Use of GIS Databases in Urban Air Quality Modeling

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ABSTRACT

Surfaces of buildings can absorb, process, and release atmospheric pollutants such as nitrogen oxides, while building volumes affect pollutant concentrations. Emerging models for the atmospheric chemistry which governs urban air quality require surface and volume statistics for the urban canopy. Morphometric analysis of urban areas using GIS can provide these statistics. The impact of explicitly including building surfaces and volumes on model results is striking, and the effects of database shortcomings can also be seen. This is one of many areas where atmospheric science is turning to GIS to provide needed urban canopy parameters. This paper presents the use of a high resolution urban GIS, from Santa Monica, to determine parameters for an atmospheric chemistry model. Approaches for deriving parameters using GIS and estimates of their fidelity are presented. Database characteristics which enable determination of the parameters as well as those which limit its usefulness are discussed.

INTRODUCTION

It has long been recognized that air quality in urban areas is typically poorer than in rural areas. This is true not only because of the presence and concentration of pollution sources, particularly traffic, but also is caused by the presence of buildings. Building surfaces and volumes influence urban air quality in a number of ways. The geometry and geometrical arrangement (morphology) of buildings impacts the horizontal and vertical flow of the air, thus influencing the horizontal transport and the vertical mixing, i.e., dilution, of the pollutants. In addition, buildings can occupy a large fraction of the available volume near the ground, where many pollutants and precursors originate. As a result, the concentration of pollutants in the air at low elevations can be high and can remain high at increasing elevations when many taller buildings are present, such as in urban canyons. Finally, buildings can process pollutants on their surfaces, absorbing some and, through surface reactions, producing others.

Analysis of urban surface form has been used for some time in studies where aerodynamic roughness parameters are needed to evaluate air flow, turbulence, urban micrometeorology, and other physical problems (no chemistry). Recently, GIS technology has been applied to facilitate this morphometric analysis. For example, Grimmond and Oke developed their own GIS using aerial photography, field surveys, and sampling techniques (Grimmond and Oke 1999). Availability of high resolution GIS databases rich in the information needed to characterize the urban morphology, combined with GIS technology to extract the required information, provides the opportunity to accurately determine roughness parameters for any urban area for which a GIS database has been developed. The GIS from Santa Monica, California used here is an excellent example of such a resource[1].

Incorporating the further effects of building volumes and surfaces into atmospheric chemistry models is just beginning and is also greatly facilitated by use of GIS data and technology. With buildings explicitly considered in the model, the resulting time dependent vertical profiles for trace gases such as ozone, nitrogen oxides and hydrocarbons such as formaldehyde are significantly different than those obtained without consideration of the buildings. At last year's ESRI Users' Conference, we presented our approaches and some results in this emerging area of GIS and urban atmospheric chemistry (Hurlock and Stutz 2004). In this year's paper, we exploit GIS further by extracting aerodynamic roughness parameters for the urban canopy from the data. We also examine the data in more detail and combine it with a field survey to evaluate uncertainties in the parameters and statistics derived from the data base and suggest areas where relatively minor changes to such a data base could improve the fidelity of our model calculations.

BACKROUND

Air pollution is caused by direct emissions of pollutants or precursors, especially by motor vehicles, and subsequent chemical and photochemical reactions among the emitted pollutants and other trace gases already present in the atmosphere. The spatial distribution is characterized by time-dependent concentration profiles of the pollutants. Of particular interest in understanding the chemistry and transport involved are the vertical profiles in the concentrations of the pollutants. Measurement of the profiles is typically accomplished in major field studies involving many research groups participating in a localized set of measurements over an extended period of time, typically weeks or months. In one such study, in Phoenix in the summer of 2001, our group made measurements leading to time dependent vertical profiles of a number of trace gases (Wang, Ackerman et al. 2003; Stutz, Alicke et al. 2004). These measurements remain the definitive observations of vertical concentration gradients of pollutants in and above an urban canopy. The gradients develop strongly at night due to the stability of the nocturnal boundary layer.

The measurements and results can be summarized using Figure 1. A transmitting/receiving telescope was mounted on the top story of the tallest building in downtown Phoenix. Retroreflectors were mounted at three different elevations on buildings about 3.5 km away in uptown Phoenix. These measurements, using Differential Optical Absorption Spectroscopy (DOAS) methods, allow time dependent concentrations of a variety of pollutant gases to be determined in the three altitude intervals. Cross plots of the concentrations shown in Figure 1 result in the profiles shown in Figure 2. Also shown are profiles resulting from UCLA's Nocturnal Chemistry and Transport model, NCAT. This model is a highly resolved one-dimensional chemistry and transport model that includes the altitude dependent calculation of vertical trace gas fluxes, gas-phase

[1] Santa Monica GIS data used here was provided by the city of Santa Monica, California and is used with permission.

chemistry production and loss rates based on the Regional Atmospheric Chemistry Mechanism (Stockwell, Kirchner et al. 1997), biogenic and anthropogenic emission rates, and deposition and heterogeneous chemistry on aerosols, the ground surface, and the surface of a canopy such as grass (Geyer and Stutz 2004; Geyer and Stutz 2004). The model results shown in Figure 2 do not include buildings.

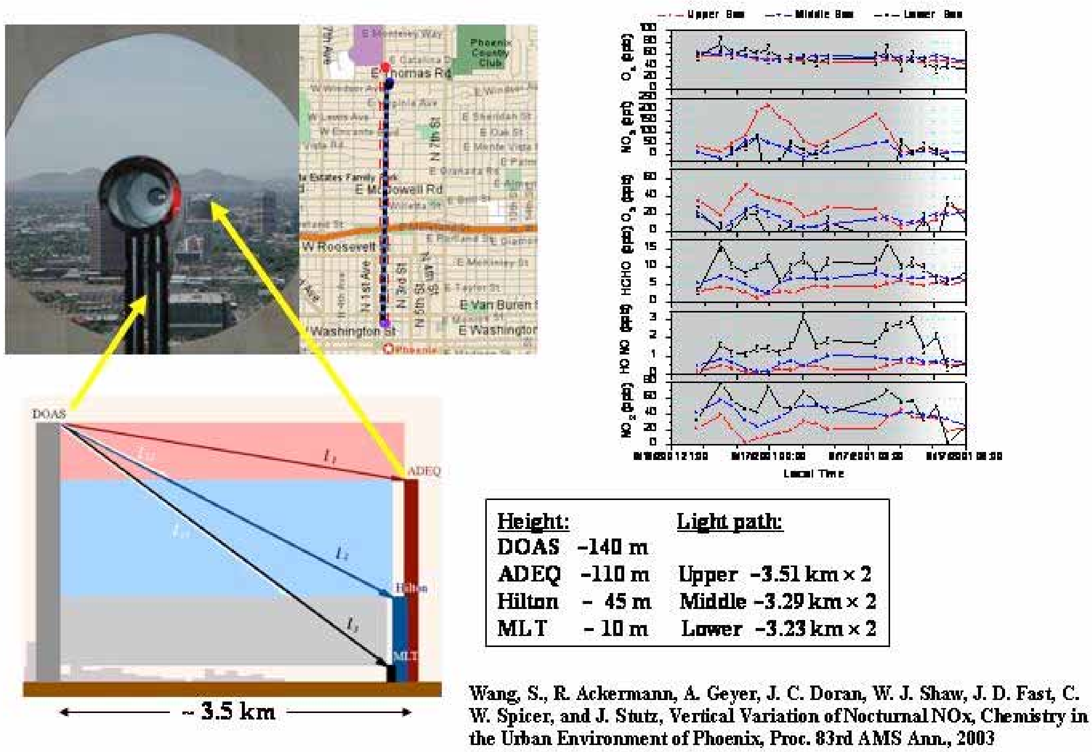
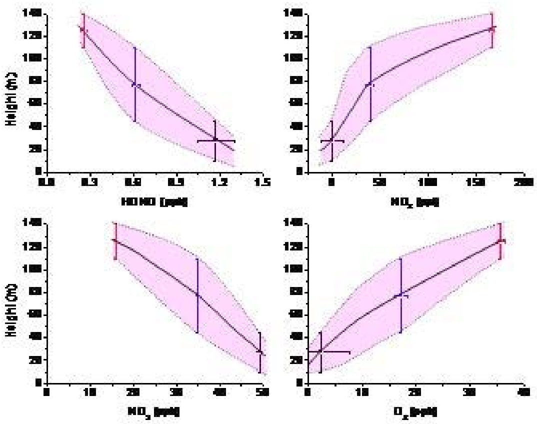
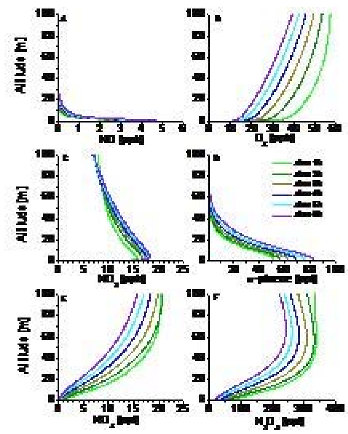


Figure 1. Measurement of pollutant vertical profiles in Phoenix, June, 2001

Building volumes and surfaces have not been previously included in urban atmospheric chemistry models.



Derived profiles at 00:19am 6/17/2001 Phoenix



Geyer, A., and J. Stutz, Vertical Profiles of NO3, N2O5, O3, and NOx in the Nocturnal Boundary Layer: 2. Model studies on the altitude dependence of composition and chemistry, J. Geophys Res., vol. 109, doi:10.1029/2003JD004211, 2004

Figure 2. Measurement results can be compared with model calculations

Prior to our presentation at the 2004 Users' Conference (Hurlock and Stutz 2004), the model was expanded to consider the buildings in the urban canopy. Modification of the NCAT model to explicitly consider building surfaces and volumes led to identification of building statistics describing the urban canopy which were needed as input to the calculation. In particular, a specific surface area of the buildings and a specific volume of the buildings, both as functions of the height above ground level, were needed. A specific area is a ratio of surface area to volume, S/V, in units of length^{-1}. In some applications, the volume is the total volume and in others, it is the open volume. The latter is used here, namely, the volume of the open air not occupied by buildings. The formulation of the model also requires a specific volume (dimensionless) that is defined as the ratio of the open area (not occupied by buildings) to the total area.

Using an approach described below, the required building statistics were determined from the Santa Monica GIS data base and used as input to the model. Model results in Figure 3 show some very significant differences when compared with results obtained without considering buildings.

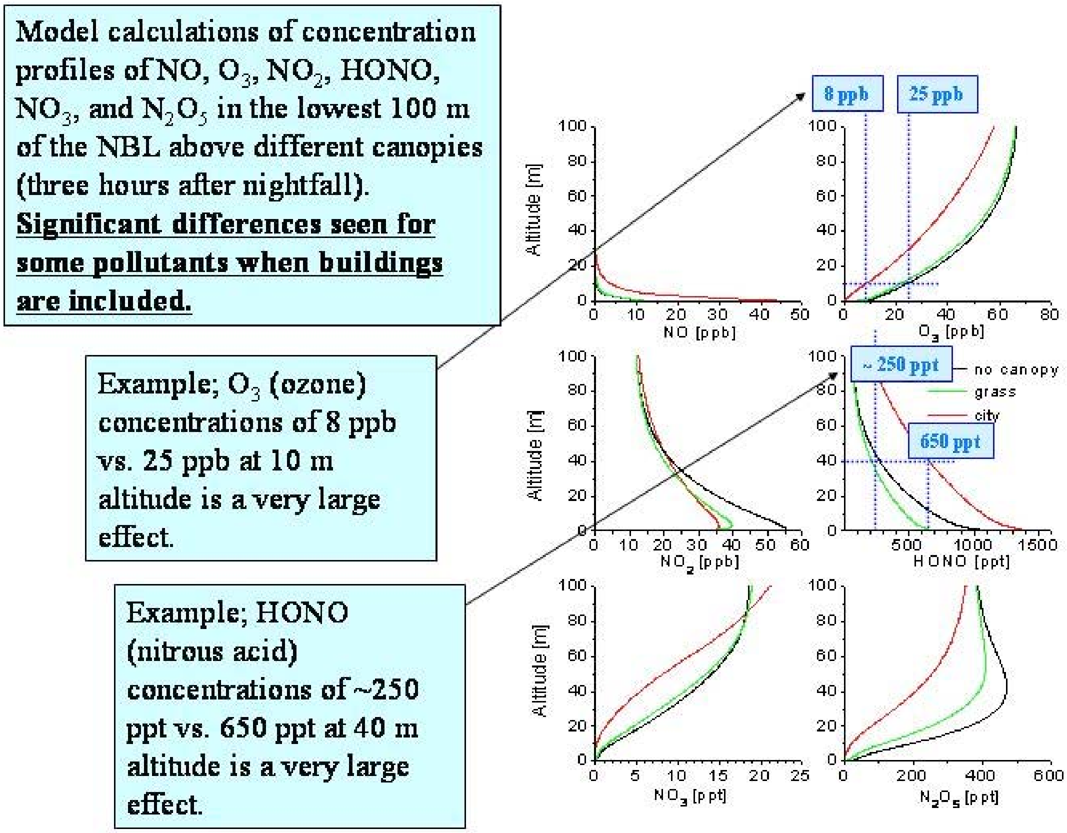


Figure 3. The presence of buildings significantly changes model predictions of pollutant profiles.

Study Area

Using aerial photography and a knowledge of Santa Monica, a study area was selected representing a typical downtown area, with a mix of high rise and lower buildings along the main thoroughfare (Wilshire Boulevard in this case) with lower buildings behind. The study area actually spans the border between Santa Monica and Los Angeles. It is shown in Figure 4, along with an ArcScene projection. There are about 200 buildings in the study area.

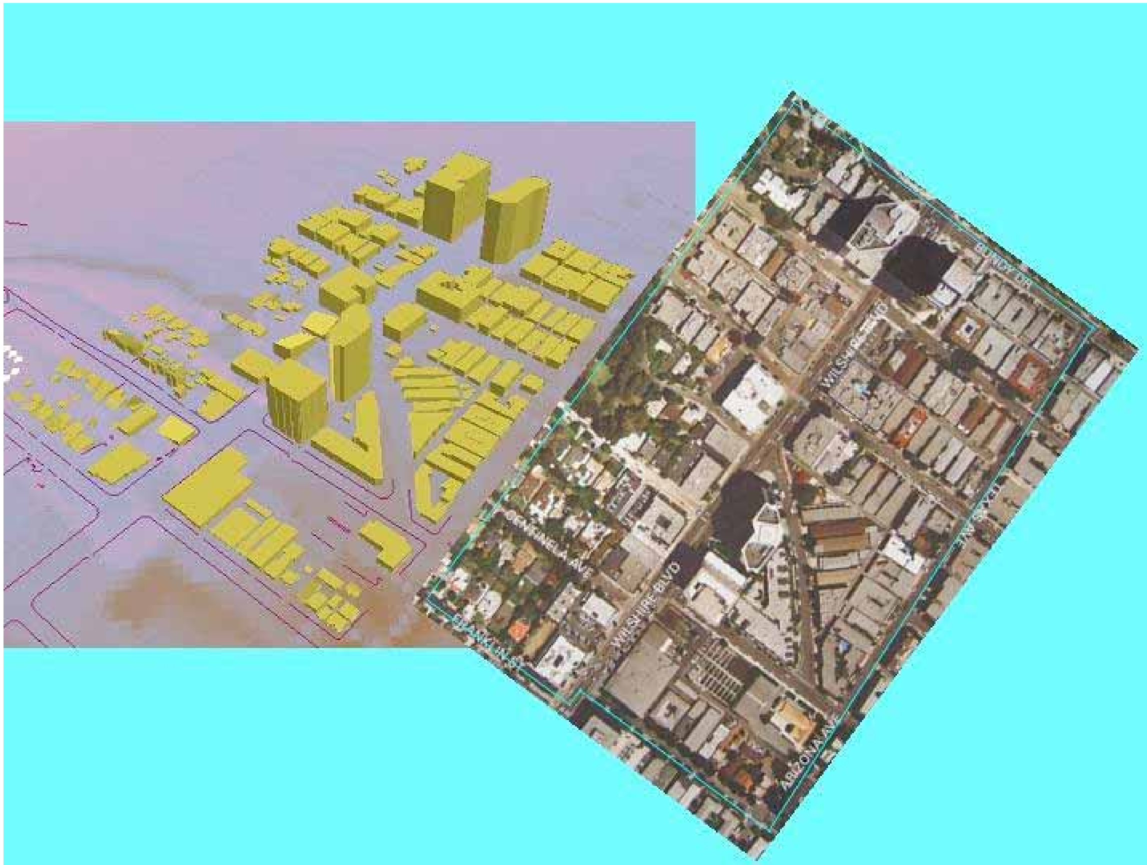


Figure 4. Study area in Santa Monica, California

Specific Area and Specific Volume Associated with Buildings

The approach to using the GIS data base and tools for obtaining height-dependent statistics for the study area is illustrated in Figure 5, which is intended to be self-explanatory. The procedure shown in Figure 5 was needed because the roof height field in the building attributes table was height above the geod, not height above ground. The attributes table of the point feature class shown as the Final Result in Figure 5 was exported to Microsoft Excel for further processing using Microsoft Visual Basic for Applications, VBA. This table, shown in Figure 6, contains the required information to determine the building statistics, namely: the building perimeter, footprint area, and height of the roof above ground. It may be noted that the spatial join of Figure 5 results in a field being added which is the horizontal offset (Distance) between the calculated building centroid and its corresponding point in the raster-to-point-feature conversion. The table illustrated in Figure 6 resulted from rasters of 25 foot cell size and all the Distance values in the table are less than this, resulting in very small errors or uncertainties in the centroid locations relative to the elevation raster. More recently, 5 foot cell rasters have been used. The VBA calculation process is also illustrated. An interrogation increment which extends horizontally over the whole selected study area and has a narrow vertical extent ($\Delta H = 1/3$ meter was used) is marched vertically upward. At each step, the required surface-to-volume and volume-to-volume ratios are calculated. If a roof falls within the vertical extent of the element, its surface area is included in the

S/V for that height. The calculated ratios are smoothed and converted to the required form before being provided as input to the NCAT model.

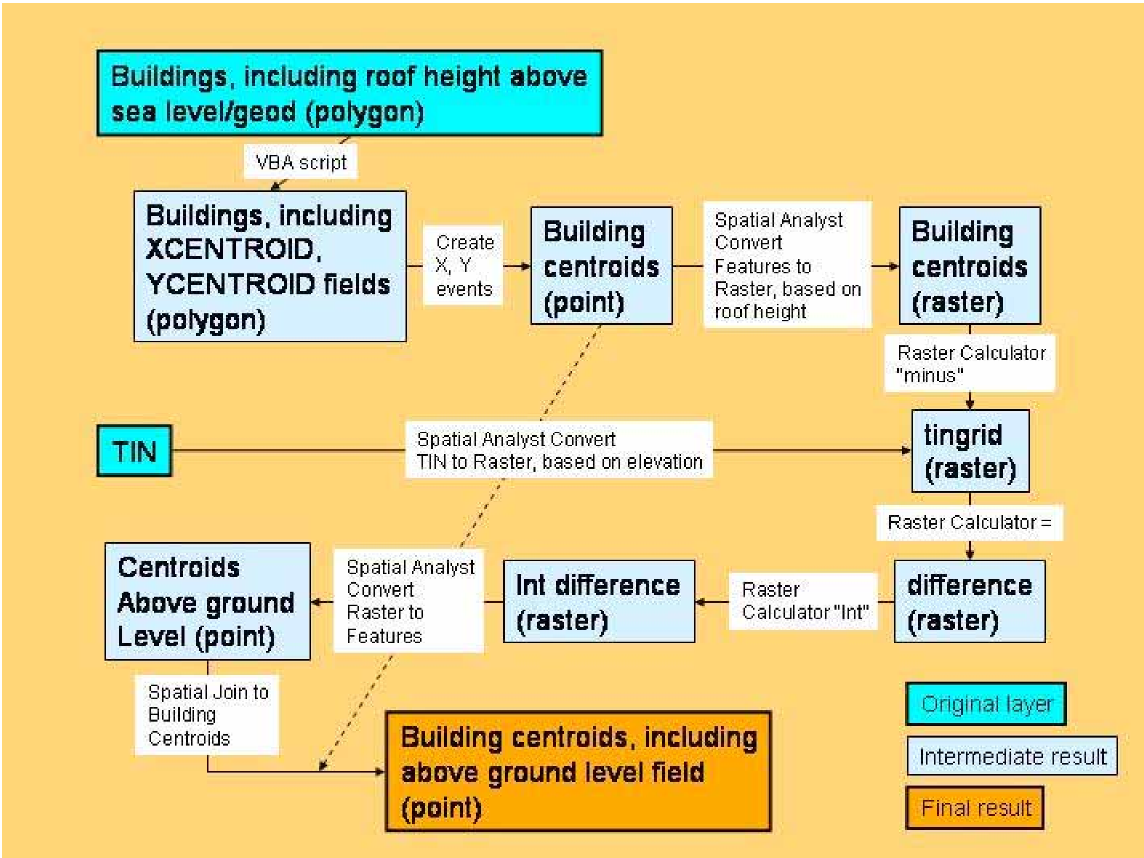


Figure 5. Process for deriving building roof heights from GIS data base

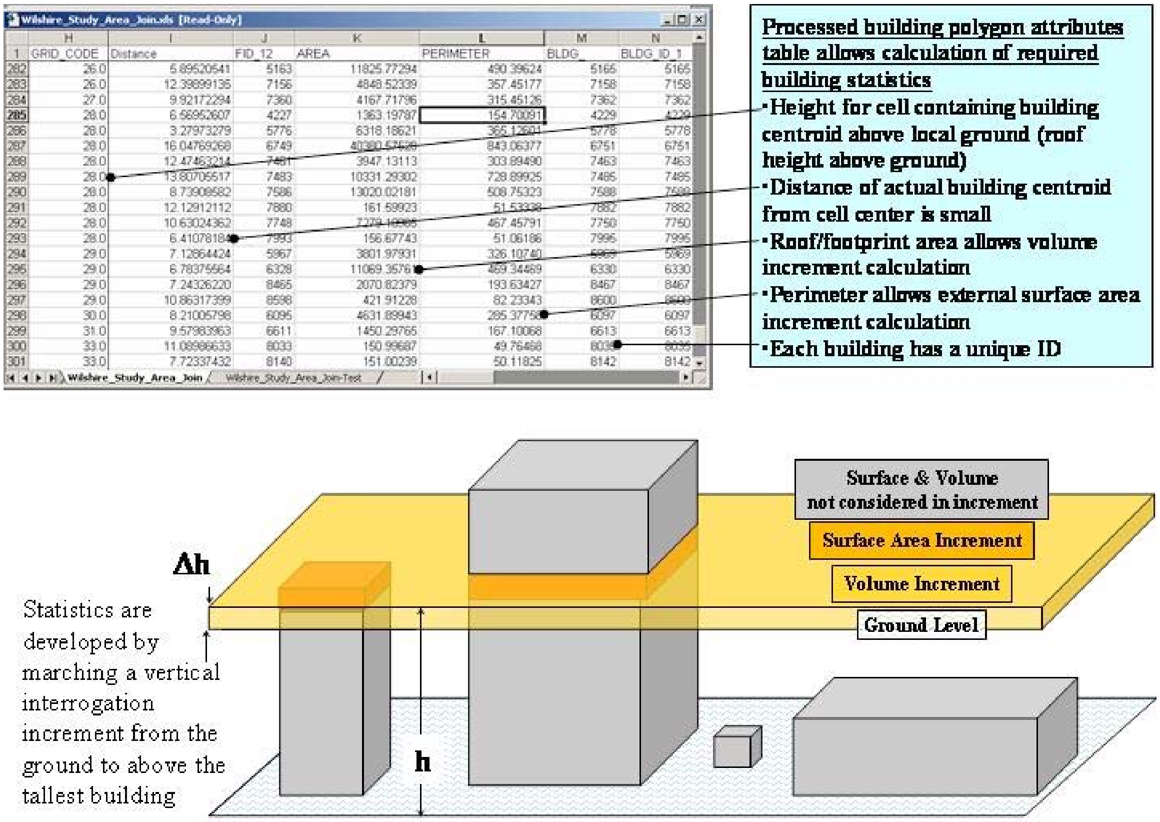


Figure 6. Process for determining surface and volume ratios as functions of height.

USE OF GIS TO OBTAIN URBAN CANOPY PARAMETERS

Two different types of urban canopy parameters needed for the NCAT model calculations are derived using GIS. The first type is aerodynamic roughness parameters, which influence wind flow and turbulence and thus the vertical transport of pollutants within and above the canopy. The second type is specific areas and volumes: ratios of building surfaces and volumes to the overall volume or to the volume of the open air, expressed as functions of height above the ground. These surfaces and volumes influence pollutant profiles through reactions on the building surfaces and through changing the concentration of the pollutants.

Aerodynamic roughness parameters

The vertical flux of a trace gas in the boundary layer is found by using a linear flux gradient model, characterized by an eddy diffusivity K that varies with altitude and sometimes called a K(z) model. The one-dimensional chemical transport model, NCAT, uses a modified K(z), applying a chemistry-dependent factor to the $K_{inert}(z)$ that is used for an inert or slowly reacting gas. Determination of the $K_{inert}(z)$ profile depends on meteorological parameters including the aerodynamic roughness parameters: z_d , the zero-plane displacement length; z_o , the roughness length; and $\overline{z_H}$, the average height of the roughness elements. For the NCAT model results presented at the 2004 Users' Conference, roughness parameters were estimated by similarity to similar archetypical areas and using typical parameters from the literature for such areas.

In the current work, we developed approaches to apply estimation methods from the meteorological literature to the GIS data for our specific area. Several methods to determine the roughness parameters of an urban site through analysis of it surface form (morphometry) were reviewed by Grimmond and Oke (Grimmond and Oke 1999) and compared with field observations. The formulas they reviewed include geometrical parameters that can be derived from a GIS such as the Santa Monica data base as described here. We use aerial photography and a high quality urban GIS data base to select the site, and then GIS processing of the vector, raster, and TIN data to develop the parameters. Applying methods identified as Ra, Ba and Ma in Grimmond and Oke, the parameters $\frac{z_d}{\overline{z_H}}$ and $\frac{z_0}{\overline{z_H}}$ were determined using the attribute table of the final result feature class shown in Figure 5. The contents of this table include a row for each building in the selected study area. Fields relevant to the calculation are: roof height above ground, footprint area and perimeter. Parameters needed in the three methods are listed in Table 1, along with a brief description of the approach we used to calculate them from the data.

Table 1. Geometrical Parameters Needed for Calculation of Surface Roughness

Parameter	**Description**	**Determination from Building Attributes**
$\overline{z_H}$	mean height of the roughness elements	Average of heights of the building roofs above ground level
$\overline{L}_y$	building cross-wind width	Average of building lateral dimensions. Lateral dimension of each building determined as average of perimeter/4 and area$^{1/2}$
$(\overline{D}_x \overline{D}_y$	$\overline{D}_x$ and $\overline{D}_y$ are the along-wind and cross-wind dimensions of the total area element associated with the mean building.	Product is the area element associated with the average building, found as $1/\rho_{el} = A_T/n$, where A_T is the total area and n is the number of buildings

Specific Area and Specific Volume Associated with Buildings

Methods were developed and presented at the 2004 Users' Conference for determining the required specific area and specific volume statistics as a function of height. These were described earlier under Background. The same methods were used for the current evaluation except that the elevation TIN was converted to a raster with 5 foot cells and the point feature class containing the elevation of the building roofs was converted to a 5 foot cell raster instead of the 25 foot cells used last year.

EVALUATION OF THE CONTENT AND FIDELITY OF THE GIS DATA BASE FOR URBAN ATMOSPHERIC CHEMISTRY/TRANSPORT CALCULATIONS

In the report presented at last year's ESRI Users' Conference (Hurlock and Stutz 2004), we used the GIS data base provided by the City of Santa Monica with no changes. This high resolution data base includes a set of shapefiles and TINs, with a rich array of attributes that are very well suited to our atmospheric chemistry application. In the continuation of this work, we were motivated to evaluate this data set in more detail in order to identify strengths and weaknesses with respect to use in those areas of atmospheric science which are concerned with the urban canopy. This evaluation is not intended to criticize the quality and utility of this or other similar GIS's for their intended application by municipal and other agencies. However, the atmospheric science community has an ongoing interest in understanding the role of the urban canopy and a growing recognition of the utility of GIS data and technology in studying it. This is exemplified by such initiatives as "A federated partnership for urban meteorological and air quality modeling" (Williams and Ching). In the interest of providing insight to the urban GIS community, the urban atmospheric science community, and the overlap community, we discuss here limitations and possible future extensions/additions to GIS data bases such as Santa Monica's when applied to urban canopy atmospheric science.

Surface and volume adjustments and corrections

Superfluous features and Common and Inaccessible Walls

There are some features in the buildings shapefile that appear to be superfluous. An example is shown in Figure 7, where each dot represents a feature in the attribute table. Some of these features were examined in the field survey to confirm that no real features are there. Although such features are small, they have perimeters and areas which were previously counted in the analysis. Such features have now been removed in terms of their perimeters and areas being set = 0. This is an insignificant source of error, amounting to a decrease of about 0.15% in surface area and much less than that in volume.

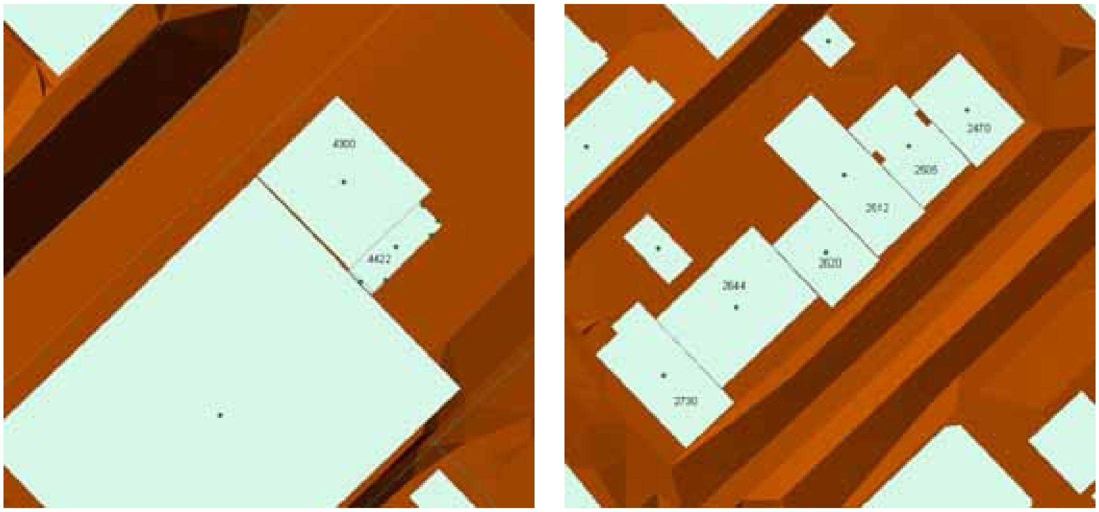


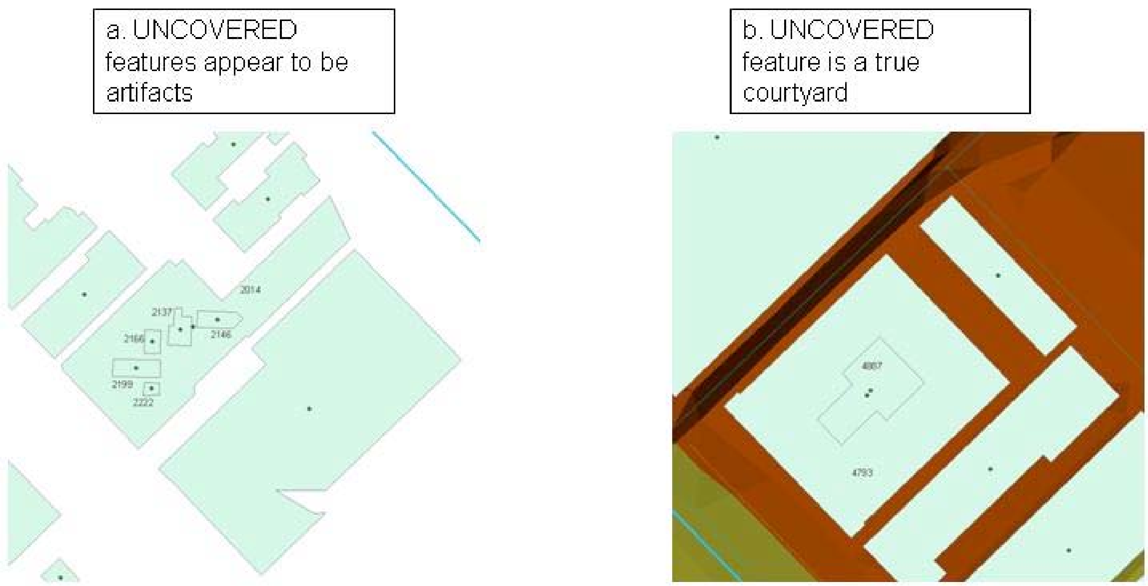
Figure 7. Examples of superfluous features and common or inaccessible walls.

Some of the buildings share a common wall and in some other cases the separate walls are so close that they are not accessible to meteorological exchange with the ambient air. Examples are shown in Figure 7. For the study area here, the adjustment is insignificant, a decrease in surface area of about 0.5%. For other areas, the effect could be significant, even dominant if a large fraction of the individual building features shared common walls.

COVERED vs. UNCOVERED Features

Some of the buildings have features within them which are identified as UNCOVERED in an IGDS_LAYER attribute field. For example, Figure 8 a shows six polygon features associated with building 2014: One of the polygons, representing the building has an attribute; COVERED. The other five features are UNCOVERED. For some buildings, the UNCOVERED features are true inner courtyards, but in this case, they appear to be something else, possibly incorrectly identified features. Figure 8 b shows a building with a true inner courtyard. In all UNCOVERED feature cases, whether they are true inner courtyard features or not, we do not want to include their surface areas in the calculation. However, we do want to include the footprint area of the courtyards as part of the total footprint area of the building. It was found that, for the Santa Monica data base, the PERIMETER property adds the UNCOVERED features' PERIMETERS to that of the building containing them and assigns this sum of perimeters to the building, while also assigning the perimeter of each UNCOVERED feature to that UNCOVERED feature. On the other hand, the AREA property for the COVERED feature (the actual building) is calculated based on the actual building footprint area, ignoring the UNCOVERED features. This is appropriate for our application. However, an AREA value remains assigned to each UNCOVERED feature and this is not appropriate, resulting in the UNCOVERED feature areas being counted twice. Adjustments need to be made to the attribute table to get the correct volume and surface area for this set of features. The adjustments are shown in the table inset in Figure 8. In the case of building 2014, this leads to no direct change in the calculated volume for this building, but a 37.5% decrease in the calculated surface area when the perimeter is adjusted to the perimeter of the actual, COVERED, building. In addition, the procedure used previously treats the

UNCOVERED features as buildings, leading to contributions to both the surface area and volume that needs to be adjusted. When the appropriate adjustments are made, the surface area and volume associated with this building are reduced by 55% and 12%, respectively. However, over the entire study area, adjustment of areas and perimeters to achieve the desired treatment of UNCOVERED features and their associated COVERED buildings results in only a -0.4% decrease in the total building volume within the study area, in comparison with the previous analysis. The total surface area changed by -4.2% after the adjustments.



BLDG_ID	AREA (Original)	PERIMETER (Original)	IGDS_LAYER	ROOF HEIGHT	Surface Area	Volume	AREA (Adjusted)	PERIMETER (Adjusted)	Adjusted Surface Area	Adjusted Volume
2014	16633	1183	COVERED	40	47328	665304	16633	740	29618	665304
2137	532	106	UNCOVERED	41	4345	21815	0	0	0	0
2145	538	102	UNCOVERED	41	4189	22061	0	0	0	0
2166	294	70	UNCOVERED	40	2790	11770	0	0	0	0
2199	661	115	UNCOVERED	41	4715	27099	0	0	0	0
2222	153	50	UNCOVERED	40	1993	6139	0	0	0	0
				SUMS	**65360**	**754189**	**16633**	**740**	**29618**	**665304**
									-54.7%	-11.8%

Figure 8. UNCOVERED features are courtyards or can be artifacts

Buildings with Negative Heights or Low Heights above Ground Level

The process shown in Figure 5 for determining the building centroid above ground level returned negative values for a few buildings in the study area and unrealistically low values for others. Building 3077 is a typical example and sits at a location with quite a bit of elevation variation in the TIN, as shown in Figure 9. The value returned for this building was -10 feet. Also shown in Figure 9 is a photograph of the building, which appears to have a roof height above street level of about 10 feet. In the previous treatment of this data, (Hurlock and Stutz 2004), all buildings with roof heights above ground of less than 4 feet (thus including all negative values) were eliminated from the analysis. The revised approach is to assign a roof height above ground of 22 feet, which is half of a typical classification interval for the tingrid resulting from converting the TIN to a grid and a 9 class Jenks classification. The effect of this adjustment by itself was to increase the surface area by about 5%, more than offsetting the negative effect of the COVERED/UNCOVERED adjustment and leading to a net adjustment of just over 1%. The volume increase due to this adjustment by itself was 2.7%, again more than offsetting the COVERED/UNCOVERED adjustment and leading to a net adjustment of 2.4%. However, it was assumed that no systematic bias or offset exists between the IGDS_ZVALUs assigned to the building polygons and the Elevation of the TIN. If such a bias existed, it could lead to more significant errors in the derived urban canopy parameters.

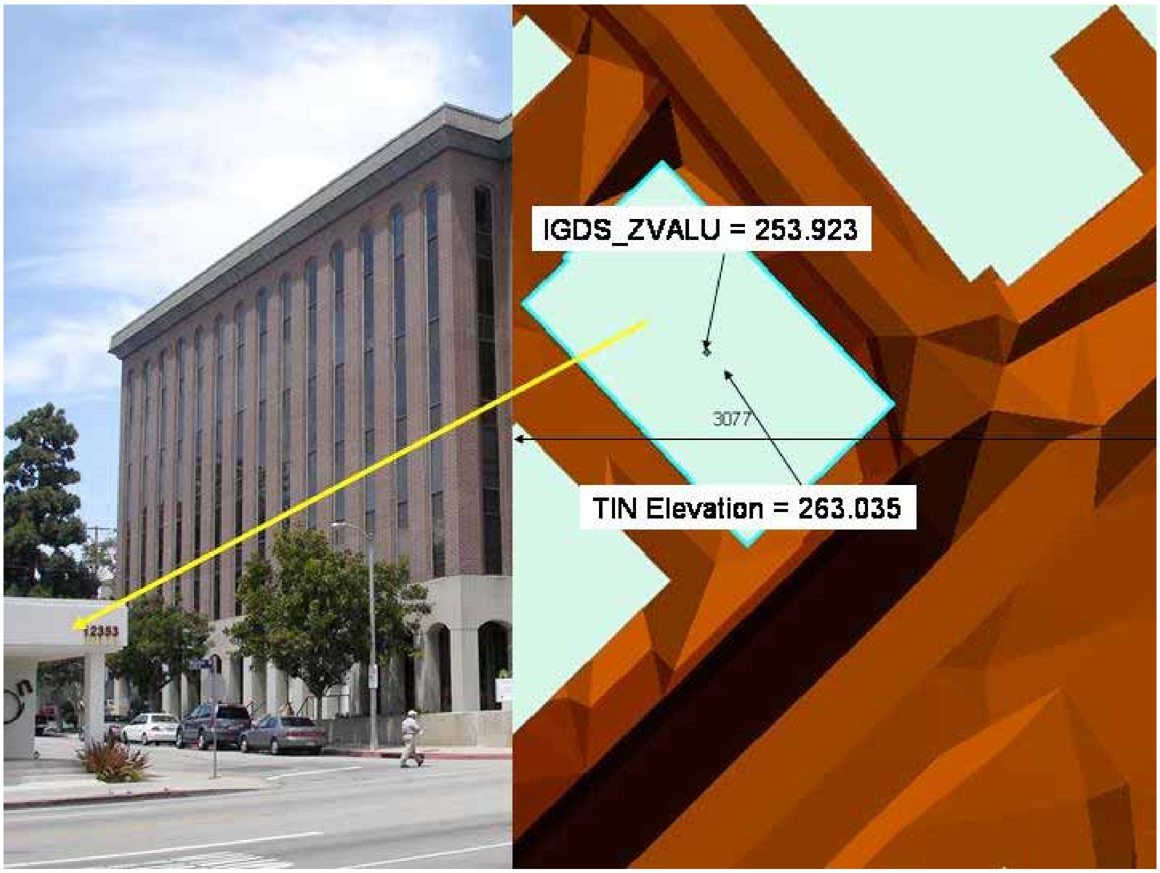


Figure 9. Some buildings had ZVALUs below local TIN.

Real Building Surfaces and Volumes

The approach illustrated in Figure 6 treats each building as a right polygonal cylinder, having footprint area and perimeter as tabulated in the attributes table of the building polygon shapefile and roof height above ground height as determined by the process illustrated in Figure 5. This is obviously a simplification of real buildings. In this section, we discuss the impact of this simplification on the surface area and volume, combining observations from a field survey with GIS, Excel and VBA results.

Some Examples from Field Survey

A fairly extreme example of the issue is shown in Figure 10, where photographs of a real building can be compared with the polygonal cylinder representing it in the analysis. This tall building, BLDG_ID = 2069, on the corner of Wilshire Boulevard and Bundy Drive, has significantly less total volume than the extruded polygon, primarily because of the lower sections on the north and south corners and also because of the setback along Wilshire. The total surface area for the real building appears to be somewhat less than for the extruded polygon, but the vertical distribution of the area for the polygon is significantly skewed to higher elevations because all of the roof area is placed at the highest elevation as opposed to the real building, where much of the roof only covers areas 20-30 feet above the street level. The building appears not to have a great deal of fine structure articulation which would cause its real surface area to be significantly higher than that of the polygon. Detailed analysis of this building reduced its volume by 25% and decreased its surface area by 7%.

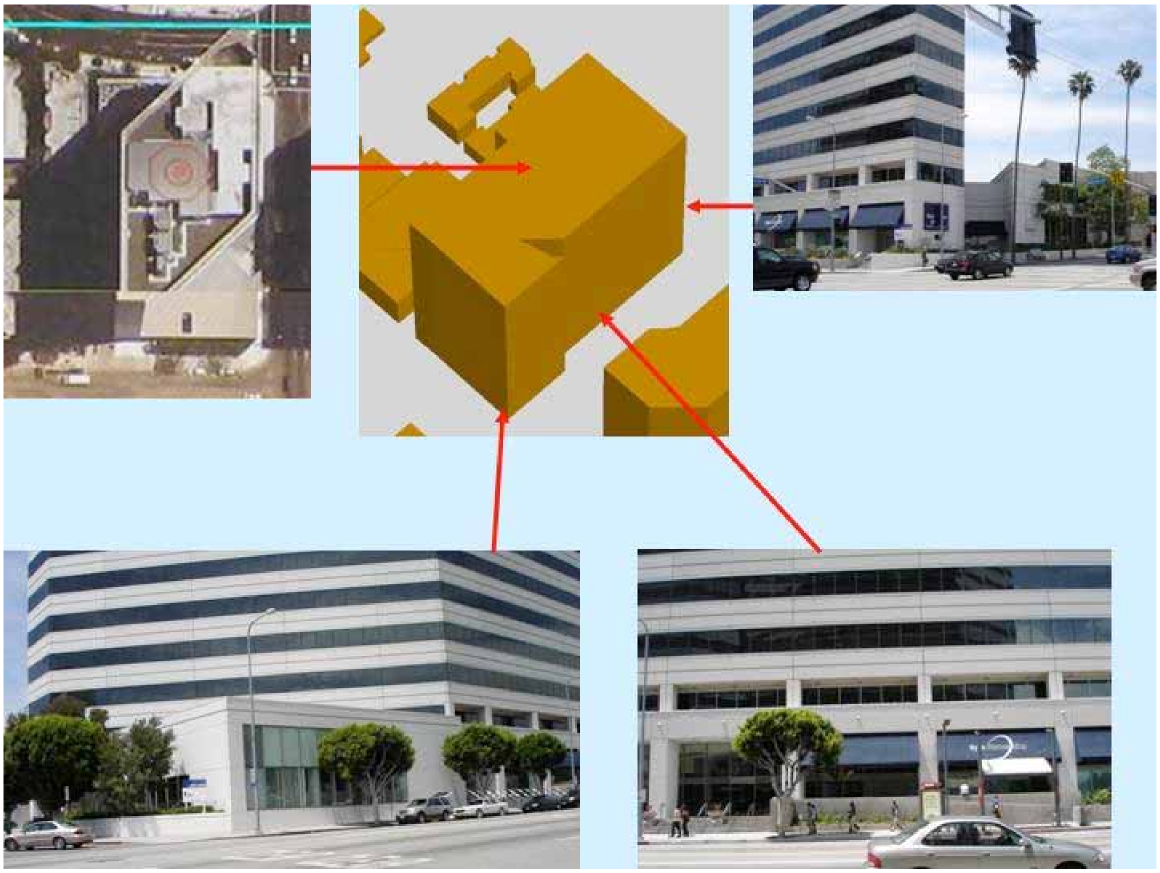


Figure 10. Extruded polygon of building footprint significantly different from real building.

Another type of example, which is representative of apartment buildings and is widespread in the study area, may be seen in the photos and corresponding extrusions of Figure 11. These buildings have a lot of articulation, so that the surface area that they present to the atmosphere is significantly higher than the product of the perimeter and roof height of the right polygonal pyramid, which is the approach we use to calculate surface area. Detailed analysis of the building on the right of the figure resulted in increasing the surface area by 42% and reducing the volume by 4%, relative to the extruded polygon.

Some high-rise buildings also have articulation and other architectural features resulting in actual surfaces and volumes that differ from the simple extruded polygon calculation.

Some examples are shown in Figure 12, where actual buildings and extruded polygons may be compared.

Figure 11. Many apartment buildings highly articulated.

Figure 12. High rise architectural features different from extruded polygons.

Field Survey Results

Many buildings were photographed and characterized in a field survey and a sample made up of 16 of these was evaluated in detail. The sample represented 58% of the unadjusted building volume and 44% of the building surface area, as calculated from the extruded polygons. The high values of the sample volume and surface area resulted because most of the largest buildings were included. The total of the sample's adjusted surface area and volume represented a 7% increase in surface area and a 9% decrease in volume, relative to the corresponding extruded polygons. These factors were used to recalculate the specific surface and specific volume ratios as functions of height for input to the model.

ATMOSPHERIC CHEMISTRY MODEL CALCULATIONS USING THE GIS-DERIVED INPUT

As we reported at the 2004 Users' Conference, the results of model calculations when buildings are explicitly considered can be significantly different from results when the canopy is ignored or for other canopies, such as flat ground or grass. The results shown here include two improvements in the fidelity of our modeling. The first is the use of the GIS data base to derive more representative aerodynamic roughness parameters for our study area. This yields a different K(z) profile from one derived using parameters from the literature for supposedly similar urban canopies. The second difference involves improving the fidelity of the attributes of the building features, as discussed in detail above. The most significant change here resulted from applying “real building” factors of +7% to the building surface areas and -9% to the building volumes when computing the surface and volume ratios as functions of height. Other corrections: superfluous features, courtyards, common walls, and inaccurate Z values, were made by modifying the attribute table accordingly and individually resulted in surface area or volume changes as high as ±5%. In our case, some changes were offsetting, resulting in net changes of under 5%. When all these changes are made, the resulting calculated pollutant vertical profiles will also change. However the differences are expected to be relatively minor compared with the large changes shown in Figure 2, where initial model results using the urban canopy parameters of this study area were significantly different from those when buildings are ignored.

CONCLUSIONS AND RECOMMENDATIONS

Buildings play a significant role in the temporal and spatial development of air pollution in the urban environment. Explicit consideration of buildings is shown to result in significant differences in computed pollutant profiles as compared with results for canopies having less aerodynamic roughness, less occupied volume and less surface area. Existing GIS data bases, such as the Santa Monica data used here, provide a data-rich resource containing much of the information needed to model the urban canopy. GIS tools and technology can be adapted to extract the data needed, as shown using approaches developed here. For the study area considered here, a typical downtown area, the fidelity of the data base and the methods used to extract the required model inputs produced surprisingly accurate results, with corrections of only a few percent or less for all error sources considered, except for the extruded polygons-to-real buildings corrections. A field survey was conducted to evaluate this correction, with the expectation that it would be large. However, changes of only ~7-10% were found to apply. Thus, it appears that a high quality, high resolution GIS data base and appropriate data processing can be used to develop very good first order estimates for the urban canopy parameters needed in understanding and predicting urban air quality.

The data base used included building perimeters, footprint areas, and roof heights. These attributes were essential for our analysis, which would have had much less fidelity without them. It is recommended that these attributes be part of any urban GIS database which might be used for urban meteorology and air quality analysis. In the case of roof heights, the process of determining the heights above the local terrain as differences, illustrated in Figure 5, produced errors. The source of the errors appears to be inherent in the absolute elevation of the TIN or the building roofs or both. Only those obvious errors that resulted in negative or extremely low heights were corrected, somewhat arbitrarily. Other errors of unknown magnitude and sign most likely remain in the calculated roof heights above the ground. It is recommended that building heights above ground be directly determined and included as a building attribute in the data to avoid this source of uncertainty. Other characteristics of roofs also produced uncertainty. Buildings having multilevel roofs, peaked or otherwise structured roofs are all treated as right polygonal cylinders with flat tops located at the ZVALU height. Different strategies might be recommended for alleviating this problem, such as a roof type attribute or, better yet, subdivision of some buildings into parts.

Future efforts in modeling urban air quality will include consideration of building surface materials because the uptake coefficients of pollutants on different surfaces can differ by more than an order of magnitude (Trick 2004). Thus, it is recommended that building surface materials be included in future urban GIS data bases. Vegetation also presents roughness and surfaces which can influence aerodynamic mixing and process pollutants. Although not considered in this study, vegetation will be included in future studies. It will then be necessary to know the spatial distribution of different vegetative cover in the urban environment and this data would best be accessed using GIS data and tools.

ACKNOWLEDGEMENTS

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