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Modeling Lead Pollution In a Watershed–Ecosystem

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ABSTRACT

An interdisciplinary study is currently in progress at the University of Illinois at Urbana-Champaign under a grant from the National Science Foundation RANN Program. Objectives of the study include understanding and modeling the movements and effects of heavy metals (initially lead) in the environment.

A model has been constructed which simulates the movements and predicts the accumulation points of lead in a 76-square mile watershed-ecosystem in Champaign County, Illinois. The model includes components of both aquatic and terrestrial ecosystems and represents the ecosystem by a network of nodes and branches where the nodes represent the components of the ecosystem in a general sense and the branches indicate possible transport mechanisms between nodes. Results of a two year simulation using a network of 36 nodes and 121 branches is presented.

The model provides a method for the study of pollutant transport and accumulation in ecosystems.

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National Science Foundation RANN Program. Objectives of the study include understanding and modeling the movements and effects of heavy metals (initially lead) in the environment. Information of this nature is critical to the making of more rational decisions concerning environmental problems.

This discussion deals with the modeling of lead transport in a watershed-ecosystem. The objectives of the model are to simulate the movements of lead in an ecosystem, to determine the points of accumulation, to predict future transports and accumulations, and to suggest how various alternative controls of lead sources and emissions may affect the ecosystem. The model is continually refined and tested by correlating it with field data from the ecosystem. This study of lead transport in the environment helps define inputs for biological uptake models currently being developed for plants and animals and serves to guide future avenues of research on plant, animal, and human effects.

Description of Watershed-Ecosystem

To facilitate development of a transport model and to provide a basis for interdisciplinary action a 76-square-mile watershed in Champaign County, Illinois was selected. The watershed lies primarily to the north of Champaign-Urbana but includes approximately 80 per cent of the city. This results in at least five distinct compartments of land use which can be examined separately or as a unit. These compartments are:

1. cultivated cropland,
2. pasture or sod cropland,
3. forest,
4. wasteland (roadsides, fencerows, etc.) and
5. residential and urban development.

The watershed is drained by the Saline Branch Drainage Ditch, originating in the northern rural portion of the watershed and the Boneyard Creek, a totally urban drainage channel originating in northwest Champaign. Boneyard Creek joins the Saline Branch on the northeast edge of Urbana. Lead outputs and movements within the stream portion of the watershed are constantly monitored at five locations within the watershed. This allows comparisons between units of different land use. Soils, plants, and animals are also sampled on a yearly basis to determine lead concentrations in these components and biomass estimates. Lead inputs to the watershed mainly through the combustion of leaded gasoline are determined by traffic volume data converted to gallons of gasoline consumed in the watershed. The conversion of gasoline consumed to lead emitted is then estimated using data available in the literature. These input data are substantiated and supplemented with air sampling and particulate deposition data collected at various locations within the watershed.

In order to account for non-homogeneous lead inputs, the watershed has been divided into four zones. The rural area consists of three zones and the urban area is the fourth.

The three rural zones are distinguished by the amount of lead deposited per unit area (based on traffic volume data). Zones 1 and 2 are essentially marginal strips of land along the roads within the watershed. North-south roads have a strip 30 meters wide on the west side of the road and 50 meters wide on the east side to account for the prevailing winds; while east-west roads have a strip 40 meters wide on each side. Zone 1 is a high-input zone with 4,000 or more vehicles per 24 hour period, while zone 2 is an intermediate-input area consisting of all land within the rural portion of the watershed not bordering a roadway. Initially, the urban area (zone 4) has not been subdivided. However, further divisions in both rural and urban compartments may ultimately become necessary.

The percentage of the total lead input to the watershed deposited into each zone and the percentage of the total area occupied by each zone is estimated to be as shown in Table 1.

Table 1. Lead Input and Area by Zones

	Zone			
		Rural		*Urban*
	1	*2*	*3*	*4*
Per cent area	8	17	60	15
Per cent lead input	15	4	1	80

Basic System Model

The basic system model is shown in Figure 1. The model includes components of both aquatic and terrestrial ecosystems and describes the interrelationships within the system. The arrows represent transports of lead between components or nodes, e.g., the atmosphere transports lead to the soil, to water, to primary producers, and to paved surfaces. The atmosphere may receive lead from industrial and residential areas and from auto emissions both inside and outside the watershed boundary. Also, lead may be transported between this particular watershed and adjacent watersheds.

The ecosystem is represented by a network where the nodes represent the various components of the ecosystem and the branches indicate possible transport mechanisms between nodes. For example, the primary

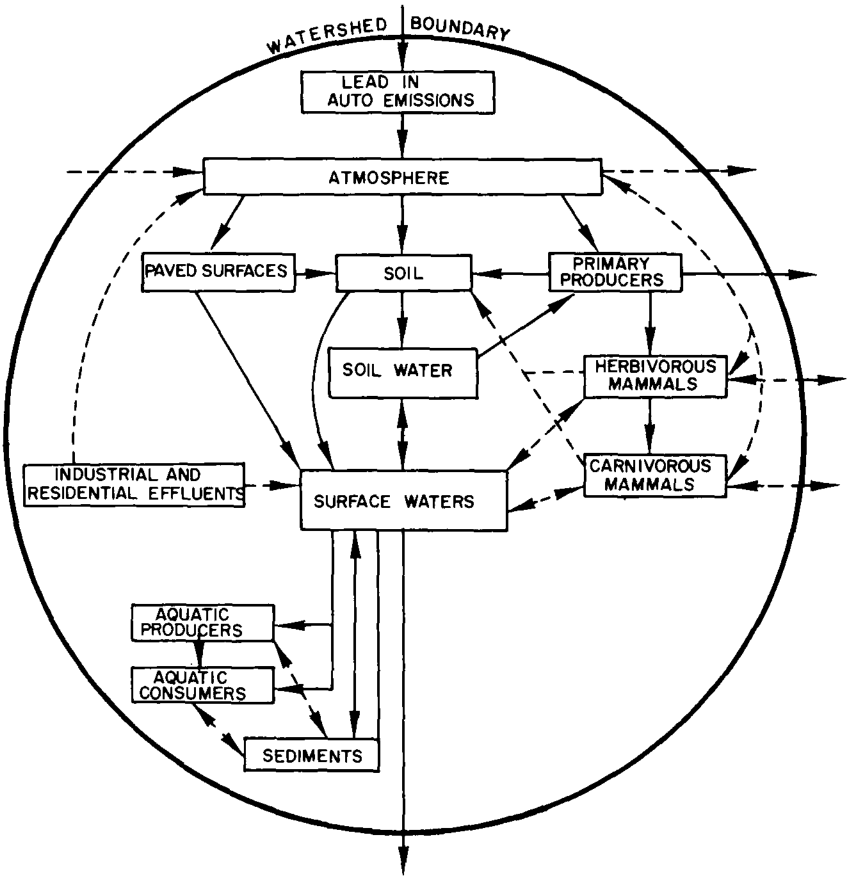

Figure 1. Basic system model.

producer node represents all of the plants of the ecosystem. This, of course, can be further subdivided into plant species or zone in which it occurs as data become available. A source node (e.g., auto emissions) only has branches exiting while a sink node (e.g., outflow water) only has branches entering. Three attributes are associated with each node: 1) a mass (to allow computation of nodal concentrations), 2) a quantity of lead input per unit time for source nodes, and 3) the initial concentration in the node.

Branches can represent a variety of transport mechanisms such as diffusion, leaching, biological uptake, and erosion. Self-loops represent the fraction of the lead content of a node which remains in it between time periods.

Distribution factors and seasonal factors are used to quantitatively describe the branch flows. The distribution factors specify the fraction of the lead content of a node which flows in the branches emanating from that node. These distribution factors can be constant or random variables following various probability distributions such as uniform, normal, log-normal, beta, gamma, Erlang, or Poisson.[1] The transports may also be affected by the seasons of the year. This is taken into consideration by modifying the distribution factor of each branch according to an appropriate seasonal factor.

A network representation of the model appears in Figure 2. The node

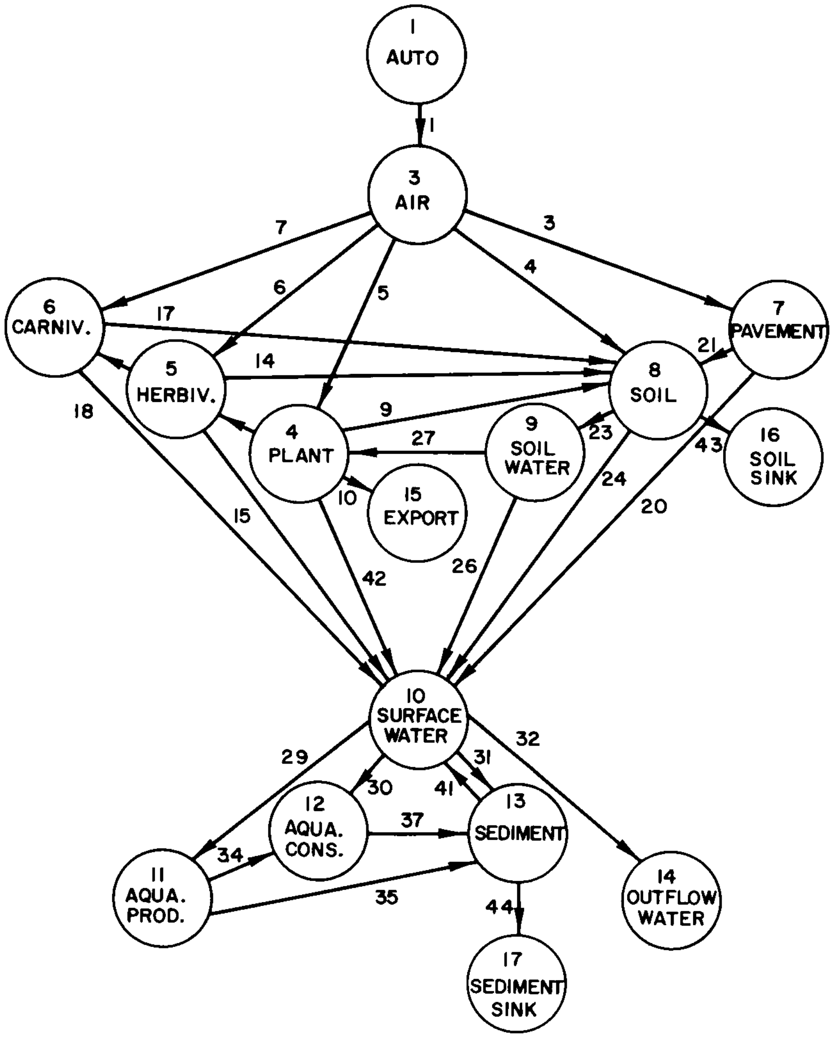

Figure 2. A network representation of the model.

representing industrial and residential effluents has been omitted since these emissions are negligible in the ecosystem. Two sink nodes are added (soil sink and sediment sink). The soil sink, for example, represents a portion of the soil which holds lead and does not release it to other environmental compartments and thus accumulates lead. The basic network of 17 nodes and 44 branches shown in Figure 2 has been expanded in the present model to 36 nodes and 121 branches to accommodate zonation of the system. Nodes such as primary producers, herbivores, and carnivores are defined generally in this model but future refinement and data availability may allow more detailed examination of these compartments by species or family.

The procedure used to simulate the flow of lead through the network begins by determining the order in which the nodes should be processed. If the original network is acyclic, a topological sort of the nodes provides a satisfactory order. However, if the network contains directed cycles it can be made acyclic by neglecting some links (preferably branches where small return flows are expected); the simplified network is then topologically sorted.

For each time period (a one week cycle was used for the example shown in a later section) a distribution of lead through the network is performed. The distribution procedure is listed in the following steps:

1. generation of a distribution factor for each branch;
2. seasonal adjustment of the distribution factors;
3. updating of the nodal accumulations by adding the external inflows;
4. distribution of the lead in the nodes through exiting branches (including self-loops).

In step 4, the nodes are processed in the previously determined order. Lead is sent from a node i to the end node j of branch (i, j) in proportion to the adjusted and scaled distribution factor for branch (i, j). Scaling (i.e., dividing by the sum of the adjusted distribution factors of all the branches exiting from node i) is done to maintain equilibrium.

A more precise description of the manner in which nodal lead content changes between time periods follows. The input into node i, $I_i(t)$ is equal to the external inflow E_i plus the sum of the contributions of all the branches entering node i:

$$I_i(t) = E_i + \sum_{i=1}^{m_i} \frac{d_{1i}\ S_{1i}(t)}{\sum_{k=1}^{n_i} d_{1k}\ S_{1k}(t)}\ Y_1(t) \qquad (1)$$

Where:

m_i = number of branches entering node i (excluding the self loop)

n_1 = number of branches exiting from node 1 (including the self loop)

$Y_1(t)$ = lead content of node 1 at time t

d_{1i} = distribution factor of branch (1, i)

$S_{1i}(t)$ = seasonal factor of branch (1, i) at time t (see Figure 3)

After the lead in node i is distributed, $Y_i(t)$ assumes the value.

$$Y_i(t) = (Yi(t-1) + I_i(t))\, d_i(t) \tag{2}$$

Where:

$$d_i(t) = \frac{d_{ii}\, S_{ii}(t)}{\sum_{k=1}^{n_i} d_{ik}\ S_{ik}(t)} \tag{3}$$

The above formulae show that equilibrium is always maintained at the nodes.

The lead distribution method, which corresponds to the Gauss Seidel method[2] is similar to a Hardy Cross distribution[3] and yields a good approximation in one iteration. When the original network is acylic, the results are exact. However, if directed cycles exist, a small error may be incurred. An exact solution could be obtained by solving a system of simultaneous linear equations or by using flow graph theory.[4] However, this was found to be only a small improvement over the approximate but efficient method described.

True simulation analysis requires many repetitions of the procedure using different random numbers. This requires much additional computer time. A computer program to perform the distribution has been developed. The program uses a problem oriented language (POL) whereby the ecosystem model can be described in free form input. Information required for simulation includes distribution and seasonal factors, nodal base level concentrations and masses, cycles to be traced, and length of the simulation period. The program output provides the user with nodal accumulations and concentrations including average, standard deviation, minimum and maximum. Plots of nodal accumulations or concentrations may also be obtained.

Simulation Example

Typical results of 100 cycle (two years) simulation using a zoned network of 36 nodes and 121 branches are shown in Table 2. Results are

Table 2. Average Concentration (ppm)

	Zone							
	I		*II*		*III*		*IV*	
Node	*Predicted*	*Actual**	*Predicted*	*Actual**	*Predicted*	*Actual**	*Predicted*	*Actual**
Soil & Soil Sink	63	50	26	23	17	13	128	115
Plants & Litter	5	35	0.78	18	0.03	5	41	38
Herbivores	5	12	0.7	5	0.04	4	16	-
Carnivores	3	12	0.4	9	0.02	4	10	-

*Actual Concentrations are based on preliminary data.

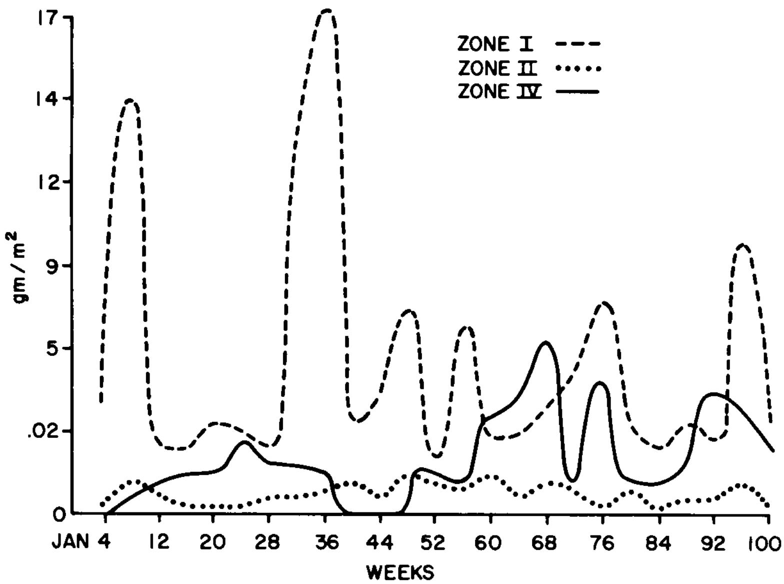

Figure 3. Pavement.

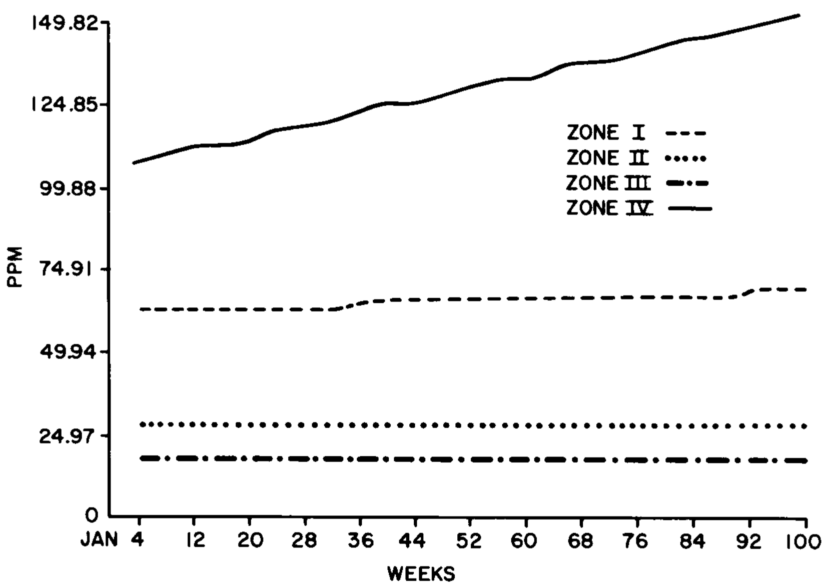

Figure 4. Soil sink.

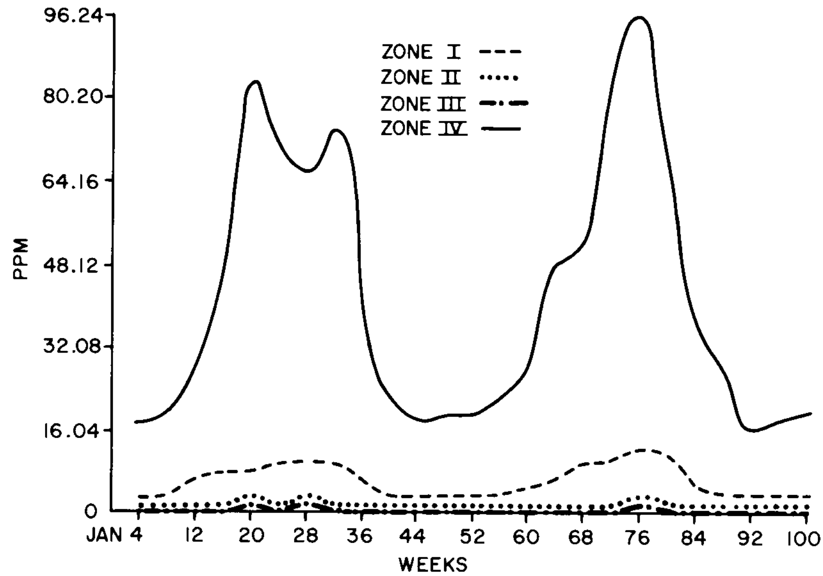

Figure 5. Plants and litter.

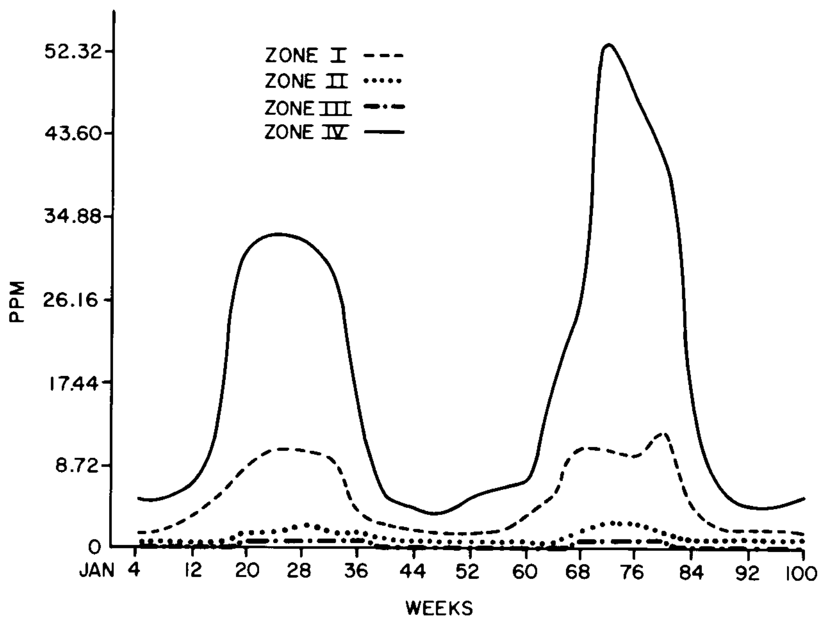

Figure 6. Herbivores.

shown for several nodes including a comparison with actual field concentrations. The 100 cycle result for soil and soil sink are based on the node containing a base level before simulation. Other nodal concentration data represent simulation beginning with a clean node. Results are considerably in error at present but with further modification of branch properties as more field data become available they can be adjusted. Figures, 3, 4, 5, and 6 show plotted output data by zone for pavement, soil sink, plants and litter, and herbivores respectively. Concentration variation with time is quite evident and corresponds favorably with field variation. The random effect of storm cleansing of paved areas is shown in Figure 3.

Conclusions and Further Study

The model presented here provides a method for the study of the transport and accumulation of a pollutant in an ecosystem. Compartments or nodes can be identified at any organizational level depending on data availability. Transport processes, seasonal variation, and spatial location are considered. A stochastic variation is utilized in the model to account for variability not related to location or season.

The reliability of the entire model, however, is dependent upon the determination of branch distribution factors which are dependent upon data availability and knowledge of transport processes between compartments of the ecosystem.

Once adjusted and validated with additional experimental data, the model should be quite useful in the study and prediction of heavy metal transport and accumulation in ecosystems. The model will also be valuable in evaluating various alternatives of lead pollution control.

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