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Hydraulic impacts of hydrokinetic devices☆

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ABSTRACT

A simple technique to estimate the far-field hydraulic impacts associated with the deployment of hydrokinetic devices is introduced. The technique involves representing hydrokinetic devices with an enhanced Manning (bottom) roughness coefficient. The enhanced Manning roughness is found to be a function of the Manning roughness, slope, and water depth of the natural channel as well as device efficiency, blockage ratio, and density of device deployment. The technique is developed assuming simple open channel flow geometry. However, once the effective bottom roughness is determined, it can be used to determine the hydraulic impact of arbitrary device configurations and arbitrary flow situations.

1. Introduction

The kinetic energy of flowing water, or hydrokinetic energy, is a large potential source of renewable energy [12,17]. Hydrokinetic energy conversion devices are deployed in flowing water, and they extract energy according to the kinetic energy or velocity of the flowing water. The power available from hydrokinetic devices, per unit swept area, is termed the hydrokinetic power density (PD, W/m^2). Hydrokinetic power density is a function of fluid velocity (V, m/s), fluid density (ρ, kg/m^3), and device efficiency (ξ):

$$\mathrm{PD} = \xi \frac{\rho}{2} V^3 \tag{1}$$

However, as hydrokinetic (HK) devices extract power from flowing water, they can alter the flow velocity, water elevation, sediment transport and other river properties/processes. The goal of this paper is to present a simple way of estimating and representing the far-field hydraulic impacts of HK device deployments. In particular, a technique for representing the presence of hydrokinetic devices with an enhanced bottom roughness is developed. The enhanced bottom roughness can be used in standard hydraulic calculation procedures and models to determine the device impact.

A widely-used open channel flow equation for relating flow velocity (or discharge) to bottom roughness and channel properties is the Manning Equation. Here, the equation is presented in two forms:

$$V = \frac{1}{n} R^{2/3} S^{1/2} \text{ or } Q = \frac{A}{n} R^{2/3} S^{1/2} \tag{2}$$

where V = cross-section averaged velocity (m/s); n = Manning roughness coefficient (s/m$^{1/3}$); R = hydraulic radius (cross-sectional area/wetted perimeter, m); S = slope; Q = discharge (m^3/s); and A = cross-sectional area (m^2).

Note, the second version of the Manning Equation is obtained from the first through application of the continuity principle ($Q = VA$). Since HK devices tend to impede the flow of water, they can be represented with an enhanced bottom roughness, n_t. According to the Manning equation, all other parameters being unchanged, an enhanced bottom roughness would cause a reduction in velocity. In a river setting, where the discharge can be considered constant, the reduced velocity will be compensated for with an increase in water depth.

The majority of previous research on the interaction of HK devices and flowing water focused on the calculation of the available HK power in tidal systems [4,5,9,10,15,20]. In tidal systems, often conceptualized as a channel connecting two basins [6] – one semi-infinite and one finite – the central question is: what fraction of the total energy passing through the tidal channel is available for HK extraction? The researchers found that as the number of HK devices increased, the flow rate of water through the channel decreased. Further, as the number of devices increased, there was a peak in total energy extraction followed by a decline.

Researchers [19] have also addressed the question of the relationship between the power extracted by hydrokinetic devices

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($P_{extracted}$) and the total power dissipated by the presence of the devices ($P_{dissipated}$). The power extracted by hydrokinetic devices is the product of the power density (PD) and the swept area of the devices. Focusing on a single device in a channel, Garrett and Cummins [8] and Polagye [19] noted that the devices generated a low velocity zone in their wake. Further, when the low water velocity wake mixed with the high velocity water that flowed around the device, significant energy was dissipated. Polagye concluded that with a turbine operating at the efficiency close to maximum theoretical limit, the ratio of power extraction ($P_{extracted}$) to power dissipation ($P_{dissipated}$) can be approximated as follows:

$$\frac{P_{extracted}}{P_{dissipated}} = \frac{2}{3(1+\varepsilon)} \tag{3}$$

where ε = blockage coefficient (i.e., the fraction of the river cross-sectional area occupied by the HK device); and $P_{dissipated}$ is the total power dissipated in a river stretch due to the presence of the devices. $P_{dissipated}$ includes the extracted power and additional dissipation due to mixing. It is assumed that there are negligible drag losses.

Here, we derive an expression for an enhanced or effective Manning roughness coefficient (n_t) that can be used to represent the presence of hydrokinetic devices. The expression is obtained by considering the conservation of energy equation in two simple flow situations – case A and case B. Case A is a wide open channel flow situation in which the flow is steady and uniform. In case B, hydrokinetic devices have been deployed such that they are distributed uniformly throughout the channel bottom. The channel in case B is otherwise identical to the one in case A. Assuming that the total flow rate is the same in both situations, an expression for an enhanced Manning roughness that accounts for the presence of devices is readily determined.

In a river deployment of hydrokinetic devices, it is reasonable to assume that the flow rate will be largely unchanged by the presence of devices. Rivers are water conveyance systems for transporting water from high in the watershed to lower in the watershed. However, in parallel with river flow, some amount of water will be transported (from higher to lower in the watershed) in the form of groundwater flow. Neglecting changes in storage, which would be transient, the total flow rate will be unaffected by the deployment of hydrokinetic devices, due to the conservation of mass principle. The build-up of river water upstream of a large deployment of devices could potentially shift some of the downward flow from river flow to groundwater flow. However, the shift would normally be relatively small because the resistance to flow of underground water is extremely large compared to the resistance to flow of surface water. Hence, it is reasonable to assume that the flow rate is the same in case A and B.

2. Representation of hydrokinetic devices with an enhanced bottom roughness

2.1. Case A – uniform open channel flow with no hydrokinetic devices

Assuming flow from location 1 to location 2, the energy conservation equation (or modified Bernoulli Equation) for case A (no devices) can be written [18]:

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + h_L \tag{4}$$

where P_1 and P_2 = pressure (Pa) at locations 1 and 2, respectively; V_1 and V_2 = velocity (m/s) at locations 1 and 2, respectively; z_1 and z_2 = elevations (m) at locations 1 and 2, respectively; γ = specific weight (N/m^3); g = acceleration due to gravity (9.8 m/s^2); and h_L = head loss (m) due to bottom friction.

Since flow is uniform in the direction of flow, the pressure and velocity terms cancel out and the energy equation can be written:

$$z_1 - z_2 = \Delta z = h_L \tag{5}$$

Further, recognizing that, for uniform flow, the bottom slope is the ratio of the head loss to the length of the channel section (i.e., $S = h_L/L$), Manning's Equation (Eq. (2)) can be rearranged to obtain head loss in terms of the flow rate, Manning's roughness, channel cross section area (A, m^2), and hydraulic radius (R, m):

$$h_L = \Delta z = \left(\frac{Qn}{AR^{2/3}}\right)^2 L \tag{6}$$

2.2. Case B – uniform open channel flow with uniform distribution of hydrokinetic devices

In case B, the channel of case A is altered to include hydrokinetic devices (i.e., turbines) that are distributed uniformly on the channel bottom. Water pressure (P_{1t} and P_{2t}) and flow velocity (V_{1t} and V_{2t}) differ from that seen in case A due to the presence of the devices. However, variables such as discharge, channel width, and bottom slope remain the same. The energy conservation equation for case B has the following form:

$$\frac{P_{1t}}{\gamma} + \frac{V_{1t}^2}{2g} + z_1 = \frac{P_{2t}}{\gamma} + \frac{V_{2t}^2}{2g} + z_2 + h_{Lt} + h_p \tag{7}$$

where h_{Lt} = head loss due to the bottom friction (i.e., contact of the flowing water with the "natural" channel bottom); and h_p = "head loss" associated with the presence of the hydrokinetic devices (described below).

Since the turbines are uniformly distributed, flow conditions continue to be uniform in the direction of flow. Consequently, upstream and downstream velocity and pressure heads are the same and Eq. (7) can be simplified to:

$$z_1 - z_2 = \Delta z = h_{Lt} + h_p \tag{8}$$

Consideration of Eqs. (5) and (8), for case A and B, respectively, allows one to readily see that the addition of a uniform distribution of hydrokinetic devices in a river segment leaves the total energy loss in the segment unchanged. However, while the energy loss (head loss) is attributable entirely to bottom friction in case A (without devices), in case B (with devices) the head loss has a contribution due to bottom friction and a contribution due to hydrokinetic devices. Essentially, shifting from case A to B, the natural energy dissipation is reduced to exactly compensate for the increase dissipation from turbines.

Using the same approach as for Eq. (5), the head loss associated with bottom friction can be expressed:

$$h_{Lt} = \left(\frac{Qn}{A_t R_t^{2/3}}\right)^2 L \tag{9}$$

where A_t and R_t are the cross-sectional area and hydraulic radius of the channel when turbines are present.

Since the channel geometry in the two cases is the same, Eq. (8) can be written using Eqs. (6)–(9) obtaining:

$$\left(\frac{Qn}{AR^{2/3}}\right)^2 L = \left(\frac{Qn}{A_t R_t^{2/3}}\right)^2 L + h_p \tag{10}$$