Design of Georeference-Based Emission Activity Modeling System (G-BEAMS) for Japanese Emission Inventory Management

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ABSTRACT

It comes near to stating the obvious to say that an emission inventory is essential to understanding the status of pollutant emissions and to designing comprehensive countermeasures for mitigating them. To improve the accuracy of an inventory and to allow data management, it is necessary to develop methods for systematizing an emission inventory. We developed an emission inventory system, the Georeference-Based Emission Activity Modeling System (G-BEAMS). The primary function of our system is to estimate the spatial and temporal distributions of chemical emissions and air pollutants in Japan. It uses mathematical functions to estimate emissions; emissions maps to show differences over time; and databases of emission factors, activity data, spatial weighting factors, and temporal weighting factors. G-BEAMS standardizes emission-source categories and geographic position. Unfortunately, there is no Japanese standard source classification for an emission inventory like the US SCC (Source Classification Code) or the EU SNAP (Selected Nomenclature for Air Pollution) code. Therefore, we coded our own classification by considering a combination of industries, production processes, and production technologies. Geographic positions were defined with polygonal, linear geometry or coordinate values on a GIS layer; each geometry has a unique index. Basic layers in the system were chosen with regard to the public availability of statistical data, including geographic position information. This standardization enables us to systematize procedures for compiling an emission inventory by both top-down and bottom-up approaches, and by spatially and temporally allocating estimated emissions.

INTRODUCTION

An emission inventory helps us to quantify the status of environmental burdens. Compiling an emission inventory by emission source is useful for figuring out not only the total environmental burden, but also the contribution of each source to the total. Moreover, an emission inventory showing the geographical distribution of emissions (an "emission map") can supply input data to atmospheric dispersion and environmental fate models. From the outputs of these models, we can evaluate environmental impacts of emission sources. Knowing this helps us to manage environmental risks and to design policy measures to reduce them. Evaluation of the effects of countermeasures needs recompilation of the emission inventory, to reflect changes in emission factors and related activities. Systematizing the procedures for building an emission inventory facilitates such recompilation. So far, however, most emission inventories compiled in Japan have been static, and methods of systematizing inventories have not been discussed sufficiently.

The methods for and approaches to estimating emissions depend on the type of environmental burden and the emission source; hence, it can be very difficult to develop a systematized method independent of burden and source, as for all inventory processes. However, as proposed by the US EPA (Ryan, 2003), procedures needed in emission inventorying can be classified into four steps: emission estimation, temporal allocation, spatial allocation, and pollutant speciation. In order to systemize an emission inventory, it is important to focus on these common fundamental procedures.

The primary aim of our study was to develop a system to compile an emission inventory (an inventory system). This paper describes its design; in particular, system configuration, techniques of data management, and key methods corresponding to the formulation of emission estimation. We roughly classify the fundamental procedures to build an emission inventory into three steps: estimation of emissions, estimation of spatial distribution, and estimation of temporal distribution. In line with these estimation procedures, the following section explains the characteristics of our system design and methods.

MATERIALS AND METHODS

System configuration and data management

As essential data on emission activity, for each entry, an inventory system needs to assign an emission source category, geographical location, and an emission estimation method. To manage these data, we use a geographical information system (GIS) and database software. Figure 1 illustrates the system configuration. The emission source categories are identified by a unique code. Because of the lack of a standard system for coding emission sources in Japan like the SCC in the USA and SNAP in the EU, we devised our own code, the Hierarchical Source Classification Code, or HSCC. Under the HSCC, each emission source can be categorized by the combination of three type codes representing industry, industrial process, and technology. The geographic position is preliminarily defined by geometry on a GIS layer. The system prepares standard layers and gives a unique code (the LinkID) to each geometry on a layer (Suzuki et al., 2003). Since geometry in a GIS is a figure having geographical position and shape, we can handle emission locations by LinkIDs. A GIS is a powerful tool for mapping emission distributions. G-BEAMS calculates emissions from the corresponding HSCC and LinkID and saves the results in the database. Considering the public availability of Japanese statistics applicable as emission activity data, we

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selected 13 standard type layers (Suzuki et al., 2003). These layers are summarized in Table 1. Handling emission activity data with LinkIDs enables us to manage them with just database software, because the actual location of an emission source can be identified by converting its LinkID into geometry on the layer in the GIS.

Methods for estimating emissions take the form of functions written in computer language. By using a common format for inputting data with LinkID into the function and outputting the result with LinkID from it, G-BEAMS allows accumulation, choice, and replacement of various estimation methods.

Understandably, defining geographic position by geometry has the disadvantage of limiting the geographical resolution of an emission inventory. But the geographical resolutions of our standard layers can cover those of most Japanese social statistics applicable to activity data; therefore, G-BEAMS can be used to build inventories of various pollutants.
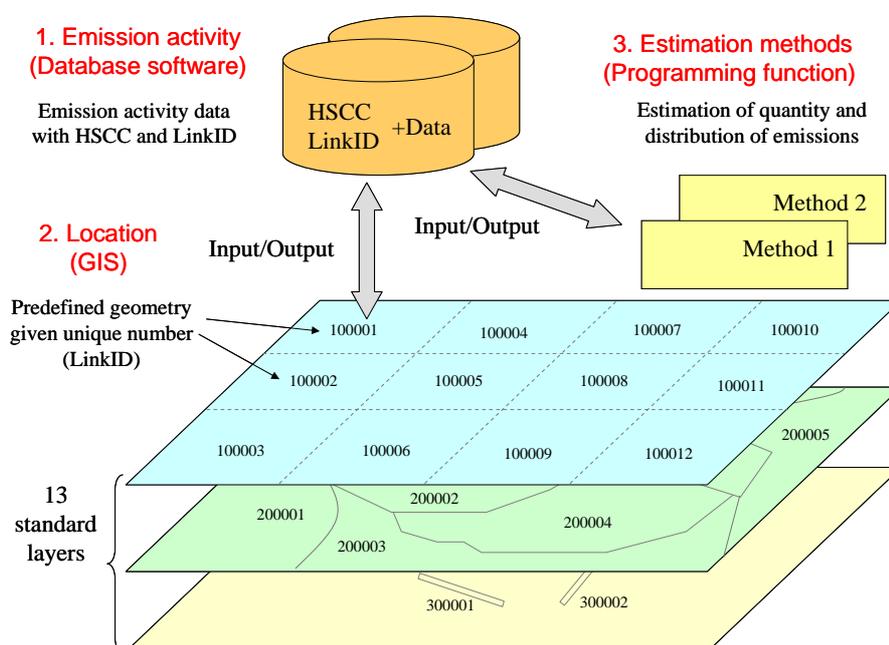
Figure 1. Schematic of configuration of G-BEAMS

Table 1. Speciation of predefined geometries on the standard layer in the inventory system

No.	Layer name	Feature of geometry on the layer	Geometry type	Number of geometry (No. of LinkID)
1	Japan	Whole of Japan	Polygon	1
2	First-mesh	Grid of about 80 km by 80 km	Polygon	162
3	Second-mesh	Grid of about 10 km by 10 km	Polygon	4 811
4	Quarter-mesh	Grid of about 5 km by 5 km	Polygon	17 262
5	Third-mesh	Grid of about 1 km by 1 km	Polygon	386 246
6	Prefecture	Area of prefecture	Polygon	47
7	City	Area of city	Polygon	3 387
8	Basin	Area of basin	Polygon	37 750
9	Agricultural village	Area of agricultural village	Polygon	150 057
10	Sea	Defined segment of sea	Polygon	250
11	Lake	Area shape of lake	Polygon	263
12	River	River network	Line	38 164
13	Road	Road network	Line	33 772

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Emission estimation

As illustrated in Figure 2, we have two main approaches to building an emission inventory: top-down and bottom-up. In the top-down approach we first calculate emissions for large geometries on a certain layer and then convert them into emissions for smaller geometries on another layer. This approach could be appropriate for calculation of pollutant emissions with a very small site-dependency of their emission factors and sufficient national-level statistics to allow estimation of their emissions. For example, CO_2, NO_x, and SO_x emissions from stationary sources can be valid.

By contrast, in the bottom-up approach, emission calculation starts in small geometries on a certain layer, and then the emissions are converted into larger geometries on another layer. This can be suitable for pollutants whose emission factors are highly dependent on the environment (e.g., temperature, humidity, and insolation) of the emission location. Volatile organic compounds and NH_3 are representatives of such pollutants. Our system identifies an emission location only by LinkID, so differences between the two approaches result in differences just of the LinkID of initial geometries for which we calculate emissions. In other words, G-BEAMS treats both approaches as the same method.
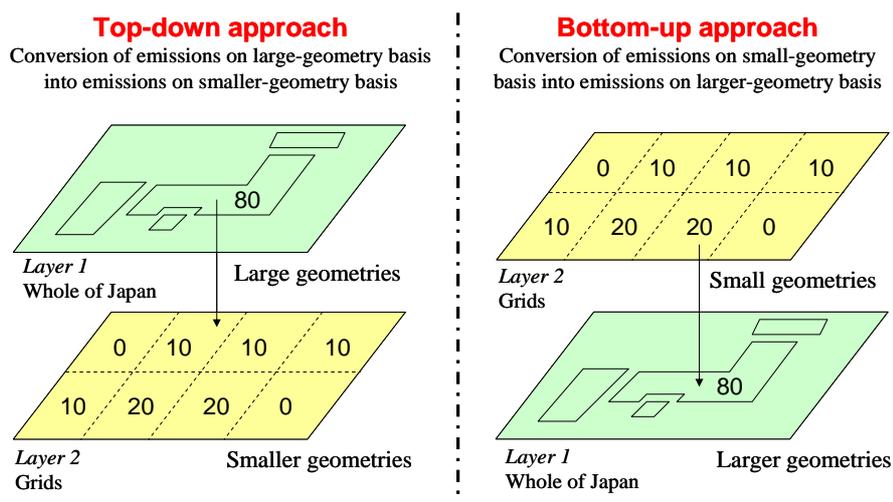
Figure 2. Two approaches to building an emission inventory

Spatial distribution of emissions

To create an emission map for environmental fate models, an emission inventory needs the spatial distributions of emissions. The bottom-up approach sums the calculated emissions into the total emissions of a country or region. As described above, G-BEAMS can convert emissions in the initial layer to emissions in other layers. Taking into account characteristics of public statistics and GIS functions, we discuss two methods to meet the requirements: the cascade weighting method and the hybrid weighting method.

Cascade weighting method

Figure 3 illustrates the relationship among the number of source categories used in Japanese statistics and their geographical resolution. Generally, types and source classifications of the statistics decrease as their geographic

resolutions increase. For example, a country-level statistic shows activity data by many sectors, but as we move toward the grid level, some sectors are consolidated. Thus, the uncertainty of the activity value of each sector tends to increase as the geographical resolution of the statistic increases. Considering these characteristics of statistics, it can be effective to convert initial estimated emissions (allocation or integration) by the cascade weighting method, as illustrated in Figure 4.

In this method, we prepare spatial weighting factors (SWFs) of geometries on each layer in order that the sum of SWFs for each layer is 1. This normalized factor represents the ratio of the magnitude of emission activity for a geometry to that of total activity. Hence, it needs to be determined by statistics related to emission activity, for example, fuel consumption and commodity production. But the more the geographical resolution of a statistic increases, the lower the precision of SWFs becomes (Fig. 3). The initial estimated emissions are converted step by step from geometries on the layer with higher-precision SWFs into geometries on the layer with lower-precision SWFs. Therefore, compared with methods in which emissions based on a layer are directly allocated rough SWFs of geometries of high geographical resolution, the cascade weighting method can be effective at preventing an increase in the uncertainty of estimating the emission distribution.

Here, fundamental calculation steps are explained by using the simple example in Figure 4. There are three layers, A, B, and C. We assume that the uncertainty of SWFs of geometries on layer B is lower than that on layer C. When we estimate emission Y_h on layer C from the initial estimated emission W_j on layer A, initial emission X_i is obtained from the allocation of W_j by Eq. (1):

$$X_i = W_j \cdot \frac{SWF_i}{\sum_{m=i \in j} SWF_m} \tag{1}$$

where SWF_m is the SWF of geometry m, which geographically overlaps geometry j on a different layer. Next, similarly according to Eq. (2), emission Y_h can be determined by using emission X_i and SWF_n of geometries overlapping geometry i. These procedures enable G-BEAMS to convert emissions between the standard layers.

$$Y_h = X_i \cdot \frac{SWF_h}{\sum_{n=h \in i} SWF_n} \tag{2}$$

Number of source category
types of statistical data

Many

Few

Low   *High*   Geographical
resolution

Country → Prefecture → City → Grid
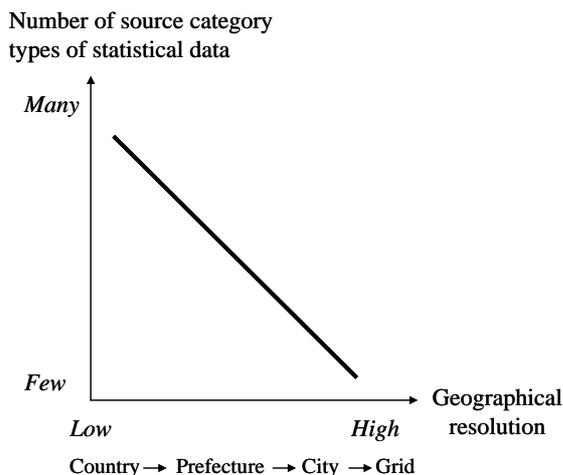
Figure 3. Relationship among types, sector categories, and geographical resolution of Japanese statistics
applicable as emission activity data

Low

Uncertainty of *SWFs*

High

Layer A

W_j

Layer B

$X_i \; (SWF_i)$

$X_{i+1} \; (SWF_{i+1})$

Layer C

$Y_h \; (SWF_h)$ $Y_{h+1} \; (SWF_{h+1})$

$Y_{h+2} \; (SWF_{h+2})$ $Y_{h+3} \; (SWF_{h+3})$

1. Conversion of emissions on the
layer A into on the layer B

$$X_i = W_j \cdot \frac{SWF_i}{\sum\limits_{m=i \in j} SWF_m}$$

2. Conversion of emissions on the
layer B into on the layer C

$$Y_h = X_i \cdot \frac{SWF_h}{\sum\limits_{n=h \in i} SWF_n}$$

$$= W_j \cdot \frac{SWF_i}{\sum\limits_{m=i \in j} SWF_m} \cdot \frac{SWF_h}{\sum\limits_{n=h \in i} SWF_n}$$

W, X, Y: Emissions for each geometry

SWF: Spatial weighting factor

$i \in j$: Geometries i geographically
overlap geometry j
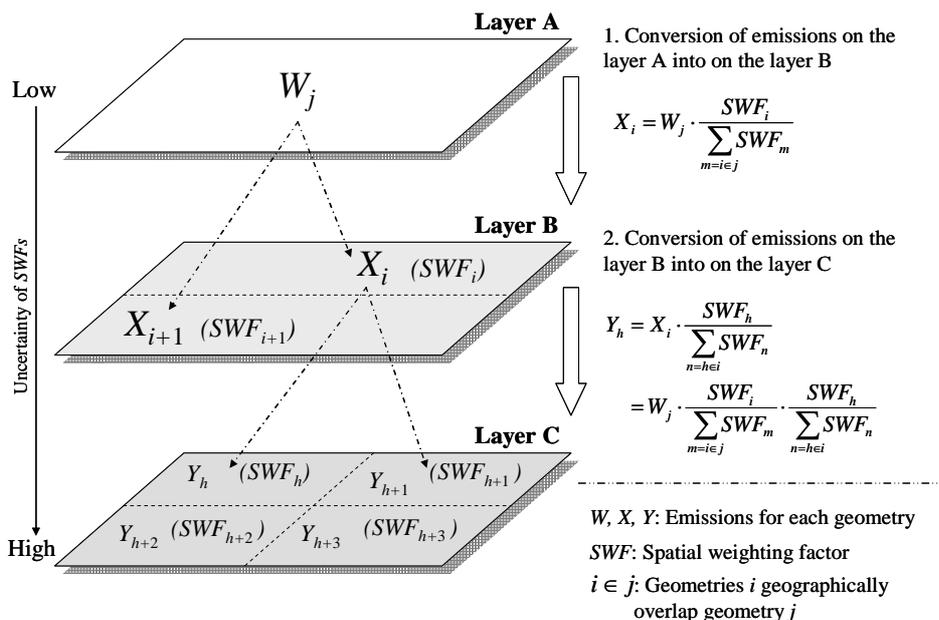
Figure 4. Schematic of the cascade weighting method for estimating emission distribution

Hybrid weighting method

Using emissions monitoring and survey data in addition to estimated emissions is another useful way to improve
the accuracy of an emission inventory. The hybrid weighting method determines emission distributions by
combining the cascade weighting method with existing emission data. A simple example is shown in Figure 5.
Here, we assume that there are 3 layers, A, B, and C; and emissions a_h and a_{h+1} are extrapolated into geometries h
and $h+1$ on layer C. The extrapolated emissions are preferentially used, and the balances are estimated by the

cascade weighting method. Besides the extrapolated emissions a_h and a_{h+1}, we need to prepare r_h and r_{h+1}, which are the ratios of the SWF of the extrapolated emissions to the total SWF of the extrapolated geometries.

When X_i and a_n are related by Eq. (3), emission Y_h is determined from extrapolated a_h by deducting the sum of extrapolated emissions from X_i and allocating the rest of it proportionally to the SWFs, as in Eq. (4):

$$X_i - \sum_{n=h\in i} a_n \geq 0, \tag{3}$$

$$Y_h = a_h + \left(X_i - \sum_{n=h\in i} a_n \right) \cdot \frac{SWF_h\left(1-r_h\right)}{\sum_{n=h\in i} SWF_n\left(1-r_n\right)} \tag{4}$$

But when X_i and a_n are related by Eq. (5), the sum of extrapolated emissions is deducted from the initial estimated emission W_j of the layer 2 layers above C in the order used by the cascade weighting method. Then X_i is derived from Eqs. (6) and (7), and in the same way as emission Y_h is determined from Eq. (2) with the cascade weighting method.

$$X_i - \sum_{n=h\in i} a_n < 0 \tag{5}$$

$$X_i = \sum_{n=h\in i} a_n + \left(W_j - \sum_{n=h\in i} a_n \right) \cdot \frac{SWF_i\left(1-r_i\right)}{\sum_{m=i\in j} SWF_m\left(1-r_m\right)} \tag{6}$$

$$r_i = \frac{\sum_{n=h\in i} r_n SWF_n}{\sum_{n=h\in i} SWF_n} \tag{7}$$
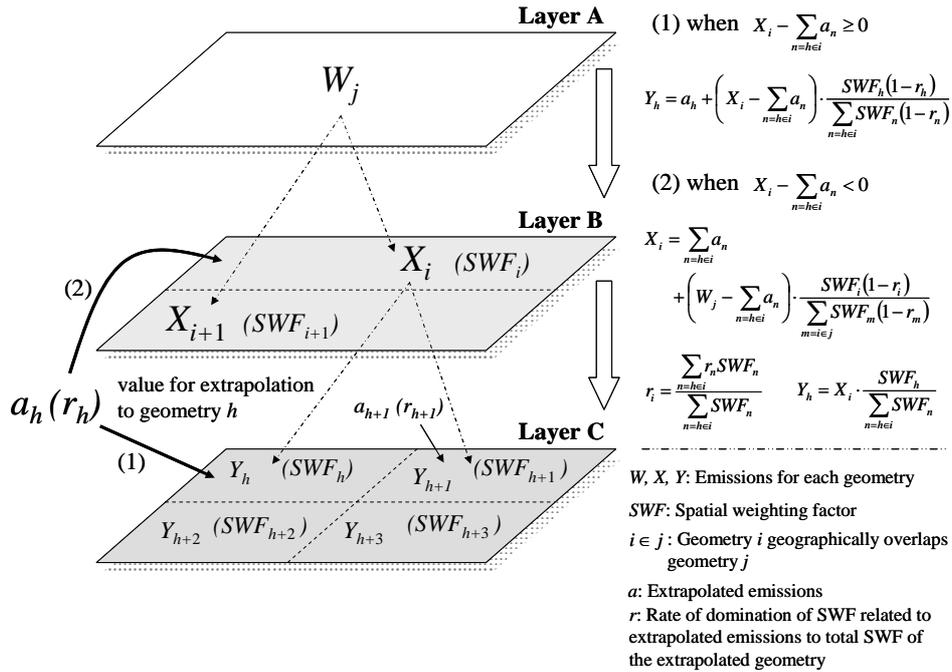
Figure 5. Schematic of the hybrid weighting method for estimating emission distribution

Transformation of SWF by use of geographical information

In the cascade weighting method, emissions are converted in proportion to the SWF of the geometry of the conversion destination. However, there are cases where the original geometry to be converted partly overlaps the geometry of the conversion destination. In these cases, the SWFs are transformed on the basis of the geographic information (area ratio or length ratio of the projected geometry). Given the geographic relationship between polygonal geometries in Figure 6, we can define the projected areas A_1B_1 and A_1B_2 (Suzuki et al., 2003). Emission X_j of geometry A_1 is converted into emissions of geometries B_1 and B_2 by using SWFs of the projected areas A_1B_1 and A_1B_2. From Eqs. (8) and (9), their SWFs (SWF_{A1B1} and SWF_{A1B2}) can be determined by multiplying the SWF of the conversion destination geometry and the area ratio of the projected area to the conversion destination geometry:

$$SWF_{A1B1} = SWF_{B1} \cdot Ar(A_1B_1 / B_1) \tag{8}$$

$$SWF_{A1B2} = SWF_{B2} \cdot Ar(A_1B_2 / B_2) \tag{9}$$

where $Ar(G_1/G_2)$ means the area ratio of geometry G_1 to geometry G_2. Next, as a matter of convenience, when calculating emissions x_jy_i of the projected area A_jB_i by Eq. (10), emission Y_i of geometry B_i can be determined by Eq. (11):

$$x_j y_i = X_j \cdot \frac{SWF_{A_jB_i}}{\sum_{k=i \in j} SWF_{A_jB_k}} \tag{10}$$

$$Y_i = \sum_{p=j \in i} x_p y_i \tag{11}$$

On the other hand, as illustrated in Figure 7, in the case of conversion of emissions between polygonal and linear geometries, SWFs of the projected lines A_jB_i and A_jB_{i+1} can be calculated by Eqs. (12) and (13), respectively:

$$SWF_{A_jB_i} = SWF_{B_i} \cdot Lr\left(A_jB_i / \sum_{s=j \in i} A_sB_i \right) \tag{12}$$

$$SWF_{A_jB_{i+1}} = SWF_{B_{i+1}} \cdot Lr\left(A_jB_{i+1} / \sum_{t=j \in i+1} A_tB_{i+1} \right) \tag{13}$$

where $Lr(G_1/G_2)$ means the length ratio of geometry G_1 to geometry G_2. In a similar way to the previous example of polygonal geometries, emissions x_jy_i of the projected line A_jB_i are calculated by Eq. (10), and then Eq. (11) determines emission Y_i of geometry B_i.

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1. Transformation of SWFs

$$SWF_{A_jB_i} = SWF_{B_i} \cdot Ar\left(A_jB_i / B_i\right)$$

$$SWF_{A_jB_{i+1}} = SWF_{B_i} \cdot Ar\left(A_jB_{i+1} / B_{i+1}\right)$$

2. Emissions x_jy_i of the projected area A_jB_i

$$x_jy_i = X_j \cdot \frac{SWF_{A_jB_i}}{\displaystyle\sum_{k=i\in j} SWF_{A_jB_k}}$$

3. Emissions Y_i of geometry B_i

$$Y_i = \sum_{p=j\in i} x_p y_i$$

X, Y: Emissions for each geometry

SWF: Spatial weighting factor

$i \in j$: Geometries *i* geographically overlap geometry *j*

Ar(G₁/G₂): the area ratio of geometry G_1 to geometry G_2
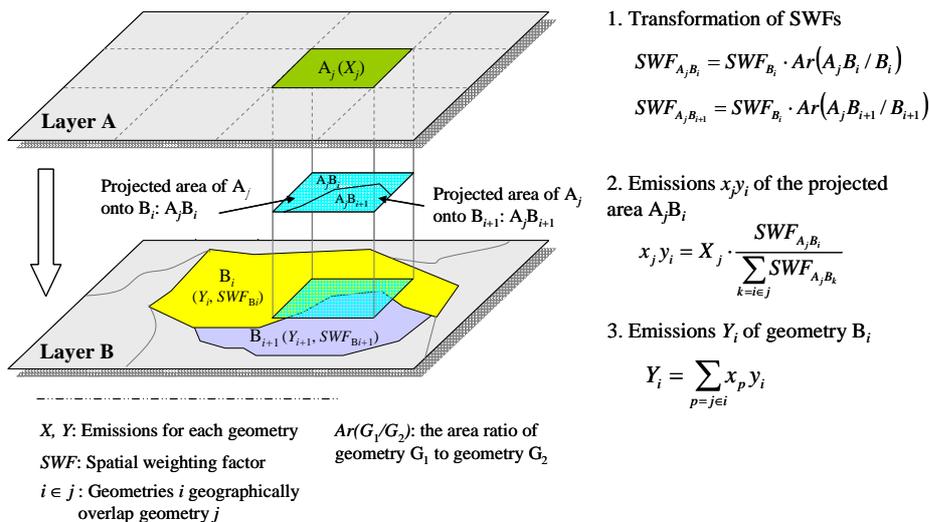
Figure 6. Method of transforming spatial weighting factors between polygonal geometries

1. Transformation of SWFs

$$SWF_{A_jB_i} = SWF_{B_i} \cdot Lr\left(A_jB_i / \sum_{s=j\in i} A_sB_i\right)$$

$$SWF_{A_jB_{i+1}} = SWF_{B_{i+1}} \cdot Lr\left(A_jB_{i+1} / \sum_{t=j\in i+1} A_tB_{i+1}\right)$$

2. Emissions x_jy_i of projected line A_jB_i

$$x_jy_i = X_j \cdot \frac{SWF_{A_jB_i}}{\displaystyle\sum_{k=i\in j} SWF_{A_jB_k}}$$

3. Emissions Y_i of geometry B_i

$$Y_i = \sum_{p=j\in i} x_p y_i$$

X, Y: Emissions for each geometry

SWF: Spatial weighting factor

$i \in j$: Geometry *i* geographically overlaps geometry *j*

Lr(G₁/G₂): Length ratio of geometry G_1 to geometry G_2
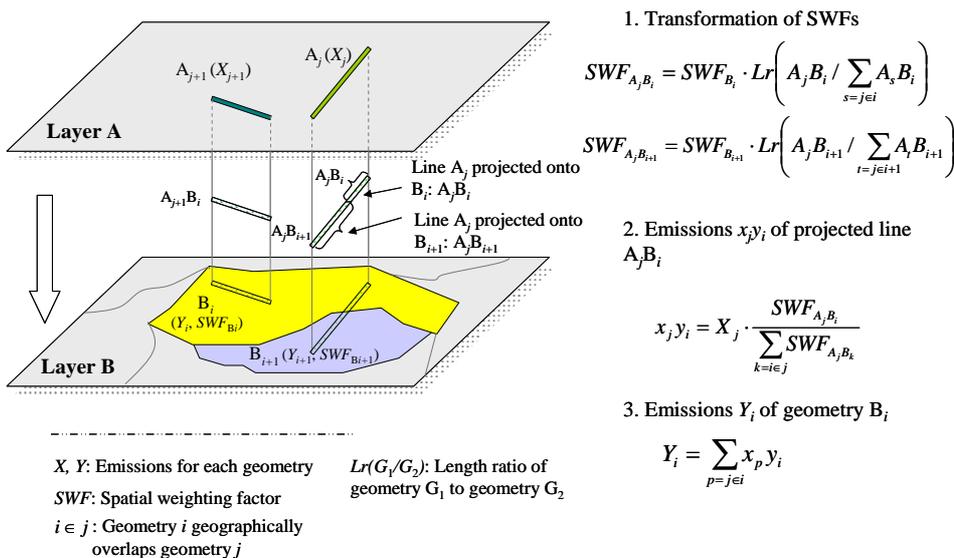
Figure 7. Method of transforming spatial weighting factors between polygonal and linear geometries

Preparation of geographical information data set

In the inventory system, the database is prepared preliminarily from a combination of LinkIDs whose geometries geographically overlap each other, and area or length ratios of the projected areas to the respective original geometries. Therefore, G-BEAMS is able to easily and quickly perform the above conversions of emissions between layers.

Temporal distribution of emissions

Allocation of estimated emissions over time follows the US EPA's method (Ryan, 2003). We use temporal weighting factors (TWFs) for each time unit (year, month, week, day, and hour) for the allocations. As shown in Figure 8, we need to design appropriate TWFs to display temporal differences in emissions in order that the sum of TWFs for each time unit equals 1. Estimated emissions are divided or expanded step-by-step in time unit order. For instance, to estimate emission $X_{m,w,d,h}$ (on h hour of d day of w week in m month), first the estimated emission X_p, which is a potential quantity considered to be fully emitted over more than a year, is multiplied by the annual TWF, TWF_a. This produces an estimate of the annual amount of emissions. Next, by multiplying this by the monthly, weekly, daily, and hourly values of TWF, we can obtain emission $X_{m,w,d,h}$ (Eq. (14)). Alternatively, we can calculate emission $X_{m,da,h}$ (on h hour of da date in m month) (Eq. (15)):

$$X_{m,w,d,h} = X_p \cdot TWF_a \cdot TWF_m \cdot TWF_w \cdot TWF_d \cdot TWF_h \tag{14}$$

$$X_{m,da,h} = X_p \cdot TWF_a \cdot TWF_m \cdot TWF_{da} \cdot TWF_h \tag{15}$$
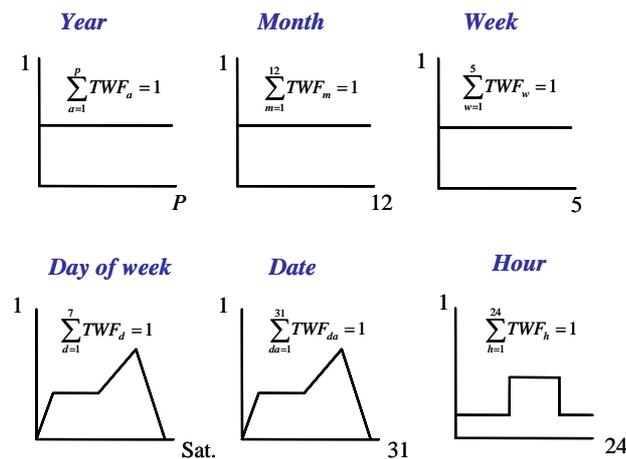
Figure 8. Schematic graphs of temporal weighting factors by time unit

CONCLUSIONS

This article proposed the methodologies to systematize fundamental procedures of building an emission inventory. Using these methods, we are now developing the inventory system (G-BEAMS) on GIS platform. When it is finished, we will build an emission inventory for traditional air pollutants and examine the validity of our systematic estimation methods. We have also been developing a "Virtual World" for environmental risk assessment and management, which is an integrated environmental information system on a GIS platform (Suzuki et al., 2003). One salient characteristic of this virtual world is the calculation of environmental risks through data exchange between respective models: emission inventory, environmental fate, and exposure. G-BEAMS is planned to function as emission inventory model for the virtual world in the near future.

KEYWORDS

Emission inventory, Systemization, GIS, Database software

ACKNOWLEDGMENTS

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