Effects of Tidal Stream Energy Extraction on Water Exchange and Transport Timescales

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Introduction

Tidal stream energy is one of the most attractive marine renewable energy resources because tidal currents are highly predictable. Rapid development of tidal stream device technologies has occurred to maximize energy extraction. However, tidal stream energy development is heavily constrained by the environmental concerns, at both local and system-wide spatial scales, as well as at short-term and long-term temporal scales. During the past decade, numerous studies have investigated the upper limit of theoretical extractable energy and exploited the tidal energy resource in coastal waters around the world using analytical methods and numerical models (Garrett and Cummins 2005; Myers and Bahaj 2005; Bryden et al. 2007; Garrett and Cummins 2007; Sutherland et al. 2007; Polagye et al. 2009; Vennell 2010; Defne et al. 2011; Karsten et al. 2013; Venugopal and Nemalidinne 2014; Yang et al. 2014; Evans et al. 2015; Lo Brutto et al. 2016; Rao et al. 2016). One of the major barriers to tidal stream energy development is the potential environmental impact of deployment and operation of tidal energy converters (TECs) on marine systems. Compared to tidal energy resource characterization and assessment, assessments of environmental impacts as a result of tidal stream energy extraction have been limited, partially due to the complex relationships between energy extraction and many environmental variables, challenges in field observations related to environmental impacts, as well as high uncertainties associated with the assessment of environmental effects.

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Z. Yang and A. Copping (eds.), *Marine Renewable Energy*,
DOI 10.1007/978-3-319-53536-4_11

Environmental effects due to TECs can be largely grouped into two categories: effects on marine life and habitats, such as turbine collision risks, fish migration, seabird population (Ward et al. 2010; Furness et al. 2012; Alexander et al. 2013; Criales et al. 2013; Miller et al. 2013; Schlezinger et al. 2013; Benjamins et al. 2015; Hammar et al. 2015; Copping et al. 2016; Gove et al. 2016), and effects on physical and biogeochemical transport processes, such as hydrodynamics, underwater acoustics, sediment transport, and water quality (Shields et al. 2011; Kadiri et al. 2012; Nash et al. 2014; Martin-Short et al. 2015; VanZwieten et al. 2015; Long et al. 2016; Roche et al. 2016; Williamson et al. 2016). To date, most of the existing studies of physical effects have been based on the characterization of the influence of tidal energy extraction on the volume flux across a TEC farm, i.e., the changes in hydrodynamics alone (Polagye et al. 2008; Hasegawa et al. 2011; Shapiro 2011; Thiebot et al. 2015; Yang and Wang 2015). Although velocity field or tidal volume flux is the most direct physical property to be affected by TECs, the most critical environmental concerns about tidal stream energy development are closely related to biogeochemical transport processes driven by the flow field, such as sediment erosion and transport, mixing and water exchange, and changes in water quality in marine systems (Neill et al. 2009; Nash et al. 2014; Wang et al. 2015; van der Molen et al. 2016). One parameter that closely links tidal volume flux, or tidal prism, to the biogeochemical transport processes in coastal and estuarine systems is flushing time (Dyer 1973; Officer 1976), which has been widely used as the transport timescale to represent the overall flushing capability of an aquatic system.

This chapter explores the flushing time approach for assessing the system-wide effect of tidal stream energy extraction on the physical marine environment. The flushing time concept and tidal prism theory are presented first, followed by a detailed review of the analytical methods and numerical models, from simplified one-dimensional (1-D) to advanced three-dimensional (3-D) models, which are used for characterizing the theoretical tidal energy resource and evaluating the impacts on tidal flows. Finally, two case studies using a 3-D model and tidal flushing time method are given to illustrate the flushing time approach for assessing the impacts of TECs on physical systems.

Definition and Calculation Methods of Flushing Time

Flushing time is one of the most widely used transport timescales for describing the rate of water exchange in a waterbody. The flushing time concept was first introduced by Dyer (1973) and Officer (1976) to quantify the time required for flushing existing water out of an estuary or coastal embayment as a function of freshwater discharge and tidal prism. It is generally regarded as a bulk or integrative property that describes the overall exchange/renewal capability of a waterbody. Its calculation methods are described below.

Tidal Prism Method

Dyer (1973) and Officer (1976) defined flushing time as a function of freshwater discharge R and tidal prism P, which is the volume of water in an estuary or bay between high tide and low tide. The tidal prism method has been widely used to estimate flushing time T_f. The most common and simplest tidal prism model has the following form (Dyer 1973; Wang et al. 2004):

$$T_f = \frac{V+P}{Q+R} \tag{1}$$

where $Q = P/T$ is the tidal volume flux in and out of the bay, V is the volume of the bay at low tide, and T is the tidal period. Equation 1 does not consider the effect of the return flux of tracer and net inflow. Several modifications were made on the simple tidal prism model to include the effect of return flux and the influence of net inflow on tidal prism (Wood 1979; Kuo and Neilson 1988; Sanford et al. 1992; Luketina 1998). Based on Luketina (1998), the governing equation for the rate of change of a conservative trace concentration $c(t)$ is described as follows:

$$\frac{dc(t)}{dt} = -\left[\frac{(1-b)\frac{P}{T}+(1+b)\frac{R}{2}}{V+P}\right]c(t) \tag{2}$$

where t is time and b is the return factor in the range of 0–1. Solving Eq. 2 for an initial condition problem with $c(0)=c_0$ yields $c(t)=c_0\,exp\left(-t/T_f\right)$ with the flushing time T_f defined as follows (Sanford et al. 1992; Luketina 1998):

$$T_f = \frac{V+P}{(1-b)Q+(1+b)R/2} \tag{3}$$

Clearly, T_f is the time required for the tracer concentration to drop to e-fold of the initial concentration ($c_o/e = 0.3679 \cdot c_o$), also called the e-folding time. Note that Eq. 3 is slightly different from Eq. 1 even when the return flux factor is not considered ($b = 0$). This discrepancy is due to the consideration of the effect of net inflow on tidal prism (Luketina 1998). Equation 3 reduces to the classical form $T_f = (V+P)/R$ when river flow is dominant over tidal volume flux ($R >> Q$). For cases in which river flow can be neglected and the return flux factor is not considered ($b = 0$), Eq. 3 is identical to Eq. 1.

Numerical Simulation

The tidal prism method for estimating flushing time assumes the tracer concentration in the bay is fully mixed and controlled by volume exchange, which typically is not the case under real-world conditions. A more accurate method for estimating the system-wide flushing timescale is based on numerical simulations of tracer transport in the bay. Assuming the system-wide averaged tracer concentration follows an exponential decay relationship with a decay rate K,

$$\frac{dc(t)}{dt} = -Kc(t) \tag{4}$$

Similar to Eq. 2, the solution of Eq. 4 has the following form:

$$c(t) = c_o e^{-Kt} \tag{5}$$

and the e-folding flushing time T_f is given by:

$$T_f = \frac{1}{K} \tag{6}$$

The flushing time then can be calculated based on Eq. 6 by fitting Eq. 5 to the model results and determining the decay rate K. The accuracy of this method depends on the characteristics of the coastal bay and the accuracy of the model results. Therefore, model validation against observations is an important first step in calculating the flushing time.

Effects of TECs on Flows—Analytical and Numerical Approaches

Significant efforts have been made in developing analytical and numerical models to evaluate the effects of tidal stream energy extraction on the hydrodynamics and transport processes in marine systems. This section provides a detailed review of different methods for assessing the maximum extractable tidal energy and its associated effect on volume flux across a tidal channel.

Analytical and 1-D Models

One-dimensional models, especially analytical models, are useful for providing fundamental understanding of the effects of tidal stream energy extraction. Many studies have been conducted to determine the upper limit of extractable tidal stream energy and the effects on flow fields based on 1-D governing equations. Bryden et al. (2004) first examined the potential extractable energy in a natural channel with uni-directional flow using a steady-state 1-D momentum equation. An approximate linear relationship was found between the reduction in flow speed and the extracted energy across the channel when a maximum extraction of 20% of natural energy flux was considered. Their results showed that extraction of 10% of the energy flux would cause a 3% reduction in the flow speed in the channel. In their pioneering work on the theoretical extractable energy in a tidal channel, Garrett and Cummins (2005) developed a formula for the maximum tidally averaged extractable power P_{max} as a function of the maximum volume flux Q_{max} in the channel based on a 1-D model:

$$P_{max} = \gamma \rho g a Q_{max} \tag{7}$$

where ρ is water density, a is the amplitude of the tidal height difference across the channel, g is the gravity acceleration, and γ is a coefficient varying from 0.20 to 0.24. Equation 7 has been validated by others using two-dimensional (2-D) and 3-D model simulations (Sutherland et al. 2007; Hasegawa et al. 2011; Yang et al. 2013), and applied for large-scale regional resource assessment as a first-order approximation (Defne et al. 2012). A relationship between potential extractable power P and volume flux Q was also established with added tidal turbines in the tidal channel, as shown by Garrett and Cummins (2005) and Sutherland et al. (2007):

$$\frac{P}{P_{max}} = \left(\frac{3^{\frac{3}{2}}}{2}\right)\left(\frac{Q}{Q_{max}}\right)\left[1 - \left(\frac{Q}{Q_{max}}\right)^2\right] \tag{8}$$

Clearly, the normalized power P/P_{max} is a nonlinear function of the normalized volume flux Q/Q_{max} (Fig. 1). A similar distribution pattern was found between extracted power and flow speed in a study by Bryden and Couch (2007).

To evaluate the effect of power extraction on the volume flux reduction, the relative volume flux reduction is introduced: $\Delta Q_r = (1 - Q/Q_{max})$. Equation 8 can be rearranged as follows:

$$\frac{P}{P_{max}} = \left(\frac{3^{\frac{3}{2}}}{2}\right)\left(2\Delta Q_r - 3\Delta Q_r^2 + \Delta Q_r^3\right) \tag{9}$$

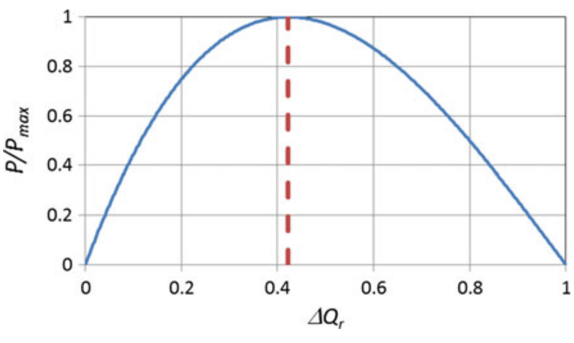

Fig. 1 Relative power as a function of volume flux reduction ΔQ_r

Equation 9 shows that the relative extractable power is a third-order polynomial function of the relative volume flux reduction ΔQ_r. Taking the derivative of P/P_{max} with respect to ΔQ_r, the maximum power ($P/P_{max} = 1$) can be determined when $\Delta Q_r = 0.423$, which indicates that the extractable power has a diminished return when the volume flux Q is reduced by approximately 42%, as shown by the red dashed line in Fig. 1.

Figure 1 also shows that a substantial percentage (44.5%) of energy can be extracted from the tidal channel with a 10% reduction in volume flux. Assuming that no more than a 10% reduction in volume flux would be acceptable for environmental concerns, dropping the higher order terms in Eq. 8 yields a linear approximation for reductions up to 10%:

$$\frac{P}{P_{max}} = 3^{3/2}\Delta Q_r = 5.2 \cdot \Delta Q_r \tag{10}$$

Equation 10 shows that if a fraction of the volume flux reduction is acceptable in a tidal channel, the percentage of extractable energy is about five times the volume flux reduction. Conversely, extraction of 10% of the maximum theoretical energy will only result in a 2% volume flux reduction. This sounds very promising as far as environmental impacts are concerned, because tidal energy extraction at specific real-world sites will likely be within 10% of the maximum theoretical energy in the system. However, because Eq. 10 is derived based on a 1-D model, which could be overly simplified for any real-world conditions, it must be used with caution in applications to real project sites considering its high uncertainty.

Following the work by Garrett and Cummins (2005), a number of studies were conducted to extend the analytical solution to various conditions. Garrett and Cummins (2007) further examined the maximum power for the condition in which a partial tidal turbine fence is placed across the tidal channel. Blanchfield et al. (2008) showed that Eq. 7 is also suitable for a tidal channel linking to a coastal bay, when a is defined as the tidal amplitude outside of the channel and γ equals 0.22. Solving a similar 1-D model with turbine effect, Vennell (2010) showed that the potential power production depends on the tidal farm's configuration and channel geometry. Tidal turbine arrays must occupy the largest fraction of a channel's cross section in order to reach maximum turbine efficiency. Polagye and Malte (2011) developed a 1-D model for channel networks to investigate the tidal energy resource and far-field effects in the channel networks. Specifically, effects on tidal amplitude, transport, kinetic power density, and frictional power dissipation were quantified.

2-D and 3-D Models

While analytical solutions and 1-D models are useful for determining the upper limit of the resource and providing insight into the fundamental relationship between tidal energy resource and far-field effects on hydrodynamics, high uncertainties exist in resource estimates because of assumptions and simplification applied to the governing equations. It is also impossible to use analytical solutions and 1-D models to quantify the spatial (both horizontal and vertical) variability of far-field effects due to TECs deployment. To accurately assess tidal energy potential and far-field effects in real-world sites, advanced 2-D or 3-D numerical models are required.

Sutherland et al. (2007) applied a depth-averaged 2-D model to simulate the tidal energy potential in multiple tidal channels in the Johnstone Strait near Vancouver Island, Canada. By increasing the bottom drag in the model to represent the turbine power dissipation, they found that the modeled volume flux reduction corresponding to the maximum extractable power in all of the channels agreed very well with the analytical solution (Eq. 7) developed by Garrett and Cummins (2005), with a discrepancy of ~1% of volume flux reduction. Using the similar approach of representing energy extraction by increasing of bottom drag, Karsten et al. (2008) applied a coastal Finite Volume Community Ocean Model (FVCOM; Chen et al. 2003) to estimate the maximum theoretical tidal energy of Minas Passage in the Bay of Fundy. The authors found their model results were in a good agreement with the analytical solution (Eq. 7) when it was extended to the case of a channel connecting to a tidal basin, assuming a in Eq. 7 is the amplitude of the tidal forcing. Their model results showed that the maximum extractable power of 7,000 MW in the Minas Passage corresponded to 40% flow reduction through the passage.

Nash et al. (2014) conducted a comprehensive modeling study to evaluate the impacts of tidal stream energy extraction on tidal regimes, intertidal zones, and flushing time in the Shannon Estuary in Ireland using a depth-averaged 2-D hydrodynamic and water quality model. The effect of a tidal farm was simulated based on the Linear Momentum Actuator Disc Theory (LMADT) (Draper et al. 2010; Roc et al. 2014). Averaged residence time was estimated by simulating tracer distribution and was used to evaluate the effect of tidal energy farms on the flushing timescale in the estuary. Nash et al. (2014) found that the normalized tracer concentration in the estuary followed the exponential decay curve, and the residence time for the high-density turbine farm scenario increased approximately 70% due to the blockage effect of the tidal turbine farm. Their model results also indicated that over 30% of the intertidal zone could be lost because some intertidal areas became permanently wet or dry due to distortion of the tidal regime caused by high-density tidal turbine farms.

The horizontal 2-D modeling approach assumes that turbines are able to capture tidal energy throughout the entire water column. This assumption is not realistic because tidal turbines are typically deployed at a specific level in the water column (called the "hub height"). Therefore, 3-D models are necessary to accurately simulate the energy extraction by TECs. Shapiro (2011) first quantified the back effect of tidal stream energy extraction on ocean currents and alterations in regional-scale residual currents and passive tracers in the Celtic Sea using a 3-D ocean circulation model. A kinetic energy loss (sink) term in the 3-D model was introduced to represent the energy dissipation by tidal turbine farms. Shapiro (2011) found that in the case of a high-power turbine farm, the kinetic energy of currents can be altered significantly. Furthermore, model simulations suggested that at a high level of energy extraction, the currents tended to bypass the tidal turbine farms; therefore, the increase in extracted energy is much smaller than the increase in the rated power capacity of farms. The effect of tidal energy extraction on passive tracers was evaluated using neutral buoyant drifter simulations. Simulated Lagrangian trajectories indicated that the effects of tidal energy extraction on passive tracers vary significantly in the horizontal domain; the effects range from 13 to 238% and are extremely sensitive to the drifter release locations.

A number of 3-D model applications have been conducted to assess tidal stream resource potential and far-field effects since the initial work performed by Shapiro (2011) (Hasegawa et al. 2011; Hakim et al. 2013; Work et al. 2013; Yang et al. 2013; Roc et al. 2014; Yang et al. 2014; Pacheco and Ferreira 2016; Rao et al. 2016; van der Molen et al. 2016). In a 3-D modeling study for an idealized tidal channel linked to a bay, Yang et al. (2013) examined the theory of maximum extractable power developed by Garrett and Cummins (2005) and Blanchfield et al. (2008). A tidal turbine module was implemented in FVCOM using the momentum sink approach. Yang et al. (2013) found that the estimated maximum extractable power based on 2-D simulations matched the analytical solution (Eqs. 7 and 8) very well. However, model results from 3-D simulations showed that the volume flux reduction corresponding to the maximum power extraction was much lower than the analytical solution of 42%, and it varied significantly from 23 to 36% when turbine hub height increases near the bottom to the mid-layer of the water column. They found that the maximum extractable power and turbine farm efficiency (power/turbine) were sensitive to the hub height, and that the maximum extractable power occurs near the mid-layer of the water column. Yang et al. (2013) also evaluated the effect of energy extraction on flushing time in the bay connecting to tidal channel based on model simulations of tracer transport.

In recent years, coupled hydrodynamic and biogeochemical models have been used to directly simulate the effect of tidal stream energy extraction on biogeochemical processes. For example, Wang et al. (2015) developed a 3-D biogeochemical model coupled with FVCOM to assess the effects of tidal energy extraction on water quality in an idealized coastal bay. They found that the responses of water quality variables to tidal energy extraction, such as dissolved oxygen, depended highly on the decrease in flushing time in the bay and increase in vertical mixing in the tidal channel. van der Molen et al. (2016) applied a 3-D coupled hydrodynamic-biogeochemical model to investigate the large-scale environmental impact of tidal energy generation in the Pentland Firth. Simulated biogeochemical variables include suspended sediment, silicate, chlorophyll a, and nitrate. Their model results suggested that realistic scale power generation from the tidal stream has minor effects on tidal circulation and undetectable effects on biogeochemical processes. However, large-scale tidal energy extraction of 8 GW such as that proposed in Pentland Firth would result in up to 10% changes in marine environmental variables.

Case Studies for Assessing the Effects on Flushing Time

Idealized Channel Linking to a Bay

Yang et al. (2013) simulated the effects of tidal energy extraction on volume flux and tracer flushing time in a tidal channel connecting to a bay. The tidal channel is 30 km long, 6 km wide, and 60 m deep. The semi-enclosed bay is 150 km long, 30 km wide, and 100 m deep. The detailed model setup was described by Yang et al. (2013). The change in tracer concentration in the bay was simulated with initial conditions of unity concentration in the bay and clean water in the tidal channel and coastal ocean. Figure 2 shows the simulated surface distribution of tracer concentration after 5 days of initial tracer release inside the bay. Strong lateral mixing induced by tidal vortexes and tidal intrusion of coastal water are clearly seen from the tracer distribution.

The flushing time of the bay was estimated based on the numerical simulations, as well as Eqs. 5 and 6. Changes in the flushing time in the bay were determined as a function of volume flux reduction through different turbine farms occupying the tidal channel. Results showed the increased flushing time in the semi-enclosed bay roughly follows an exponential distribution as a function of the volume flux

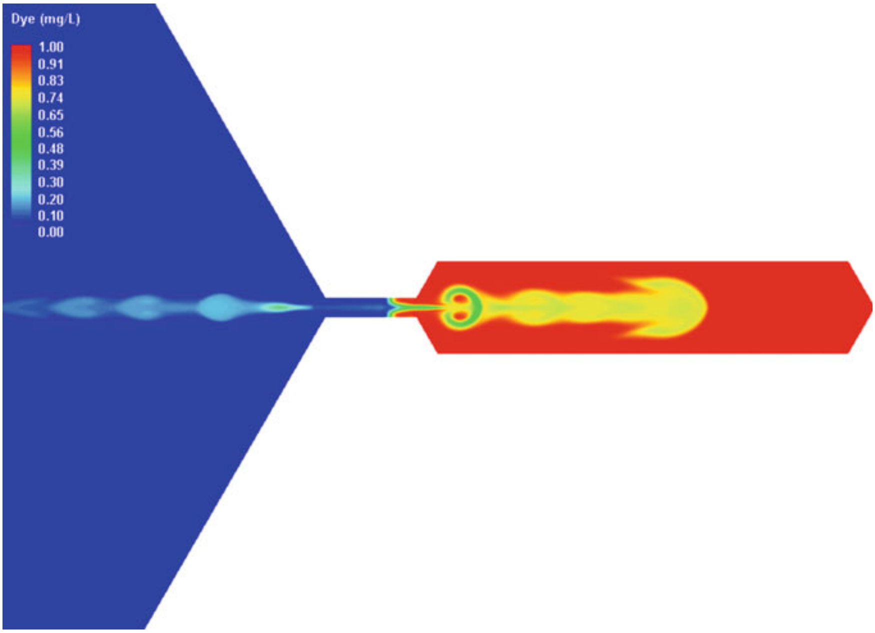

Fig. 2 Simulated tracer concentration in a tidal basin connecting to a tidal channel occupied by turbines after 5 days of tidal flushing. The *red color* represents unit tracer concentration and the *blue* represents zero concentration (clean water) in the open ocean

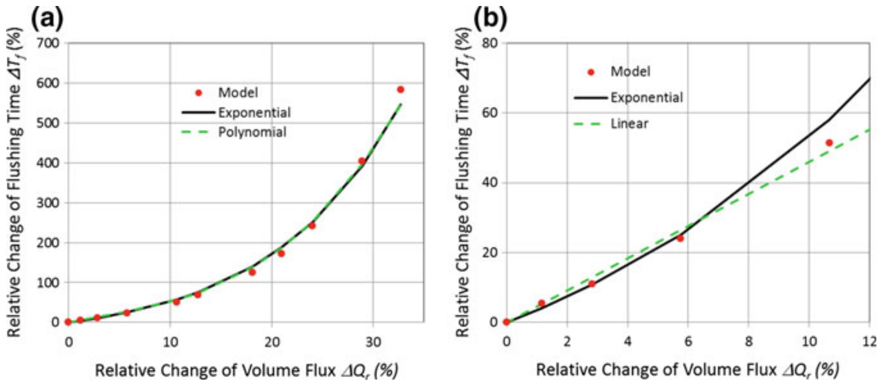

Fig. 3 **a** Simulated relative change in the flushing time ΔT_f (%) as a function of relative volume flux reduction ΔQ_r (%) (*red circle*), exponential fit (*solid black line*), and third-order polynomial fit (*dashed green line*); **b** change in ΔT_f (%) in the small range of ΔQ_r (%). The *dashed green line* represents linear regression

reduction (Fig. 3a). Applying exponential or third-order polynomial regressions to the model results (red circle) in Fig. 3 shows the following:

$$\Delta T_f = \begin{cases} 43 \cdot \ \exp(0.08\,\Delta Q_r); & \textit{Exponential Fit} \\ 5 \cdot \Delta\, Q_r - 0.1181 \cdot \Delta Q_r^2 + 0.0145 \cdot \Delta Q_r^3; & \textit{Polynomial Fit} \end{cases} \tag{11}$$

The comparison of changes in flushing time calculated from model simulation (red circle), the exponential fit (black line), and the polynomial fit (dashed green line) is presented in Fig. 3a. Clearly, both the exponential and the third-order polynomial regression formulas match the model results well. As discussed in the previous section, practical power extraction is likely being constrained by the concerns of environmental impacts, such as an upper limit of 10% charge in volume flux. Re-plotting Fig. 3a for a small range of ΔQ_r (%) indicates the relative change in flushing time ΔT_f (%), and volume flux reduction ΔQ_r (%) approximately follows a linear relationship (Fig. 3b):

$$\Delta T_f = \beta \cdot \Delta Q_r \tag{12}$$

where β = 4.6, which is close to the linear coefficient of 5.0 in the polynomial regression (Eq. 11). Equation 12 shows that the effect of tidal energy extraction on flushing time is several times greater than its effect on volume flux. This result suggests that if flushing time is used as an environmental impact indicator and a 10% change is the acceptable upper limit, the 10% change in volume flux may not be a good reference for environmental impact assessment.

Tacoma Narrows in Puget Sound

A case study at a real-world site, Tacoma Narrows in Puget Sound, Washington State, USA, was conducted to demonstrate that flushing time is a unique indicator for assessing the impacts of tidal energy extraction on transport processes. Puget Sound is a large estuarine system that is identified as one of the top potential sites for tidal energy development in US coastal waters (Kilcher et al. 2016). Tacoma Narrows is a narrow and shallow channel that, as a glacial sill, separates the south Puget Sound (South Sound) from the rest of the waterbodies in Puget Sound (Fig. 4). Tacoma Narrows has an average length of 9,000 m, width of 2,000 m, and water depth of 35 m. Tidal currents in Tacoma Narrows are extremely strong because of the narrow channel and strong tidal forcing, which makes the site ideal for exploring tidal stream energy production (Polagye et al. 2009; Kilcher et al. 2016).

The 3-D coastal hydrodynamic model used in the present study was based on a previously validated Puget Sound model (Yang and Khangaonkar 2010), which was further refined by Yang et al. (2014) to estimate the practical extractable power with a relatively small number of turbines (<100) and evaluate the effects of TECs

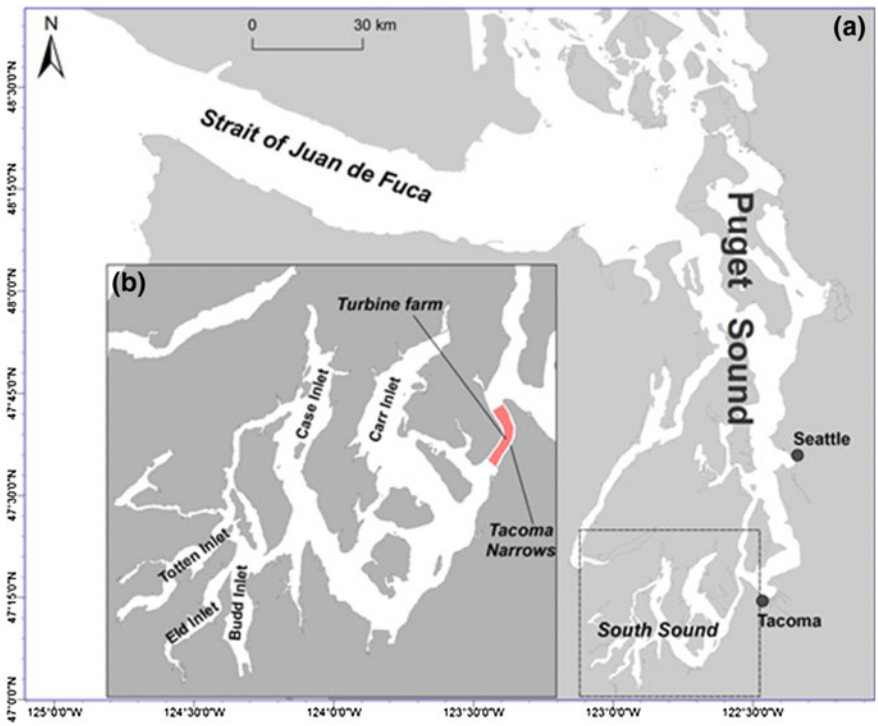

Fig. 4 Puget Sound (**a**) and the study site of Tacoma Narrows and South Sound (**b**). The location of turbine farm is located in the central area of Tacoma Narrows, as marked in *red* in (**b**)

on the flow field and bottom shear stress in Tacoma Narrows. In the present study, hypothetical tidal turbine farms were simulated with turbine density ranging from 17- to 2-rotor-diameter spacing. Tidal turbines were uniformly distributed in the entire central deep region of Tacoma Narrows (Fig. 4b) where water depth is mostly greater than 30 m. The turbine diameter was 10 m, and the hub height was specified at 15 m from the sea bed. The turbine thrust coefficient was specified as 0.9, the same value used in the previous study (Yang et al. 2014). Because the primary focus of this study was to quantify the impact of tidal energy extraction on tidal flux and water exchange, the hydrodynamic model was run in the barotropic mode, i.e., temperature and salinity were not simulated. In addition, river discharge and meteorological forcing were not included as a simplification. The rest of the model configuration remained the same as that used by Yang et al. (2014).

All simulations were conducted for a period of 125 days, and the first 5 days represented the model spin-up time. The simulated changes in volume flux corresponding to different energy extraction scenarios in Tacoma Narrows are presented in Fig. 5a. The average extractable power was calculated based on a 120-day period. While the distribution of extractable power as a function of volume flux reduction in Tacoma Narrows is similar to the results from analytical solutions (Garrett and Cummins 2005; Sutherland et al. 2007), the volume flux reduction corresponding to the maximum extractable power of 130.5 MW is only about 10.8%, which is much smaller than the theoretical value of 42% derived by Garrett and Cummins (2005). The discrepancy was noted by Yang et al. (2013) in their study that assessed the impact of tidal energy extraction in an idealized tidal channel using a 3-D model. One of the shortcomings of 1-D and depth-averaged 2-D models is the assumption that tidal energy is extracted through the entire water column of the channel cross section. In real-world applications, TECs only extract energy at a water depth around the hub height, and therefore water flow can bypass the turbine farms above and below the turbines. Yang et al. (2013) found that the volume flux corresponding to the maximum extractable power in the idealized channel was only reduced by 23% when the

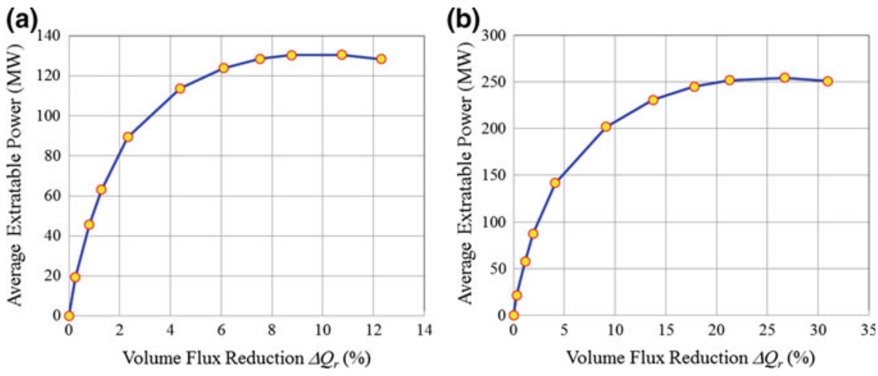

Fig. 5 Average extractable power versus volume flux reduction in Tacoma Narrows. **a** Results from 3-D model simulations. **b** Results from depth-averaged 2-D model simulations

turbine hub height was specified to be near the bottom of the water column. Karsten et al. (2013) combined LMADT with volume flux to assess the extractable tidal energy and effect of turbine fence blockage ratios in Minas Passage, in the Bay of Fundy. They found that the maximum extractable power became much smaller and the corresponding flow reduction was less than 10% when small turbine blockage ratios were considered. Hasegawa et al. (2011) investigated the far-field hydrodynamic impacts of tidal energy extraction in Minas Passage using a 3-D coastal circulation model and showed that the volume flux reduction corresponding to the maximum power output was only about 10% when energy was extracted from the lower water column, and over 38% when energy was extracted from the whole water column, which is much closer to the theoretical value of 42% given by Garrett and Cummins (2005).

To illustrate the difference between 2-D and 3-D modeling approaches for assessing extractable tidal energy in Tacoma Narrows, model simulations were conducted for the same tidal turbine farms (as shown in Fig. 5a), but in a depth-averaged 2-D mode such that tidal energy was extracted from the entire water column. Simulated average extractable power versus volume flux reduction from the 2-D model runs is presented in Fig. 5b. The simulated maximum extractable power from 2-D model simulation increased from 130.5 MW (3-D result) to 254.4 MW, which was very close to the theoretical extractable power of 248 MW derived by Yang et al. (2014) based on a modified form of Eq. 7 using amplitudes of eight tidal constituents (S_2, M_2, N_2, K_2, K_1, P_1, O_1, and Q_1) at the entrance of Tacoma Narrows. The relative volume flux reduction corresponding to maximum extractable power increased from 10.8% in 3-D mode to 26.7% in 2-D mode. Polagye et al. (2009) applied a 1-D model to investigate the far-field effects of tidal stream energy extraction in Puget Sound. They found that a 5% reduction in volume flux would correspond to 120 MW of power dissipation by TECs in Tacoma Narrows. Their findings were similar to the results of the present study, as shown in Fig. 5. It should be noted that the estimated maximum extractable power highly depends on the turbine farm configurations and the exact values should be used as general guidance.

Tracer transport simulations were conducted in 3-D mode to estimate the flushing time in the South Sound, a sub-basin connected to the main basin of Puget Sound through Tacoma Narrows. The initial tracer concentration was specified as 1.0 inside the South Sound and zero in Tacoma Narrows and the rest of Puget Sound. Figure 6a shows the depth-averaged instantaneous tracer concentration distribution for the baseline condition after 100 days of tracer release. It can be seen that for most areas of the South Sound, tracer concentration has decreased to less than 0.5 or 50% of the initial value. As expected, higher tracer concentrations are restricted to upstream tributaries that are relatively far away from Tacoma Narrows, e.g., Case Inlet and Carr Inlet. Figure 6b shows the tracer concentration difference between the scenario with 63 MW averaged power extraction and the baseline condition. Positive values occurred in most areas of the South Sound with highest concentration differences (>0.06) in Case Inlet. This suggests that extracting tidal power from Tacoma Narrows will reduce tidal flushing in tidal basins behind the

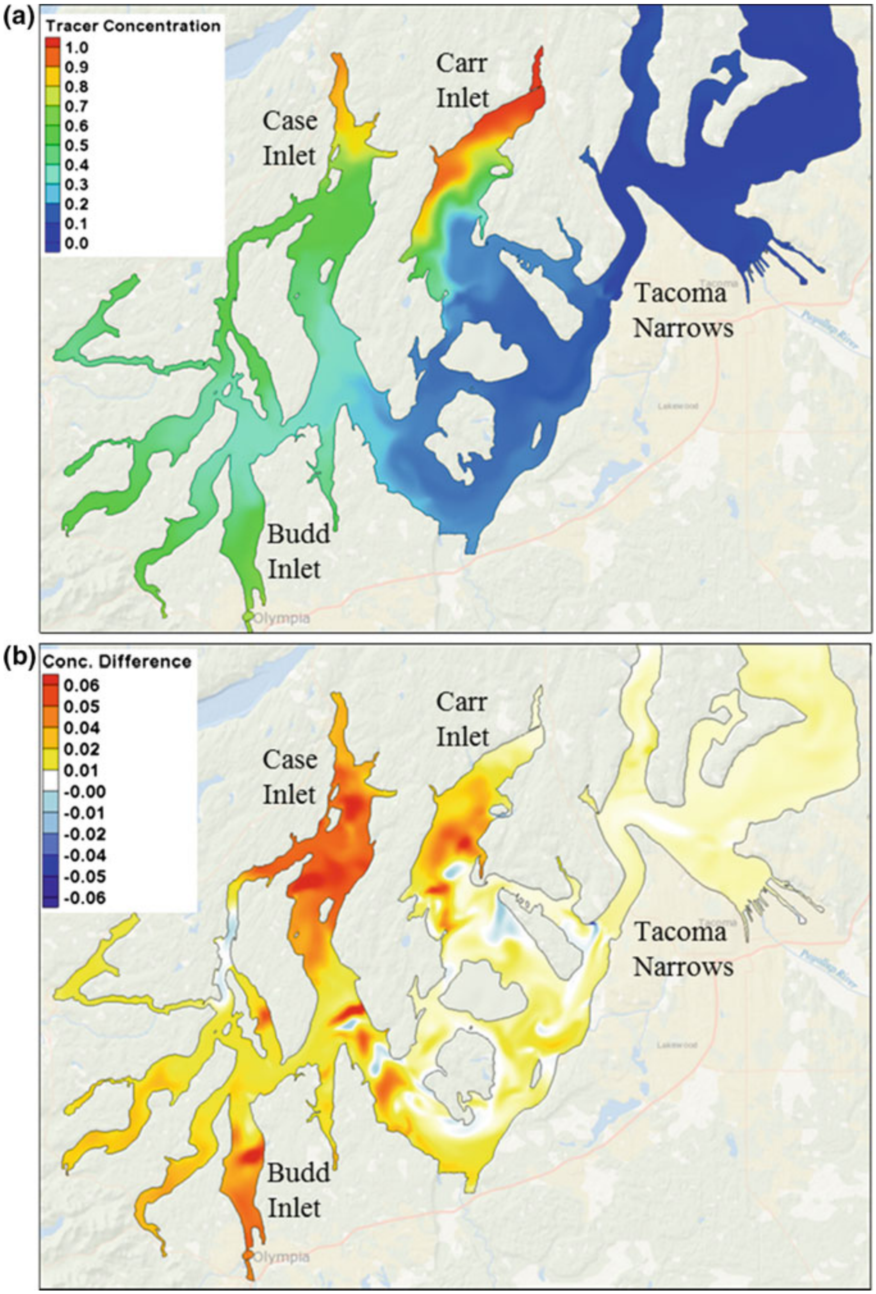

Fig. 6 **a** Simulated instantaneous tracer concentration for the baseline condition (without tidal turbine) in Tacoma Narrows of Puget Sound. **b** Difference in tracer concentrations between 63 MW power and baseline condition in the South Sound sub-basin. Tidal turbines were specified in Tacoma Narrows of Puget Sound

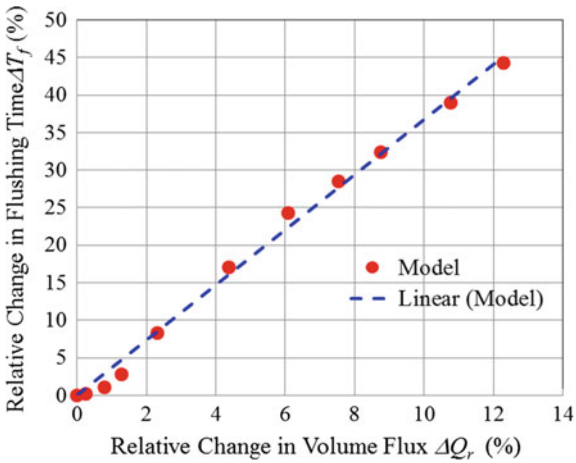

Fig. 7 Simulated change in flushing time (%) versus volume flux reduction caused by tidal stream energy extraction in Tacoma Narrows of Puget Sound. Simulations were conducted in 3-D mode and turbine configurations are the same as Fig. 5a

strait. The maximum impact is likely to occur in Case Inlet, potentially as a result of its relative deep depth and far distance from Tacoma Narrows.

Assuming the spatially averaged tracer concentration in the South Sound follows an exponential distribution after the initial release, as described by Eq. 5, the decay rate K can be determined by an exponential regression to spatial-average tracer concentration simulated by the model. The flushing time in the South Sound then can be estimated based on Eq. 6 for the baseline condition and all tidal farm configurations. The relative change in flushing time as a function of volume flux reduction is presented in Fig. 7. As can be seen, there is an approximate linear relationship between change in flushing time and volume flux reduction, similar to the idealized case study results (Fig. 3b). Applying the linear regression of Eq. 12 to the model results yields $\Delta T_f = 3.7 \cdot \Delta Q_r$, which indicates that the effect of tidal energy extraction in Tacoma Narrows on flushing time is several times greater than the effect on the volume flux. As a result, the potential impact on key physical and biogeochemical processes such as sediment transport and primary productivity should be much greater than that indicated by the change in volume flux alone. This suggests that care should be taken when harnessing more energy from a tidal system because the potential environmental impact could increase more rapidly.

Summary

The effects of TECs on physical processes in marine systems, such as far-field hydrodynamics and transport processes, are one of the environmental concerns in tidal stream energy development. Due to spatial and temporal limitations of field measurements, numerical models are useful tools for assessing tidal energy resources and evaluating the impacts of energy extraction on physical systems, such as circulation and transport processes. This chapter provides a detailed review of various methods, including simple 1-D models and analytical solutions to advanced 3-D models for assessing the theoretical extractable tidal energy across a tidal channel and the effects of energy extraction on far-field hydrodynamics and transport processes. Examples based on an idealized tidal channel linking to a coastal bay and a realistic site—Tacoma Narrows—illustrate the use of numerical models for evaluating the effects of tidal energy extraction on volume flux and transport processes. Specifically, the flushing time concept was used to quantify the impact of TECs on the change in transport timescale. The flushing time of a coastal bay was calculated using an exponential decay formula based on tracer simulations from a 3-D hydrodynamic and transport model. One of the key findings from this study is that if a 10% change in flushing time is the acceptable upper limit for the concern of environmental impact due to TECs, a smaller percentage reduction in volume flux must be considered because the change in flushing time is several times greater than the change in volume flux.

While analytical solutions or 1-D models are useful for estimating the upper limit of theoretical extractable power, they should be used with caution when applied to real-world sites because of the strict assumptions underlying the governing equations. Results derived from the case studies for idealized tidal channel connecting to a coastal bay and Tacoma Narrows in Puget Sound suggest that the maximum extractable power and the corresponding volume flux reduction in a real-world site could be much smaller than those derived from idealized conditions, because in reality flow can bypass tidal turbines in both the horizontal and vertical planes. The impact of tidal energy extraction on volume flux and flushing timescales is a 3-D problem, which highly depends on the turbine hub height in the vertical water column as well as on the horizontal array layout. Study results indicate that, within a small range of volume flux reduction (less than 10%), the change in flushing time is approximately linearly proportional to the volume flux reduction but shows a greater rate of change. Therefore, flushing time in a coastal bay or estuary system is a better parameter for quantifying the impact of tidal energy extraction on the transport processes in the physical system.

To improve the accuracy of environmental impact assessments associated with the installation and operation of TECs, it is necessary to include these physical variables and processes in the model simulations, especially in an estuarine system like Puget Sound where density-driven two-layer circulation is evident (Yang and Wang 2015). The present study also suggests that unless tidal farms consist of high densities of turbines, the volume flux across Tacoma Narrows will be restricted to less than a few percent. Therefore, available marine space may become a bigger factor than the system-wide impact in decision making for practical energy extraction (Polagye et al. 2009; Nash et al. 2014). Environmental impact assessments for tidal energy extraction should be combined with marine spatial planning analysis and focus on tidal farms with reasonable turbine densities that are not limited by marine space. In the present study, river inflows and baroclinic effects due to temperature and salinity gradients were not considered in the circulation and transport simulations.

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