for an MHK array layout. This includes changes in circulation patterns, sediment bed disturbance, and water-quality effects, among many others. While the latter have not yet been included as areas of focus, they are available within SNL-EFDC. Extending Scenario 2 from above, an unoptimized array of 3 rows with 6 platforms per row was spaced with 0 spanwise spacing and 7.5-platform streamwise spacing. For this unoptimized array, the velocity increased to either side of and below the array, and can be seen in Figure 8. This increase in velocity could change the noise characteristics within the channel and impact both wildlife and shipping traffic. A known effect of the velocity change is its increase on bed and bank shear stress, which could negatively impact sediment transport by increasing risk of bank erosion and modification of benthic habitat.

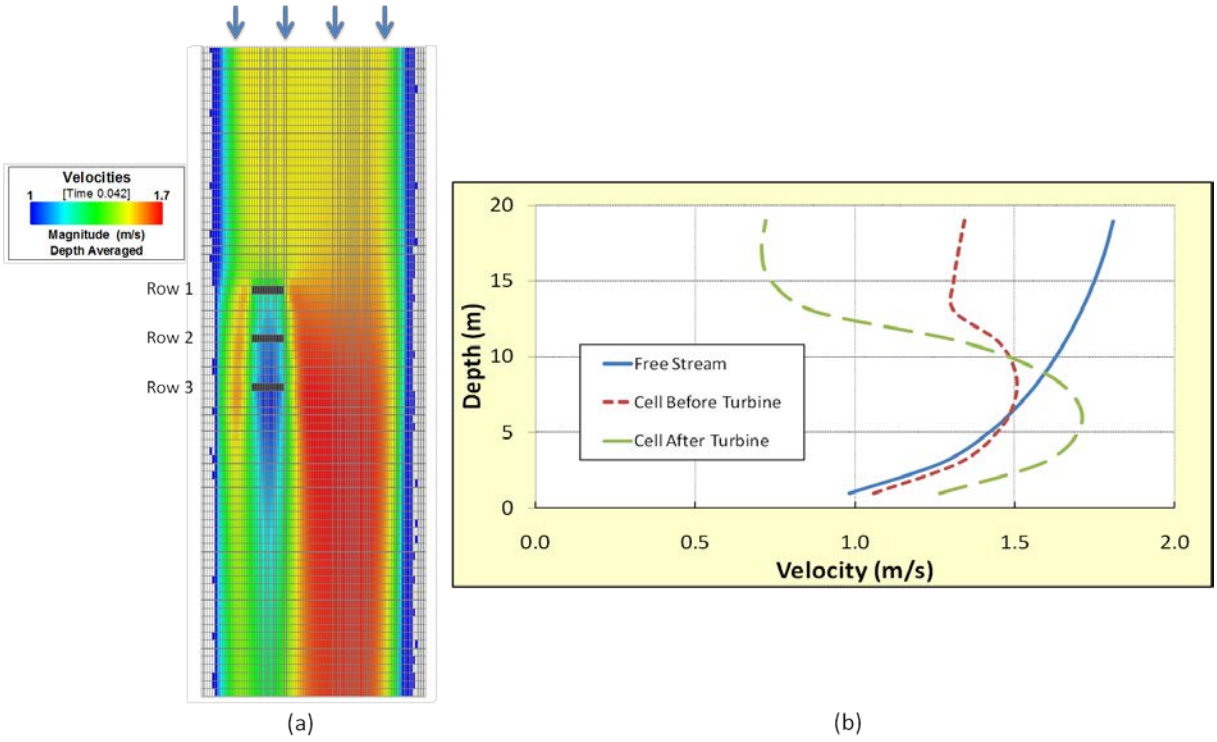


Figure 8. Environmental effects on an unoptimized array.
(a) An unoptimized array layout and its effect on the channel velocity.
(b) The velocity profile before and after the introduction of the MHK array.

4. NEXT STEPS

While this study gives a representative idea of how spacing affects array performance and alters flow for the River Reference Model, an optimization scheme has not been applied to maximize the power captured and minimize environmental effects that may result in unique device layouts. As a first study on array optimization, this effort minimized the number of variables to consider (i.e., constant depth and velocity in a simplified channel) and identified model accuracy and sensitivity. The tool will be applied to actual resources with variable depth, flow, and channel morphology, such as the Mississippi River.

The SNL-EFDC model has proven it is a robust and proven hydrodynamic scheme for MHK simulation that can be applied to future aspects of real-world array optimization and environmental evaluation. Future efforts will determine which environmental effects need to be focused on and used within the optimization strategy. SNL-EFDC's "MHK-friendly" array-optimization tool is and will remain open source and includes advanced sediment transport and water-quality routines for environmental evaluations.

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