



PEMSEA Regional Methodology for Blue Carbon Project Accounting

A Harmonized Guide for Estimating Carbon Stocks, Sequestration, and GHG Reductions in Coastal Ecosystems

Annex E

Monitoring Environmental Parameters Influencing Blue Carbon Ecosystems



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About Us

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E.1 Introduction

Monitoring environmental parameters beyond biomass and soil organic carbon is essential for defining the health, productivity, and long-term viability of blue carbon ecosystems (BCEs). These parameters provide the environmental context needed to interpret observed changes in carbon stocks and sequestration rates, and to understand how BCEs respond to climatic variability and anthropogenic pressures (Duarte et al., 2013; Macreadie et al., 2019).

This annex provides guidance on the identification and monitoring of key oceanographic, biogeochemical, physical, meteorological, and biological parameters that influence carbon dynamics in mangroves, seagrass meadows, and salt marshes. While these parameters do not represent direct carbon pools, they play a critical supporting role in explaining why carbon stocks change over time and in assessing the stability and performance of blue carbon projects. The scope and structure of this annex are aligned with regional coastal monitoring frameworks, including the Core and Network System (CNS) Monitoring Guidelines for Blue Carbon Ecosystems (Nakaoka et al., 2023).

Environmental monitoring supports strategic project management by capturing both natural variability and human-induced changes in water quality, hydrology, and sediment processes. Monitoring designs commonly include environmental reference stations to characterize natural or reference conditions, trend stations to track long-term changes in impacted areas, and flux stations to quantify integrated inputs of water, sediments, nutrients, and pollutants from upstream sources (Nakaoka et al., 2023). Where feasible, continuous measurements using in situ sensors are encouraged to capture diurnal and seasonal variability as well as episodic events, such as extreme rainfall or storms, that may disproportionately influence sediment transport and ecosystem condition (Alongi, 2014).

The capacity of BCEs to sequester and retain carbon is closely linked to their environmental condition. Temperature and light regulate metabolic and photosynthetic rates, nutrient availability influences primary production and eutrophication risk, and salinity controls species distribution as well as the potential for non-CO₂ greenhouse gas emissions, particularly methane (Alongi, 2014; Waycott et al., 2009; Taillardat et al., 2018). Physical drivers such as tides, currents, and bathymetry determine inundation regimes and sediment burial rates, which are fundamental to long-term soil carbon storage (Alongi, 2014; Duarte et al., 2013).

Within a Measurement, Reporting, and Verification (MRV) framework, environmental parameter monitoring enhances the transparency, accuracy, and credibility of carbon accounting. These data support baseline establishment, refinement of activity data and emission factors, movement toward higher methodological levels, and assessment of risks related to leakage and non-permanence, consistent with IPCC good practice guidance (IPCC, 2013). Environmental

monitoring is therefore treated as supporting information that strengthens carbon inventories but does not replace direct measurements of carbon stocks and fluxes unless explicitly required by an approved methodology.

This annex is applicable across mangroves, seagrass meadows, and salt marshes, while recognizing ecosystem-specific monitoring priorities. Mangrove systems place greater emphasis on porewater salinity, nutrients, and tidal inundation; seagrass meadows prioritize light availability, water clarity, and depth constraints; and salt marshes require close attention to elevation, hydroperiod, and flooding duration (Nakaoka et al., 2023). Together, these parameters provide a coherent framework for interpreting blue carbon dynamics across diverse coastal ecosystems.

E.2 Classification of Environmental Parameters

Environmental parameters relevant to blue carbon ecosystems operate across multiple spatial and temporal scales and influence ecosystem processes, carbon cycling, and project performance. For clarity and consistency, this annex groups parameters according to their primary functional role in shaping ecosystem condition and carbon dynamics.

The parameters presented here reflect the commonly monitored variables reported in blue carbon and coastal ecosystem studies, but are not exhaustive, nor are all parameters required for every project. Parameter selection should be guided by the ecosystem type and the dominant environmental drivers influencing carbon stocks and sequestration at the site. Reviews of mangrove, seagrass, and coastal monitoring practices consistently identify temperature, salinity, light availability or water transparency, nutrients, chlorophyll-a, and hydrodynamic conditions as core indicators of ecosystem condition and productivity (Ahmad-Kamil et al., 2013; Howard et al., 2014). These variables are also consistent with the Essential Ocean Variables (EOVs) framework of the Global Ocean Observing System, which prioritizes key physical, biogeochemical, and biological variables for sustained marine observation (Muller-Karger et al., 2018; Miloslavich et al., 2018).

The classification adopted here serves as a practical organizational framework for environmental monitoring in blue carbon projects. While individual parameters may influence multiple processes, they are assigned to the category most relevant to their dominant role in carbon accounting, ecosystem interpretation, and Measurement, Reporting, and Verification.

The environmental parameters addressed in this annex are grouped into the following categories:

Oceanographic Parameters

Oceanographic parameters describe the physical and optical properties of the water column that regulate energy availability, mixing, and water mass characteristics. These parameters directly affect photosynthesis, metabolic rates, and sediment–water interactions, particularly in tidally influenced and shallow coastal systems.

Biogeochemical Parameters

Biogeochemical parameters capture the availability and cycling of nutrients and organic matter in the water column and sediments. They provide indicators of ecosystem productivity, trophic status, and eutrophication risk, and are essential for interpreting changes in vegetation condition and carbon sequestration potential.

Physical Parameters

Physical parameters describe hydrodynamic and geomorphological processes, including tides, currents, and seabed morphology. These drivers control inundation regimes, sediment transport, and carbon burial rates, and are central to understanding spatial patterns of carbon storage and system resilience.

Soil Porewater Parameters

Soil porewater parameters characterize the chemical environment within sediments that governs plant rooting conditions, microbial activity, and greenhouse gas production. These parameters are particularly important in mangroves and salt marshes, where vertical gradients strongly influence productivity and carbon stability.

Meteorological Parameters

Meteorological parameters represent atmospheric forcing that shapes coastal hydrodynamics and ecosystem stress. Variables such as wind, rainfall, and air temperature influence water circulation, salinity gradients, erosion, and disturbance regimes at both short and long timescales.

Biological Community Characteristics

Biological community parameters describe species composition, structural attributes, and material properties of vegetation that support biomass estimation and ecosystem condition assessment. While not direct environmental drivers, these characteristics provide essential context for interpreting carbon stock measurements and ecosystem responses to environmental change.

E.3 Oceanographic Conditions

Oceanographic conditions regulate the physical and optical properties of coastal waters and are fundamental to the productivity and functioning of blue carbon ecosystems. Parameters such as water temperature, salinity, light availability, and turbidity directly influence metabolic rates, photosynthesis, water column stratification, and sediment–water interactions in mangroves, seagrass meadows, and salt marshes. Monitoring these parameters provides essential context for interpreting ecosystem condition and observed changes in carbon stocks and sequestration rates.

Where feasible, continuous monitoring is preferred over discrete sampling, as it captures diurnal and seasonal variability as well as short-lived but influential events such as heavy rainfall, flooding, or storms.

E3.1 Water Temperature and Salinity

Water temperature and salinity determine seawater density and stratification, influencing circulation patterns, freshwater intrusion, and nutrient transport. These parameters also affect physiological processes in vegetation and microbial activity relevant to carbon cycling.

Equipment

Monitoring typically uses logger-type underwater sensors capable of continuous recording. Many salinity and turbidity sensors (Figure 1 and Figure 2) include integrated temperature probes. In mangrove and marsh environments, soil porewater salinity provides additional context for interpreting surface-water salinity gradients; porewater sampling methods are described in Section E.6.

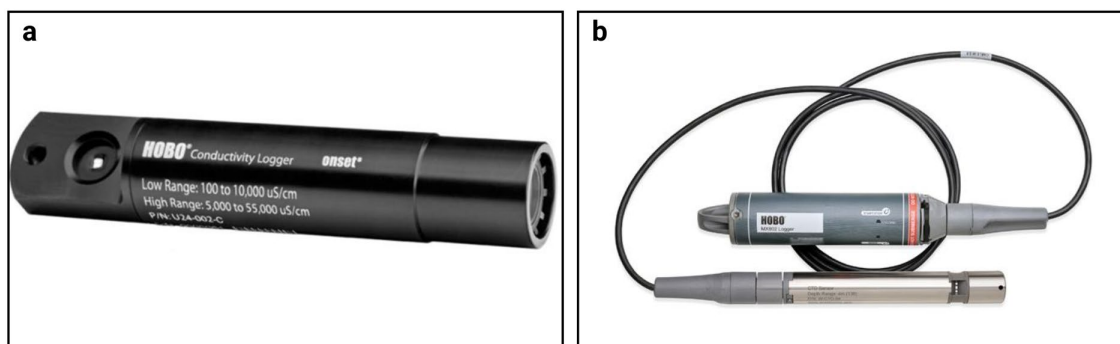


Figure 1: Commercial salinity and turbidity sensors (a) HOB0 Saltwater Conductivity/Salinity Data Logger (b) HOB0 CTD Sensor (Image Source: Onset Computer Corporation)

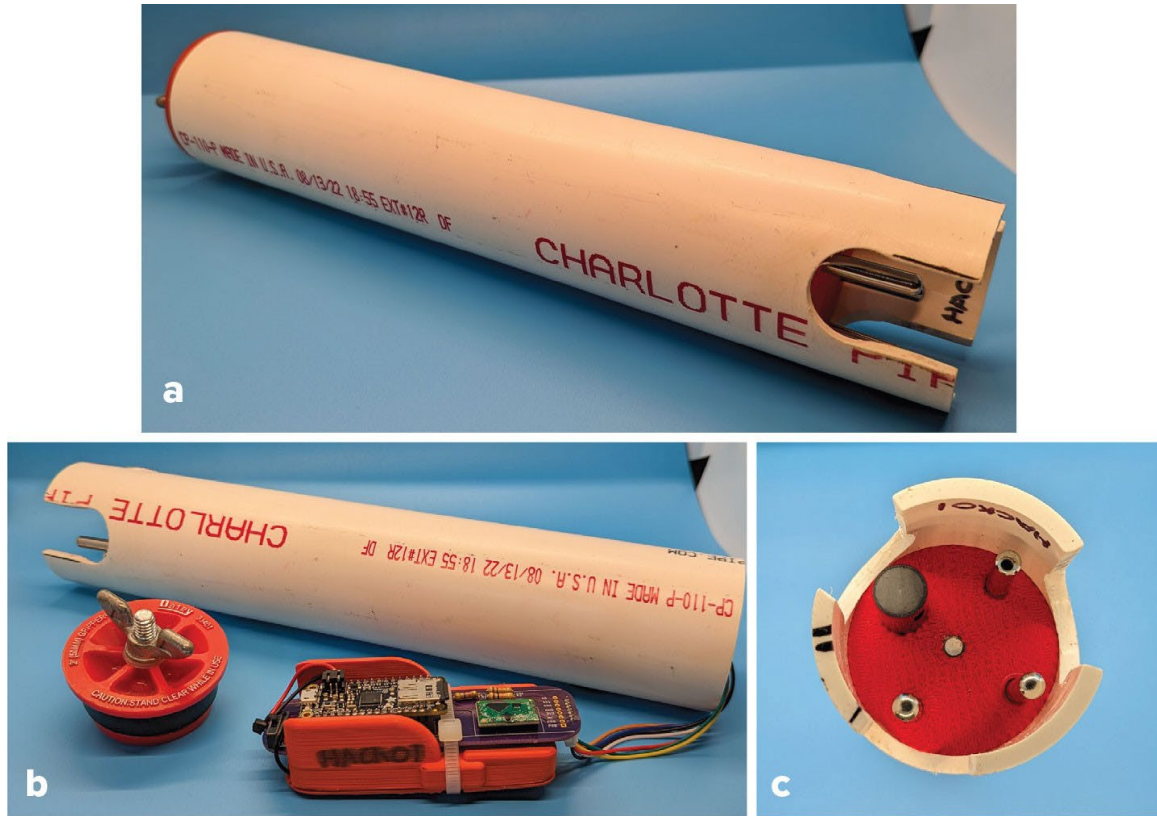


Figure 2: The OpenCTD, a low-cost, open-source oceanographic instrument (a) The assembled and sealed OpenCTD ready for deployment. (b) The OpenCTD with plumber's test cap removed and control unit showing Arduino microcontroller, Atlas EZO conductivity circuit, wiring harness, and 3D-printed chassis protecting. (Thaler et al., 2024)

Monitoring procedures

- Continuous logging: Sensors are deployed to record temperature and salinity at fixed intervals. Typical logging configurations include 10–30 minutes for short-term deployments (approximately 2–4 weeks) and 30–60 minutes for longer deployments (approximately 1–3 months).
- Select logging intervals and deployment durations to capture the relevant tidal, diurnal and seasonal variability, taking account of sensor capacity, maintenance requirements and monitoring objectives.
- Strategic placement: To capture vertical mixing and freshwater influence, sensors should be deployed at both surface and near-bottom waters. Where river inputs are present, additional sensors may be positioned at increasing distances from the river mouth to characterize spatial gradients.

E3.2 Light Availability, Turbidity, and Transparency

Light availability is the primary limiting factor for seagrass growth and an important driver of productivity in shallow coastal systems. Turbidity reflects the concentration of suspended sediments and phytoplankton, both of which reduce light penetration and are therefore critical environmental indicators. Transparency, which integrates the effects of suspended solids and water clarity, is commonly monitored as a simple indicator of light penetration in the water column.

Equipment

- Photosynthetically Active Radiation (PAR) sensors to measure the light spectrum relevant for photosynthesis.
- Logger-type turbidity sensors to quantify water column clarity and suspended particle concentrations.
- Secchi disk, a low-cost visibility disk for transparency measurements; typically a white or black-and-white disk of approximately 20–30 cm diameter, attached to a calibrated line, used to determine Secchi depth as a simple indicator of overall water clarity.

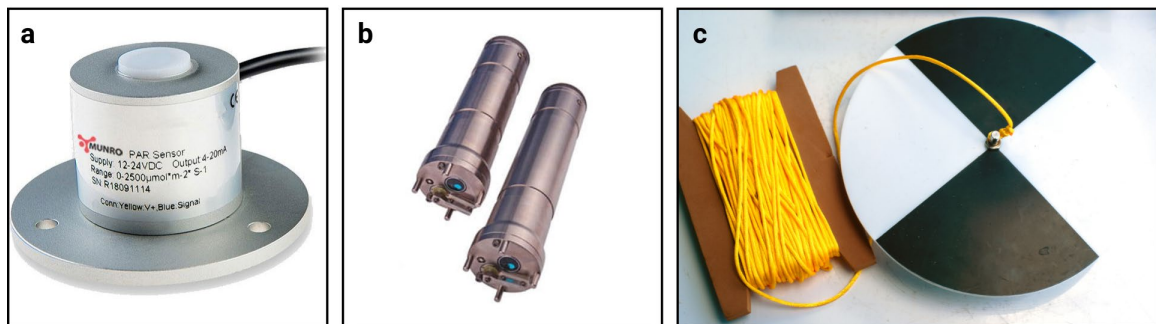


Figure 3: Sample instruments for monitoring light availability and water clarity in blue carbon ecosystems. (a) Photosynthetically Active Radiation (PAR) sensor from Munro Instruments; (b) Representative multiparameter water quality loggers (JPE Advantech); (c) Secchi disk

Monitoring procedures

Continuous monitoring is recommended to capture variability driven by tidal cycles, river discharge, resuspension events, and phytoplankton blooms. Sensor deployment along spatial gradients, particularly in relation to river inflows or other disturbance sources, allows assessment of how light and turbidity conditions vary across the ecosystem.

Secchi disk transparency method

The Secchi disk method provides a simple, cost-effective measure of water transparency that integrates the effects of suspended particles and phytoplankton on light penetration. The Secchi depth is defined as the depth at which the disk is no longer visible when lowered into the water and is inversely related to turbidity.

1. Position the boat or platform on relatively calm water with the sun behind the observer to minimize glare and shadow effects.
2. Slowly lower the Secchi disk into the water column until it just disappears from sight; record this disappearance depth.
3. Continue lowering the disk a little further, then slowly raise it until it first becomes visible again; record this reappearance depth.
4. Calculate the Secchi depth as the average of the disappearance and reappearance depths.
5. Repeat the measurement at least three times at each station and record the mean transparency value.

Record any conditions that limit the observation. If the disk remains visible at the seabed, record the water depth and flag the observation as bottom-limited; do not report it as a measured disappearance depth. Select complementary optical measurements where the Secchi method does not meet the monitoring objective.

Interpretation

High Secchi depth values indicate clearer water with greater light penetration, while low Secchi depth values suggest high turbidity and limited light availability. These measurements are especially valuable when interpreted alongside PAR and turbidity sensor data, as they provide a simple, integrative indicator of water clarity that can be easily collected across wide spatial extents.

E3.3 Community-Based Water Transparency Monitoring

Community-based transparency measurements can complement instrument-based observations and provide spatial and temporal information on water clarity. Use a defined, repeatable procedure and record whether the measurement represents vertical Secchi depth or horizontal visibility distance.

Equipment

Use a Secchi disk with a calibrated line for vertical depth measurements, or a white target board and a measured distance for horizontal visibility observations.

Monitoring procedures

- For vertical Secchi depth, follow the lowering and raising procedure in E3.2 and report depth in metres.
- For the horizontal white-board method, one participant holds the board while another observes it from increasing measured distances. Record the visibility distance in metres and document the target depth and viewing conditions.
- Record the method, date, time, location, tidal conditions, weather and observer. Use consistent procedures when comparing observations over time. Do not combine horizontal visibility distance and vertical Secchi depth as though they were the same measurement.

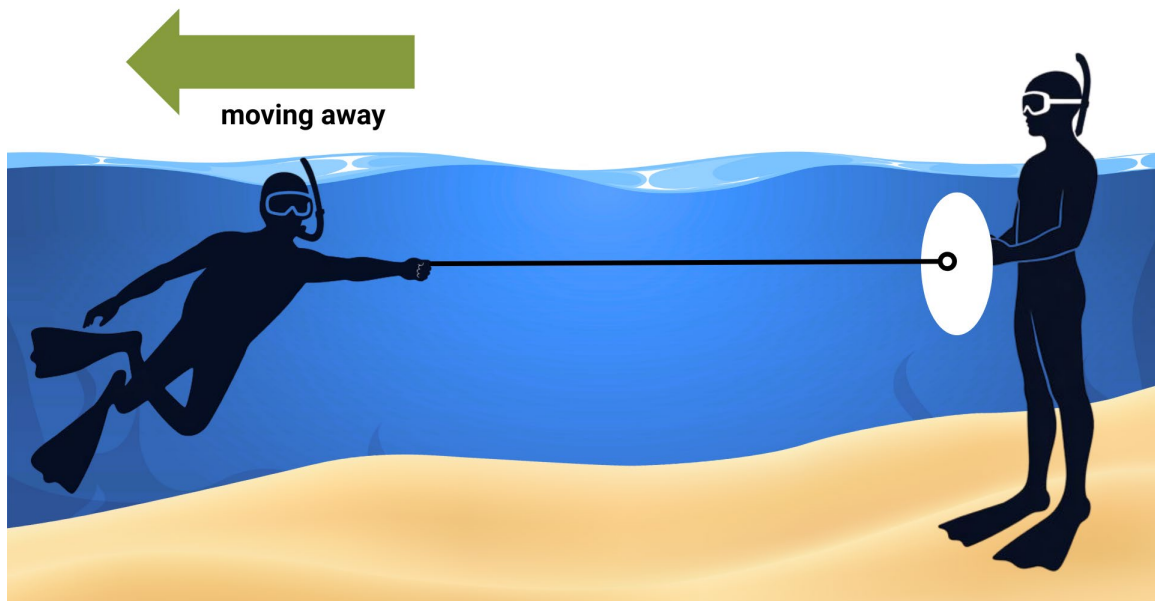


Figure 4: Community-based transparency monitoring set up (modified from Nakaoka et al., 2023)

Data use and limitations

Community-based transparency data are best used to:

- Supplement PAR and turbidity sensor data
- Identify spatial patterns in water clarity
- Provide early indication of changes affecting light availability

Because results are observer-dependent and influenced by ambient light and sea state, transparency measurements collected through participatory approaches should be interpreted cautiously and documented with basic metadata (date, time, location, weather conditions).

E.4 Biogeochemical Parameters

Biogeochemical parameters describe nutrient availability and primary productivity within coastal waters and sediments and are critical for assessing ecosystem condition in blue carbon projects. Monitoring nutrients and chlorophyll-a supports early detection of eutrophication, which can trigger algal blooms, reduce light availability, and lead to the degradation of seagrass meadows and adjacent coral systems. These parameters also provide important context for interpreting changes in vegetation productivity and carbon sequestration potential.

Among biogeochemical indicators, chlorophyll-a is widely used as a reliable proxy for micro-algal and phytoplankton biomass and is highly responsive to nitrogen and phosphorus enrichment.

E4.1 Nutrients (Nitrogen, Phosphorus, and Silicate)

Nutrients regulate primary production and influence trophic status in coastal waters. While moderate nutrient availability supports ecosystem productivity, excess inputs can disrupt ecosystem structure and compromise blue carbon stability.

Equipment

- Water collection: Niskin water sampler (Figure 5) for discrete depths; bucket for surface water
- Sample handling: High-density polyethylene (HDPE) bottles (approximately 250 mL for nutrients), 50 mL plastic syringes, and 0.45 μm syringe filters
- Preservation: Freezer capable of maintaining $-20\text{ }^{\circ}\text{C}$. Confirm that filtration, freezing, storage temperature, holding time and thawing procedures are suitable for each analyte and sample matrix under the selected laboratory method. Document any method-specific departures from this example workflow.
- Laboratory analysis: UV–Visible spectrophotometer



Figure 5: A Niskin water sampler (Image Source: General Oceanics)

Monitoring procedures

1. Field collection: Collect water samples using a Niskin sampler or bucket and transfer immediately into clean HDPE bottles.
2. Filtration: Draw subsamples using a plastic syringe and filter through a 0.45 μm filter directly into capped plastic test tubes.
3. Preserve each sample according to the selected analyte-specific laboratory method, including its filtration, temperature, holding-time and thawing requirements. Freeze only where that method supports freezing for the analyte and sample matrix.
4. Analysis: Common analytical methods include the indophenol blue method for ammonium, pink azo-dye methods for nitrite and nitrate, and the molybdenum-blue method for phosphate.

E4.2 Chlorophyll-a

Chlorophyll-a provides an integrated indicator of phytoplankton biomass and nutrient enrichment in the water column and is useful for tracking changes in productivity and water quality over time.

Equipment

- Water collection: Niskin water sampler or bucket
- Sample handling: HDPE bottles (approximately 1 L), 47 mm GF/F filters
- Preservation materials: Magnesium carbonate (MgCO_3), aluminum foil
- Storage and analysis: Freezer at $-20\text{ }^{\circ}\text{C}$ and UV–Visible spectrophotometer

Monitoring procedures

1. Field collection: Transfer water from the sampler into a clean HDPE bottle.
2. Filtration: Filter the sample through a 47 mm GF/F filter, adding a small amount of MgCO_3 to stabilize pigments.
3. Light protection: Fold filters and wrap them in aluminum foil to prevent photodegradation.
4. Preservation: Freeze filters immediately and keep frozen until laboratory extraction and analysis.
5. Laboratory analysis: Chlorophyll-a can be quantified using standard methods such as spectrophotometry, fluorometry, or high-performance liquid chromatography (HPLC), depending on available equipment and project requirements.
6. Record the volume filtered and the extraction and analytical method used. Apply the selected method's storage limits, calibration and quality-control requirements.

E4.3 Soil Porewater Nutrients (Mangrove-Specific)

In mangrove ecosystems, nutrient concentrations in soil porewater strongly influence vegetation productivity, species zonation, and belowground carbon processes.

Monitoring procedures

Soil porewater nutrients are sampled using standardized porewater extraction procedures described in Section E.6. In mangrove ecosystems, nutrient concentrations should be assessed across multiple depths to capture strong vertical gradients associated with root density and redox conditions.

E.5 Physical Dynamics

Physical dynamics govern water circulation, sediment transport, and geomorphological processes that highlight the stability and carbon sequestration capacity of blue carbon ecosystems. Parameters such as tides, currents, and bathymetry determine inundation regimes, sediment burial rates, and the spatial distribution of habitats in mangroves, seagrass meadows, and salt marshes. Monitoring these drivers provides essential context for interpreting changes in soil carbon stocks and ecosystem resilience.

E5.1 Tides and Water Level

Tides are the primary driver of water exchange in estuaries and coastal embayments and directly control the wetting and drying cycles of intertidal ecosystems. Accurate water level measurements are required to characterize inundation frequency, duration, and depth.

Equipment

Water level is typically monitored using water level sensors deployed on or near the seabed.



Figure 6: Water level sensors (Image Source: Royal Eijkelpkamp)

Monitoring procedures

- Deployment: Sensors should be installed below the lowest expected tide level to ensure continuous recording of water depth throughout the tidal cycle.
- Pressure correction: For absolute, non-vented pressure sensors, subtract concurrent atmospheric pressure from the recorded absolute pressure to obtain water pressure. Do not apply a second atmospheric correction to measurements already compensated by the instrument or processing system. Document the sensor type and correction procedure.
- Depth calculation: Water depth (h) is calculated as

$$h = \frac{P_{water}}{\rho g}$$

Equation 1

where h is water depth above the sensor (m), P_{water} is pressure attributable to the water column after any required atmospheric correction (Pa), ρ is water density appropriate to the measured temperature and salinity (kg/m^3), and g is gravitational acceleration (m/s^2).

- Reference level: Express water levels relative to a documented vertical datum or stable local benchmark, accounting for the sensor's elevation. Where a deployment-period mean is subtracted from instantaneous measurements, report the results as deviations from that mean and state the observation period. A short deployment mean, such as a 14-day mean, shall not be labelled an established Mean Sea Level datum without an appropriate datum-establishment or datum-transfer procedure.

E5.2 Currents and Flow Velocity

Water currents control the transport of nutrients, sediments, and pollutants and influence erosion, deposition, and carbon burial processes within BCEs.

Equipment

- Eulerian (fixed-point) measurements: Acoustic Doppler Current Profilers (ADCPs) for vertical velocity profiles or electro-magnetic (EM) velocity sensors for horizontal flow, typically mounted on buoys or fixed to the seabed.
- Lagrangian (drifting) measurements: Neutrally buoyant floats, drifters, or drogues that move with the water and are tracked acoustically or via GPS.

Monitoring procedures

- Burst sampling: Flow velocity is measured in short bursts (e.g., 60 measurements at 1-second intervals) to reduce noise caused by turbulence.
- Temporal averaging: Mean flow velocity is calculated through temporal averaging of burst measurements to obtain stable and representative flow estimates.

E5.3 Bathymetry

Bathymetric mapping provides the depth profile of coastal waters and is essential for modeling circulation patterns, water quality, and habitat suitability, particularly in shallow and tidally influenced systems.

Equipment

- Primary method: An echosounder with integrated GPS mounted on a motorized vessel.

- Manual alternative: A combination of smartphone GPS for positioning, a marked rope for depth measurement, and a meter stick for recording tide-related water level changes.

Monitoring procedures

- Depth sounding: The echosounder emits sound pulses toward the seabed and calculates depth based on the return travel time.
- Water-level correction: Reduce depth soundings to a documented common vertical datum using concurrent water-level observations. Account for transducer depth and other applicable instrument corrections, and document the relationship between the sounding and water-level reference systems.
- Spatial interpolation: As complete seabed coverage is not feasible, collected depth points are interpolated using appropriate software to generate a continuous bathymetric surface.

E5.4 Other Physical Forcing Factors

Additional physical drivers may be monitored depending on project objectives and site conditions.

- Waves: Wave height, period, and attenuation can be measured to assess exposure and coastal protection services provided by BCEs.
- Meteorological forcing: Wind speed, wind direction, and atmospheric pressure are monitored using weather stations to characterize atmospheric controls on coastal hydrodynamics.

E.6 Soil Porewater Parameters

Soil porewater quality exerts a strong control on vegetation productivity, species zonation, and belowground biogeochemical processes in blue carbon ecosystems, particularly in mangrove forests and salt marshes. Parameters such as salinity and nutrient concentrations influence root function, microbial activity, and greenhouse gas dynamics, and therefore provide critical context for interpreting ecosystem condition and carbon stability.

Equipment

Soil porewater is typically collected using Rhizon syringes, which are equipped with porous cups that allow water to be extracted through suction. A soil corer, often with small pre-drilled access holes, is used to facilitate precise sampling at defined depths. Handheld salinity refractometers are commonly used for rapid field measurements of salinity, while collected samples may be retained for laboratory analysis of nutrients or dissolved organic carbon.

Monitoring procedures

- Core extraction: Because porewater properties vary substantially with depth, a soil core is typically extracted prior to porewater sampling.
- Sampling intervals: Finer depth intervals (e.g., 2 cm) are recommended near the soil surface, where gradients are steep, with coarser intervals (e.g., 5–10 cm) at greater depths.
- Extraction duration: After installation, Rhizon syringes may require up to approximately 2 hours to collect sufficient sample volume for chemical analysis.
- Shallow porewater focus: For some applications, salinity measurements are targeted within the upper 30 cm of the soil profile, where root density and biogeochemical activity are highest.

E.7 Meteorological Parameters

Meteorological parameters represent atmospheric forcing that shapes coastal hydrodynamics, salinity regimes, and disturbance patterns in blue carbon ecosystems. These variables influence sediment transport, freshwater inputs, and ecosystem stress, and are therefore important for contextualizing both short-term variability and long-term trends in carbon dynamics.

Parameters and equipment

On-site monitoring is commonly conducted using an integrated weather station that includes:

- Thermometer: air and, where applicable, sea surface temperature
- Barometer: atmospheric pressure
- Hygrometer: relative humidity
- Anemometer: wind speed and wind direction
- Rain gauge: localized precipitation

Monitoring procedures

- Deployment location: Weather stations should be installed in open or elevated areas free from obstructions that could interfere with wind and rainfall measurements.
- Spatial configuration: A single weather station may be sufficient where it represents the project's relevant meteorological conditions. Assess coverage in relation to project extent, exposure, topography and spatial variability. Additional stations or rain gauges may be needed to characterize rainfall gradients and runoff events.
- Alternative data sources: Where on-site monitoring is not feasible, meteorological data may be obtained from regional or global reanalysis products and established databases (e.g., national meteorological agencies). Such datasets provide useful background information but may not fully capture localized or short-duration events, such as tropical squalls or convective storms.

E.8 Biological Community Characteristics

Biological community characteristics support ecosystem-condition assessment and, where required by the selected method, biomass and carbon estimation. This section addresses their monitoring context; measurement and calculation procedures for accounting inputs are provided in the relevant ecosystem annexes.

Key characteristics include species composition, structural attributes, and material properties that influence ecosystem function and sensitivity to environmental change. Variations in species dominance, stand density, canopy height, or mortality patterns may reflect underlying stressors such as altered hydrology, nutrient enrichment, or salinity shifts captured through environmental monitoring.

Wood density is recognized as an important biological parameter affecting biomass estimates and uncertainty propagation. However, procedures for wood density measurement, biomass estimation, plot design, and carbon pool calculation are fully addressed in the ecosystem-specific annexes (e.g., mangroves, seagrass meadows, salt marshes) and are not repeated here.

E.9 Monitoring Design Considerations

Effective monitoring design for blue carbon ecosystems requires a strategic framework that integrates physical, oceanographic, biogeochemical, and biological parameters to support robust Measurement, Reporting, and Verification. Monitoring systems should be designed to characterize baseline conditions, detect project-induced changes, and capture natural variability that influences ecosystem processes and carbon dynamics.

Designing an effective monitoring program involves balancing scientific rigor with logistical feasibility through the following considerations.

E9.1 Strategic station placement

Projects are encouraged to deploy multiple monitoring stations to capture environmental gradients and external influences. Common station types include:

- Environmental reference stations: Stations selected to characterize relevant background conditions and provide comparisons with the project area. Document their ecological and hydrological comparability. Conditions at a reference station shall not automatically be

treated as the project's counterfactual baseline, which shall be established under main Chapter 8.

- Trend stations, placed in areas influenced by human activity (e.g., near settlements, agriculture, or industry) to track long-term changes in water quality and environmental stressors.
- Flux stations, typically positioned at river mouths or major inflow points, to measure the transport of sediments, nutrients, and pollutants from watersheds into coastal systems.

E9.2 Stratification and sampling approach

Large or heterogeneous project areas should be subdivided into homogeneous strata based on relevant attributes such as vegetation type, soil properties, salinity regime, or water depth. Stratification improves the precision of environmental and carbon estimates and supports representative sampling. Within strata, random or systematic sampling designs should be applied to minimize subjective bias.

E9.3 Temporal and spatial resolution

Where feasible, continuous monitoring using in situ sensors is preferred to capture diurnal and seasonal variability, as well as episodic events such as storms or heavy rainfall that can strongly influence sediment transport, inundation, and carbon burial. Spatial coverage should be sufficient to capture key gradients and boundary influences affecting the project area.

E9.4 Integration of participatory monitoring

Because professional monitoring can be resource-intensive, projects may incorporate community-based or participatory monitoring approaches to enhance spatial coverage and temporal continuity. Simple methods, such as transparency measurements using Secchi disks, can provide valuable contextual data while fostering local engagement and stewardship.

E9.5 Use of Multiparameter Water Quality Meters

Multiparameter water quality meters, often referred to as multiparameter sondes, are integrated instruments designed to measure multiple physical and chemical parameters simultaneously from a single probe housing. These devices are widely used in coastal, estuarine, and inland water

studies to provide continuous, high-resolution data on variables such as temperature, conductivity (and derived salinity), pH, dissolved oxygen (DO), turbidity, and other constituents important for water quality assessment. The use of integrated sondes enables consistent, real-time characterization of environmental drivers that influence carbon dynamics and ecosystem health, reducing the need for separate instruments and facilitating synchronized data collection in long-term monitoring programs. The utility of multiparameter sondes in coastal water quality studies has been demonstrated in peer-reviewed research, including applications of HYDROLAB sondes in marine waters to track temporal trends in temperature, salinity, pH, and turbidity with high temporal resolution (Marku et al., 2024) and as part of online and real-time water quality monitoring frameworks that provide high-resolution temporal data and support early detection of environmental change (Farouk et al., 2023).

Equipment and configurations

Multiparameter sondes range from handheld, portable units to submersible loggers capable of long-term deployment. Common commercial sondes include multi-sensor instruments such as those produced by JFE Advantech, HORIBA, YSI, and OTT Hydrolab (**Figure 8**), which integrate multiple sensors into a single watertight body. Commercial sondes are typically equipped with sensors for temperature, conductivity (for salinity), pH, DO, and turbidity, and may support additional modules for parameters such as oxidation–reduction potential (ORP) or chlorophyll-a. For example, integrated sonde systems available from manufacturers can include ports for multiple sensor types and onboard data logging capability for unattended deployments.



Figure 7: Different types of Multiparameter Water Quality Meters (a) AAQ-RINKO Compact multiparameter profiler for profiling salinity, DO, pH, and other variables (Image source: JFE Advantech); (b) OTT Hydrolab HL4 Multiparameter water quality sonde with integrated sensors (Image source: OTT HydroMet); (c) Portable multiparameter water quality checker (HORIBA U-50) (Image source: HORIBA)

General monitoring procedures

To ensure reliable and consistent multiparameter data, the following procedures should be incorporated into monitoring protocols (and documented in Standard Operating Procedures):

1. Pre-deployment preparation and calibration:
 - Perform calibration of individual sensors (e.g., pH, conductivity, DO) using certified standards prior to deployment, following manufacturer guidelines.
 - Document calibration date, standards used, and calibration results in monitoring records.
2. Deployment setup:
 - Install the sonde at representative depths and locations consistent with the monitoring design (e.g., fixed stations or along environmental gradients).
 - Allow adequate time for the instrument to equilibrate in situ before logging begins to ensure stable measurements.
3. Data logging and metadata:
 - Configure the instrument for appropriate logging intervals (e.g., 10–60 minutes depending on monitoring objectives).
 - Record associated metadata, including deployment date/time, GPS location, water depth, and tidal stage, with each data record.
4. Maintenance and biofouling control:
 - Inspect and clean sensors periodically during extended deployments to reduce biofouling and sediment adhesion that can bias readings.
 - Replace consumable components (e.g., membranes or optical windows) as recommended by the manufacturer.
5. Cross-validation and QA checks:
 - Periodically validate sonde measurements against discrete water samples analyzed in the laboratory to detect sensor drift or systematic biases.
 - Report discrepancies and corrective actions taken in QA/QC records.

By following these practices, multiparameter sondes provide a robust and integrated method for capturing the dynamics of key water quality drivers across temporal and spatial scales relevant to blue carbon ecosystems.

E.10 Minimum Monitoring and Documentation Requirements

Projects shall document the environmental parameters required by the selected accounting methods and those selected to monitor material ecosystem pressures and project risks. The following minimum documentation requirements apply to those parameters, regardless of the methodological level used. Not every parameter described in this annex is required for every project; parameter selection and any exclusions shall be justified in the monitoring plan.

Geographic and boundary documentation

- Project boundaries should be clearly delineated using GPS coordinates or high-resolution spatial data, with typical positional accuracy of 1–2 m where feasible.
- Boundary data should be archived in standard vector formats (e.g., .shp, .kml) to support validation and verification.

Environmental and biological parameter records

Projects should document key environmental and ecosystem indicators relevant to carbon dynamics, including:

- Biological community characteristics, such as species composition and structural attributes (e.g., plant density, height, DBH in mangroves; percent cover or shoot density in seagrasses), as contextual indicators of ecosystem condition.
- Soil properties used in carbon accounting, including assessed depth, dry bulk density and organic carbon concentration, shall be measured and reported in accordance with the applicable ecosystem annex.
- Oceanographic drivers, particularly salinity and water temperature, which are critical for interpreting ecosystem productivity and assessing methane (CH₄) emission potential.

Quality assurance and quality control (QA/QC)

- Standard Operating Procedures (SOPs) should be documented for all field and laboratory methods to ensure consistency and reproducibility.
- Field data should be reviewed regularly for completeness and accuracy, with clear documentation of data checks and reviewer sign-off.
- Data entry into electronic databases should include cross-verification of a subset of records (e.g., ≥10%) by a second individual.

Reporting and data archiving

- Monitoring outputs should be compiled into structured reports that clearly describe objectives, methods, and results for both baseline and project scenarios.
- Retain raw and processed monitoring records, laboratory results, spatial files, calibration records and supporting photographs in accordance with the main methodology's monitoring-record retention requirements. Apply longer retention periods where required by national regulations or the applicable certification framework.

E10.1 Reporting templates

Use these supporting records with Annexes A–C and, where relevant, the mapping records in Annex D. Use identical project, stratum, station/sample and reporting-period identifiers. Reference existing field sheets, laboratory reports and instrument files instead of duplicating them. Repeat rows or tables as needed; use “not applicable” with a reason where appropriate. Blank cells are for project records, not worked examples.

These templates organize the monitoring and documentation requirements in this annex, drawing on the CNS Guidelines and Appendix I and the data-management guidance in Howard et al. (2014). Parameter selection, sampling methods and QA/QC shall follow the adopted monitoring plan. Environmental observations do not by themselves establish a carbon stock change or a creditable GHG benefit.

Template R1: Parameter monitoring plan

Field	Record
Project ID and name; reporting period; plan version and date	
Ecosystem and stratum IDs; linked A–C and D report IDs	
Station register / map reference, coordinates and coordinate reference system	
Purpose of monitoring: accounting input, ecosystem condition or project risk	
Parameter selection and justification; reasons for exclusions	

Responsible organization, field team and laboratory	
Reference/background stations and their purpose, where used	
Planned review and response to missing data or material environmental change	

Parameter / unit	Station / depth	Method / instrument ID	Timing / frequency	Purpose / linked calculation

Specify parameter-specific units, methods and sampling conditions. Distinguish vertical Secchi depth from horizontal visibility; identify the salinity scale and turbidity method/unit. For water level and bathymetry, identify the vertical reference and datum. Select frequency to represent relevant diurnal, tidal and seasonal variation.

Template R2: Observation and sample records

Field	Record
Dataset / field sheet ID and version; observer and date	
Time zone; station coordinates and positioning method / accuracy	
Depth definition and reference surface; tide, water level, weather and relevant site conditions	
Instrument and method codes; linked calibration records	
Sample IDs and chain-of-custody reference, if laboratory analysis is used	
Sample collection, preservation, transport and analysis records / timestamps	
Missing, invalid or below-detection results: flag definitions and treatment	

Date / time	Station / sample ID	Depth / reference	Parameter / method code	Result / unit	QA flag / evidence ID

Retain the raw record and any corrected result with an audit trail. Do not record non-detects or missing observations as zero. Reference method-specific detection or quantification limits and applicable holding times in the laboratory record. Summarize results by station and reporting period only with the aggregation method and data coverage documented.

Template R3: Calibration, maintenance and laboratory QA/QC

Field	Record
Instrument / laboratory and method identification	
Applicable calibration, preservation and analytical procedures / versions	
Acceptance criteria and their source	
Linked sample batch, deployment or observation dataset	
Reviewer, review date and release status	

Date / record ID	Instrument / sample batch	Check / standard / maintenance	Result and acceptance status	Action / affected data

Include the checks relevant to the adopted method, such as calibration verification, sensor drift or fouling, blanks, duplicates and reference materials. Document failed checks, corrective actions and which observations were retained, corrected, qualified or rejected. Retain supporting instrument and laboratory records.

Template R4: Environmental events, interpretation and follow-up

Field	Record
Event / assessment ID; date or period; affected stations and strata	
Event or observed trend; supporting observations and evidence IDs	
Interpretation, uncertainty and possible effects on ecosystem condition	
Action taken, responsible person and follow-up date	
Whether an accounting input, monitoring design or risk assessment requires revision; justification	
Linked A–C event, monitoring or accounting record; D map update if applicable	
Archive location and custodian; retention basis under the main methodology	
Prepared by / date; reviewed by / date; closure status	

Distinguish a measured observation from an inferred cause or carbon consequence. Where a parameter is used in an accounting calculation, identify the receiving calculation, units, applicable conversion and uncertainty treatment. Report any GHG consequence through the main methodology and the relevant ecosystem annex, avoiding duplicate accounting.

E.11 Relevance to Measurement, Reporting, Verification and Permanence

Monitoring environmental parameters supports the interpretation of carbon stocks, greenhouse gas emissions and project risks. Some parameters also serve as inputs to the selected accounting model or support the selection of applicable emission factors. Distinguish parameters used quantitatively in accounting from indicators used to interpret ecosystem condition, and document their respective uses.

Within a Measurement, Reporting, and Verification (MRV) framework, environmental monitoring supports transparent interpretation of changes in carbon stocks and fluxes by documenting background variability and external influences. These data help distinguish project-induced effects from natural fluctuations driven by tides, rainfall, seasonal productivity, or extreme events. Environmental parameters also contribute to refinement of activity data and emission factors, supporting progression toward higher methodological levels where site-specific conditions are required.

Environmental monitoring is particularly relevant for baseline definition and scenario assessment. Long-term records of hydrological, oceanographic, and biogeochemical conditions provide evidence for plausible baseline trajectories and support defensible assumptions regarding ecosystem response in the absence of project interventions. In addition, monitoring beyond project boundaries assists in identifying potential ecological leakage, such as unintended changes in water levels or salinity that could influence greenhouse gas emissions in adjacent areas.

From a permanence and risk management perspective, environmental parameters function as early-warning indicators of stress or instability. Changes in salinity, inundation regime, sediment dynamics, or water quality may signal increased vulnerability to degradation, erosion, or non-CO₂ greenhouse gas emissions. Tracking these parameters allows project proponents to anticipate risks, implement adaptive management measures, and document responses over time.

Where identified project risks include oil spills, storms, flooding or other acute disturbances, the monitoring plan shall specify appropriate event-triggered observations, incident documentation and follow-up assessment. Record the affected area, observed ecosystem impacts, response measures and any implications for carbon stocks or GHG emissions. Link these activities to the project's risk-management and emergency-response arrangements.

Overall, environmental parameter monitoring enhances the robustness of blue carbon projects by linking carbon accounting results to ecosystem processes and external drivers. When integrated with ecosystem-specific measurement protocols and MRV systems, these data improve transparency, support verification, and strengthen confidence in long-term climate mitigation outcomes.

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