Operational GHG Emissions Assessment – Site C

Monitoring Plan

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GHD
Contact: Pooya Shariaty, Business Group Leader - EHS Compliance | GHD
140 - 10th Avenue SE, Suite #600
Calgary, Alberta T2G 0R1, Canada
T +1 403 271 2000 | **F** +1 403 271 3013 | **E** info-northamerica@ghd.com | **ghd.com**

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1. Introduction

GHD Limited (GHD) was retained by the British Columbia Hydro and Power Authority (BC Hydro) to perform a post-impoundment greenhouse gas (GHG) emissions monitoring and reporting (Assessment) for the Site C Clean Energy Project (Site C) near Fort St. John, British Columbia (BC).

The objective of the Assessment is to support BC Hydro's commitment to GHG emissions monitoring for Site C, as required by Condition 65 of Environmental Assessment Certificate #14-02, issued by the British Columbia Environmental Assessment Office (BC EAO). Condition 65 mandates the development of a robust and defensible Greenhouse Gases Monitoring and Follow-Up Program (the Monitoring Program) to validate the predictions of the GHG model completed as part of the environmental assessment application (prepared by Stantec Consulting Ltd., December 2012). Condition 65 specifies that the Monitoring Program must include protocols for monitoring and reporting GHG emissions from the Site C reservoir for the first 10 years of operation, including emissions from both operation and maintenance activities.

To meet these requirements, GHD has developed this monitoring plan. The purpose of this plan is to outline the monitoring and reporting activities that will be undertaken during operations to monitor and estimate net emissions from the entire reservoir domain with reasonable accuracy. It is important to note that net emissions from reservoirs vary based on the ecosystem types and components present within the reservoir footprint before impoundment. Net emissions are defined as the changes in emissions within the reservoir footprint caused by the creation of the reservoir, accounting for exchanges occurring before, during, and after project construction. Consequently, given the numerous variables involved in emissions conditions within Site C large domain, it is essential to integrate multiple methods to develop a comprehensive estimation approach for the entire domain.

The following section provides the necessary details for the program design and subsequent follow-up activities.

1.1 Plan Objectives

The objective of this plan is to provide the necessary information for GHG monitoring activities and reporting at Site C, in compliance with the requirements set forth by the BC EAO under Condition 65 of Environmental Assessment Certificate #14-02.

1.2 Plan Scope

The scope of this plan encompasses the monitoring and reporting of greenhouse gas GHG emissions from the Site C reservoir during the initial ten years of operation. It includes detailed descriptions of the specific monitoring methods to be employed. This plan is subject to future amendments aimed at enhancing the monitoring program, contingent upon approval by the BC EAO.

1.3 Site C Reservoir Area Understanding

Site C Clean Energy Project is located in Fort St. John, BC. Site C reservoir area extends west of Fort St. John up the Peace River. The proposed maximum normal operating range for the Site C reservoir will be 1.8 metres (m) — between 460.0 m and 461.8 m. However, during typical operations the reservoir is expected to fluctuate within a smaller range. The Site C reservoir will be approximately 83 kilometres (km) long and will be, on average, two to three times the width of the current river. The reservoir will flood approximately 6,357 hectares (ha) of land and will have a total surface area, including the current river area, of approximately 9,330 ha. The 461.8 m elevation boundary is used to quantify the pre-impoundment reservoir footprint area.

GHD also understands that substantive air and water quality measurements have been completed for years at various locations across the Site C reservoir area. GHD reviewed the historical air and water quality data provided by BC Hydro as well as the publicly available meteorological data to better understand the site conditions. This historical site data as well as information obtained during some preliminary monitoring activities prior to and during the reservoir impoundment were used to develop the post-impoundment Monitoring Program, which can be conducted considering the reservoir footprint area, identification of the emissions sources/sinks, and accessibility.

Figure 1.1 shows the site location map including the reservoir area.

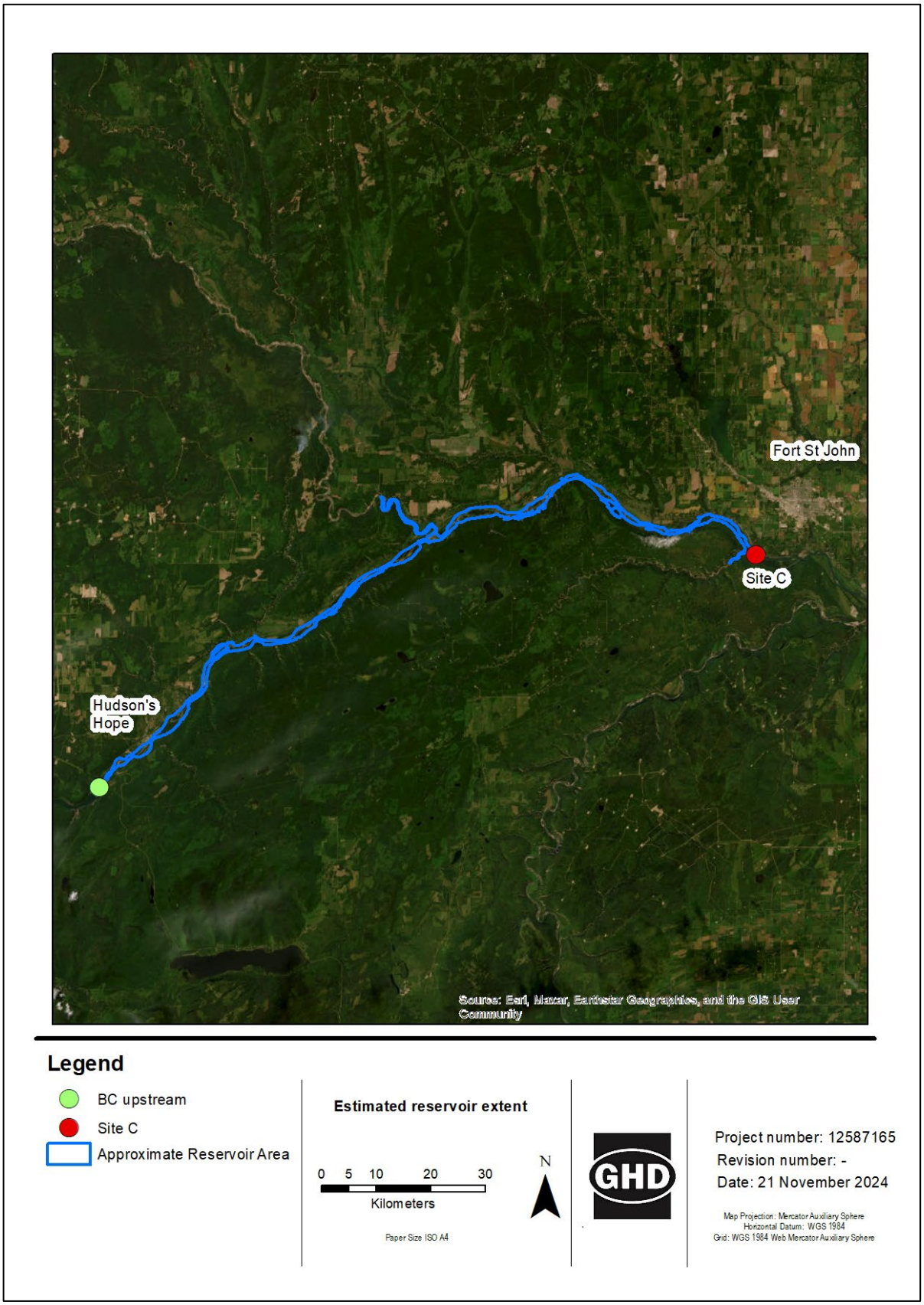

Figure 1.1 Estimated Reservoir Extent

2. Literature Review

Since there are no established guidelines in Canada for this type of study, GHD conducted a comprehensive literature review to gain an understanding of main GHG emission sources, factors impacting GHG emissions from hydroelectric reservoirs, and measurement methods and technologies that can be used for the program design. Several studies have been completed over the past 20-years to investigate the GHG footprint of hydroelectric reservoirs and to provide guidance in the measurement of these emissions, such as the "GHG Measurement Guidelines for Freshwater Reservoirs" (Guideline) by IHA/UNESCO (2010). Previous studies identified that emissions from tropical reservoirs are typically higher due to higher temperatures and decomposition rates (St. Louis et al., 2000) than the limited GHG emissions from reservoirs in cold and temperate climates (IHA/UNESCO, 2010). For the purposes of this project, the literature review focused on reservoirs in cold and temperate climates, which would better reflect the conditions at Site C reservoir area.

GHD also evaluated different available monitoring methods and their applicability to Site C, considering cost effectiveness, reliability of operation (durability/low maintenance), data analysis requirements, and suitability for continued use into the post-impoundment Monitoring Program. This review identified the key variables that influence GHG emissions and are relevant to the post-impoundment monitoring planning.

2.1 Consideration of Net Emissions

To accurately estimate the GHG emissions resulting from the creation of a hydroelectric reservoir, the concept of net GHG emissions must be considered. Areas that are flooded to create reservoirs are usually made up of a variety of ecosystem types (e.g., terrestrial, wetland and aquatic). These different ecosystem types support different ecosystem units, each with their own GHG balance, being either sources or sinks (Prairie et al., 2018). Terrestrial ecosystems include upland forests, floodplains, grasslands, and agricultural fields. Wetlands include bogs, fens, marshes, and swamps. Aquatic ecosystems include rivers, ponds, and other open water features that support aquatic organisms.

Net GHG emissions from a reservoir can be estimated by determining the difference between pre-and post-impoundment emissions from the reservoir area (IHA/UNESCO, 2010). During the operational period, the pre-impoundment emissions should be subtracted from the operational emissions (post-impoundment) to estimate the net emissions from a reservoir over the years. Although some studies showed carbon neutral conditions and small GHG emission prior to flooding of the reservoir area (Hydro Quebec Eastmain-1 reservoir in northern Quebec), this may not apply to all reservoirs.

The pre-impoundment landscape and the carbon stocks in the different ecosystem types present in the pre-impounded reservoir area will impact the spatial variation in reservoir surface emissions after impoundment (Brothers et al., 2012; Teodoru et al., 2010). To accurately capture the net GHG emissions from a reservoir area, it is important to have a good understanding of the ecosystem types present in the undisturbed area prior to the reservoir flooding.

GHD has conducted preliminary sampling and reviewed historical data to better understand the pre-impoundment conditions within the Site C reservoir footprint area. A pre-impoundment emissions estimation will be completed and utilized as part of the future net emissions calculation and reporting. GHD may also consider additional measurements at representative reference sites alongside the post-impoundment Monitoring Program to further refine the pre-impoundment GHG emissions estimation if necessary. Where applicable, GHD will use similar studies and publicly available data to estimate the pre-impoundment GHG emissions and sinks from ecosystems disturbed during the pre-impoundment monitoring program.

2.2 GHG Emission Sources and Pathways in Hydroelectric Reservoirs

Emissions from reservoirs are dependent on a variety of factors including location, climate, reservoir morphometry, time since flooding, watershed properties, flooded vegetation types, and reservoir management (Teodoru et al., 2012; IHA/UNESCO, 2010).

To fully understand the impacts of a reservoir creation and calculate net GHG emissions, it is important to identify potential GHG emission sources/sinks during different reservoir phases (pre-impoundment, construction, and post-impoundment) and understand the carbon cycle and carbon pathways in each phase. Freshwater reservoirs process and transport carbon much like other inland aquatic systems by receiving, converting, storing, and emitting (Prairie et al., 2018). However, in general, the creation of a reservoir changes the natural carbon pathways and dynamics of systems within the reservoir's area (Jager et al., 2022).

1.1.1 GHG Emission Sources

The GHG species expected to be emitted from reservoirs include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (IHA/UNESCO, 2010). The source of carbon for CH_4 and CO_2 emissions from reservoirs are usually derived from the organic matter (OM) from the catchment, OM produced in the reservoir, and breakdown of OM in flooded soils and vegetation. The source of nitrogen for N_2O emissions can be both from anthropogenic and natural activities. This is explained in further details below:

– Carbon Cycle in the Catchment: In a natural catchment, in terrestrial ecosystems, the main source of carbon is the atmospheric CO_2, which is converted to OM by plants during photosynthesis. The OM could partly be transferred to soil as Soil Organic Carbon or stored in the living plant. CO_2 and CH_4 can be produced under oxic and anoxic soil conditions. Lowland soils, closer to the river basin and usually anoxic, may be a source of CH_4 while aerobic CH_4 oxidation occurs in upland soils, producing CO_2. Runoff carries part of the carbon into aquatic components of the system. OM that was stored in soil is converted and released as CO_2 or CH_4 or can be stored in the aquatic system (IHA/UNESCO, 2010).

– CO_2 fluxes at terrestrial ecosystems are expressed by the Net Ecosystem Exchange (NEE) which shows the balance between the CO_2 uptake through photosynthesis and release through respiration (NEE>0 as C-source, NEE<0 as C-sink). Net Ecosystem Productivity (NEP) represents the annual carbon stock for a specific location which includes the CH_4 fluxes, loss of carbon from forest fires, insect outbreaks, and dissolved organic carbon (DOC) export (NEP>0 as C-sink, NEP<0 as C-source).

– Carbon Burial: Reservoirs can act as sediment traps by accumulating carbon in sediments (IHA/UNESCO, 2010). Carbon burial in reservoirs can occur with high sediment deposition rates and anoxic conditions that limit mineralization of the organic carbon in the sediment (Jager et al., 2022).

– GHG Production in Reservoirs: GHGs may be produced in reservoirs by microbial decomposition of the OM in the reservoir footprint area after flooding (Deemer et al., 2016).

CO_2 is produced in the reservoir water column and in the flooded soils and sediments in oxic and anoxic conditions and is consumed in eutrophic zones of reservoir (by aquatic primary producers) (IHA/UNESCO, 2010). There may also be flux through plant stems (macrophytes) on the surface of the water. CO_2 makes up the largest type of emission from a reservoir. It can account for up to 80% of a reservoirs GHG emissions (UNESCO/IHA, 2010).

CH_4 is produced under anaerobic conditions in reservoirs, usually in the sediments. Under aerobic conditions, methanotrophic bacteria will oxidize some of this to CO_2 (IHA/UNESCO, 2010). Boreal reservoirs are generally colder and do not develop anoxic conditions that would generate CH_4 (Teodoru et al., 2012). In boreal systems, most CH_4 is oxidized before it can be emitted to the atmosphere (Brothers et al., 2012). There may also be flux through plant stems (macrophytes) on the surface of the water. Methane has a 100-year global warming potential (GWP) of 28 times that of CO_2 (IPCC 5th Assessment Report, 2014).

N_2O can be produced by anthropogenic activities (agriculture, sewage treatment, fossil fuel combustion, etc.) and in natural processes (microbial production) (IHA/UNESCO, 2010). Microbiological processes that produce N_2O as a by-product (nitrification and denitrification) occur at the sediment water interface and in water columns with elevated levels of organic matter (IHA/UNESCO, 2010). Higher N_2O emissions are found in tropical climates. This is thought to be due to the influence of higher temperatures on microbiological processes producing N_2O. Tropical forests also have higher nitrogen availability than those in boreal and temperate areas (IHA/UNESCO, 2010). In boreal reservoirs, N_2O emissions make up significantly less of the gross GHG emissions (usually less than 1%) (IHA/UNESCO, 2010). N_2O has a 100-year GWP of 265 times that of CO_2 (IPCC 5th Assessment Report, 2014).

No detectable N_2O concentrations were found during preliminary sampling in October 2022. This agrees with the literature as insignificant N_2O emissions are expected from reservoirs in boreal climates GHD has not planned for any N_2O emissions measurements during the post-impoundment emissions due to the limitations in time and budget as well as the accessibility limitations to the potential N_2O emissions hotspots within the flooded areas.

1.1.2 Emission Pathways from Reservoirs

The GHG emission pathways in hydroelectric reservoirs include diffusion at the reservoir surface, bubbling, downstream emissions (mainly due to degassing at the turbines and downstream diffusive/bubbling emissions), and emissions from the plant stems on the benthic surface of the reservoir (Demarty and Tremblay, 2017) which are expected to be low emissions in Canada. Of these, degassing and downstream diffusive emissions are only expected after impoundment of the reservoir area and dam operation, while other pathways may be present both pre- and post-impoundment. Following sections provide more information for each pathway.

1.1.2.1 Diffusive Emissions – Reservoir

Diffusive emissions occur when gas concentrations in the water become greater than in the atmosphere. The dissolved gases travel across the water-air interface and are emitted to the atmosphere. Flooding of carbon-rich soils causes production of diffusive CO_2 emissions (Jager et al., 2022). CO_2 diffusive emissions are increased in areas with higher temperatures and OM, and are usually observed in deep areas of reservoirs (Jager at al., 2022). Higher CH_4 diffusion rates are usually observed if there is a large amount of organic material with favouring methanogenesis conditions and it is more significant in high surface area reservoirs.

Diffusive emissions can be a challenge to estimate, as they typically have high spatial and temporal variance within a reservoir (Rust et al., 2022). Diffusive emissions can be measured using floating chambers, eddy covariance (EC) systems, or the thin boundary layer (TBL) method (IHA/UNESCO, 2010). More details on measurement methods can be found in Section 2.3.

1.1.2.2 Emissions from Ebullition – Reservoir

Compared to CO_2 and N_2O, CH_4 is less soluble in water and will form bubbles when produced in water (Deemer et al., 2016). CH_4 ebullition emissions occur in shallow areas of reservoir where the hydrostatic pressure is insufficient to dissolve the gas in the water (IHA/UNESCO, 2010). Also, they can be expected in areas with enough depth that bubbles can form, but not too deep that oxidation occurs before the bubbles reach the water surface, usually in areas 3 – 6 m deep (Jager et al., 2022). The CH_4 ebullition emissions may increase during drawdowns or high temperatures at the shallower areas of the reservoir with abundant vegetation and depending on the conditions, the ebullition fluxes may vary from 0 to 99.6% of the total CH_4 flux from reservoir water surfaces (Deemer et al., 2016) with a global average contribution of 65% of the total CH_4 emissions from freshwaters (Jager at al., 2022). Demarty and Tremblay (2017) found that bubbling contributed much less to overall emissions than diffusive fluxes in Canada.

Given the significant potential contribution of ebullition as a methane (CH_4) emission pathway, it is essential to account for ebullition emissions in any monitoring activities conducted. Methane (CH_4) ebullition can be quantified alongside diffusive emissions using EC systems. It can also be directly measured through methods such as inverted funnels, floating chamber measurements, or acoustic techniques (Deemer et al., 2016).

1.1.2.3 Degassing Emissions – Downstream

Degassing emissions occur when water drawn from the reservoir passes through the turbines and spillway in the generating station. The sudden pressure-drop and aeration causes the dissolved gases to be emitted. The monitoring area for this type of emissions would include all downstream areas with emissions that are higher than background/baseline. Higher degassing emissions would be expected if water is drawn from the deeper part of the reservoir due to the higher pressure and GHG concentrations compared to water at the surface (Deemer et al., 2016). The proportion of total emissions that come from degassing varies depending on the design of the dam and the GHG concentrations within the reservoir (UNESCO/IHA, 2010).

Degassing emissions can be estimated by determining the difference in the gas concentration upstream and downstream of the dam by taking water samples and multiplying the concentrations by the discharge flow rate (UNESCO/IHA, 2010).

1.1.2.4 Diffusive Emissions – Downstream

The influence of degassing emissions can be observed from up to 50 km downstream of dams (Demarty and Tremblay, 2017). Dissolved CO_2 and CH_4 as well as dissolved and particulate organic carbon pass through the dam and discharge into the downstream water body (IHA/UNESCO, 2010). Downstream diffusive emissions consist of the GHGs produced in the reservoir that are emitted from downstream of the dam via diffusion from the river (Deemer et al., 2016).

A simple and conservative method is to determine the difference between the measured GHG concentrations at the spillway intake (or within the conduit) and those at an appropriate distance downstream, where dissolved gas levels return to natural background levels. According to available studies, the best practice is to conservatively conduct this measurement 50 kilometers downstream of the spillway to ensure the attainment of natural background levels.

2.3 Available Monitoring Methods and Equipment

Various measurement methods are available to determine post-impoundment GHG emissions from reservoirs. The Guideline and other relevant studies provide some guidance on measurement and calculation methods for GHG emissions from different emission sources and pathways related to reservoirs (IHA/UNESCO, 2010). According to Prairie et al. (2018), there is still no standard method for measuring GHG emissions from reservoirs. The methods highlighted in this section may all be used depending on the individual reservoir and purpose of the study.

When assessing the GHG emissions from a reservoir site, it is important to analyse the potential spatial and temporal variability. Previous studies showed higher variabilities between seasons than the inter-annual measurements due to the seasonal variation in organic carbon supply, thermal stratification, irregular convective mixing, water depth, and reservoir operation (IHA/UNESCO, 2010). The spatial and temporal resolution of the sampling depends on the measurement program's budget, human resources, objectives, heterogeneity of the system, and the desired resolution. There should be a balance between choosing more measurement locations (when higher spatial variation is expected) or a smaller number of locations with more frequent measurements (when temporal variation is expected). A general principle specifies that more measurements should be collected in locations or at times of higher expected flux.

– The following sections provide detailed information on the methods and equipment that can be used for each of these measurements:

1.1.3 GHG Air Emission Measurement Methods

GHG measurements should consider all the emissions pathways upstream, in the reservoir footprint area, and downstream of the reservoir, all considered as aquatic terrain. Floating chamber, EC, and TBL methods are recommended for the aquatic diffusive surface GHG flux measurements. Open floating chambers, acoustic techniques, inverted funnels, and EC are the methods used for measuring bubbling emissions from aquatic ecosystems.

The following methods have been selected for the aquatic GHG flux measurements from Site C to be used in this monitoring campaign. The methods may need to be changed or modified during completion of the Monitoring Program based on the site conditions and the potential limitations in accessibility, and safety considerations.

1.1.3.1 Eddy Covariance System

Eddy covariance (EC) is the most widely used defensible methodology to measure carbon fluxes (NEE) directly and continuously over a large landscape. EC measures the net vertical fluxes of gaseous compounds in the turbulent atmosphere boundary layers. Fast response sensors (10 Hz) are used to measure the rapid fluctuations in gas

concentrations and wind speed in the atmosphere (IHA/UNESCO, 2010). EC calculates GHG fluxes using mean air density and instantaneous deviations in vertical wind speed and gas concentrations.

EC systems use a combination of instruments, including a three-dimensional sonic anemometer to measure wind data, gas analysers to measure target gas concentrations, and a standard meteorological instrument to provide other necessary meteorological data. These instruments are mounted on a tower or tripod (depending on the scale of the measurement footprint) and oriented on-site towards the dominant wind direction. A fast response thermocouple is often added to measure the sensible heat flux, which alternatively can be calculated using the temperature data collected by the sonic anemometer or the CO_2 analyzer.

Traditionally, EC towers are placed at sites in homogeneous areas. However, they are now used more and more in heterogeneous areas. It is important to understand the spatial homogeneity or heterogeneity of the EC monitoring area to ensure that the fluxes measured are representative of the area. One method that can be used to understand variations in fluxes around EC towers is using footprint weighted flux maps (Rey-Sanchez et al., 2022).

– Using this method, data quality control and gap filling are crucial steps in the data processing. The unreliable data (due to maintenance, power loss, malfunction, etc.) shall be eliminated from the dataset by reviewing the spatial representativity of the measurement at turbulent conditions and flux quality controls at low-turbulence conditions. The data gap filling may then be completed using the internationally acceptable methods.

EC towers can also be considered to determine net gas fluxes from aquatic environments (IHA/UNESCO, 2010). This application is relatively new and there can be some difficulties in estimating measurement footprints if installed on an island or small water bodies.

1.1.3.2 Isolation Flux Chambers

Flux chambers can be used to measure fluxes from aquatic ecosystems. In this method, GHG fluxes can be estimated by measuring the change in gas concentrations in the chamber over the isolated area (Abril et al., 2005; Guérin et al., 2007; Tremblay and Bastien, 2009). The sampling duration for flux chamber measurements can vary from 2-minutes to 90-minutes per sample location depending on the chamber volume and the intensity of the respective fluxes.

Smaller, static flux chambers equipped with floats are most applicable for use in aquatic environments (IHA/UNESCO, 2010). The lack of vegetation allows for smaller volumes, which in turn allow for smaller rates of change in gas concentration. For static chambers, ideally a fan should be used to ensure the mixing of gases inside the chamber. Additionally, the flux chamber frames must be completely sealed to ensure no leakage between the chamber headspace and the atmosphere.

2.3.1.1 Dissolved Gas Concentration Measurements

Measurements of dissolved gas concentration can be used to compare the dissolved GHG in the water immediately upstream and downstream of the dam, and immediately downstream and a significant distance downstream (i.e., 50 km). Concentrations in water samples can be directly compared, with the difference equal to the amount of GHG emitted to atmosphere (IHA/UNESCO, 2010).

Concentration measurements are useful when determining emissions between two spatial points in different parts of the reservoir's flow, particularly when one point is in proximity to the dam. The hazards associated with the dam can make flux chambers impractical. Additionally, no meteorological or atmospheric data is required for the concentration method. The method can be used to determine degassing and downstream diffusive emissions.

1.1.3.3 Thin Boundary Layer (TBL) Method

TBL method is another approach to calculate diffusive GHG fluxes over water using partial pressures at the air and water interface and an exchange coefficient. This coefficient depends on wind speed, temperature gradient across the air-water interface, water current, and rainfall. To use this method, the concentration of GHG in the air and water, the wind speed, and the water temperature must be measured (UNESCO/IHA, 2010).

The advantage of the TBL method is the quick sample collection procedure. However, the relationships determined by the method are site-specific and the theory may not be valid at high and low wind speeds (UNESCO/IHA, 2010). The assumptions made about wind speed and gas exchange coefficients can have a large impact on estimates made using TBL method (Teodoru et al., 2012). As such, flux chambers are generally preferred and considered more accurate than the TBL method (UNESCO/IHA, 2010).

2.3.1.2 Inverse Funnels

CH_4 ebullition is important to measure at shallow parts of the water and peatlands. It may have high spatial and temporal variability and can be difficult to measure (Deemer et al., 2016). The most common measurement method is the use of inverted funnel traps. These are placed below the water surface to capture bubbles rising through the reservoir water (Deemer et al., 2016). Funnels can be placed at different depths, which gives the method good accuracy (IHA/UNESCO, 2010). However, it can be difficult to capture spatial and temporal variability as funnel traps are usually only placed for short periods in few locations (Deemer et al., 2016). To ensure accurate quantification of bubbling emissions, measurements should be made over long periods (days – weeks) (IHA/UNESCO, 2010). The method can also be improved by modifying the funnel traps to include automated equipment to better measure ebullition fluxes (differential pressure sensor, optical bubble size sensor) (Deemer et al., 2016).

3. Proposed Operational Monitoring Program

The Operational Monitoring Program has been developed to measure post-impoundment gross GHG emissions with a reasonable level of precision. Additionally, the program will involve calculating net GHG emissions by comparing pre-impoundment and post-impoundment gross emissions.

3.1 Monitoring Activities

The proposed monitoring activities will incorporate a combination of different methodologies, which can be integrated to estimate the total emissions from the reservoir within a reasonable accuracy. This approach will account for spatial and temporal variations in emissions as well as all primary emission pathways within the domain. The following sections provide detailed descriptions of each method, including the proposed locations and frequencies of monitoring and sampling efforts.

3.1.1 Eddy Covariance

EC systems were selected as the monitoring method to obtain near real-time, high-frequency data over an area of the reservoir located within their footprints (approximately 100 times the height of the sensors from the water surface). This method is the only established technique for continuous direct flux emissions measurement over area sources. Utilizing this capability aids in understanding the temporal variation of emissions near the primary emission areas within the domain, facilitating more accurate data extrapolation and total net emissions estimation.

3.1.1.1 Overview

In order to quantify the GHG emissions from reservoir diffusion and ebullition, two EC systems will be positioned around the perimeter of the reservoir, as detailed below:

1. Dam EC System - the first EC system will be placed immediately near the dam area, with a footprint capturing emissions in the area immediately upstream of the dam, spillways, and turbines. The system will be located to target the least stable area of the reservoir where higher emissions are expected.
2. Midstream EC System - the second system will be placed further upstream, on the north bank of the reservoir near the Bear Flat area. This location is intended to be a more representative of the midstream emissions and will be selected to be immediately downstream of the where emission hotspots are expected (i.e. previous large wetland areas).

Both systems are designed to be portable, mounted on trailer towers, enabling their relocation in response to changes in emissions and site conditions such as hotspots, atmospheric conditions, and site access during the monitoring period. With sensors positioned at an approximate height of 10 meters, the fetch is estimated to be within 1 kilometer radius of the EC system.

Figure 3.1 and Figure 3.2 show the approximate proposed locations for the EC systems. The locations were chosen based on anticipated GHG hotspots, prevailing wind directions, and site access.

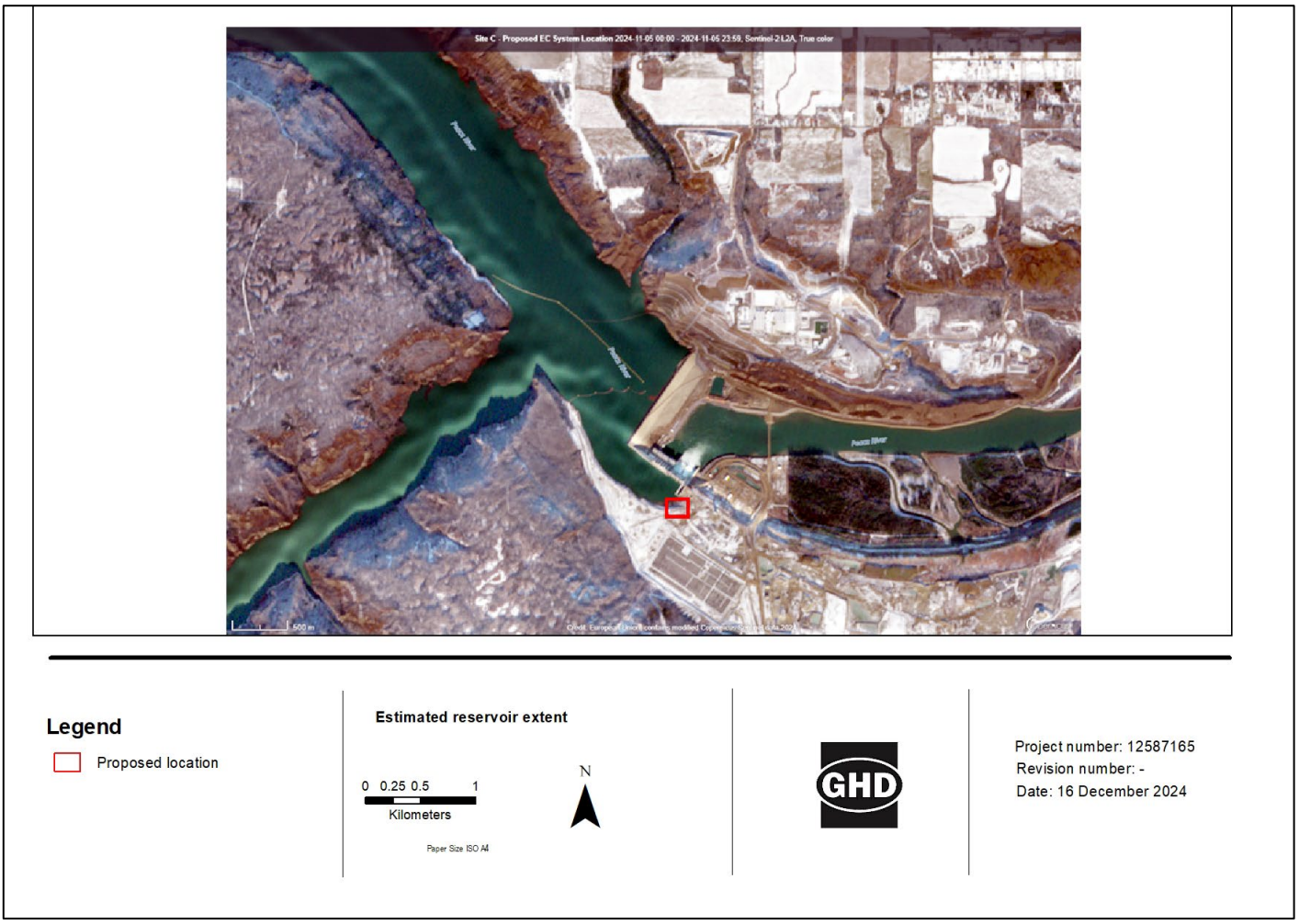

Figure 3.1 Proposed Dam EC System Location

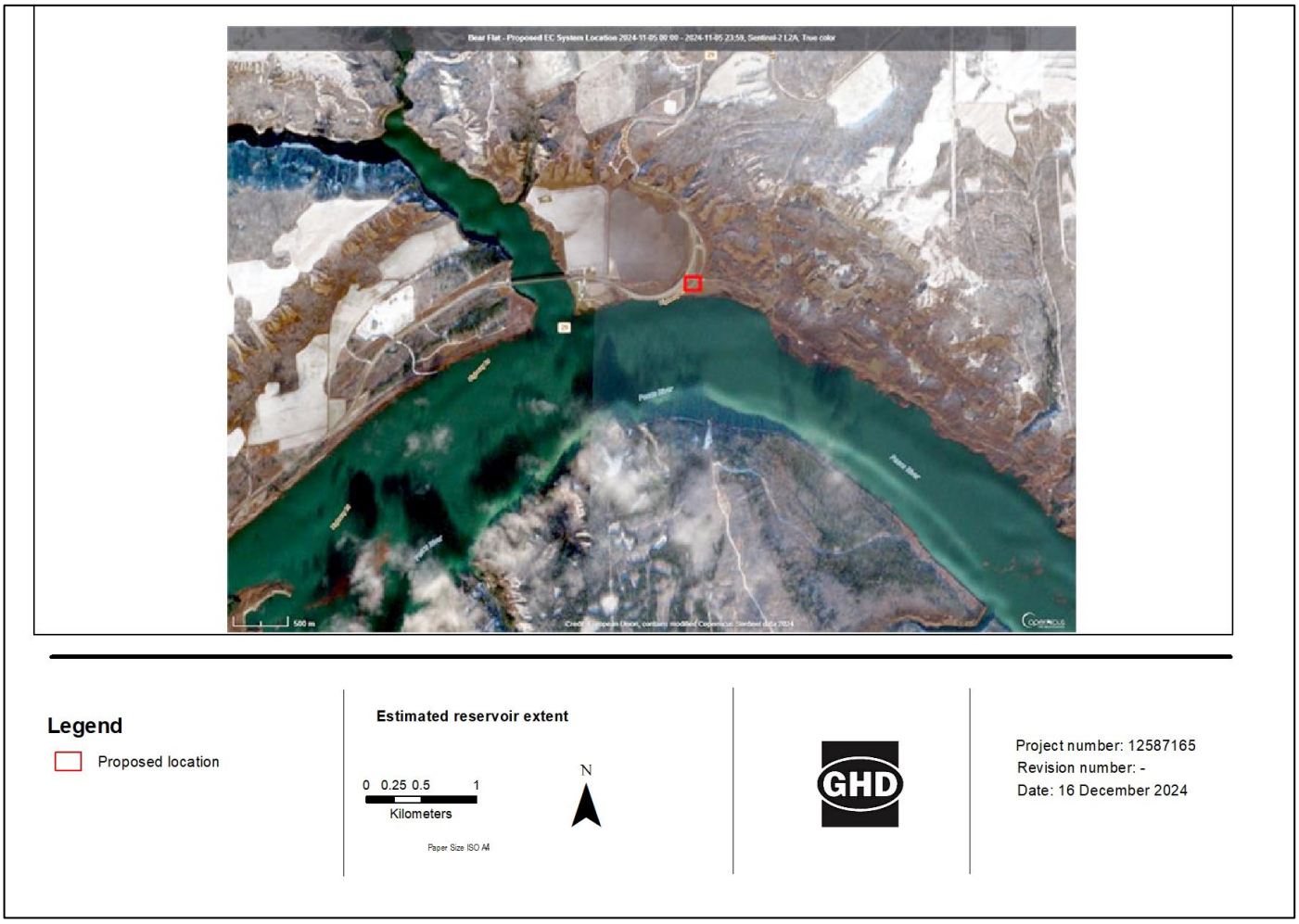

Figure 3.2 Proposed Midstream EC System Location (Near Bear Flat Area)

Table 3.1 presents the primary system components and specifications for both EC systems.

Table 3.1 Eddy Covariance System Main Components

Component	Instrument	Specifications
CO_2 Analyzer	LI-7500DS	- CO_2: 0 to 3,000 µmol/mol, ±1% accuracy - H_2O: 0 to 60 µmol/mol, ±1% accuracy - Air Temp: -40 to 70°C, ±0.25°C (-20 to 70°C) - Air Pressure: 20–110 kPa, ±0.4 kPa (50 to 110 kPa)
CH_4 Analyzer	LI-7700	- CH_4: 0–25 ppm @ -25°C, 0–40 ppm @ 25°C, ±1% accuracy
Sonic Anemometer	Gill WindMaster Pro	- Wind Speed: 0 to 65 m/s, 0.01 m/s resolution, <1.5% RMS accuracy @ 12 m/s
Biomet Instruments	Vaisala HMP155	- Humidity and Temperature Probe (0 to 100% RH and -80 to 60ºC)
	Kipp & Zonen NR Lite2	- Net Radiometer (-200 to 1000 W/m^2)
Datalogging and processing	SmartFlux 3 System	- Provides GPS position and time synchronization, connections for digital sonic anemometer data, a USB port for logging data to a USB storage device, and a microcomputer that runs EddyPro Software.
	Data Acquisition Module (DAqM) and Data Retention Module (DRM)	- Data pass-through devices from Biomet instrument to SmartFlux System
Remote control and data Access	- Brainboxes SW-508 network switch - AirLink RV50X Modem SIERRA WIRELESS	- Instrument settings control and data access using cellular communication
Measurement Frequency	All instruments	- Operate at 10 Hz - Data averaged in 1-minute increments - Analyzed in 30-minute batches

3.1.2 Flux Chambers

Flux chambers were selected to capture spatial variations in GHG emissions, specifically over the reservoir shallow areas. The results from flux chamber monitoring, combined with EC data, will integrate both spatial and temporal variations, enabling the extrapolation of emissions across the entire reservoir area. Additionally, flux chamber measurements will help identify significant changes in emission hotspot locations during the monitoring program, guiding any necessary relocation of the EC systems.

3.1.2.1 Overview

To quantify diffusive GHG emissions, flux chamber measurements will be conducted once per location per month, during ice-free periods (expected May through October) at various locations along the reservoir's edge. To ensure good spatial distribution and consistency for fair monthly comparisons, the reservoir is divided into the following segments:

1. Upstream segments: Defined as 5 km intervals for the first 20 km and 10 km intervals for the remaining reservoir length.
2. Downstream segments: Two 5 km segments, one immediately downstream of the spillways and another 50 km downstream of the dam.

Downstream segments will be used to calculate degassing and the downstream diffusive emissions, as described in Sections 2.2.2.3 and 2.2.2.4. Figure 3.3 shows the approximate segment locations. Exact measurement points within each segment will be determined based on site conditions during each month.

Data from both EC systems and flux chambers will be integrated to calculate total reservoir emissions. EC data captures the full temporal range, while flux chamber data ensures comprehensive spatial coverage.

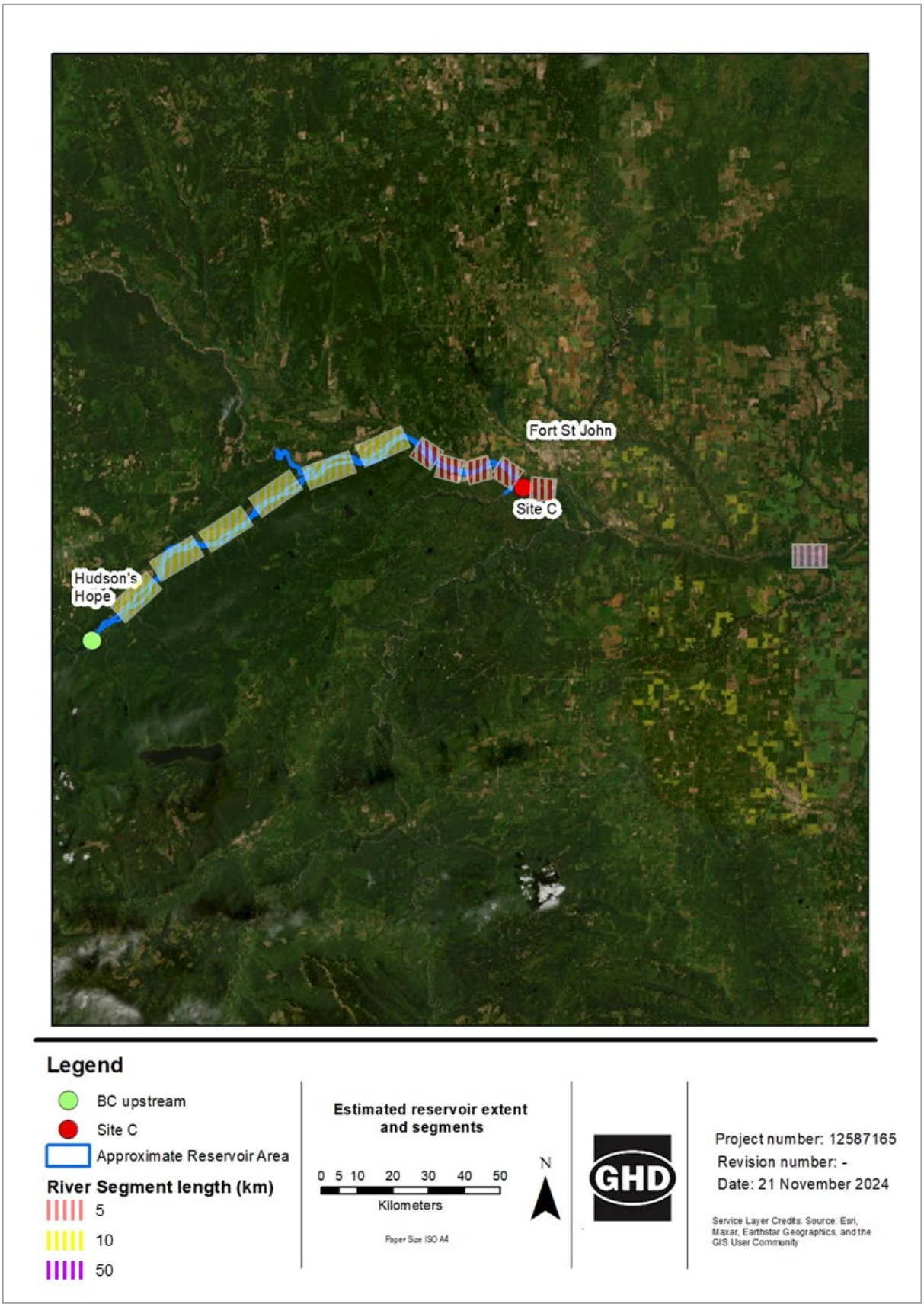

Figure 3.3 Flux Chamber Measurement Segments

3.1.2.2 Flux Chamber Design and System Components

The proposed flux chamber design is a stainless-steel isolation chamber based on the United States Environmental Protection Agency (USEPA) specifications, with a surface area of approximately 0.073 m² and a volume of approximately 0.020 m³.

The chamber will operate in static mode, connected to a $CO_2/H_2O/CH_4$ gas analyzer (LI-7810, LI-COR Biosciences) to continuously measure gas concentrations in a closed-loop system, where the analyzer's outlet directs gases back to the chamber. If issues arise during measurements, a dynamic system may also be considered as an alternative.

Readings will be recorded over 20-minutes, with the rate of gas concentration change used to calculate GHG fluxes at each measurement location.

To accommodate measurements on the reservoir surface, a floating system has been designed to minimize interference with the reservoir's natural flow.

3.1.3 Dissolved Gas Concentration Measurements

Measurements of dissolved GHG concentrations were chosen as a monitoring method to effectively capture the spatial variation of emissions in the midstream. The results can be incorporated into the annual emissions estimation and serve as an indicator for emission hotspot migration during the monitoring program.

3.1.3.1 Overview

Measurements will be undertaken by collecting water samples and sending them to a third-party laboratory for analysis. Specifically, these results will be utilized in conjunction with the flux chamber measurements to estimate degassing and downstream diffusive emissions.

Degassing emissions from the turbines and spillways can be estimated by subtracting the CO_2 and CH_4 concentrations in the water immediately downstream from those immediately upstream. Water samples should be taken within 500 meters of either side of the dam, or as close to 500 meters as is safe and practical. The difference in dissolved GHG concentrations, multiplied by the total dam discharge (including both spillway and turbine throughputs), will provide the total degassing emissions.

Downstream diffusive emissions can also be determined by subtracting the CO_2 and CH_4 concentrations in the water at a significant distance downstream from the concentrations immediately downstream. Water samples should be taken approximately 50 kilometers downstream of the dam to ensure that concentrations have returned to typical background levels, unaffected by the dam and reservoir.

These measurements will be conducted at pre-established water sampling locations once per location per month during the ice-free periods of the reservoir, similar to the flux chambers.

3.1.4 Potential Alternative Methods

Two alternative approaches have been identified for potential implementation if primary methods fail to capture the full range of data required for annual emissions calculations:

1. TBL Method
    a. Not initially selected due to the complexity of determining the exchange coefficient, which is highly variable and influenced by atmospheric and aquatic turbulence, water and air temperatures, and atmospheric pressure.
    b. Flux chambers were deemed easier to deploy and more accurate than the TBL method.
2. Inverse Funnels
    a. Wind direction along with the footprint area will be analyzed to determine if EC systems can capture ebullition emissions.
    b. Since flux chambers are impractical for slow-releasing ebullition emissions, inverse funnels may be deployed if the footprint of the EC systems does not sufficiently cover shallow, ebullition-prone areas.

During the first year of operational monitoring, observed meteorological conditions (e.g., wind direction) and measured GHG concentrations will be assessed to ensure all emissions pathways are captured. If data gaps are identified, the TBL and inverse funnel methods may be implemented. In such cases, the monitoring plan will be updated and resubmitted with a detailed plan for these methods.

3.2 Data Analysis

The following general data analysis activities will be performed. The detailed approach will be provided as part of the annual report:

1. EC System Measurements – The EC system data analysis will primarily be conducted using EddyPro 7.0.9 (LI-COR Biosciences) with advanced mode calculations. If additional data gap filling or corrections are required, GHD will perform post-processing using in-house R scripts developed specifically for this EC application. During the data analysis, one or a combination of the following correction methods will be considered:
    a. Double-coordinate rotation method by Wilczak et al. (2001): In the ideal situation, the anemometer needs to be leveled using the instrument's built-in round leveler. However, it is sometimes difficult or impossible to completely level the anemometer considering the site conditions and uneven ground. Therefore, the double-coordinate rotation will be applied to correct for the tilt of the sonic anemometer during analysis. The correction aims to align the vertical axis of the anemometer perfectly perpendicular to the wind vectors.
    b. Humidity correction of sonic temperature: Correction of air temperature estimated via sonic temperature will be made for accounting the effects of humidity. This includes mean temperature values as well as any covariance (and related fluxes) that include sonic temperature.
    c. Frequency Response Factor: Some frequency losses may occur due to path averaging, sensor separation, and their response times (Burba, 2021). A co-spectral model or other applicable method, will be used to make a correction for this factor during analysis.
    d. WPL correction for the air density fluctuations by Webb et al. (1980): Concentrations will be corrected for variations in temperature and humidity for all measured gas concentrations.
2. Flux Chamber Measurements – Since the measurements will be conducted in static mode, flux calculations will be based on the cumulative mass of GHG measured by the analyzer over the measurement period per area isolated within the chamber. This approach will produce a normalized emission flux since continuous homogeneous emissions are not expected from the reservoir area.
3. Dissolved Gas Concentration Measurements – While these measurements will primarily be used to observe dissolved gas variation trends within the reservoir, this method will also provide a conservative estimate of emissions by comparing data points from nearby locations. These estimates will be utilized to validate the flux chamber measurement results and to develop statistical extrapolation factors, which will be applied to integrate the data into total annual emissions calculations.

3.3 QA/QC Protocols

Quality Assurance/Quality Control QA/QC protocols will be implemented to enhance transparency, consistency, comparability, completeness, and confidence in the GHG monitoring program. These procedures will include:

– A QA/QC management plan.
– Instrument operation and calibration requirements.
– Sample preparation and handling protocols to prevent contamination and deterioration.
– Replicate measurements to ensure data reliability.
– Laboratory internal controls.
– Comprehensive data validation processes.

Regular accuracy checks will be conducted on data acquisition, measurement methods, calculations, uncertainty assessments, data management, and reporting procedures. Quality assurance measures will ensure that all procedures align with study objectives.

Each GHG sampling method will utilize specific data analysis and processing methodologies. Detailed QA/QC procedures for each monitoring method will be outlined in the annual reports.

3.4 System Maintenance

GHG monitoring equipment will be maintained in accordance with vendor guidelines and equipment specifications. GHD personnel will visit the site approximately once per month to perform routine maintenance. Additional site visits will be arranged promptly in response to critical issues, such as connectivity loss or physical damage. Adhering to effective maintenance procedures and schedules will help ensure system longevity, high data quality, and data completeness.

3.5 Annual Methodology Review

The monitoring program outlined above has been designed based on the anticipated reservoir conditions during the first year of GHG monitoring. As part of the annual reporting process, GHD will review all methods employed to quantify GHG emissions, identify any data gaps, and provide recommendations for future monitoring activities. If changes to the program are deemed necessary, GHD will update the monitoring plan and submit it to the BC EAO for review and approval.

3.6 Reporting

Per Condition 65 of *Environmental Assessment Certificate #14-02* issued by the BC EAO, the operational phase GHG monitoring program must include "a reporting structure for reporting results at least annually." Table 3.2 includes the proposed reporting schedule. Annual reports will be submitted to the BC Ministry of Environment (MOE) and Environment and Climate Change Canada (ECCC).

The annual reports will include, but are not limited to, the following key information:

- A summary of all monitoring activities conducted over the past calendar year.
- A summary of all maintenance activities performed over the past calendar year.
- A detailed description of data analysis methods and QA/QC activities applied to the collected data.
- Comprehensive monitoring results, including quantification of GHG emissions, comparisons to previous reporting years, and evaluation against estimated values from the EA application modelled results.
- Recommendations for the following year's monitoring program, including updates to monitoring activities, potential new methods for data analysis and emissions estimation, and enhancements to QA/QC procedures and reporting.

3.7 Monitoring Program Schedule

Table 3.2 provides the proposed program schedule and submission deadlines:

Table 3.2 Proposed Operational Monitoring Program Schedule

Operational Monitoring Program Activity	Proposed Schedule	Deadline per EAC #14-02
Eddy covariance station setup and testing	31 March 2025	N/A
Draft GHG Monitoring Plan submission for regulatory review and approval	26 January 2025	Within 90 days after commencement of operations
Final GHG Monitoring Plan submission	27 March 2025	Within 150 days after commencement of operations
Begin GHG monitoring for reporting purposes	1 April 2025	Within 180 days after commencement of operations
Annual report submission	31 April 2026, annually thereafter	Annually

4. Disclaimer

This report has been prepared by GHD for British Columbia Hydro and Power Authority and may only be used and relied on by British Columbia Hydro and Power Authority for the purpose agreed between GHD and British Columbia Hydro and Power Authority. GHD otherwise disclaims responsibility to any person other than British Columbia Hydro and Power Authority arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report. The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report.

If this report is required to be accessible in any other format, this can be provided by GHD upon request.

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