# 8.1 RELATIVE EFFECTS OF TERRAIN AND MORPHOLOGY COMPLEXITIES UPON VERY LOCAL AIRFLOW AND DIFFUSION

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## 1. INTRODUCTION

In order to improve the present application of meso-meteorological modeling to a variety of field application problems and everyday meteorology, a higher resolution, micro-meteorological analysis could provide a more local and relevant set of meteorological conditions which are directly affected by forested areas and adjacent built up areas. The intent is not to replace meso-scale analyses, but rather to augment and enhance the coarser analysis with finer details that reflect locally-influenced changes in flow fields as well as the behavior of aerosol dispersion. As a result of the increased resolution, i.e. 100m or 50m, the morphology of land features can now contribute to part of the underlying surface's interaction with the boundary layer of the atmosphere. For analyses with computational grids of 100m in x and y, morphological features such as vegetation, buildings, and simple surfaces can be more important than nominal changes in terrain elevation over the 100m grid.

The Army Research Laboratory's (USARL) high resolution wind model with canopy and building effects is applied to several non-homogeneous, terrain-morphology scenarios to simulate finer variations in the resultant local flow fields. Example solutions are given for complex terrain and again for the added effects due to the presence of morphological features upon these same flow fields. The wind fields are then prepared to drive a diffusion code to produce the downwind behavior of puffs and plumes on the same local scale.

The premise of this paper is to exhibit, by example, when: a.) surface morphology features dominate the flow field, b.) terrain dominates the flow field, and c.) modest effects of each interplay.

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## 2. MODELS

### 2.1 High Resolution Wind Model/Code

As described by Cionco (1985), HRW is a 2-dimensional, diagnostic, time independent model that simulates airflow over complex terrain including the effects of vegetation, buildings, and simple surfaces with a high computational resolution - such as 100 m (ranging from 40 to 400m) and for a very local area - such as 5 km x 5 km (2 km to 20 km on a side).

Originally, HRW was designed to be initialized by a network of surface-based meteorological stations. Then it was reconfigured to be driven by output from meso-meteorological models (Cionco, 1987). Having successfully done that, the model now also runs as a stand-alone type analysis code driven by field observations. As the stand-alone code, HRW is initialized with single values (nominally at 10 m agl) of wind speed, wind direction, temperature, pressure, and buoyancy (stability computed from an upper air sounding) derived from field observations or output from a coarser meso-scale model analysis. Digitized terrain elevation also is required at each grid point within the area as is digitized land morphology data sets of land feature height and type (Cionco and Ellefsen, 1998 and Ellefsen, 1985).

The model's output is composed of the u and v wind components, a vector field, potential temperature, friction velocity, Richardson Number, Power Law Exponent, and a partial component of the vertical motion (not always the total w component). Each parameter is calculated for the entire horizontal array and is tabulated and viewable with the appropriate graphics. A streamline field also can be calculated from the u and v components.

Physically, calculations are performed on an array of air parcels in a pressure field such that accelerations of these parcels are determined as they negotiate the changing slopes of the terrain and the added thermal lift or suppression component imparted by the buoyancy. Computations are for the array of cells as flux boxes defined by each four adjacent grid points and the under laying terrain-morphology surface. These calculations are completed in an iterative manner. Simulation values are obtained by direct variational relaxation of the wind field in the layer near the surface.

Numerically, the variational over-relaxation method is used to obtain a minimum of the combined acceleration forces in a pressure field. After the first iteration, the flow computations resolve changes of the field of accelerations over variable terrain with thermal lift and suppression effects. The solution is established when a minimum is reached in all of the computational cells (flux boxes) in the domain. The method of vector of steepest decent is used during the calculations to approach the minimum. The solution is reached when the internal constraints forces imposed by the warped terrain surface, thermal structure, and requirements for flow continuity are minimized.

The procedure makes use of Gauss' Principle of Least Constraints (Lanczos, 1962) that requires the forces to be minimized in order to satisfy the equations of motion. Mass is conserved during the calculations. Empirical wind and temperature vertical (structure) profiles are used also in the computational integration through the vertical thickness of the prescribed vertical layer.

Based upon previous research, airflow within and above vegetative canopies is also calculated in the extended version of HRW, called CCSL (Cionco, 1985). The analysis of the horizontal fields can be complemented by constructing vertical profiles of wind (Cionco, 1985) at each grid point as follows: a) within the canopy layer using the exponential relationship; b) within the surface roughness layer above ground or above vegetation and building layers using the log law; and c) the power law exponent and relationship to extend the surface layer profile upward to 50m and possibly up to 200m at each grid point in the array.

The effects of the presence of discrete canopy domains on the variable terrain contribute to producing finer variations in the wind field simulated by HRW. Recent additions of buildings and clusters of buildings also are included in the HRW/CCSL analyses along with effects of simple surfaces (Cionco, 1999). HRW has been validated (Cionco and Byers, 1995) using the MADONA Field Study database (Cionco et al, 1999).

### 2.2 Diffusion Model/Code

Most recently, HRW is used in tandem with a Gaussian Puff diffusion code where HRW's deformed, terrain-influenced and morphology-influenced wind fields drive the downwind diffusion of puffs and plumes modified by the interaction with the under laying complex terrain (Cionco et al, 1997) and morphology features (Cionco, 1999) such as canopies, buildings, and simple surfaces. A 'coupled' set of HRW and the Gaussian puff code simulations are presented to exhibit these effects.

RIMPUFF is the Gaussian Puff diffusion model/code by Mikkelsen (Thykier-Nielsen and Mikkelsen, 1993) that computes the downwind behavior of aerosol puffs and plumes in a deformed wind field such as is provided by HRW. The code also has a puff splitting feature to deal with plume bifurcation and flow divergence due to channeling, slope flow, and inversion effects in complex terrain. The code can be driven by a wind flow model or a network of micrometeorological data collection towers. Puff/plume diffusion processes are controlled by local turbulence levels, either provided directly from on-site measurements or provided from a pre-processor calculations code. RIMPUFF is further equipped with standard plume rise formulas, inversion and ground-based reflections, gamma dose algorithms, and wet/dry depletion. Plume meander is also a feature for solutions that represent more that one hour of downwind diffusion. The code outputs concentration and dosage values downwind from the release point. Multiple releases can be handled within one simulation case. At the moment, the deposition feature can be switched on or off.

## 3. SIMULATIONS FOR TERRAIN AND THEN MORPHOLOGY

The following conditions are used to initialize the wind and diffusion simulation cases. The initialization data sets contain meteorological observations, digitized terrain elevation, digitized morphology characteristics (types and heights), and arbitrary aerosol source data.

Digitized terrain elevation data of the 5Km x 5Km domain are extracted from the NIMA DTED Level

1 CD-ROM with a 100 m resolution. (See Figure 1). Digitized morphology land feature data are derived from previously developed data sets by Ellefsen (1998). USARL scientists digitized the final data set with the same 100m resolution as required by the airflow model.

Wind directions of north, east, south, west, southeast, and southwest for a wind speed of 2 m/s with unstable atmospheric conditions are the basis for these simulations. For the sake of brevity in this presentation, solutions of only southwest flow will be presented. The diffusion code is driven by the wind fields of HRW with 100m resolution. The source term is not known for these simulation cases, therefore, an arbitrary source term of 1000 kg with no heat generated during the release is prescribed. The plume concentrations, therefore, can be normalized to the input value in the calculations.

Two sets of simulations are presented for reference cases. The first set shows the high-resolution effects of terrain with minimum variability. The second set exhibits the combined effects upon the flow fields produced for morphology added to this minimal terrain.

**3.1 Terrain-only Simulations:**

Wind Fields: Using only the terrain elevation (Figure 1 with 2m contours) and the prescribed meteorological inputs, several solutions are prepared for an eastern US coastal area. By example, a vector field is given in Figure 2 to exhibit the change in speed over the domain. Unfortunately, minor changes in the vectors are not discernable at this scale so streamline flow plots will be used to depict the flow field. The resultant simulation of southwest flow, thus, is shown in Figure 3 as a lightly deformed directional field of long, sweeping streamline flow. The result is light terrain effects upon the flow field due to the minimal terrain profile.

Plume Behavior: The diffusion code is driven by the u and v components of the HRW vector field as shown in Figure 2. Figure 4 presents the growth of two plumes at 60 minutes from release time (over plotted onto the same gray-shaded terrain without the vector field shown). Moving from the smooth water surface, the south plume is responding to the slightly deformed wind field over the terrain area and then recovering over the downwind water surface. The north plume is turning more northerly being steered by the frictional effects of the somewhat higher terrain elevations. Plume concentrations (contours of 1000, 300, 100, 30, and 10 kg) decrease in a normal manner with little loss to the terrain effects.

**3.2 Morphology-dominated Simulations:**

The second set of simulations require the construct of a digitized morphology data base to interpret the existing morphology as exhibited by this color-enhanced version of a high altitude image (Figure 5) for the simulation domain. The methodology established by Ellefsen (1985) is adapted using the Urban Terrain Zones (16 categories) and a finer set of characteristics and attributes (21 types) (Cionco and Ellefsen, 1998). The resultant data set per hectare (100m x 100m) resides in an EXCEL spreadsheet. The digitized morphology data is plotted as contoured data for 100m resolution in Figure 6 without terrain elevation being included. The combined terrain and morphology features are shown in Figure 6. This is the data set used for the following simulations

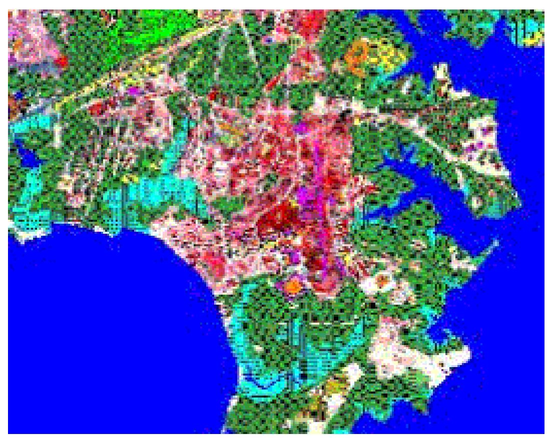

Figure 5. Aerial image of the simulation domain of Figure 1 depicting the morphological features

Wind Fields: All of the wind direction and speed combinations are prepared, but not all are shown here. The southwest flow simulation is given in Figure 7 over plotted with combined terrain and morphology features for comparison to the terrain-only influenced wind field of Figure 3. To better view the moderately deformed streamline field, Figure 8 is presented over plotted on to terrain only for clarity. This plot more clearly exhibits the greater influence of the added morphology upon the same initial flow field. There are few long, sweeping streamlines over land due to the interaction of the morphology features. There are notable differences for Figure 3 and Figure 8 directly attributable to the inclusion of morphology into the simulation process.

Plume Behavior: The resultant diffusion simulations prove to be as interesting as the morphology-influenced wind fields. Sixty (60) minutes after the start of the release, both plumes in Figure 9 exhibit significant differences in their downwind behavior versus the terrain-only simulations of Figure 4. The north site plume width expands, constricts, and expands again as the underlying morphology allows accelerations and decelerations to modify the otherwise smooth transport shown in Figure 4. The south site plume's transport and diffusion differs greatly from the terrain-only behavior of Figure 4. The south site plume not only expands and constricts, but it also develops a secondary and tertiary maximum of concentrations that do not occur for the terrain-only dispersion behavior. The patchwork of alternating low morphology and tall trees (up to 25m) is causing accelerations and decelerations to influence pooling of higher concentrations especially in the vicinity of the forest clearing. The notable differences in these diffusion fields in comparison to the previous simulations are in direct response to the wind field's interaction with the morphological features.

## 4. TERRAIN DOMINATED SIMULATIONS

Additional simulations are run to display aerosol (smoke) plume behavior under stable, nighttime conditions in a complex river valley with farmed, forested and urbanized terrain. These examples relate to field operations extending into the evening hours. The geographic location of these simulations is the middle section of a German River valley. Figure 10 locates the discrete areas of forested land, crop lands/vineyards, buildings/villages, and the serpentine path of the river as it flows northward. The patchwork areas of morphology are color-coded for crop and grass lands as yellow, river channel as light blue, buildings/villages as red, and forests as green. The steep valley walls have a nominal relief of 170m in relation to the level of the river (100m).

Figure 11 presents the vector field and the downwind behavior of smoke plumes from two widely-separated vegetation-covered sites over plotted onto contoured terrain (white lines) and morphology (same as Figure 10). Initialized with a southwest ($225^0$) wind of 2 m/s during the stable evening hours, HRW simulates a modestly deformed wind vector field exhibiting some down slope accelerations from higher terrain into the river valley and some channeling along the downwind valley walls. Note that a wind of 2 m/s is not drainage flow and is capable of flowing over the terrain features and not being totally captured in the lowest elevations. Both plumes, therefore, flow downward into the river channel and then outward and beyond. For each plume the heaviest concentrations of aerosols remain within the river valley and the lesser concentrations escape the valley. Figure 12 is an enlargement of the south site plume that displays the plume behavior and the vector field within the river valley in the vicinity of villages. The finger ridge feature prolongs a channeling effect on the very local wind field such that the heaviest concentrations remain in the valley while the lighter concentrations transport onward and over the finger ridge area. The effects of morphology upon the flow field are minimal.

For a second scenario, flow from the northwest ($315^0$) also at 2 m/s during stable evening conditions shown in Figure 13 produced plume dispersion with similar behavior. After sixty minutes of continuous release generated from two adjacent, open burning sites, the plumes combine to result in a complex pattern of 'smoke' concentration behavior. As was the situation of Figure 11, the heaviest concentrations occur in the river valley close to the sources. The combined plumes flow over the 'loop' of land and downwind into the valley's river channel again. As the plume flows up slope to leave the southeast valley wall, aerosol concentrations (shown as smoke) increase in the locally slower up slope flow field. During the next hour, the aerosol plume continues to accumulate on the far valley wall and encroaches on the adjacent village causing an air quality and health problem. Clearly, the terrain configuration is dominating the flow field with little or no contribution by the morphology features.

## 5. BALANCED TERRAIN AND MORPHOLOGY CONTRIBUTIONS

A third scenario of modest terrain and a built-up area of low structures, mixed vegetation and simple surfaces suggests a situation where both surfaces contribute in a more equal manner. Micro-scale wind fields were simulated for an area along a shoreline section of a large west coast bay. Figure 14 depicts the terrain-only scenario where uniform flow off the bay (gray) is disturbed by terrain features (green) most notably about a hill in the northeast area and into a canyon for this 3km)$^2$ area. Adding morphological features to the terrain, results in a wind field with greater interactions and deformation. Figure 15 shows the bay (white), buildings (red), trees (green), grass (yellow), and impervious surfaces (asphalt, cement, etc) and how much more the vector field is modified versus the terrain-only scenario. Closer inspection of each simulation is provided in Figures 16 and 17 for the same 1km x 1km area extracted from Figures 14 and 15. Figure 16 shows smooth westerly flow up to where the canyon channels the wind southeasterly. Figure 17 depicts how the flow is modified by the interaction with the morphology features in terms of speed and direction before it reaches the terrain the canyon area where the terrain effects take over. On this neighborhood scale of motion, both effects co-exist within this very local domain.

## 6. SUMMARY

The resultant wind fields show that there can be notable differences between the terrain-morphology influenced simulations versus the terrain-only influenced wind fields. These differences, of course, are seen also in the resultant diffusion analyses. There are also conditions on the local scale where terrain effects upon the flow filed dominate and, therefore, minimize morphology contributions. When contributions tend to be more equal, one must sort out which feature(s) is modifying the flow field , as well as the diffusion behavior, on a very local basis such as within an area of 1Km x 1Km. Several cases show in a qualitative manner where these effects can occur.

These simulation methods can be used for several common, re-occurring meteorological and diffusion applications. Some of these applications are: (1) agricultural meteorology including aerial spray operations; downwind diffusion of agricultural sources; (2) forest meteorology and diffusion and fire weather/wildfire operations; (3) urban neighborhood scale airflow and dispersion; (4) HAZMAT emergency response system for dispersion problems; (5) training personnel on behavior of wind and aerosol plumes in complex terrain and within and above vegetative and urban canopies; (6) preliminary simulations to design field studies; (7) placement of sensors and detectors in the field; (8) monitoring and forecasting for the environments of fixed installations; (9) for ground-based operations and the behavior of the transport and diffusion for the defense against WMD, smoke, and obscurants materials; (10) research modeling and laboratory studies and more.

Follow-on research now includes the 'coupling' of this high resolution micro-scale simulation capability to our meso-scale analysis capability as reported by Cionco and Luces during concurrent sessions of Urban Environment Symposium (paper 16.3).

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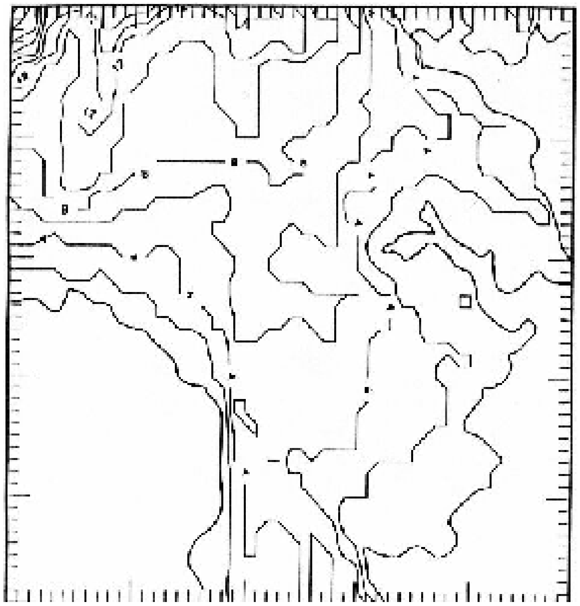

Figure 1. Contoured map of terrain elevation with 2m increments for a low elevation peninsula for a domain size of 5Km x 5Km

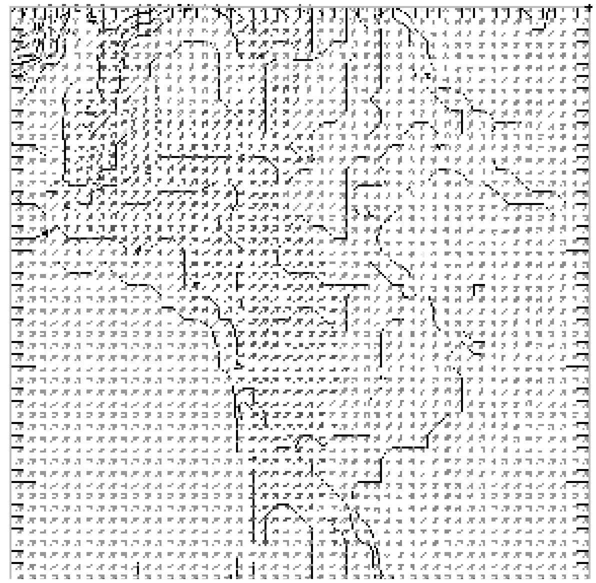

Figure 2. Simulated vector field initialized for SW flow at 2m/s during unstable conditions

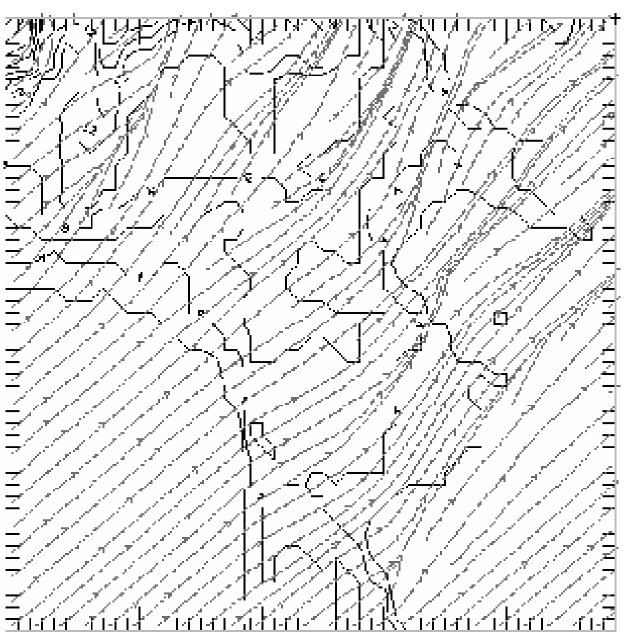

Figure 3. Streamline analysis initialized for SW flow at 2m/s during unstable conditions

Figure 4. Diffusion simulation 60 minutes after release time driven by HRW vector field of Figure 2. Terrain is shaded in gray tones

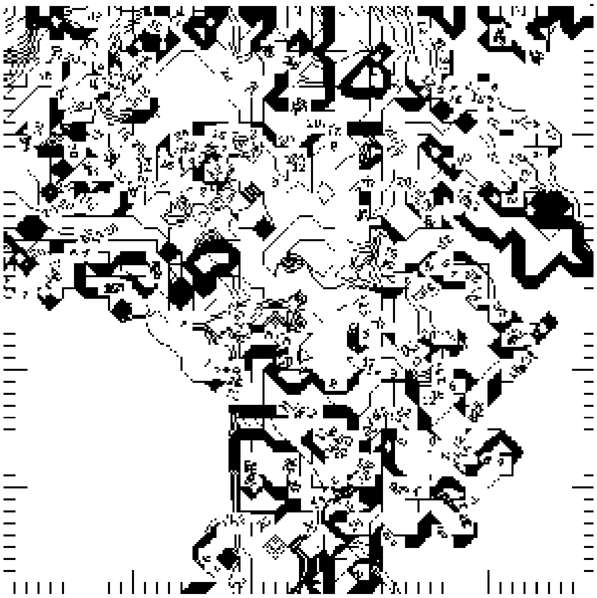

Figure 6. Contour map of combined terrain elevation and morphology features (1m contours)

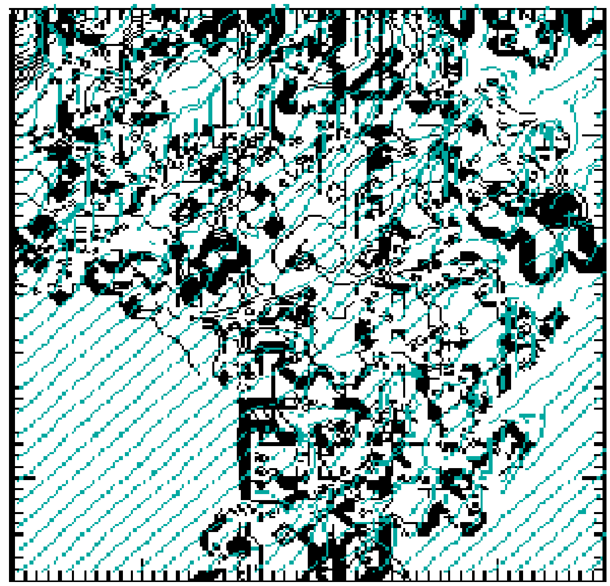

Figure 7. Streamline analysis with morphology and terrain effects for SW flow at 2m/s, unstable

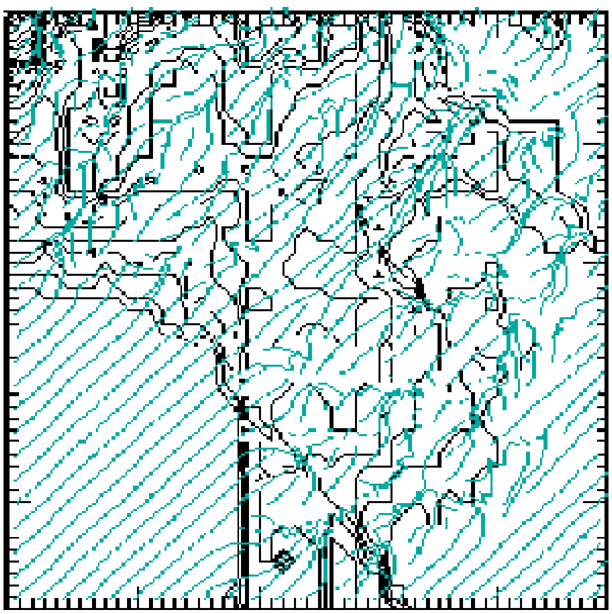

Figure 8. Same solution as Figure 7 with only terrain over plotted to better exhibit the detailed flow

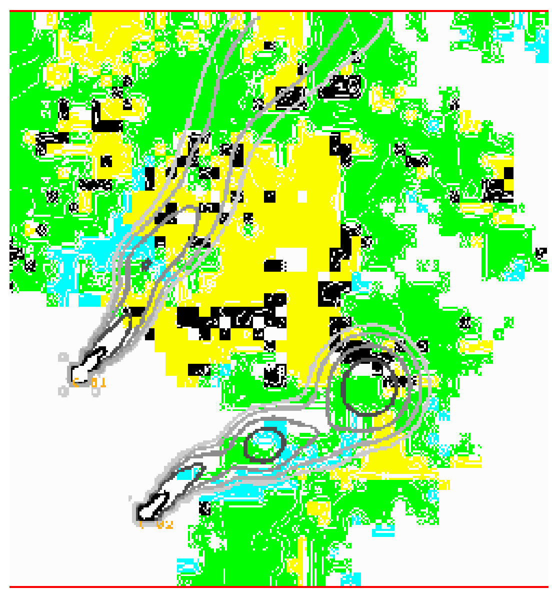

Figure 9. Diffusion simulation 60 minutes after release time influenced by terrain + morphology (Figure 7)

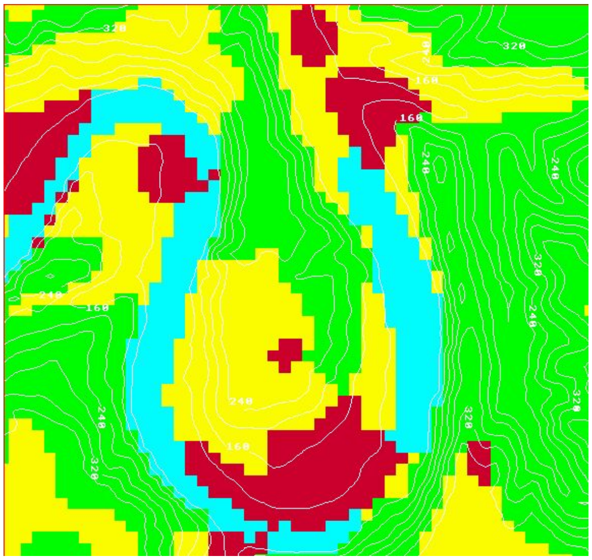

Figure 10. Complex River valley domain with discrete areas of crop and grass lands (yellow), buildings/villages (red), forests (green), and river (light blue)

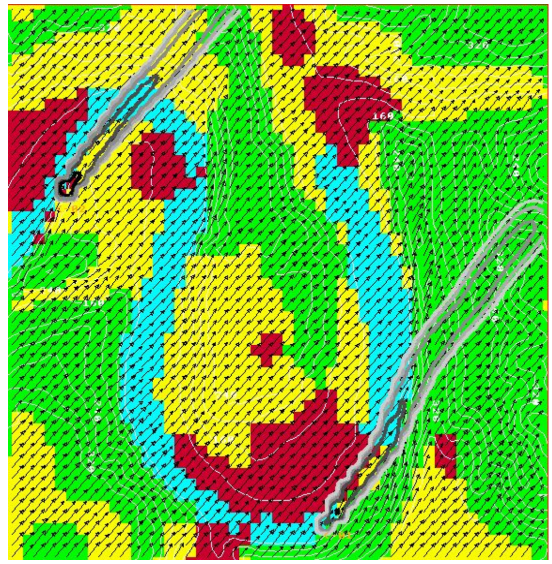

Figure 11. Simulated vector field and two widely-spaced plumes with heaviest concentrations remaining in the river valley during stable evening hours

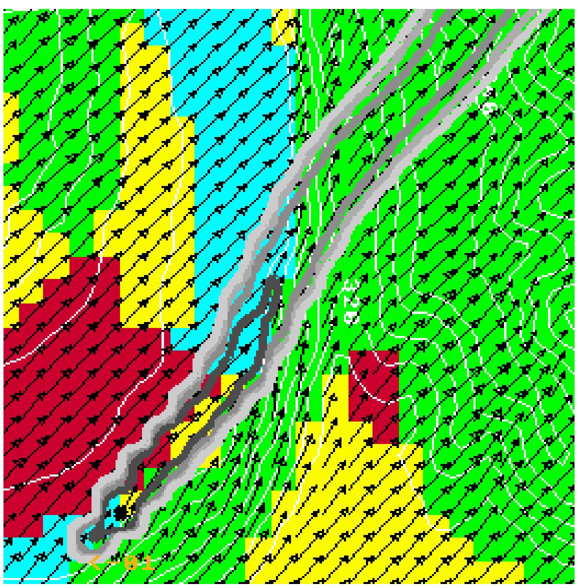

Figure 12. Enlargement of south site plume of Figure 11 to show channeling along the valley wall and higher concentrations remaining in the River valley

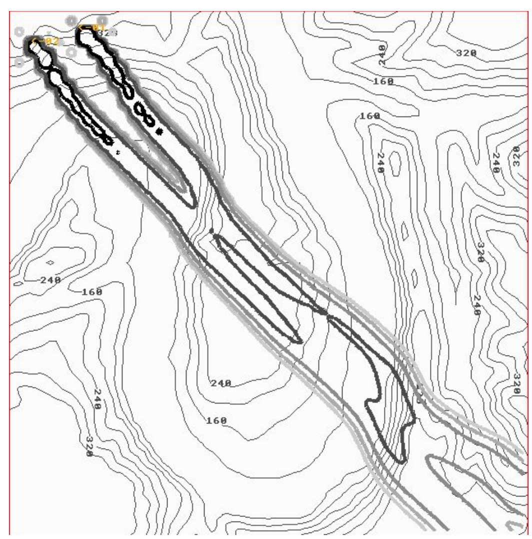

Figure 13. Two adjacent plumes being dispersed, in a northwesterly flow field, into the valley, combining and then collecting at the southeast wall

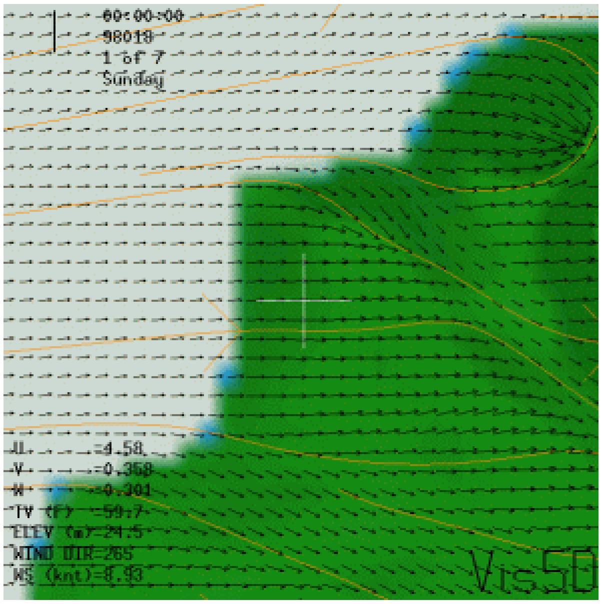


Figure 14. Domain of 3Km x 3Km of terrain with the relatively smooth vector field: Terrain contours not shown, but there is a hill in the NE corner and a canyon just east of center point (white cross) running diagonally to the SE.

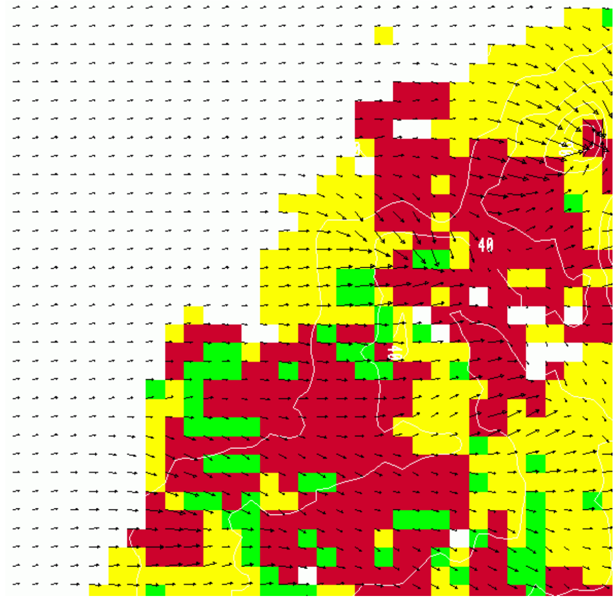


Figure 15. Same 3Km x 3Km domain with morphology features included. The vector field exhibits more deformation through the interaction with the morphology features

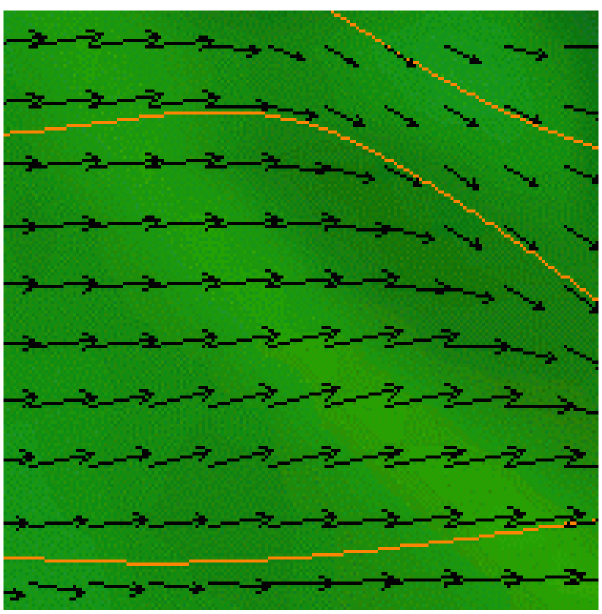

Figure 16. Domain of 1Km x 1Km extracted from Figure 14 above with vector and streamline fields (orange). Note that the otherwise smooth flow is diverted into the canyon showing only terrain effects

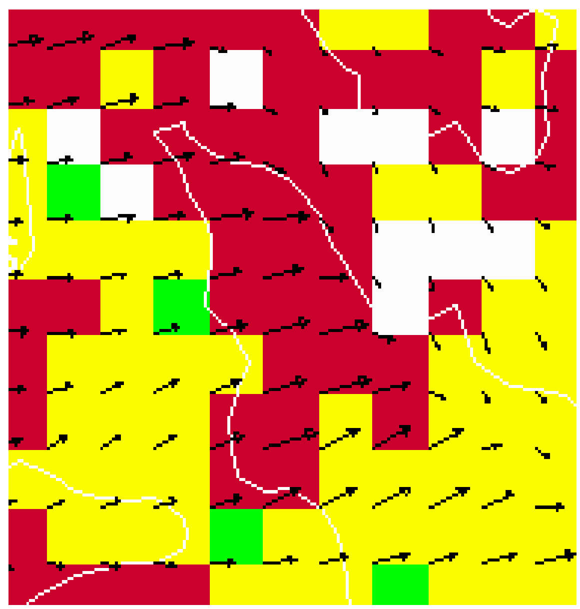

Figure 17. Same1Km x 1Km domain extracted from Figure 15 above with the vector field and terrain contours (white lines). The vector field is more variable in speed and direction about the features before it turns SE into the canyon