Geographic Resolution Issues in RAM Transportation Risk Analysis

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Introduction

Over the years that radioactive material (RAM) transportation risk estimates have been calculated using the RADTRAN code [1], demand for improved geographic resolution of route characteristics, especially density of population neighboring route segments, has led to code improvements that provide more specific route definition. With the advent of geographic information systems (GISs), the achievable resolution of route characteristics is theoretically very high. We have compiled population-density data in 1-kilometer increments for routes extending over hundreds of kilometers without impractical expenditures of time. Achievable resolution of analysis is limited, however, by the resolution of available data. U. S. Census data typically have 1-km or better resolution within densely-populated portions of metropolitan areas [2] but census blocks are much larger in rural areas. Geographic resolution of accident-rate data, especially for heavy/combination trucks, are typically tabulated on a statewide basis. These practical realities cause one to ask what level(s) of resolution may be necessary for meaningful risk analysis of transportation actions on a state or interstate scale.

Our quantitative approach to this question is divided into two separate aspects that coincide with the RADTRAN risk analysis code: transportation under normal or incident-free conditions, and accident conditions. Estimation of population radiation doses in the incident-free analysis is proportionally dependent on the population density within a band that extends out to one-half mile (≈800 meters) on either side of the route centerline. Calculation of population dose-risks resulting from potential accidents, in which a portion of the shipment radioactivity is released in a plume extending down-wind from an indeterminate accident site, requires knowledge of the population density in the area under the plume. Each of these analysis categories has distinct resolution issues which are addressed in separate sections of this paper.

Using a commercial geographic information system and U. S. Census population-distribution data together with digital highway (or rail) maps, we have carried out investigations of the effects of improved population-density resolution on typical RAM transportation risk estimates [3, 4]. These studies have been applied to Interstate 70 across the state of Missouri because it is part of a reference transcontinental route, and because it traverses a representative mix of rural, suburban and urban population densities. The current study employs this same route for the reasons just given and to provide continuity with the previous studies.

Incident-Free Analysis

In early versions of the RADTRAN code, population-density data for the entire route were always aggregated into three distance-weighted averages for rural ($\leq$ 66 persons/km), suburban (> 66, $\leq$1670 persons/km), and urban (>1670 persons/km) ranges. This approach simplified data input but did not specify the location of an individual range of population densities. HIGHWAY, the routing code used to define population densities [5] broke each route into segments between highway intersections, but the rural, suburban and urban components of each such node-to-node segment were already aggregated.

On the other hand, when the density of population within a perpendicular distance of 0.8 km from the highway centerline is compiled for each kilometer of a route using the GIS, the input to RADTRAN (and the results) become exceedingly cumbersome for routes of several hundred kilometers or more. In addition, further attempts at increased geographic specificity of risk analysis may lead to errors because of the approximation made in calculating the integrated dose, at an arbitrary point near the route, as the shipment passes by. In RADTRAN, the finite length of each component portion of the route (LINK) is modeled as being infinitely long for the sake of obtaining a mathematically more convenient form of the integral:

$$I(x) = C\int_0^{L/2} \frac{dl}{(l^2 + x^2)} \Rightarrow C\int_x^{\infty} \frac{dr}{r(r^2 - x^2)^{1/2}}$$

where:

L is the length of the LINK
x is the perpendicular distance from the route centerline
$r = (l^2 + x^2)^{1/2}$ is the distance between the shipment and the point of interest
C is a constant.

For LINKS that are comparable to 1 km or longer, this is a good approximation for the desired accuracy (~2x). If routes are subdivided into very small segments (i.e., much less than 1 km), the error due to this approximation could become significant, i.e. greater than a factor of two.

Aggregation of individual 1-km segments into longer LINKS for analysis also is desirable for a practical reason - it reduces the amount of data to entered into RADTRAN. In order to preserve the maximum amount of geographic specificity of significant population-density variations with the minimum necessary number of route segments, aggregation must be performed in the sequential order of the basic (e.g. 1-km) segments. This aggregation is readily accomplished by transferring data tabulated with the GIS to a spreadsheet program and combining sequential segments into LINKS having population densities falling within the same rural, suburban or urban range. These LINKS are then assigned population densities equal to the averages of the corresponding segment-population-densities (distance-weighted averages since the basic segments are all equal in length). Although other aggregation schemes can be employed, that subject was not examined in this study. The effects of this type of aggregation can be seen in the example shown in Figure 1, depicting a representative section of the I-70 route in the suburbs of St. Louis, MO.

Note that a single, 1-km segment may intersect several U. S. Census blocks extending over an area that is substantially larger than the 1-km-by-1.6-km rectangle of interest, as shown in Figure 2. Calculation of population density as the total population in this area divided by the total area yields an area-weighted average. That is, blocks with larger areas (which tend toward lower population densities) are emphasized. Calculation of population density as the average of the individual block population densities (tabulated in the Census block data) yields higher densities since small blocks (tending toward higher population density) are weighted the same as large blocks. Use of the latter average leads to more conservative tabulation of population densities within the rectangles of interest.

The preferred method of calculating average population densities for the individual segments (described in the preceding paragraph) yields conservative results, but aggregation based on these values was found to result in many LINKS that were only one kilometer in length and often located between two longer LINKS of a different population-density group (see the arrows in Figure 1). A modification of the spreadsheet aggregation method was instituted to eliminate *isolated* 1-km LINKS; this further reduced the total number of LINKS describing the route without obscuring substantial highly-populated areas traversed by the route. The effects of applying these aggregation steps are illustrated in Figure 3; in this example, the number of RADTRAN separate inputs (LINKS) is reduced from 34 to 16. In Table I, the numbers of LINKS describing the entire route across Missouri are compared. In addition, the total exposed population, calculated as the sum of the products of LINK-length, population density and band width (1.6 km), is tabulated for each aggregation scheme to verify that aggregation does not change the population exposed over the entire route (or the calculated population dose).

Table I – Comparison of Aggregation Schemes

Aggregation	Number of LINKS	Total Exposed Population
None	421	283685
Sequential	89	283685
No 1-km *	45	283685

* Isolated, single segments eliminated

Accident Analysis

The model employed in RADTRAN for estimation of accident risks assumes that a fraction of the shipment radioactive contents is released and forms an airborne, diffused plume that moves downwind from a hypothetical accident site. The time-integrated result of the plume formation and propagation is represented in RADTRAN by a set of dilution factors and isopleths (contours of constant concentration). In current and past versions of RADTRAN, a set of 18 dilution factors and isopleths was made available for code users who were not interested in performing their own plume propagation calculations. The isopleth areas, maximum radii and dilution factors are presented in Table II; the maximum radius of 120 km and an associated dilution factor of 3.42E-08 were chosen as representative of the limit of plume-modeling accuracy while maintaining conservatism in the risk estimates calculated by RADTRAN. However, recent benchmarking of plume dispersion-model calculations [6] would seem to bring such extremes into question: 80% to 100% of the comparisons of calculations with measurements at 8 km and 16 km radii were found by the authors to be within a factor of five. These values were presented for the arc-integrated concentration performance measure (their Table VI), which are most closely related to the RADTRAN parameters. Correlation coefficients calculated for the same measure of performance ranged from 0.38 to 0.74.

Table II – Sample (RADTRAN) Isopleth Areas, Radii and Dilution Factors

Area (m^2)	Radius (km.)	Dilution Factor*
4.59E+02	0.0334	3.42E-03
1.53E+03	0.0680	1.72E-03
3.94E+03	0.105	8.58E-04
1.25E+04	0.244	3.42E-04
3.04E+04	0.360	1.72E-04
6.85E+04	0.561	8.58E-05
1.76E+05	1.018	3.42E-05
4.45E+05	1.628	1.72E-05
8.59E+05	2.308	8.58E-06
2.55E+06	4.269	3.42E-06
4.45E+06	5.468	1.72E-06
1.03E+07	11.136	8.58E-07
2.16E+07	13.097	3.42E-07
5.52E+07	21.334	1.72E-07
1.77E+08	40.502	8.58E-08
4.89E+08	69.986	5.42E-08
8.12E+08	89.860	4.30E-08
1.35E+09	120.878	3.42E-08

* units are (Ci-sec/m^3/Ci-released).

Because of this implied uncertainty at large radii, an investigation of the contributions from the outer isopleths to the total calculated accident-risks was undertaken. The same route along I-70 across Missouri was used to tabulate population densities within various distances (radii in Table II) from the route centerline. The values of the radii and the population densities derived for the area between the radius and the next-smaller radius (averaged over the entire length of the route) are listed in Table III. These population densities were entered as RADTRAN input parameters and the total accident-risk was calculated using only the isopleths and dilution factors within the radius listed in Table III. The resulting values of total risk are also listed in Table III.

Table III – Comparison of Isopleth Radii, Population Densities and Total Risks

Radius (kilometers)	Differential Pop. Den. (persons per sq. km)	Total Accident-Risk (person-rem)	Percent Change in Total Risk
0.805*	140	---	---
1.63	234	---	---
2.31	220	---	---
5.47	228	---	---
11.1	140	0.0103	-25
21.3	165	0.0126	-8.0
40.5	45	0.0132	-3.6
121	11	0.0137	0.0

* Incident-free bandwidth; included for comparison.

It is clear from Table III that the population densities drop significantly beyond 21 km, primarily because these large radii reach well beyond the bounds of the two major cities on the route. Also, population tends to concentrate nearer to roadways in general, as may be discerned from the peak in differential population density between 0.805 and 1.63 kilometers in Table III. The decrease in calculated accident-risk resulting from truncation of the isopleths beyond 21 km is negligible compared to the general accuracy of the risk calculations (factor of ~2). Given the findings of Rood, et al. and the results in Table III, any estimates of risk to population beyond 21 km would not contribute meaningfully to the accuracy of the risk estimates in most circumstances. However, estimates beyond 21 km (out to approximately 40 km) remain useful for conservative bounding of any real risk, and for analyzing isolated instances of accidents occurring more than 21 km upwind from a highly-populated area large enough to fill the isopleths extending beyond 21 km.

Conclusions

Unless the basic RADTRAN equations for calculation of incident-free doses are modified, the minimum increment of distance along a route, that preserves the accuracy of the model, is of the order of 1 kilometer. Significantly shorter increments are expected to incur "multiple counting" errors which could become significant (~2X) in extreme cases.

Results from analysis of the representative route selected for this study indicate that accident dose-risks do not appear to benefit in accuracy by inclusion of population under hypothetical plumes extending beyond approximately 20 kilometers. Certain routes may be found for which this limit does not yield satisfactory bounding of the accident risks; therefore, inclusion of population out to approximately 40 km is recommended for general, conservative accident-risk analyses.

Whenever the analyst has resources with which to determine variation of population with distance from the route are available (a GIS and population data), sensitivity tests of accident-risk to plume extension beyond approximately 16 km are recommended, based on the benchmarking results cited here [6].

References

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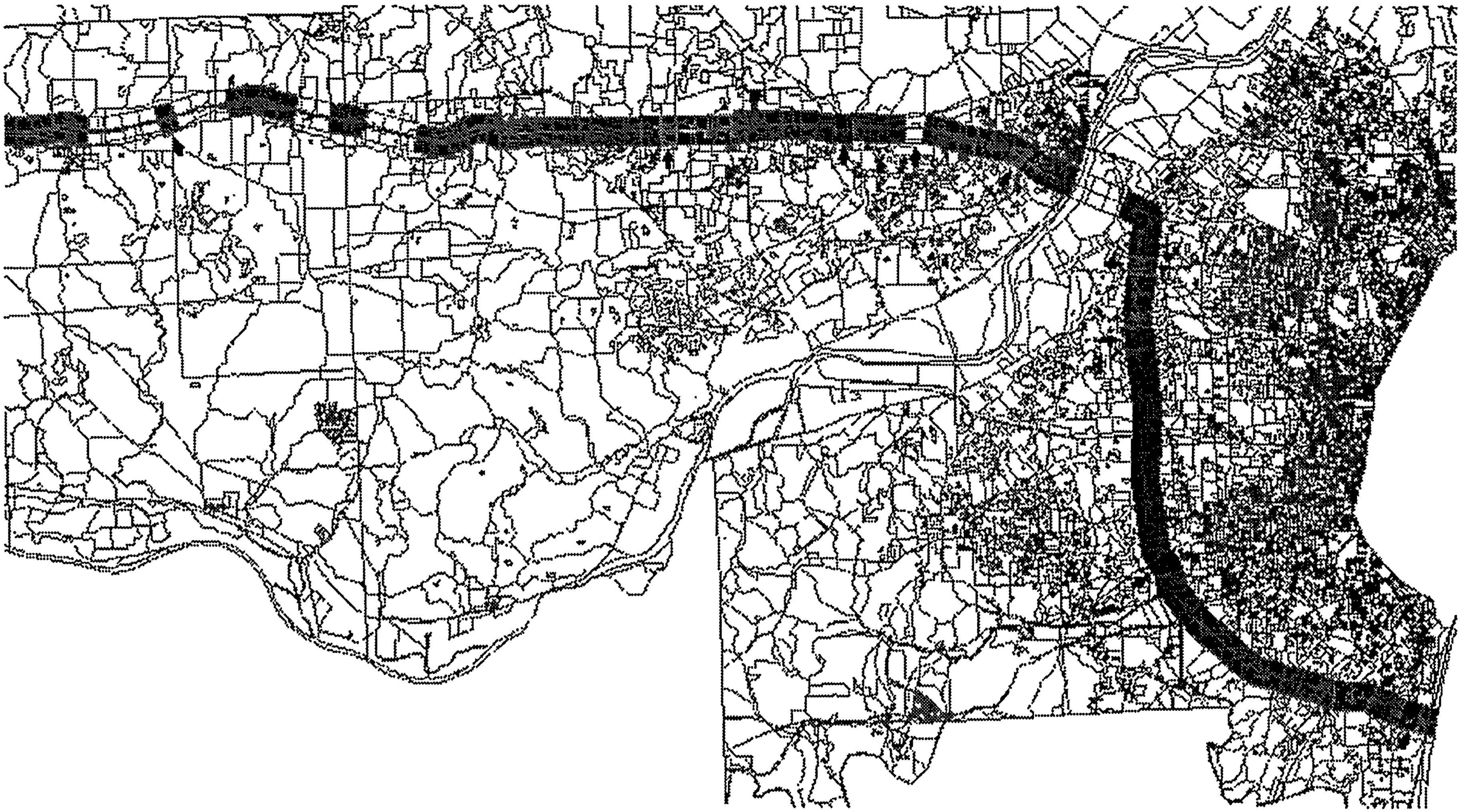

Figure 1 – Example of LINKS of Aggregated 1-km segments of the same population-density range (Rural – white, Suburban – gray, Urban – black)

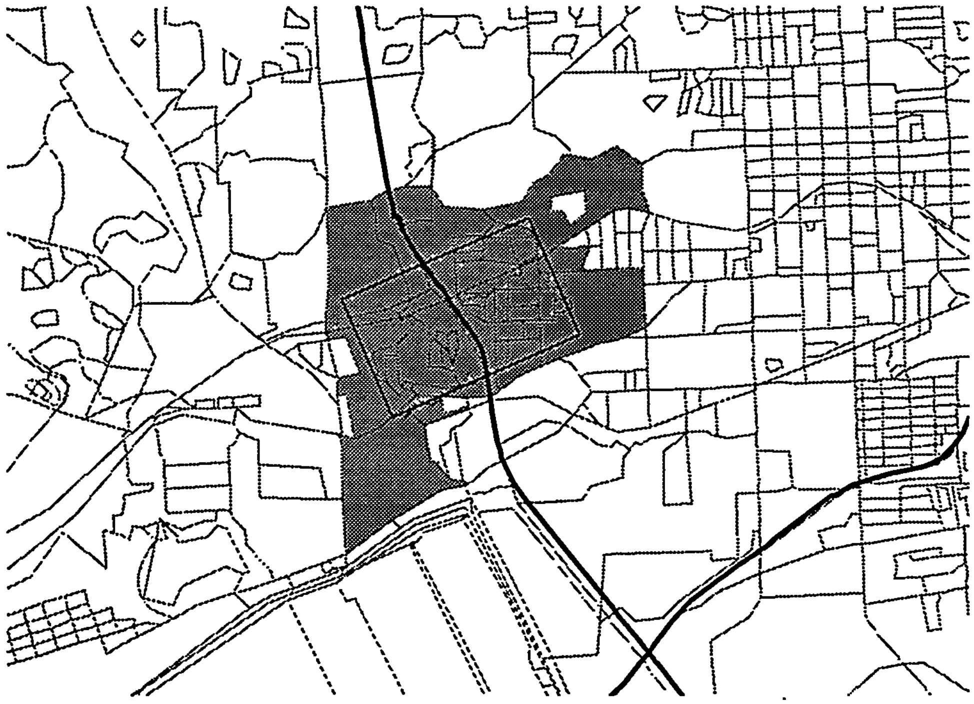

Figure 2 – Example of Census Blocks Intersected (gray) by a 1.0 x 1.6 km Rectangle Defining a Single Route Segment in a Suburban Area

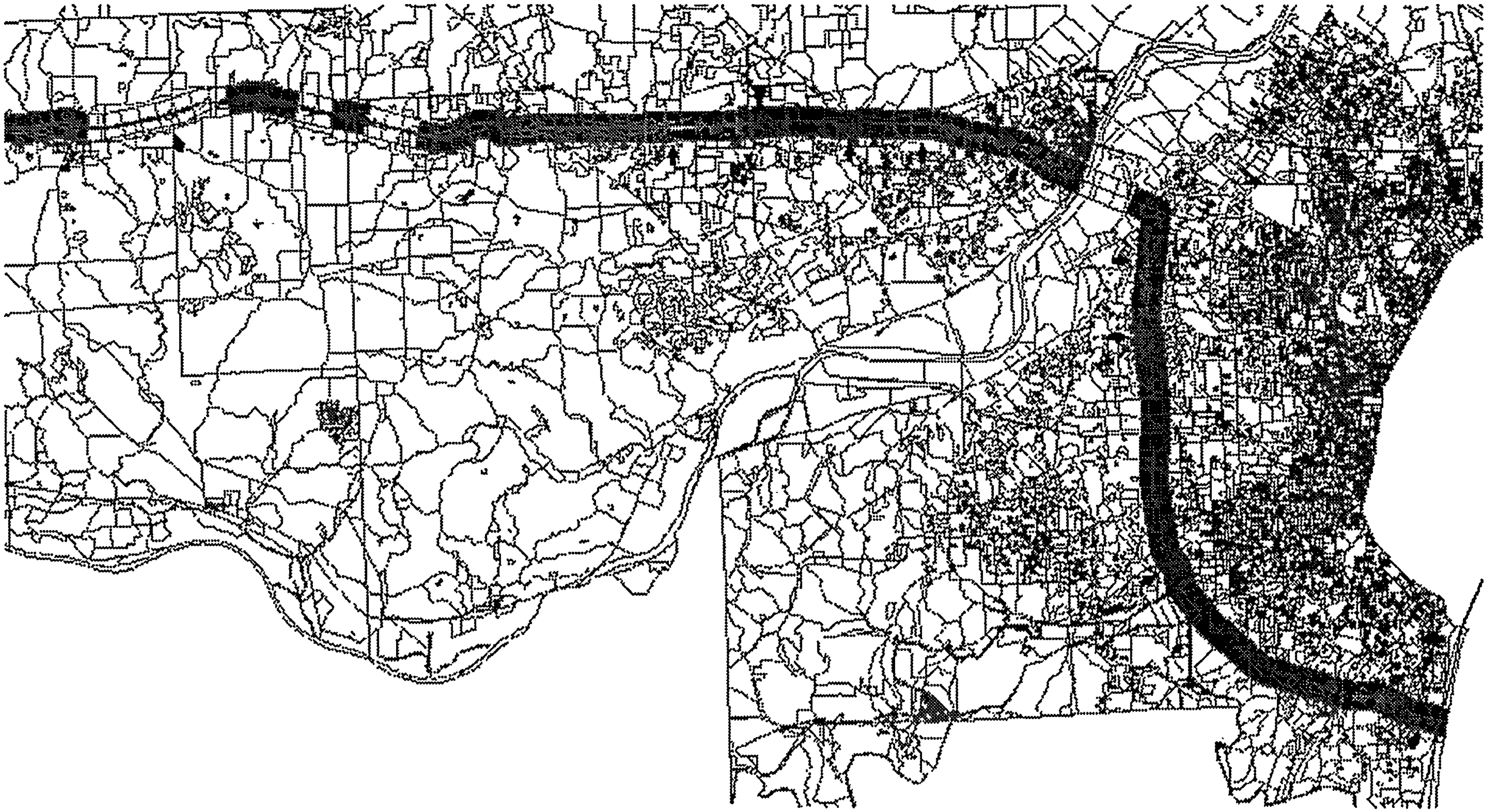

Figure 3 – Example of LINKS of Aggregated 1-km segments after Eliminating Isolated segments (Rural – white, Suburban – gray, Urban – black)