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A SCAVENGING-DEPENDENT AIR-BASIN ECOLOGICAL RISK ASSESSMENT (SABERA) MODEL APPLIED TO ACID RAIN IMPACT AROUND DELHI CITY, INDIA

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ABSTRACT

Many of even the most recently applied ecological risk assessment models have dealt with ecological risks only on the basis of single-species toxicity tests. Moreover, they have seldom treated the integrated and the complete ecological unit for the risk assessment. In other words, they have ignored parameters which regulate many of those very important ecological interactions at land-water, air-land, and air-water interfaces. Therefore, in view of the above-mentioned facts, a realistic ecological risk assessment model incorporating the essential interfacial ecological interactions has been developed for quantifying the impact of acid rain in air-basins. To start with, the model has been applied for the air-basin surrounding Delhi City in India. Variations in the ecological risks have been analyzed with respect to changes in four important parameters—leaf area index, precipitation intensity, plant-leaf stomatal density, and mixing height—as they are significantly different for different air-basins.

INTRODUCTION

Acid rain is no longer just a local problem of urban areas, its impact has spread into pristine rural areas too [1]. It adversely affects both terrestrial and aquatic ecosystems. In terrestrial ecosystems, these adverse impacts are generally manifested through effects like necrosis of the plant-leaf, stomatal aberrations and clogging, root-decay, and the resultant decline in the vegetative productivity. In aquatic ecosystems, these adverse effects result in the enhancement of species-mortality at different trophic levels (phytoplankton, zooplankton, and fish, etc.), and are essentially the results of severe perturbations in nitrogen and phosphorus cycling [2], retardation in chlorophyll growth [3, 4], and subsequent effects on feeding, respiration, and mortality of various higher-level species [5]. Thus, instead of studying the environmental impacts in isolation on these two separate types of ecosystems (terrestrial and aquatic), it would be more realistic to assess their impacts on an integrated watershed of a given air-basin [6].

The concept of an air-basin basically pertains to a large region that shares a common geographical area of sources and several atmospheric interactions [6]. The boundaries of an air-basin are usually determined by mountains, large hills, and bodies of water therein. Thus, an air-basin consists of the terrestrial ecosystem and along with the water bodies of the enclosed watershed, all enveloped by the atmosphere. The stability of the watershed or catchment basin is largely determined by the rate of inflows or outflows of water, materials, and organisms from the adjacent parts [2].

There were two main objectives of the present modeling exercise. First, to develop an integrated and realistic model for quantifying ecological risk assessment of a given air-basin, and second, to apply the model for quantification of impact due to acid rain and study the relative changes in risks by varying different important parameters of the model: leaf area index (LAI), mixing height (H), precipitation intensity (P), and stomatal density (N) on the plant-leaves of the dominant terrestrial and wetland vegetative species. These parameters show wide variations from one air-basin to another.

As far as ecological risk assessment (ERA) is concerned, very few models are, in fact, available in literature for quantifying ecological risks appropriately. Therefore, the development of the present model assumes significance. One recently developed ERA-model [7] has studied the ecological risk for only the aquatic ecosystem; another [8] pertains to the treatment of terrestrial ecosystem only, i.e., on the basis of ecotoxicological assessment of hydro-carbon contaminated soils. Indian studies, which are still fewer in number, have also ignored the need for an integrated treatment of these ecosystems for quantification [9, 10]. The present model can be refined by gradually including additional relevant processes and the parameters representing them. The initial application is to the air-basin surrounding Delhi City in India. Variations in the ecological risks have been analyzed with respect to changes in the four parameters mentioned.

OBJECTIVES AND METHODOLOGY

An integrated model (Figure 1) for quantifying the ecological risk due to the impact of acid rain in a watershed ecosystem of a given air-basin must include the

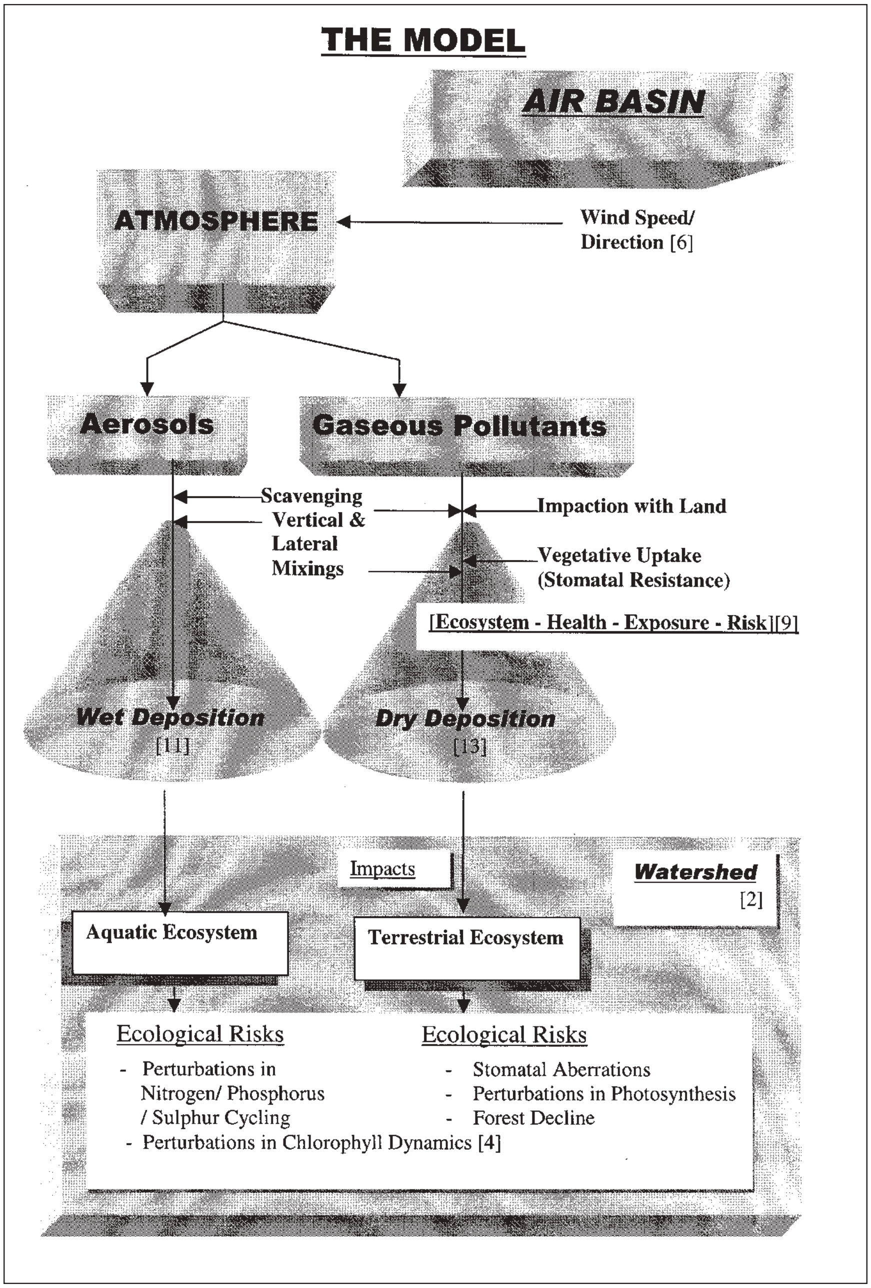

Figure 1. Scavenging-Dependent Air-Basin Ecological Risk Assessment Model (SABERA).

most essential physical, chemical, and biological parameters representing various physico-chemical and biological processes at air-water, air-land, and land-water interfaces.

The present exercise started with the model developed by Okita et al. [11] for determining the wet scavenging coefficient of sulfate aerosols over the sea of Japan. Precipitation intensity (P) and mixing height (H) happen to be the most important parameters as far as wet deposition of air-pollutants is concerned. In an air-basin, however, the role of dry deposition (of air pollutants) is equally important [21]. Hence, in order to quantify the cumulative effect, the processes of wet scavenging as well as dry deposition were included together for the model developed [11-13].

Mixing of air pollutants takes place vertically as well as laterally. Therefore, role of mechanical mixing [6] must also be included, which depends mainly on the terrain roughness and wind-speed at ground-level. A Leaf Area Index (LAI) has been included in order to account for lateral mixing within a vegetative canopy. The importance of lateral mixing in the context of dry deposition of air pollutants was discussed earlier in [14].

THE MODEL

The model for quantifying risk to the terrestrial portion [9] of the watershed (TE), includes mean wind-speed (u), stomatal resistance (as a function of significant stomatal attributes (N, a, b, & L) of dominant plant-species of the region), photosynthetically active radiation (PAR), and air-gas diffusivity (D).

The risk to the aquatic portion (AE) of the watershed has been represented in terms of aerosol scavenging as a function of precipitation intensity (P) and mixing height (H) mainly [11]. Subsequently, because of the fact that impact of acid-rain on water-body leads to significant perturbations (PE) in chlorophyll-production, the impact has been assumed to be proportional to relative sensitivity of chlorophyll with respect to mortality rate and been assigned the numerical value of 1.099×10^{-3} [4]. Ultimately, the Scavenging-Dependent Air-Basin Ecological Risk Assessment (SABERA) model attains the following form:

$$\text{SABERA} = \text{TE} \times \text{AE} \times \text{PE} \qquad (1)$$

SABERA yields units in m^{-1}, which makes it very convenient for its analysis in terms of the distance at which the risk needs to be quantified at the regional level, where

$$\text{TE} = (1.0)/[(1.0/u) + (\text{LAI} \times p/(b \times D))(1.0 + k/\text{PAR})] \qquad (2)$$

The following terms are employed:

p = physiological parameter $= 4L/(\pi\, a\, N)$ (2a)
a = major-axis-length of stomatal opening (m) (2b)

b = minor-axis-length of stomatal opening (m) (2c)
L = effective length of stomatal opening (m) (2d)
N = no. of stomatal pores per unit leaf-area (m^{-2}) (2e)
D = air-gas diffusivity (m^2/s) (2f)
k = PAR-curvature coefficient (W/m^2) defined as the PAR-level at twice the minimum stomatal resistance (2g)
PAR = photosynthetically active radiation (W/m^2) (2h)

AE (Risk to the Aquatic Ecosystem) is represented in terms of aerosol-scavenging as follows:

$$AE = (P/H) \times [conc\_water/conc\_air] \times 10^6 \quad (3)$$

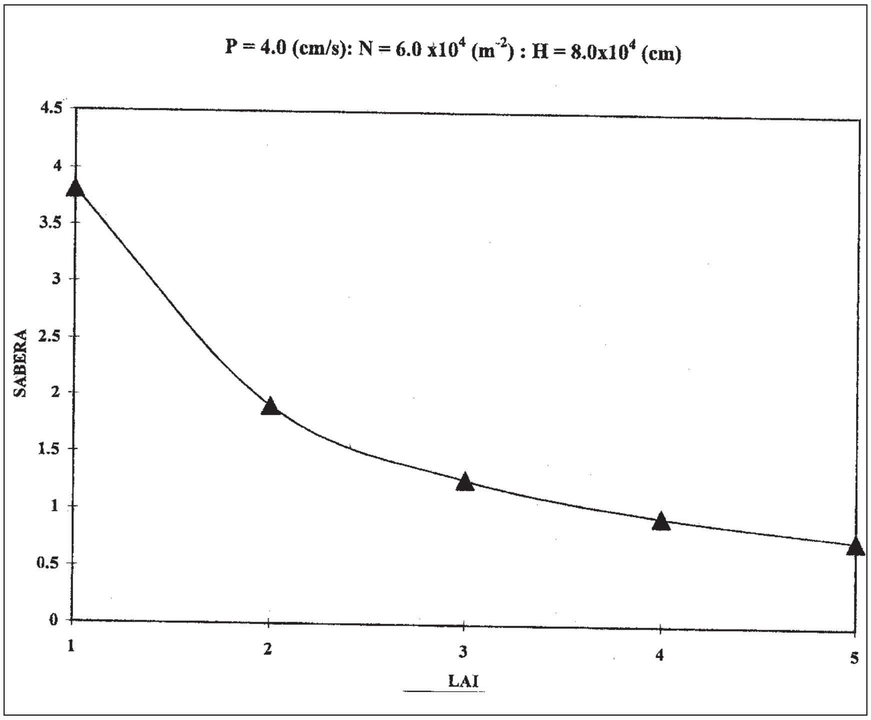

Figure 2. Variations in SABERA (×10^4 m^{-1}) with respect to LAI (Leaf Area Index) with P, N, and H at fixed values of 4.0 (cm/s), 6.0×10^4 (m^{-2}) and 8.0×10^4 (cm) respectively. LAI has been varied in the range of 1.0 to 5.0.

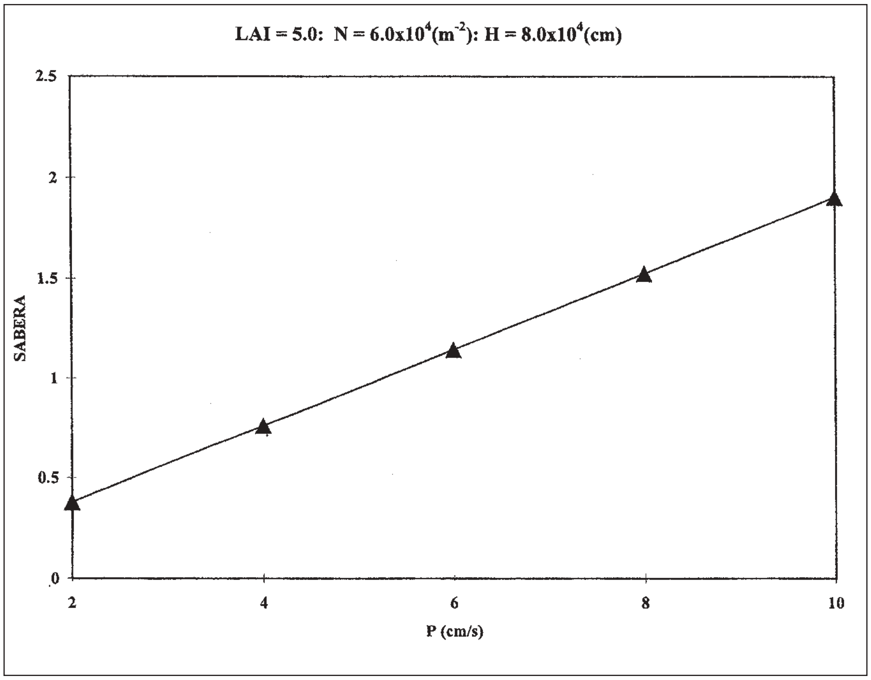

Figure 3. Variations in SABERA ($\times 10^4$ m^{-1}) with respect to P (Precipitation Intensity) with LAI, N, and H at fixed values of 5.0, 6.0×10^4 (m^{-2}) and 8.0×10^4 (cm) respectively. P has been varied in the range of 2.0 to 10.0 (cm/s).

where,

P = precipitation intensity (cm/s) (3a)
H = mixing height (cm) (3b)
conc_air = sulfate-aerosol concentration in air (μg/m^3) (3c)
conc_water = sulfate-concentration in water (mg/l) (3d)

RESULTS

For Delhi City in India, conc_air (sulfate-aerosol-concentration) and conc_water (sulfate-concentration in precipitation-water) have been reported to be 10.2 (μg/m^3) and 6.0 (mg/l) respectively [15]. u has been taken to be 4.0 m/s, and k and PAR have respectively been taken as 50.0 and 100.0 W/m^2. D has been taken as 2.0×10^{-5} (m^2/s) and values of L, b, and a have been taken as representative values of an Indian Neem tree, i.e., 20.0×10^{-6} m, 15.0×10^{-6}, and 25.0×10^{-6} m

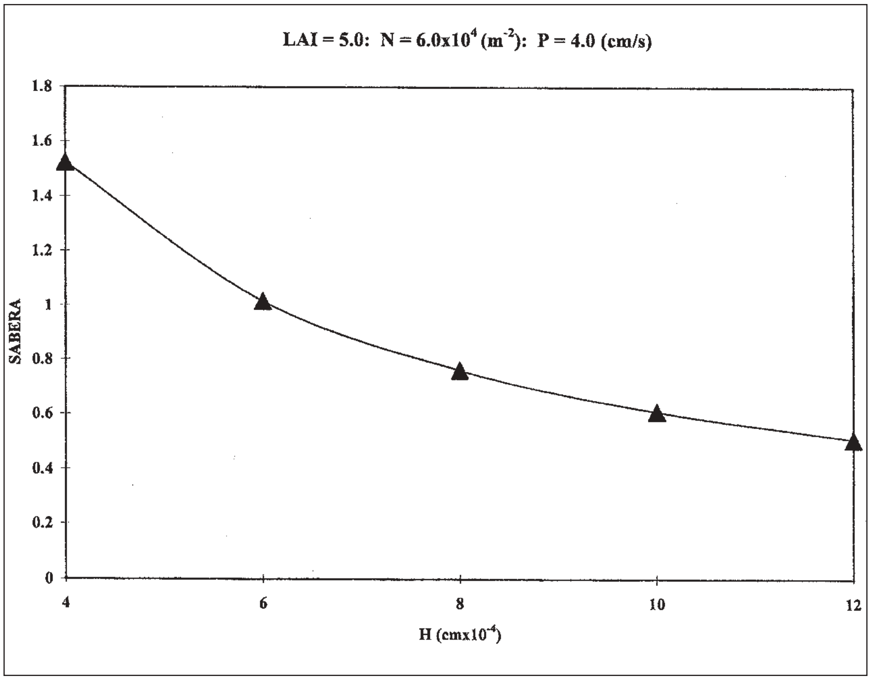

Figure 4. Variations in SABERA ($\times 10^4$ m^{-1}) with respect to H (Mixing Height) with LAI, N, and P at fixed values of 5.0, 6.0×10^4 (m^{-2}) and 4.0 (cm/s) respectively. H has been varied in the range of 4.0×10^4 to 12.0×10^4 (cm).

respectively. Subsequently, changes in SABERA ($\times 10^4$ m^{-1}) were studied by varying LAI, N, P, and H, keeping the remaining parameters constant. Resulting changes in SABERA were subsequently plotted (Figures 2 through 5). Changes in SABERA with respect to variations in LAI and H are found to be non-linear (Figures 2 and 4); whereas the corresponding changes with respect to N and P were linear. LAI was varied in the range of 1.0 to 5.0; P(cm/s) in the range of 2.0 to 10.0; H(10^4 cm) in the range of 4.0 to 12.0; and N (10^4 m^{-2}) in the range of 2.0 to 10.0.

Maximum risk (3.81×10^4 m^{-1}) was observed when leaf area index (LAI) had the value of 1.0 (Figure 2) with P, N, and H fixed respectively at the values of 4.0 (cm/s), 6.0×10^4 m^{-2} and 8.0×10^4 (cm). Minimum value of risk (0.25×10^4 m^{-1}) was observed (Figure 5) when stomatal density (N) had the value of 2.0×10^4 m^{-2} with LAI, H, and P at the fixed values of 5.0, 8.0×10^4 (cm), and 4.0 (cm/s). An attempt was also made to find out the extent of fluctuations in the value of SABERA with respect to variations in LAI, P, N, and H. The largest fluctuation observed was with respect to leaf area index (LAI), and was 3.05×10^4 (m^{-1})

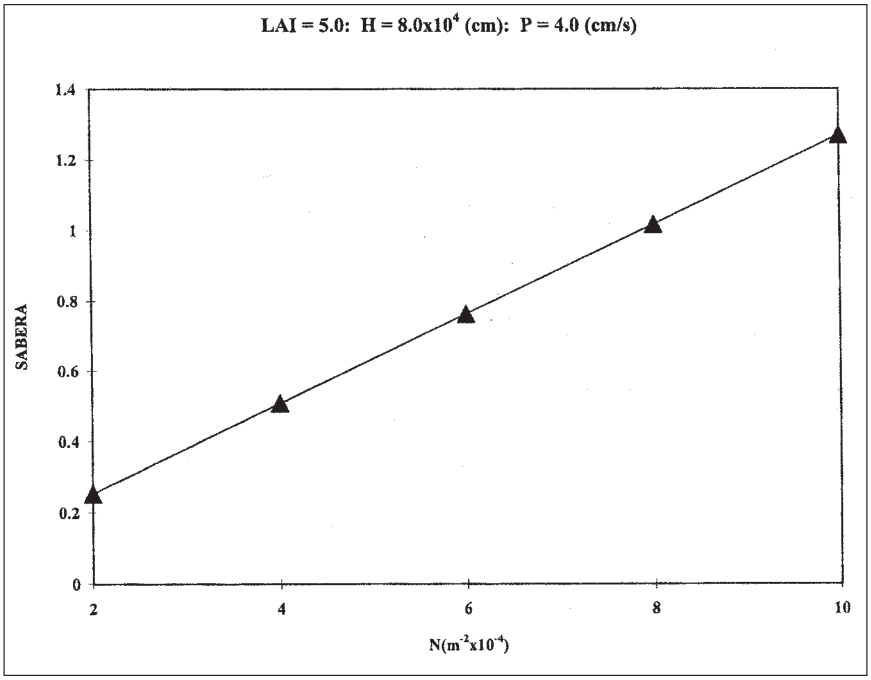

Figure 5. Variations in SABERA ($\times 10^4$ m^{-1}) with respect to N (Stomatal Density) with LAI, H, and P at fixed values of 5.0, 8.0×10^4 (cm) and 4.0 (cm/s) respectively. N has been varied in the range of 2.0×10^4 to 10.0×10^4 (m^{-2}).

when LAI was varied from 1.0 to 5.0 (Figure 2); whereas smallest fluctuation (1.01×10^4 m^{-1}) observed (Figure 4) was with respect to mixing height (H), when H was varied from 4.0 to 12.0 ($\times 10^4$ cm).

DISCUSSION

The well-known uncertainty principle in ecology states that at any given time no ecological model can satisfy the three properties of generality, reality, and precision simultaneously [2]. The present model, in this context, is an attempt toward developing a real(istic) model, albeit at the cost of generality and some precision, which are, in any case, inevitable in a modeling exercise requiring integration of many ecophysiological processes at air-land, land-water, and air-water interfaces. The precision of the model can be increased by incorporating various intermediate processes, such as leaf-senescence and litter-decomposition on the forest-floor, in a step-wise mode.

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