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Abstract: This work presents a case study for the power potential of a tidal stream connecting a bay to the open ocean. The extractable power, averaged over the tidal cycle, from Masset Sound, located in Haida Gwaii, Canada, is estimated as 79 MW when only the dominant M2 tidal constituent is included in the analysis. The value increases to 87 MW when the three dominant constituents are included. It is shown that extracting the maximum power from Masset Sound will decrease both the maximum water surface elevation within the bay and the maximum volume flowrate through the channel to approximately 58 per cent of their undisturbed values.

Keywords: tidal power, tidal stream, resource assessment, ocean energy

1 INTRODUCTION

Electricity may be generated from tidal streams found in a channel connecting two large basins or in a channel linking a bay to the open ocean. There have been several recent demonstration projects including the installation of tidal stream energy converters in the East River of New York, United States [**1**], Juan de Fuca Strait off the southern coast of Vancouver Island, Canada [**2**], the arctic seas of northern Norway [**3**], and in Orkney, Scotland [**4**]. In addition, a 1.2 MW tidal stream energy converter is scheduled for installation at Strangford Lough, located in Northern Ireland, during the spring of 2008. This will be the largest capacity tidal stream energy converter in the world [**5**]. These developments are driven by the desire for energy supply security and concerns with the environmental impacts of fossil fuel combustion.

There has been continued development of the theory behind the accurate assessment of this resource [**6–11**]. An extensive literature review is provided in reference [**12**]. For isolated turbines in large channels, the extractable power is simply proportional to the turbine cross-section and the local kinetic energy flux per unit area [**8**, **10**, **11**]. It is often assumed that the *maximum* extractable power for a tidal stream in a channel is also proportional to the kinetic energy flux in the undisturbed state through the whole channel cross-section [**13–15**]. Here, the term *undisturbed* describes the natural state prior to installing energy converters. It has been shown, however, that this method is incorrect and that there is no simple relationship between the maximum extractable power from a channel and the undisturbed kinetic energy flux [**6**, **7**].

A one-dimensional theory for the extractable power from a channel linking two large basins was developed in reference [**7**] and supported by a detailed numerical model for Johnstone Strait, Canada [**16**]. A similar theory for the extractable power from a channel linking a bay to the open ocean was developed in references [**6**] and [**9**]. These works concluded that the maximum extractable power, averaged over the tidal cycle, may be estimated within 10–15 per cent as

$$(P_{\text{avg}})_{\max} = 0.22\rho g a Q_0 \tag{1}$$

where ρ is the water density, g is the acceleration due to gravity, and Q_0 is the maximum volume flowrate in the undisturbed state. For a channel connecting two large basins, a is the sinusoidal amplitude of the sea level difference between the ends of the channel. For a channel connecting a bay to the open ocean, a is

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the amplitude of the dominant tidal constituent just outside the channel in the open ocean.

The one-dimensional theories presented in references [**6**], [**7**], and [**9**] assume that all the flow is intercepted by the turbines. Garrett and Cummins [**8**] extended the theory presented in reference [**7**] to allow for turbines occupying only a fraction of the cross-section of the channel, as might be required for navigational and ecological reasons. They showed that power is likely to be lost as the water moving slowly in the wake of the turbines merges with faster moving water in the free stream. With the further assumption that the turbines are operating at maximum efficiency, it was shown that the power lost is 1/3 the values calculated in reference [**7**] if the turbines occupy only a small part of the cross-section. The fractional power loss increases to 2/3 as the turbine area increases and approaches that of the cross-section. These results depend on the assumption of uniform flow through the cross-section. The problem needs to be reinvestigated to take into account vertical and lateral gradients in the flow but the problem will not be pursued further here. There are also reductions in the power potential associated with the drag on the turbine support structures and with the internal operation of the turbine itself.

This work summarizes the theory developed in reference [**9**] and presents a case study of the tidal stream energy potential for Masset Sound, a channel in Haida Gwaii, British Columbia, which links Masset Inlet to the Pacific Ocean (Fig. 1). This region may be suitable for tidal stream energy systems due to the high cost of fuel associated with the existing, predominantly diesel-fuelled, power generation, strong tidal currents, and close proximity to load centres, highways, and transmission lines [**17–20**].

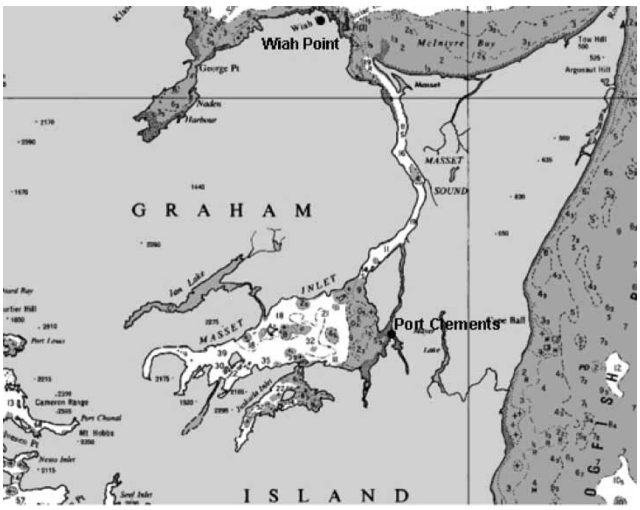

Fig. 1 Masset Sound on Graham Island in Haida Gwaii [**21**]

2 FLOW THROUGH A CHANNEL LINKING A BAY TO THE OPEN OCEAN

A mathematical model was developed in reference [**9**] for a tidal stream in a channel linking a bay to the open ocean. The model solves for the volume flowrate, Q, and the water surface elevation within a bay, ζ_{Bay}, as a function of time, t, given a bay surface area, A, and channel cross-sectional area, $E(x)$, which may vary along the length of the channel, L. The water surface elevation just outside the channel in the open ocean, ζ_0, is assumed independent of the volume flowrate through the channel. A schematic drawing for this model is presented in Fig. 2.

2.1 Momentum balance

The model assumes one-dimensional flow and a constant volume flowrate along the channel, as for a channel which is short compared with the tidal wavelength and has a surface area much less than that of the bay. Bottom drag and turbine drag are quadratic in the flowrate and turbines are deployed uniformly across the entire cross-sectional area of the channel. It is assumed that the cross-sectional area of the channel and the surface area of the bay are unaffected by the rise and fall of the tides, as for flow at low Froude number and with a tidal range which is not a significant fraction of the water depth. The tidal regime just outside the channel in the open ocean is first approximated by a single sinusoid as

$$\zeta_0 = a \cos \omega t \tag{2}$$

where a and ω are the amplitude and frequency of the dominant tidal constituent. It is assumed that the tides rise and fall uniformly within the bay, as for a bay with a horizontal scale much less than the tidal wavelength.

The governing equations are derived from momentum balance and continuity. The momentum balance

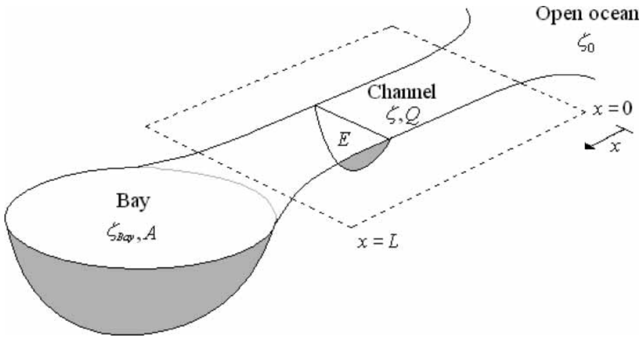

Fig. 2 Schematic drawing of a channel linking a bay to the open ocean [**9**]

is presented in its non-dimensional form as

$$\frac{dQ^*}{dt^*} = \zeta_0^* - \zeta_{Bay}^* - (\lambda_1^* + \lambda_0^*)Q^*|Q^*| \quad (3)$$

where $Q^* = (c\omega/ga)Q$, $t^* = \omega t$, $\zeta_0^* = \zeta_0/a$, and $\zeta_{Bay}^* = \zeta_{Bay}/a$.

The channel geometry term, c, is

$$c = \int_0^L E^{-1} dx \quad (4)$$

The resistance force associated with extracting energy using tidal stream energy converters, F_{turb}, is expressed as a function of the turbine drag parameter, λ_1, and the volume flowrate as

$$\int_0^L F_{turb}\, dx = \lambda_1 Q|Q| \quad (5)$$

The non-dimensional turbine drag parameter, λ_1^*, is

$$\lambda_1^* = \lambda_1 \frac{ga}{(c\omega)^2} \quad (6)$$

Turbines are assumed to be deployed such that all the flow passes through a turbine. The maximum extractable power is, therefore, independent of the location of the turbines along the length of the channel [**6–9**]. For engineering purposes, the uniform *fences* of turbines may be deployed at the most constricted location along the channel to minimize the required number of turbines and associated support structures.

The loss parameter, λ_0, represents the sum of the bottom drag parameter, λ_2, and the effects of flow separation at the exit of the channel. The bottom drag parameter is

$$\lambda_2 = \int_0^L \frac{C_d}{hE^2} dx \quad (7)$$

where C_d is the bottom drag coefficient and $h(x)$ is the average water depth of the cross-section at x [**7**, **22**].

The loss parameter in non-dimensional form, λ_0^*, is then given as

$$\lambda_0^* = \frac{ga}{(c\omega)^2}\left(\int_0^L \frac{c_d}{hE^2} dx + \frac{1}{2E_e^2}\right) \quad (8)$$

where E_e is the cross-sectional area where the flow is exiting the channel to either the bay or open ocean, depending on which way the flow is travelling. The cross-sectional areas at either end of the channel, E_e, are assumed the same.

2.2 Continuity

From continuity, the water surface elevation within the bay may be expressed as a function of the volume flowrate as

$$\frac{d\zeta_{Bay}^*}{dt^*} = \beta Q^* \quad (9)$$

where the bay geometry term, β, is

$$\beta = \frac{g}{cA\omega^2} \quad (10)$$

Equations (3) and (9) are solved simultaneously to determine the flowrate and water surface elevation within the bay for increasing turbine capacity, simulated by increasing the turbine drag parameter, λ_1^*. The result depends on the bay geometry term, β, and the loss parameter, λ_0^*, which describe the site-specific undisturbed dynamical balance in the channel.

2.3 Power

The average extractable power for electricity generation over the tidal cycle may be expressed as

$$P_{avg} = P_{avg}^* \rho \frac{(ga)^2}{c\omega} \quad (11)$$

where the non-dimensional average extractable power is expressed as a function of the turbine drag parameter as

$$P_{avg}^* = \lambda_1^* \overline{Q^{*2}|Q^*|} \quad (12)$$

with the overbar indicating an average over the tidal period.

It was shown in references [**7**] and [**9**] that the maximum average extractable power may be expressed as

$$(P_{avg})_{max} = \gamma \rho g a Q_0 \quad (13)$$

where Q_0 is the maximum volume flowrate in the undisturbed state. This is convenient since the multiplier, γ, was shown to only vary between 0.26 and 0.19 [**9**] as a function of β and λ_0^*. The extractable power may, therefore, be estimated for any channel connecting a bay to the open ocean to within 10–15 per cent using equation (13) and $\gamma = 0.22$. A precise value of γ for a particular situation may be obtained by determining β and λ_0^*.

3 THE EXTRACTABLE POWER FROM MASSET SOUND

3.1 Tide regime

The tidal regimes for Canadian coastlines have been closely analysed by the Canadian Hydrographic Service (CHS). Tidal constituents for a local tidal regime are calculated from water surface elevation data. The amplitude, a, and phase angle, ϕ, of all regional tidal constituents are available from CHS [**23**]. The tidal constituents for Wiah Point and Port Clements, whose locations are shown in Fig. 1, will be used to represent the water surface elevations of the open ocean and the bay, respectively. Tidal predictions for both these locations, over a seven day period, beginning 7 January 2007 are shown in Fig. 3 [**22**].

The tidal regime just outside the channel in the open ocean is first assumed to be expressed as a single sinusoidal waveform as given in equation (2). The dominant tidal constituent for Wiah Point and Port Clements is the semi-diurnal (twice daily) M2 tide with a frequency of $1.4 \times 10^{-4}\,\mathrm{s}^{-1}$ and magnitudes 1.47 and 0.80 m, respectively.

It is apparent from Fig. 3, however, that the tidal regime in Masset Sound is composed of multiple tidal constituents. The impact of including multiple tidal constituents on the average extractable power will be analysed in section 3.5.

The volume flowrate, Q, and water surface elevation within the bay, ζ_{Bay}, were shown in equations (3) and (9) to be functions of the bay geometry term, β, and the non-dimensional loss parameter, λ_0^*. Therefore, β and λ_0^* must be determined to assess the tidal energy resource.

3.2 Determining the bay geometry term and loss parameter

Two methods are used to calculate the bay geometry term, β, and the loss parameter, λ_0^*, for Masset Sound. In the first method, presented in section 3.2.1, the bay geometry term, β, is determined using equation (10)

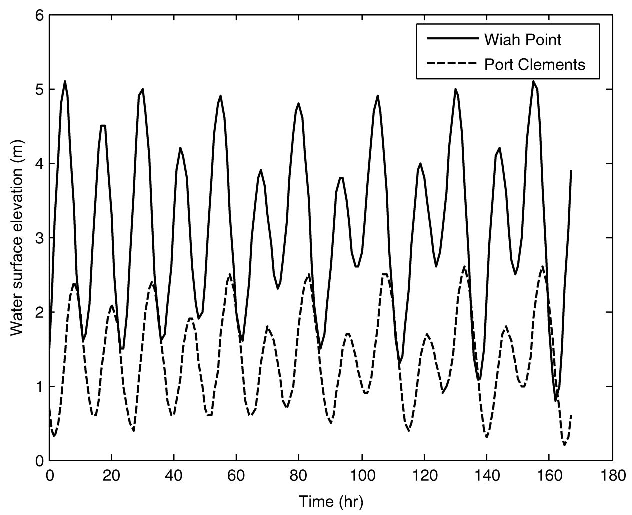

Fig. 3 CHS tidal predictions for Wiah Point and Port Clements for 7–14 January 2007 [**23**]

and measurements of the surface area of the bay and the cross-sectional area of the channel as it varies along its length. The loss parameter is calculated using equation (8) and a typical quadratic bottom drag coefficient. In the second method, the model developed in reference [**9**] is applied. It was shown in reference [**9**] that β and λ_0^* may be determined if the amplitude ratio and phase lag along the channel are known in the undisturbed state. This method will be discussed further in section 3.2.2.

3.2.1 Method 1

The surface areas of Masset Inlet and Masset Sound were measured to be approximately 238 and 49 km^2, respectively, using the Land and Resource Data Warehouse Catalogue [**24**] available from the Government of British Columbia. The channel geometry term was calculated as $c = 1.64\,\mathrm{m}^{-1}$ by digitizing the highest resolution chart soundings available from CHS. The digitized soundings are shown in Fig. 4. The cross-sectional area at either end of the channel, E_{e}, is approximately $1.5 \times 10^4\,\mathrm{m}^2$.

Substituting $g = 9.81\,\mathrm{m/s}^2$, $c = 1.64\,\mathrm{m}^{-1}$, $A = 238$ km^2, and $\omega = 1.4 \times 10^{-4}\,\mathrm{s}^{-1}$ into equation (10), the bay geometry term for Masset Sound is

$$\beta = 1.28 \tag{14}$$

Substituting a typical bottom drag coefficient of 3.0×10^{-3} [**25–27**] into equation (8), the non-dimensional loss parameter for Masset Sound is

$$\lambda_0^* = 7.87 \tag{15}$$

3.2.2 Method 2

The modelling results in reference [**9**] may also be used to calculate the bay geometry term and loss parameter based on the observed amplitude ratio and phase lag in the undisturbed state. The maximum water surface elevation within the bay, $|\zeta_{\mathrm{Bay}}|$, is 0.80 m. Since the water surface elevation outside the channel in the open ocean, a, is 1.47 m, the amplitude ratio, defined as $|\zeta_{\mathrm{Bay}}|/a$, for Masset Sound is

$$\frac{|\zeta_{\mathrm{Bay}}|}{a} = 0.54 \tag{16}$$

The phase angles of the M2 tides at Wiah Point and Port Clements are 33° and 121°, respectively. Therefore, the maximum water surface elevation within the bay *lags* the maximum water surface elevation in the open ocean just outside the channel by $\theta = 88°$.

Based on the contour plot of amplitude ratios and phase lags for varying β and λ_0^* presented in reference [**9**], a channel linking a bay to the open ocean with an

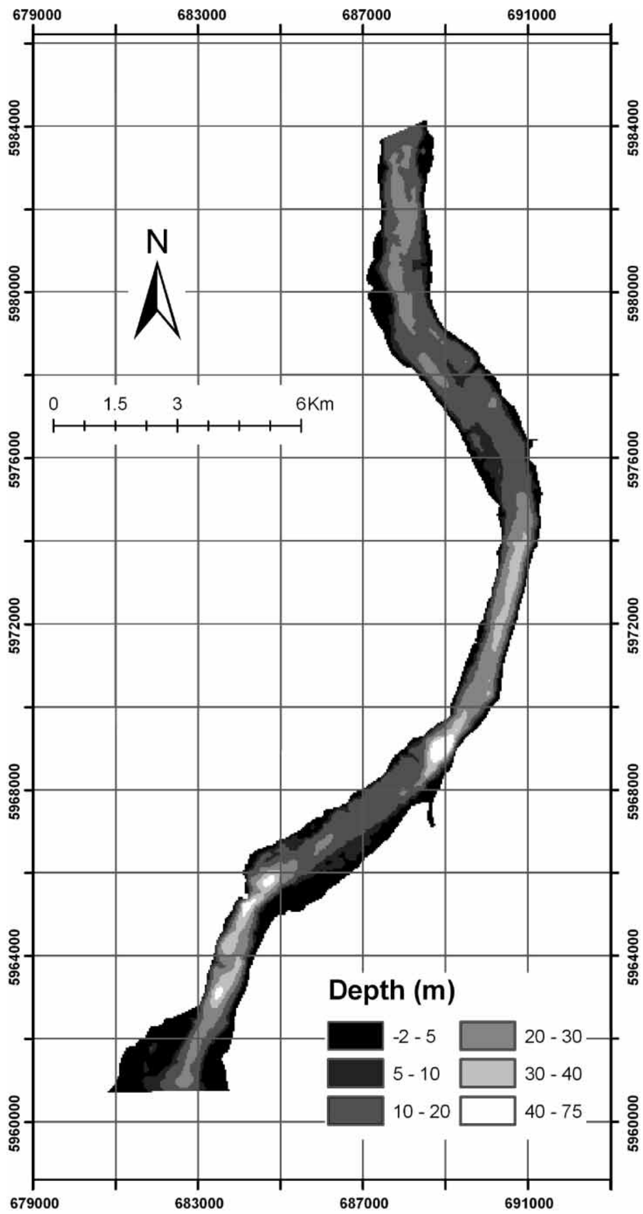

Fig. 4 Digitized soundings for Masset Sound in Haida Gwaii, British Columbia, Canada. 1927 North American Datum. Soundings in metres. Universal Transverse Mercator Grid, Zone 8. Depths measured from low water line. Original soundings (Field Sheet #4523-S) provided by the CHS, Department of Fisheries and Oceans

observed phase lag of 88° and an amplitude ratio of 0.54 is associated with $\beta = 1.45$ and $\lambda_0^* = 8$.

Substituting $\beta = 1.45$, $g = 9.81\,\text{m/s}$, $A = 238\,\text{km}^2$, and $\omega = 1.4 \times 10^{-4}\,\text{s}^{-1}$ into equation (10), the channel geometry term using this second method is $c = 1.45\,\text{m}^{-1}$. This is 13 per cent less than the channel geometry term that was calculated using bathymetric data in the first method.

Rearranging equation (8), the bottom drag coefficient is

$$C_\text{d} = \left(\int_0^L \frac{1}{hE^2}\text{d}x\right)^{-1}\left[\frac{(c\omega)^2}{ga}\lambda_0^* - \frac{1}{2E_\text{e}^2}\right] \tag{17}$$

Substituting $c = 1.45\,\text{m}^{-1}$ and $\lambda_0^* = 8$ into equation (17), the drag coefficient is 3.1×10^{-3}. This value is close to the typical drag coefficient assumption [**25**]. It is apparent from equation (17) that the drag coefficient is sensitive to the loss parameter and the cross-sectional area at the ends of the channel. The first term inside the square bracket is $2.3 \times 10^{-8}\,\text{m}^{-4}$ and the second term is $2.2 \times 10^{-9}\,\text{m}^{-4}$, a factor of 10 smaller than the first term. This implies that the estimated drag coefficient is not particularly sensitive to the cross-sectional area where the flow is exiting to Masset Inlet or the Pacific Ocean.

Solving equations (3) and (9) with $\beta = 1.45$, the maximum non-dimensional volume flowrate, in the undisturbed state, is calculated and plotted as a function of the loss parameter in Fig. 5. For $\lambda_0^* = 8$, the maximum non-dimensional volume flowrate, Q_max^*, in Masset Sound is expected to be 0.35. Since

$$Q = \frac{ga}{c\omega}Q^* \tag{18}$$

the maximum volume flowrate in the undisturbed state, Q_0, in Masset Sound is expected to be 2.5×10^4 m^3/s.

For comparison

$$Q_0 = \omega A|\zeta_\text{Bay}| \tag{19}$$

when drag is assumed linear in the flowrate [**9**]. For Masset Sound, this gives a maximum volume flowrate

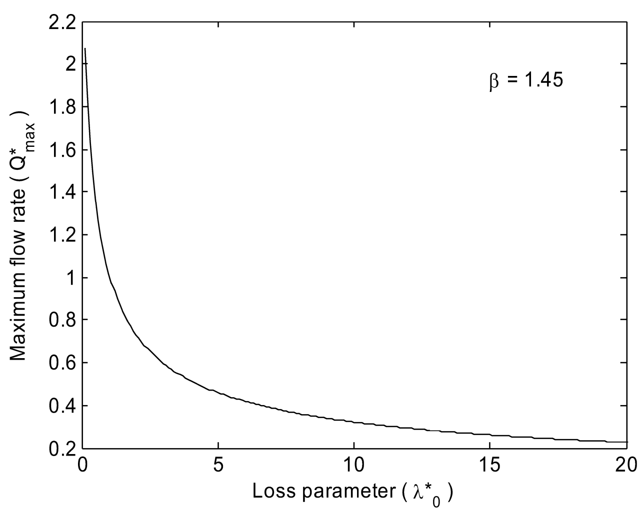

Fig. 5 Maximum non-dimensional undisturbed flowrate as a function of the loss parameter for a bay defined by $\beta = 1.45$

of $2.7 \times 10^4\,m^3/s$, only 8 per cent greater than the results based on the quadratic drag assumption.

The smallest cross-sectional area, E_{min}, in Masset Sound is approximately $1.0 \times 10^4\,m^2$ located near UTM Northing 5975500 (Fig. 4). Since

$$u = \frac{Q}{E} \tag{20}$$

where u is flow velocity, the maximum flow velocity, u_{max}, in Masset Sound is expected to be 2.5 m/s. This agrees with the observed maximum flow speeds published by the CHS [**22**].

3.3 Extractable power

Initially, the average extractable power for electricity generation increases as turbines are installed in the tidal stream. Too many turbines, however, will reduce the volume flowrate excessively and eventually reduce the extractable power. The non-dimensional average extractable power is plotted in Fig. 6 as a function of the turbine drag parameter, λ_1^*, for $\beta = 1.45$ and $\lambda_0^* = 8$. The maximum extractable power is $P_{avg}^* = 7.5 \times 10^{-2}$ when $\lambda_1^* = 15$. Substituting $c = g(\beta A\omega^2)^{-1}$ into equation (11), the average extractable power may be written as

$$P_{avg} = P_{avg}^* \beta \rho g a^2 A \omega \tag{21}$$

Therefore when $P_{avg}^* = 7.5 \times 10^{-2}$ is substituted into equation (21), the maximum average extractable power is 79 MW.

The multiplier, γ, is plotted in Fig. 7 as a function of the loss parameter, λ_0^*, for $\beta = 1.45$. When $\lambda_0^* = 8$, the multiplier is approximately 0.21. Therefore, the maximum average extractable power in Masset Sound may be also be expressed as

$$P_{max} = 0.21 \rho g a Q_0 \tag{22}$$

which agrees with the theory presented in reference [**9**] and equation (1).

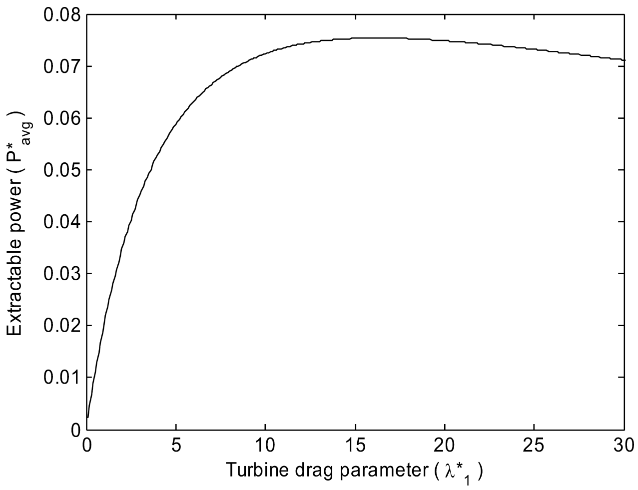

Fig. 6 Non-dimensional average extractable power as a function of the turbine drag parameter for Masset Sound when defined by $\beta = 1.45$ and $\lambda_0^* = 8$

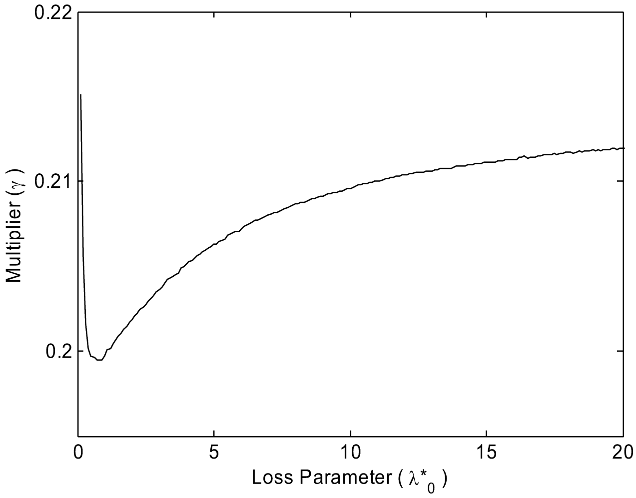

Fig. 7 Power multiplier as a function of the loss parameter for Masset Sound as defined by $\beta = 1.45$

3.4 Multiple tidal constituents

It was shown in reference [**7**] that multiple constituents can be included in the analysis of a channel connecting two large basins. In this work, the average extractable power is calculated from a year long time series based on the three dominant tidal constituents; the semi-diurnal M2, semi-diurnal S2, and the diurnal K1 tides. The undisturbed tide elevation just outside the channel in the open ocean, ζ_0, is then

$$\zeta_0 = a\cos(\omega t + \phi) + a_1\cos(\omega_1 t + \phi_1) + a_2\cos(\omega_2 t + \phi_2) \tag{23}$$

where the magnitude, frequency, and phase for all three tidal constituents are shown in Table 1.

Equations (9) and (3) are solved simultaneously for one year as a function of the turbine drag parameter, λ_1^*. The instantaneous extractable power is then

Table 1 Magnitude, frequency, and phase for dominant tidal constituents at Wiah Point [**22**]

Constituent	Magnitude (m)	Frequency (s^{-1})	Phase (°)
M2	1.47	1.41×10^{-4}	33
S2	0.47	1.45×10^{-4}	55
K1	0.46	7.3×10^{-5}	138

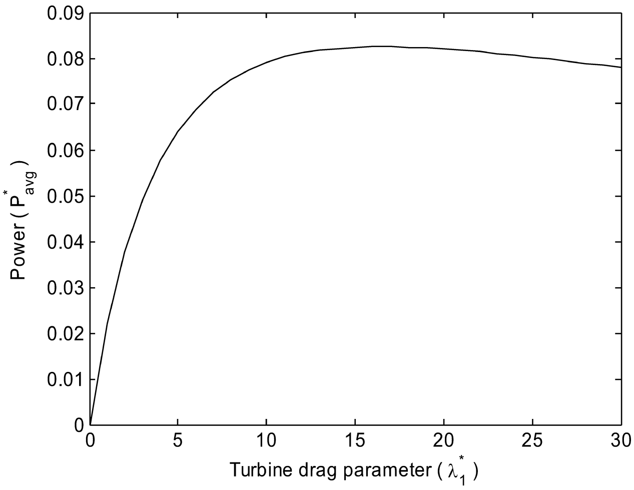

Fig. 8 Maximum average extractable power as a function of the turbine drag parameter when the independent tide regime is modelled using the three dominant tidal constituents and $\beta = 1.45$ and $\lambda_0^* = 8$

averaged over the entire year for each value of λ_1^*. The results are plotted in Fig. 8. A maximum average power of $P_{avg}^* = 8.2 \times 10^{-2}$ or $P_{avg} = 87$ MW is extractable when $\lambda_1^* = 16$. This is 9 per cent greater than the results obtained when only the dominant M2 tidal constituent is included in the analysis.

4 TIDAL REGIME PERTURBATION

The maximum water surface elevation within the bay and the maximum volume flowrate through the channel decrease as power is extracted from Masset Sound for electricity generation. For this analysis, perturbations to the tide regime are explored when Masset Sound is defined by $\beta = 1.45$, $\lambda_0^* = 8$, and the tides at Wiah Point are approximated as a single sinusoid.

When 79 MW is extracted, the water surface elevation within the bay and maximum volume flowrate are reduced to 58 per cent of their undisturbed values. The tidal regime may be kept to within 90 per cent of the undisturbed state, while extracting 37 MW, when $\lambda_1^* = 2$. The extractable power for electricity generation calculated based on this theory neglects mechanical and electrical inefficiencies of the turbines, additional drag on the supporting structures, and further losses associated with isolated turbines as described in reference [**8**]. Only a portion of the extractable power would be available to meet the load.

In Haida Gwaii, the peak demand is approximately 10 MW. A significant amount of Haida Gwaii's electricity demand may be met using tidal energy extracted from Masset Sound, while maintaining 90 per cent of the undisturbed tidal regime.

5 CONCLUSIONS

A case study for Haida Gwaii, reveals that the maximum average extractable power from Masset Sound is approximately 79 MW when the tides in the open ocean just outside the channel exit are assumed to be sinusoidal. It was determined that extracting 79 MW from Masset Sound would decrease the maximum water surface elevation within the bay and the maximum volume flowrate through the channel to approximately 58 per cent of their undisturbed values. The tidal regime may be kept to within 90 per cent of the undisturbed state by limiting the average extracted power to approximately 37 MW. Only a portion of this extractable power will be available to meet the load since mechanical and electrical inefficiencies of the turbines, additional drag on the supporting structures, and further losses associated with isolated turbines as described in reference [**8**] are neglected in the analysis.

The maximum average extractable power increased to 87 MW when the three dominant tidal constituents were included in the analysis. It was also shown that a drag coefficient of 3.0×10^{-3} accurately describes the bottom drag in Masset Sound.

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APPENDIX

Notation

a	amplitude of dominant tidal constituent outside channel in open ocean (m)
A	surface area of bay (m^2)
c	channel geometry term (m^{-1})
C_d	bottom drag coefficient
E	cross-sectional area of channel linking bay to the open ocean (m^2)
E_e	cross-sectional area of channel where the flow is exiting the channel to either the bay or the open, depending on tide (m^2)
F_{turb}	resistance force in channel due to installed turbines (m/s^2)
g	acceleration due to gravity (m/s^2)
h	height of water (m)
L	length of channel (m)
P	power (N m/s)
Q	volume flowrate through channel (m^3/s)
Q_0	maximum volume flowrate in undisturbed state (m^3/s)
t	time (s)
u	flow velocity (m/s)
x	Cartesian coordinate
β	bay geometry term
ζ_{Bay}	water surface elevation within the bay (m)
ζ_0	water surface elevation just outside the bay in the open ocean (m)
θ	phase lag
λ_1	turbine drag parameter (m^{-4})
λ_2	bottom drag parameter (m^{-4})
λ_0	loss parameter (m^{-4})
ρ	density of sea water (kg/m^3)
ϕ	phase angle of tidal constituent
ω	frequency of dominant tidal constituent outside channel in open ocean (s^{-1})

Subscripts

avg	average
max	maximum
min	minimum

Superscript

*	non-dimensional value
°	unit of phase angle