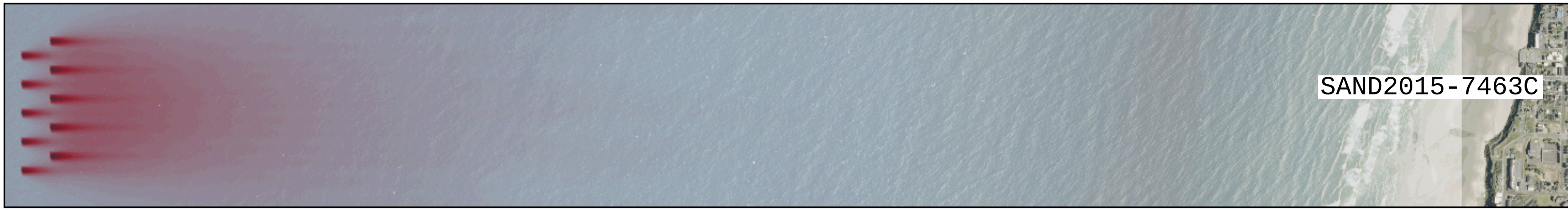

DEVELOPMENT, VERIFICATION AND APPLICATION OF THE SNL-SWAN OPEN SOURCE WAVE FARM CODE

EWTEC 2015

Sept 9, 2015

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Coast & Harbor Engineering
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Outline

- Intro
- Background
- New Code Features
- Example WEC-Module Implementation
- Summary
- Acknowledgements/Questions

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- Water Power Department MHK R&D
- Focused on wave and current energy devices and arrays
- Open source code development, resource characterization, technology design and optimization, instrumentation and monitoring, and environmental impact.

COAST & HARBOR ENGINEERING
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- Full service coastal engineering firm
  - Coastal processes
  - Resource assessment
  - Coastal/port infrastructure
  - Numerical modeling
  - Construction/design
  - Marine Structures
  - Vessel Navigation/Hydrodynamics

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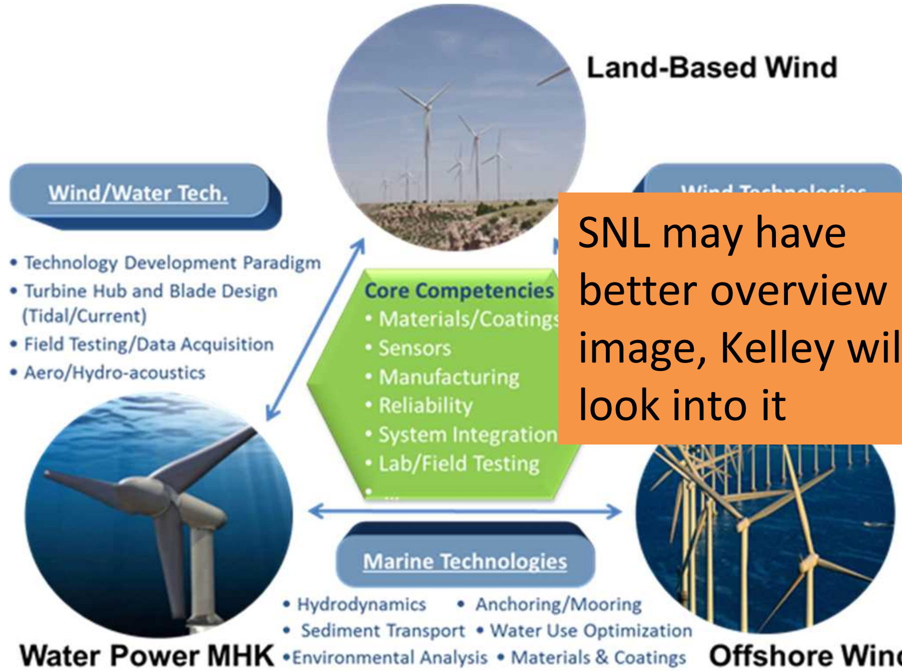
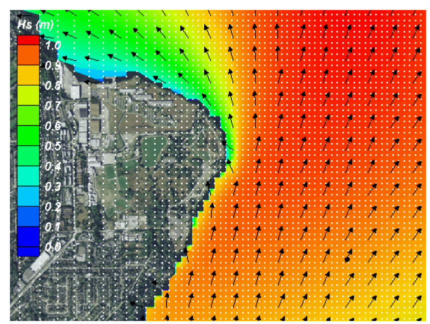
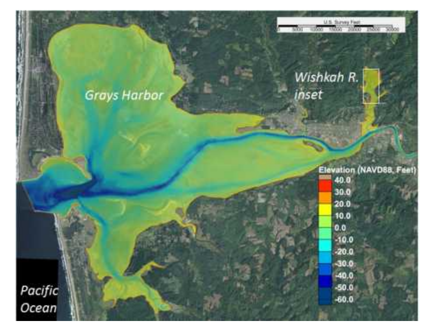
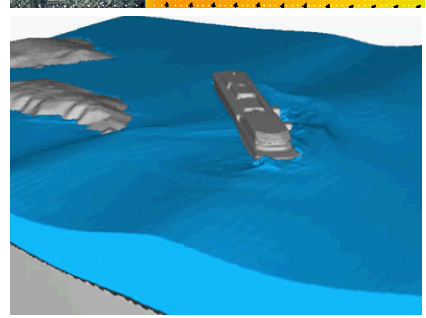
Wind and Water Research Program



SNL may have better overview image, Kelley will look into it







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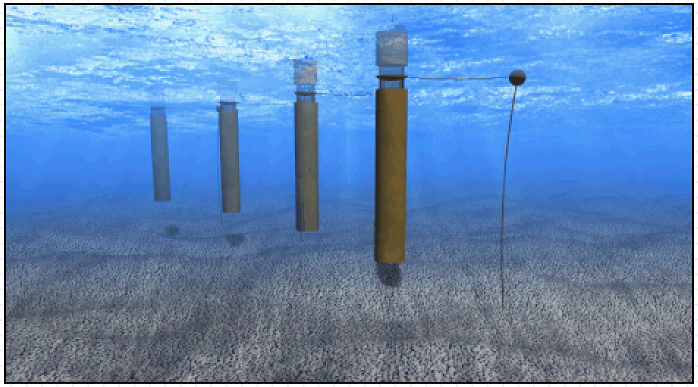
Introduction

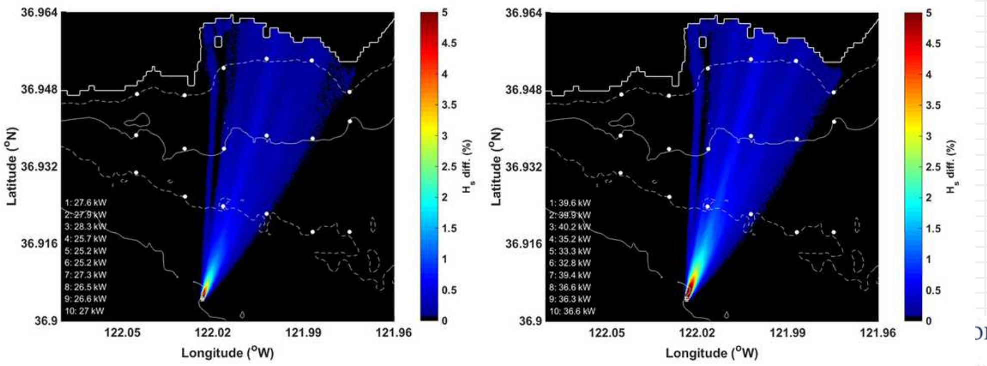
In order for wave energy to be commercially viable, Wave Energy Converters (WECs) will be deployed in arrays

Conduct Environmental Assessment, proving little to no environmental impact

Limited field data to assess potential WEC-Array impacts.

Must rely on numerical modeling to assess potential impacts





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WEC-Array Wave Modeling

Folley et al. (2012) reviewed suitability of numerical modeling techniques for different purposes

- Found no single best technique for WEC-Array

Model Types:

- Potential Flow
- Boussinesq
- Mild-Slope
- Spectral
- Computational Fluid Dynamics

Potential Applications:

- Localized Effects
- Dynamic Control
- **Energy Production Estimates**
- **Environmental Impact**

Spectral Wave Models	
Task	**Suitability [1]**
Potential EIAs	Highly Suitable
Annual Energy Prod.	Moderately Suitable

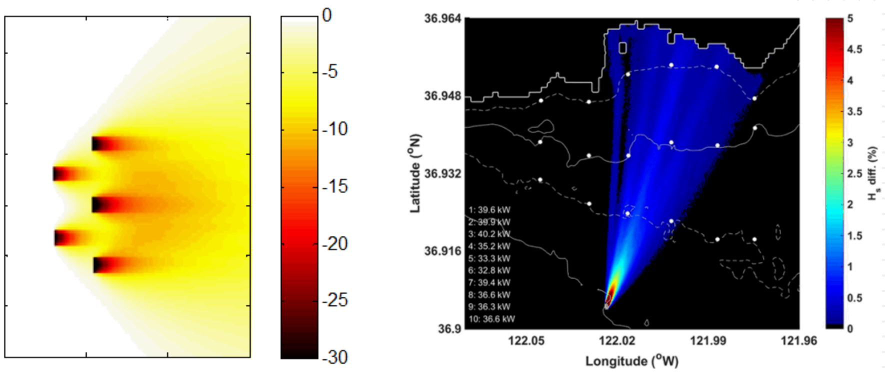
1. Folley et al. (2012)

Existing Spectral Wave Models

- SWAN – Simulating Waves Nearshore
  - Delft Institute of Technology
  - Open source at time of project startup
- TOMAWAC
  - TELEMAC-based Operational Model Addressing Wave Action Computation
  - Recently open source

Model Characteristics:

- Tracks the propagation of wave energy spectra
- Lab scale to global scale wave modeling



- Obstacles: **Constant transmission coefficient** for all frequencies, Kt.

WEC wave transmission is variable

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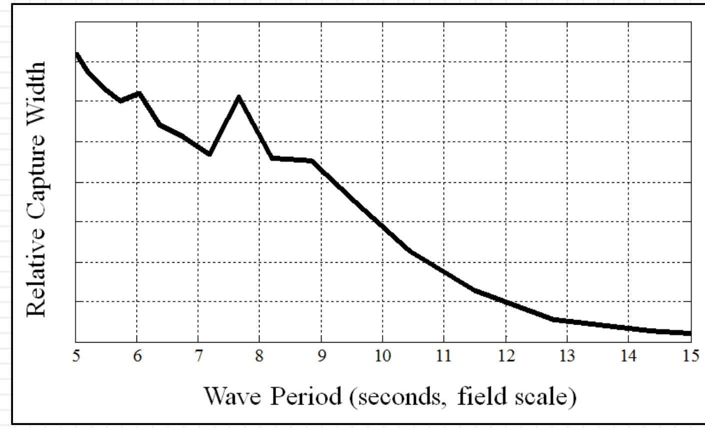
Background Summary

- Provide an open source, publicly available, validated code that can parameterize WEC physics
- Various methods of modeling wave farms (BEM/spectral models/time-domain/etc…)
  - Smith (2012), Child (2013) , Silverthorne (2011)
- Spectral wave models used to evaluate large areas with varying bathymetry, including nearshore
- Simulating WAves Nearshore (SWAN), an open source spectral code developed by TU Delft
- SWAN currently models WECs as obstacles with constant transmission coefficients (Kt)
- WECs extract wave energy at variable levels dependent on wave period and height

SNL-SWAN v1.0

- Release Date: Dec, 2014
- Incorporates frequency variable obstacle transmission
- Inputs:
  - WEC Power Matrix, or
  - Relative Capture Width
  - *Obtained numerically or experimentally*
- New method of determining Kt. Obstacle energy sink in the SWAN spectral action balance equation
- Preliminary validation conducted (METS, 2014)
- Users provided feedback



$$\left(\frac{1}{\Delta t} + \left(D_{x,1} + D_{x,2}\right)c^{+}_{x,i,,j} + \left(D_{y,1} + D_{y,2}\right)c^{+}_{y,i,,j}\right) N^{+}_{i,,j} - \frac{N^{-}_{i,,j}}{\Delta t} - D_{x,1}\left(c_x \boldsymbol{K_{t,1}}^{\boldsymbol{2}} N\right)^{+}_{i-1,j} - D_{y,1}\left(c_y \boldsymbol{K_{t,1}}^{\boldsymbol{2}} N\right)^{+}_{i-1,j} - D_{x,2}\left(c_x \boldsymbol{K_{t,2}}^{\boldsymbol{2}} N\right)^{+}_{i,j-1} - D_{y,2}\left(c_y \boldsymbol{K_{t,2}}^{\boldsymbol{2}} N\right)^{+}_{i,j-1} = S^{+}_{i,j}$$

$$K_t^2 = 1 - \frac{P_{Absorbed}}{P_{Incident}} = 1 - RCW$$

Update to SNL-SWAN v1.1

- User feedback helped determine new model features in development:
  - WEC Power Output Estimate File
  - Directional Dependence
  - Frequency Dependent Reflection Coefficient
  - WEC Power Matrix Implementation
- Release of v1.1: Oct 2015

SNL-SWAN Power Absorption

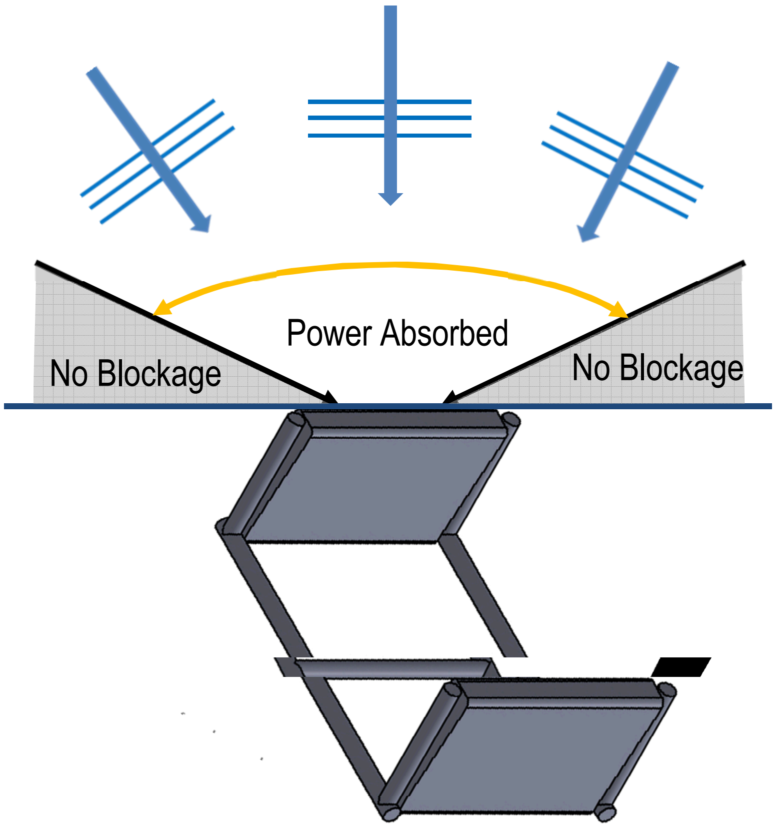
- Wave power removed from wave field in SNL-SWAN model at each obstacle (WEC) face.
  - Does not account for WEC-WEC interaction (i.e. q-factor = 1.0)
- Initially output in as part of model Print file, now is output as separate data file (Power_ABS.out)
- Conceptual-level Annual Energy Production

```
Power absorbed by obstacle   1 =  172152.2968750 W
Power absorbed by obstacle   2 =  172150.4843750 W
Power absorbed by obstacle   3 =  172149.5312500 W
Power absorbed by obstacle   4 =  153264.1875000 W
Power absorbed by obstacle   5 =  152004.9062500 W
```

Example Stationary Power Output File Format

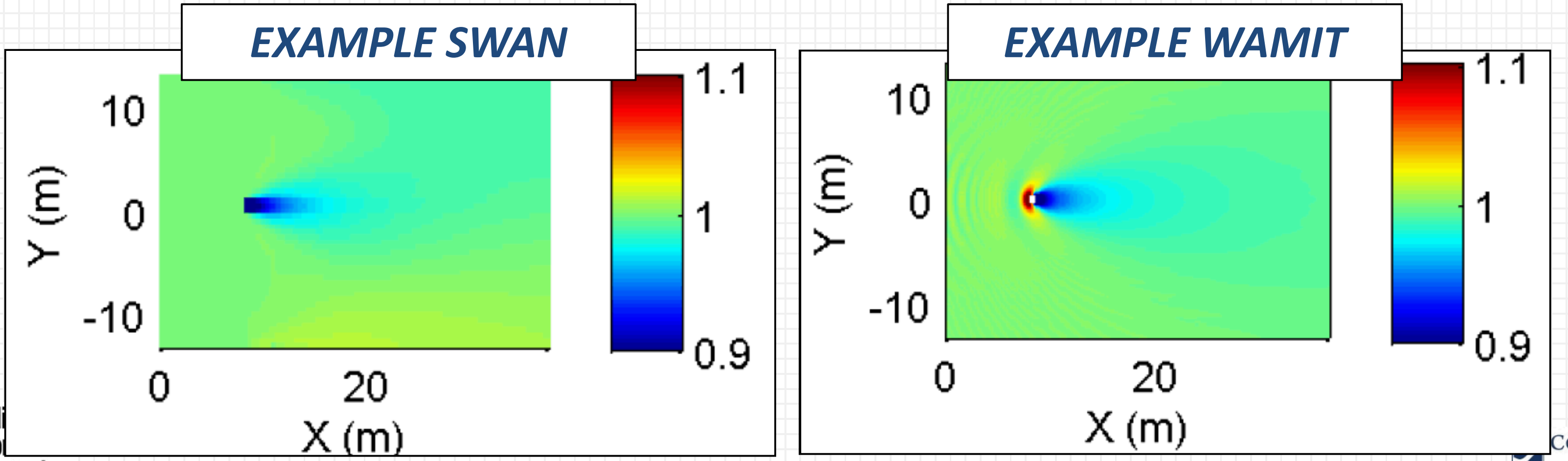
Binary Directional Dependence

- SWAN obstacles only attenuate the power transport normal to an obstacle line, resulting in an implicit cosine dependence on wave direction
- SNL-SWAN v1.1 will enhance directional dependency by incorporating a binary limitation on power extraction/obstacle transmission coefficients.
- At wave directions outside the WEC absorption criteria, transmission will be 100% (absorption 0%).



Frequency Dependent Obstacle Reflection

- Other factors than absorption can be a relatively significant contributor to reducing wave heights in the lee of a WEC array in certain wave climates.
- Goal: Parameterize the re-distribution of waves interacting with WECs (such as scattering) in SNL-SWAN
  - Not attempting to accurately simulate interactions between WECs on a small scale
- Details on specular or diffuse reflection not yet determined



Model Feature Update Summary

– **WEC Power Output Estimate File**

– **Directional Dependence**

– **Frequency Dependent Reflection Coefficient**

– **Power Matrix Implementation**

Example Model Implementation

- **Model case using Power Matrix as Input**
- **Two (2) methods of populating Matrix**
  - **Regular Waves**
  - **Random wave sea states**

INPUT	PARAMETER
WECS	10
Spacing	6 Diameters
Location	Santa Cruz, CA
Hs	1.7 meters
Direction	205 Degrees From North
Tp	12.5 seconds
OBCASE	#1, #3
DEVICE	Idealized floating three-body oscillating flap-type

Example Model Implementation

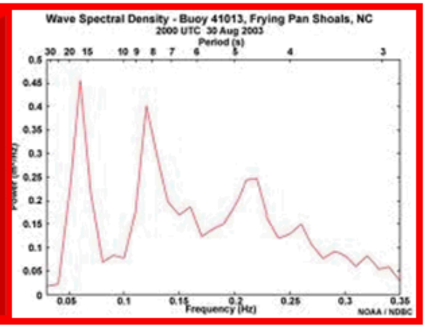
- **Model case using Power Matrix as Input**
- **Two (2) methods of populating Matrix**
  - **Regular Waves**
  - **Random wave sea states**

<u>Obcase 1</u> *Populated with Random Waves*

Wave Period (Tp)

Wave Height (Hs)

MEAN	3	4	5	6	7	8	9	10	11	12	13	14	[illegible]	16	17
0.5	4.44	5.07	7.97	12.15	16.77	17.14	11.94	9.16	6.57	4.39	4.00	3.00	2.86	1.95	1.71
1	16.65	19.00	29.48	46.94	56.61	52.38	37.14	28.73	19.84	16.62	12.94	[illegible]	7.29	7.40	4.49
1.5	0.00	41.54	63.14	92.37	110.74	109.49	64.96	55.91	38.49	29.09	22.06	[illegible]	12.74	11.21	11.50
2	0.00	66.29	99.03	150.67	200.97	164.91	105.27	85.30	58.63	52.31	[illegible]	28.76	24.22	19.31	17.57
2.5	0.00	0.00	160.23	241.82	261.83	226.36	166.20	117.65	83.09	69.87	[illegible]	39.24	28.51	26.20	23.73
3	0.00	0.00	212.52	319.26	372.09	327.17	210.96	151.98	116.43	93.66	75.42	66.09	44.81	42.09	30.83
3.5	0.00	0.00	270.15	436.02	503.15	407.75	292.71	203.22	148.33	[illegible]	92.63	74.81	57.97	44.27	41.16
4	0.00	0.00	0.00	553.82	540.26	521.33	355.46	260.73	191.66	144.19	122.78	84.04	81.01	55.80	53.24
4.5	0.00	0.00	0.00	645.46	746.22	586.83	378.72	302.18	[illegible]	189.64	154.41	105.88	89.58	74.26	55.78
5	0.00	0.00	0.00	796.15	926.13	694.67	485.91	341.08	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5.5	0.00	0.00	0.00	939.38	954.73	807.95	603.12	429.61	343.03	231.19	201.49	150.14	120.29	96.75	89.90
6	0.00	0.00	0.00	0.00	1161.42	956.67	642.03	480.81	329.09	289.47	212.26	171.77	145.82	110.89	100.85
6.5	0.00	0.00	0.00	0.00	1476.47	1039.27	702.04	487.62	396.60	311.56	236.66	203.88	153.43	120.26	102.25
7	0.00	0.00	0.00	0.00	1664.93	1197.05	820.77	612.40	465.98	384.59	251.62	222.70	180.55	146.28	131.44
7.5	0.00	0.00	0.00	0.00	1608.45	1407.61	922.63	703.98	508.65	373.47	325.45	229.49	190.53	151.78	149.26



No information about individual wave frequencies

<u>Obcase 3</u> *Populated with Regular Waves*

Wave Period (T)

Wave Height (H)

MEAN	3	4	5	6	7	8	9	10	11	12	13	14	[illegible]	16	17
0.5	4.44	5.07	7.97	12.15	16.77	17.14	11.94	9.16	6.57	4.39	4.00	3.00	2.86	1.95	1.71
1	16.65	19.00	29.48	46.94	56.61	52.38	37.14	28.73	19.84	16.62	12.94	[illegible]	7.29	7.40	4.49
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2.5	0.00	0.00	160.23	241.82	261.83	226.36	166.20	117.65	83.09	69.87	[illegible]	39.24	28.51	26.20	23.73
3	0.00	0.00	212.52	319.26	372.09	327.17	210.96	151.98	116.43	93.66	75.42	66.09	44.81	42.09	30.83
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4.5	0.00	0.00	0.00	645.46	746.22	586.83	378.72	302.18	[illegible]	189.64	154.41	105.88	89.58	74.26	55.78
5	0.00	0.00	0.00	796.15	926.13	694.67	485.91	341.08	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5.5	0.00	0.00	0.00	939.38	954.73	807.95	603.12	429.61	343.03	231.19	201.49	150.14	120.29	96.75	89.90
6	0.00	0.00	0.00	0.00	1161.42	956.67	642.03	480.81	329.09	289.47	212.26	171.77	145.82	110.89	100.85
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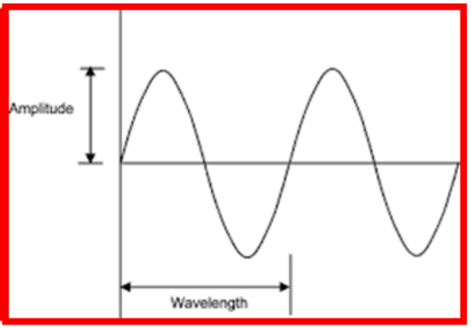
7.5	0.00	0.00	0.00	0.00	1608.45	1407.61	922.63	703.98	508.65	373.47	325.45	229.49	190.53	151.78	149.26



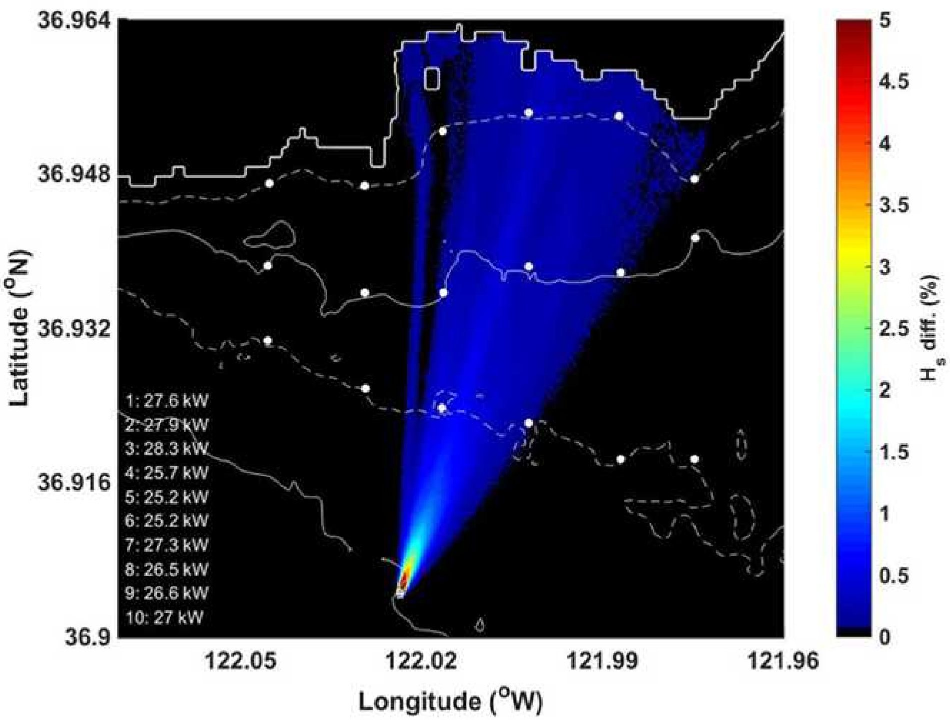
Information about individual wave frequencies

Example Implementation Result

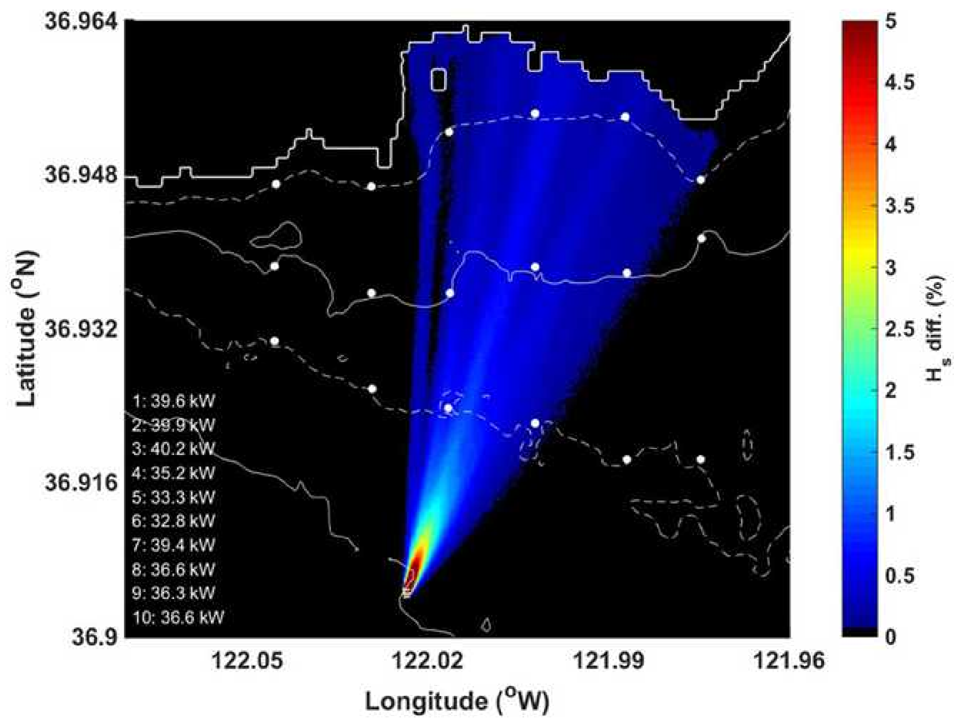
Obcase 1: Constant Transmission Coefficient, populated with random waves
Obcase 2: Variable Transmission Coefficient, populated with regular waves

Example case: Assuming different population/application methods, Obcase 3 results in more wave attenuation. Results will vary on wave climate and device.

Obcase 1



Obcase 3



Summary

- SNL-SWAN v1.1 is intended to assess potential environmental impacts, and conceptual level annual energy production estimates.
  - Planned release date: Oct, 2015 (Github, Sandia Website)
- Based on user feedback on SNL-SWAN v1.0, new features are in development for SNL-SWAN v1.1.
  - Conceptual Level WEC power output file
  - Scattered/reflected wave parameterization
  - Binary obstacle transmission directional dependence
- SNL-SWAN may parameterize WECs with:
  - Power Matrix (random waves → constant Kt)
  - Power Matrix (regular waves → variable Kt)
  - RCW curve (random/regular waves → constant or variable Kt)
- Correct implementation of WEC parameterization is key. Implementation of different WEC parameterizations can have impact on results.

Acknowledgements

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