Hydraulic flow and energy dissipation over the Hood Canal sill

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Project Summary

Energy is dissipated across the South Point Sill in Hood Canal due to friction with the bottom and tidally induced mixing. Current estimates of the total tidal dissipation in all of Hood Canal are 16 MW (Lavelle *et al* 1988). The model attributes 9 MW to the M_2 tide while 1 MW is dissipated by the K_1 tide. Others have found that the amount of energy dissipated across a sill is related to internal tides (deYoung and Pond 1989) and internal waves (Wessels and Hutter 1996). It has been shown that large deep water intrusions occur on neap tides (Geyer and Cannon 1982) while small amounts of deep water do intrude on each flood tide (Gregg *Personal Communication Feb. 5, 2004)*. These intrusions are mixed across the sill and there is evidence (Freeland and Farmer 1980; Stacy and Zedel 1986; Stacy 1984) that this may occur more rapidly in the spring when the surface layer is more distinct due to river runoff. As the field program for this work is to take place in the spring there will likely be a thin surface layer in Hood Canal. The crucial measurement to make these calculations is the difference in tidal phase lag as the tides progress across the sill.

The field program will entail three different types of measurements. First will be a set of tide gauges (Fig. 1). These will be placed on either side of the South Point Sill. The set will be vital in measuring the pressure drop across the sill on the ebb and flood tides. Each gage will be installed approximately 1 m below mean lower low water and will record pressure readings every 10 minutes. Tidal energy dissipation can then be calculated from these measurements using formulae developed by Freeland and Farmer (1980) and revised by Stacey (1984). To measure the influence of a possible internal seiche and internal tide on mixing in Hood Canal, one Seabird SeaCat 16 mooring will be placed at Anna's Bay and a mooring consisting of two HOBO temperature sensors will be placed west of Seabeck Bay. These moorings will be near shore in approximately 20 m water depth with the SeaCat placed in the thermocline at ~10 m water depth and the HOBO sensors at ~5 and 15 m water depth. These moorings will be set to record every 10 minutes. Tide gauges will be installed on private docks through snorkeling and CTD moorings will be installed with the aid of the Wee Lander. These instruments will be deployed the last week of February and retrieved the first week in April to capture a complete fortnightly tidal cycle. To characterize tidally driven mixing and the stratification of Hood Canal, CTD sections will be made from the *R/V Clifford A. Barnes*. Four stations from Foulweather Bluff to the mouth of Dabob Bay will be revisited on both flood and ebb tides. The complete field program will provide the most insight to the energy dissipated across the Hood Canal sill and what processes that energy went into.

Introduction

Puget Sound is a glacially carved fjord with five major basins located in western Washington State (Fig. 1) (Collias *et al* 1974). Hood Canal is the westernmost basin in the system with a total length of just over 100 km and a maximum depth of nearly 200 m. The basin is relatively straight for the majority of its length, but for one major embayment, Dabob Bay, extending from it. The sill, located near South Point, has a minimum depth of 40 m and extends nearly 40 km along the thalweg. Nine major rivers discharge into Hood Canal as well as many other small creeks. The largest of which is the Skokomish River with an average discharge of 14.5 m^3 s^{-1}. The annual discharge cycle is similar to most other Northwest rivers with a spring freshet from snowmelt and lower winter discharge as the snowpack accumulates.

The tides in Hood Canal have the most significant impact on circulation in this system with a total tidal prism of 1.14 km^3 or roughly 4.6% of the volume of Hood Canal being exchanged on each tidal cycle (Mofjeld and Larsen 1984). This tidal prism represents 14.6% of the total water flushed from Puget Sound on a tidal cycle (Levelle *et al* 1988) and results in average tidal amplitudes of ~3 m near the head of Lynch Cove. In the area of the South Point sill, tidal amplitudes for the M_2 tide are about 1 m and 0.84 m for the K_1 tide (Mofjeld and Larsen 1984). Tidal currents in the sill region are generally 0.4 knots on ebb and 0.6 knots on flood. These speeds are significantly slower than any other sill region in Puget Sound where speeds frequently exceed 1.5 knots. The phase lag has also been historically observed to be 10º relative to Greenwich transit in the neighborhood of the sill (Mofjeld and Larsen 1984).

The basin is most stratified in the summer after the spring freshet and solar radiation has warmed the surface layer. Deep water intrusions have been found to occur most often during neap tides in the late summer and early fall also increasing stratification at that time (Geyer and Cannon 1982). Smaller amounts of deep water have recently been found to intrude on most strong flood tides. (*Gregg Personal Communication Feb. 5, 2004).* This water was not, however, found to be a significant source of change in overall stratification. Stratification influences on energy dissipation will be discussed later in this proposal.

Studies of other fjords in the Pacific Northwest have calculated the tidal energy dissipated across the entrance sill. Field programs conducted in Knight Inlet, British Columbia found a substantial amount of tidal energy removed from the barotropic tide by forces other than friction with the bottom (deYoung and Pond 1989; Freeland and Farmer 1980; Klymak and Gregg 2003; Stacey 1985; Webb and Pond 1986). As friction was only able to account for 2-4% of the energy dissipated, other mechanisms must account for the remaining dissipation such as hydraulic jumps as the water passes over the sill (Farmer and Freeland 1983; Freeland and Farmer 1980; Klymak and Gregg 2003), internal waves (Freeland and Farmer 1985; Stacey 1985), and internal tides (deYoung and Pond 1989; Webb and Pond 1986). These methods of circulation account for approximately 95% of the energy dissipated with the largest portion being dissipated by the internal tide (40%) (deYoung and Pond 1989).

Studies of Observatory Inlet have made similar findings to those in Knight Inlet (deYoung and Pond 1989; Stacey 1984; Stacey and Zedel 1986). Nonlinear processes such as hydraulic jumps were also investigated more thoroughly and found the majority (95%) of the energy dissipated by water flowing over a sill is removed by linear processes (Stacey and Zedel 1986).

All of these studies found a significant seasonality to the amount of energy dissipated in the basin. Stacey (1985) summarizes that the second mode is amplified when the stratification is the greatest during the summer river runoff and *N*, the Brunt-Väisälä frequency, is decreased. Conversely, he also found that a deep water intrusion would increase *N* and thus increase the relative importance of the first mode. It is noted that the importance of the first mode relative to the second will be dependent on the specific inlet stratification and bathymetry. This seasonal variability accounts for the doubling of energy dissipation in the summer months in Knight and Observatory Inlets (deYoung and Pond 1989).

The one study in Puget Sound examining energy dissipation is a model developed by Lavelle *et al* (1988). The model predicts that of the 733 MW dissipated in Puget Sound, only 16.5 MW are dissipated in Hood Canal (Fig. 2). Though the model fits well with the tidal amplitudes and phase lags for most of the tidal components, assumptions are made that would affect calculations of energy dissipation. The model oversimplifies many of the processes occurring in the channels by linearizing the equations of motion. It was also assumed that channel cross-sections were rectangular and friction coefficients are constant over Hood Canal.

It is for these reasons that an observational approach must be made to determine the real amount of energy dissipated over a fortnightly tidal cycle.

The proposed field program will illuminate just how much energy is dissipated across the Hood Canal sill in spring and will either validate or contradict the model by Lavelle *et al* (1988). The measurements made will characterize the energy dissipated on both mixed semidiurnal and fortnightly tidal cycles. Field work will be occurring during the spring when the surface layer is thick so the calculated energy dissipation will likely be larger than if the measurements were made at other times of the year. Fitting with other concurrent student projects, it will be possible to determine if processes that are known to contribute to energy dissipation are playing key roles in Hood Canal.

Proposed Work

The field program will consist primarily of a set of tide gages placed on either side of the sill (Fig. 1). These gages will be deployed on March 6, 2004 and collected on April 4, 2004 for a total deployment of 31 days. The north gage will be deployed at the Lofall community dock. This location is ~5 km northeast of the minimum sill depth on the eastern shore. The southern gage will be deployed at the Seabeck Marina in Seabeck Bay approximately 20 km southwest of the minimum sill depth. This gage cannot be placed closer to the sill due to restrictions from the naval submarine base at Bangor and a lack of public pilings in the area. The instruments will be Seabird SeaGauge temperature and pressure gages with a tidal resolution of 0.01mm. Gages will be hose clamped to the outermost pier on the docks approximately 1 m below the lower low water mark. Gages will record data every 10 minutes for a total of over 4400 measurements over the deployment period. It should be noted that the time to use each of these instruments has been donated by Dr. Mike Gregg at the Applied Physics Laboratory and as such will not impact the budget of this project.

Other supporting elements to the field program will be the work conducted by Noel Gray and Eric Higgins. Noel's field work will illuminate processes such as internal seiche and internal tides in Hood Canal (*Personal Communication Feb. 2004)*. This will be done through the use of two moorings at either end of the straight segment of the basin. Both moorings will be located in 20 m of water on the eastern shore. The southern mooring will consist of a Seabird SeaCat at 10 m water depth while the north mooring will be made with two HOBO temperature sensors at 5 and 15 m water depth. These moorings will be deployed February 27, 2004 and recovered April 3, 2004 for a total of 38 days in the field. Deployment and recovery of these moorings will be made from the Wee Lander. As was said above, these processes account for a large amount of tidal energy dissipated in Knight and Observatory Inlets and will be important to explain where the dissipated tidal energy is going (deYoung and Pond 1989; Farmer and Freeland 1983; Freeland and Farmer 1980; Stacey 1984; Stacey 1985; Webb and Pond 1986).

Eric's field program though looking for deep water intrusions will gather CTD data that will reflect changes in mixing occurring south of the sill and will also function as an indicator of stratification changes over the month of March. He is planning to repeatedly profile four PRISM stations near the mouth of Dabob Bay as well as one station north of the sill. If significant deep water intrusions are found to be occurring during the field period, this would influence the stratification and the amount of energy dissipation at this time.

As the data from Noel's moorings will be quite useful to this research, I have agreed to split the costs to build and deploy the moorings between the two budgets. This will entail two days aboard the Weelander, the calibration of one SeaCat CTD (courtesy Knut Aagaard), the purchase of two HOBO temperature sensors and other mooring equipment costs.

Analysis of the tide gage data will be conducted in Matlab where the two time series will be aligned according to the observed phase lag in the area (Mofjeld and Larsen 1984). Attempts will be made to separate the individual tidal constituents from the original time series (Mosetti and Manca 1972) in addition to calculating the energy dissipated across the sill. These calculations will be following the equations developed by Freeland and Farmer (1980) and refined by Stacey (1984). Those equations follow:

$$A_1 u_1 \cos(\omega t - \varepsilon) - A_2 u_2 \cos(\omega t - \phi_2) \approx S_o \frac{d}{dt}\left[\frac{h_1 \sin(\omega t) + h_2 \sin(\omega t - \phi_1)}{2}\right]$$

where if the turbulent dissipation rate, ε , and phase lags, ϕ_1, and ϕ_2, are small you can get

$$\begin{aligned}\varepsilon &\approx \left[1 - \frac{S_0}{2S_1}\right]\phi_1 + \frac{A_2 u_2}{A_1 u_1}(\phi_2 - \phi_1)\\ &= \left[1 - \frac{S_0}{2S_1}\right]\phi_1 + \frac{S_2}{S_1}(\phi_2 - \phi_1)\end{aligned}$$

where $A_i(i=1,2)$ is the cross-sectional area of the section and $S_i(i=1,2)$ is the surface area of the inlet upstream of section i and S_0 is the surface area between the two sections. If P is to be equal to the total power dissipated from the barotropic tide upstream of section 1, then if ε is small, becomes

$$P \approx \frac{\rho g \eta_0^2 \omega S_1}{2}\left[1 - \frac{S_0}{2S_1}\right]\phi_1 + \frac{\rho g \eta_0^2 \omega S_2}{2}(\phi_2 - \phi_1).$$

These equations by Stacey (1984) have modified those of Freeland and Farmer (1980) such that all the tidal energy is no longer assumed to have been lost between sections 1 and 2, but rather the second term accounts for the power removed from the barotropic tide upstream of section 2. Similar to findings in Knight and Observatory Inlets (deYoung and Pond 1989; Stacey 1984;

Stacey 1985) and the model of Puget Sound (Lavelle *et al* 1988), I expect to find the M_2 component of the tide to account for the majority of the energy dissipated across the South Point sill.

The data from the Noel's moorings will primarily be analyzed by Noel as he will have a better understanding what that signal from the internal seiche will look like. The CTD data collected by Eric Higgins will be referenced for the magnitude of stratification that is encountered during the deployment. If enough data is gathered on varying tidal cycles it would be helpful to objectively map the data to visualize where mixing processes are occurring on either side of the sill. These locations will be identified by noting decreases in stratification and variations in the depth of the pycnocline.

Through these observations, all of the energy dissipated by both linear and nonlinear processes will be taken into account bringing a clearer understanding of the circulation processes in Hood Canal. The results of this work will verify or nullify the model by Lavelle *et al* (1988) with respect to energy dissipation in Hood Canal. This is an important process that has not yet been conducted, but rather assumed to be true as the model is good at predicting other tidal constituents. Many researchers use the models energy dissipation results as a foundation for their work (*Gregg Personal Communication Feb. 5, 2004; MacCready Personal Communication Mar. 5, 2004).* Should the model be significantly different than the observed results, the results of their work would need re-evaluation. This would suggest further studies in Puget Sound are needed to determine more precisely the tidal energy dissipated in the basin over the seasonal cycle and the internal processes that result.

Budget

Item	Serial Number	Quantity	Cost	per unit	# units	Projected Cost	Projected Cost / 2	Actual Cost	Supplier	Notes
Dock stations										
Tide Gauge (SBE 26-03)	2610973-0118	2	$34.00	per day	38	$2,584.00	$1,292.00	$0.00	Mike Gregg	Wave and tide recorder
D battery pack (6 pack)			$15.00	per 10 pack	2	$30.00	$15.00	$15.00	Corporate Express	Total cost split between Gray and Kellogg Budgets
Hose clamps			$5.00	per item	8	$40.00	$20.00	$0.00	Eric D'Asaro	
2"x4"x96" lumber		1	$2.52	board		$2.52	$1.26	$0.00	Damian Evans	
Mooring Equipment										
Surface float		3	$3.00	per item	38	$342.00	$171.00	$0.00	Bill Fredericks	Panderas floats
subsurface float (36 lb)		4	$3.00	per day	38	$456.00	$228.00	$0.00	Bill Fredericks	Panderas floats
Mooring cable (Nilspun cable)		2	$3.00	per day	38	$228.00	$114.00	$0.00	Jim Johnson	26 m of cable
Mooring anchor (100 lb)		2	$3.00	per day	38	$228.00	$114.00	$0.00	Bill Fredericks	
Mooring anchor (40 lb)		2	$3.00	per day	38	$228.00	$114.00	$0.00	Bill Fredericks	
shackles			$4.00	per item	7	$28.00	$14.00	$0.00	Bill Fredericks	
Polypro rope			$0.15	per foot	60	$27.00	$13.50	$13.50	Pooled Equipment	
1/2" Thimbles			$0.79	per item	12	$9.48	$4.74	$0.00	Bill Fredericks	
D rings			$1.25	per item	5	$6.25	$3.13	$0.00	Bill Fredericks	
Nicopress Sleeve		1	$3.49	per item	5	$3.49	$1.75	$0.00	Jim Johnson	
Duct Tape		1	$5.47	per roll		$5.47	$2.74	$0.00	Jonathan Kellogg	

1/2" 3 strand nylon line			$0.25	per foot	225	$56.25	$28.13	$28.13	Pooled Equipment	
Mooring instrument										
Seabird Seacat 16	1400	1	$45.00	per day	38	$1,710.00	$855.00	$125.00	Knut Aagard	CTD instrument: Requires post-calibration, total cost of $500.00 for one instrument. Administration will pay first $250.00 and the remainder will be split between Gray and Kellogg budgets.
Seacat 19 (hand-held)		1	$45.00	per day	1	$45.00	$22.50	$0.00	Eric D'Asaro	Will be used only to take a water column profile at the mooring locations
HOBO water temp Pro	726365 & 726366		$110.00	per item	2	$220.00	$110.00	$110.00	Onset	Total cost split between Gray and Kellogg Budgets
IR Basestation (required)	BST-IR		$60.00	per item	1	$60.00	$30.00	$30.00	Onset	Total cost split between Gray and Kellogg Budgets
BOXCAR 4.0 Software		1	$95.00	per item		$95.00	$47.50	$0.00	Debbie Kelley	
Tax / Shipping fees			$13.00	per order	1	$13.00	$6.50	$6.50		
Laptop		1	45	per day	2	$90.00	$45.00	$0.00	CSS	Will be borrowed from CSS

Transportation / Communication / Location										
R/V Weelander		1	$70.00	per day	2	$140.00	$70.00	$70.00	Pooled Equipment	
Operator (Dave Thorson)		1	$45.00	per hour	16	$720.00	$360.00	$360.00		
Trailer Rental		1	$0.20	per mile	260	$52.00	$26.00	$26.00	Pooled Equipment	
Truck Rental		1	$0.65	per mile	260	$169.00	$84.50	$84.50	Dave Thorson	Dave Thorson requires we pay for gas but not truck rental
Truck Rental		1	$15.00	per use	2	$30.00	$15.00	$0.00	Dave Thorson	Dave Thorson requires we pay for gas but not truck rental
Ferry service			$10.50	per one way	4	$42.00	$21.00	$21.00		Cost will be split between Gray and Kellogg budgets
Ferry Service w/ Wee Lander			$49.50	Westbound	2	$99.00	$49.50	$49.50		
VHF radio		1	$3.00	per day	2	$6.00	$3.00	$3.00	Weelander	provided by Weelander
GPS (Magellan Handheld)	J02	1	$6.00	per day	2	$12.00	$6.00	$6.00	Weelander	provided by Weelander
Easyfish winch with battery	V03	1	$6.00	per day	2	$12.00	$6.00	$6.00	Pooled Equipment	Cost will be split between Gray and Kellogg budgets
Total						**$7,746.71**	**$3,873.36**	**$942.88**		

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Figures

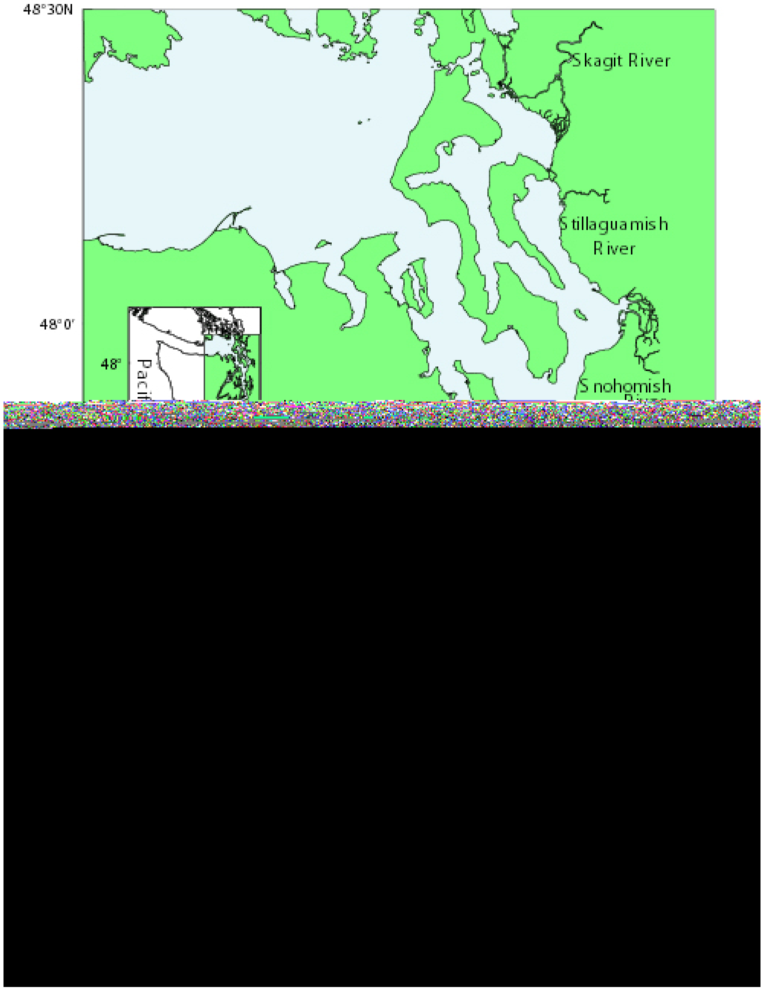

Figure 1 Hood Canal in Puget Sound with the placement of tide gauges to the (1)north and (2) south of the sill.

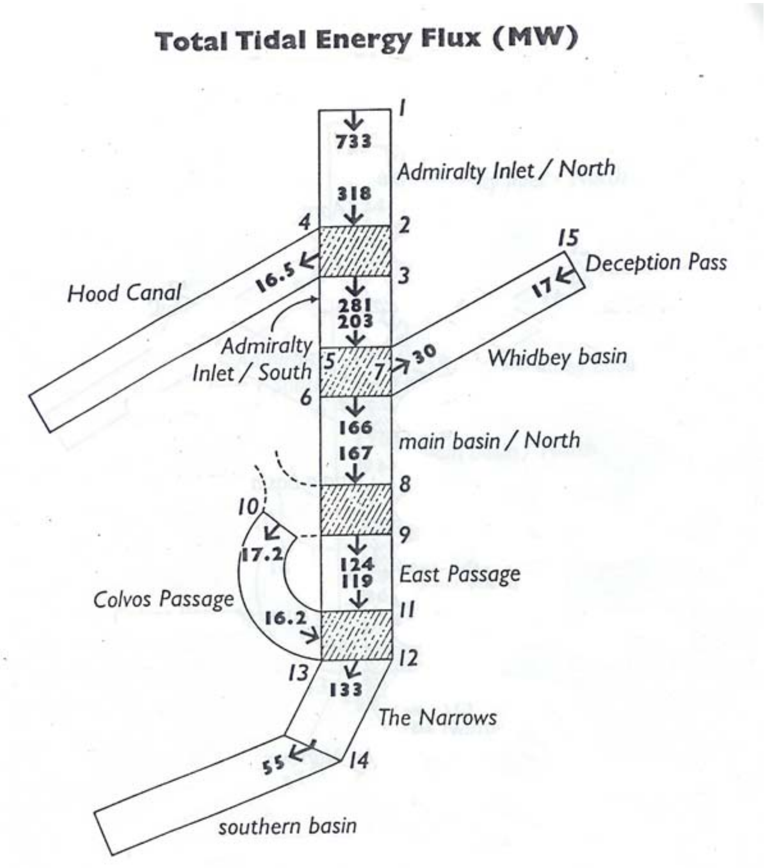

Figure 2 Total energy dissipation as calculated by Lavelle et al (1988)