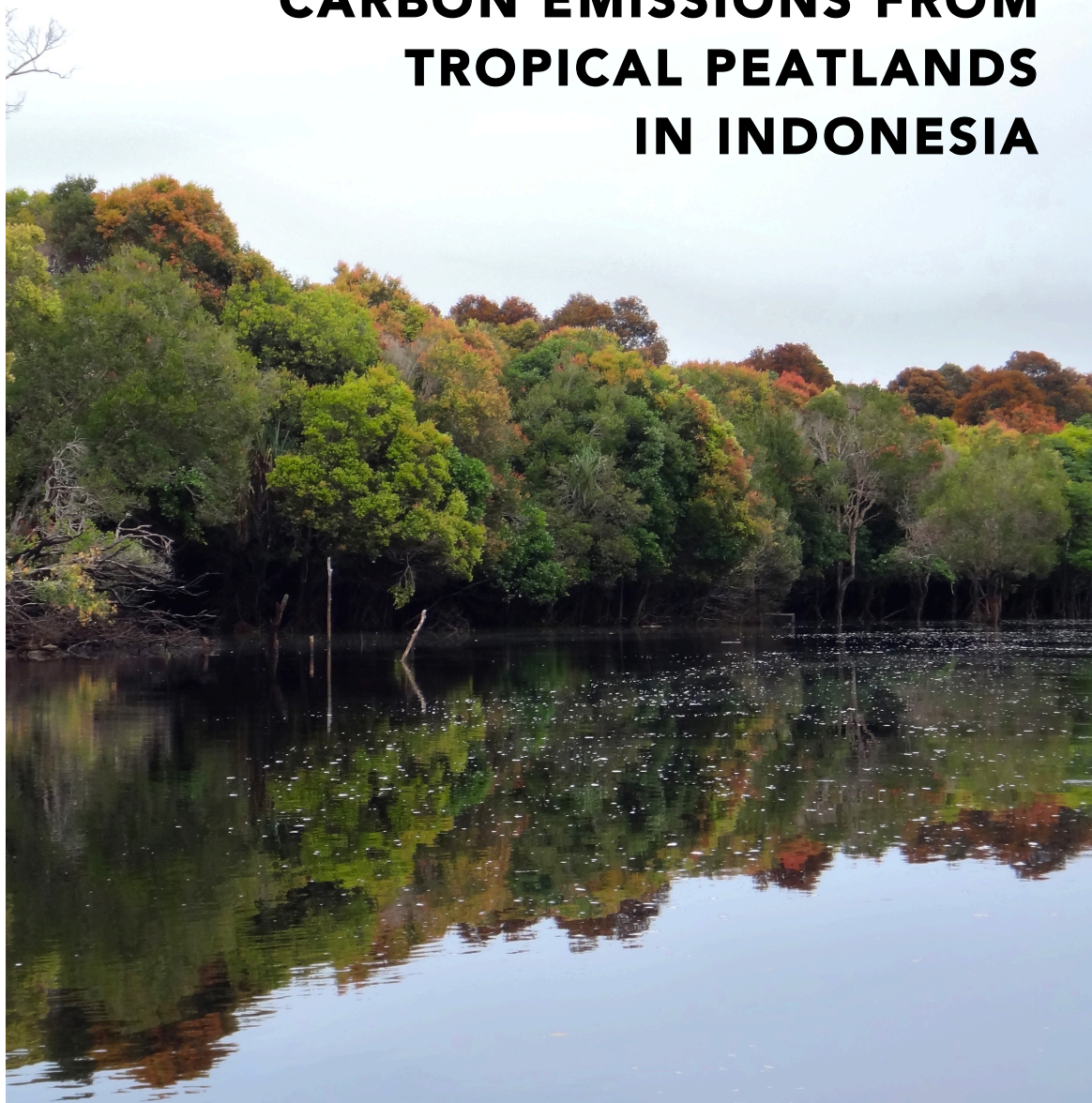


# GUIDEBOOK FOR ESTIMATING CARBON EMISSIONS FROM TROPICAL PEATLANDS IN INDONESIA



**IJ-REDD+ PROJECT**  
Indonesia-Japan Project for Development  
of REDD+ Implementation Mechanism



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# GUIDEBOOK FOR ESTIMATING CARBON EMISSIONS FROM TROPICAL PEATLANDS IN INDONESIA

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# PREFACE

Hokkaido University and Palangka Raya University have a long history of cooperation in research on tropical peatland ecosystems, dating back to 1997. The Japan International Cooperation Agency (JICA) and the Japan Science and Technology Agency (JST) have also supported this cooperation through the Science and Technology Research Partnership for Sustainable Development (SATREPS) program, a Japanese government program that promotes international joint research, with the title “Wild Fire and Carbon Management in Peat-Forests in Indonesia” for five years since 2009. These cooperation programs have generated much important research on tropical peatland ecosystems in Central Kalimantan, and many outcomes of this cooperation have been included in a recently published book edited by M. Osaki & N. Tsuji (2016), “Tropical Peatland Ecosystems”. This book, containing 651 pages and 41 scholarly articles, describes various aspects of tropical peatland ecosystems, and is the world’s first complete book on this topic.

In line with these research developments, one of the recommendations that emerged from a joint workshop between the SATREPS program and the IJ-REDD+ Project in January 2014 was to develop methodologies to mitigate climate change due to carbon emissions. To this end, an effort was needed to translate the research results into a guide that can be easily understood by all stakeholders who need it at the provincial government level. For this purpose, the IJ-REDD+ Project has coordinated and facilitated the preparation of this guidebook on estimating carbon emissions from peatlands in Indonesia with stakeholders particularly from Central Kalimantan.

To prepare this guidebook, the IJ-REDD+ Project has cooperated with a team from Hokkaido University as technical consultants, Starling Resources as the local consultant, and members of the Core Team from 5 Indonesian institutions – Environment Agency of Central Kalimantan Province (BLH Provinsi Kalimantan Tengah), Agency for the Assessment and Application of Technology (BPPT), Agency for Research and Development of Environment and Forestry (BPPLHK) Banjarbaru, and Sebangau National Park Office. We would like to express our appreciation to all parties who have supported this cooperation.

15 March 2016

Hiroshi Kobayashi  
Acting Chief Advisor  
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# ACRONYMS

|                  |   |
|------------------|---|
| AVHRR            | Advanced Very High Resolution Radiometer                                  |
| BIG              | Geospatial Information Bureau of Indonesia                                |
| C                | Carbon  |
| CH <sub>4</sub>  | Methane   |
| CO               | Carbon Monoxide   |
| CO <sub>2</sub>  | Carbon dioxide  |
| DB               | Drained and Burned Land   |
| DEM              | Digital Elevation Model   |
| DF               | Drained Forest  |
| DOC              | Dissolve Organic Carbon   |
| EC               | Eddy Covariance   |
| ECMWF            | European Center for Medium-Range Weather Forecast                         |
| ER               | Ecosystem Respiration   |
| GHG              | Greenhouse Gas  |
| GIS              | Geographic Information System   |
| GOI              | Government of Indonesia   |
| GPS              | Global Positioning System   |
| GWL              | Groundwater Level   |
| GWP              | Global Warming Potential  |
| IJ-REDD+ Project | Indonesia-Japan Project for Development of REDD+ Implementation Mechanism |
| INDC             | Intended Nationally Determined Contribution                               |
| JICA             | Japanese International Cooperation Agency                                 |
| LIDAR            | Light detection and ranging (an optical remote sensing technology)        |
| MODIS            | Moderate Resolution Imaging Spectroradiometer                             |
| MRV              | Monitoring, Reporting and Verifying                                       |
| N <sub>2</sub> O | Nitrous Oxide   |
| NDVI             | Normalized Difference Vegetation Index                                    |
| NEE              | Net Ecosystem Exchange  |
| NEP              | Net Ecosystem Production  |
| NOAA             | National Oceanic and Atmospheric Administration                           |
| OP IRGA          | Open-Path CO <sub>2</sub> Infra-Red Gas Analyzer                          |
| PALSAR-2         | Phased Array type L-band Synthetic Aperture Radar                         |

|         |  |
|---------|--|
| PAR     | Photosynthetically Active Radiation  |
| PM      | Particulate Matter   |
| RAN-GRK | <i>Rencana Aksi Nasional Penurunan Emisi Gas Rumah Kaca</i><br>(National Action Plan for Reducing GHG Emissions) |
| REDD+   | Reducing Emissions from Deforestation and Degradation<br>Plus Carbon Stock Enhancement                           |
| SAR     | Synthetic Aperture Radar   |
| SAT     | Ultra-Sonic Anemometer-Thermometer   |
| SESAME  | Sensory data transmission Service Assisted by Midori<br>Engineering  |
| SRTM    | Shuttle Radar Topography Mission   |
| UNFCCC  | United Nations Framework Convention on Climate Change  |
| WI      | Wetlands International   |



## **1.1. Background**

Indonesia holds approximately 15 million hectares of peat soil, which represents 50% of the world's total tropical peatland area (DNPI, 2014). Peatlands store a huge amount of carbon in the form of organic matter accumulated in waterlogged and anaerobic conditions. In natural conditions when peatland hydrology is intact, peatlands are capable of providing multiple environmental benefits including water regulation, carbon storage, and biodiversity maintenance.

Despite such ecological functions, peatlands have been utilized for economic development for decades. Peatland development often involves the construction of drainage canals, which inevitably lower water levels and put hydrological integrity at risk. Once peat soils are exposed to the air, they start to decompose and become dry and vulnerable to fires – which are major sources of greenhouse gas (GHG) emissions. In 2010, emissions from peat decomposition and burning contributed to 44 percent of Indonesia's total GHG emissions (DNPI, 2014).

For this reason, sustainable peatland management must be a central component in Indonesia's strategy to combat climate change and its devastating impacts on its land and people. The important role of peatlands is also reflected in the recent Ministry of Environment and Forestry decree (No. S.661/MenLHK-Setjen/Rokum/2015), as well as the national action plan for GHG (RAN-GRK). The decree not only bans the issuance of new business licenses on peatlands, but also requires concession holders to halt peatland clearing and maintain the minimum groundwater level (GWL) at 40cm.

Groundwater level is the most important environmental factor in peatland management (Shigenaga et al., 2016). This guidebook aims to provide practical methods for estimating carbon emissions from peat decomposition and burning by using real-time GWL data as a key parameter. It also provides a method for predicting GWLs for several days into the future. These models can be used for various purposes in practice, including developing science-based national and regional development strategies and early fire warning systems.

## **1.2. What is this guidebook about?**

This guidebook provides step-by-step procedures to:



- Collect spatial information from remote sensing data sources
- Collect field sampling data of GWL and other parameters
- Estimate GWL distribution based on the field samples and remote sensing data
- Establish a linear relationship (model) between carbon emissions and GWLs
- Predict GWLs several days into the future based on field sampling data.

Although the methods outlined in this guidebook were initially developed in Central Kalimantan during the JICA-JST Project from 2010 to 2014 (see Preface for the project background), this guidebook provides general procedures which are replicable for peatlands throughout Indonesia.

### **1.3. How is this guidebook organized?**

This guidebook is organized into four parts – **I.** Introduction; **II.** Carbon Emission Model; **III.** GWL Prediction Model; and **IV.** Future Considerations.

**Part I** of this guidebook provides introductory information including its structure.

**Part II** of this guidebook explains how to estimate the amount of carbon emissions from peatland due to microbial decomposition and peat burning. It is divided into four sections – 1) Data collection and processing; 2) Data analysis; 3) Carbon emission modeling from peat decomposition; and 4) Carbon emission modeling from peat burning. Based on the framework presented in Figure 1, each section provides step-by-step procedures in Sub-sections.

**Part III** of this guidebook explains how to predict GWLs several days into the future based on daily average GWL data observed in the field. Figure 17 shows the framework of the GWL Prediction Model.

**Part IV** of this guidebook suggests areas of improvements for the models explained in Part II and Part III. It also discusses the potential application of these models in practice.

### **1.4. Who is this guidebook for?**

This guidebook is intended to be used by a wide range of stakeholders in Indonesia who wish to develop and implement sustainable management practices on peatland by knowing the amount of carbon emissions from land use and land use change, and by preventing peatland fires. These stakeholders include:

- Policy makers;
- Peatland managers (such as concession holders);
- Researchers; and
- Local authorities.



## ❖ What will you learn in Part II? ❖

### ➤ How to estimate **CO<sub>2</sub> emissions from peat decomposition**

#### ✓ Key points to understand:

- Real-time GWL measured at a study area is used as a key parameter to estimate CO<sub>2</sub> emissions from peat decomposition.
- The study area should be classified into different types of peatland based on distinctive land use and land cover characteristics (hereinafter, collectively termed “peatland types”). This is because CO<sub>2</sub> emissions are to be estimated by each peatland type.
- CO<sub>2</sub> flux measured at the study area is used to obtain net ecosystem exchange (NEE) values. A positive NEE value (>0) means the area is a source of CO<sub>2</sub> emissions.
- A linear relationship (regression line) between NEE and GWL values must be obtained. This is the most important part of this model.
- There is a strong correlation between GWL and soil moisture. Therefore, the spatial distribution of GWL in the study area can be estimated by using remote-sensing-based soil moisture data.
- This model allows you to estimate NEE (or CO<sub>2</sub> emissions) for different years, or other areas throughout the study area based on the estimated spatial distribution of GWL.

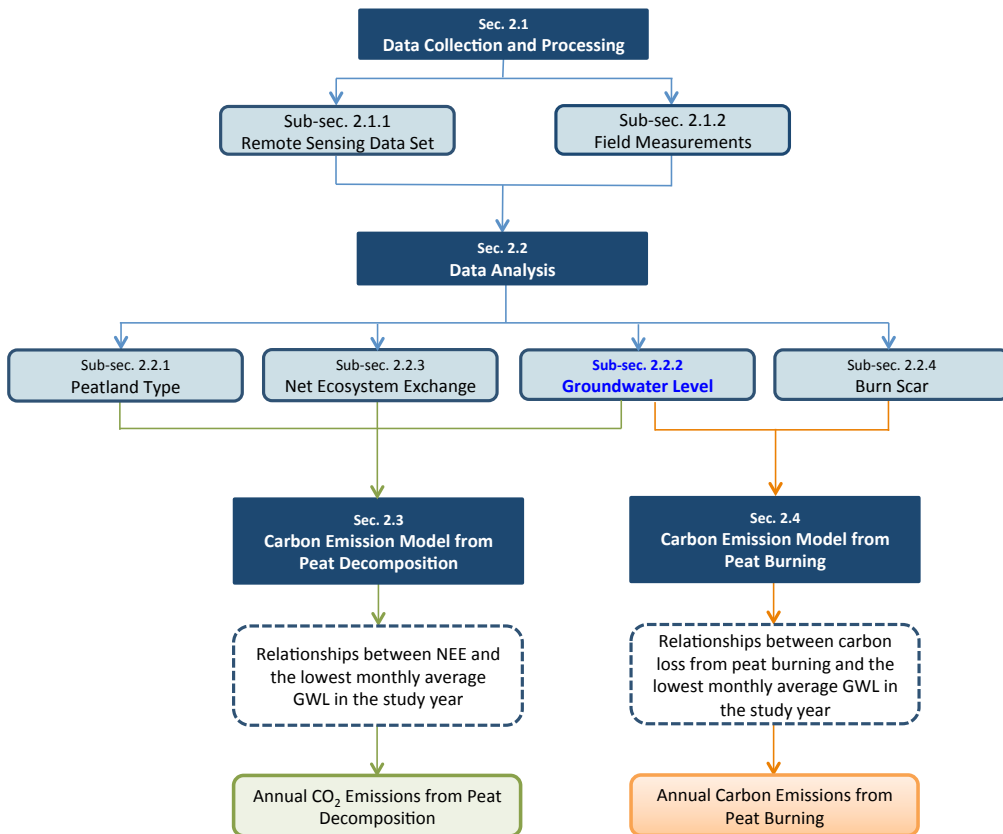
### ➤ How to estimate **carbon emissions from peat burning**

#### ✓ Key points to understand:

- Real-time GWL measured at a study area is used as a key parameter to estimate CO<sub>2</sub> emissions from peat burning.
- Burn scar volume must be estimated by field sampling. Bulk density and carbon content can be determined by laboratory analyses on peat soil samples collected near the burned area. They are used to estimate the amount of carbon loss (emissions) due to peat burning.
- A linear relationship (regression line) between carbon loss and GWL values must be obtained. This is the most important part of this model.
- This model allows you to estimate the amount of carbon emissions for different years, or at other areas beyond sampling locations as long as those areas show similar characteristics to the burned area.

Figure 1 illustrates the steps to estimate carbon emissions from peatland due to microbial decomposition and peat burning. The initial step of data collection and processing involves the acquisition of a remote sensing data set and field sample data. These data are analyzed to estimate: 1) the classifications of peatland present based on distinctive land use and land cover characteristics (i.e., peatland types) and their spatial distribution in the study area; 2) annual average net ecosystem exchange (NEE) values; 3) the lowest monthly average GWL(s) in the study year(s); and 4) the amount of annual carbon emissions from peat burning.

The Carbon Emission Model from Peat Decomposition requires peatland types, annual NEE values and the lowest monthly average GWL(s) in the study year(s) to estimate the amount of annual CO<sub>2</sub> emissions. Similarly, the Carbon Emission Model from Peat Burning uses the amount of annual carbon loss (emissions) and the lowest monthly average GWL(s) in the study year(s) to estimate the amount of annual carbon emissions from peat burning. Detailed procedures to develop these models are provided under the relevant sections and/or sub-sections.



**Figure 1. Carbon Emission Estimation Model framework**

## 2.1 Data Collection and processing

### 2.1.1 Remote sensing data set

#### ❖ What remote sensing data will you need? ❖

The Carbon Emission Models are based on remote sensing data. A set of remote sensing data is needed to classify the study area into different types of peatland (see Sub-section 2.2.1), to estimate the spatial distribution of GWL, and to detect burn scars (see Sub-section 2.2.3). There are different types of secondary data sources available which can be used to fulfill each purpose, as listed below.

| No. | Remote sensing data         | Purpose  |
|-----|-----------------------------|--|
| 1   | Peatland map                | To estimate the extent of peatland                   |
| 2   | Soil moisture product       | To estimate the spatial distribution of GWL          |
| 3   | Forest cover change product | To define forest and non-forest areas                |
| 4   | Surface reflectance product | To define undrained and drained areas                |
| 5   | Burned area product         | To estimate the spatial distribution of burned areas |

#### Step 1. Download an existing peatland map

A peatland map of the study area is needed to delineate peatland<sup>1</sup> from non-peat areas. Indonesia has several peatland maps developed by various institutions and organizations, including the Ministry of Agriculture (MoA) and Wetlands International (WI) (see Figure 2). These are the most frequently cited maps in Indonesia. Peatland maps (in ESRI shape file) from these sources may be obtained by sending a formal letter of request.

- Ministry of Agriculture  
<http://www.pertanian.go.id>
- Wetlands International  
<http://indonesia.wetlands.org/infolahanbasah/PetaSebaranGambut/tabid/2834/language/id-ID/Default.aspx>



Figure 2. Peatland map of Central Kalimantan by Wahyunto, et al. (2004)

<sup>1</sup> Peatland is defined as “an area with accumulation of partly decomposed organic matter with ash content equal to or less than 35%, peat depth equal to or deeper than 50 cm, and organic carbon content (by weight) of at least 12%” (Purnomo et al., 2012).

### **Box 1. An alternative approach: Create a new peatland map**

A new peatland map be developed by using a spatial model. There are various methodologies to create a new peatland map, and the following is an example.

- Obtain and pre-process satellite imagery of the study area. In order to reduce data gaps and improve interpretation, it is recommended to use a combination of medium- to high-resolution optical satellite images as well as Synthetic Aperture Radar (SAR) data.
- Obtain BIG (Badan Informasi Geospasial) topography maps at the 1:50,000 scale and SRTM digital elevation model data. These data are used to determine geomorphological features such as peat dome structures and hydrological networks of the study area.
- Obtain NOAA Advanced Very High Resolution Radiometer (AVHRR) data of selected years from the USGS Global Land 1-km AVHRR Project, and evaluate vegetation activities by normalized difference vegetation index (NDVI). In order to estimate accurate peatland distribution in the study area, it is recommended that the NDVI analysis be based on the land cover of the past (e.g., 1990), when peatland was relatively undisturbed and its original condition and distribution could be assessed.
- Conduct ground-truthing to verify peat and non-peat areas in the study area.
- Manually delineate peat boundaries on a GIS platform based on the NDVI values, slope raster data, and morphological and hydrological network information obtained through remote sensing analyses. Peatlands generally occur on gentle slope areas with slope angles of less than or equal to 0.2°, and manual delineation should be conducted in reference to such areas.
- Conduct a geo-statistical analysis to estimate peat thickness distribution within the study area.
- Based on the distribution of peat thickness, filter out areas with peat thickness less than 50 cm (according to the definition of peatland), and develop the final peatland map of the study area.

### *Step 2. Download soil moisture data*

- Download soil moisture data from an available source to be used to estimate the spatial distribution of GWLs in the study area.
  - One source of global soil moisture data available for free of charge is the volumetric soil water layer product of the European Center for Medium-Range Weather Forecast (ECMWF). It is available at <http://apps.ecmwf.int/datasets/data/interim-full-daily/>.
  - Before downloading the data, you must select the applicable time-series (i.e., daily), coordinate system (e.g., WGS 84), coordinates, and grid size (e.g., 0.5 degrees). They must match those applied in Step 2 of Sub-section 2.2.1 (Peatland Type).

### *Step 3. Download forest cover change data*

- Download a forest cover change data product from an available source to be used to identify forest and non-forest areas in the study area.
  - One source of forest cover change data is the Global Forest Change product developed by NASA, available at <https://earthenginepartners.appspot.com>.

### *Step 4. Download surface reflectance data*

- Download a surface reflectance data product from an available source to be used to identify undrained and drained areas in the study area.
  - One source of surface reflectance data is the MODIS surface reflectance product (MOD09A1). It is available at <http://modis.gsfc.nasa.gov/data/dataproduct/mod09.php>.
  - This MODIS surface reflectance product allows you to identify these areas based on plant physiological responses to different degrees of dryness on vegetated land surfaces.

### *Step 5. Download burned area data*

- Download a burned area data product from an available source to be used to estimate the spatial distribution of burned areas in the study area.
  - One of the burned area products available globally is MODIS burned area product (MCD45A1). It is available at <http://modis.gsfc.nasa.gov/data/dataproduct/mod45.php>.
  - Original imagery data obtained by aerial photography may be used in combination with the MODIS burned area product to improve the accuracy.
  - Advanced techniques such as LiDAR (Light Detection and Ranging) and PALSAR-2 (Phased Array type L-band Synthetic Aperture Radar) may be

used if they are available and applicable. They are high resolution and can determine ground surface levels with an accuracy of several centimeters. However, even if these high-resolution remote sensing techniques are adopted, field measurements must still be conducted for ground-truthing purposes (see Sub-subsection 2.1.2.3 on Burn Scar Measurements).

### 2.1.2 Field measurements

#### ❖ What sample data do you need to collect in the field? ❖

You will need sample data in order to develop the Carbon Emission Models as explained in Sections 2.3 and 2.4. The greater the sample size is, the more accurate these models become. Therefore, it is recommended to set up observation points at various locations representing the distinctive characteristics of land use and land cover types in the study area. The following sample data must be collected in the field.

- ✓ GWL
- ✓ CO<sub>2</sub> flux
- ✓ Burn scar

#### 2.1.2.1 Groundwater level measurements

GWL is a key parameter for estimating carbon emissions from peat decomposition and burning. Therefore, it is important that GWL is measured in every type of peatland identified based on distinctive land use and land cover characteristics in the study area (see Sub-section 2.2.1). GWL data are collected through the steps described below.

##### *Step 1. Prepare equipment for field measurements*

- A minimum list of equipment needed for the field measurement of GWL is provided below, and should be adjusted based on the field condition. This guidebook suggests that GWL be monitored and recorded by using the SESAME system<sup>2</sup>, which comes with water level, temperature and precipitation sensors (see Figure 3).
  - SESAME system
  - SIM card for mobile network
  - Laptop computer with a modem
  - Iron pipe
  - PVC pipe

---

<sup>2</sup> SESAME system SESAME 01-II: [http://www.midori-eng.com/english/image/sesame-01-2\\_pamph.pdf](http://www.midori-eng.com/english/image/sesame-01-2_pamph.pdf)

- Eijkelkamp<sup>3</sup> peat auger
- Cleaver
- GPS receiver
- Compass
- Measuring tape
- Activate the SIM card. Top up the card (if it is prepaid) before it expires for seamless data transmission.



Figure 3. SESAME system

- Obtain a server access license (user ID and password) for data acquisition<sup>4</sup>.
- Set up the modem on a laptop computer for data transmission.
- Test the Internet connection.

## Step 2. *Select locations for field measurements*

- Select field measurement locations based on the following conditions:
  - The locations must be physically accessible and legally permissible for the installation of the SESAME system and its maintenance.
  - GSM/GPRS/Q-CDMA network coverage is available (because the SESAME system transmits data through the mobile network).
    - If the network coverage is not available at the ground surface level, an antenna may be mounted above the vegetation canopy to catch the signal.
  - The locations are representative of distinctive peatland types identified by the remote sensing imagery (see Sub-section 2.2.1 on Peatland Type).
    - The SESAME system should be installed at every distinctive type of peatland, as the Carbon Emission Model will be developed per peatland type.
    - The SESAME system should be installed at the CO<sub>2</sub> flux observation sites as well (see Sub-subsection 2.1.2.2).
  - The location is safe from potential thefts of instruments.

---

<sup>3</sup> The Eijkelkamp auger is a peat sampler used for soil profile description and classification. The details about the Eijkelkamp auger are available at <https://en.eijkelkamp.com/products/augering-soil-sampling-equipment/peat-sampler.html>.

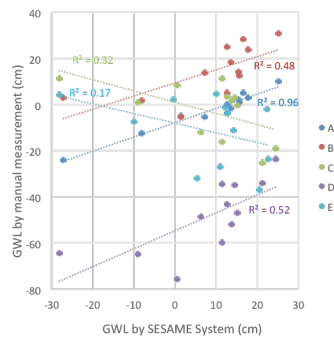
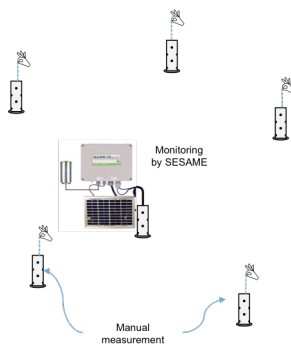
<sup>4</sup> The server is currently maintained by Midori Engineering Laboratory in Japan. Contact Mr. Yukihsa Shigenaga (email: [shigenaga@midori-eng.co.jp](mailto:shigenaga@midori-eng.co.jp); Telephone: +81-11-555-5000; URL: <http://www.midori-eng.co.jp>) for details.



## Box 2. How many units of the SESAME system should be installed in the area of interest?

Because GWL is affected by a number of factors including precipitation, vegetation types, land cover, slope of the land, peat depths and water channels (i.e., rivers and canals), there is no single answer to which how many units of the SESAME system are needed in order to represent GWLs over a certain area of peatland. The following method can be adopted to determine the number of SESAME system units to be installed in the study area.

- Install one SESAME system at a sampling location representative of a peatland type based on distinctive land use and land cover characteristics (e.g., drained forest or DF) found in the study area, and measure and record GWL at the location.
- Additionally, set up PVC pipes for manual GWL monitoring randomly in several locations within the same peatland type (DF) in the area. Measure and record GWLs manually at these locations once a month at least for one year. 12 GWL data from each monitoring pipe will be obtained. Then plot GWL data from the SESAME system on the X axis and manual GWL data on the Y axis to obtain their relationships.



- Examine the correlation of each regression line. If the correlation is strong, the data obtained by the SESAME system can be used to represent GWLs at the manual monitoring location. Consider to install another SESAME system at the manual monitoring location which showed a weak correlation.
- Caution needs to be taken for areas in which GWLs tend to change considerably within a short distance and/or short time interval (e.g., areas close to a drainage canal).

### Step 3. Install a SESAME system in the selected location

- Measure peat depths at the selected location to install the SESAME system.
- Install an iron pipe all the way into the mineral soil through the peat layer so that the pipe stays stable (①).
- Build a metal platform to hold a rain gauge sensor and the SESAME instrument cabinet. The metal platform must be placed high enough to be free from potential flood damage (②).
- Make 0.5 cm diameter holes in a PVC pipe to serve as a water gauge (③).
- Install the SESAME instrument cabinet on the iron pipe (④). There is a solar panel on the box. Therefore, the installation must be directed into the sunlight.
- Install the rain gauge sensor on the metal platform (⑤).
- Install the water logger sensor into the PVC pipe (⑥).
- Install an iron pipe all the way into the mineral soil through the peat layer. It must be placed several meters away from the SESAME system (⑦).
- Install a ground surface elevation laser sensor into the PVC casing. The laser sensor must be placed high enough to be free from potential flood damages (⑧).

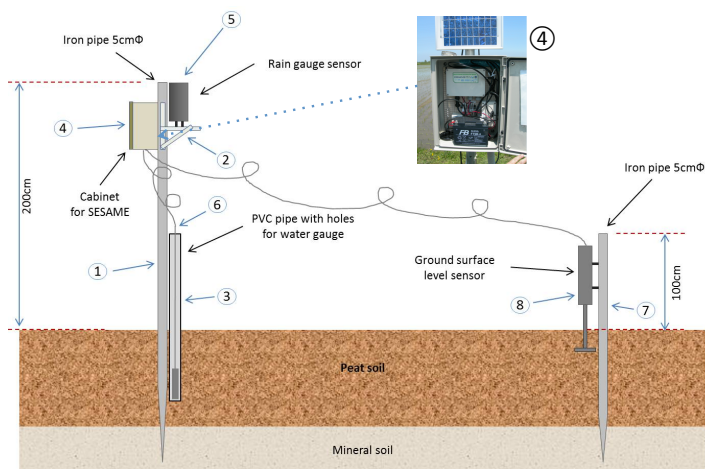


Figure 4. Illustration of SESAME system installation

#### *Step 4. Activate the SESAME system and start recording GWL and other microclimate parameters*

- Check that all components (GWL sensor, rain gauge, temperature sensor and ground surface elevation sensor) are working properly.
- Activate the SESAME system and start recording GWL at the interval of 10 minutes and other microclimate parameters (i.e., precipitation and air temperature).
- Check that the data from the SESAME system are transmitted to the server without any errors. If there are errors, you must check whether the SESAME system is properly installed in the field.

#### **2.1.2.2 CO<sub>2</sub> flux measurements**

CO<sub>2</sub> movement or CO<sub>2</sub> flux between the soil and the atmosphere is the primary function of soil respiration. Soil respiration returns substantial amounts of carbon to the atmosphere and is a major component of CO<sub>2</sub> emissions or NEE. Ecosystem disturbances, including climate change, deforestation, peatland drainage, forest and peatland fires, and land conversion, provoke changes in soil respiration and the resulting carbon balance, as the ecosystem loses important soil carbon storage due to such disturbances. Therefore, direct measurements of CO<sub>2</sub> fluxes should be conducted at various sites which include both intact peatland and other peatland areas characterized by varying degrees of ecosystem disturbances (see Sub-section 2.2.1 on Peatland Type). The results of these CO<sub>2</sub> flux measurements are used for the NEE analysis as described in Sub-section 2.2.3.

There are various methods to measure CO<sub>2</sub> fluxes, each with its own advantages and limitations. This guidebook recommends a micrometeorological method using a flux tower. Secondary CO<sub>2</sub> flux data may also be used, if such data are available for the study area.

### Box 3. Alternative approaches to flux measurements

If it is not feasible to measure CO<sub>2</sub> fluxes with a flux tower, there are some alternative methods available, as presented below.

**Incubation method:** This method uses undisturbed sample soil columns stored in containers and incubated over a period of time. CO<sub>2</sub> fluxes are measured using a chamber which is attachable to the top of the container. Undisturbed peat samples from each peatland type should be used to avoid measurement errors. CO<sub>2</sub> fluxes should be measured repeatedly with different GWLs, which can be changed by supplying or draining the groundwater inside the containers. The groundwater used for this method should be drawn from the soil sampling locations.

**Closed chamber method:** Small chambers are used to directly measure CO<sub>2</sub> fluxes over a small surface area in the closed headspace for a short period of time. Chambers should be set up at each peatland type. The advantage of using this method is that it is relatively low in cost and simple to operate. However, it is easily affected by various environmental conditions in the field, and tends to create errors and biases in gas sampling.

#### Step 1. Prepare equipment for field measurements

- A list of key instruments necessary for measuring CO<sub>2</sub> fluxes using a flux tower is provided below (see Figure 5).

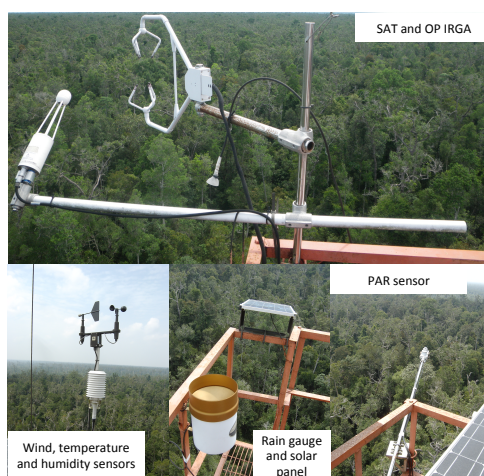


Figure 5. Flux tower instruments

- Ultra-Sonic Anemometer-Thermometer (SAT):
  - Measures the sound speed in air in three-dimensions (especially vertical direction) in order to determine sonic virtual temperature and wind velocity in three-dimensions.
  - Must be settled exactly horizontally (or perpendicularly to the incline of the slope); otherwise, systematic errors will be included in the vertical wind velocity.
- Open-Path CO<sub>2</sub> Infra-Red Gas Analyzer (OP IRGA):
  - Measures the attenuation of infrared radiation absorbed by CO<sub>2</sub> molecules intervening in the open path of the radiation in order to determine CO<sub>2</sub> concentration.
  - Recommended to be settled with 10–15 degrees slant from the vertical position in order to minimize the influences of wind distortion and raindrops sticking on the lens located at the end of the open path.
  - The surface of the lens should be kept clean. Ideally it should be gently wiped every ten days to every month. Application of water repellent on the surface of the lens is recommended.
  - Most of the commercially available OP IRGAs can simultaneously measure water vapor density. CO<sub>2</sub> and H<sub>2</sub>O are individually determined using the infrared radiations with different wavelengths. Based on the same eddy covariance theory, H<sub>2</sub>O flux (i.e., evapotranspiration) from the ecosystem into the atmosphere above can be determined.
- Data logger:
  - Stores CO<sub>2</sub> flux data.
  - The specifications required:
    - Performance high enough to capture signals from several instruments at least ten times per second (>10 Hz)
    - Memory capacity high enough to temporarily store the huge amount of eddy covariance data for several days
    - Connections between the data logger and each sensor without noise and delay of signals
- Power source:
  - Supplies power to run the equipment.
  - Recommended to use a stable commercial power supply with sufficient capacitance.
  - Recommended to use solar cells with rechargeable batteries.
    - In this system, the power generated by the solar cells is used both to drive the instruments and to charge the batteries during the daytime. In the nighttime, the power charged to the batteries is then consumed to drive the instruments.

- The number of solar cells and batteries should be determined based on the power required by each instrument. It should also be taken into account that the power generation will be decreased on cloudy days and in the rainy season.
- If the flux observation tower is covered by dense canopy, a solar cell panel should be placed on top of the tower. Make sure that the panel does not disturb the flow of the wind.
- GPS receiver
- Other microclimate measurement instruments:
  - Microclimate measurements are needed not only to record general weather conditions at the observation tower, but also to detect and correct invalid values in CO<sub>2</sub> fluxes.
  - Key microclimate parameters controlling rates of CO<sub>2</sub> fluxes should be recorded (temperatures, precipitation and GWL should be recorded with the SESAME system as described in Sub-subsection 2.1.2.1):
    - Photosynthetically active radiation (PAR) as the main variable, since it strongly affects CO<sub>2</sub> uptake rate during photosynthesis.
    - Air and soil temperatures
    - Precipitation
    - GWL

### *Step 2. Select locations for field measurements*

- Select CO<sub>2</sub> flux observation locations which satisfy the following conditions:
  - General wind direction in the area is known.
  - Land surface condition in the upwind area should be generally uniform and representative of the distinctive peatland types (see Sub-section 2.2.1 on Peatland Types).
  - Ideally, the length of the surface area from the observation tower toward the upwind direction, also known as the fetch length, should be 100 times greater than the height of the observation tower.
  - Permission for building of an observation tower must be available.
  - There must be accessible paths for the construction of the observation tower and its maintenance.
  - The location is safe from potential thefts of instruments.

### *Step 3. Build an observation tower at the selected location*

- Build CO<sub>2</sub> flux observation towers at the locations selected in Step 2.
  - The tower must be taller than the surrounding vegetation.
  - Ideally, the height of the tower is one and a half times to twice of the

height of the canopy.

- For a long-term observation, the growth of vegetation should be taken into account.
- The tower must be strong enough to withstand the weight of instruments and strong wind. A weak tower swaying in the wind makes the observations erroneous.
- A lightning rod should be mounted on top of the tower to protect the instruments in the event of lightning strike. Working around the tower during a thunderstorm is strictly prohibited.

#### *Step 4. Install and activate the instruments, and start recording CO<sub>2</sub> fluxes and other microclimate parameters*

- Install SAT and OP IRGA in the upwind direction from the flux tower to avoid wind distortion effects.
  - If the prevailing wind direction changes seasonally, the direction of SAT and OP IRGA should be also adjusted toward the upwind direction.
  - The distance between SAT and OP IRGA should be between 15 and 30 cm.
    - If <15 cm, the airflow will be disturbed.
    - If >30 cm, the synchronicity of both sensors will be reduced.
- Activate the data logger, and start recording time-series data.
- Obtain the data from the data logger every 2 – 3 months.

#### **2.1.2.3 Burn scar measurements**

The area and depth of burn scar in the study area are needed when estimating carbon emissions from peat burning, as the volume of burn scar is given by the burned peat area and burned peat depth (see Section 2.4). The area of burn scar can be detected with remote sensing data (e.g., MODIS burned area product) and/or original images taken by aerial photography (see Sub-section 2.1.1 on Remote Sensing Data Set). Burned peat depths in selected sampling plots can be measured through the steps described below (see Figure 6).



**Figure 6. Illustration of burn scar measurement**

### Step 1. Make a burn scar map

- Make a burn scar map of the study area just after a fire event, using the data prepared in the procedures described in Sub-section 2.1.1 (Remote Sensing Data Set).
- Determine the burned area by a geometric analysis on the map on GIS.

### Step 2. Prepare equipment for field survey

- A minimum list of equipment necessary for burn scar field survey is provided below. This list should be adjusted based on the field condition.
  - Eijkelkamp peat auger
  - Aluminum cups and plastic bags
  - Measuring tape and a rope
  - Compass
  - Measuring pole
  - Theodolite
  - GPS receiver

### Step 3. Select sampling plots for field survey based on the burn scar map

- Select sampling plots for field survey. The selected locations must represent the general condition of the burned area as shown in Figure 7.
  - The total area of plots should cover at least 15% – 20% of the total burned area.
  - If the number of plots is large, the locations can be randomly determined.

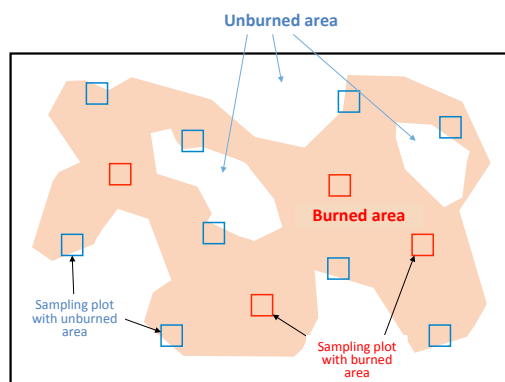


Figure 7. An example of burn scar sampling design



#### Step 4. Measure and record burned peat depths at the selected plots

- Measure burned peat depths at several places in the sampling plots, and record them on a datasheet.
- Once the rainy season begins, the burn scar gradually starts to fill in from the ingression of peat from the surrounding unburned area. Therefore, the survey should be conducted as soon as fires are out.
- A measurement basis which indicates the level of ground surface before peat burning must be determined. The following objects can be used as the basis (also see Figure 8).

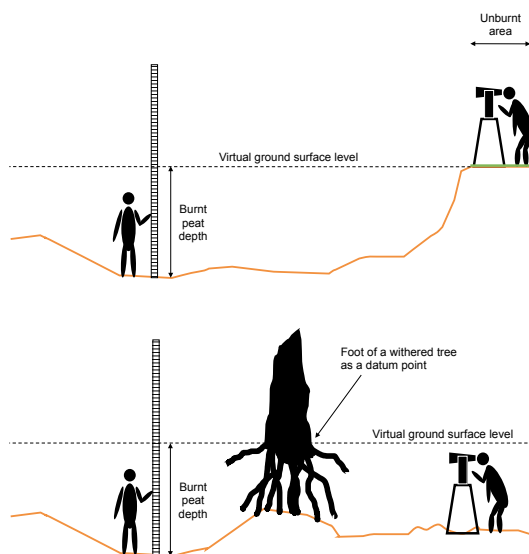


Figure 8. Illustration of burned peat depth measurements using an iron rod and a small unburned area (top) and a withered tree stand (bottom)

- **A small area which remains unburned:** This is the most reliable basis, provided that the study area is generally flat and the ground surface level before burning can be assumed to be almost the same as the level in the surrounding area. If the plot contains an unburned area, its level can be used as the virtual ground surface level in the burned area before peat burning. If the size of each plot is large and the distribution of burned area is patchy, it is recommended to set up sampling plots at locations where plots can contain both burned and unburned areas.
- **An iron rod penetrated to the mineral soil underlying the peat layer:** If the plot does not contain an unburned area, an iron rod may be used as the measurement basis. However, the iron rod must be installed before peat burning occurs (i.e., the beginning of the dry season). After the installation of an iron rod, scratch a line on the rod at the ground

surface level. After the peat burning, measure the distance between from the scratched line and the burn scar surface (the new ground surface). This is the depth of burned peat layer.

- **Withered tree stand:** If the plot does not contain an unburned area, a tree trunk may be used as the measurement basis. The level of withered tree foot suggests the ground surface level before peat burning. If the area suffers from peat fires repeatedly, however, this level may suggest the ground surface level from several years ago and may not reflect the peat depth burned by the latest fire.

### Step 5. Collect peat samples in an unburned area near burn scar survey plots

- Determine peat-boring points at an unburned area surrounding the burned peat depth plots measured in Step 4 above. The selected unburned area should be representative of land surface conditions of the burned area. It is recommended that at least 5 boring holes be made for each plot.
- Collect peat samples in 50 cm segments with an auger (see Figure 9). Take 5 cm (50 cm<sup>3</sup>) from each sample and place it into an aluminum cup before sealing it into a plastic bag. The number of samples to be collected at each boring point depends on the peat depth there.

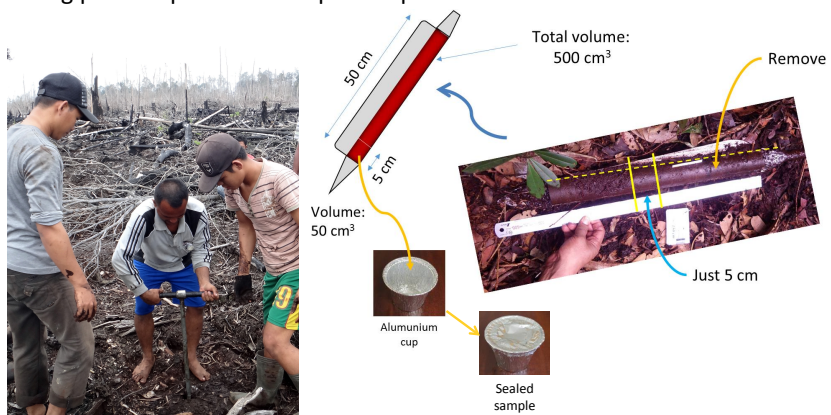


Figure 9. Procedure of peat sampling

### Step 6 (Optional). Use advanced techniques for burned peat depth measurements

- Select which advanced techniques to use (see Sub-section 2.1.1 on Remote Sensing Data Set).

- Measure burned peat depths using the selected advanced techniques, and record data on the datasheet.
- Verify the recorded data through ground-truthing.
  - Advanced techniques such as LiDAR and PALSAR-2 can replace the field measurement of burned peat depths. However, the analysis results should always be ground-truthed.

## 2.2 Data Analysis

### ❖ What data do you need to analyze? ❖

You will need to analyze raw data collected in field measurements in order to obtain linear relationships between GWL and remote sensing based soil moisture data (Figure 13), between GWL and NEE (Figure 14), and between GWL and carbon emissions from peat burning (Figure 16). These regression models are used to estimate carbon emissions from peat decomposition and burning, as explained at the end of the Part II of this guidebook. Therefore, the following data must be analyzed and each parameter must be calculated.

- ✓ Peatland types classified on a grid file covering the entire study area
- ✓ Lowest monthly average GWL(s) in the study year(s)
- ✓ Annual NEE in the study year
- ✓ The mass of carbon loss (or carbon emission) due to peat burning

### 2.2.1 Peatland type analysis

Peatland in the study area may consist of a variety of land use and land cover types with different degrees of ecosystem disturbances. The Carbon Emission Model from Peat Decomposition estimates the amount of CO<sub>2</sub> emissions from each type of peatland found in the study area. If land use and land cover characteristics were different, GWLs would be different as well; hence, the amount of CO<sub>2</sub> emissions from peat decomposition would vary, because the NEE is affected by the GWL. Therefore, it is important to classify the study area into different peatland types which represent distinctive characteristics of land use and land cover. Each peatland type must be clearly defined first.

#### *Step 1. Classify the study area into distinctive peatland types*

- Classify the study area into distinctive types of peatland by using remote sensing data set as described in Sub-section 2.1.1.
  - Peatland types may include:
    - Undrained (intact) forest (UF)
    - Drained (degraded) forest (DF)

- Drained and burned land or non-forest area (DB)
  - Cropland
  - Oil palm plantation
  - Acacia plantation
- Define forest and non-forest areas in the study area (if both areas exist).
    - Canopy loss areas may be classified as a drained and burned land (DB).
  - Define drained and undrained forest areas in the study area (if both areas exist).
    - Drained and undrained forest areas can be identified based on the relative dry tendency of dense forest surface. Lower dry classes can be classified as undrained forest (UF), and higher dry classes as drained forest (DF).

*Step 2. Create a grid file, and extract pixel values of each peatland type into the grids*

The classified study area must be prepared on a grid file, because the amount of CO<sub>2</sub> emissions from each peatland type will be calculated per grid cell.

- Create a grid file on WGS 84 on GIS. NEE values are calculated based on a grid file on WGS 84. Therefore, it is necessary to cover the entire area of interest and to fit each grid to the pixel placement of ECMWF soil moisture data (the same grid size) described in Sub-section 2.1.1. Figure 10 shows an example of a grid file on 0.5-degree for Central Kalimantan. It shows the boundary of Central Kalimantan (blue line), new grids (black line) and ECMWF soil moisture data (gray scale).
- Extract the pixel number of each peatland type from Step 1 above into every grid cell.
- Calculate the area of each peatland type in each grid cell as illustrated in Figure 11. This will be used for NEE calculation in Section 2.3.
- Upload the spreadsheet as an attribute table of the grid file on GIS.

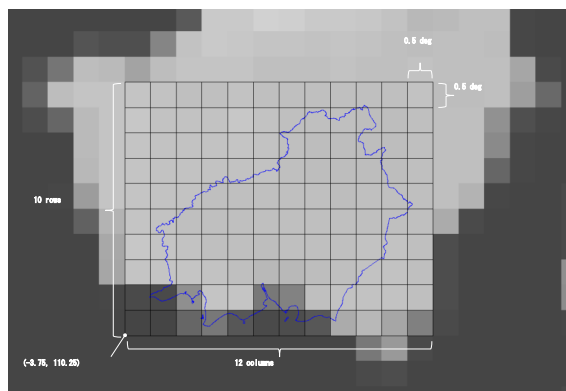


Figure 10. A grid file for Central Kalimantan

Example:  
Peat swamp forest area  
of this grid is 100 ha

|           |           | Area of each type | Peatland type |
|-----------|-----------|-------------------|---------------|
| DB<br>50% | UF<br>20% | 100*0.50 ha       | DB            |
|           | DF<br>30% | 100*0.20 ha       | UF            |
|           |           | 100*0.30 ha       | DF            |

Figure 11. Example for the calculation of areas based on peatland types in a grid cell

### 2.2.2 Groundwater level (GWL) analysis

The SESAME system records real-time GWL data at a 10-minute interval (see Sub-section 2.1.2.1). The data must be downloaded from the server and analyzed to obtain the lowest monthly average GWL(s) in the study year(s). This value will be used as a key parameter for the Carbon Emission Models explained in Sections 2.3 and 2.4. Obtain at least several lowest monthly average GWL values in the study years (i.e., several continuous years of GWL observation) in order to improve the accuracy of the models.

#### Step 1. Download raw data from the SESAME server

- Access the SESAME server and download raw GWL data for the selected time and location.
  - You must install the SESAME software on your computer first to be able to access the server. To obtain this software, contact Midori Engineering Laboratory.

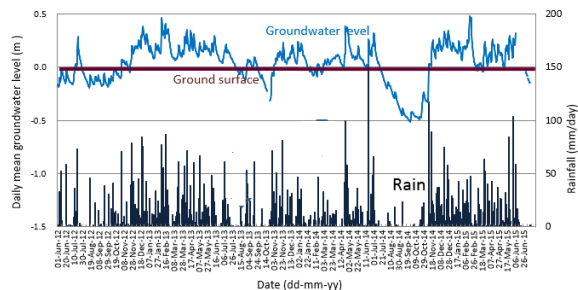
#### Step 2. Organize the raw data into observation data

- Make a .csv file (e.g., Excel), and add field names to the spreadsheet.

- Organize the downloaded raw data as observation data for each variable (i.e., GWL, precipitation, and ground surface level).
- Repeat this for all downloaded raw data collected at each type of peatland.
- Check to see if data are complete.
  - If there are missing data for a short time period, make an interpolation and fill the data gaps.
  - If data gaps are caused by mobile network failure, the missing data can also be obtained directly from the SESAME system (data logger). The SESAME system stores data in a memory card for three months.

*Step 3. Convert the observation data into daily average values for each parameter*

- Take the daily average of each observation data recorded at a 10-minute interval.
- Add the daily average values for each variable in a new column on the spreadsheet (see Figure 12).

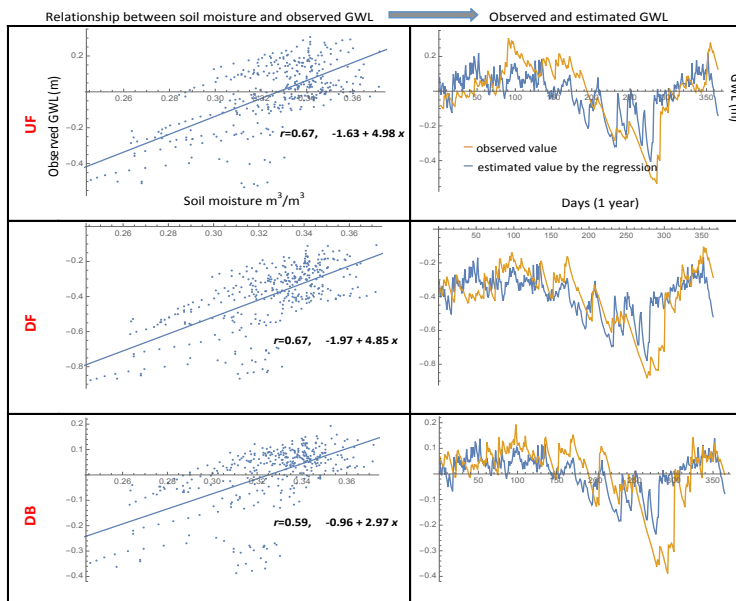


**Figure 12. Example for time-series daily average GWLs with other parameters**

*Step 4. Obtain a linear relationship between daily soil moisture and daily average GWL for each type of peatland*

- Draw a scatter graph by plotting the observed (measured) daily average GWLs on the Y-axis and the remote-sensing based daily soil moisture data of all grid cells on the X-axis.
  - Soil moisture data can be obtained in the procedure explained in Step 2 of Sub-section 2.1.1, and daily average GWL values obtained in Step 3 above.
- Obtain a linear regression equation between the daily soil moisture and the daily average GWL.

- Repeat this for all peatland types (see Figure 13). The equations obtained for the regression lines will be used to simulate daily average GWLs at each peatland type in all other grids throughout the study area.



**Figure 13. Example of GWL estimations for each peatland type based on the relationship between soil moisture and observed GWL data**

### Step 5. Estimate daily average GWL values in all other grid cells

- Estimate daily average GWL at each peatland type in all other grid cells, using the equations obtained in Step 4 above and daily soil moisture data in each grid.

### Step 6. Obtain the estimated monthly average GWL values in all other grid cells

- Calculate monthly average GWL at each peatland type in all other grid cells based on the estimated daily average GWL values obtained in Step 5 above.

### Step 7. Find the lowest value of the estimated monthly average GWLs for each peatland type in every grid cell

- Find the lowest value from the estimated monthly average GWLs of the selected year obtained in Step 6 above.

- Repeat this for each peatland type in every grid cell. These values are the **lowest monthly average GWLs in the study year** used as a key parameter for estimating annual average carbon emissions as described in Sections 2.3 (Carbon Emission Model from Peat Decomposition) and 2.4 (Carbon Emission Model from Peat Burning).

### 2.2.3 Net ecosystem exchange (NEE) analysis

The Carbon Emission Model from Peat Decomposition, described in Section 2.3, uses the eddy covariance (EC) technique to estimate NEE. Raw EC data recorded at 10 Hz (see Sub-section 2.1.2.2 CO<sub>2</sub> flux measurements) are used to calculate physical parameters such as three-dimensional wind velocity, air and soil temperatures and CO<sub>2</sub> fluxes at the interval of 30 minutes to one hour. In this calculation process, many kinds of data correction, quality control and gap filling must be conducted.

#### Box 4. What is Eddy Covariance?

Eddy Covariance (EC) is a method for evaluating vertical transport of energy, water vapor and gases in the near-ground atmosphere. Near the ground surface, wind blows as a turbulent flow, meaning there are many “eddies” with wide ranges in size and duration. These eddies exchange the energy and gases between the upper and the lower atmospheric layers. According to the turbulent flow theory, these vertical fluxes can be given as a function of covariance of vertical wind velocity and gas concentration. Therefore, this method is called “eddy covariance”.

#### Step 1. Conduct quality control on raw data

- Check the raw data obtained in Sub-subsection 2.1.2.2 (CO<sub>2</sub> flux measurements), and make corrections if necessary.

#### Step 2. Calculate NEE values for the selected time interval

- Organize the sequential raw data into a specific time interval (also known as averaging time). Averaging time is usually 30 minutes or 1 hour.
- Calculate NEE values for each type of peatland by using the following equation.

$$NEE = \overline{w'c'} \quad (1)$$

Where:

$W$  = vertical wind velocity (m/s)

$C$  = CO<sub>2</sub> concentration (mg/m<sup>3</sup>)



' = fluctuating component

– = mean value

### Step 3. Conduct quality control on calculated NEE values

- Check the calculated NEE values, and remove all erroneous data.
  - Certain climatic conditions, such as heavy rain and irregular wind direction, may cause errors in NEE calculation.
- If necessary, correct the erroneous NEE values with some parameters obtained in the same time interval.

### Step 4. Fill data gaps in calculated NEE values

- Find data gaps, and estimate missing NEE values using several techniques such as regression, lookup table, or mean daily variation.

### Step 5. Calculate annual NEE values

- Calculate annual NEE for each type of peatland by accumulating all values of the observation year as expressed in the following equation.

$$\text{Annual NEE} = \sum_{\text{Year}} (\text{NEE value at each time interval}) \quad (2)$$

## 2.2.4 Burn scar analysis

### Step 1. Calculate the mean and standard deviation of burned peat depths

- Calculate the mean and standard deviation of burned peat depths collected inside each plot as described in Step 5 of Sub-subsection 2.1.2.3.

### Step 2. Take the average of burned peat depths among all sampling plots

- Take the average of burned peat depths among all sampling plots with a standard error as given by:

$$\bar{d} = \frac{\sum_{i=1}^N d_i}{N}, \quad \Delta \bar{d} = \sqrt{\frac{\sum (\Delta d_i)^2}{N}} \quad (3)$$

Where:

$N$  = the number of sampling plots

$\bar{d}$  = average burned peat depth among all sampling plots

$\Delta \bar{d}$  = the standard error of average burned peat depth

$d_i$  = average burned peat depth in Plot  $i$

$\Delta d_i$  = standard deviation of burned peat depth in Plot  $i$

### Step 3. Calculate burn scar volume

- Calculate the volume of burn scar as given by:

$$\text{Burn scar volume (m}^3\text{)} = \text{Burn scar area (m}^2\text{)} \times \text{Average burn peat depth (m)} \quad (4)$$

- If the burn scar area contains an error ( $A \pm \Delta A$ ), burn scar volume  $V$  and its standard error  $\Delta V$  is given as follows. If there is no error,  $\Delta A$  is assumed to be zero.

$$V = A \times \bar{d}, \quad \Delta V = \sqrt{(A \times \Delta \bar{d})^2 + (\bar{d} \times \Delta A)^2} \quad (5)$$

### Step 4. Calculate bulk density of peat samples

- Dry peat samples collected in Step 6 of Sub-subsection 2.1.2.3 (Burn scar measurements) in an oven at 105°C for 24 hours or longer until the constant weight is achieved.
- Measure the dry weight of peat ( $W_p$ ) and the weight of aluminum cup ( $W_c$ ).
- Determine the volume of peat samples ( $V$ ). It is 50 cm<sup>3</sup>, if samples are collected according to Step 6 of Sub-subsection 2.1.2.3 (Burn scar measurements).
- Calculate the bulk density of peat samples as expressed in the following equation.

$$BD = \frac{(W_p + W_c) - W_c}{V} \quad (6)$$

### Step 5. Calculate carbon content of peat samples

The following procedures are based on the loss on ignition (LOI) method. Carbon content can also be calculated by using an elemental analyzer.

- Take a tablespoon of peat sample oven-dried as in Step 4 above, grind it, and measure the weight ( $M_p$ ).
- Measure the weight of a small, heat-resistant porcelain cup ( $M_c$ ).
- Place the peat sample into the porcelain cup, and measure the weight ( $M_p + M_c$ ).

- Burn the peat sample in a muffle furnace at a temperature >900 °C for 5 to 6 hours.
- Cool the burned peat sample (ash) to room temperature in a desiccator, and measure the weight of the ash ( $M_a$ ) with the porcelain cup.
- Calculate the ash content ( $C_a$ ) of the peat sample as:

$$C_a = \frac{(M_a + M_c) - M_c}{M_p + M_c - M_c} \times 100 \quad (7)$$

- Calculate the content of organic matter in the peat sample ( $C_o$ , %) as:

$$C_o = 100 - C_a \quad (8)$$

- Calculate the carbon content of peat samples ( $C$ , %), using the following equation.

$$C = C_o \times 0.58 \quad (9)$$

#### Step 6. Calculate total peat carbon loss (emissions) from peat burning

- Calculate the total amount of peat carbon loss due to peat burning by:

$$\text{Peat carbon loss (kgC)} = \text{Burn scar volume (m}^3\text{)} \times \text{Bulk density (kg/m}^3\text{)} \times \text{Carbon content (\% of dry weight peat)} \quad (10)$$

- If the bulk density and carbon content contain errors ( $BD \pm \Delta BD$  and  $C\% \pm \Delta C\%$ , respectively), calculate carbon content ( $C \pm \Delta C$ , kgC/m<sup>3</sup>) first as follows. If there are no errors,  $\Delta BD$  and/or  $\Delta C\%$  are assumed to be zero.

$$C = BD \times C_{\%}, \quad \Delta C = \sqrt{(BD \times C_{\%})^2 + (\Delta BD \times C_{\%})^2} \quad (11)$$

Where:

$C$  = carbon content

$BD$  = bulk density

- After this, calculate the total peat carbon loss ( $F_b \pm \Delta F_b$ ) given as follows. The value,  $F_b$ , will be used as the amount of carbon emissions in Section 2.4 (Carbon Emission Model from Peat Burning).

$$F_b = V \times C, \quad \Delta F_b = \sqrt{(V \times \Delta C)^2 + (C \times \Delta V)^2} \quad (12)$$

Where:

$F_b$  = carbon loss (emission)

## 2.3 Carbon Emission Model from Peat Decomposition

### ❖ What is a Carbon Emission Model from Peat Decomposition? ❖

The Carbon Emission Model from Peat Decomposition is based on the assumption that there is a linear relationship between NEE and GWL. Based on this relationship, this model allows you to estimate an annual NEE of the study area by using the lowest monthly average GWL(s) in the study year(s) as a key parameter.

NEE means the difference between CO<sub>2</sub> amount which is 1) emitted by ecosystem respiration (RE) and 2) absorbed by photosynthesis (gross primary production; GPP). Therefore, the relationship between net ecosystem production (NEP) and NEE is given by:

$$NEE = - NEP$$

$$NEP = GPP - RE$$

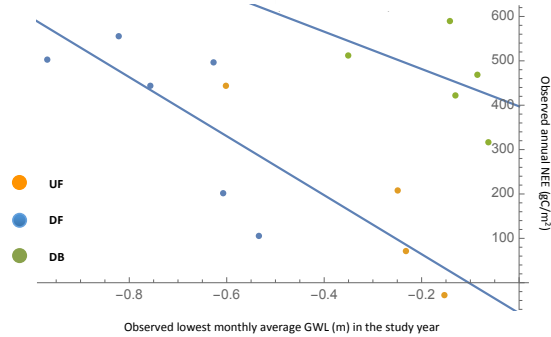
RE is found to increase with soil temperature, and decrease as GWL (or soil moisture) rises. In forest ecosystems, CO<sub>2</sub> exchange between biomass and the atmosphere usually occupies most of the carbon flow. If other carbon sources are negligible, the carbon balance of forest ecosystems can be determined by NEE as follows:

- NEE > 0: carbon source (emission)
- NEE = 0: carbon neutral
- NEE < 0: carbon sink

### *Step 1. Obtain a linear relationship between the observed lowest monthly average GWL(s) in the study year(s) and annual NEE*

- Use the lowest monthly average GWL value for each peatland type selected from the observed monthly average GWLs in the study years as described in Step 7 of Sub-section 2.2.2.
- Use the annual NEE values for each peatland type obtained in Sub-section 2.2.3.
- Draw a linear regression line between the observed lowest monthly average GWL(s) in the study year(s) on the x axis and observed annual NEE on the y axis, and obtain a relationship for each peatland type (see Figure 14) identified for the study area. Each regression equation obtained in this step will be used to estimate annual NEE values throughout the study area.

- You can use the equation to estimate NEE (or CO<sub>2</sub> emissions) for different years, or other areas throughout the study area based on the estimated spatial distribution of GWL.



**Figure 14. Example of relationships between the lowest monthly average GWLs (m) in the study years and annual NEE (gC/m<sup>2</sup>/year) observed in Central Kalimantan (Hirano et al., 2012)**

*Step 2. Estimate annual NEE using the estimated lowest monthly average GWL(s) in the study year(s) in all other grid cells*

- Estimate annual NEE for each peatland type in all other grid cells (areas beyond the observation points), using the equations obtained in Step 1 above. Use the estimated lowest monthly average GWL value in the study year obtained in Step 7 of Sub-section 2.2.2 (Groundwater level analysis).
- Calculate the total NEE from the study area by summing up NEE values from each grid cell by using the following equation.

$$T = \sum_{i=1}^N A_i [\alpha_i X_i + \beta_i Y_i + \gamma_i Z_i + \dots] \quad (13)$$

Where:

$T$  = total NEE

$A_i$  = peatland area in grid cell  $i$

$\alpha_i$  = the ratio of peatland type  $X$  area in grid cell  $i$

$\beta_i$  = the ratio of peatland type  $Y$  area in grid cell  $i$

$\gamma_i$  = the ratio of peatland type  $Z$  area in grid cell  $i$

$X_i$  = NEE value of peatland type  $X$  area in grid cell  $i$

$Y_i$  = NEE value of peatland type  $Y$  area in grid cell  $i$

$Z_i$  = NEE value of peatland type  $Z$  area in grid cell  $i$

$N$  = the number of grid cells

### Step 3. Generate a map of estimated annual CO<sub>2</sub> emissions

- Generate a map of estimated annual CO<sub>2</sub> emissions (positive NEE values) based on the grid file created in Step 2 of Sub-section 2.2.1 (Peatland Type) and the NEE values obtained in Step 2 above. Figure 15 shows an example of annual NEE maps of 2012 for Central Kalimantan created on a 0.5-degree grid file.

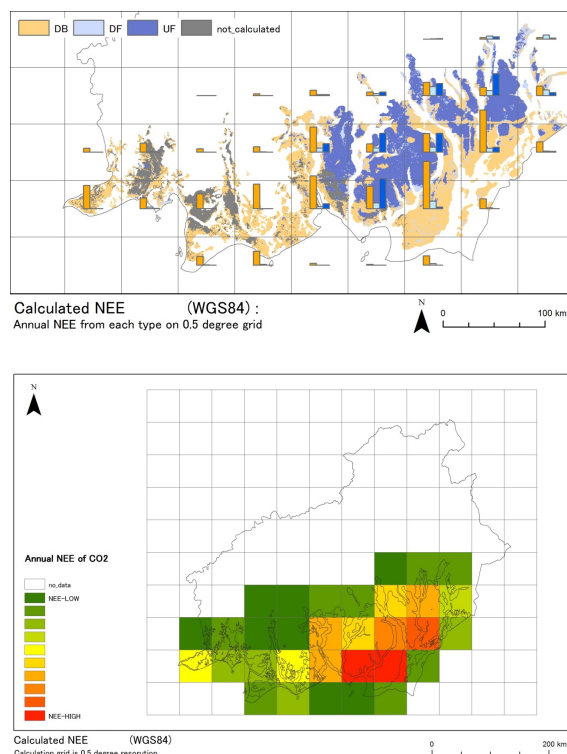


Figure 15. Map of estimated annual NEE values for each peatland type (top) and for total NEE (bottom) of 2012 on grid files for Central Kalimantan

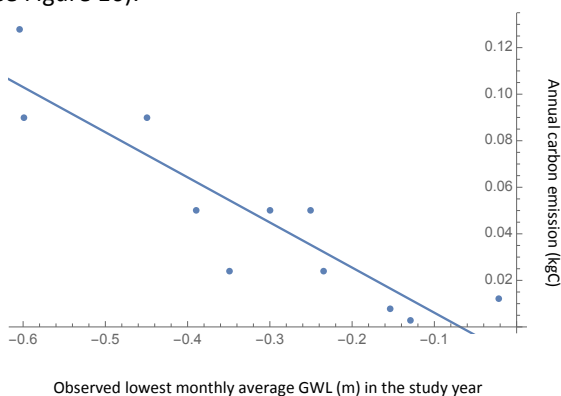
## 2.4 Carbon Emission Model from Peat Burning

### ❖ What is a Carbon Emission Model from Peat Burning? ❖

Similar to the Carbon Emission Model from Peat Decomposition explained in Section 2.3, this model is based on the assumption that there is a linear relationship between the mass of carbon loss from peat burning and GWL. Based on this relationship, the Carbon Emission Model from Peat Burning allows you to estimate the amount of annual carbon emissions by using the lowest monthly average GWL(s) in the study year(s) as a parameter.

Step 1. Obtain a linear relationship between the amount of annual carbon emission from peat burning and observed lowest monthly average GWL(s) in the study year(s)

- Draw a linear regression line between the lowest monthly average GWL(s) in the study year(s) observed at a location representative of the characteristic of the burned area on the x axis, and observed annual carbon emission from peat burning obtained in Step 6 of Sub-section 2.2.4 on the y axis (see Figure 16).



**Figure 16. Example of a linear relationship between the lowest monthly average GWL(s) in the study year(s) and annual carbon emission from peat burning observed in the ex-Mega Rice area in Central Kalimantan (Putra et al., 2009)**

Step 2. Estimate annual carbon emission from peat burning

- Estimate annual carbon emissions from peat burning for other areas of interest. The equation obtained in Step 1 above can only be applied to other areas which indicate similar characteristics of the observed burned area.
  - You can use the equation to estimate the amount of carbon emissions from peat burning for different years, or in other areas beyond sampling locations as long as those areas show similar characteristics to the burned area.



# GWL PREDICTION MODEL

## ❖ What will you learn in Part III? ❖

- How to predict daily groundwater level (GWL) for several days ahead
  - ✓ Key points to understand:
    - The GWL Prediction Model uses the Kalman Filter technique introduced by Rudolf E. Kalman.
    - The Kalman filter is an algorithm or mathematical calculation which uses time-series values observed over time and returns estimates of uncertain variables in a linear system. It separates time-series noise, and can be used to estimate the past, present and future state of the variables (i.e., GWL).
    - The GWL Prediction Model takes a linear model based on the observed GWL values. This means that the future state of the variables (i.e., predicted GWL) has a proportional value to the current average value and statistical noise.
    - The model reduces the noise from the observed GWL values. In this model, the slope is assumed constant.
    - It is useful to apply the GWL Prediction Model in practice. **40 cm below the ground surface** is the threshold of GWL not only for preventing peatland fires but also for keeping peat carbon stored belowground.

Groundwater level can be used as an ecological indicator for peatland management. Lowering GWL causes various ecological disturbances such as carbon emissions, damages to faunal and floral species, loss of ecosystem services, and devastating peatland fires. Early information about the condition of GWLs will help local authorities, land managers and local communities prevent the occurrence of such disturbances and act upon them in a timely manner. The GWL Prediction Model forecasts GWLs for several days ahead.

Surface peat fires tend to start when the GWL drops to about 20 cm below the ground surface, and expand to the surrounding area when it becomes lower than 40 to 50 cm (Putra et al., 2008). Similarly, it is necessary to maintain the GWL higher than 40 cm below the ground surface in order to make replanting successful and minimize fire risks (Wösten et al., 2006).



Figure 17 shows the framework of the GWL Prediction Model. It only uses observed daily average GWLs obtained in Step 3 of Sub-section 2.2.2 (GWL analysis). Therefore, the data collection and analysis procedures can be seen in the relevant sections above (see 2.1.2.1 on GWL measurements and 2.2.2 on GWL analysis), and will not be repeated in this section.

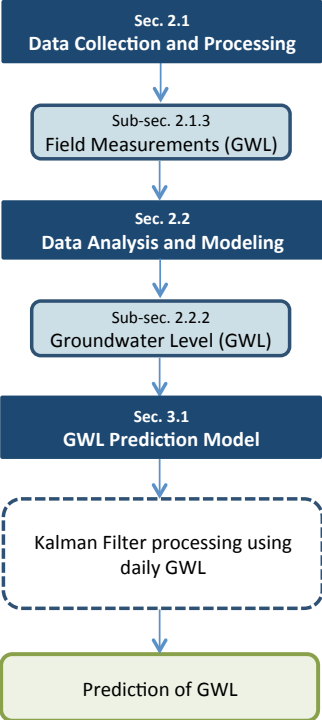


Figure 17. Framework for the GWL prediction

### 3.1 GWL Prediction Model

Figure 18 is a graphical representation of the model described through the following steps.

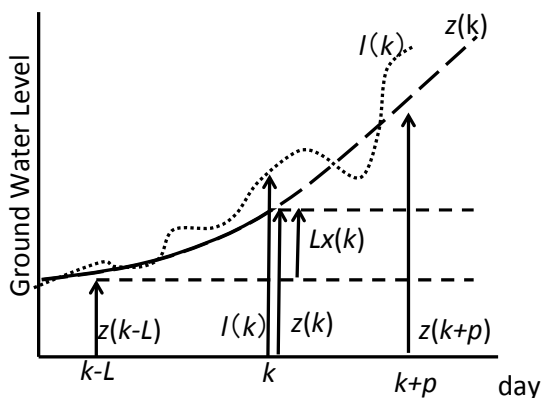


Figure 18. Illustration of the GWL prediction model based on the Kalman Filter technique

- $N$  = the number of daily average GWL observation data
- $k$  = current date -  $N$
- $p$  = the number of days ahead for the prediction of GWL
- $z(k)$  = moving average of the observed GWL data at day  $k$
- $l(k)$  = observed GWL from the SESAME system data at day  $k$
- $(2N+1)$  = range of moving average
- $x(k)$  = a changing rate in GWL per day (state variable)
- $L$  = time step width of the slope between the past and present data

#### Step 1. Select the daily average GWL observation data

- Select the daily average GWL observation data which is to be used as an initial value for the calculation of predicted GWL values. The data may be selected arbitrarily, but must be larger than  $(2N+1)$ .
- Determine the value of parameters as follows.
  - $N$  = the number of daily average GWL observation data
  - $p$  = the number of days ahead for the prediction of GWL

#### Step 2. Calculate a moving average of the daily average GWL observation data

- Calculate a moving average of the GWL observation data value based on the  $N$  value determined in Step 1.

$$z(k) = \sum_{i=-N}^N l(k+i) / (2N+1) \quad (14)$$

Where:

$z(k)$  = moving average

$l(k)$  = observed GWL from the SESAME system

### Step 3. Calculate a state variable

- Calculate a state variable as defined below.

$$x(k) = [z(k) - z(k - L)] / L \quad (15)$$

Where:

$x(k)$  = the rate of change (slope) in GWL value per day (state variable)

$L$  = time step width of the slope between the past and present data

### Step 4. Apply the Kalman Filter

- Apply the Kalman Filter as expressed in the following equations. The equation (16) is based on the assumption that the slope changing rate is constant.

$$x(k+1) = x(k) + w(k) \quad (16)$$

$$y(k) = Lx(k) + v(k) \quad (17)$$

Where:

$w(k)$ ,  $v(k)$  = white Gaussian noise

$y(k)$  = observed data at day  $k$  (observed state variable)

- Calculate the observed state variable, using the following expression.

$$y(k) = l(k) - z(k - L) = Lx(k) + v(k) \quad (18)$$

- Calculate  $w(k)$  and  $v(k)$ , using the following expression.

$$w(k) = x(k) - x(k-1) \quad (k = N + L + 2, \dots, q - N) \quad (19)$$

$$v(k) = l(k) - z(k) \quad (k = N + L, \dots, q - N) \quad (20)$$

- Run the Kalman Filter, using the following iteration.

$$\begin{aligned} x(k|k) &= x(k|k-1) + K(k) [y(k) - Lx(k|k-1)] \\ x(k+1|k) &= x(k|k) \\ C(k|k) &= C(k|k-1) - LK(k) C(k|k-1) \\ C(k+1|k) &= C(k|k) + W(k) \end{aligned} \quad (21)$$

$$K(k) = LC(k|k-1) / [L^2C(k|k-1) + V(k)]$$

Where:

$C(k|k)$  = Variance of  $x(k|k)$

$C(k+1|k)$  = Variance of  $x(k+1|k)$

$W(k)$  = Variance of  $w(k)$

$V(k)$  = Variance of  $v(k)$

### Step 5. Make a prediction of the GWL for $p$ days ahead

- Use the following model (equation) to estimate predicted values of the GWL.

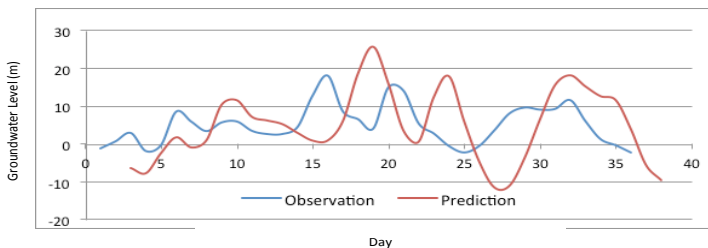
$$z(k+p|k) = z(k) + px(k|k) \quad (22)$$

- This equation can also be expressed as:

Forecasted GWL at day  $p+k$   
 = moving average + day  $p \times$  (forecasted value at day-  $k$ )

- The predicted daily GWL values may be applied to the surrounding areas of SESAME GWL observation points, if there are no environmental factors affecting the GWL in those areas. In other words:
  - Peatland depth is even.
  - There are no drainage canals or rivers nearby the SESAME observation point.
  - Peatland type is uniform.

Figure 19 shows an example of GWL prediction for 3 days ahead.



**Figure 19. Illustration of GWL prediction for 3 days ahead**



# IV FUTURE CONSIDERATIONS

There are several important points that should be considered in order to improve and apply the Carbon Emission Models presented in this guidebook.

## **On data management:**

- Develop a SESAME server and manage all data obtained from each SESAME system in Indonesia. This is likely to improve the network connection between the server and each SESAME system installed in the field in Indonesia, and thus reduce the number of data gaps. This is also likely to reduce the server maintenance cost.

## **On greenhouse gas sources:**

- Expand carbon flux measurement including methane ( $\text{CH}_4$ ), nitrous oxide ( $\text{N}_2\text{O}$ ) and desorbed organic carbon (DOC).
  - $\text{CH}_4$ -C emission is usually smaller than  $\text{CO}_2$ -C emission even in peatland ecosystems; however,  $\text{CH}_4$  has a Global Warming Potential (GWP) value 25 times higher than  $\text{CO}_2$ .
  - In general,  $\text{CH}_4$  emission from tropical peatland is much smaller than that in northern peatland (Couwenberg et al., 2010). However, large  $\text{CH}_4$  fluxes were actually observed especially in burned areas (Adji et al. 2014), because of low  $\text{O}_2$  transportation into peat layer via plant roots.
  - $\text{N}_2\text{O}$  emissions from natural tropical peatland are negligible due to its nutrient-poor condition. In croplands and plantations, however, the application of N-fertilizers will cause considerable amount of  $\text{N}_2\text{O}$  emissions, which have a GWP value 298 times higher than  $\text{CO}_2$ .
  - Organic carbon outflow in water should be taken into account when evaluating the carbon balance in tropical peatland ecosystems.
- Evaluate the composition of gaseous carbon emitted from peat burning.
  - Peat burning emits many kinds of gaseous carbon. Usually  $\text{CO}_2$  is dominant, but other gaseous carbons such as CO,  $\text{CH}_4$  and PM are also present. These gases have different impacts on climate change, environment, and human health. It will be meaningful to assess the impact of peat burning more precisely, not only by estimating total peat carbon loss but also by evaluating the composition of fire-generating gaseous carbon sources.

### **On the application of the models:**

- Use the GWL Prediction Model as an early fire warning system.
  - Work with relevant local institutions to develop and implement practical and user-friendly information communication systems (e.g., Android-based platform). These systems must be tailored to meet the needs of different user groups at the local level (e.g., communities, firefighting teams, companies, and government agencies).
  - Develop a central information communication system at the national level, and work with relevant institutions at all levels (i.e., national and regional) to integrate the system.
  - Use the Carbon Emission Models to estimate the amount of emissions in land use change as part of constructing regional development plans.

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