Inter-American Development Bank

# Assessing the Risk of Greenhouse Gas Emissions from Reservoirs

Environmental Safeguards Unit

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## 1. Executive Summary

1.1 Hydropower accounted for 52% of all electricity consumed in Latin America and the Caribbean (LAC) in 2012, the largest source of electricity in the region.[1] Hydropower will continue to be exploited by countries in LAC: there are an estimated 608 GW of hydropower potential in the region (IPCC 2011), which contains 32.6% of the world's freshwater resources.[2] In addition to hydropower, water stored by reservoirs is used for irrigation, is consumed by manufacturers, and serves as an important municipal utility. Water storage may also provide security against erratic rainfall patterns associated with climate change.[3]

1.1 While reservoirs provide multiple benefits, they may also produce greenhouse gas emissions under certain conditions (Le, et. al 2014). Several factors may contribute to the supply, generation, and release of greenhouse gases from reservoirs, including reservoir age and latitude, existing soil and vegetation types, and organic matter and nutrient inflows, among others (Barros, et.al 2011).

1.2 Generally, there is a greater risk of emissions from reservoirs located in tropical and subtropical zones compared to those located in temperate zones, making the topic especially pertinent to LAC countries. To date, the number of measurements of greenhouse gas emissions from reservoirs in LAC has been limited (see Annex E). In the worst case, total greenhouse gas emissions in 2005 from the reservoir of the Balbina Hydroelectric Dam in Brazil were estimated to be 3 Tg $CO_2e$ $yr^{-1}$, giving the plant an estimated emissions density of 2.9 $tCO_2e/MWh$ (Kemenes, et. al, 2011).

1.3 The IDB promotes sustainable hydropower at the regional level through supporting dams that meet international best practices and comply with IDB environmental and social safeguard policies. Directive B.11 on Pollution Prevention and Abatement of the Bank's Environmental and Social Safeguards Compliance Policy (OP-703) mandates emissions to be calculated and reported annually for operations that are expected to produce significant amounts of greenhouse gases. In addition, the Bank's Sustainable Energy Sector Guidelines (GN-2613) states that new hydroelectric plants should have a positive contribution to GHG balance. As a result, the IDB will assess and manage the risk of greenhouse gas emissions from reservoirs associated with hydropower and water storage operations.

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[1] At a level of 752,057 GWh/year. IDB Energy Database, 2012. http://www.iadb.org/en/topics/energy/energy-database/energy-database,19144.html

[2] FAO AQUASTAT, http://www.fao.org/nr/water/aquastat/main/index.stm

[3] From an energy systems perspective, hydropower may allow for overall emission reductions— both directly, by displacing fossil fuel generation, and indirectly, by providing flexible generation and energy storage. In addition, energy storage provided by hydropower may enable additional sources of generation, such as wind and solar power.

1.4 Cognizant that scientific understanding of greenhouse gas emissions from reservoirs and possible mitigation options continues to evolve, the purpose[4] of the following technical note is to orient the IDB Group's Environmental Safeguards Specialists in their assessment and management of reservoir emissions risk. The note consists of the following structure: (i) a summary of the current knowledge about reservoir emissions; (ii) a conceptual framework for the assessment of reservoir emissions risk; (iii) procedures for IDB Group Environmental Safeguards Specialists to follow in order to screen for reservoir emissions risk and to provide due diligence on borrower capacity; and (iv) a brief discussion of actions that the IDB may require of the borrower to mitigate and monitor reservoir emissions risk.

## 2. Our Current State of Knowledge about Reservoir Emissions

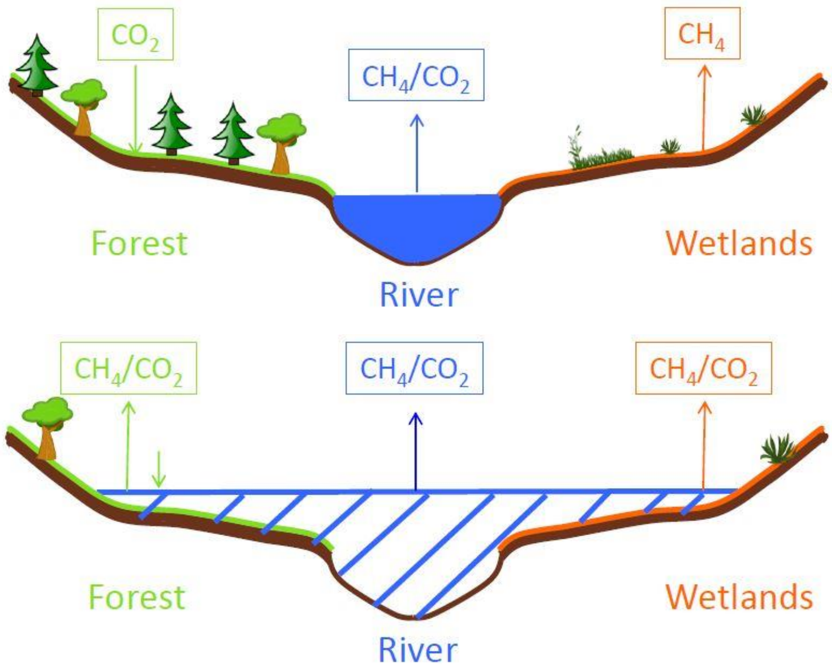
2.1 The exchange of greenhouse gases at the water-atmosphere interface includes both outward flows (from the water body to the atmosphere), and inward flows (from the atmosphere to the water body). Outward flows occur when the concentration of insoluble greenhouse gases in the water is higher than the concentration of greenhouse gases in the atmosphere. In the inverse, inward flows occur when the concentration of soluble greenhouse gases in the water is lower than the concentration of gases in the atmosphere (Mendonça, et. al 2012).

2.2 The introduction of a reservoir into a river system may alter the balance of inward and outward flows of GHGs that occur prior to impoundment **(Figure 1)**. The balance of GHG flows from reservoirs is highly site-specific, and depends on multiple variables. While many variables may lead to a higher concentration of GHGs in reservoirs, these same variables in different conditions may also lead to a lower concentration of GHG in reservoirs; for example, while methanogenesis of soil nutrients can occur at the bottom layer of a reservoir, trapped sediment may also serve to bury carbon (Mendonça et al. 2012, Mendonça et al. 2014, Sobek et al. 2012).

2.3 The introduction of a reservoir into a river system is not the only factor to alter the balance of inward and outward flows of GHGs. Reservoirs also collect organic matter from the watershed—both existing material from within the immediate reservoir area, as well as material that originates upstream. Due to naturally-occurring cycles, organic matter is flushed into reservoirs from the surrounding terrestrial ecosystems. Material from anthropogenic sources, such as domestic sewage, industrial waste, and agricultural runoff may also enter these systems.

[4] This technical note is not meant to provide a policy directive on the assessment and management of reservoir emissions.

**Figure 1. Reservoir Area GHG Sources and Sinks, Pre- and Post-Impoundment**



Prarie, et.al (2015)

2.4 The most common greenhouse gases that may be stored, generated, and released from reservoirs include carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$)(IPCC, 2011).[5] Most GHG production in reservoirs takes place in two areas: in the water column and in sediment **(Figure 2)**.

2.5 Methane may be stored in reservoirs when, for example, biomass, soil, or litter of high carbon content decomposes in the bottom layers of a reservoir. If the water column is thermally stratified, methane may be generated in the bottom, anoxic layer of the reservoir. Reservoirs can release $CH_4$ through the water intake for a hydroelectric dam when it is located in the anoxic bottom layer, or by bubbling to the top of the reservoir's surface. In contrast, when methane that is diffused in the water column is oxidized by bacteria upon entering oxygenated layers of the reservoir, it may be converted into $CO_2$ and released (Mendonça, et. al 2012).

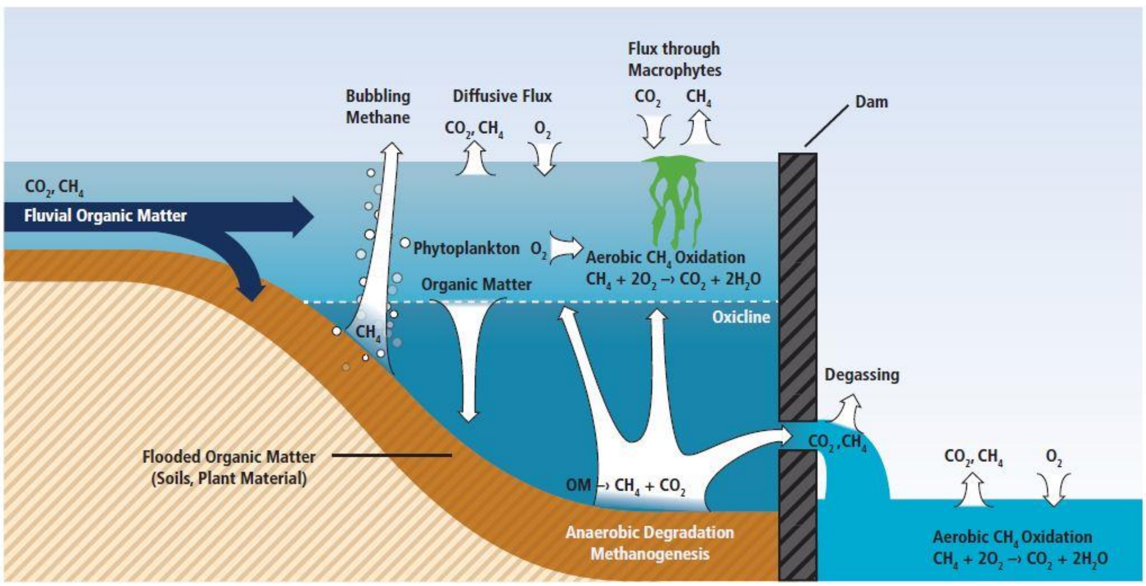
2.6 Carbon dioxide may be stored in reservoirs when, for example, biomass (vegetation, soil) containing carbon is present in the flooded area, or a significant inflow of nutrients from upstream sources (Mendonça, et. al 2012). $CO_2$ generation tends to occur in the top, oxygen-heavy hypoxic layers of stratified reservoirs, but may occur throughout the water column if stratification is low. $CO_2$ may be released through diffusive flux at the reservoir surface, or

[5] Over a 100 year period, the Global Warming Potential (GWP) of $N_2O$ is 298 times higher than $CO_2$, and that of $CH_4$ is 34 times higher than $CO_2$ (IPCC 2013). However, methane degrades faster, so the more relevant GWP for methane is 84 times $CO_2$ over a 20 year period. This higher GWP highlights the need to study the significance of methane to reservoir emission risk.

through degassing at turbines, spillways, or downstream. Major contributors to net emissions of $CO_2$ over the lifespan of a reservoir may include flooded biomass, litter, and soil carbon, as well as the removal of carbon sinks such as forests from the inundated area.

2.7 Nitrous oxide may be stored in reservoirs when upstream sources of nitrogen are deposited, such as from agricultural runoff or point sources of pollution (Le, et. al 2014). Similar to $CO_2$, $N_2O$ may be released either through diffusive flux at the reservoir surface, or through degassing. The IPCC (2006) recognized that $CH_4$ and $CO_2$ emissions from flooded areas may be significant, but found that $N_2O$ emissions tend to be less so, unless there are significant sources of nitrogen flowing into the reservoir, usually associated with upstream anthropic activities.

**Figure 2. Biochemical Production and Release of GHG Emissions from Reservoirs**




IPCC (2011)

2.8 Greenhouse gases may be released by reservoirs into the atmosphere through four major pathways. *Diffusion* refers to the exchange of molecules at the water-air interface, reflecting the difference between gas concentrations in water and in the atmosphere. Diffusion tends to occur more commonly with $CO_2$ and $CH_4$. *Ebullition* at the reservoir surface refers to the discharge of gaseous bubbles from the water body to the air. Bubbling tends to be more common for $CH_4$, as $CH_4$ has a low solubility in water, allowing methane bubbles formed in the bottom layer or sediments of reservoirs to raise to the surface (Mendonça, et. al 2012). *Emission through macrophytes* refers to the release of greenhouse gases from aquatic plants that are found on, near, or submerged below a reservoir's surface. This pathway tends to be less significant for deep reservoirs. *Degassing* refers to the rapid emission of gases found in the reservoir by turbines, due to differences in pressure and temperature. Degassing is common for both $CH_4$

and $CO_2$, and may occur via the spillway or downstream of a dam, where the dissolved gases have mixed with shallow water. Factors both internal and external to the reservoir may influence how or whether emissions are released.

2.9 Due to differing levels of gas solubility in water, different GHGs tend to dominate the different emission pathways. Each gas' solubility in water relative to air determines the direction of flow of GHGs between a given reservoir component and the atmosphere. $CO_2$ tends to dominate in diffusive emissions, while $CH_4$ tends to dominate bubbling emissions. Degassing at turbines, spillways, and downstream tend to be dominated by both $CO_2$ and $CH_4$.

2.10 External climatic factors may act as stressors that increase the risk of GHG being released from a reservoir. These include wind speed and direction, precipitation, temperature, and the shape and location of the reservoir in the watershed. Reservoirs located in the tropics tend to emit larger quantities of greenhouse gases, of special relevance to IDB investments in Latin America.

## 3. A Conceptual Framework for Assessing Reservoir Emissions Risk

3.1 Over the past years, multilateral institutions have worked towards the creation of a conceptual framework for the assessment of reservoir emissions risk. The IHA-UNESCO developed a guideline and tool in 2010 to assess *gross* reservoir emissions, defined as the total amount of greenhouse gases released by a reservoir body during operation (IHA-UNESCO 2010).

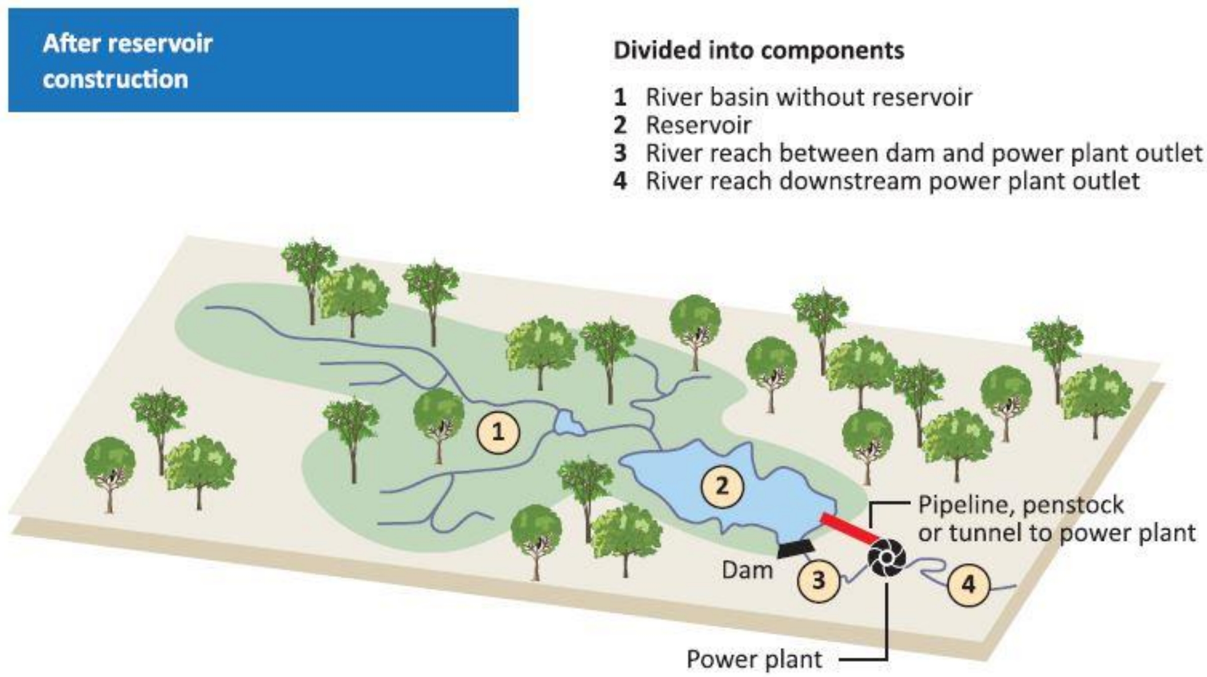
3.2 Nonetheless, rivers, lakes, and water bodies naturally produce greenhouse gases prior to impoundment, while unrelated, upstream anthropogenic emissions may be collected in the reservoir. Similarly, soils in a watershed naturally sequester carbon prior to impoundment, while increased sedimentation due to impoundment may further sequester carbon. Therefore, any assessment methodology must attempt to distinguish between naturally-occurring emissions, unrelated anthropogenic emissions, carbon burial, and emissions that result from impoundment. The IPCC (2011) defined biochemically generated *net* emissions from reservoirs as 1) gross reservoir emissions minus 2) emissions occurring naturally in the area's ecosystem prior to impoundment, minus 3) emissions related to inflow from the upstream ecosystem caused by human activities. In other words:

***Net emissions =***

*Gross emissions –*
*Pre-impoundment emissions –*
*Unrelated anthropogenic emissions*

3.3 Following the IPCC, the IHA-UNESCO Working Group on Greenhouse Gas Status of Freshwater Reservoirs and the International Energy Agency Annex XII 2012 Hydropower Agreement developed guidelines for performing quantitative analysis of net GHG emissions from human-made reservoirs, containing advice and recommended procedures for performing measurements, data analysis and modeling. The conceptual framework described in the Scoping Paper of IHA-UNESCO (2008) and the Volume 1 (2012) of the IEA guidelines further divides the assessment of net reservoir emissions into spatial components **(Figure 3)**.

**Figure 3. Reservoir Components for GHG Measurement**




IHA-UNESCO (2010)

3.4 A World Bank Interim Technical Note (Liden, 2013) provides guidance for the assessment of reservoir emissions risk. Following the conceptual framework established by the IHA, the IPCC, and the IEA, the Technical Note conceives of reservoir emissions risk as an expression of the ability of the spatial components to 1) stock greenhouse gases; 2) generate greenhouse gases; and 3) emit greenhouse gases.

3.5 *The Ability to Stock GHG.* An impounded area's ability to stock GHG refers to whether the reservoir will serve to store and/or receive high levels of organic matter found in biomass. The ability to supply a stock of GHG may be influenced by factors such as:

(i) The size of the surface area of the reservoir
(ii) The percentage of forested land cover in the area of impoundment

(iii) The density, quantity, and type of surrounding vegetation, plus the age and decay rate of the biomass present
(iv) The level of carbon content found in the area´s existing soil

3.6 *The Ability to Generate GHG.* A reservoir´s ability to generate GHG refers to the likelihood that gases will be produced by a reservoir's stock of organic matter. The ability to produce GHG may be influenced by factors such as:

(i) The temperature of the water body and the external air temperature
(ii) The duration of water retention in the reservoir
(iii) The degree to which the water body is thermally stratified
(iv) The degree to which chlorophyll and phosphorus are present in the water body (e.g. trophic state, see Annex D)
(v) The amount of organic matter and nutrient inflow entering the reservoir from upstream areas

3.7 *The Ability to Emit GHG.* A reservoir´s ability to release GHG refers to the likelihood that gases will be released from the reservoir via emission pathways. The ability to emit GHG depends on factors internal to the reservoir as well as factors of external forcing, such as:

(i) The depth of the reservoir measured in meters (Shallow depths present higher risk for $CH_4$ release, while greater depths present higher risk for $CO_2$ release)
(ii) The degree to which the hypolimnion (reservoir bottom layer) is characterized by anoxic conditions
(iii) The extent to which the intake for downstream releases is located in an anoxic zone
(iv) The degree to which precipitation and wind act as external forces

3.8 Other factors may also play a strong role in influencing the overall risk of greenhouse gas emissions from reservoirs. These include watershed factors such as the size of the drawdown area, the reservoir's position in the river basin system, and the quantity and rate of organic matter sedimentation.

## 4. Protocol to be Followed by IDB Environmental Safeguard Specialists to Assess Reservoir Emissions Risk

4.1 In accordance with Directive B.11 on Pollution Prevention and Abatement of the Bank's Environmental and Social Safeguards Compliance Policy (OP-703), IDB Environmental Safeguard Specialists will assess reservoir emissions risk as a part of Project Screening and Due Diligence for any IDB operation which consists of the construction or rehabilitation of a reservoir.

4.2 *Project Screening.* IDB Environmental Safeguard Specialists will screen any operation or associated facility that includes a water storage reservoir for greenhouse gas emissions risk using the Reservoir Emissions Risk Screening Tool (Annex A), in order to inform the Environmental and Social Strategy (ESS). A project presents high reservoir emissions risk if a "yes" is obtained at least once in each of the three screening stages (Primary, Secondary, and Tertiary); medium risk if obtained at least once in two of the three stages; and low risk if obtained at least once in only one of the three stages.

4.3 *Due Diligence.* The IDB specialist will confirm the level of reservoir emissions risk associated with the project during due diligence by obtaining information related to pre-impoundment conditions, project design, and post-impoundment conditions, using the IDB Reservoir Emissions Risk Factor Survey (Annex B). If reservoir emissions risk is determined to be high as a result of project screening and due diligence, the IDB specialist will require a quantitative calculation or estimate of reservoir emissions associated with the project, utilizing international best practices for the quantitative assessment of reservoir emissions such as the IHA-UNESCO GHG Reservoir Screening Tool. In addition, the specialist will ascertain the capacity of the borrower to eliminate or reduce the reservoir emissions risk associated with the project through the implementation of mitigation action plans. This information will orient the project's Environmental and Social Management Report (ESMR) and Environmental and Social Action Plan (ESAP).

4.4 *Environmental and Social Management Report.* According to the level of reservoir emissions risk confirmed during Due Diligence, specific actions to be implemented by the borrower may be required in the ESMR and ESAP. Examples of possible actions follow below.

## 5. Potential Borrower Actions to Mitigate Reservoir Emissions Risk

5.1 If as a result of screening and Due Diligence it is determined that reservoir emissions risk is present, the borrower may be required to implement actions in accordance with the mitigation hierarchy, in consultation with the IDB.[6] Depending on the level of risk associated with the project, the project status, and the information available, such actions may include:

5.2 *During project preparation:*

1) *Engineering and design changes*, such as re-siting, changes to reservoir depth, surface area, and position in the basin, repositioning water intakes, or reducing residence time, based on a sound cost-benefit analysis of the proposed measures or alternatives.

2) *The realization of additional studies*, including on topics such as biomass, litter, and vegetation characteristics; soil studies to determine existing soil carbon, phosphorus, and nitrogen content; and/or water quality studies to determine whether the water body is or will be anoxic or stratified, and to determine its trophic state;

[6] Reducing reservoir emissions risk or observable reservoir emissions may aid clients in accessing lines of credit contingent on complying with emissions criteria.

3) *Basin management actions* to minimize risk during the lifetime of the operation, including collaboration with upstream producers to reduce runoff and point source pollution entering the reservoir;

5.3 *During project execution:*

1) *Project-related mitigation actions* to minimize risk during the first ten years of operation, such as through the establishment of riparian buffer zones to reduce nutrient inflows; the introduction of biotic populations to reduce nitrogen levels and suspended soils in the water column; or methane recovery through the installation of reservoir membranes.

5.4 In addition to the possible actions listed above, the borrower may also be required to create and implement a *Reservoir Emissions Monitoring Plan* in consultation with the IDB, as follows:

*1) Prior to Construction:*

   *a.* Measure naturally-occurring pre-impoundment emissions ($CH_4$, $CO_2$, and $N_2O$) and existing organic carbon sequestration in the area of impact of the reservoir.

   *b.* Measure existing unrelated anthropogenic emissions ($CH_4$, $CO_2$, and $N_2O$) that would be introduced into the reservoir system.

*2) Prior to Operation:*

   *a.* Estimate net reservoir GHG emissions ($CH_4$, $CO_2$, and $N_2O$) during the first ten years of operation and over the useful life of the plant.

   *b.* Estimate unrelated anthropogenic emissions ($CH_4$, $CO_2$, and $N_2O$) that would be introduced into the reservoir system during the first ten years of operation.

*3) Once Operation Begins:* Measure reservoir GHG emissions ($CH_4$, $CO_2$, and $N_2O$) monthly for the first ten years of operation. Adaptive management actions may be required as a result of emissions measurements.

5.5 The cost of reservoir emissions monitoring campaigns depends on the methodology used (see Annex C).

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## Annex A. Reservoir Emissions Risk Screening Tool

6.1 IDB Group Environmental Safeguards Specialists should use this tool to screen for reservoir emissions risk. Place a checkmark in the corresponding box. A project presents high reservoir emissions risk if a "yes" is obtained at least once in each of the three screening stages (Primary, Secondary, and Tertiary); medium risk if obtained at least once in two of the three stages; and low risk if obtained at least once in only one of the three stages.

| **Primary Screening: The Ability to Stock GHG** | **Yes** | **No** | **Unsure** |
|---|---|---|---|
| Is the proposed reservoir located in an area of high total soil organic carbon? (e.g. Humic soils, especially Gleysols, Histosols, or Andosols, among others) | | | |
| Is the proposed reservoir located in an area of high biomass, forest litter, or vegetation density? | | | |
| Is the proposed reservoir likely to have a large surface area (≥ 100 $km^2$)? | | | |
| Is the proposed reservoir located in tropical or subtropical latitudes? | | | |
| | | | |
| **Secondary Screening: The Ability to Generate GHG** | | | |
| Is the trophic state index of the existing water body above 40 (mesotrophic, eutrophic, or hypereutrophic)?[7] | | | |
| Is the proposed reservoir located in an area of high average monthly air temperature? | | | |
| Is the proposed reservoir likely to have a moderate to significant residence time (≥ 60 days)?[8] | | | |
| Is the proposed reservoir likely to receive moderate to significant inflows of upstream organic nutrients, such as naturally occurring sediments, runoff,[9] point source pollution,[10] atmospheric deposition,[11] naturally-occurring phytoplankton, or algae blooms? | | | |
| Is the proposed reservoir likely to experience moderate to significant thermal stratification during any time of the year? | | | |
| | | | |
| **Tertiary Screening: The Ability to Emit GHG** | | | |
| Is the proposed reservoir likely to have a shallow average depth (≤ 10 m)?[12] | | | |
| Will the hypolimnion of the proposed reservoir likely experience moderate to significant anoxic conditions? | | | |
| Will the intake of the proposed reservoir be located in an anoxic zone during | | | |

[7] See Annex D for a table of trophic values.
[8] Based on Rueda, et. al (2006).
[9] For example, runoff from agriculture/irrigation, runoff from pasture and range, urban runoff from un-sewered areas, septic tank leachate, runoff from construction sites >20,000 $m^2$, runoff from abandoned mines, atmospheric deposition over a water surface, or other land activities generating contaminants.
[10] For example, wastewater effluent (municipal and industrial), runoff and leachate from waste disposal systems, runoff and infiltration from animal feedlots, runoff from mines, oil fields, un-sewered industrial sites, overflows of combined storm and sanitary sewers, runoff from construction sites less than 20,000 $m^2$ (220,000 $ft^2$), or untreated sewage.
[11] For example, acid rain created from fossil fuel combustion or ore smelting can deposit nitrogen in water and soils.
[12] Based on Le, et. al (2014).

| | | | |
|---|---|---|---|
| any time of the year? | | | |
| Does the proposed reservoir already exist? | | | |
| If so, is it younger than 10 years old? | | | |
| Is the proposed reservoir likely to be affected by moderate to significant precipitation and/or wind speed during any time of the year? | | | |

**Annex B. Due Diligence Reservoir Emissions Risk Survey (Pre-impoundment, design, and post-impoundment)**

The IDB specialist will confirm the level of reservoir emissions risk associated with the project during due diligence by obtaining information related to pre-impoundment conditions, project design, and post-impoundment conditions, using the below survey as a guide.

7.1 Questions to ask related to pre-impoundment conditions:

a. What is the trophic quality of the existing water body? What is the dissolved oxygen concentration of the water body?
b. What are the biomass type, quantity, age, and decay rate of existing organic matter (vegetation and soils) in the reservoir area?
c. What are the existing, naturally-occurring nutrient inputs to the river system from the watershed?
d. What are the existing, anthropogenic sources of nutrient inputs to the river system from the watershed? What are the surrounding land use types?

7.2 Questions to ask related to dam and reservoir design:

a. Is the reservoir sited in a tropical or subtropical latitude?
b. Is the reservoir sited in lowland or highland topography?
c. Is the reservoir traditional storage, or run-of-the-river?
d. Is the reservoir surface area large? Is the shape dendritic, round, or narrow?[13]
e. Is the water volume large? Is the average depth of the reservoir ≤10 meters?
f. Is the water retention time ≥60 days? What is the inflow rate?
g. Is the water intake located in an anoxic zone?
h. Will biomass/organic matter be removed from the reservoir area?
i. Does the reservoir already exist? If so, is it younger than 10 years old?

7.3 Questions to ask related to post-impoundment conditions:

*Internal stressors: GHG production in water column and sediment*

a. What will be the quantity and rate of sediment retention?
b. What will be the degree of thermal stratification of the reservoir during the seasons of the year?

*External stressors: Climatic conditions*

a. Will the reservoir area be characterized by high average monthly wind velocity? What is the direction of the wind? Will there be upwelling and downwelling inside the reservoir as a result?
b. Will the reservoir area be characterized by high average monthly precipitation?

[13] Dendritic reservoirs tend to create hotspots for CH4 production and emission. See Del Sontro, et. al (2015).

c. Will the reservoir area be characterized by high average monthly air and water temperatures?

*External stressors: Watershed inputs*

a. Will the reservoir be located downstream of significant nutrient sources?
b. Is the reservoir density projected to be significantly different from river inflow density?
c. Is river inflow characterized by multiple tributaries directly upstream of the reservoir?

**Annex C. Methodologies for the Measurement of GHG Emissions from Reservoirs**

8.1 *Measurement Methodologies.* Multiple methodologies exist for the measurement of *gross* reservoir greenhouse gas emissions, according to their possible pathways (diffusive fluxes, bubbling, and degassing), possible generation sites (within sediment at reservoir bottom layers, in the water column, and at the surface), and possible release sites (the reservoir surface, turbines, spillways, and downstream). Borrowers should follow international best practices on the modeling, measurement, and calculation of GHG emissions from reservoirs, as outlined by IHA-UNESCO (2010) and IEA (2012). A summary of the most common measurement methodologies follows.

8.2 *Measuring diffusive fluxes.* The most common methodology to measure emissions via diffusive flux is through the deployment of *floating chambers*. Floating chambers are inverted containers that sit on the surface of a reservoir. The gas content of the air contained in the chamber is a known constant. Diffusive fluxes released at the reservoir surface are captured in the chamber and measured by trace gas analysis software. Floating chambers are widely used, given that they are cost effective and easily deployable.

8.3 A second methodology to measure diffusive flux is the use of *eddy covariance towers*. These are atmospheric flux measurement instruments hosted on towers usually located on islands in the middle of a reservoir. These instruments measure and analyze vertical turbulent fluxes in atmospheric boundary layers to provide an estimate of GHG emissions. This methodology tends to be more expensive and less accurate (IHA-UNESCO 2010).

8.4 One methodology used to estimate emissions via diffusive flux are *thin boundary layer calculations*. Thin boundary layer calculations consist of semi-empirical equations that estimate greenhouse gas emissions. The mechanisms of this methodology are poorly understood and resulting estimates may range considerably.

8.5 *Measuring ebullition.* The most common methodology to measure emissions via bubbling is the use of floating chambers. Chambers may be rested on the reservoir surface to capture gas bubbles expunged at the water/air interface. The chambers are coupled with gas collecting tubes filled with desiccant to prevent water condensation from affecting the samples. The collected gas samples may be analyzed *in situ* using trace gas analyzers, or analyzed *ex situ* in the laboratory.

8.6 It has been suggested that ebullition in reservoirs is underestimated by one order of magnitude (Del Sontro, et. al., 2015). This may occur because the selection of locations to deploy the chambers is frequently not based on scientific information. To correct this bias and make estimations more accurate, bubble sonars have been used. This methodology consists of using sonar that can detect bubble hotspots. Once those hotspots are detected, inverted funnels can be deployed.

8.7 *To measure degassing at turbines, spillway, and downstream.* To measure the gas content of water that enters turbines, samples should be collected at the powerhouse suction pipe, taken directly from the spiral casing (pre-turbine), through the spiral casing outflow pipe. To measure the gas content of water evacuated by a spillway, water samples should be collected at the reservoir area near the inlet structure (at a safe distance) at different depths until the crest level. To measure the gas content of downstream water, samples should be collected after the turbulence region in front of the outlet structure. The samples must be poisoned with mercury chloride (HgCl) in order to inhibit biological activities after collection, and taken immediately to the laboratory, where the concentrations of $CO_2$ and $CH_4$ dissolved in the water are measured through the headspace technique (IEA 2012).

8.8 *Measurement Analysis.* The most common technology used for the analysis of emissions measurements is trace gas analysis. A number of trace gas analyzers are commercially available.

8.9 *Spatial Considerations.* Independent of the methodology, measurements of reservoir emissions should be well-distributed spatially and temporally so as to provide abundant data. Measurement locations should be designed along multiple transects in order to produce a faithful spatial representation of the reservoir, while surface measurements should be taken at locations of high, average, and low reservoir depth.

8.10 *Temporal Considerations.* Reservoir emissions measurements should be taken at multiple time intervals, including both continuous measurements (for example, once a month) and concentrated measurements (for example, more frequent measurements during seasons of high wind speed, air temperature, or precipitation and during reservoir drawdown).

8.11 *Sediment Measurements.* The measurement of soil organic carbon in reservoir sediments may be useful in estimating the potential for either GHG burial in or emission from reservoirs (Mendonça et al., 2014). The use of seismic transects allows to model the shape of soil deposition along a reservoir’s bed, while soil coring provides an understanding of the content and composition of soil organic carbon. The seismic transects and the characterization of sediment deposition can be used to measure the carbon stock in the sediment or organic carbon burial.

**Annex D. Trophic State Index**

9.1 The amount of biomass found in a reservoir may be characterized according to the reservoir's trophic state. The trophic state expresses the quantity of nutrients found in the water body. The trophic state is defined as the total weight of biomass found in a given water body at the time of measurement.

| TI | Chl | P | SD | Trophic Class |
|---|---|---|---|---|
| <30—40 | 0—2.6 | 0—12 | >8—4 | Oligotrophic |
| 40—50 | 2.6—20 | 12—24 | 4—2 | Mesotrophic |
| 50—70 | 20—56 | 24—96 | 2—0.5 | Eutrophic |
| 70—100+ | 56—155+ | 96—384+ | 0.5—<0.25 | Hypereutrophic |

9.2 Based on Carlson (1996), total Trophic Index (TI) expresses the weight of biomass nutrients in micrograms per liter (chlorphyll-Chl and phosphorus-P), Secchi depth (SD) is the measurement of transparency in meters, and the corresponding Trophic Class. Eutrophic systems are a $CO_2$ sink but a $CH_4$ source.

# Annex E. Measurements of Reservoir Emissions from Latin America and the Caribbean Prior to 2015

Table adapted from Le, et. al (2014). Additional measurements may be found in Governo do Brasil (2014).

| | Reservoir name | Age at measurement (years) | Diffusive flux (mg $m^{-2}$ $d^{-1}$) | | Bubbling flux (mg $m^{-2}$ $d^{-1}$) | | Degassing (Tg C $y^{-1}$) | | Downstream river (mg $m^{-2}$ $d^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | CO2 | CH4 | CO2 | CH4 | CO2 | CH4 | CO2 | CH4 |
| **French Guiana** | Petit Saut | 1–10 | −440 to 16280 | 10–3200 | | 11.2–800 | 5–30 | 5–40 | 41800 | 1440 |
| **Panama** | Gatun Lake | 84 | | 10.7 | | 526.3 | | | | |
| **Brazil** | Miranda | | 4389 | 130.35 | 0.25 | 23.85 | | | | |
| | Três Marias | | 1117 | 31.85 | 3.76 | 164.5 | | | | |
| | Barra Bonita | | 3986 | 16.95 | 0.13 | 3.95 | | | | |
| | Segredo | | 2695 | 7 | 0.07 | 1.8 | | | | |
| | Xingó | | 6138 | 29.3 | 0.05 | 10.75 | | | | |
| | Samuel | 4–5 | 7448 | 87.55 | 0.5 | 16.5 | 0.052–0.076 | 65700 | 192 | |
| | Tucuruí | 8–9 | 8475 | 101.55 | 0.1 – 0.2 | 7.85 | 1.67 | | | |
| | Itaipu | 8 | 171 | 10.15 | | 0.55 | 0.31 | | | |
| | Serra da Mesa | | 2645 | 24.6 | 1.7 | 88.65 | 0.21 | | | |
| | Balbina | 18 | 13845 | 193 | 0 | 13 | 0.081 | 0.065 | 18000 | 28.4 |
| | Curuá-Una | 13 | | 36 | | 77 | 0.022 | | | |