COMMISSION OF THE
EUROPEAN COMMUNITIES

Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

Grant agreement number: 213380

D2.7 Protocols for wave and tidal resource assessment

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D2.7

Protocols for wave and tidal resource assessment

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Executive Summary

A wave or tidal resource assessment should provide a quantified estimate of the available energy and an assessment of the operating and survival characteristics of a specific site. This process may be performed through a combination of in-situ measurements and numerical modelling. Key elements described in this protocol include: measurement and raw data analysis; key descriptive parameters; numerical modelling guidance; assessment of extreme conditions; and the identification of constraints on development. The protocol does not consider the interaction of the device with the environment or potential interference due to multiple devices located at one site.

The main drivers for the resource assessment process to be considered are: assessment of the available *energy resource*; information for *engineering design* such as wave and current loading on structures; information for planning and implementing *marine operations* such as installation, operation and maintenance.

The scope and detail of a resource assessment is dependent on the stage of the project. *Early stage* resource assessment is conducted to establish first order resource characteristics. This *resource characterisation* process may be conducted at geographical scale to identify specific regions suitable for a more detailed *site assessment.* The analysis conducted under this *project development* phase should establish detailed site characteristics for assessing the exploitable potential of the site along with information for site specific engineering design. Finally the *operation* phase of the project will involve the assessment of operating conditions for benchmarking purposes and possibly short term resource forecasting.

Key parameters for both wave and tidal resource assessment are outlined. These may be provided by a combination of numerical modelling and measurement. Models and measurement devices shall be validated and proven.

Wave Resource

Early Stage: Resource characterisation should provide an estimate of the annual resource along with quantification of the seasonal and inter-annual variability. This assessment should be conducted over a period of 10 years with the data provided by hindcast modelling and/or existing data.

Project Development: Site assessment provides detailed information on a deployment site including information on spectra and extremes. This process should be based upon data covering a period of 10 years which in the vast majority of cases is likely to be supplied through numerical modelling. It is required that the numerical modelling programme be supported by measurements made at the deployment site. The extreme sea states at specified return periods should also be assessed.

Operation: This phase of the project is likely to be a continuation of the site assessment conducted during the project development phase. In-situ measurements may be used for benchmarking purposes while the modelling programme may be used for forecasting energy production in the short term.

Tidal Resource

Early Stage: Resource characterisation should estimate the peak resource along with the seasonal variability. This may be achieved using tidal stream atlases or shelf tidal models. Coarse grid models and area models may also be utilised.

Project feasibility and development: At these project stages the site specific resource is quantified with detailed tidal stream information and detailed tidal level. Modelling using shelf model inputs and detailed bathymetry shall be conducted with Acoustic Doppler Profiler (ADP) measurements providing data for model calibration and validation. Wave modelling may be necessary to inform device survival studies.

Operation: Simultaneous measurement of device output and the resource may be required for benchmarking purposes. If short term forecasting is required the model used during the project development phases may be applied with periodic re-calibration from the measurement programme.

Contents

1 Introduction

1.1 Need for resource assessment

Resource assessment should provide

- A quantified estimate of the available energy resource;
- An assessment of the operating and survival characteristics of a specific site.

There are *three* main drivers for wave and tidal resource assessment for marine renewable energy developments:

(i) *The Energy Resource:* A primary focus is to ascertain the level of resource, at an appropriate level of confidence, through the development of a project. This information will provide the basis for a specification of power produced over the length of the project. This information will be necessary to *device developers, investors, utilities and government (both national and local).*

(ii) *Engineering Design:* Although the major design considerations for any device will be decided it is probable that individual sites may require adaptation of the base design. Certainly, issues of wave and current loading will have to be considered on a site-by-site basis (e.g. for the design of the moorings). This information will be necessary to *designers, constructors, insurers and "classifiers".*

(iii) *Marine Operations*: For a fully operating project the wave/ wind and tidal characteristics are necessary to predict the installation & maintenance strategy which for a large farm in a high energy site may be highly limiting. This information will be necessary to *designers, constructors, marine contractors, insurers and "classifiers".*

A project can be broken down into the stages illustrated in Figure 1.1. The level of assessment needed will vary with the stage of the project and the purpose of the assessment.

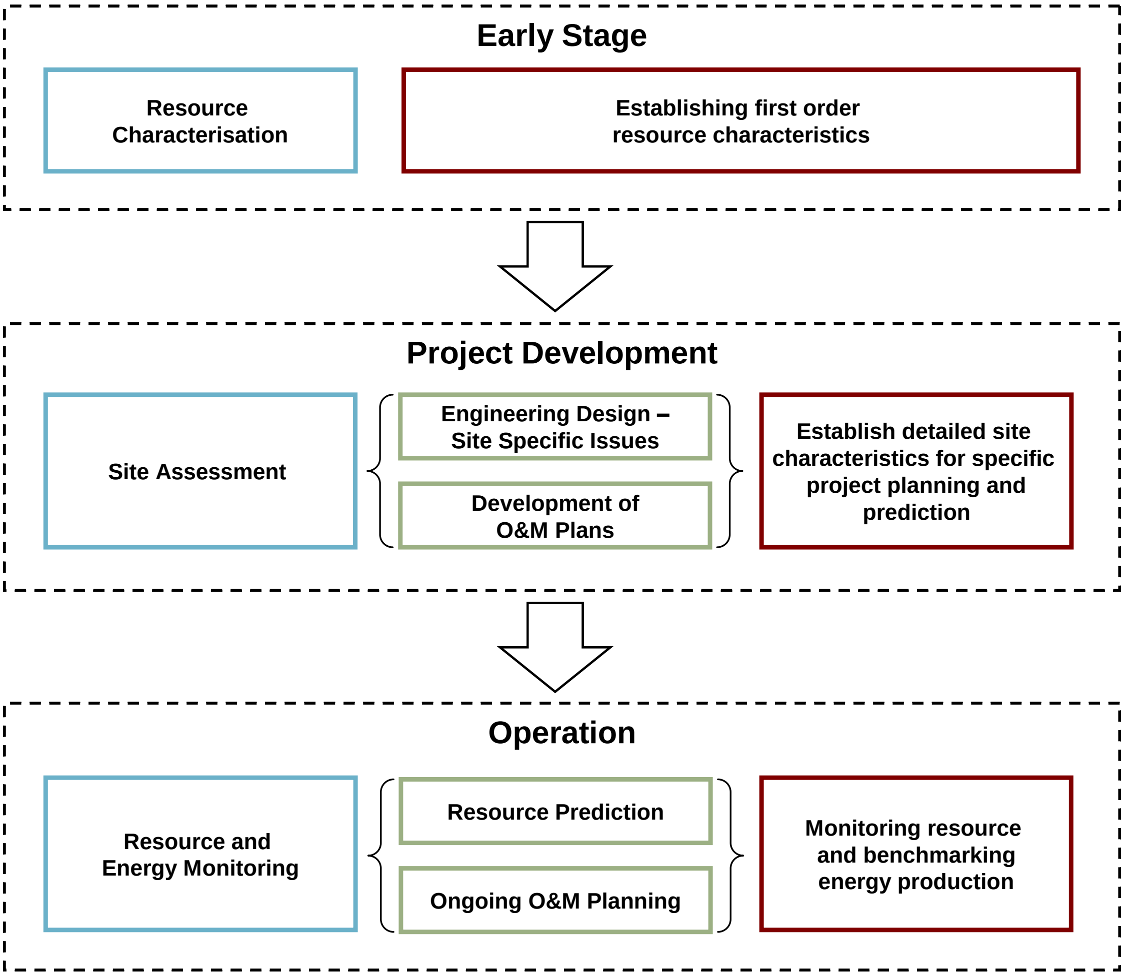


Figure 1.1 The stages of a marine energy project, and how resource assessment will be utilised during each stage.

1.2 Scope of this document

Resource assessment can be performed through in-situ measurements or numerical modelling. This document will give recommendations for the application of both these methods for wave and tidal renewable energy developments.

This document will consider the following aspects of resource assessment:

- Measurement and raw data analysis
- Key descriptive parameters
- Guidance on numerical modelling
- Assessment of extremes and device survivability
- Identification of constraints on development at a specific site
- Reporting

This document will not consider:

- Potential interference and impact on resource due to multiple devices located at a site. Refer to the 'IIC - Deployment and Performance Assessment of Multi-Megawatt arrays' for further information
- Any aspect of environmental assessment or monitoring. Refer to 'IB - Environmental Assessment' for further information.

This document represents the contribution of 24 partners including scientists, engineers, device developers and standards agencies and has been developed from widespread international engagement. There are several other documents that cover similar issues which have been used to inform this work. For further reference please see:

EMEC – Assessment of Wave Energy Resource, 2009.
EMEC – Assessment of Tidal Energy Resource, 2009.
DTI – Preliminary Wave Energy Device Performance Protocol, 2007

Much of the background information supporting this document can be found in the appropriate sections of the following EquiMar deliverables:

- D2.2 – Wave and tidal resource characterisation
- D2.3– Application of numerical models
- D2.4 – Intercomparison of wave models
- D2.5 – Intercomparison of tidal models
- D2.6 – Assessment of extremes

2 Wave Resource Characterisation and Site Assessment

2.1 Overview

Section 2 of the protocol will focus on resource assessment for wave energy developments. Figures 2.1 to 2.3 summarise the methods used for resource assessment at each stage of the process for a wave energy project and the intended outputs. Figure 2.4 provides an at-a-glance summary of the methods used for wave resource assessment, the data that can be obtained through these methods, and the applications for this data.

2.1.1 Early Stage Assessment

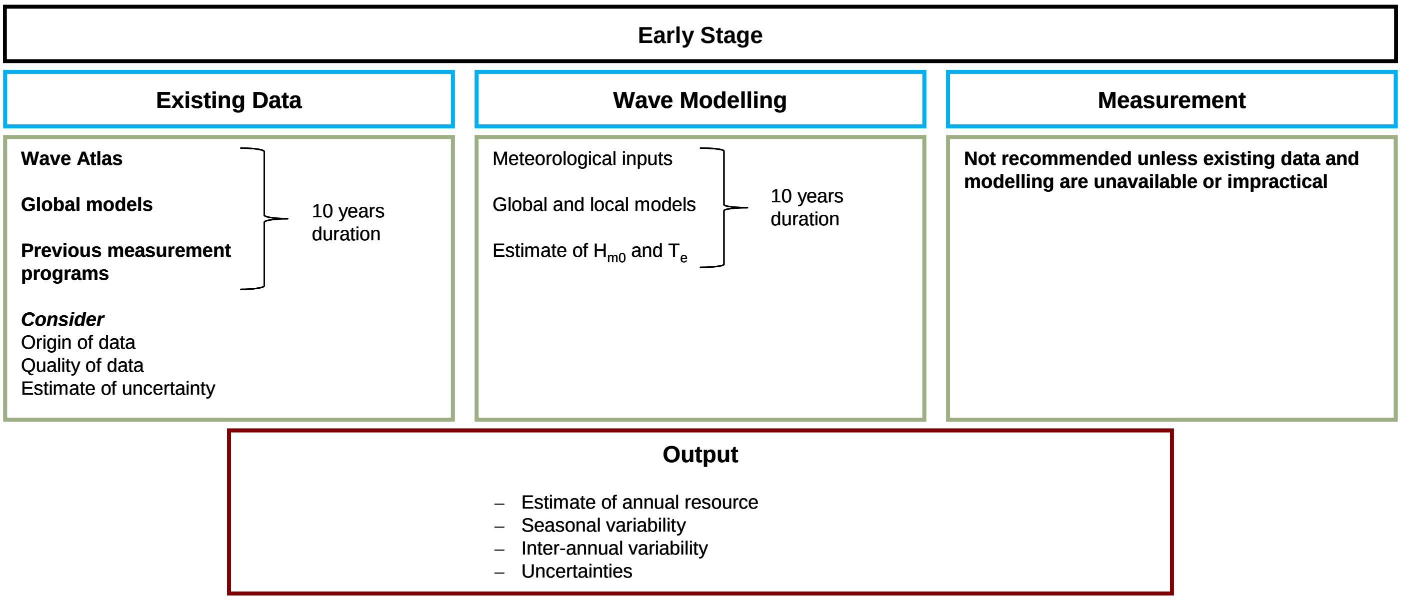


Figure 2.1 Resource assessment for the 'early stage' aspect of a wave energy development.

Early stage *Resource Characterisation* is concerned with providing a first-order assessment of the available resource over a particular area (geographic scale). This process will primarily rely on existing data such as wave atlases and historical measurement programmes. It is recommended that a minimum of 10 years data is used to understand the inter-annual variation of the resource. Obtaining data of this duration will usually require a numerical modelling programme to transform the output of a global model (or more rarely, a measurement programme) to the region under consideration. The output from the process is a high level estimate of the annual resource with wide spatial coverage and low spatial resolution. The process should include an estimate of seasonal and inter-annual variability. Sources of uncertainty should be identified and quantified where possible.

2.1.2 Project development assessment

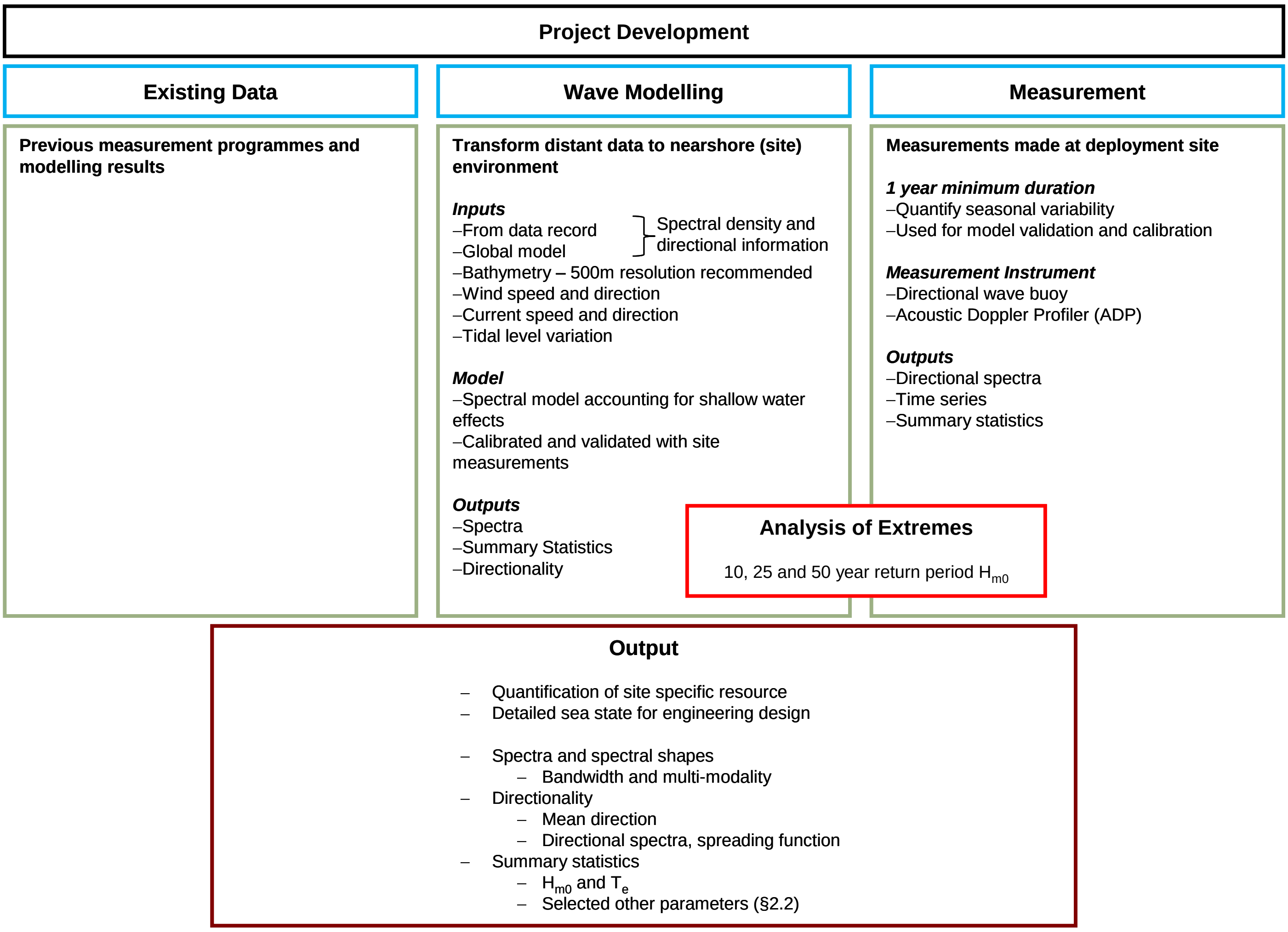
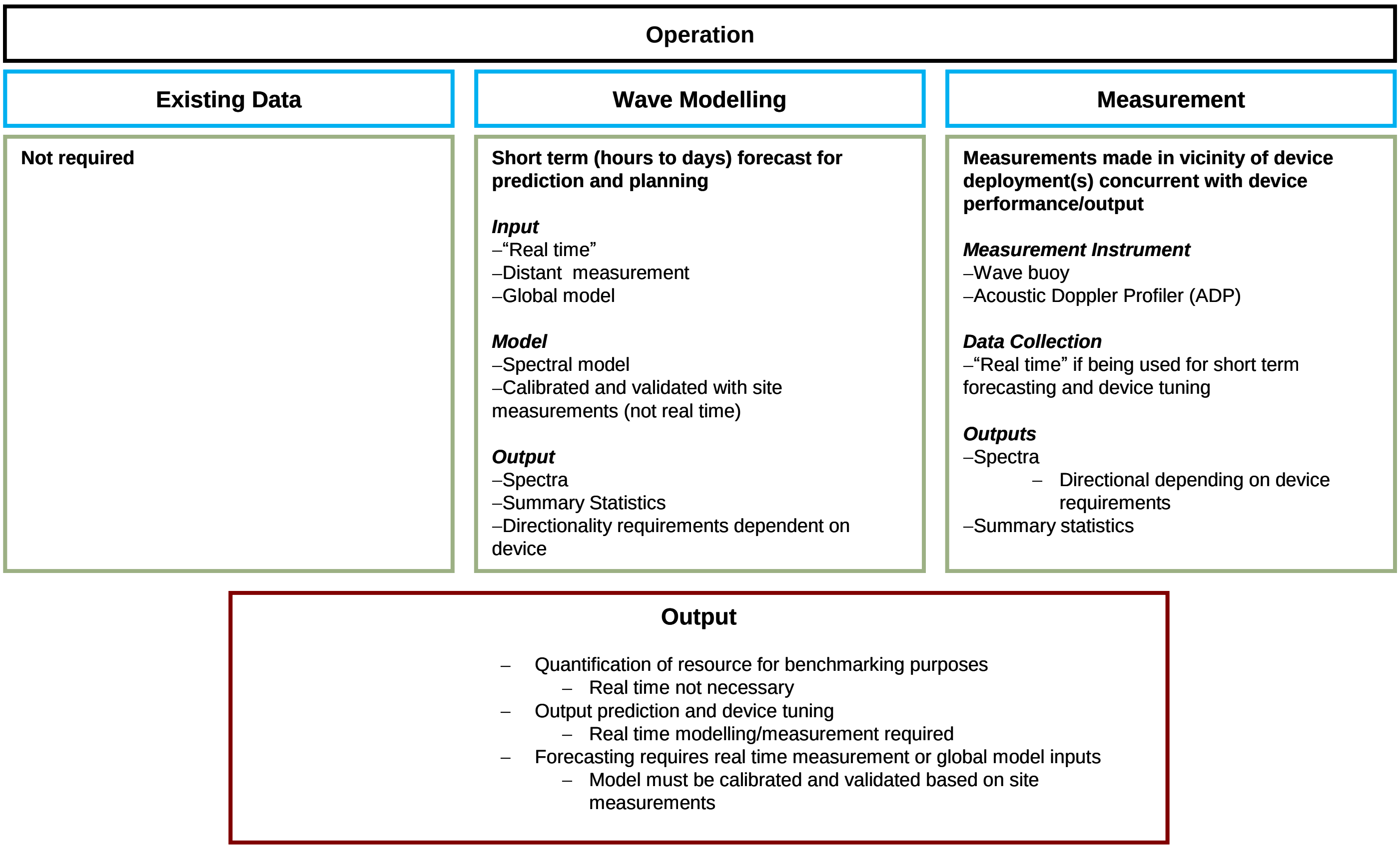


Figure 2.2 Resource assessment for the 'project development' stage of a wave energy development.

Site Assessment during the project development stage is conducted to establish detailed characteristics at a specific site. This will typically involve a coordinated numerical modelling and physical measurement programme. The modelling programme is conducted to supply extended temporal and spatial coverage at the site through transformation of distant, reliable, data. Typically this input data will be obtained from a global model or offshore measurement (if available). An in situ measurement programme will provide data to characterise the site and to calibrate/validate the numerical model. The output of the site assessment process will include a detailed characterisation of the sea states as well as high level summary parameters.

2.1.3 Operational assessment



Operation

Existing Data

Not required

Wave Modelling

Short term (hours to days) forecast for prediction and planning

Input
–"Real time"
–Distant measurement
–Global model

Model
–Spectral model
–Calibrated and validated with site measurements (not real time)

Output
–Spectra
–Summary Statistics
–Directionality requirements dependent on device

Measurement

Measurements made in vicinity of device deployment(s) concurrent with device performance/output

Measurement Instrument
–Wave buoy
–Acoustic Doppler Profiler (ADP)

Data Collection
–"Real time" if being used for short term forecasting and device tuning

Outputs
–Spectra
  – Directional depending on device requirements
–Summary statistics

Output

- Quantification of resource for benchmarking purposes
  - Real time not necessary
- Output prediction and device tuning
  - Real time modelling/measurement required
- Forecasting requires real time measurement or global model inputs
  - Model must be calibrated and validated based on site measurements

Figure 2.3 Resource assessment for the 'operations' stage of a wave energy development.

The resource assessment requirements during the operational phase will be dependent on the specific demands of the deployment. As a minimum standard it is expected that the resource will be measured concurrently with device output and performance for benchmarking purposes. This data may also be used for device tuning purposes. If short term forecasting is required for production and management purposes a continuous modelling programme will be necessary. This model will use either offshore measurement or a global model as an input.

2.1.4 Assessment summary

The requirements for the *Early*, *Development* and *Operation* stages of a project are summarised in Figure 2.4. The source of this information (modelling and/or measurement) is also indicated.

				Early	**Development**			**Operation**		
		Modelling	Measurement	Resource Characterisation	Engineering Design	Site Assessment	Operational Planning	Level of Resource	Ongoing Operation & Maintenance	Prediction & Tuning
Summary statistics		•	•	✓	✓	✓	✓	✓	✓	
Spectra	Directional	•	•		✓	✓		✓		✓
	Non-directional	•	•		✓	✓		✓	✓	✓
Elevation Time series	Directional		•		✓					✓
	Non-directional		•		✓					✓
Extremes		•			✓	✓				
Long-term temporal variation		•		✓		✓				
Mean and maximum currents		•	•	✓	✓	✓	✓		✓	✓
Tidal level		•	•	✓	✓	✓	✓		✓	
Wind (model input)		•	•	✓		✓	✓		✓	✓

Figure 2.4 Summary of methods used and data required for resource assessment at each stage of a wave energy development.

2.2 Key Wave Parameters

The primary output of a wave resource assessment shall be parameters that describe the level of resource throughout the life of a project. The key parameters that should be obtained through the resource assessment are described in Table 2.1 below. All parameters should be calculated through spectral analysis methods (see Section 2.2.2). Time domain analysis is not recommended for calculation of key parameters where a spectral alternative is available. The process of obtaining parameters is illustrated in Figure 2.5.

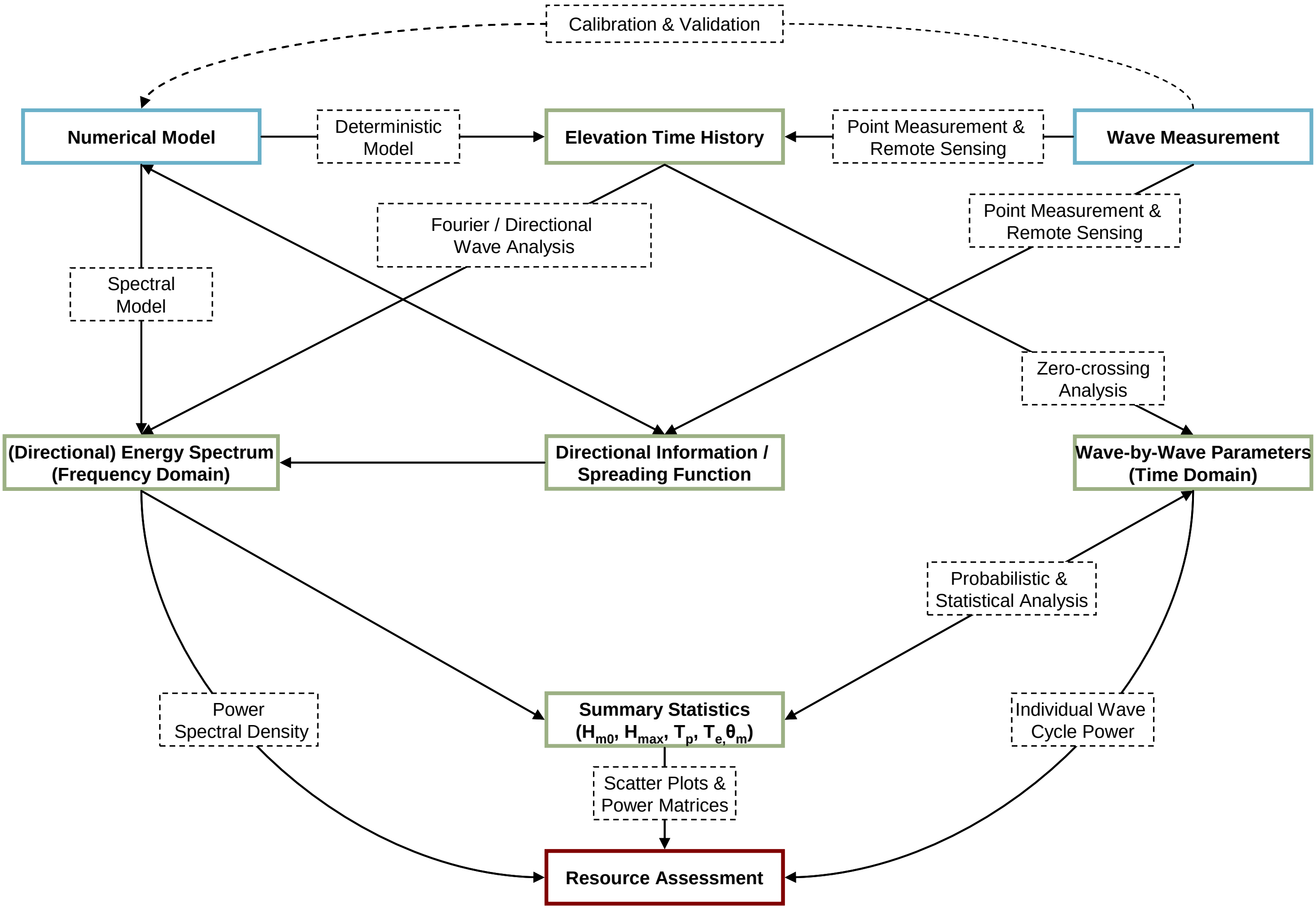


Figure 2.5 Methods for obtaining key parameters from resource assessment

2.2.1 Calculated parameters

The parameters outlined in Table 2.1 should be considered in a resource assessment. Those highlighted in bold shall be mandatory. These parameters have applications for:

- *Wave power level* - Accurate quantification of H_{m0} and T_e is essential for estimation of the wave power level.
- *Device performance* - Understanding the directional characteristics of the site is important for devices for which the sea's directionality influences the energy production process. It is also key to predicting array performance.
- Quantifying the spectral bandwidth v allows for assessment of device production where performance across a range of frequencies is known , e.g. a sea with a narrow bandwidth will contain more energy concentrated close to the peak period).
- *Device Survivability* - Quantification of H_{m0} over an extended period of time (minimum 10 years duration from modelling) is required for the assessment of extreme operating conditions.

Definitions of the mandatory parameters in terms of spectral moments are given in Table 2.2. See Section 2.3.2 for the method of calculation of spectral moments.

2.2.2 Site characteristics

The following site characteristics shall be recorded at the start of the project development stage of a wave energy project:

1. *Wind* characteristics of the site should be established through an ongoing measurement programme. Offshore measurement at the site is recommended, but shoreline measurement is acceptable if this is not possible. Output from meteorological models should be used for numerical modelling studies.
2. *Maximum current velocity* at the site shall be established through a short-term (~1 month) measurement programme using an Acoustic Doppler Profiler (ADP). When currents are dominated by tidal effects, tidal modelling software may be used in preference to measurement.
3. *Tidal range* at the site shall be established using measurement or tidal software.
4. *Bathymetry* at the site shall be established through a bathymetric survey (existing survey data contained in e.g. Admiralty charts are acceptable).

Table 2.1 Key wave parameters obtained through resource assessment with mandatory outputs highlighted in bold.

Name	**Symbol**	**Units**	**Method of calculation (see Section 2.3.2)**	**Notes**
Significant wave height	**H_{m0}**	**[m]**	**Spectral**	Statistical measure of the largest wave heights in an irregular sea state. In time domain calculations, it is defined as $4\cdot\sigma_{\eta}$, where σ_{η} is the standard deviation of sea surface elevation. In frequency domain, it is expressed as $4\sqrt{m_o}$, where m_o is the zeroth moment estimated from a wave spectrum. H_{m0} is approximately 5%-10% larger than $H_{1/3}$ (IEC definitions). H_{m0} is fundamental in calculating power. The *n*th spectral moment is defined by $m_n = \int_0^\infty S(f)\, f^n\, df$, hence $m_0 = \int_0^\infty S(f)\, df$
	H_s or $H_{1/3}$	[m]	Time domain	
Maximum wave height	H_{max}	[m]	Time domain	Height of the largest wave measured over a defined period of time.
Maximum crest height	Cr_{max}	[m]	Time domain	Largest wave crest height recorded over a defined period of time. Crest height is the vertical distance between the crest of a wave and the still water level.
Mean wave period	T_{01}	[s]	Spectral	A measure of the mean time between wave cycles obtained from the energy spectrum [see Table 2.2]
	T_{02}	**[s]**	**Spectral**	
Zero crossing wave period	T_z	[s]	Time domain	A measure of the mean time between wave cycles obtained from the sea surface elevation record (equivalent to T_{02})
Energy wave period	**T_e**	**[s]**	**Spectral**	The period of a monochromatic wave (height H) which contains the same mean energy as the irregular sea ($H_{m0}=\sqrt{2}$ H) during T_e., T_e is fundamental in the calculation of wave power [see Table 2.2]
Peak wave period	T_p	[s]	Spectral	Inverse of the most energetic frequency of the energy spectrum ($T_p = 1/f_p$)
	T_{pc}	**[s]**	**Spectral**	Statistical calculation of peak period from spectral moments
Mean direction	**θ_m**	**[^{o} or rad]**	**Spectral**	Mean direction of propagation of wave energy calculated from the directional wave spectrum
Group velocity	**C_g**	**[m/s]**	**Time domain**	Wave Group velocity, expressed as a function of water depth and wave number *k* $(= 2\pi/\lambda)$.

				$c_g = \frac{1}{2} c_p \left(1 + \frac{2kd}{\sinh 2kd}\right);$ where $c_p = \left(\frac{g}{k} \tanh kd\right)^{1/2}$ c_p = wave phase velocity k = wave number corresponding to energy period T_e d = water depth
Wave power	***P***	[W/m]	Spectral	The power in a sea state transported per unit crest length in unidirectional se In deepwater, $P = \rho g^2 / 4\pi \quad H_{m0}^2 / 16 \; T_e$ For other water depths, $P = \rho g \int S(f) \, c_g(f) \, df$
Directional spread	σ	[^{o} or rad]	Spectral	Represents the degree of directional energy concentration. Takes a peak value around T_p.
Spectral bandwidth	**ν**	**[-]**	**Spectral**	A measure of the width of the spectrum, defined as the normalised radius of gyration of the spectrum about its mean frequency. For a Pierson-Moskowitz spectrum **ν =** 0.425. For a JONSWAP spectrum with γ = 3.3, σ_a = 0.7, σ_b = 0.9, **ν =** 0.39.

2.3 Wave Measurement

2.3.1 Measurement process

Need

A physical measurement programme shall be established during the development and operational stages of a wave energy project. The type of data to be obtained (summary statistics, spectra or time series) shall be determined by the stage of the project and the purpose for which it is required. The scale of the measurement programme shall be determined by the size of the wave energy development. An individual WEC deployment should require a single upstream measurement device. An array deployment may necessitate multiple measurement devices to quantify variations in the resource over the site. This shall be informed by numerical modelling and the complexity of the site.

Time series data should be recorded and archived for validation. Periodic summary reports including metadata shall be produced at appropriate intervals. For buoy measurements where data are transmitted to shore, reports should be produced on a monthly basis. However, when data recovery must be performed at sea because transmission is not possible, longer periods between reports are acceptable.

Data types

Summary statistics are essential to provide an overview of the device performance, and shall be calculated from a suitable wave spectrum. Wave height and period parameters are mandatory as the prime parameters for calculating mean power. For more detailed development and operational activities, summary statistics alone are insufficient.

Spectra provide fundamental methods for calculating the key parameters including wave power. They shall be calculated from time series data (§2.3.2) in either a directional or non-directional form. Spectra shall always be utilised when the purpose of measurement is engineering design and marine operations. Full directional spectra should also be used to identify mixed sea states.

Time series data present time-ordered records of wave motion. Non-directional data is presented as a record of sea surface elevation, while directional datasets additionally include horizontal displacements/accelerations. Time series data are required for spectral analysis, but should not be used for direct calculation of parameters.

Methods of measurement

All physical wave measurements should be performed with either a wave measurement buoy or an acoustic Doppler profiler (ADP). Additional measurement methods including remote sensing and pressure transducers are not recommended because of their lack of validation for resource assessment purposes.

Wave buoys are designed for surface measurements in water depths greater than 10m. *ADPs* are usually seabed mounted and suitable for wave measurement in depths of 5 – 60m. They will also provide measurements of current.
See D2.2 for further description of wave measurement devices.

The following operational requirements shall be addressed:

- Calibration of the measurement device shall be performed both pre-deployment and post-recovery
- For buoy measurement, the mooring system shall be demonstrated to provide minimal effect on the buoy motion
- For ADP measurement, an anti-trawl seabed mount should be used to minimise risk of loss or damage due to fishing vessels
- The minimum sampling frequency of the measurement device shall be 1 Hz, although a higher sampling frequency is preferable where operational issues permit
- An ongoing maintenance programme shall be established for long-term deployments.

Quality control

The adoption of adequate data qualification and quality control is mandatory. A suitable description of QC may be found in QARTOD (Quality Assurance of Real-Time Ocean Data, http://nautilus.baruch.sc.edu/twiki/bin/view). The data provider shall demonstrate that their methods are robust in dealing with foreseeable quality control issues and that the data is fit for the intended use. The principal QC process is to confirm whether the acoustic quality of the ADP measurements composing an ensemble average is satisfactory.

A description of the quality control methods shall be included with any data acquisition and analysis report. A description of the experience and expertise of the data providers may be included to provide confidence in the process. Additional reporting may include a description of any issues relating to the data that have been identified.

Metadata

In the reporting of wave measurement data, the following metadata shall be provided:

- Time stamp for each record in accordance with IS0 8601: YYYY-MM-DDThh:mm:ss<time> where *<time>* indicates the offset to UTC (*Z* in the case of no offset).
  Examples:
  2010-10-05T10:00:00Z *10 a.m. 5 October 2010 – no UTC offset*
  2011-04-15T13:30:00+02:00 *1:30 p.m.15 April 2011 – UTC + 2 hours*
- Location of the measurement device in latitude and longitude, measured in decimal degrees. The datum used must be stated.
- Mean water depth of the instrument deployment site.

2.3.2 Methods of analysis

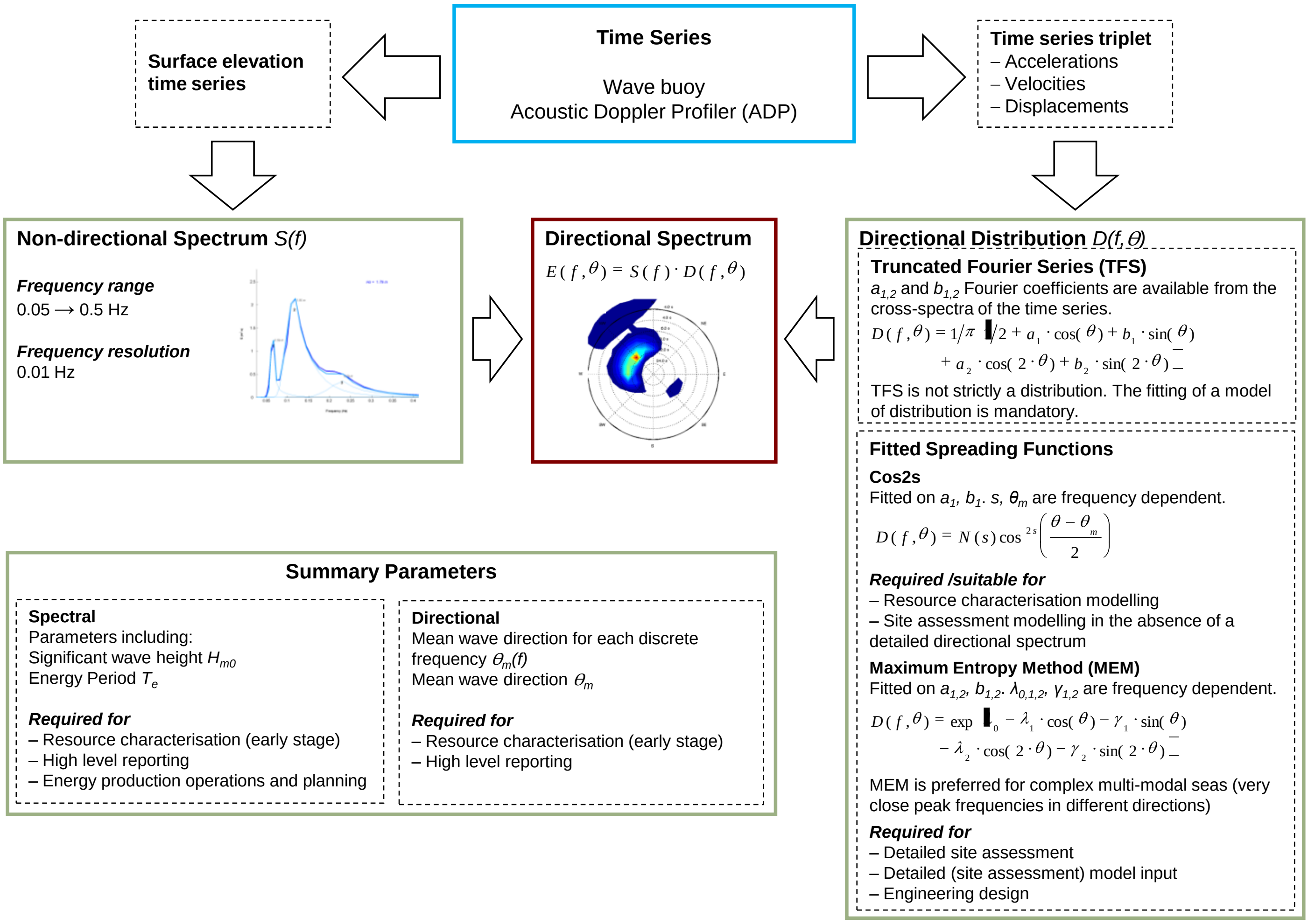
Raw time series data (sea surface elevation for non-directional measurement, elevation and horizontal displacement/acceleration triplets for directional measurements) should be transformed into frequency domain energy spectra for further analysis. The only exception is when the purpose of measurement is to investigate individual wave forms for the purpose of engineering design or device tuning.

Non-directional spectra $S(f)$ shall be produced through Fourier analysis of the sea surface elevation time series. The raw spectrum obtained through Fourier analysis shall be smoothed using a stated method. See D2.2 for further details.

Directional spectra $E(f,\theta)$ should be calculated by multiplying a non-directional spectrum $S(f)$ by a directional distribution $D(f, \theta)$. The directional distribution of a sea state may be described at several levels of detail:

- *Directional distribution for each frequency*: Typically described by the four principal Fourier components for each discrete frequency.
- *Cos2s spreading function*: The spreading value *s* and the principle wave direction calculated with the first Fourier component are given for each discrete frequency. The spreading function is typically used as simplified description of the measured directional distribution or as an input to a numerical model (in the absence of a full directional distribution). If parametric spreading values are used the assumptions supporting this must be reported. If multimodal directional distributions are expected (energy at the same frequency in two different directions), MEM (Maximum Entropy Method, Lygre and Krogstad, 1986) must be used.
- Summary parameters: The high level directional properties may be assessed using the mean wave direction (averaged across all frequencies) and the mean power direction Θ_w. The principle wave direction for each frequency may also be recorded, although this information is difficult to present in an early stage, high-level, resource characterisation.

The application of these directional distributions and parameters are described in Figure 2.6.



Surface elevation time series

Time Series

Wave buoy
Acoustic Doppler Profiler (ADP)

Time series triplet
– Accelerations
– Velocities
– Displacements

Non-directional Spectrum *S(f)*

Frequency range
0.05 ⟶ 0.5 Hz

Frequency resolution
0.01 Hz

Directional Spectrum

$E(f,\theta) = S(f)\cdot D(f,\theta)$

Directional Distribution *D(f,θ)*

Truncated Fourier Series (TFS)

$a_{1,2}$ and $b_{1,2}$ Fourier coefficients are available from the cross-spectra of the time series.

$$D(f,\theta) = 1/\pi\,\left[1/2 + a_1\cdot\cos(\theta) + b_1\cdot\sin(\theta) + a_2\cdot\cos(2\cdot\theta) + b_2\cdot\sin(2\cdot\theta)\right]$$

TFS is not strictly a distribution. The fitting of a model of distribution is mandatory.

Fitted Spreading Functions

Cos2s

Fitted on a_1, b_1. s, θ_m are frequency dependent.

$$D(f,\theta) = N(s)\cos^{2s}\left(\frac{\theta-\theta_m}{2}\right)$$

Required /suitable for
– Resource characterisation modelling
– Site assessment modelling in the absence of a detailed directional spectrum

Maximum Entropy Method (MEM)

Fitted on $a_{1,2}$, $b_{1,2}$. $\lambda_{0,1,2}$, $\gamma_{1,2}$ are frequency dependent.

$$D(f,\theta) = \exp\left[\lambda_0 - \lambda_1\cdot\cos(\theta) - \gamma_1\cdot\sin(\theta) - \lambda_2\cdot\cos(2\cdot\theta) - \gamma_2\cdot\sin(2\cdot\theta)\right]$$

MEM is preferred for complex multi-modal seas (very close peak frequencies in different directions)

Required for
– Detailed site assessment
– Detailed (site assessment) model input
– Engineering design

Summary Parameters

Spectral
Parameters including:
Significant wave height H_{m0}
Energy Period T_e

Required for
– Resource characterisation (early stage)
– High level reporting
– Energy production operations and planning

Directional
Mean wave direction for each discrete frequency $\theta_m(f)$
Mean wave direction θ_m

Required for
– Resource characterisation (early stage)
– High level reporting

Figure 2.6 Calculation of the directional spectrum from raw time series data.

For both directional and non-directional spectral analysis, the following aspects must be considered:

- The maximum achievable spectral frequency is defined by the Nyquist frequency (= $1/f_s$, where f_s is the sampling frequency)
- Lower frequency cut-off should be in the range 0.025 – 0.05Hz and may be dependent on the proprietary measurement system and software used. This shall be explicitly stated in any report.
- Recommended upper frequency cut-off is 0.5Hz
- Recommended frequency resolution is 0.01Hz or better

Key parameters shall be calculated from non-directional spectra using spectral moments. The nth spectral moment is defined as

$$m_n = \int_0^\infty f^n S(f)\,df \qquad (1)$$

The moments m_{-2}, m_{-1}, m_0, m_1, m_2 shall be calculated and reported as a minimum requirement. Caution should be exercised when calculating higher order moments (e.g. m_3, m_4) because they might be unrealistically dominated by high frequency components of the energy spectrum and instrument noise. Table 2.3 defines the key parameters in terms of the spectral moments.

Table 2.2 Definition of key parameters in terms of spectral moments.

H_{m0}	**T_{02}**	**T_e**	**T_{pc}**	**ν**
$4\sqrt{m_0}$	$\sqrt{\frac{m_0}{m_2}}$	$\frac{m_{-1}}{m_0}$	$\frac{m_{-2}m_1}{m_0^2}$	$\left(\frac{m_0 m_2}{m_1^2}-1\right)^{\frac{1}{2}}$

The wave power density level in a directional sea shall be calculated as

$$P_w = \int_0^{2\pi}\int_0^{\infty} c_g(f,d)E(f,\theta)\,dfd\theta \qquad (2)$$

where the group velocity $c_g(f)$ is defined as

$$c_g(f,d) = \frac{g}{4\pi f}\sinh\left(1+\frac{2kd}{\sinh(2kd)}\right)\tanh\left(\frac{2\pi d}{\lambda}\right) \qquad (3)$$

This is a transcendental equation and may be solved iteratively or using an approximate formulation (Fenton & McKee ,1990).

In deep water where $d > \lambda/2$, $c_g(f)$ approximates to $\frac{g}{4\pi f}$, allowing the mean power level to be calculated in terms of key parameters as

$$P_{dw} = \frac{\rho g^2}{64\pi}H_{m0}^2 T_e \qquad (4)$$

This may be used for an initial estimate of power level, but for accurate quantification, Equation (2) should be used.

Spectra should be visually inspected to qualitatively assess the occurrence of multi-modal sea states. If quantitative analysis is required e.g. for detailed engineering design, a number of methods exist for calculating the component sea states of a spectrum, and are described in D2.2.

The mean power wave direction may be expressed as (Pontes et al., 2005)

$$\theta_w = \tan^{-1}\left(\frac{\int_0^{2\pi}\int_0^{\infty} c_g(f,d)E(f,\theta)\sin(\theta)\,dfd\theta}{\int_0^{2\pi}\int_0^{\infty} c_g(f,d)E(f,\theta)\cos(\theta)\,dfd\theta}\right) \qquad (5)$$

2.3.3 Quantification of uncertainty

The uncertainty in the resource assessment comes from two main sources. Firstly, the measurement uncertainty from the field survey, and secondly the uncertainty arising from the modelling process.

Measurement uncertainty applies to all measurable quantities, such as site bathymetry, wave elevation, etc. A detailed budget of the measurement process should be assembled to determine this. The method of measurement should be rigorously analysed to account for all uncertainties involved in the instrumentation calibration, prior to instrumentation deployment.

Modelling uncertainty will depend on the modelling technique chosen, and may be addressed by sensitivity studies as part of the calibration process.

2.4 Wave Modelling

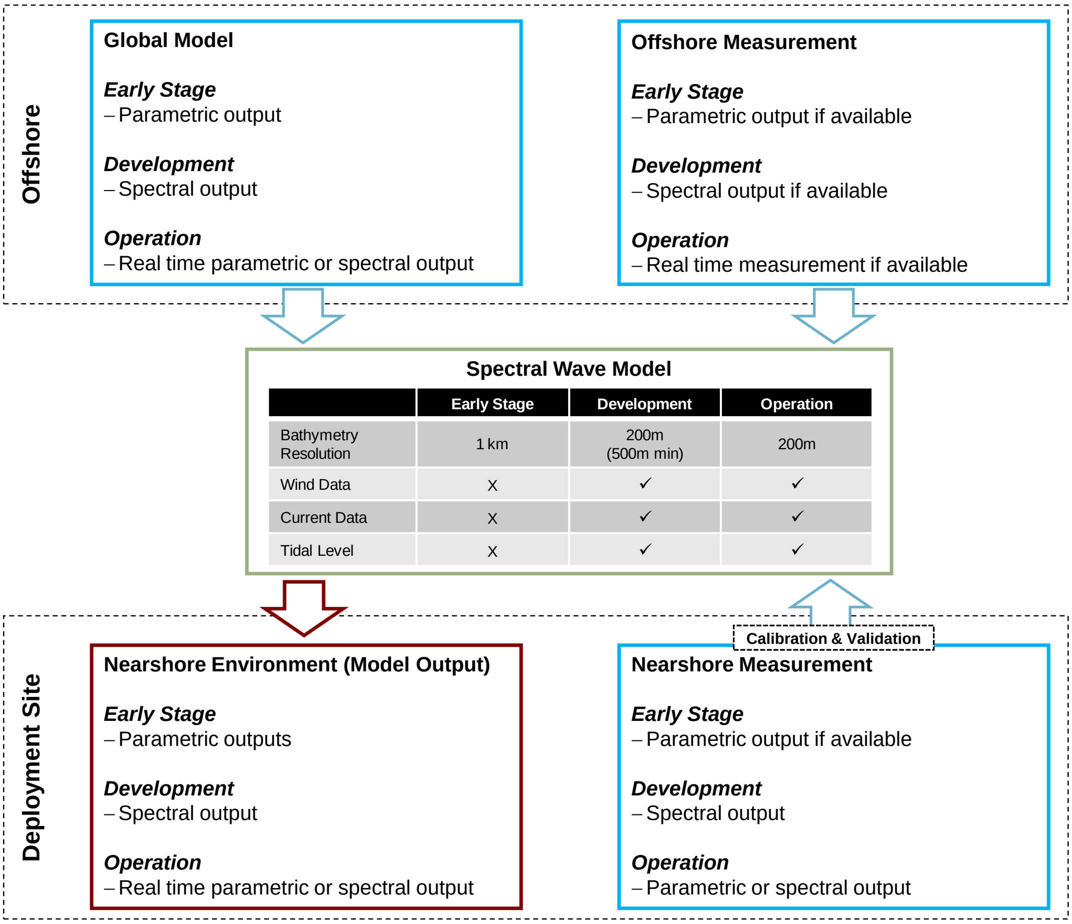
2.4.1 Rationale

Wave modelling shall be used for resource assessment in the following situations:

1. Transfer of data from a remote site to the region of interest
2. To obtain data over a wide geographical area
3. To obtain long-term statistics not possible via a measurement programme.

Third-generation spectral models should be used to transform offshore data to nearshore regions of interest. For early stage assessments, global models, i.e. those intended for use over ocean-scale deepwater regions at low resolutions, may be used. For project development and operational modelling, dedicated nearshore models shall be used. See D2.3 for further discussion of such models. The use of numerical wave models for wave energy resource assessment is summarised in Figure 2.7.

Careful consideration shall be given to the model inputs as discussed in the following sections. Studies have shown (see D2.4) that given identical inputs and grid domain, most nearshore spectral models produce very similar results. Errors and inaccuracies in the model outputs will be primarily due to poor quality input data.



	Early Stage	Development	Operation
Bathymetry Resolution	1 km	200m (500m min)	200m
Wind Data	X	✓	✓
Current Data	X	✓	✓
Tidal Level	X	✓	✓

Figure 2.7 Summary of the required inputs and expected outputs for numerical modelling for wave energy resource assessment.

2.4.2 Offshore boundary conditions

The type of data required for input at the offshore model boundaries shall be determined by the stage of the project.

Early stage resource assessment shall result in a minimum of ten years of data over a wide geographic area to allow selection of a particular site for development and provide an indication of inter-annual variation of the resource. The primary output shall be parameters (H_{m0}, T_e, Θ_m), therefore parametric data will be sufficient for input at the offshore boundaries. These shall be obtained from one of three sources:

1. Archived global model output
2. Results from running a global model using wind data as input
3. Long-term offshore measurements. This option is not recommended because of the lack of spatial coverage of most measurement programmes.

Modelling for project development and operation shall result in spectral output rather than simple parameters. To obtain meaningful results, inputs at the offshore boundary should be in the form of 2D spectral data. The minimum acceptable input is a separate description of wind waves and swell, each characterized by its own H_{m0}, T_p and θ_m. Input data shall be obtained from one of the following sources:

1. Archived spectral global model output
2. Offshore measurement programmes

Both the temporal and spatial scales involved in project development and operation are shorter and it is more likely that measured spectra will be available as model input. The accuracy gained from using measured data as input should be balanced with the spatial variability provided by global model outputs when assessing which data source to use.

2.4.3 Bathymetry

The bathymetric resolution shall be high enough to ensure appropriate seabed features are resolved and shall thus be determined by the stage of the project. For early stage modelling, coarser resolution bathymetry (~1000–5000m grid spacing) will be acceptable. For more detailed modelling for project development and operation over smaller geographic areas (~50km), the minimum grid resolution shall be 500m. A resolution of 200m is recommended where data availability and computational capacity allow. Sources of bathymetric data are discussed in D2.3.

Model nesting should be used when higher resolution bathymetry is not available for the whole model domain or for reasons of computational efficiency. An irregular grid with variable resolution may alternatively be used with some nearshore models rather than regular or curvilinear grids.

2.4.4 Metocean conditions

The inclusion of metocean data (wind, tides, currents) is unnecessary for long-term early stage modelling studies, but shall be considered if modelling is being applied for the later stages of a project development.

Wind shall always be included in detailed modelling studies. Where available, variable wind conditions should be applied across the model domain. Otherwise, a constant wind condition may be applied across the whole grid.

The inclusion of tidal data shall be determined by the tidal range at the site and the depth of the region of interest. In deep water areas, change of depth due to the tide will be unimportant and tidal data may be excluded. However, in intermediate and shallow water regions ($d < \lambda/2$) where the tidal excursion may modify the depth by more than 5%, the effects may be significant and shall be accounted for in the modelling process.

Currents shall be included in the model if their velocity is greater than 2-3% of the local group velocity of the dominant waves. Where possible, the spatial distribution and time variance of currents in the area of interest should be determined. For long term simulation, tidal currents may be used in a parametric form.

2.4.5 Calibration and validation

Data from nearshore measurement devices located within the model domain shall be used to calibrate and validate the model performance for detailed site assessment studies. Parameters such as RMS errors, Scatter Index etc. should be calculated to quantify the model performance. See deliverable D2.3 for details.

2.5 Interpretation and application of data to wave energy developments

2.5.1 Presentation of data

Data from a wave resource assessment shall be presented in a means appropriate to the stage of the project and the aim of the modelling. The following methods may be used:

- H_{m0}-T_e scatter plots
- Parameter time series
- 1D spectral plots
- 2D polar spectral plots

The appropriate method will be determined by the purpose of the assessment and the timescale over which data is required. Data requirements will usually fall into the following temporal categories:

1. *Long-term* assessments are performed to identify the level of resource and to investigate its inter-annual and seasonal variations. A minimum of ten years of data is recommended for such a study. The level of resource over this period should be summarised with scatter plots. Seasonal variations and inter-annual trends should be identified with plots of parameter time series for H_{m0} and T_e.
2. *Medium-term* assessments over a minimum of one year are required for more accurate predictions of power output, site-specific engineering design and the planning of operation and maintenance. Scatter diagrams should still be produced, but broken down into seasonal or monthly plots. Spectral data may be required in addition to basic parameters, and these should be presented in the form of 1D or polar 2D plots.
3. *Short-term* assessments are performed over a timescale of hours or days to assess short-term changes in the sea state for engineering design and operational issues. These should be presented as 1D or polar 2D spectral plots.
4. *Very short-term*: For operational prediction and device tuning, data in the form of elevation time series will be required to give individual wave states.

Scatter Diagrams

Scatter diagrams should plot H_{m0} against a measure of period T^* (T_p, T_{02} or T_e) in tabular form, although other combinations of parameters may be used. Each bin in the table shall represent the relative frequency of occurrence of that particular H_{m0}-T^* combination.

Scatter diagrams illustrating H_{m0} and T_e shall be produced to allow direct calculation of the mean wave power. If records of H_{m0} and T_e are not available due to the historic nature of the dataset this limitation should be noted and alternative scatter diagrams produced using significant wave height ($H_{1/3}$ or H_σ) and mean period (T_{02}, T_z or T_{01}).

Scatter diagrams shall be produced to summarise the annual wave resource. Seasonal diagrams corresponding to *winter* (December, January, February), *spring* (March, April, May), *summer* (June, July, August) and *autumn* (September, October, November) may additionally be presented.

Scatter diagrams shall meet the following requirements:

- Each bin shall display the cumulative occurrences of the H_{m0}-T^* pair. Normalised scatter diagrams may additionally be presented, but the total number of data points used must be stated.
- H_{m0} bins shall be defined in 0.5m intervals over the range 0.5 to 15m
- Wave period (T_e, T_{pc}, T_{02}) bins shall be defined in 0.5s intervals over the range 0.5s to 25s
- Bin boundaries shall be defined by the relationship: *lower limit* $< H_{m0}, T_e \leq$ *upper limit*
- The minimum and maximum bins shall have no lower and upper limit respectively. i.e. all H_{m0} observations exceeding 12m shall be contained within the largest bin. This shall be reflected in the axis labels

Scatter diagrams displaying H_{m0}-T_e pairings may be translated into expected gross wave power levels. If the power output of a particular WEC is being considered it is necessary to refer to the *power matrix*. The power matrix gives the expected power output (in kW) for a particular combination of H_{m0} and period (typically T_e), calculated from a combination of tank testing, site testing and numerical modelling.

Parameter time series

Parameter time series provide plots of particular wave parameters over a fixed period of time. With a likely measurement interval of 3h, a full year's plot of significant wave height will appear very messy. Techniques such as applying a moving average to the data can smooth such plots and assist in identifying trends in the data.

Persistence tables

For operational planning, persistence tables shall be used to assess the availability of maintenance windows. These give the probability of occurrence that a particular wave height will be exceeded over a certain length of time.

2.5.2 Spatial variation

The spatial variation of the resource should be considered on both a wide geographical scale (~ 100km) and on a site specific scale (~<5km). Variations on the geographic scale should be identified by numerical modelling as discussed in §2.4, and results used to identify locations for wave energy developments. On a site specific scale, the need for the information is as follows:

1. Power variation and averaging
2. Optimum positioning of devices
3. Power performance testing
4. Establishment of limits of accuracy for data output for the site
5. Comparison of 'before and after' effects from deployment of an array

The quantification of variation in resource over site scales is the subject of ongoing research.

2.5.3 Extreme Value Analysis Requirements

Sea State Extremes

The mandatory requirement is to quantify the 10, 25 and 50 year return period H_{m0} at the project development stage. The 90% and 95% confidence intervals shall be reported. This analysis will usually be based upon the output of the modelling program due to the typically short duration of site measurements. Guidance on the analysis methodology is given in §4.2.

The assessment of extremes is not mandatory, but is recommended at the early stage of a project where a wide geographical area may be under consideration.

Individual Wave Extremes

The quantification of extreme individual waves is not mandatory but is recommended for 10, 25 and 50 year return periods. It is rarely feasible to examine statistics of individual waves directly as this information is not available from model hindcasts. Instead probabilistic techniques, as detailed in §0.0.0, should be employed.

3 Tidal Resource Characterisation and Site Assessment

3.1 Overview

Section 3 of the protocol will focus on resource assessment for tidal energy developments. Figures 3.1 – 3.4 summarise the methods used for resource assessment at each stage of the process for a tidal energy development and the intended outputs.

3.1.1 Early Stage Assessment

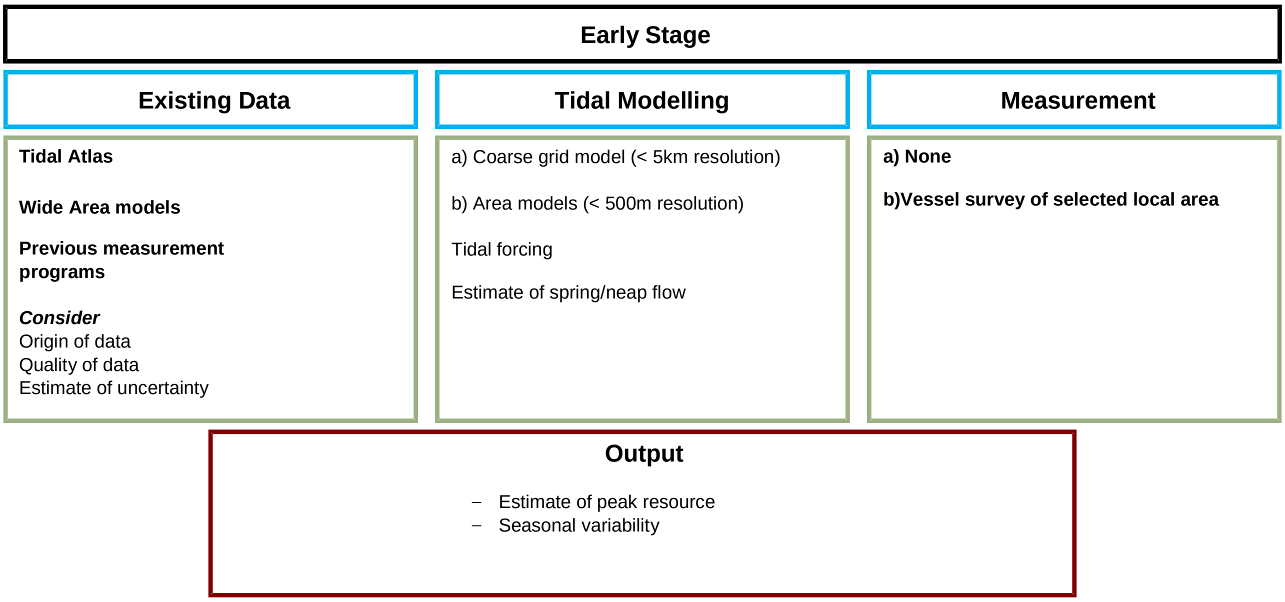


Figure 3.1 Resource assessment for the ‘early stage’ aspect of a tidal energy development.

Early stage *Resource Characterisation* is concerned with providing a first-order assessment of the available resource over a particular area (geographic scale). At the national or regional level, this may only require an assessment of pre-existing data such as tidal stream atlases or shelf tidal models. If used, a suitable model may be based on bathymetry soundings spaced about 1 or 2 km apart, and modelled at a resolution of not more than 5km. This acts a screening stage before selecting local areas for further development. Chosen local areas (e.g. strait, basin, headland) should be confirmed by a vessel ADP survey undertaken at spring tide. This is to understand the general pattern of the local flow. The local area must also be modelled in higher detail, using a shelf model as a boundary source. The local model should be based on bathymetry soundings of about 100m spacing, with a grid resolution of not more than 500m. Where local geography requires it, the model may need to resolve features of the order of 200m in scale.

3.1.2 Project feasibility assessment

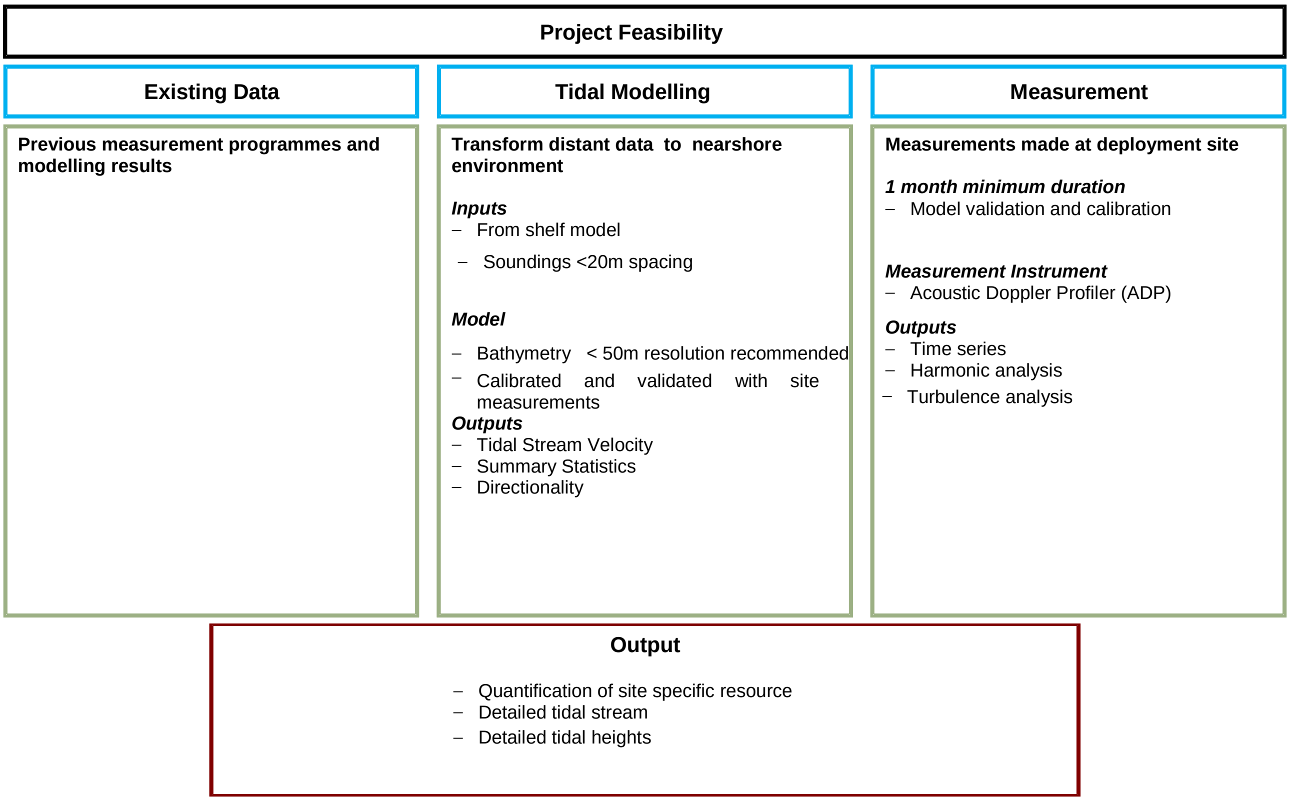


Figure 3.2 Resource assessment for the 'project feasibility' stage of a tidal energy development.

Feasibility Assessment during the project feasibility stage is conducted to establish general characteristics at a specific site. This will involve a coordinated physical measurement and numerical modelling programme. The modelling programme is conducted to supply detailed spatial coverage at the site, and will require a bathymetry derived from soundings with a spacing of about 20m or better. The model resolution should be of the order of 50m. Typically this model will include boundary data from a regional model. An in situ measurement programme will provide data to characterise the site and to calibrate/validate the model. The output of the site assessment process will include a detailed characterisation of the tidal stream as well as high level summary parameters. This stage will also provide a detailed economic model of the development.

3.1.3 Project development assessment

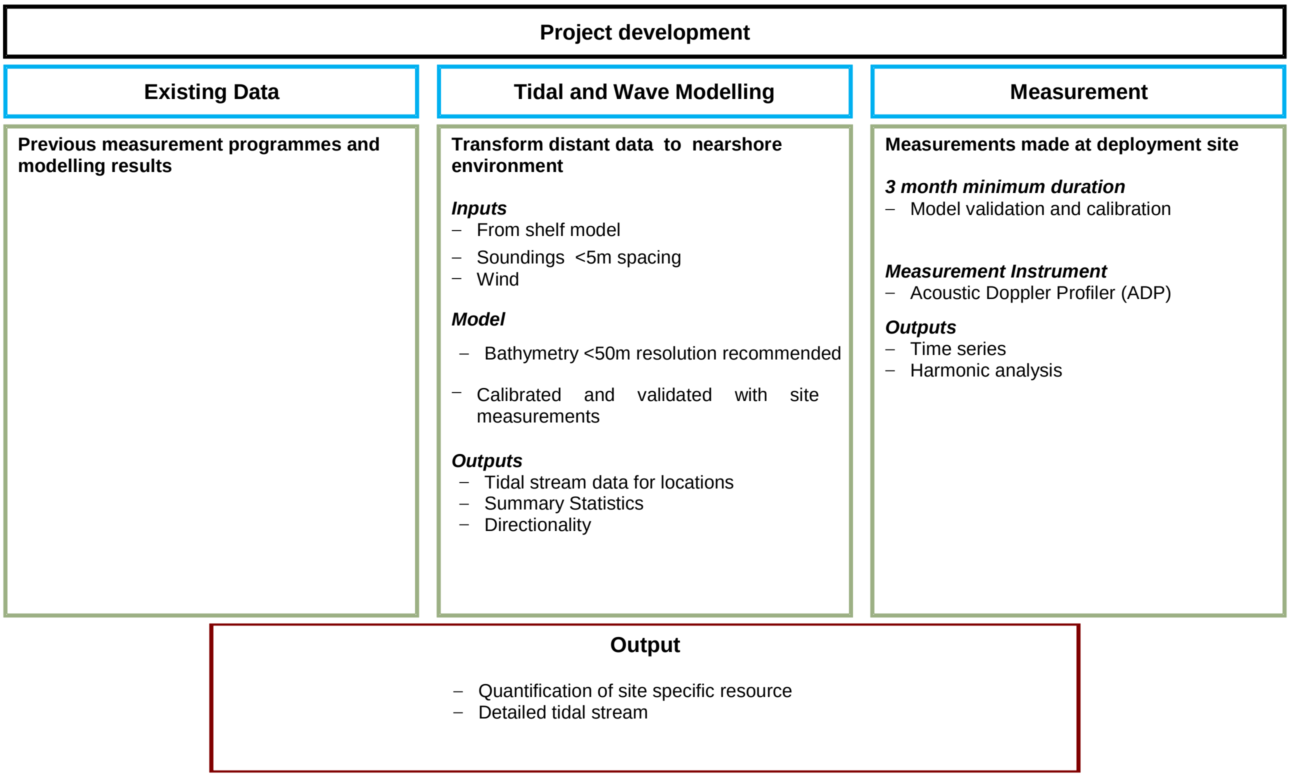
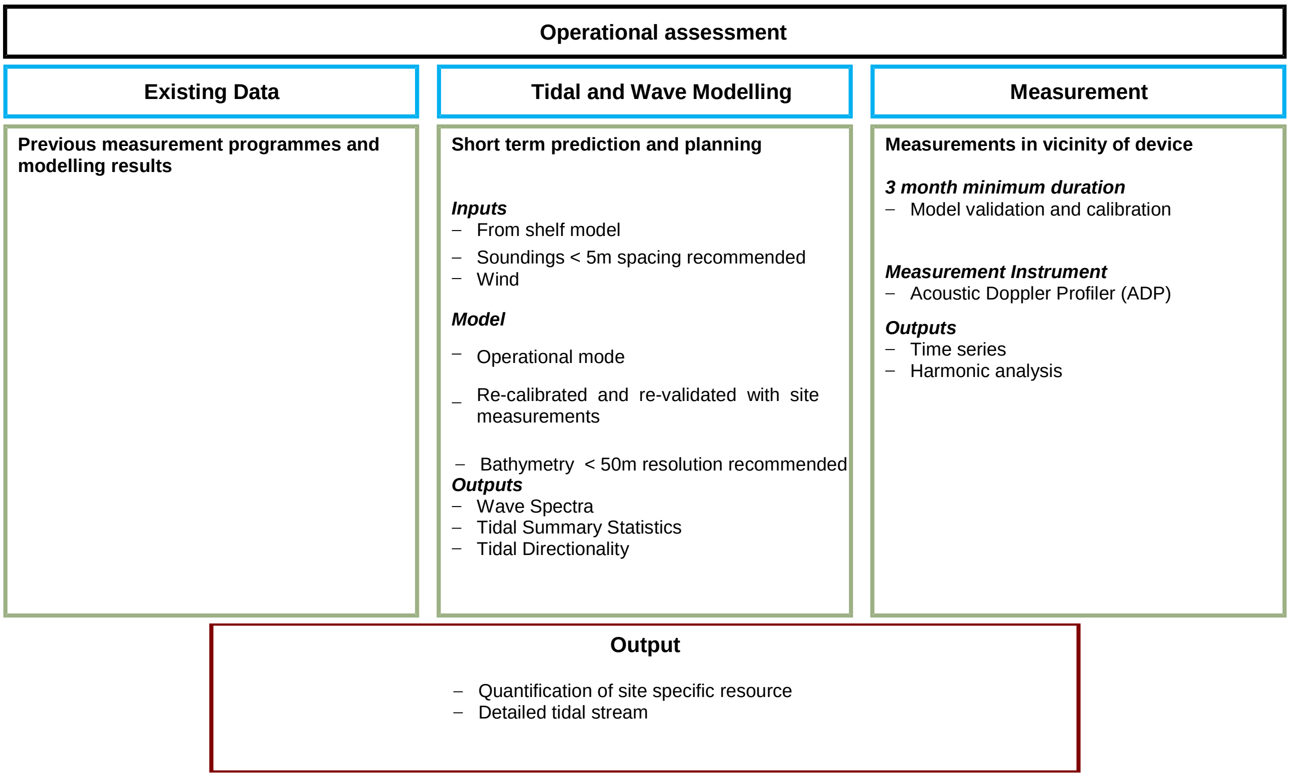


Figure 3.3 Resource assessment for the ‘project development’ stage of a tidal energy development.

Site Assessment during the project development stage is conducted to establish detailed characteristics at a specific site. At this stage the appropriate generating technology should be determined, and this stage should provide detailed information on individual TEC locations. Allowance should be made for the physical dimensions of a TEC, and for sufficient top clearance (to provide for navigational safety and to avoid excessive wave loading) and bottom clearance (to minimise shear loading in the bottom boundary, and to avoid damage from submerged bed load materials). The full assessment will extend the modelling and measurement programme of the feasibility stage, to provide full information of the tidal components present at the site. The model bathymetry should be derived from soundings with a spacing of about 5m. The output of the site development process will include a detailed characterisation of the temporal variability of the tidal stream. Wave modelling may also be applied, to understand wave loading on the TEC and to inform device survival studies.

3.1.4 Operational assessment



Operational assessment

Existing Data

Previous measurement programmes and modelling results

Tidal and Wave Modelling

Short term prediction and planning

Inputs
- From shelf model
- Soundings < 5m spacing recommended
- Wind

Model
- Operational mode
- Re-calibrated and re-validated with site measurements
- Bathymetry < 50m resolution recommended

Outputs
- Wave Spectra
- Tidal Summary Statistics
- Tidal Directionality

Measurement

Measurements in vicinity of device

3 month minimum duration
- Model validation and calibration

Measurement Instrument
- Acoustic Doppler Profiler (ADP)

Outputs
- Time series
- Harmonic analysis

Output
- Quantification of site specific resource
- Detailed tidal stream

Figure 3.4 Resource assessment for the ‘operational assessment’ stage of a tidal energy development.

Operational Assessment during the operational stage will be dependent on the specific demands of the development. A minimum requirement is likely to be the simultaneous measurement of resource and TEC performance for benchmarking. Short term forecasting may assist device tuning and maintenance scheduling. Modelling is expected to be a continuation of the development assessment model in the previous stage, and may require periodic re-calibration as the body of site measurements grows.

3.2 Key tidal parameters

The primary output of a tidal resource assessment shall be parameters that describe the level of resource throughout the life of a project. The key parameters that should be obtained and reported through the resource assessment are described in Table 3.1 below. All tidal current parameters should be calculated through tidal harmonic analysis. Other parameters are a necessary part of the evaluation, particularly for model validation although they need not form part of the reporting process.

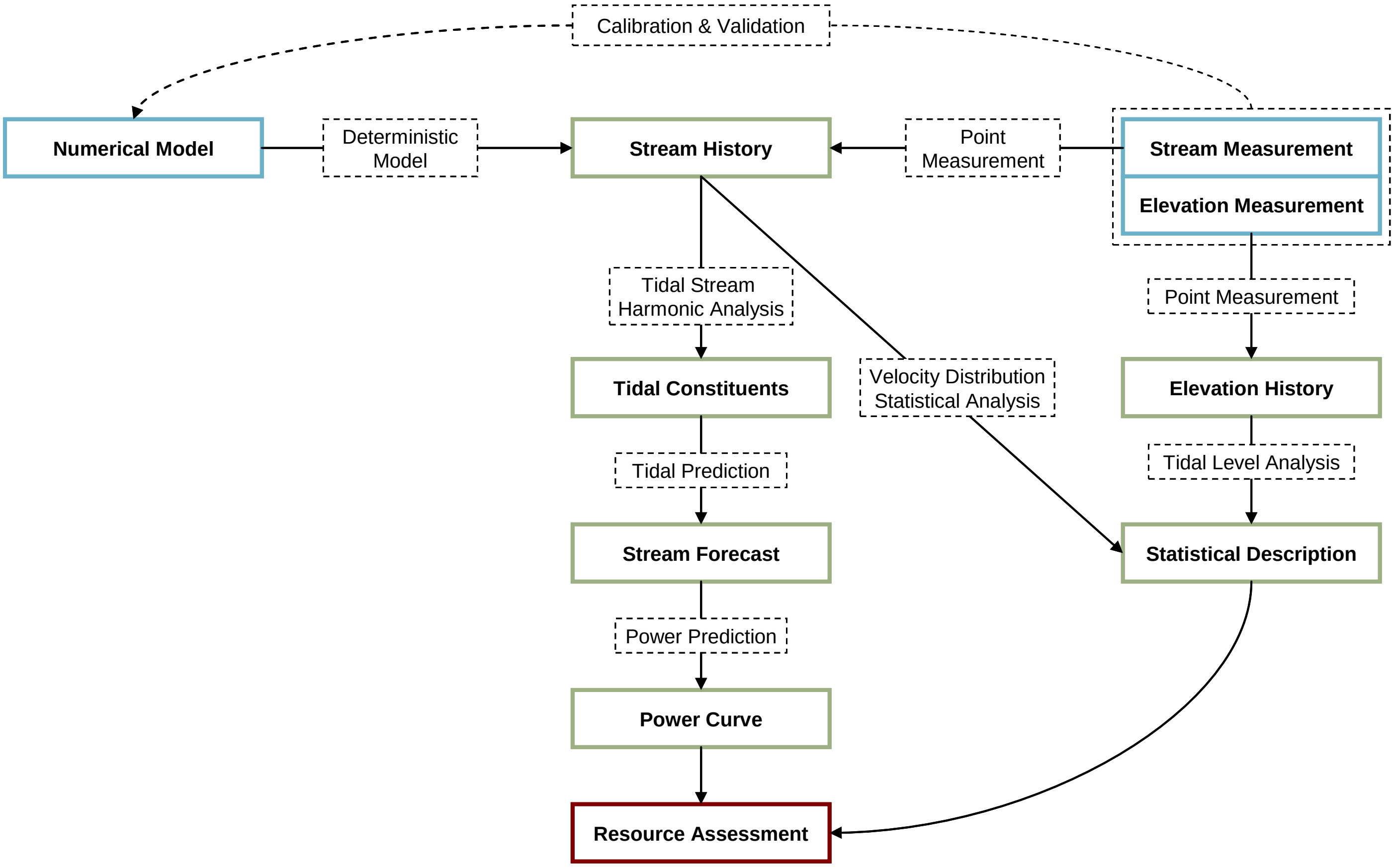


Figure 3.5 Methods for obtaining key parameters from resource assessment

Table 3.1 Key tidal parameters

Tidal range	MHWS,MLWS,MHWN,MLWN,MHW,MLW. Tidal constituents
Tidal currents	Monthly and annual variation. Tidal constituents
Power density	Exceedence curves showing the expected power availability

Site characteristics

The following site characteristics shall be recorded at the start of the project development stage of a tidal energy project.

1. *Bathymetry* at the site shall be established through a bathymetric survey.
2. *Tidal range* at the site shall be established by measurement.
3. *Tidal constituents* at the site shall be established by combined modelling and site survey. Maximum tidal currents shall be extrapolated from the harmonic information. Examples of the typically more important constituents are shown in Table 3.2

Wind at the site shall be established using ongoing measurement. Meteorological model output and/or offshore wind measurement stations may be needed for operational forecasting.

Table 3.2 Common tidal constituents, in usual order of importance

Common name	Description	Period (hrs)	Rank
M2	Principal lunar semidiurnal	12.42	1
S2	Principal solar semidiurnal	12.00	2
N2	Larger lunar elliptic semi diurnal	12.66	3
K1	Lunisolar diurnal constituent	23.93	4
M4	Lunar quarter-diurnal shallow water overtide	6.21	5
O1	Lunar diurnal	25.82	6
M6	Lunar sixth-diurnal shallow water overtide	4.14	7
MK3	Terdiurnal shallow water compound tide (M2 + K1)	8.18	8
S4	Solar fourth-diurnal shallow water overtide	6.00	9
MN4	Quarter –diurnal shallow water compound tide (M2 + N2)	6.27	10

Calculated parameters

The following parameters shall be considered for a resource assessment:

1. *Tidal stream power* at the locations shall be established through survey and measurement.
2. *Power exceedence curves* showing generating availability at the locations
3. *Direction* of axes of tidal ellipses at the locations
4. *Vertical velocity profile* of the tidal stream at the locations

3.3 Tidal Measurement

3.3.1 Measurement process

Need

A physical measurement programme shall be established during the development and operational stages of a tidal energy project. The principal measurement instrument is the ADP, and the number of deployed sensors shall be determined by the stage of the project. An individual TEC deployment should usually require a single measurement device located near to, and on the minor axis of the tidal ellipse centered at the TEC. An array deployment may necessitate multiple measurement devices to quantify variations in the resource over the site. This shall be informed by numerical modelling and the complexity of the site.

Time series data should be recorded and archived for validation. Periodic summary reports including metadata shall be produced at appropriate intervals. For measurements where data are transmitted to shore, reports should be produced on a monthly basis. However, when data recovery must be performed at sea because transmission is not possible, reports should be produced for each instrument deployment.

Data types

Summary statistics are essential to provide an overview of the device performance. Peak ebb and flood in each spring and neap should be recorded. Wave height and period parameters are likely to be useful for device endurance purposes.

Tidal components provide the principal method for calculating long-term statistics.

Time series data present time-ordered records of tidal stream data. The velocity data and the acoustic quality data should be archived. The velocity data will be used to establish tidal parameters and turbulence parameters. The acoustic quality data is used in the QC process

Methods of measurement

All principal tidal stream measurements should be performed with an acoustic Doppler profiler (ADP). Wave measurements may be needed for operational use, and ADP’s may also be used for this purpose. Wave buoys are not suitable for use in a high tidal stream . Remote sensing may also be used to measure surface velocities, to assist model calibration, but are not able to measure sub-surface velocities.

ADPs are usually seabed mounted and suitable for current measurement in all applicable water depths. They are capable of surface (i.e. downward looking) mounting, which may be of use in certain applications. In this mode the stability and movement of the mounting platform must also be considered. The maximum vertical distance (bin spacing) between samples shall be 1 metre. Sufficient bins shall be recorded to provide complete coverage of the TEC cross-sectional capture area in the tidal stream. An ADP with a pressure sensor should be deployed to measure tidal elevation at the site.

See D2.2 for further description of tidal measurement devices.

The following operational requirements shall be addressed:

- Calibration of the measurement device shall be performed both pre-deployment and post-recovery
- For ADP measurement, an anti-trawl seabed mount should be used to minimise risk of loss or damage due to fishing vessels
- The minimum sampling frequency of the measurement device shall be 2Hz.
- An ongoing maintenance programme shall be established for long-term deployments.

Quality control

The adoption of adequate data qualification and quality control is mandatory. A suitable description of QC may be found in QARTOD. The data provider shall demonstrate that their methods are robust in dealing with foreseeable quality control issues and that the data is fit for the intended use. The principal QC process is to confirm whether the acoustic quality of the ADP measurements composing an ensemble average is satisfactory.

A description of the quality control methods shall be included with any data acquisition and analysis report. A description of the experience and expertise of the data providers may be included to provide confidence in the process. Additional reporting may include a description of any issues relating to the data that have been identified.

Metadata

In the reporting of tidal measurement data, the following metadata shall be provided:

- Time stamp for each record in accordance with IS0 8601: YYYY-MM-DDThh:mm:ss<time> where *<time>* indicates the offset to UTC (*Z* in the case of no offset).
  Examples:
  2010-10-05T10:00:00Z *10 a.m. 5 October 2010 – no UTC offset*
  2011-04-15T13:30:00+02:00 *1:30 p.m.15 April 2011 – UTC + 2 hours*
- Location of the measurement device in latitude and longitude, measured in decimal degrees. The datum used must be stated.
- Mean water depth of the instrument deployment site.

3.3.2 Methods of analysis

After applying the QC process, tidal stream data should be averaged into 10 minute samples. For each sample, the vertical binning should be applied across the capture surface of the TEC to determine the available stream power during the sample. Consider the power capture surface area of the device to consist of a series of horizontal strips. Each strip shall be denoted by subscript *k*. Each strip has the height of the vertical bin separation, $z_k = Z$, and each strip shall have width b_k, and there are a total of *S* such horizontal strips. The stream speed through each slice *k* in a sample shall be denoted U_k. The notional capture area of the device is $\hat{A} = \sum_{k=S}^{k=1} b_k . z_k$. The ‘performance velocity’, U_{perf} of the sample shall be computed by $U_{perf} = \left[\frac{1}{\hat{A}} \sum_{k=S}^{k=1} U_k^3 . b_k . z_k \right]^{1/3}$. Lastly, the total available stream power (= P_{KE}) in the sample may be calculated by $P_{KE} = \frac{1}{2} \rho \hat{A} U_{perf}^3$

3.3.3 Quantification of uncertainty

The uncertainty in the resource assessment comes from two main sources. Firstly, the measurement uncertainty from the field survey, and secondly the uncertainty arising from the modelling process.

Measurement uncertainty applies to all measurable quantities, including site bathymetry, tidal stream velocity, local water density, etc. A detailed budget of the measurement process, including the instrumentation calibration process, should be assembled to determine this. The ADP measurements will depend on local water temperature, for example.

Modelling uncertainty will depend on the modelling technique chosen, and may be addressed by sensitivity studies as part of the calibration process.

3.4 Tidal Modelling

3.4.1 Rationale

Hydrodynamic modelling shall be used for resource assessment in the following situations:

1. To provide data on water levels and currents over a wide geographical area. Indeed, measurements may provide good information on water levels and currents but, when available, the information is usually based upon a limited number of point measurements and for a limited duration. Modelling provides an effective means of completing this information in time and space given knowledge of the local bathymetry.
2. To predict the resource and its temporal variations.
3. To evaluate the impact of power systems on the resource.
4. To investigate the potential impact of climate change on energy production

Hydrodynamic models can represent tidal flows as well as wind-driven and wave-driven flows. The models are generally based on shallow water equations (2D models) solved using finite difference or finite element methods. These models are able to provide data on water levels and barotropic currents over a wide geographical shallow water area, and to optimise device positioning.

Careful consideration shall be given to the model inputs and calibration. Model results will only ever be as good as the equations the model is based on and the quality of the input data used. Given identical bathymetry resolution and offshore boundary conditions, the state of the art tidal models produce generally very similar results (see D2.5). Higher quality results are obtained with good quality input data (bathymetry and offshore tidal constituents) and with a well calibrated drag coefficient.

3.4.2 Offshore Boundary Conditions

On the open boundaries, the sea surface elevation must be specified. It shall be obtained from different sources:

1. *Harmonic composition using tidal constituents*: Heights of tidal constituents are provided in various databases (FES2004, Schwiderski datasets). Careful consideration shall be given to the number of components considered in harmonic composition.
2. *Parent models*: This applies in the case of model nesting.

If information is available, e.g. from a parent model, boundary currents may also be prescribed.

The influence of open boundary conditions is particularly significant if boundaries are close to the area of interest and located in shallow water area. If reliable boundary conditions are not available, it is therefore necessary to build a sufficiently large approach model to propagate the tidal data from offshore to the coastal area. This may be achieved by using nested models or with a finite element triangular grid.

3.4.3 Bathymetry

Currents and water levels are influenced by deep ocean tides, the shape of the coastline and the near-shore bathymetry. In shallow water, a coarse bathymetry leads to a coarse representation of current. For early stage modelling, bathymetry may be extracted from global databases such as GEBCO or ETOPO (see Deliverable D2.3 for further discussion on sources of bathymetry data). These databases provide bathymetry with a resolution up to 0.5°, which is an acceptable grid resolution at this stage. Data coherence must be checked through comparison between the different databases and, if available, visual comparison with charts.

For more detailed modelling of the project and to optimise positioning of the devices, a computational grid resolution of 10 - 50 m is recommended. However, this must be coherent with input data available. To achieve 10m resolution, model nesting should be used with finite difference methods, for reasons of computational efficiency. Finite elements offer more flexibility with a variable spatial resolution of their triangular elements. They avoid nesting; however, the construction of the computational grid is more complex and they require specific tools for pre and post-processing of the modelling.

3.4.4 Metocean conditions

The inclusion of metocean data (wind and wave) is unnecessary for early stage modelling studies, but wind effects shall be considered in detailed modelling studies for the later stage of a project development.

If available, variable (in time and space) wind conditions should be applied on the computational domain. Otherwise, wind effects should be studied with schematic wind scenarios. The aim is to inform engineering design with respect to expected exposure to damaging currents under extreme wind conditions combined with high tidal range.

For operational assessment, forecast atmospheric conditions shall always be provided as input into the hydrodynamic modelling.

Wave-driven flows become significant in the very near shore area; typically in the surf zone. So, their action domain is out of the region of interest for tidal energy devices.

3.4.5 Calibration and validation

Current and water level measurements must be used to calibrate and to validate hydrodynamic modelling. If available, meteorological information (wind and pressure) shall be used since atmospheric conditions may affect the strength of currents and the evolution of the water level.

Initial model calibration may be performed using long-term records of tidal elevation from tide gauge networks. Current data from atlases and navigation charts may also be used. As a second step, when in-situ current and water level measurements are available, the quality of the modelling may be assessed.

Validation of modelling may be achieved in different ways:

1. Comparison with rose diagram for typical current conditions (usually mean neap tide and mean spring tide).
2. To compute statistical errors between model and measurement (RMSE, Scatter Index, phase difference, tidal amplitude difference)
3. Performance of tidal harmonic analysis of both model results and measurements and comparison each tidal constituent (amplitude and phase) separately. This method avoids the consideration of meteorological effects. However, it requires a long measurement and simulation period of a minimum 1 year.

Two dimensional models based on shallow water equations are generally sufficient for tidal resource assessment. For such barotropic models, the main physical parameter to adjust during the calibration phase is the bottom friction coefficient. Drag coefficient acts on tidal propagation and have an influence on both amplitude and phase. Other processes can interfere with tidal propagation and modify current and sea levels, e.g. wind stress may affect current velocity like atmospheric pressure affects the sea level. These effects must be evaluated for project development and for operations.

3.5 Interpretation and application of data to tidal energy developments

3.5.1 Presentation of data

At a specified location, tidal data may be presented in different forms:

1. Rose diagrams for typical current conditions during mean neap tide and mean spring tide.
2. Time series for current velocity and water level.
3. Tidal spectrum, i.e. computation of the tidal constituents.

During the development phase of the project, rose diagrams and tidal spectra are produced. For operational assessment time series for current velocity and water level are required.

3.5.2 Spatial variation

The spatial variation of the resource shall be considered on both a wide geographical scale and on a site specific scale. Variations on the geographical scale may be identified by coarse numerical modelling. On a site specific scale, the need for the information is as follows:

1. Power variation and averaging (the tidal resource is the most accurately predictable ocean resource)
2. Optimum positioning of devices
3. Power performance testing
4. Impact of the devices on the resource, leading to interaction between the devices (local impact)
5. Impact of the devices on the environment (regional impact)

3.5.3 Extremes

Extreme sea levels and currents may be specified in several different ways. For clarity, the discussions will distinguish extreme high sea levels from extreme currents.

Extreme sea levels

These levels, including the tide, surge and mean sea level, may be called *still water levels* to distinguish them from the total levels, which include waves. Waves may be accounted for separately in risk analyses, although more elaborate procedures may allow for some correlation between storm surge and high-wave conditions.

High water extreme events typically result from a high water on a spring tide and a storm surge. So, a good way of estimating probabilities of extreme levels is to make use of separate distribution of tidal and surge frequencies (joint tide-surge probability approach). Otherwise (i.e. annual maxima approach), if the largest meteorological surge of a dataset coincides with a low tidal level, this information is ignored despite its obvious relevance to the problem of estimating extreme level probabilities.

The JPM (joint probability method) uses the fact that the statistics of tide and surges are largely independent and compiles separate tables of the distributions of both quantities. The principle advantages of the joint tide-surge probability approach are:

1. Stable values are obtained from relatively short periods of data. A single year can yield useful results, but four years is desirable to sample several storms.
2. There is no waste of information.
3. The probabilities are not based on large extrapolations.
4. Estimates of low water level probabilities are also produced.

Joint tide-surge probability estimates of extremes require datasets of good quality, with timing accuracy to better than a few minutes, and a high degree of analytical skill.

Extreme currents

Extreme currents are more difficult to estimate than extreme levels. The first difficulty is to obtain a sufficiently long series of data; few in situ data extending over more than a year exist because of the expense and the technical difficulties of making good measurements. Further complications arise because currents are variable with depth at each location, and because they change over short distances, particularly near the shore and around shallow sandbanks. In those cases, the most powerful approach is to use the results of numerical models.

As for levels, extreme currents may be estimated by separation of the observed current vectors into tidal and surge components. Two dimensional frequency distributions are obtained for each component, but in the simplest case of the currents being rectilinear or if only speeds are considered; the problem may be treated in exactly the same way as for estimating extreme levels. Where the flow is not rectilinear, the flow in two orthogonal directions may be treated separately. North-south and east-west components are usually chosen, but the directions of the major and minor axes of the current ellipses are also suitable. The maximum components in each of the four directions may be then estimated from probability plots produced by combining the probability distributions of the separate tidal and surge components. The joint probability technique for estimating extreme currents has the same advantages and disadvantages when applied to levels.

For more detail on extreme statistics and methods of calculation see deliverable D2.6.

4 Site Considerations

4.1 Constraints on Exploitation

A resource assessment shall also consider physical and technical constraints on exploitation of the marine energy resource at a particular site due to device-specific requirements. These shall include:

- Required water depth for deployment and operation
- Seabed composition for device installation and cable-laying
- Extreme wave predictions

Additional constraints on exploitation will occur due to existing structures and exclusion zones, and co-existing marine activities such as fishing grounds, shipping lanes and military practice areas. These factors shall all be considered during the project scoping and environmental assessment. See Protocol IB, ‘Environmental Assessment’, for further details.

4.2 Device Survivability and Assessment of Extremes

The calculation of extreme wave or sea state statistics (e.g. 50-year return period H_{m0} value) is challenging due to the typically short duration of physical measurements and the possible bias in long duration hindcasts. The return period will usually be longer than the duration of the dataset (whether from measurements or modelling). There is a low probability that an event close to the return period value will be observed during the observation period. It is, therefore, necessary to apply extrapolation techniques using empirical distributions to quantify these long return period values. As with all techniques of extrapolation the result is very sensitive to the chosen extrapolation model. This model must be chosen based upon robust physical or statistical considerations.

In order to estimate the value (of e.g. H_{m0}) associated with a particular return period the distribution of the annual maxima must be estimated from the time series (typically sampled at 20 minutes, 1 hour or 3 hours).

The parameter examined by the analysis is usually the annual maximum. The first phase is to estimate the distribution of this annual maximum from time series classically sampled to 20min, 1h or 3h. The return value x_N is then simply obtained by:

$$P(X_{\max\_year} \leq x_N) = 1 - \frac{1}{N} \tag{6}$$

where P is the distribution of the annual maximum and N is the number of years. For example, N = 100 for the hundred-year H_{m0} return value $H_{m0,100}$.

Two general techniques, the block maxima and storm maxima methods, are available for the calculation of the distribution of the annual maximum. These techniques are described in more detail below.

Block maxima methods

If the database is sufficiently long (e.g. 40 years for the ERA40 ECMWF hindcast), the empirical distribution of the annual maximum can be obtained directly from the sample of the 40 annual maxima. Generally, it is better to consider a smaller block size (e.g. a month), that remains sufficiently large to maintain independence between values. In that case the distribution of the annual maximum is obtained from the monthly maximum by

$$P(X_{\max\_year} \leq x) = P(X_{\max\_month} \leq x)^n, \tag{7}$$

with n = 12, the number of months in a year

The last step is to fit an analytical distribution to the empirical for extrapolation to high levels and to calculate x_N. The application of a GEV distribution is recommended as described in deliverable D2.6.

Storm maxima methods may be used as an alternative to the block maxima approach but greater user expertise is necessary. For details see deliverable D2.6.

Seasonality

Seasonality should be taken into account as it can significantly affect the results of the extrapolation (see D2.6). The effects of climate change may also be introduced given that robust models of such an evolution exist to describe sea-state or wind storm severity.

Sample Size

The return value confidence interval reduces with increasing dataset duration. Longer return periods require a longer duration dataset. **The minimum dataset requirement is a duration 20% of the return period (e.g. 10 years data for a 50 year return period).** The confidence intervals of the return period value shall be reported.

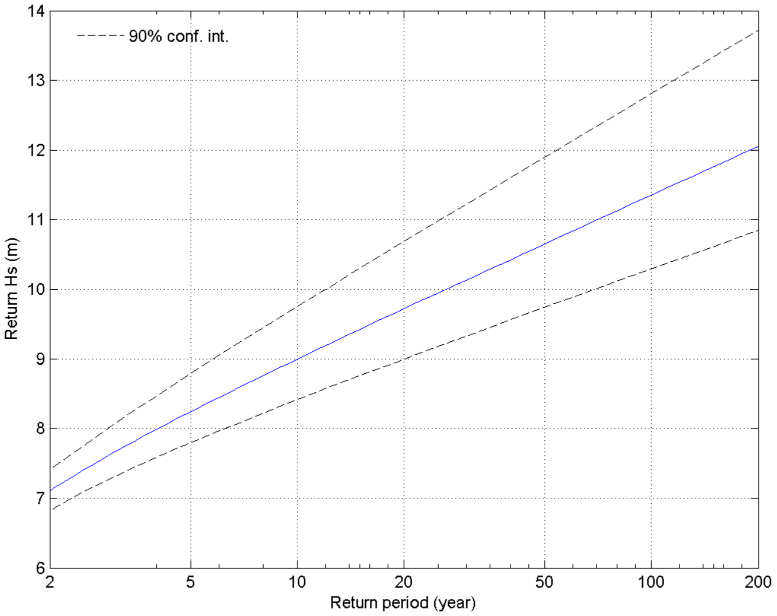


Figure 4.1 Typical representation of return values

n-year individual wave height

Time series of individual wave heights (or sea state H_{max}) values are rarely available over long periods and are not available from hindcasts. Methods can be used, based upon the knowledge of the conditional distribution (to H_{m0} and T_m) of H_{max}, to quantify the n-year H_{max} value.

This conditional distribution can be used, either directly on the sea-state with n-year Hm0 return value or in the calculation of the wave height maximum distribution by applying the law of total probability

$$P(H_{\max} \le h) = \int P(H_{\max} \le h \,|\, H_{m0}, T_m) . f_{Hm0,Tm}(h_{m0}, t_m) . dh_{m0} . dt_m \tag{8}$$

with the H_{m0} maxima distribution.

The joint distribution of significant wave height and period is generally given in the form

$$f_{Hs,Tm}(h_{m0}, t_m) = f_{Hm0}(h_{m0}) . f_{Tm|Hm0}(t_m \,|\, h_{m0}) \tag{9}$$

The methods described here to waves can be applied to wind or current speed, and other short term parameters such as crest height.

Multivariate extreme extrapolation

The examination of multivariate extreme statistics is more complex. The simplest approach is to associate different return values to define the n-year conditions, e.g. 100-year H_{m0} associated with 20-year wind speed associated with 10-

year current speed. The choice of the set of return periods is based on experience and is dependent on the design criteria. A new approach (I-FORM environmental contours) provides a pure metocean answer to this issue. It is based upon First Order Reliability Methods (FORM).

For more details on extreme sea state statistics and these methods of extrapolation, see D2.6.

5 Reporting

Level of the Resource

The resource shall be quantified over the periods outlined in §2 and §3 depending on the project stage. This quantification will be conducted using the key parameters as defined in this protocol (§2.2/3.2). Guidance on the presentation of this information is given in §2.5.1 and §3.5.1.

Limits of the Assessment

The level of detail required from the resource assessment is dependent on the project stage, as broadly defined in §1 and in more detail in §2.1 and §3.1. The purpose of the resource assessment should be clearly stated (e.g. early stage resource assessment to establish first order resource characteristics). Any deviations from the outputs listed in this protocol should be stated.

Site Particulars

The particulars of a site shall be presented including

- A chart detailing the geographic area covered by the resource assessment. This chart shall include a clearly legible scale and geographic coordinates in decimal degrees.
- An overview of the site bathymetry. If a modelling programme has been conducted the bathymetry used in the programme should be presented.
- Any constraints (§4.1) on exploitation should be reported. If these constraints relate to a particular geographic area this should be noted on the site chart.

Measurement Programme Instrumentation

The particulars of the measurement devices and data collection procedures shall be recorded. This includes

- Instrument type, manufacturer and model.
- Confirmation that device has been calibrated in accordance with the manufacturer's specification and that this calibration is valid over the duration of the deployment.
- Deployment information including location and water depth in accordance with the metadata requirements detailed in §2.3.1/3.3.1
- For a wave buoy details of the mooring system (e.g. schematic) should be given.
- The sampling frequency and bin sizes (for an ADP) should be given along with any instrument specific settings that may be relevant to the interpretation of the data.
- Quality control procedures applied to the data prior to analysis should be noted and explained.

Analysis Methodology

The analysis methodologies and techniques applied to the raw data should be detailed. This should include

- Details of the software utilised. This may include proprietary and non-commercial software (e.g. custom MATLAB scripts).
- The underlying theory should be explained or referenced. For example, if a directional spectrum is presented the analysis methodology (e.g. MEM) should be stated.
- The methodology used for the analysis of extreme conditions (where applicable).

Numerical Modelling Programme

If a numerical model programme has been conducted the following information should be reported

- Details of the model and software version.
- The model domain, mesh details and resolution
- Details of the model input (e.g. global model) including inputs such as wind
- The source and resolution of bathymetry data
- Any other model specific information

Model and Measurement Data

- The metadata describing the data source (i.e. modelling or measurement programme) should be referenced in accordance with the requirements given above.
- The time stamp for each sample shall be recorded in accordance with §2.3.1/3.3.1.

- All recorded parameters should be clearly defined using recognised terminology (see §2.2/3.2)
- Electronic data shall be stored using a non-proprietary format (e.g. ASCII, NetCDF).

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