Simulating Environmental Changes Due to Marine Hydrokinetic Energy Installations

Scott C. James*
Eddy Seetho
Sandia National Laboratories
Thermal/Fluids Science and Engineering Department
P.O. Box 969
Livermore, CA 94551-0969
scjames@sandia.gov
eseehto@sandia.gov

Craig Jones
Sea Engineering Inc.
200 Washington Street Suite 210
Santa Cruz, CA 95060
cjones@seaengineering.com

Jesse Roberts
Sandia National Laboratories
Wind and Water Power Technologies
P.O. Box 5800
Albuquerque, NM 87185-1124
jdrober@sandia.gov

Abstract- Marine hydrokinetic (MHK) projects will extract energy from ocean currents and tides, thereby altering water velocities and currents in the site’s waterway. These hydrodynamics changes can potentially affect the ecosystem, both near the MHK installation and in surrounding (i.e., far field) regions. In both marine and freshwater environments, devices will remove energy (momentum) from the system, potentially altering water quality and sediment dynamics. In estuaries, tidal ranges and residence times could change (either increasing or decreasing depending on system flow properties and where the effects are being measured). Effects will be proportional to the number and size of structures installed, with large MHK projects having the greatest potential effects and requiring the most in-depth analyses. This work implements modification to an existing flow, sediment dynamics, and water-quality code (SNL-EFDC) to qualify, quantify, and visualize the influence of MHK-device momentum/energy extraction at a representative site. New algorithms simulate changes to system fluid dynamics due to removal of momentum and reflect commensurate changes in turbulent kinetic energy and its dissipation rate. A generic model is developed to demonstrate corresponding changes to erosion, sediment dynamics, and water quality. Also, bed-slope effects on sediment erosion and bedload velocity are incorporated to better understand scour potential.

I. INTRODUCTION

Effective and efficient renewable power generation is a growing global priority given that the world’s power usage is expected to increase by more than 70% over the next 30 years due to both population growth and accelerated industrialization [1]. Fossil fuels are the de facto source of energy, but with their use come consequences. Moreover, rapid depletion of fossil-fuel resources is a growing concern, not to mention that increased atmospheric CO₂ concentrations contribute to climate change. These issues focus increasing attention upon renewable energy as a global solution to both energy and environmental challenges.

Renewable energy sources such as wind power, solar power, or hydroelectric dams are increasingly implemented with generally excellent success. Nevertheless, the weather dependency and transmission costs (many suitable sites are not collocated with population centers) of wind and solar power installations pose significant challenges. Hydroelectric dams, while quite efficient, may have unforeseen ecological consequences, and many more dams are being removed than built in the United States [2]. Recently, marine hydrokinetic (MHK) devices (e.g., water turbines) are being considered as a practical and effective solution to power generation with reasonable cost, increased predictability, and less intrusion on the environment compared to other, more traditional power systems. Also, because MHK technology has yet to be widely implemented, there is a high availability and low exploitation of suitable sites. Moreover, MHK installations are likely to be located near population centers (e.g., Cook Inlet, Puget Sound, Hawaii, San Francisco Bay), which will help control transmission costs.
II. MARINE HYDROKINETIC STUDIES

II.A Ecological Considerations

While MHK devices hold promise, significant research is needed to quantify and understand their potential environmental effects. When MHK devices extract energy from a system, volumetric flows and tidal ranges can be affected [3]. In conjunction, sediment dynamics can be altered, changing both erosion/deposition regions and the size and composition of eroded particles. Because water circulation patterns may change, the residence times (flushing rates) may also change, potentially changing algae growth patterns as well as concentrations of nutrients and dissolved gasses [4]. Acoustic energy and electromagnetic waves emanating from MHK devices and infrastructure may perturb wildlife behavior or vary the ecosystem [5, 6]. Holistically these factors may modify biological dynamics, intrude upon migration paths, disturb life cycles and communication, or alter resource availability.

II.B Economic Considerations

The economic cost and benefit of MHK installations must also be carefully considered. MHK devices may cost significantly more to install and maintain than their land-based counterparts. Mooring MHK devices in high-velocity and possibly high-salinity waters can add significant expense because devices must be ruggedized to these conditions. As many MHK devices are most effective for flow velocities in excess of 2.5 m/s, the viability of installing in slower waters must be considered [7]. Although some technologies may be appropriate for slowly moving flows, such waterways have commensurately low power densities. Recall that the power in a fluid scales with the velocity cubed [8]. The benefit of economies of scale must be weighed against diminishing levels of return per turbine as more are installed [3]. The overall efficiency of an MHK installation, coupled with power generation viability and total cost, are covariant concerns.

III. MARINE HYDROKINETIC CODES

This effort applies SNL-EFDC to example environmental flow systems where MHK devices are emplaced. SNL-EFDC is an upgraded version of EPA’s environmental flow and transport code, Environmental Fluid Dynamics Code (EFDC) [9-12], coupled to both the US-ACE’s water quality code, CE-QUAL-ICM [13, 14], and the sediment dynamics code, SEDZLJ [15-18]. A new module considers energy removal from MHK devices and commensurate changes to turbulent kinetic energy and turbulent kinetic energy dissipation.

III.A EFDC

EFDC was selected over other models of flow and transport in rivers, lakes, and estuaries because it is an open-source 3-D flow and transport code that directly couples water-quality simulations. It has been successfully applied at numerous sites [19-24] and is sponsored by the US Environmental Protection Agency and maintained by its original author, John Hamrick, now with Tetra Tech. It has even been used to model laboratory experiments [25].

The hydrodynamic portion of the model solves the hydrostatic, free surface, Reynolds-averaged Navier-Stokes equations with turbulence closure, similar to the models of Blumberg and Mellor [26] and Johnson et al.[27]. The numerical solution techniques are the same as those of Blumberg and Mellor [26], except for the solution of the free surface, which is implemented with a preconditioned conjugate gradient (direct) solver rather than an alternating-direction-implicit-method [12]. EFDC, like many atmospheric and oceanic models, uses a stretched or sigma, $\sigma$, coordinate system [12]. That is, it allows a curvilinear orthogonal (or Cartesian) grid in the horizontal, but has a specified number of layers in the vertical. Each layer is assigned a constant (often equal) fraction of the flow depth throughout the model domain; the absolute height of each layer changes with the topology of the model domain (i.e., at 10 m depth and 10 layers, each $\sigma$ layer might be 1 m thick, however at 25 m depth each layer would be 2.5 m thick). EFDC’s time integration uses a second-order-accurate, three-time-level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear (or baroclinic mode calculated across each $\sigma$ layer) from the external free-surface gravity wave (or barotropic mode calculated on the depth average).

III.B CE-QUAL-ICM

The US Army Corps of Engineers CE-QUAL-ICM [13] is a water-quality model implemented in EFDC that simulates eutrophication kinetics. This finite-volume model computes constituent concentrations in well-mixed cells that can be arranged in arbitrary one-, two-, or three-dimensional configurations. After distributing 23 scalar water-quality parameters according to the advection-dispersion calculations from EFDC, the water-quality model simulates transient reactions for parameters including dissolved $O_2$ and $CO_2$, algae (cyanobacteria, diatoms, and green algae), and various components of carbon, nitrogen, phosphorus, and silica [28, 29]. Each state variable can be independently activated or deactivated depending on the important water-quality variables. The authors of this manuscript have successfully applied this model to various systems [30, 31].
III.C SNL-EFDC

The newest iteration of SNL-EFDC, Sandia National Laboratories’ enhanced version of the EFDC code, provides enhancements to sediment dynamics modeling through the SEDZLJ algorithms. Also, it simulates the effects of MHK-device energy extraction.

III.C.1 SEDZLJ

EFDC’s sediment dynamics are enhanced with the SEDZLJ algorithms (named after its authors Ziegler, Lick, and Jones from UC Santa Barbara) [32]. SEDZLJ provides an alternative to EFDC’s original sediment-dynamics formulations and provides a unified treatment of sediment transport, as opposed to considering cohesive and noncohesive sediments separately [16, 33]. Because erosion dynamics vary significantly between test sites, SEDZLJ is written to incorporate 3D sediment bed data collected with SEDflume (Sediment Erosion with Depth flume) [34]. Data-driven erosion rates are specified as functions of shear stress and depth in the sediment bed [17]. Sediments are discretized into size classes to evaluate the probability of bedload or suspended load transport as well as deposition locations and rates. It is best to use an odd number of size classes and, of course, fewer size classes is less computationally demanding (i.e., computationally three size classes would be about as accurate as four, and less computationally expensive) [35]. Furthermore, SEDZLJ considers bed armoring and consolidation, factors that account for decreased erosion rates with time.

III.C.2 MHK Simulation

A new module to SNL-EFDC simulates removal of energy by MHK devices. Changes are manifest 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. Sink terms, $S_Q$, $S_K$, and $S_\varepsilon$, appropriate to each type of MHK device, represent the rate of momentum extraction, net change to turbulent kinetic energy, and the increase in turbulent kinetic energy dissipation rate, respectively [36]. In addition to the effects from the moving MHK device, the effects of affiliated support structures are also considered.

IV. THEORY

MHK devices remove momentum from a system, but also alter the turbulent kinetic energy, $K$, and turbulent kinetic energy dissipation rate, $\varepsilon$. These effects are captured with appropriate sink terms. $S_Q$ (m$^4$/s$^2$) is the volumetric momentum extraction rate by the MHK device due to energy removal, as well as due to form and viscous drag from the MHK structure. $S_K$ (m$^2$/s$^3$) represents the volumetric change in net turbulent kinetic energy in the appropriate model cell due to the MHK device (support), with $S_\varepsilon$ (m$^2$/s$^3$) as its analogous term for the volumetric kinetic energy dissipation rate equation [37]. These quantities are advected and dispersed downstream of the MHK device according to the standard conservation equations used in EFDC [12].

The standard calculation for $S_Q$ neglects viscous drag relative to energy removal and form drag by the MHK device, thereby resulting in

$$S_Q = -\frac{1}{2} C_T A_M U^2,$$  \hspace{1cm} (1)

where $C_T$ is the MHK thrust coefficient (drag coefficient, $C_D$, for the support), $A_M$ (m$^2$) is the MHK-device flow-facing area (support flow-facing area), and $U$ (m/s) is the local flow speed in a cell $(u^2 + v^2)^{1/2}$. Here, MHK-device power $P_M$ (kg·m$^2$/s$^3$) is defined as

$$P_M = \frac{1}{2} C_T A_M \rho U^3,$$  \hspace{1cm} (2)

where $\rho$ (kg/m$^3$) is the water density.

The term $S_K$ arises because MHK devices break up the mean flow motion and generate wake turbulence ($\approx \frac{1}{2} C_p A_M U^3$) [37-39]. However, such wakes dissipate fairly rapidly, speculatively within about 30 MHK device lengths (turbine diameters). Preliminary MHK CFD models have showed overly persistent wakes, perhaps in part because this term was not taken into account. The canonical (or physics-based) form for $S_K$ reflecting the effects of a momentum sink (or partial flow obstruction) is [40]:

$$S_K = \frac{1}{2} C_T A_M \rho \left( \beta_p U^3 - \beta_d U K \right),$$  \hspace{1cm} (3)

where dimensionless $\beta_p$ ($\approx 1.0$) is the fraction of mean flow kinetic energy converted to wake-generated $K$ (m$^2$/s$^2$)by drag (i.e., a source term in the $K$ budget), and dimensionless $\beta_d$ ($\approx 1.0-5.0$) is the fraction of $K$ dissipated by conversion to kinetic energy (i.e., a sink term in the $K$ budget).

The most obvious weakness of the $K-\varepsilon$ approaches is its least understood term, $S_\varepsilon$ [41]. Over the last decade or so, various models have been proposed for $S_\varepsilon$ [36, 42, 43], but the simplest is used in this model:
\[ S_x = C_{\text{sl}} \frac{\varepsilon}{K} S_x, \]  

(4)

where \( C_{\text{sl}} \) is a closure constant [36]. The formulation for (4) is based on standard dimensional analysis common to all \( K-\varepsilon \) approaches. Upon adding (1) – (4) to the momentum and \( K-\varepsilon \) equations, it is possible to solve for momentum, \( K \), and \( \varepsilon \) if appropriate upper and lower boundary conditions are specified. For this implementation, \( C_{\text{sl}} = 0.9, \beta_p = 1.0 \) and \( \beta_v = 5.1 \). In SNL-EFDC, momentum is defined as the product of flow depth, \( H \) (m), and velocity (\( u \) and \( v \)); conservation of kinetic energy is solved in terms of \( \frac{1}{2} H q^2 \), where \( q \) (m/s) is the turbulent intensity, and conservation of turbulent energy dissipation rate takes the form \( H q^2 l \), where \( l \) (m) is the turbulence length scale.

III.D Implementation into EFDC

The simplified kinetic energy equation for an MHK device in a model \( \sigma \) layer is

\[
\frac{\partial}{\partial t} \left[ \rho \delta_x \delta_y H \Delta_z \left( \frac{u^2 + v^2}{2} \right) \right] = -\rho \frac{C_r}{2} A_M \left( u^2 + v^2 \right)^{3/2} = -P_M, 
\]  

(5)

where \( \delta_x \) (m) and \( \delta_y \) (m) are the (horizontal) \( x \) and \( y \) dimensions of a model cell and \( \Delta_z \), which is the fraction of total water depth assigned to the \( k \)th \( \sigma \) layer,

\[ A_M = W_d H \Delta_z, \]

(6)

is the frontal flow area of the device, \( W_d \) (m) is the device or support width, and \( H \Delta_z \) (m) is the \( \sigma \) layer height. The corresponding components of the momentum equations, simplified to exclude advective and diffusive terms, are [12, 44]

\[
\frac{\partial}{\partial t} \left( \delta_x \delta_y H \Delta_z u \right) = -g \delta_y H \Delta_z \frac{\partial \zeta}{\partial x} - \frac{C_r}{2} A_M \left( u^2 + v^2 \right)^{1/2} u, \\
\frac{\partial}{\partial t} \left( \delta_x \delta_y H \Delta_z v \right) = -g \delta_x H \Delta_z \frac{\partial \zeta}{\partial y} - \frac{C_r}{2} A_M \left( u^2 + v^2 \right)^{1/2} v, 
\]  

(7)

where \( g \) (m/s\(^2\)) is gravitational acceleration and \( \zeta \) (m) is the free-surface potential, or the difference between the hydrostatic water level and the flow depth (this is how water elevation or pressure head drives flow) [9]. Solutions of the \( x \)-and \( y \)-momentum equations in EFDC use the form

\[
\frac{\partial}{\partial t} (Hu) = -g \delta_y H \frac{\partial \zeta}{\partial x} - \frac{1}{\delta_x \delta_y \Delta_z} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] u, \\
\frac{\partial}{\partial t} (Hv) = -g \delta_x H \frac{\partial \zeta}{\partial y} - \frac{1}{\delta_x \delta_y \Delta_z} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] v, 
\]

(8)

which can be written in terms of MHK device power (and equivalently for support-structure momentum removal) as

\[
\frac{\partial}{\partial t} (Hu) = -g \delta_y H \frac{\partial \zeta}{\partial x} - \frac{1}{\delta_x \delta_y \Delta_z} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] u, \\
\frac{\partial}{\partial t} (Hv) = -g \delta_x H \frac{\partial \zeta}{\partial y} - \frac{1}{\delta_x \delta_y \Delta_z} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] v. 
\]

(9)

The solution procedure begins by introducing the \( \sigma \) layer notation based on \( \Delta_k \):

\[
\frac{\partial}{\partial t} (\Delta_k Hu_k) = -g \Delta_k H \frac{\partial \zeta}{\partial x} - \frac{1}{\delta_x \delta_y \Delta_k} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] \Delta_k u_k, \\
\frac{\partial}{\partial t} (\Delta_k Hv_k) = -g \Delta_k H \frac{\partial \zeta}{\partial y} - \frac{1}{\delta_x \delta_y \Delta_k} \left[ \frac{P_M}{\rho \left( u^2 + v^2 \right)} \right] \Delta_k v_k. 
\]

(10)

The momentum conservation equations are
\[
\frac{\partial}{\partial t}(\Delta_i Hu_i) = -g\Delta_i \frac{H}{\delta_x} \frac{\partial \zeta}{\partial x} - \Delta_i \left( Q_i - \overline{Q} \right) u_i - \Delta_i \overline{Q} u_i,
\]
\[
\frac{\partial}{\partial t}(\Delta_i Hv_i) = -g\Delta_i \frac{H}{\delta_y} \frac{\partial \zeta}{\partial y} - \Delta_i \left( Q_i - \overline{Q} \right) v_i - \Delta_i \overline{Q} v_i,
\]
where volumetric fluxes \( Q \ (\text{m/s}) \) are
\[
Q_i = \left[ \frac{1}{\delta_i \delta_j \Delta_i} \frac{P_M}{\rho (u^2 + v^2)} \right]_i,
\]
\[
\overline{Q} = \sum_{k=1}^{\kappa} \Delta_i Q_i.
\]
From this point, the solution procedure is illustrated using only the \( u \) equation, which is summed over all \( K_C \sigma \) layers to give
\[
\frac{\partial}{\partial t}(Hu) = -g\frac{H}{\delta_x} \frac{\partial \zeta}{\partial x} - \sum_{k=1}^{\kappa} \left[ \Delta_i \left( Q_i - \overline{Q} \right) u_i \right] - \overline{Q} u,
\]
\[
\overline{u} = \sum_{k=1}^{\kappa} \Delta_i u_i,
\]
which is the simplified external mode equation [9, Section C.3]. This equation is solved with the continuity equation for the depth-averaged velocity components, \( \overline{u} \ (\text{m/s}) \) and \( \overline{v} \ (\text{m/s}) \), and the water surface elevation, \( H \), using the time-differenced form
\[
\left( 1 + \frac{\theta}{H} \right) (Hu)^{n+1} + \frac{g\theta H}{2} \frac{\partial \zeta}{\partial x}^{n+1} = (Hu)^{n} - \frac{g\theta H}{2} \frac{\partial \zeta}{\partial x}^{n} - \theta \sum_{k=1}^{\kappa} \left[ \Delta_i \left( Q_i - \overline{Q} \right) u_i \right]^{n}.
\]
where \( \theta \) (s) is the time step. The internal-mode equation solution is based on considering the difference between equations for two adjacent layers
\[
\frac{\partial}{\partial t}(Hu_{i+1}) = -g\frac{H}{\delta_x} \frac{\partial \zeta}{\partial x} - \left( Q_{i+1} - \overline{Q} \right) u_{i+1} - \overline{Q} u_{i+1},
\]
\[
\frac{\partial}{\partial t}(Hu_i) = -g\frac{H}{\delta_x} \frac{\partial \zeta}{\partial x} - \left( Q_i - \overline{Q} \right) u_i - \overline{Q} u_i,
\]
which has remainder
\[
\frac{\partial}{\partial t}(Hu_{i+1} - Hu_i) + \frac{\overline{Q}}{H} (Hu_{i+1} - Hu_i) = -\left( Q_{i+1} - \overline{Q} \right) u_{i+1} + \left( Q_i - \overline{Q} \right) u_i.
\]
Time differencing yields
\[
\left( 1 + \frac{\theta}{H} \right) (Hu_{i+1} - Hu_i)^{n+1} = (Hu_{i+1} - Hu_i)^{n} - \theta \left[ \left( Q_{i+1} - \overline{Q} \right) u_{i+1} - \left( Q_i - \overline{Q} \right) u_i \right]^{n}.
\]
The system of \( K_C - 1 \) layer-interface equations can be solved for the velocity differences across the layer and used with the definition of the depth-averaged velocity to determine the actual layer velocities.

The MHK device effect in the turbulent kinetic energy (turbulent intensity) equation is given by
\[
\frac{\partial}{\partial t} \left( \frac{H q^2}{2} \right) = \beta_p \left( \frac{1}{2} C_T \frac{A_M}{\delta_i \delta_j \Delta_i} \right) \left( u^2 + v^2 \right)^{1/2} \left( u^2 + v^2 \right)^{1/2} \left( u^2 + v^2 \right)^{1/2} - \frac{H}{B_i l} q^3,
\]
where dimensionless \( B_1 = 16.6 \) is a Mellor and Yamada [45] turbulence closure coefficient. The dissipation effect of the device is combined with the standard flow dissipation term to give
\[
\frac{\partial}{\partial t} \left( \frac{H q^2}{2} \right) + \left[ \beta_p \left( \frac{1}{2} C_T \frac{A_M}{\delta_i \delta_j \Delta_i} \right) \left( u^2 + v^2 \right)^{1/2} + \frac{q}{B_i l} \right] Hq^2 = \beta_p \left( \frac{1}{2} C_T \frac{A_M}{\delta_i \delta_j \Delta_i} \right) \left( u^2 + v^2 \right)^{1/2} \left( u^2 + v^2 \right),
\]
where the total dissipation has been moved to the left side of the equation to emphasize that it must be treated implicitly in the numerical solution procedure given by
The turbulent length scale equation (turbulent kinetic energy dissipation rate) is

\[
\left\{ 1 + \theta \left[ \beta_d \left( C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{H} + \frac{2q}{B_l l} \right) \right] \right\} (Hq^2)^{n+1} = (Hq^2)^n + \Theta \beta_p \left( C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{(u^2 + v^2)} \right) .
\]

The turbulent length scale equation (turbulent kinetic energy dissipation rate) is

\[
\frac{\partial}{\partial t} (Hq^2 l) + \left[ C_{\varepsilon \beta} \left( \frac{1}{2} C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{H} + \frac{q}{B_l l} \right) \right] Hq^2 l = C_{\varepsilon \beta} \left( \frac{1}{2} C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{(u^2 + v^2)} \right) l,
\]

which is solved similar to the turbulent kinetic energy equation using

\[
\left\{ 1 + \theta \left[ C_{\varepsilon \beta} \left( \frac{1}{2} C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{H} + \frac{q}{B_l l} \right) \right] \right\} (Hq^2 l)^{n+1} = (Hq^2 l)^n + \Theta C_{\varepsilon \beta} \left( \frac{1}{2} C_T \frac{A_M}{\delta_x \delta_y \Delta_z} \right) \left( \frac{u^2 + v^2}{(u^2 + v^2)} \right) l.
\]

For completeness, vegetative resistance effects on $K_{\varepsilon}$ were also included in the SNL-EFDC coding.

V. SINGLE-TURBINE TEST CASE

V.A Momentum Removal Only

In the momentum-removal model, a frictionless flow channel is assigned a flow (water) velocity of 2 m/s and a single MHK device is simulated as a momentum sink only. There are 8 model layers (nominally 1 m thick) with 2×2 m² horizontal grid cells with domain 200×50 m². An appropriate thrust coefficient is selected, $C_T = 0.5$, with momentum removal calculated using (1) and according to algorithm outlined above. Without adjustments to turbulent kinetic energy and turbulent kinetic energy dissipation rate due to the MHK, there is an obvious non-physicality; Fig. 1 exhibits a localized, overly persistent velocity defect behind the simulated turbine. There ought to be velocity and energy recovery downstream of the turbine; slower fluids behind the turbine should blend with the turbulent flow on either side and recover to near ambient conditions.

![Fig. 1 Single turbine model reflecting only momentum removal](image)
V.B  Momentum Removal with Turbulent Kinetic Energy Factors

Fig. 2 is a simulation with MHK effects on turbulent kinetic energy and turbulent kinetic energy dissipation rates included. The wake propagates laterally and dissipates more appropriately downstream. Effects of fluid energy loss are realistically distributed; slower fluids behind the turbine mix with the surrounding fluid and the system returns to near ambient conditions. Overall, there is a net decrease in system energy downstream of the device. It is manifest in a slower average flow speed (kinetic energy) and decrease in water level (potential energy) with much of the decrease is realized in the potential energy term.

VI.  EXAMPLE MHK ARRAY WITH SEDIMENT EROSION

Fig. 3 shows a hypothetical array of MHK devices (red cells); the devices are not arranged according to any specific studied system (not optimized). Flow in the 200-m-long, 100-m-wide 2×2-m² cells), uniform channel is initially 8 m deep and proceeds from left to right at an initial velocity of 2 m/s. There are 8 equally-divided \( \sigma \) layers (~1-m thickness each) and model cells are 2×2 m² in the horizontal. Bed roughness is set at 1 cm, but the side walls are assumed frictionless. Devices are located 2 m from the channel floor and have 4-m diameters. Thrust coefficients are \( C_T = 0.5 \). Device support structures are 3 m high, 0.25 m wide, and have drag coefficients of \( C_D = 1.2 \). The 18-device array is withdrawing 267 kW of power.

Fig. 4 shows the water depths around the simulated array of MHK devices; depth increases are apparent upstream of each MHK devices as they remove energy from the system, introduce turbulence, and also obstruct flow. Note the progressively decreased height change just downstream of each row of MHK devices; this is an indication of diminishing power generation because the first row of devices extracts the most energy from the system.
Fig. 5 shows depth-averaged velocities around the hypothetical MHK array. As expected, average velocities decrease downstream of each MHK device due to energy removal and blunt-body form drag from the MHK support structure. Velocity increases near the north and south (top and bottom) of the model domain illustrate how fluid seeks the path of least resistance; given the opportunity, it will bypass MHK arrays. Flow changes have strong implications for the design of MHK arrays; for example, they may be important factors in system flushing (residence time) and nutrient levels. While the ranges of depths and velocities are modest for this example, it is important to note that there may be processes or organisms in the system that are sensitive to small changes. For example, the delineation between erosion and deposition zones can be sensitive to MHK arrays.

Fig. 6 is a snapshot of sediment bed erosion rates (erosion is turned off at the inlet and exit cells to avoid boundary effects). Sediments are considered noncohesive and divided equally by mass into three size classes of 500, 2,000, and 4,000 μm. As expected, there is a strong correlation between velocity magnitude and erosion rate (which may scale as velocity to the fourth power, or shear stress squared, depending on the sediment). Variations from the velocity field and erosion rate can be due to the fact that depth-averaged velocities are presented and also because as erosion progresses, the bed morphology changes and bedslope effects impact both erosion rate and sediment bedload velocities. Moreover, there are some boundary effects on the south (bottom) boundary due to SNL-EFDC’s numerical velocity calculations. These are not significant. Erosion pattern analysis is an important component of an environmental study; the MHK devices may scour patterns into the seabed that may affect sea-floor conditions, benthic organisms, or even migration patterns. MHK devices should ideally be arranged in a pattern where sediment erosion patterns do not drastically deviate from naturally-occurring sediment dynamics.
VII. CONCLUSION

Of paramount importance is the establishment of metrics that can be used to design MHK arrays to provide maximal energy generation with minimal environmental and ecological harm. Factors to consider include changes to bottom shear stresses, total energy extracted from the system, net kinetic turbulent energy loss due to MHK structures, altered residence time, and water quality. Direct and indirect effects on biota are also of paramount importance (and not at all are discussed in this work).

In addition, array distribution and configuration is crucial to an effective MHK installation. By graphically modeling a system, factors such as altered velocity zones and tidal ranges, changes to sediment dynamics (relocation of erosion and deposition zones), and modifications to nutrient availability can be qualitatively examined and compared to site data.

There are additional analyses that SNL-EFDC could perform. Given a cubic relationship between velocity and power, a map that charts available power resources would be possible. Also, with CE-QUAL-ICM, factors such as algal blooms, dissolved gas levels, and other ecological factors (like nutrient concentration) can be examined. Further analysis with SEDZLJ will not only estimate changes to erosion rates and sea-floor bathymetry, but also predict the redistribution of sediment particles (perhaps an important consideration for benthic organisms). Cost-of-energy factors (including potential environmental costs) could be figured into model results to develop maps of installation economic viability.

A future goal of this project is to develop a holistic evaluation protocol based on numerical metrics and site data. This could be used to develop a grading scheme considering key factors like overall power-generation effectiveness, cost efficiency, and ecological footprint of an MHK array. Ideally, this system evaluation protocol could be used by regulators to quickly and effectively determine the feasibility of an MHK installation and then to optimize its configuration.

The key objective of this research is to effectively model the environmental effects from MHK device emplacement, particularly with regard to the physical system. Modeling is a key component to increasing predictability and reliability and to ultimately lower total system costs. MHK research should be used to justify construction of a system that provides a cost-effective power supply, a system that also blends into and mimics system environmental behaviors and minimizes the potential for ecological harm.

ACKNOWLEDGMENT

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Security Administration under contract DE-AC04-94AL85000.

REFERENCES
