Modelling of Thermodynamics of Adsorption on Sensor Array Films: Application to the Generalized Multi-Component Adsorption-Model of Langmuir

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In the present study, by using of Gibbs Duhem formalism and simple mathematics, new models, which describe the response of the elements of a sensor array, have been developed. In addition, the thermodynamic behavior of the interfaces sensor array films/gas mixture has been treated. Finally, the derived models were used for the generalized model of adsorption of Langmuir.

Keywords: Intrinsic Conducting Polymers, Sensor Array, Modeling, Adsorption of Langmuir, Gibbs-Duhem Equations.

1. INTRODUCTION
It has been demonstrated, that conjugated polymers possess interesting electronic and optoelectronic characteristics. This made them very attractive as transducer in various sensing devices. Conducting polymers such as polypyrrole, polythiophene and polyaniline are typically used as sensitive coatings in electronic nose devices, for gas sensing. The polymer film acts as reversible sponge, when the sensor adsorbs analyte vapors; the conductivity of the polymer film varies proportional to the vapors concentrations. One disadvantage of the conducting polymers is their lack of specificity. In order to analyze a gas mixture; the data of a sensor array will be treated using pattern recognition techniques.

The physical or chemical adsorption on sensor sensitive layer has been treated by many researchers. But to our best knowledge, the physical and chemical behavior of the two-phase multi-system sensor array elements/gas mixture components was investigated by no study. In previous works,1–2 we have developed differential equations, which describe the responses of the sensor array elements in the interaction with a gas mixture.

In the present work, we make the next step and extract useful thermodynamic information from these models. We were interested on resistive conducting polymer sensors, whose multi component adsorption follows the generalized adsorption model of Langmuir.

2. THEORETICAL ASPECTS
2.1. Description of the Interactions Between a Sensor Array and a Mixture of Vapors
We consider a multisystem with \( m \)-intrinsic conducting polymer based sensors and \( q \) different chemical species. The conductance \( G \) of the multi-sensor depends on the conductance of the individual sensors, which in turn depend on the concentrations of the gas mixture components and temperature. A small change \( dG \) of the sensor array conductance can be determined by using the chain rule. Furthermore, the conductivity of each chemical sensor must be a state function. This is an essential precondition for the operational and practically useful sensors.3 Therefore, a small variation of the sensor conductance can be expressed as a total differential. Mathematically the variation \( dG \) can be expressed as follows

\[
dG = \sum_{i=1}^{m} dG_i = \sum_{i=1}^{m} dG_1^{air} + \sum_{i=1}^{m} (dG_i^* + dG_i^T) \]

\[
= \sum_{i=1}^{m} dG_1^{air} + \sum_{i=1}^{m} \left( \frac{dG_i^*}{dG_i^T} dG_i^T + \frac{dG_i^T}{dG_i^T} dG_i^T \right) \quad (1)
\]

The Eq. (1) can be rewritten in simpler form as follows

\[
d(\Delta G) = \sum_{i=1}^{m} d(\Delta G_i) \]

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} \left( \frac{dG_i^*}{dG_i^T} \frac{dG_i^T}{dn_j} dG_i^T \right) + \left( \frac{dG_i^T}{dG_i^T} \frac{dG_i^T}{dT} dT \right) + \sum_{i=1}^{m} \left( \lambda_i^* S_j^* dn_j \right) + \left( \lambda_i^T S_j^* dT \right) \quad (2)
\]
where \( n_j \) in moles (or in ppm) stands for the initial number of moles of the component \( j \) of the gas mixture; \( G_{ij}^n = f(n, T) \) in \( \Omega^{-1} \) symbolizes the conductance of the single sensor \( i \) that interacts with the gas mixture at variable temperature \( T \) and at variable concentrations \( n \) of the gas mixture components; \( G_{ij}^T = f(T) \) in \( \Omega^{-1} \) stands for the conductance of the single sensor \( i \), that interacts with the gas mixture at constant temperature and at constant concentrations of the gas mixture components, respectively; \( G_i = f(T, n) \) in \( \Omega^{-1} \) stands for the response of the \( i \)th sensor array element that interacts with a mixture of vapors at variable temperature \( T \) and at variable concentrations \( n \) of the gas mixture components; \( G_{in}^n = f(n) \) and \( G_{iT} = f(T) \) in \( \Omega^{-1} \) symbolize the conductance of the \( i \)th sensor array component that interacts with the gas mixture at constant temperature and at constant concentrations of the gas mixture components, respectively; \( G_{ij}^T \) in \( \Omega^{-1} \) symbolizes the partial sensitivity of the single sensor \( i \) that interacts with the gas mixture component \( j \) at constant temperature and at constant concentrations of the gas mixture components, respectively; the coefficients \( \lambda_i^T \) and \( \lambda_j^T \) were used to describe the influence of the composition of the sensor array and the influence of the concentrations of the gas mixture components on the response of the sensor array, at constant temperature is and at constant composition of the gas mixture, respectively.

2.2. Derivation of Gibbs Duhem Like Differential Equations

To develop Gibbs-Duhem like differential equations, we consider the indefinite integral of the relationship 2. We assume that the following relationships are valid

\[
S_{ij}^n = \frac{\partial G_{ij}^n}{\partial n_j} \quad \text{and} \quad S_{ij}^T = \frac{\partial G_{ij}^T}{\partial T}
\]

\[
S_{ij}^n = \frac{G_{ij}^n}{n_j} + \frac{\partial G_{ij}^n}{\partial n_j} = \text{constant}
\]

\[
S_{ij}^T = \frac{G_{ij}^T}{T} + \frac{\partial G_{ij}^T}{\partial T} = \text{constant}
\]

where \( G_{ij}^n \) (or \( G_{ij}^T \)) stands for a partial conductance; it describes the contribution of the \( j \)th component of the gas mixture in the total conductance of the single sensor \( i \), at constant temperature (or at constant composition of the gas mixture); later, in paragraph “result and discussion,” we give more details about the physicochemical meaning of the assumptions (3) and (4). Moreover, it is obvious that for a given sensor \( i \) and a given gas mixture, the coefficients \( \lambda_i^T \) and \( \lambda_j^T \) are constant. Taking in account of the above cited conditions (or assumptions), the indefinite integral of Eq. (2) leads to

\[
\Delta G = \int \sum_{i=1}^{m} \sum_{j=1}^{q} (\lambda_i^T S_{ij}^n \frac{dn_j}{dn_j}) + (\lambda_j^T S_{ij}^T dT)
\]

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} \left( \lambda_i^T S_{ij}^n \int \frac{dn_j}{dn_j} \right) + \left( \lambda_j^T S_{ij}^T \int dT \right)
\]

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} (\lambda_i^T S_{ij}^n n_j) + (\lambda_j^T S_{ij}^T T)
\]

Since the coefficients \( \lambda_i^T \) and \( \lambda_j^T \) are constant, the differentiation of the Eq. (5) and the comparison with Eq. (2) gives the following differential equation

\[
\sum_{i=1}^{m} \sum_{j=1}^{q} (n_j \lambda_i^T dS_{ij}^n) + (T \lambda_j^T dS_{ij}^T) = 0
\]

where the symbol \( S_{ij}^n \) in \( \Omega^{-1} \) mol\(^{-1}\) (or \( S_{ij}^T \) in \( \Omega^{-1} \) Kelvin\(^{-1}\)) stands for the sensitivity of the \( i \)th element of the sensor array when it interacts with the gas mixture component \( j \) at constant temperature (or at variable temperature). The differential Eq. (6) describes the physicochemical behavior of the multi-systems. It connects the variations of sensors sensitivities with the concentrations of the gas mixture components and the temperature, so that the multi-system remains in equilibrium.

We are interested in the change of the sensitivities of the sensor array elements, when the concentrations of the gas mixture component \( j \) vary from the value 0 to \( n_j \) and the temperature \( T \) varies from 0 to \( T \) in this case \( dn_j \) is equal \( n_j \) (\( dn_j = n_j \)) and \( dT \) is equal to \( T \) (\( dT = T \)); the relationship (6) becomes

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} (n_j \lambda_i^T dS_{ij}^n) + (T dS_{ij}^T) = 0
\]

Inserting the relationships (3) and (4) into (7) gives

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} \left( n_j \lambda_i^T \frac{dS_{ij}^n}{dn_j} \right) + \left( T \frac{dS_{ij}^T}{dT} \right) = 0
\]

At constant temperature, the Eq. (8) becomes

\[
= \sum_{i=1}^{m} \sum_{j=1}^{q} \left( n_j \lambda_i^T \frac{dS_{ij}^n}{dn_j} \right) = 0
\]

The Eqs. (8) and (9) represent the condition that must be fulfilled by the responses of the sensor array elements at variable and at constant temperature, respectively, so that the multi-system remains in equilibrium.
2.3. Deduction of Thermodynamic Models

In order to develop thermodynamic models, we multiply the Eq. (6) by the constant factors $S_i^o/S_i^o$ and $S_j^o/S_j^o$ and by $G_i^*/(G_i G_i^*)$ and $G_j^*/(G_j G_j^*)$; we get the relationship

$$\sum_{i=1}^{m} \sum_{j=1}^{q} \left( \frac{G_i^*}{G_i} \sigma_j^0 d \ln S_i^o \right) + \frac{G_j^*}{G_j} \sigma_j^0 d \ln S_j^o) = 0 \quad (10)$$

The Eq. (10) may be rewritten by introducing novel coefficients $k$ and $\sigma$; we obtain

$$\sum_{i=1}^{m} \sum_{j=1}^{q} (\kappa_i^* \sigma_j^0 d \ln(S_i^o)) + (\kappa_j^* \sigma_j^0 d \ln(S_j^o)) = 0 \quad (11)$$

where the symbols $\sigma_j^0$ and $\sigma_j^*$ represent the selectivity coefficients of the sensor array element $i$ with respect to the component $j$ of the gas mixture at constant temperature and at constant composition of the gas mixture, respectively; $\kappa_i^*$ and $\kappa_j^*$ stand for the coefficients of standardization at constant temperature and at constant composition of the gas mixture, respectively.


One of defining features of polymer surfaces and coatings is the chemical regularity of the surface. While many materials can be irregular mixtures of different components, the polymer surfaces tend to be chemically uniform. Because of this, adsorption of molecules onto polymer surfaces can be easily modeled by the Langmuir isotherm. The conductivity of a single sensor based on conducting polymer, when it interacts with a single gas, depends on the density and the mobility of charge carriers; it varies linearly with the concentration of the adsorbed gas and follows the Langmuir model.$^4,5$

We consider now the interaction between a single sensor based on intrinsic conducting polymer and a mixture of $q$-vapors. We assume that there are no interactions between the adsorbed particles. Through the summation of the effects of the adsorbed components of the gas mixture can the above-cited conductivity model of Langmuir be used to the description of the interaction between a polymeric film and a gas mixture. This assumption is valid for low concentrations of the gas mixture components. We make further assumptions, that is only one type of active immobile adsorption site for which all molecules actively compete (competitive adsorption) and that the mobility depends only on temperature ($\mu = \mu(T)$; we get

$$G_i^{\text{tot}} = G_i^{\text{iso}} + \sum_{j=1}^{q} \frac{G_j^{\text{iso}}}{G_j^{\text{iso}}} + \sum_{j=1}^{q} G_j^{\text{iso}} \sigma_j^0 d \ln(S_j^o) \quad (12)$$

where $G_i^{\text{iso}}$ stands for a conductance; it describes the contribution of the $j$th component of the gas mixture in the total conductance of the single sensor $i$; at constant temperature; $b_j^{\text{iso}}$ symbolizes a binding-variable for the interface single sensor $i$/gas mixture component $j$ at constant temperature; $\gamma_j = (n_j/n_i)$ is a dimensionless coefficient, das symbol $G_j^{\text{lim}}$ describes the limit value of the conductance of the single sensor $i$; the parameter $k_j^*$ was introduced to simplify the calculations in the next paragraphs.

2.4.1. Sensitivity of Conducting Polymer Sensors at Variable Temperature

The variation of temperature not only affects the binding variables $b_*$ but also the parameters of transduction. We introduce the dimensionless coefficients $\alpha_j^0$ and $\alpha_j^*$, which describe the effect of temperature on the partitioning of the gas mixture particles between the elements of the sensor array (adsorption) and the effect of temperature on the work function of the polymer film (transduction). The conductance of the single sensor $i$ at variable temperature is then given by

$$G_i^{\text{tot}} = G_i^{\text{iso}} + \sum_{j=1}^{q} G_j^{\text{iso}} + \sum_{j=1}^{q} \frac{G_j^{\text{lim}}}{k_j^* b_j^*} n_j \alpha_j^0 \alpha_j^* T = k_j^* b_j^* T \quad (13)$$

where $G_i^{\text{tot}}$ symbolizes the conductance of the single sensor $i$ in the air at variable temperature; the symbol $b_j^*$ stands for a binding parameter at variable temperature for the interface single sensor $i$/component $j$ of the gas mixture; finally, the parameter $k_j^*$ was used to simplify the calculations in the next paragraphs.

2.4.2. Thermodynamic Models in the General Case

The general case is when both the concentration of the components of the gas mixture and the temperature vary. In this case the Eq. (11) can be rewritten by using the relationships (12) and (13); we get

$$\sum_{i=1}^{m} \sum_{j=1}^{q} (\kappa_i^* \sigma_j^0 d \ln(b_j^*)) + (\kappa_j^* \sigma_j^0 d \ln(k_j^*)) = 0 \quad (14)$$

or in vector form

$$\sum_{i=1}^{m} \vec{k}_i \cdot (\vec{f}_i + \vec{h}_i) = 0 \quad (15)$$

where the vectors $\vec{k}_i$, $\vec{f}_i$, and $\vec{h}_i$ are given by

$$\vec{k}_i = (\kappa_i^*, \kappa_j^*) \quad (16)$$

$$\vec{f}_i = \left( \sum_{j=1}^{q} \alpha_j^0 d \ln b_j^*, \sigma_j^0 d \ln b_j^* \right) \quad (17)$$

$$\vec{h}_i = \left( \sum_{j=1}^{q} \alpha_j^0 d \ln k_j^*, \sigma_j^0 d \ln k_j^* \right) \quad (18)$$
In previous work, we have already shown, that the Eq. (15) is valid if and only if \( \vec{k}_i \perp \vec{f}_j \) and \( \vec{k}_i \perp \vec{h}_j \). We are interested on the first condition \((\vec{k}_i \perp \vec{f}_j)\), which can be expressed by the relationship

\[
\vec{k}_i \cdot \vec{f}_j = \sum_{j=1}^{q} (\kappa_i^j \sigma_j^i d \ln(b_n^j)) + (\kappa_i^T \sigma_T^i d \ln(b_T^j)) = 0 \tag{19}
\]

The Eq. (19) is valid for each sensor \( i \), so that

\[
\sum_{j=1}^{q} (\kappa_i^j \sigma_j^i d \ln(b_n^j)) + (\kappa_i^T \sigma_T^i d \ln(b_T^j)) = 0 \tag{20}
\]

The binding variables \( b_n^j \) and \( b_T^j \) can be expressed as function of the adsorptions free enthalpy (difference between the free enthalpy in the adsorbed phase and in the gas phase); that in turn may be determined by the difference between the two opposing effects, the energetic effect and the entropic effect; we have10,11

\[
\ln(b_n^j) = -\frac{\Delta h_n^{ads}}{RT} + \frac{\Delta s_n^{ads}}{R} \tag{21}
\]

\[
\ln(b_T^j) = -\frac{\Delta h_T^{ads}}{RT} + \frac{\Delta s_T^{ads}}{R} \tag{22}
\]

so that the relationship (20) becomes

\[
\sum_{j=1}^{q} (\kappa_i^j \sigma_j^i d \left(-\frac{\Delta h_n^{ads}}{RT} + \frac{\Delta s_n^{ads}}{R}\right)) + (\kappa_i^T \sigma_T^i d \left(-\frac{\Delta h_T^{ads}}{RT} + \frac{\Delta s_T^{ads}}{R}\right)) = 0 \tag{23}
\]

The thermodynamic variables \( \Delta h_n^{ads} \) and \( \Delta h_T^{ads} \) in Joule molecule\(^{-1}\) symbolize the adsorption enthalpy for the interaction between the \( i \)th sensor array element and the \( j \)th component of the gas mixture at constant temperature and at constant composition of the gas mixture, respectively; \( \Delta s_n^{ads} \), and \( \Delta s_T^{ads} \) in Joule Kelvin\(^{-1}\) stand for the adsorption entropy of the interaction between the \( i \)th sensor array element and the \( j \)th component of the gas mixture at constant temperature and at constant composition of the gas mixture, respectively.

### 2.4.3. Thermodynamic Models at Constant Temperature

The second term in Eq. (23) disappears at constant temperature; so that this equation reduces to

\[
\sum_{i=1}^{p} \sum_{j=1}^{q} \left( \kappa_i^j \sigma_j^i d \left(-\frac{\Delta h_n^{ads}}{RT} + \frac{\Delta s_n^{ads}}{R}\right) \right) + (\kappa_i^T \sigma_T^i d \left(-\frac{\Delta h_T^{ads}}{RT} + \frac{\Delta s_T^{ads}}{R}\right)) = 0 \tag{24}
\]

Furthermore, when we consider homogenous polymer films, all sites of adsorptions are energetically equal. This means that the molar enthalpy of adsorption is independent of surface coverage and so not depends on the input concentrations \( (\Delta h_n^{ads} = \Delta h_T^{ads}(T)) \). This assumption implies that all the factors \( (d\Delta h_n^{ads}/dn_j) \) of the sum vanish. Consequently, at constant temperature, the relationship (24) becomes

\[
\sum_{i=1}^{p} \sum_{j=1}^{q} \kappa_i^j \sigma_j^i d \frac{\Delta h_n^{ads}}{R} = 0 \tag{25}
\]

This equation describes the variations of the adsorption entropy as function of the selectivities of the sensors at constant temperature.

### 2.4.4. Thermodynamic Models at Variable Temperature

At variable temperature and constant gas mixture composition, we have to consider the second term of the sum in Eq. (23). This can be further developed and gives

\[
\sum_{i=1}^{p} \sum_{j=1}^{q} \kappa_i^j \sigma_j^i d \left(-\frac{\Delta h_n^{ads}}{RT} + \frac{\Delta s_n^{ads}}{R}\right) = 0 \tag{26}
\]

The second term of Eq. (26) (i.e., entropy term) is not dependent on the temperature and is therefore equal to zero, so that the Eq. (26) reduces to

\[
\sum_{i=1}^{p} \sum_{j=1}^{q} \kappa_i^j \sigma_j^i d \left(-\frac{\Delta h_T^{ads}}{RT}\right) dT = 0 \tag{27}
\]

The relationship (23) can be now in simpler form as follows rewritten

\[
\sum_{i=1}^{p} \sum_{j=1}^{q} \left( \kappa_i^j \sigma_j^i \frac{\Delta h_n^{ads}}{R} \right) + (\kappa_i^T \sigma_T^i d \left(-\frac{\Delta h_T^{ads}}{RT}\right)) = 0 \tag{28}
\]

The Eqs. (25), (27), (28) describe a thermodynamic equilibrium at the interface \( i \)th sensor array element/component \( j \) of the gas mixture at constant temperature, at constant composition of the gas mixture and in the general case, respectively.

### 3. RESULTS AND DISCUSSION

#### 3.1. Transition from a Continuous System to Discrete Subsystems

At macroscopic scale, the assumption (3) is not valid; since the ratio \( dG_n^{ads}/dn_j \) (slope of the tangent of the function \( G_n^{ads} = f(n_j) \) at the point \( (n_j, G_n^{ads}) \)) is unequal \( G_n^{ads}/n_j \) (slope of the straight \( G_n^{ads} = \text{constant } n_j \)). The assumption (3) is then fulfilled; only if we make the transition from macroscopic scale to small scale. If we focus on the variation of the response of the sensor in the vicinity of the measurement point \( (n_j, G_n^{ads}) \), we can find an infinitesimal small concentration interval \( (dn_j) \) in which the partial sensitivity of the sensor remains constant; the thermodynamic equilibrium of the system will be not affected, if we add \( dn_j \) moles of the \( j \)th component of the gas mixture into the system. The Eq. (3) is a mathematical expression of this virtual model. The temperature is an intensive variable; it can’t be divided in discrete parts. Therefore, the virtual model of Eq. (4) means that the change of temperature...
must be done in infinitesimals small steps; thus the thermodynamic equilibrium of the system is not disturbed and the sensitivities of the sensors remain constant. In the integration of Eq. (5), one can imagine the sensor divided in an infinite number of discrete sub sensors, and the gas mixture $M$ decomposed into infinitely many equivalent sub mixtures $dM$. Each sub-sensor interacts independently of the other sub sensors, with a sub mixture, and shows now a constant sensitivity with respect to the components of the sub mixtures. The response of the sensor is then obtained by integrating the responses of the discrete sub-sensors. Although the decomposition of the system in subsystems and the use of the relationships (3) and (4) are virtual and cannot be realized experimentally, these models are necessary and helpful for the development of our differential equations.

3.2. Developed Models

In the works cited above, we developed equations that are similar to the relationship (6). In the present work, in order to make the Eq. (6) useful for the treatment of experimental data, we transform it to Eqs. (8), (9), which describe the variation of the response of the sensor array elements as function of the concentrations of gas mixture components at variable temperature in Eq. (8) and at constant temperature in Eq. (9). Thermodynamic models of a two phase multisystem (sensor array/gas mixture) have been deduced in Eqs. (25), (27), (28). The physicochemical models (i.e., Eqs. (8), (9)) were developed with use of the properties of a state function; therefore, they can be applied for all cross reactive sensors and all multi-component adsorption models. The Eqs. (25), (27), (28) are specific for Langmuir model based sensors. The Langmuir model is of course over-simplified; most practical surfaces are not uniform and possess adsorption sites that have different potential energies. However, many research papers have shown that the adsorption of polar vapors (such as water and ethanol) on polar polymer films (such as polypyrrole and polyaniline) may be described.

**4. CONCLUSIONS**

By using Gibbs–Duhem formalism and relatively simple mathematics, novel useful differential equations for the multisystem sensor array/gas mixture were developed. The Eq. (9) can be useful for checking experimental data for consistency. The Eqs. (25), (27), (28) open new avenues for further investigations in field of the thermodynamics of multi-interfaces (sensor array/gas mixture).

**Nomenclature**

**Subscripts:** $i$: refers to the $i$th sensor array element; $j$: refers to the $j$th component of the gas mixture; $ij$: refers to the variables that describe the interactions between $i$th element of the sensor array and the $j$th component of the gas mixture.

**Exponents:** The exponent $(T)$ was used for describing parameters and variables at temperature $T$; the exponent $(n)$ was used to describe the physical and chemical parameters when the concentrations of the components of the gas mixture are variable; the exponent $\ast$ was used to describe the variables of a single sensor when it interacts with a gas mixture; $(\text{ads})$ symbolizes the adsorption; $(\text{nads})$ refers to adsorption at constant Temperature; $(\text{Tads})$ refers to adsorption at constant gas mixture composition.

**Parameters** that describe the characteristics of a single gas and of a gas mixture:

- $n_i$ in moles: initial number of moles of the $i$th component of the gas mixture; $(n_{\text{ads}})$ symbolizes the number of moles of the gas that has been adsorbed on the sensitive film of a sensor.

**Symbols** of the parameters that describe the characteristics of the sensors:

- $G$ in $\Omega^{-1}$ symbolizes the conductance of a sensor array (or a sensor); $S^n$ in $\Omega^{-1}$ mole$^{-1}$ and $S^T$ in $\Omega^{-1}$ Kelvin$^{-1}$ stands for the sensitivity of a sensor, when the concentrations of the gas mixture components vary and when the temperature varies.

Symbols that describe thermodynamic variables and correlation parameters:

- $b$: is a dimensionless coefficient that includes exclusively thermodynamic parameters; $\Delta g^{\text{ads}}$ in Joule mole$^{-1}$
stands for the adsorption free enthalpy; $\Delta h_{\text{ads}}$ in Joule mole$^{-1}$, stands for adsorption enthalpy; $\Delta s_{\text{ads}}$ in Joule mole$^{-1}$ Kelvin$^{-1}$ stands for adsorption entropy; $\lambda$ is a dimensionless coefficient that describes the influences of the partial sensitivities of the sensor array elements and the influence of the composition of the gas mixture on the sensor array response; $\sigma$ is a dimensionless selectivity coefficient; $\kappa$ is a dimensionless standardization coefficient; the other coefficients and variables are defined in text.

References and Notes