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NATIONAL COUNCIL FOR AIR AND STREAM IMPROVEMENT

STREAM MODEL ASSESSMENT WITH AGDRIFT

TECHNICAL BULLETIN NO. 808
JUNE 2000

by

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Acknowledgments

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National Council for Air and Stream Improvement, Inc. (NCASI). 2000. *Stream model assessment with AgDRIFT*. Technical Bulletin No. 808. Research Triangle Park, NC: National Council for Air and Stream Improvement, Inc.

PRESIDENT'S NOTE

Within the past ten years, the usefulness of computer models for predicting the dispersal of aerially released agricultural spray materials has been refined and enhanced, enabling the successful use of models in place of field studies. In fact, the U.S. Environmental Protection Agency (EPA) has been working with the Spray Drift Task Force (SDTF) (a consortium of chemical manufacturers), to develop and validate such a drift prediction model. The SDTF has conducted field and laboratory studies to validate this model, which they have named AgDRIFT®, as a replacement for future drift studies.

Before spray drift models were developed, assessments for potential concentrations in streams adjacent to spray areas had to assume the spray unit application rate was being applied to the stream. Drift models allowed more realistic estimates of deposition in streams, providing a tool to assess alternative drift control strategies. But even these improvements did not address pesticide deposition at the stream over time, interception by riparian vegetation, in-stream breakdown, or dilution from groundwater and surface water inflow/exchange.

NCASI has exploited a unique opportunity to add a stream assessment calculation that considers these processes to the toolbox capability in AgDRIFT®. This report summarizes the use of this feature, and demonstrates how a simple model may actually provide an excellent first step in the analysis of stream concentration behavior after loading from a nearby aerial application. This feature greatly increases the potential utility of AgDRIFT® in forestry applications.

Ronald A. Yeske

June 2000

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ABSTRACT

From 1992 to 1995, the Spray Drift Task Force, a consortium of 38 chemical companies manufacturing pesticides in the United States, in response to a directive from the U.S. Environmental Protection Agency, conducted a series of field and laboratory studies that provided the evaluation basis for an aerial application prediction model called AgDRIFT®. This model is anticipated to become a regulatory tool for registration and support for the use of agricultural chemicals in the United States. As a part of the development cycle of AgDRIFT®, NCASI was given the opportunity to add a Stream Assessment algorithm to the toolbox capability of the model. This report summarizes the development and validation of the resulting Stream Assessment algorithm that has been programmed into AgDRIFT®, and its relationship with other available assessment tools.

KEYWORDS

aerial application, buffer, drift, forest practices, herbicides, pesticides, stream modeling, water quality

RELATED NCASI PUBLICATIONS

Special Report (In print). *State restrictions and initiatives to restrict the use of silvicultural chemicals: what we know and need to know*.

Technical Bulletin No. 672 (July 1994). *Forests as nonpoint sources of pollution, and effectiveness of best management practices*.

Technical Bulletin No. 631 (June 1992). *The effectiveness of buffer strips for ameliorating off-site transport of sediment, nutrients, and pesticides from forest operations*.

Technical Bulletin No. 480 (January 1986). *Forest management related subjects on air quality and forest health, solid waste disposal on forest land and gypsy moth control*.

Technical bulletin No. 430 (April 1984). *A guide to monitoring streamwater quality following forest herbicide application*.

Special Report No. 84-03 (April 1984). *A study of trace-enrichment cartridges for use in sample collection and analysis of silvicultural herbicides*.

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1.0 INTRODUCTION

Over the last 25 years, several government agencies (including the National Aeronautics and Space Administration, USDA Forest Service, and the U.S. Army) have been pursuing the development of computer codes to predict the deposition distribution of aerially-released spray material. The two current codes available are AGDISP (Bilanin et al. 1989) and FSCBG (Teske et al. 1993). From 1992 to 1995, the Spray Drift Task Force (SDTF), a consortium of 38 chemical companies manufacturing pesticides in the United States, in response to a directive from the U.S. Environmental Protection Agency (EPA), conducted a series of field and laboratory studies (Johnson 1995; Hewitt 1995a, 1995b; Riley et al. 1995; Hermansky et al. 1997) that provided the evaluation basis for AgDRIFT® (Teske et al. 1999), a Microsoft® Windows™-based version of AGDISP. That evaluation was recently completed (Bird et al. 1997) and presented to a Scientific Advisory Panel of the EPA, as the latest step toward making the model a regulatory tool for registration and support for the use of agricultural chemicals in the United States.

In the application issues dealt with by the SDTF, only ground and pond/wetland aquatic assessment tools were developed for AgDRIFT®. Because NCASI has a keen interest in the application of the model to evaluate control options for stream impact from aerially-released spray material as well, it seemed appropriate to extend AgDRIFT® to do just that. An agreement with the SDTF (which included the initial development of the Nozzle Position screen in Tier III) permitted this extension, discussed in this report.

2.0 MODEL PLATFORM

The intention of this effort was to extend the toolbox features in AgDRIFT® to include Stream Assessment. Before proceeding to a discussion of the stream model and its implementation, a brief review of the AgDRIFT® model and its user interface is in order.

2.1 Model Overview

AgDRIFT® is a model that predicts the motion of spray material released from aircraft, including the mean position of the material and the position variance about the mean as a result of turbulent fluctuations. It is based on a Lagrangian approach to the solution of the equations of motion, and includes simplified models for the effects of aircraft wake and aircraft-generated and ambient turbulence. The model tracks the motion of a group of similar-sized particles or droplets released into the atmosphere from specified nozzle locations. Similar-sized droplets are combined into a droplet size distribution to generate the spray droplet cloud. The novel feature developed here is that the dispersion resulting from turbulent fluid fluctuations is quantitatively computed as the group of droplets descends toward the ground. The accuracy of the dispersion calculation is related to a specification of the atmospheric turbulent fluid fluctuations through which the droplets pass, and the local fluid velocities in the vicinity of the aircraft releasing the spray material. Accurate modeling of the entire spray process permits replication of actual spray behavior leading toward ground deposition.

Reed (1953) first developed the equations of motion for spray material released from nozzles on an aircraft. His insight was the realization that the wing tip vortices played a significant role in the subsequent behavior of the released spray close to the aircraft. Other researchers expanded on his work to produce more detailed models of the problem (Williamson and Threadgill 1974; Trayford and Welch 1977; Atias and Weihs 1984; Bragg 1986). The original AGDISP model built upon these studies but included the innovative step of developing ensemble averaged turbulence equations to predict the growth of the spray cloud during the calculations (Bilanin and Teske 1984). AgDRIFT® evolved from AGDISP.

The near-wake model is described by a Lagrangian formulation of the equations of motion. Here, equations are written for the position of the droplet in the aircraft wake, one equation for each of the three coordinate directions, and for the corresponding velocity of the droplet, one equation for each of the three coordinate directions as well. Dispersion of the spray droplet cloud is computed by equations for the growth of the spread of the cloud, the correlation of the growth of the cloud with the velocity of the cloud, and the correlation of the velocity of the cloud with itself. Finally, equations are developed for the correlation of the growth of the spread of the cloud with ambient velocity in the aircraft wake, and the correlation of the velocity of the cloud with ambient velocity.

The model equations may be summarized in the form

$$\frac{d^2 X_i}{dt^2} = [U_i - V_i]\left[\frac{1}{\tau_p}\right] + g_i \qquad (1)$$

$$\frac{dX_i}{dt} = V_i \qquad (2)$$

$$\frac{d}{dt}\langle x_i x_i \rangle = 2\langle x_i v_i \rangle \qquad (3)$$

$$\frac{d}{dt}\langle x_i v_i \rangle = \left[\langle x_i u_i \rangle - \langle x_i v_i \rangle\right]\left[\frac{1}{\tau_p}\right] + \langle v_i v_i \rangle \qquad (4)$$

$$\frac{d}{dt}\langle v_i v_i \rangle = 2\left[\langle u_i v_i \rangle - \langle v_i v_i \rangle\right]\left[\frac{1}{\tau_p}\right] \qquad (5)$$

$$\langle x_i u_i \rangle = \frac{q^2}{3}\left[-\tau_p K + \frac{\tau_t}{2}\right] \qquad (6)$$

$$\langle u_i v_i \rangle = \frac{q^2}{3} K \qquad (7)$$

where X_i, V_i, and U_i are the ensemble-averaged i<u>th</u> components of droplet position, droplet velocity, and local fluid velocity, respectively. The fluctuating i<u>th</u> components of droplet position, droplet velocity, and local fluid velocity are x_i, v_i, and u_i, respectively, $g_i = (0,0,-g)$ is gravity, and t is time. The mean square turbulence level is $q^2 = \langle u_i u_i \rangle + \langle v_i v_i \rangle + \langle w_i w_i \rangle$. K is a function of the mean relaxation time τ_p (the time for V_i to approach U_i) and the turbulent travel time τ_t (the time for released spray material to pass through a typical eddy). Brackets ⟨ ⟩ indicate turbulent correlation.

Equations 1 and 2 describe the mean flight path of a droplet, its position and velocity, respectively, and track the droplet to the ground; while Equations 3 to 5 describe the spread of the droplet cloud, its correlation with cloud velocity, and cloud velocity correlation with itself; and Equations 6 and 7 describe the needed spread and velocity correlations with ambient velocity. Equations 3 to 7 are employed to determine the resulting spatial distribution of the droplet cloud on the ground. The

Lagrangian approach assumes a neutrally buoyant background, and the above equations can be solved exactly if a small enough time size is used.

The calculation of U_i near the aircraft is based on models described in Bilanin et al. (1989). For example, the aircraft wake flow field is controlled by a pair of counter-rotating vortices, which are described for a fixed-wing aircraft with an elliptically loaded wing as

$$\Gamma = \frac{2}{\pi} \frac{W}{\rho_a s U_\infty} \qquad (8)$$

where W is aircraft weight, U_∞ is aircraft flight speed, s is aircraft semispan, ρ_a is air density, and Γ is circulation strength. The vortices are located on either side of the aircraft at a distance $\pi s/4$ from the center of the aircraft.

AgDRIFT® enhancements to AGDISP include a significant solution speed increase, an in-memory computation of deposition and flux as the solution proceeds (eliminating the need for intermediate disk storage in data files), increased number of droplet categories, deposition smoothing, improved evaporation parameterization for small droplets, and extensive validation. Details on these and other issues involving the model may be found in the AgDRIFT® user manual (Teske et al. 1999).

2.2 Tier Development Philosophy

AgDRIFT® code calculations and graphical output are brought together in the personal computer Microsoft® Windows™ environment through a user interface developed in Microsoft® Visual Basic™ and scientific programming in Microsoft® FORTRAN. While a variety of approaches could be used to estimate the environmental exposure from off-target drift during the application of agricultural pesticides, in AgDRIFT® a sequential or tiered approach is used. Specifically, a three-tiered approach facilitates an efficient analysis centering on the use of general labeling instructions that maximize the amount of pesticide that remains on target, while allowing flexibility for evaluating those products requiring more or less restrictive application conditions. The results of each assessment tier include an estimate of off-target deposition as a function of distance from the application zone (in all three tiers), and vertical flux profiles, air concentration, and application variability and efficiency (in the higher tiers). All three tiers are based on the mechanistic model discussed above, and are empirically confirmed by comparisons with field data.

The Tier I aerial analysis is entered via the spray quality or atomization spectrum of the nozzle emission (the primary controlling variable for off-target drift). In Tier I the user can evaluate the upper limit of exposure and the effect of buffer zones assuming the generic labeling condition for the spray application. If spray quality and equipment usage to achieve this quality are specified on the label as well, the user can perform this analysis using the curve appropriate for that spray category rather than the default, which is likely to produce a higher drift assumption. If the estimated environmental exposure in Tier I, coupled with the product toxicity for the organisms of concern, provides an adequate safety margin with the indicated buffer zone, then no additional analysis would be required unless the applicant wishes to loosen the generic label language restriction or reduce buffer zone requirements.

Tier II aerial analysis provides the mechanism to evaluate the effects on off-target drift of the most significant application and environmental variables. The specific variables that the user can evaluate in Tier II include atomization spectra, wind speed, application area, temperature, relative humidity, aircraft class and speed, nonvolatile fraction, formulation properties, boom length, and release height above the canopy.

Tier III provides the analyst access to all aerial input variables and additional control of the variable limits. Generally, it is to be used to evaluate crop-, site-, formulation-, and equipment-specific applications. Likely uses for this tier include incident investigation, new application methods, special equipment specification, and unique site restrictions.

Each of the three sequential assessment tiers requires increasing knowledge of application techniques and environmental factors that influence the potential for a pesticide to move off the target area. Tier I is based on a set of standard "Good Application Practices" and requires little knowledge of actual application conditions or the product's properties. These variables are preset in the model to represent the upper limits expected during an application. Tier II requires an increased knowledge of the application equipment, environment, site, and product. The user can change many of the model variables within fixed, preset limits. Tier III modeling provides the free access to all model variables and assumes the user is an application specialist with a thorough understanding of the atmospheric transport of small particles.

2.3 User Interface

Operation of the model is discussed in detail in the AgDRIFT® user manual (Teske et al. 1999). Its Tier I, Tier II, and Tier III screens (Figures 1, 2, and 3, respectively) illustrate the increasing flexibility available to the user with regard to model inputs. The user may choose to examine the problem simply, or add additional complexity with additional input entries, all the way to complete specification of the spray problem at Tier III. In Tier III the user may specify the droplet size distribution, spray material details, meteorology, aircraft, nozzle locations and boom height, number of flight lines, swath width, swath displacement, and surface roughness. Advanced Settings permits access to all modeling "constants" used in the solution of the Lagrangian equations of motion. Overall, the code is fairly general and easy to use. A typical default result for a single flight line is shown in Figure 3.3.

The power of AgDRIFT® is in its toolbox menu bar option (near the top of Figures 1, 2, or 3: "File Edit View Run Toolbox Help"), which in previous versions of the model included the following:

- Aquatic Assessment (specifying a water body width and depth downwind of the spray block, and a desired distance to the water body from the edge of the field, recovers the initial average deposition and concentration in the defined pond or wetland)
- Dispersion Distance (entry of a distance downwind of the spray block recovers the deposition at that point, and vice versa)
- Drop Distance (entry of a droplet size and release height recovers the evaporated size of the droplet on the ground and the distance and time it traveled)
- In-Swath Statistics (entry of a parameter measuring the uniformity of the spray block deposition recovers the effective swath width between flight lines and the mean deposition)
- Spray Block Assessment (selecting the deposition pattern and a desired deposition level recovers the distance to this deposition level as a function of spray block width)
- Multiple Application Assessment (selecting a series of parameters to define a spray block, sprayed a multiple number of times per year and number of years, recovers the average expected deposition pattern, accounting for wind speed and direction effects at the site)

The NCASI extension enables a new toolbox option, that of Stream Assessment.

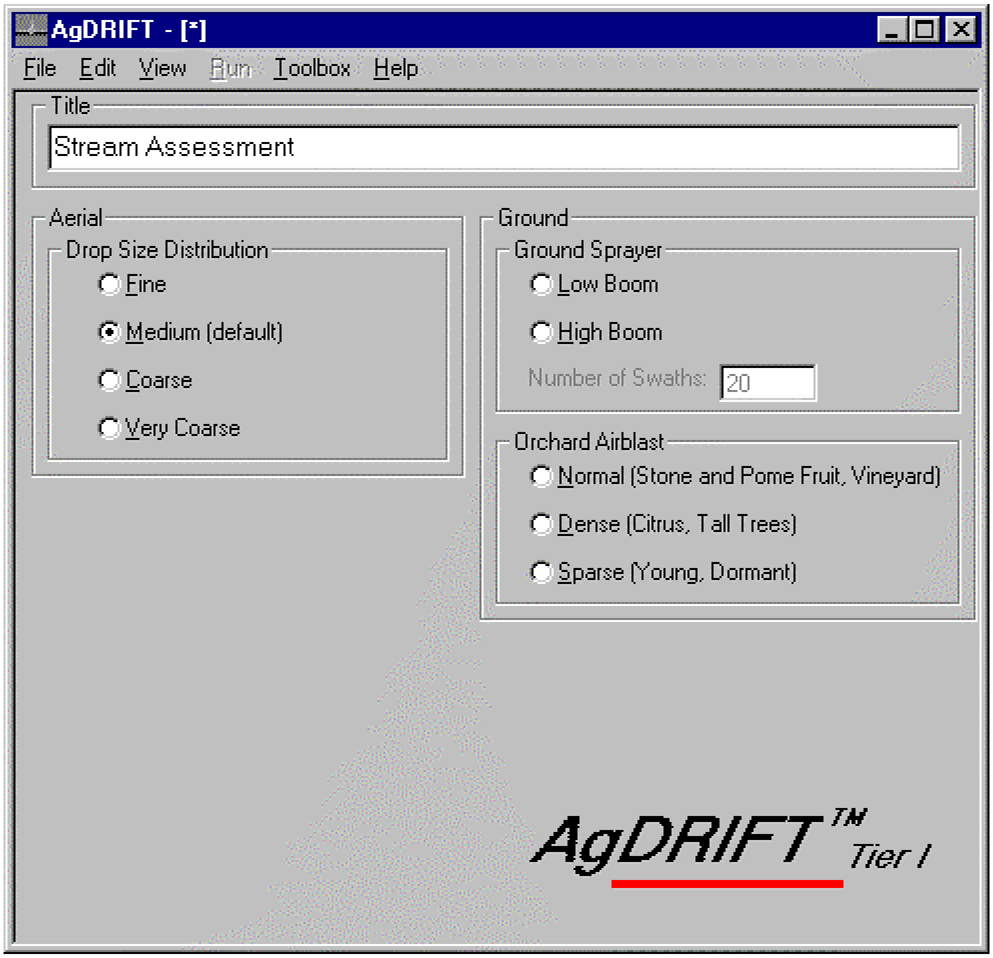

Figure 2.1. The Tier I Input Screen to AgDRIFT®, Illustrating the Simple Model Input Possibilities.

3.0 STREAM ASSESSMENT EXTENSION

Before spray drift models were developed, assessments about the potential concentration in an adjacent stream had to assume that the spray unit application rate was being deposited on the stream surface. This "worst case" assessment approach is described in Newton and Norgren (1977), where C is the concentration in a stream in µg/L, A is the active ingredient application rate in lbm/acre and d is the stream depth in feet: $C = 368\ (A/d)$. The development of spray drift models like AGDISP and FSCBG allowed more realistic estimates of the spray drift reaching streams adjacent to spray units, but these models still required the acceptance of several "worst case" assumptions. These assumptions include: all the drift material reaches the stream at the same time; the stream is not flowing; there is no interception by riparian vegetation; there is no in-stream breakdown or sorption on the stream channel; and there is no dilution from inflow or exchange of ground and surface water. Clearly, many of these assumptions are not true, especially for small streams.

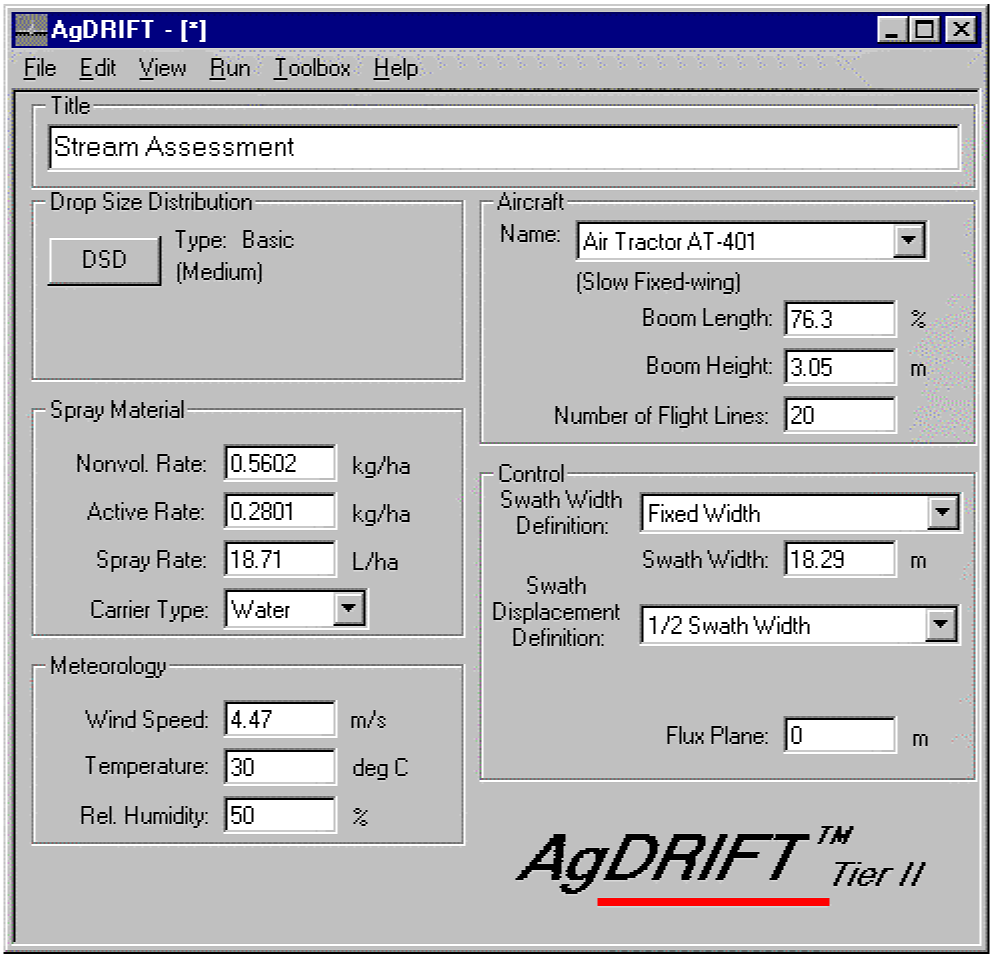

Figure 3.1. The Tier II Input Screen to AgDRIFT®, Illustrating More Model Input Possibilities.

The Stream Assessment toolbox option in AgDRIFT® seeks to better represent the spray conditions at the stream and permit movement away from the "worst case" assessment approach. To do so requires the development of a relatively straightforward model for stream assessment, one that will not be computationally burdensome to the personal computer, and yet recover reasonable (and conservative) estimates of stream diffusion. Since AgDRIFT® itself requires the identification of all needed spraying parameters for its computation of downwind deposition, we need only direct our attention to the development of the stream assessment model itself , and wrap its operation within a user interface screen consistent with the other toolbox options available in AgDRIFT®.

3.1 Model Development

For the model we solve a one-dimensional, unsteady advection-diffusion equation of the form

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = D\frac{\partial^2 C}{\partial x^2} - nC \qquad (9)$$

where C is concentration, t is time, U is the average stream flow speed, x is distance downstream, D is the diffusion coefficient, and n is the fractional rate of diffused material removed from the stream by means other than diffusion. This equation is a generalization of the standard dispersion equation written for this problem (Fischer et al. 1979). Real streams may have numerous irregularities that contribute to dispersion (bends, sandbars, side eddies, pools, etc.), but the assumption here is that an approximate one-dimensional analysis is a reasonable approach to take.

In addition, Fischer has shown that the transverse variation of velocity across the width of the stream is more strongly responsible for streamwise diffusion than the vertical variation of velocity across the depth of the stream. His diffusion coefficient (Fischer et al. 1979) may be interpreted here as

$$D = \frac{0.11Uw^2}{d} \qquad (10)$$

where w is the average stream width and d is the average stream depth. The stream is assumed to flow parallel to the flight lines of the aircraft (at least for the initial loading of the stream), and be located at a distance Y downwind of the farthest downwind flight line. Infinite diffusion rate is assumed to occur across the assumed rectangular cross-section of the stream when recovering the initial concentration.

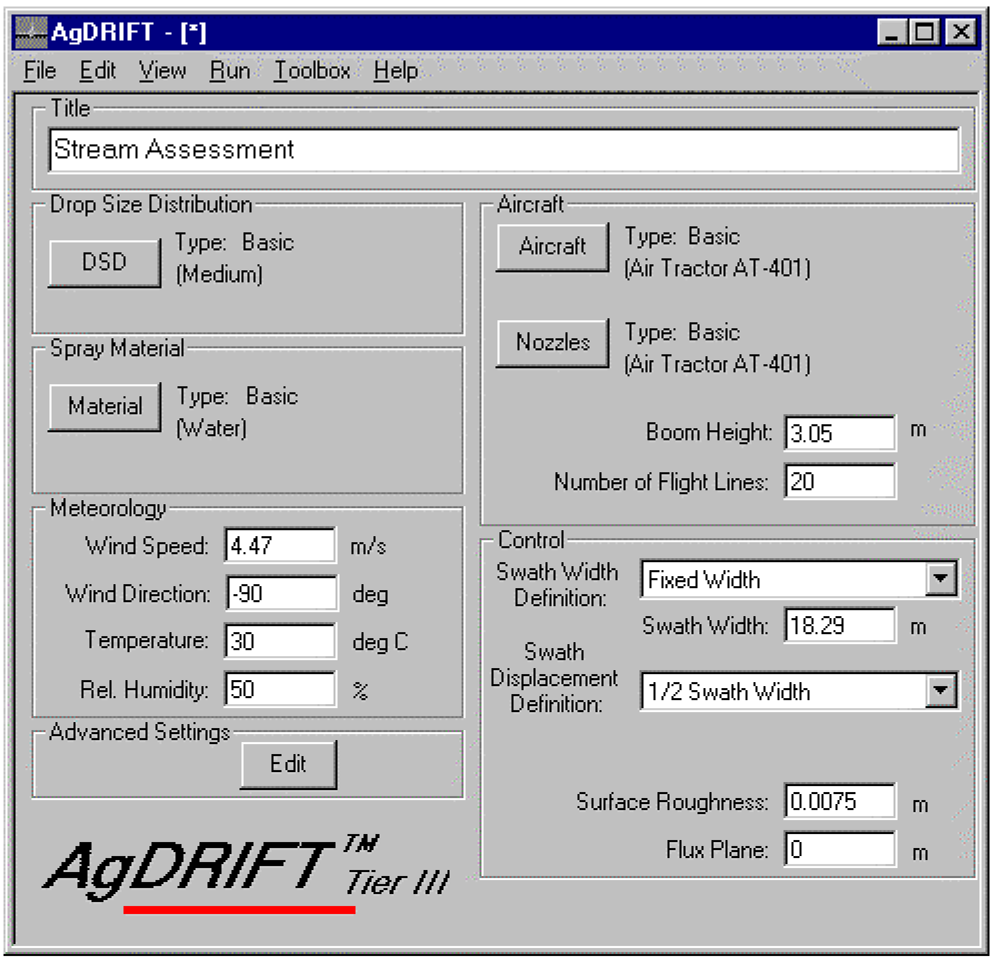

Figure 3.2. The Tier III Input Screen to AgDRIFT®, Illustrating All Model Input Possibilities.

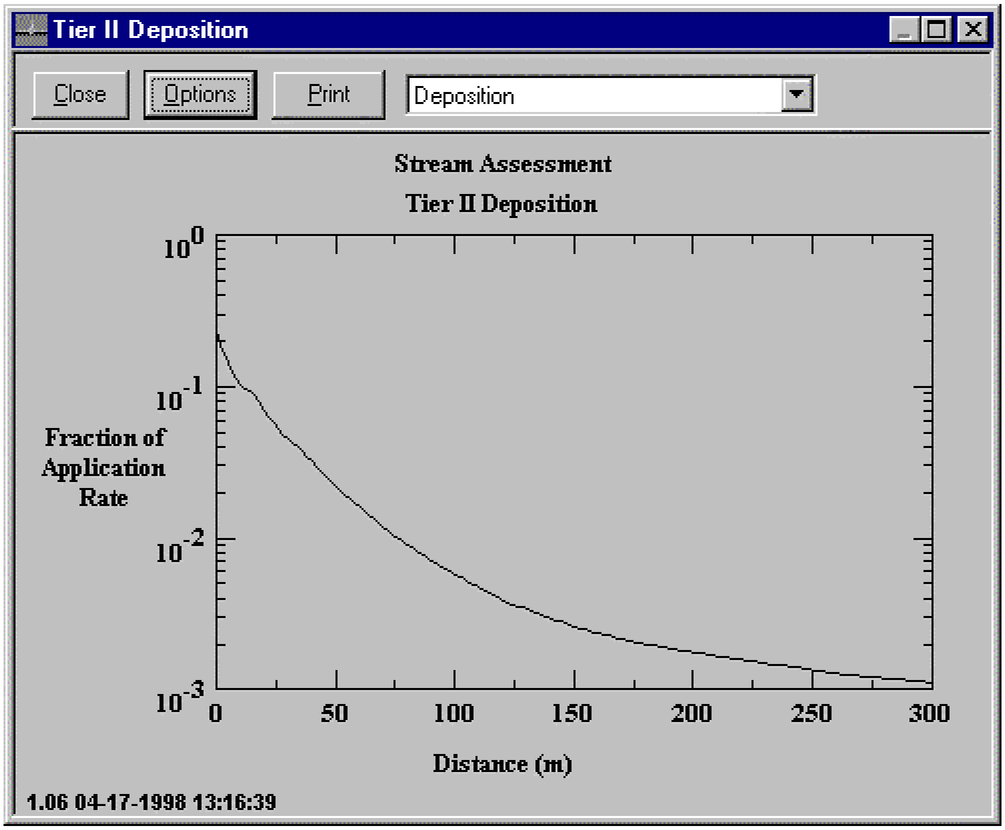

Figure 3.3. A Tier II Deposition Result for Default Aerial Conditions for a Single Flight Line.

The solution begins with an initial "top hat" concentration from the aerial spray (whose length is the length of the flight lines) on a flight line by flight line basis, and is integrated across the time and distance specified by the user until the concentration reaches a low value. Solution to Equation 9 for each flight line is the product of the exact solution to the diffusion equation (Carslaw and Jaeger 1959) and an exponential term representing the nondiffusive decay. The solution is of the form

$$C = \frac{C_i}{2}\left[\operatorname{erf}\left(\frac{a-y}{2\sqrt{Dt}}\right) + \operatorname{erf}\left(\frac{a+y}{2\sqrt{Dt}}\right)\right]\exp(-nt) \qquad (11)$$

where C_i is initial concentration, a is one-half the length of the spray block (x = 0 is at the direct downwind center of the spray block), y = x – Ut corrects downstream distance for convection, erf is the error function, and exp is the exponential function. The most downwind flight line is assumed to deposit to the stream at t = 0. Each upwind flight line deposits to the stream at uniformly increasing increments in time

$$\Delta t = m\left[t_{turn} + \frac{2a}{U_\infty} + \frac{s}{U_{ws}\cos(\theta)}\right] \qquad (12)$$

where m is the flight line counter (m = 1 is the first flight line upwind of the most downwind flight line), t_{turn} is the aircraft turning time from one flight line to the next, s is swath width, U_{ws} is wind speed, and θ is the angle of the wind from direct crosswind. The location of the center of the flight line deposit to the stream occurs at increasing distances from the center of the spray block

$$\Delta x = (Y + ms)\tan(\theta) \qquad (13)$$

where $m = 0$ recovers the most downwind flight line deposit location when $\theta \neq 0$ (otherwise $\Delta x = 0$). The initial concentration to the stream will change with each flight line because of the increasing swath width offset (as shown by the steadily decreasing levels of deposit in Figure 3.3, for example). Superposition generates the complete deposit pattern.

3.2 User Interface Development

The Stream Assessment screen (shown in Figure 3.4 and accessible from the toolbox pull-down menu from all three Tiers in AgDRIFT®) permits the user to enter needed data to solve the stream model equation. The needed inputs are: (1) Spray Line Length, the length of the spray unit in the flight direction, a direction assumed to be parallel to the stream; (2) Turn-Around Time, the time for the pilot to change from one flight line to the next; (3) Stream Width; (4) Stream Depth; (5) Stream Flow Rate or discharge; and (6) Distance from the edge of the field to the center of the stream. The Stream Flow Rate Q_i is related to the average stream flow speed by the expression

$$Q_i = Uwd \qquad (14)$$

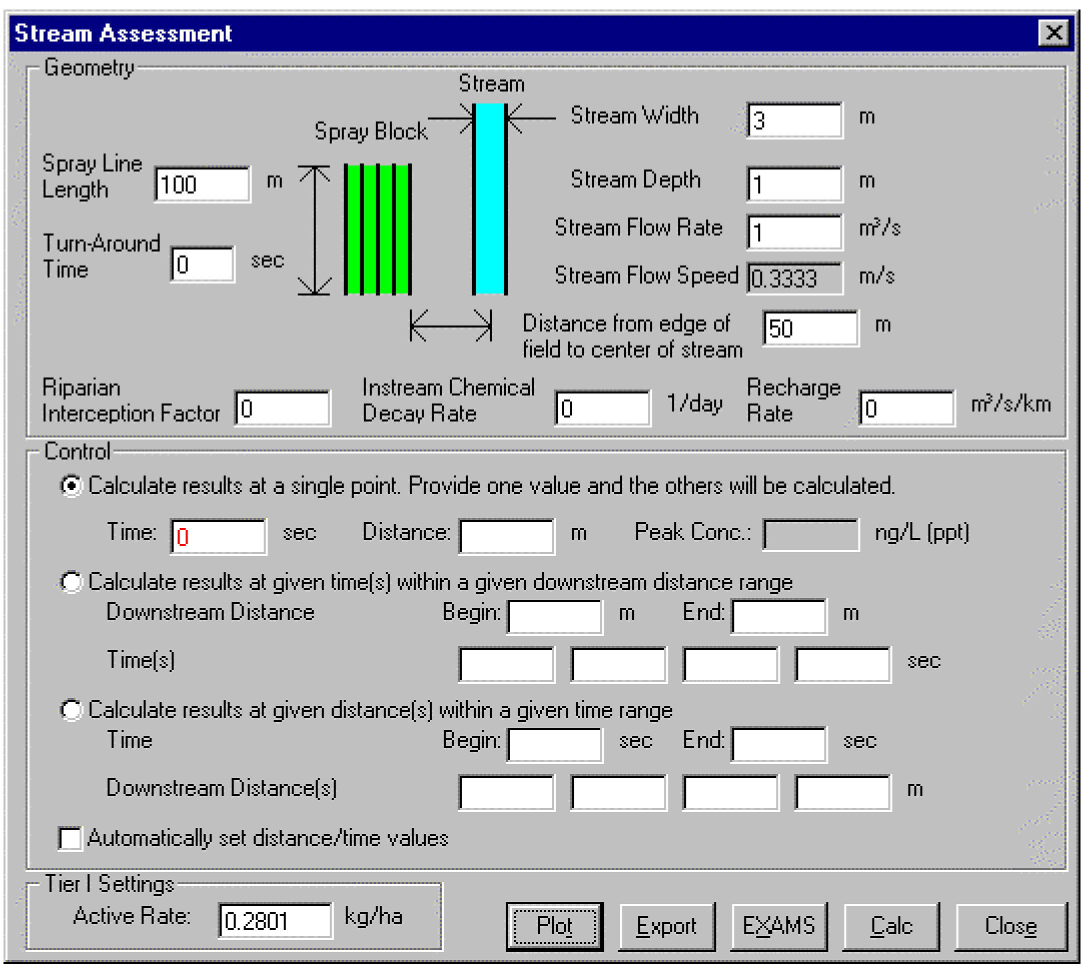

Figure 3.4. The Stream Assessment Toolbox Screen in AgDRIFT®.

Active Rate may also be entered in Tier I. These inputs are sufficient to drive the stream equation once AgDRIFT® has been run to generate the integrated deposit on the surface of the stream.

Three additional inputs may also be entered: (7) Riparian Interception Factor, a factor indicating the amount of active material removed from the air by vegetation growing upwind of the stream; (8) In-stream Chemical Decay Rate, the reciprocal time it takes for the active material to become less effective; and (9) Recharge Rate, the flow rate per distance downstream for fresh water entering the stream. In its default mode the Riparian Interception Factor is 0.0 (there is no vegetation growing near the stream), the In-stream Chemical Decay Rate is 0.0 day^{-1} (no decay), and Recharge Rate is 0.0 $m^3/s/km$.

Results may be recovered by either time or distance plots, choosing the Downstream Distance increment (Begin and End) and the Time(s) desired, or the Time increment (Begin and End) and the Downstream Distance(s) desired, and pushing the Calc or Plot button. The model will automatically generate appropriate time and distance values if requested (by checking Automatically set distance/time values), based on built-in plotting preferences. The user may then freely change these values and rerun the calculation. The predicted result is also available at a single point by providing either the Time or Distance (Distance or Time and the Peak Concentration are computed by the program). The Export button will fill an ASCII file with columns of data, so that the results may be imported into other plotting, statistical, or calculation packages. The EXAMS button will fill an ASCII file with data for input into the EXAMS model (see Section 5.5). The screen is left with the Close button, or by pressing Esc on the keyboard.

A typical result, for the Tier I default aerial conditions, with a Spray Line Length of 100 m, Turn-Around Time of 15 s, Stream Width of 3 m, Stream Depth of 1 m, Stream Flow Rate of 3 m^3/s (Flow Speed of 1 m/s), and Distance from edge of field to center of stream of 50 m, is shown in Figure 3.5 for the automatic setting over a distance range from 100 m to 10000 m, and in Figure 3.6 for the automatic setting over a time range from 3600 sec to 86400 sec. At a Time of 43200 sec, the Peak Concentration of 485 ng/L occurs at a Distance of 14400 m.

Stream Flow Rates for various rivers are summarized in Table 3.1. These parameters are representative of medium to large rivers. Most streams that foresters must consider are much smaller. For example Beschta (1997), based on stream survey data from the Wallowa-Whiteman National Forest (1991), reported that "summertime field assessments indicated that over 90% of the 38 subwatersheds comprising the Upper Grande [Ronde] River Basin have fish-bearing streams with average wetted widths of 10 feet or less …" and "… widths for the non-fish streams would be even narrower." More representative of these small stream conditions are data from small streams in Oregon (both fish-bearing and non-fish bearing) where average stream depths ranged from 0.01-0.3 m, widths from 1.0 to 3.3 m, and discharge from 0.001 to 0.016 m^3/s (Ice 1978). Streams monitored as part of the Washington Timber/Fish/Wildlife study on the effectiveness of state Best Management Practices (BMPs) for aerial application of forest chemicals (Rashin and Graber 1993) recovered discharge ranging from 0.001 to 0.28 m^3/s. The summary or collection of stream parameter data for typical forest streams in different regions has been identified as a useful task.

Because diffusion alone requires a long time (or long distance) to attenuate the deposited active material, we look to the Riparian Interception Factor, the In-stream Chemical Decay Rate, and the Recharge Rate as means to reduce the predicted concentration level in the stream.

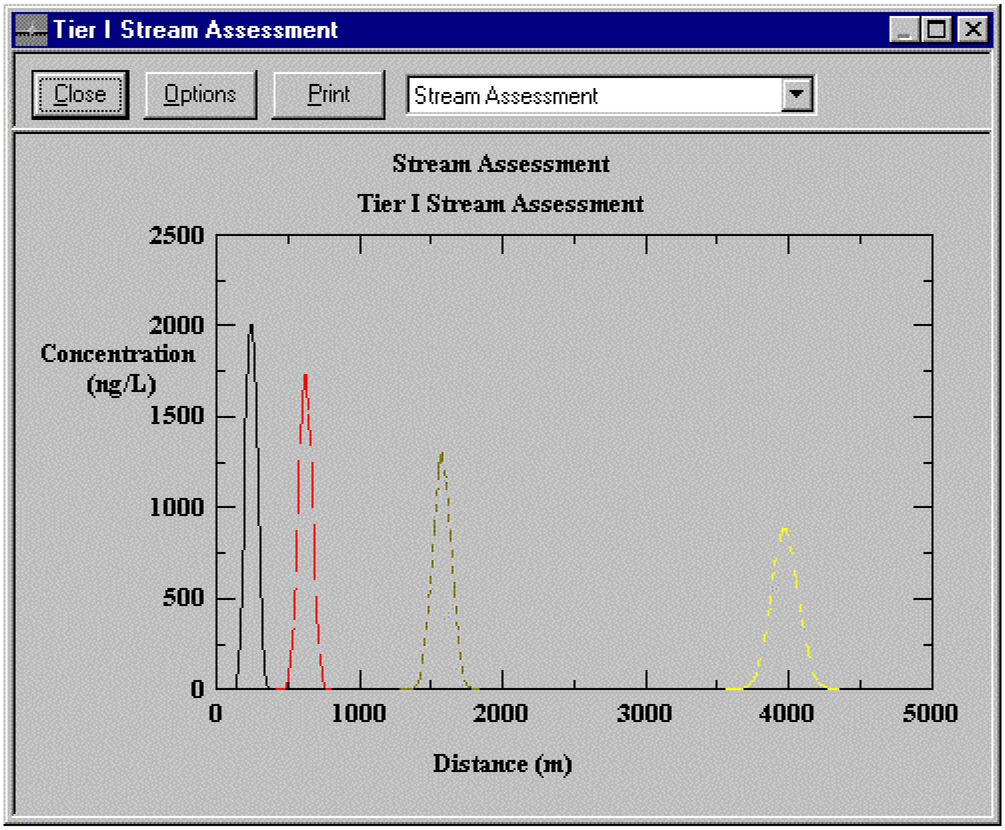

Figure 3.5. Stream Assessment Results for Distance with the Tier I Default Settings of BCPC Medium Drop Size Distribution, and the Default Stream Assessment Inputs with a Distance Range Between 100 m and 10000 m. Some Attenuation in Maximum Concentration Occurs Over this Distance.

3.2.1 *Riparian Interception Factor*

Vegetation (shrubs or trees) growing near the stream (between the spray block and the stream) would generally be available to capture airborne active material within its canopy before that material has an opportunity to deposit into the stream. Figure 3.7 illustrates the profile of vertical flux of active material passing the upwind bank of a stream with the Tier I default settings of BCPC medium drop size distribution (Tier II must be invoked to perform the flux prediction). Downwind of the spray block and past the point of turbulent decay of the aircraft vortices, active material aloft may be considered to be drifting laterally at the ambient wind speed, while also descending under the influence of gravity. Figure 3.7 suggests that vegetation near the stream could influence sizable amounts of material that would otherwise deposit into the stream (depending of course on the height of the canopy). Here it may be suggested that the fraction of drifting material influenced by the canopy would be proportional to the ratio of the height of the canopy to the width of the stream (but no greater than 1). In this example (with the Stream Assessment default settings) vegetation with a height of 3 m would be assumed to affect all of the active material about to be deposited into a stream whose width is 3 m.

Considerable research (Wilson et al. 1990; Wang and Takle 1995) has been conducted on the effects and influence of porous barriers (hedges, shelterbelts, windbreaks) on the wind speed and wind direction in their vicinity. The disappointment from this research lies in its not being extended to predict the horizontal deposit from winds moving through the canopy (the buffer situation). Most collection efficiency work has dealt with the collection of droplets falling at their terminal velocity onto essentially flat surfaces (Davis et al. 1994).

The actual amount of active material captured by the vegetation would depend on the ability of the canopy to capture the material as it drifts by. A typical formula, developed from experimental data collected by the vertical release of glyphosate in a deciduous canopy (Newton et al. 1984), may be suggested here as an approximation to the horizontal capture of the drifting material. This formula relates the amount of capture by the canopy (f_C) to its leaf area index (m^2 of leaf top-side area divided by m^2 of ground area) as

$$f_C = 1 - \left(\frac{1}{2}\right)^L \qquad (15)$$

where the ability to evade capture by the canopy is halved for every unit increase in leaf area index L. The overall proposed formula for Riparian Interception Factor (RIF) is then

$$RIF = c\frac{f_C h}{w} \qquad (16)$$

where h is the height of the canopy (h/w must be less than or equal to 1). The coefficient c corrects for horizontal capture effects. It is the value of c that is difficult to estimate.

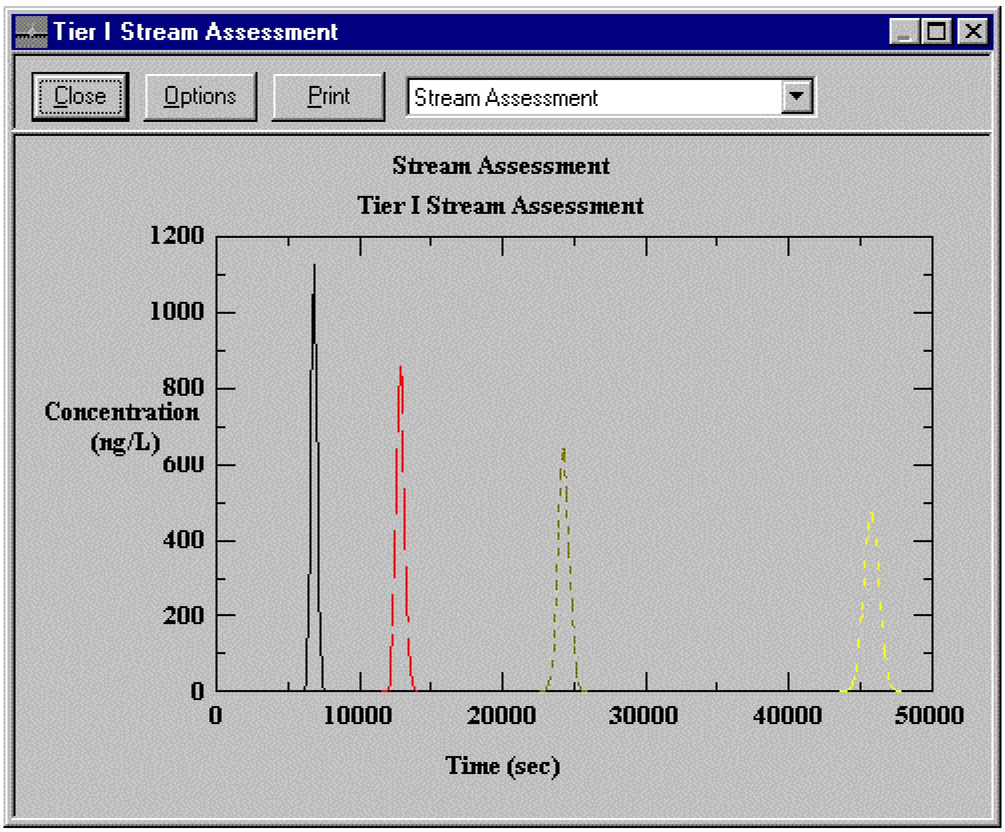

Figure 3.6. Stream Assessment Results for Time with the Tier I Default Settings of BCPC Medium Drop Size Distribution, and the Default Stream Assessment Inputs with a Time Range Between 3600 sec and 86400 sec. Some Attenuation in the Maximum Concentration Occurs in This Time.

Table 3.1. Typical Discharge Rates of Rivers (Fischer 1968; 1975)

Location	Width (m)	Depth (m)	Flow Rate (m^3/s)
Bayou Anacoco (Louisiana)	25.9	0.94	8.2
	36.6	0.91	13.5
Clinch River (Tennessee)	36.0	0.58	6.8
	47.2	0.85	9.2
	53.3	2.10	51.0
	59.4	2.13	85.0
Comite River (Louisiana)	15.8	0.43	2.4
Copper Creek (Virginia)	15.8	0.49	1.5
	18.3	0.85	8.5
	18.6	0.40	13.7
John Day River (Oregon)	25.0	0.58	14.2
	34.1	2.47	69.1
Missouri River (Louisiana)	182.9	3.29	934.5
Nooksack River (Washington)	64.0	0.76	32.6
Powell River (Tennessee)	33.8	0.85	4.0
Sabine River (Texas)	103.6	2.04	118.9
	127.4	4.75	389.4
Wind/Bighorn Rivers (Wyoming)	59.4	1.10	57.9
	68.6	2.16	230.7
Yadkin River (North Carolina)	70.1	2.35	70.8
	71.6	3.84	212.4

An alternate expression for f_C (which is essentially the collection efficiency of the canopy) may be obtained from another source (Makarov et al. 1996) as

$$f_C = \alpha (u_{term} U_{ws})^{0.65} \qquad (17)$$

where u_{term} is the terminal velocity of the droplet (this formula would have to be applied to a droplet size representative of the active spray aloft above the stream) and α is a coefficient that may typically be taken at 0.1.

Data comparisons not conducted here would be needed to quantify this correction to the amount of active material entering the stream. A nonzero value of Riparian Interception Factor will reduce the initial concentration within the stream.

3.2.2 *In-stream Chemical Decay Rate*

The second model input parameter modifying the Stream Assessment prediction is the In-stream Chemical Decay Rate. All pesticides decay in water, whether by photolysis, hydrolysis, aerobic and anaerobic biodegradation, in combination or with other rates as well[1]. The determination of the decay rate (generally designated as K in day^{-1}) can involve a very complicated calculation. To circumvent these calculations here, we merely provide an input to the model as

[1] Pesticide properties are summarized in the ARS Pesticide Properties Database found at www.arsusda.gov/rsml/ppdb.html; water quality assessment data may also be found in Mills et al. (1985).

$$n = K \qquad (18)$$

to recover the effect of the decay rate on the overall dispersion of the concentration in the stream. For example, a spray material with a decay rate of 1 day^{-1} will generate n = 0.0000116 s^{-1}. This number does not appear large here, but over stretches of several km or (certainly) times on the order of one day or more, the effect will become important. For the most part K = 0 is an appropriate assumption.

3.2.3 *Recharge Rate*

The third model input parameter modifying the Stream Assessment prediction is the Recharge Rate. Dilution from inflowing streams and groundwater may produce a significant reduction in stream concentration downstream of the spray block[2]. In general, without any other losses, the concentration in the stream must be conserved

$$C_i Q_i = C(Q_i + Q_n Ut) \qquad (19)$$

where Q_n is the average recharge rate per unit distance downstream. Differentiation of this equation, and appropriate substitution, recovers

$$\frac{\partial C}{\partial t} = -\frac{Q_n U}{Q_i + Q_n Ut} C \qquad (20)$$

For a first-order effect we neglect the second term in the denominator and correct the remaining coefficient to be consistent with exponential decay. This step results in

$$n = \frac{0.693 Q_n U}{Q_i} \qquad (21)$$

For example, if in a given stream length, fresh water is added at a cumulative flow rate equal to the initial flow rate, then n = 0.693 and the concentration is diluted by a factor of two in the given stream length, leading to a significant effect on the concentration in the stream. Rashin and Graber (1993) reported a flow increase from 9 to 12 L/s over a 730 m reach for one small Washington stream, and an increase of 7 to 11 L/s for another over a 520 m reach. However, a third stream experienced a decrease from the flow measured at the upstream edge of the unit down to the monitoring site (a drop from 5 to 3 L/s over a 40 m reach). These findings show the importance of ground and surface water input and exchange for these small streams, and even these values may underestimate the rate of exchange taking place. Fluorescent dye time-of-travel studies by Rashin and Graber (1993) showed considerable dispersion of the dye. The step-pool morphology of these small, steep streams results in water being temporarily stored in plunge pools and eddies, where it mixes with surface flows from upstream and groundwater seepage.

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[2] Dilution rates may be extracted, with some effort, from the EPA Reach File database found in many places, one of which is Lahlou et al. (1996), although the entries tend to be for rivers rather than for smaller streams.

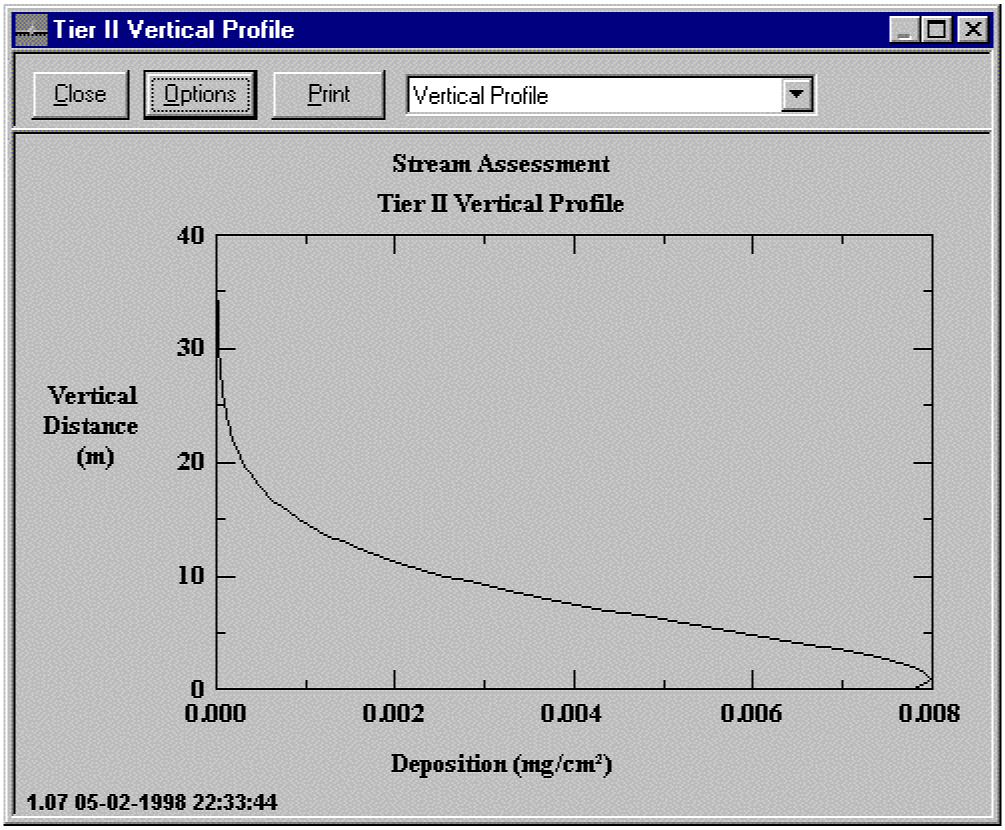

Figure 3.7. Vertical Flux Profile For the Tier I Default Settings of BCPC Medium Drop Size Distribution and the Default Stream Assessment Inputs (a Stream Width of 3 m), at a Location Downwind of the Edge of the Spray Block of 48.5 m (the Center of the Stream is at 50 m).

Dent (1995) observed rapid stream cooling in small Oregon streams where "… groundwater seepage is likely to be a dominant cause" and Dr. Mike Newton of Oregon State (personal communication) has monitored rapid cooling in small forest streams, which he concludes may be caused by groundwater inflow and water exchange (including streamwater loss due to evapotranspiration by riparian vegetation). Hyporheic zone (the area under a stream channel or floodplain that contributes water to the stream) exchange is a major potential source of dilution and peak concentration attenuation.

Since the analysis is linear, the effects of the In-stream Chemical Decay Rate and the Recharge Rate are additive in Equations 9 and 11. An example of the effects of these terms is shown in Figure 4.1.

4.0 MODEL COMPARISON WITH DATA

Research indicates that the attenuation of chemical concentrations downstream of their injection point is rapid both as measured by distance and time of travel, and especially for streams that are typical of forest sites. Factors that lead to rapid attenuation of chemical concentrations include: (1) dilution from inflowing streams and groundwater; (2) diffusion due to turbulent mixing and exchange with isolated pools of water; (3) adsorption on organics, clay particles, and other surfaces; and (4) decay as a result of chemical, biological, and physical processes. Several comparisons with point-source release data, using the same formulation as Equation 9, but without any decay effects, were presented in Fischer et al. (1979). Agreement was considered extremely good, considering the real-world geometry and physical effects of streams and rivers.

A contemporary field examination of stream attenuation was conducted by Norris et al. (1978). From direct measurements of fluorescent dyes, these researchers found that slow-moving, complex streams with pools and riffles had very large attenuation of peak concentrations downstream of the injection point, while a simpler, faster moving stream still demonstrated significant attenuation of the peak concentration. Their data are shown in Figures 10 and 11 compared with peak concentrations predicted by the stream assessment model discussed in the previous section (in all that follows the Riparian Interception Factor, the In-stream Chemical Decay Rate, and the Recharge Rate have been set equal to zero).

Model predictions were made by assuming that the length of the initial dye signature in the direction of stream flow was 0.1 m (the prediction is in fact insensitive to this length when it is small). Stream and canal width and depth were assumed to be 1 m (specific data were not available for these inputs). Because the specific initial concentration levels were also not provided, predicted peak concentrations at the last data collection location were used to normalize the predictions at the upstream locations. Examination of the data, and reconstruction of the average stream flow speed, recovered U = 0.044 m/s for Quartz Creek and U = 0.343 m/s for Madras Canal. As may be seen from the figures, the predicted times for passage of the peak concentrations, and the predicted relative peak concentrations themselves, are in good agreement with the data, although several times and peak values are slightly underpredicted.

Dye injection in these experiments was over a very small streamwise direction, whereas aerial application will generate a much longer distance over which to load the stream. These adjacent volume elements may significantly retard mixing and its subsequent diffusion. In fact model predictions show that with the more typical flight line lengths of 100 m or more, attenuation is extremely slow unless the Recharge Rate is set to a nonzero value. Reduction to one-half the maximum concentration values can take more than 3 km by diffusion alone (as shown previously in Figure 3.5).

With these observations in mind, it makes sense to consider the use of the Riparian Interception Factor (which reduces the level of initial concentration to the stream), the In-stream Chemical Half Life, or the Recharge Rate (which removes material from the stream by processes other than simple diffusion) when exercising the Stream Assessment toolbox option in AgDRIFT®.

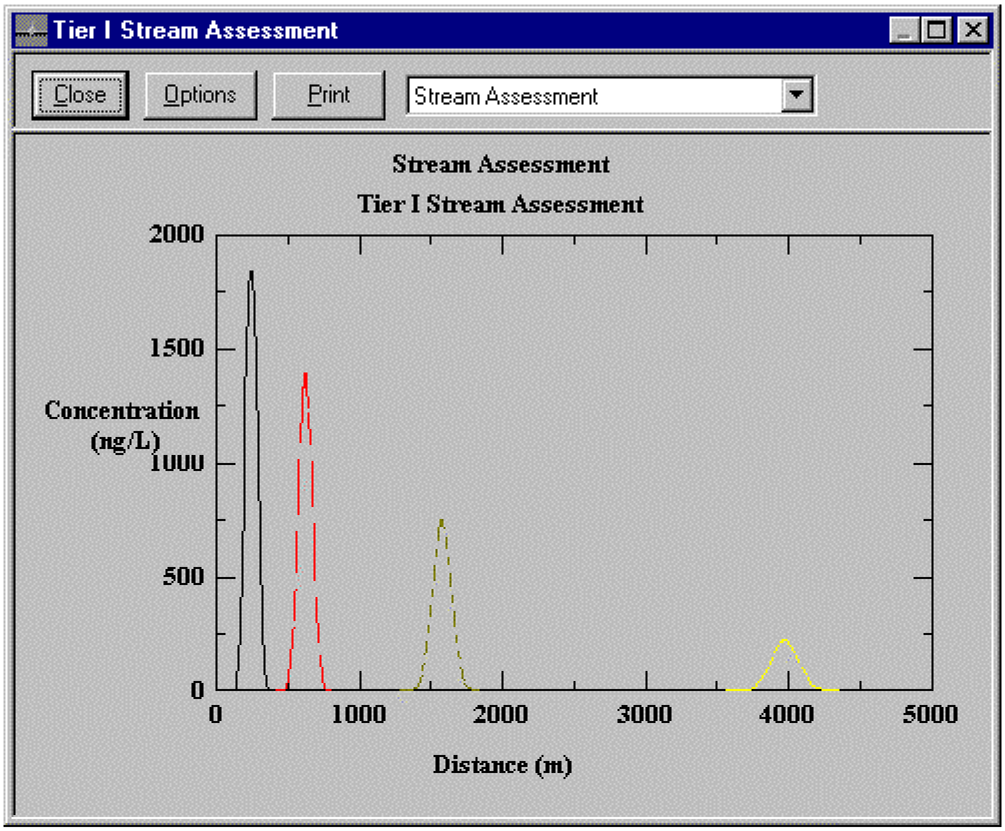

Figure 4.1. Stream Assessment Results for Distance with the Tier I Default Settings of BCPC Medium Drop Size Distribution, and the Default Stream Assessment Inputs with a Distance Range of 100 m To 10000 m. The Recharge Rate has been Set Equal to 0.5 m^3/s/km to Account for the Insertion of Fresh Water From Other Streams. Results may be Compared with Figure 3.5.

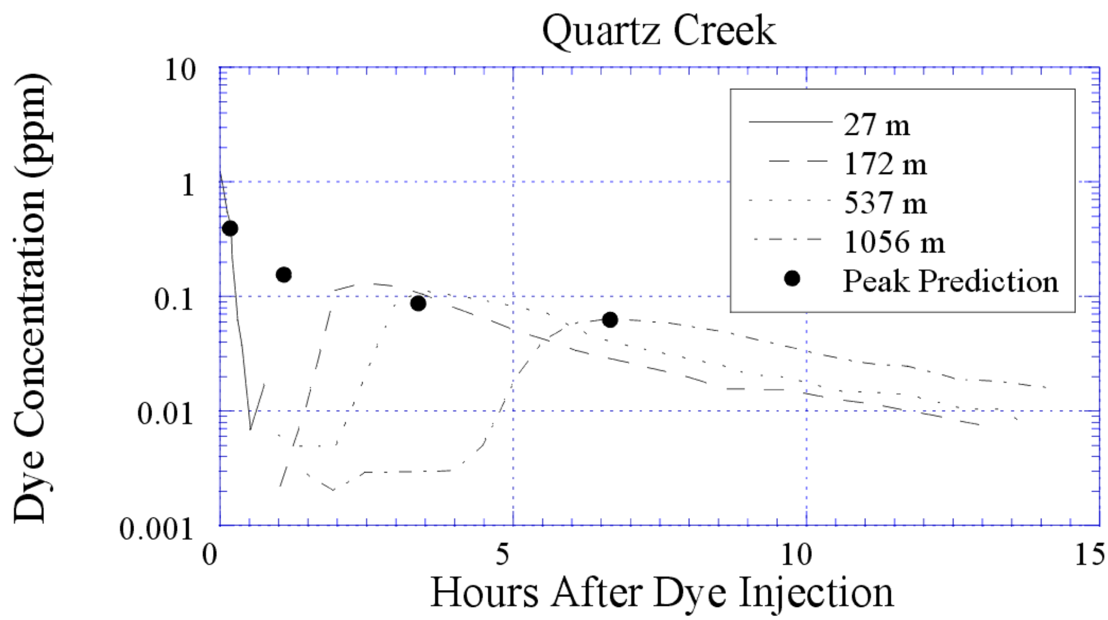

Figure 4.2. Stream Assessment Model Predictions of Peak Concentration and Time of Travel, Compared with the Data of Norris et al. (1978). Collected at Quartz Creek.

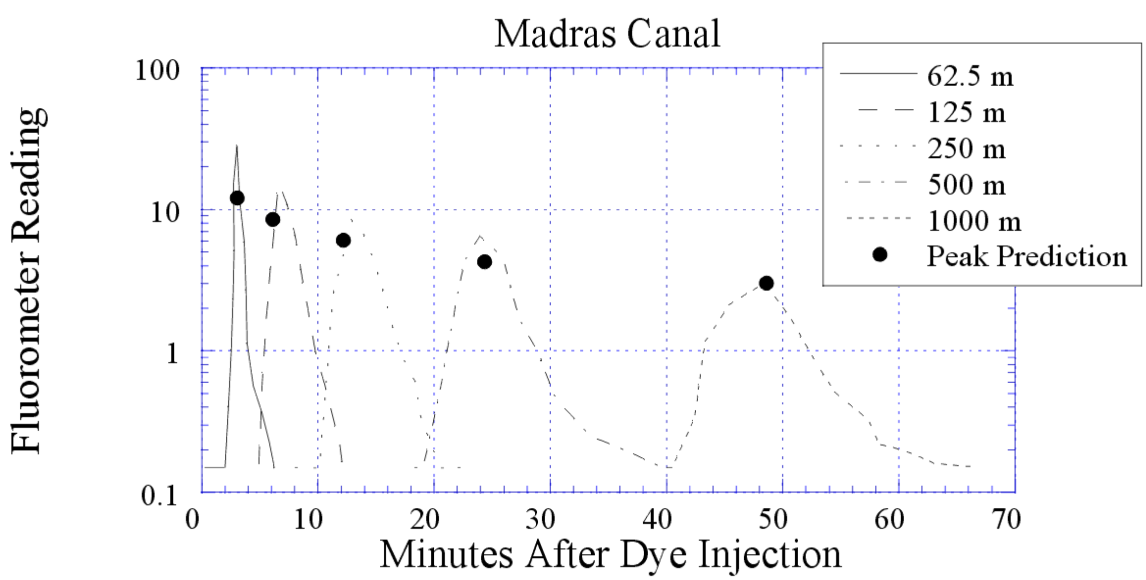

Figure 4.3. Stream Assessment Model Predictions of Peak Concentration and Time of Travel, Compared with the Data of Norris et al. (1978). Collected at Madras Canal.

5.0 OTHER ASSESSMENT MODELS

A review of the available models for assessing stream effects on deposited aerially-released spray material in a more complex manner than discussed here found five candidate models: HSPF, SMPTOX, OPUS, BASINS, and EXAMS. We will now briefly highlight these models and their relevance to our work here.

5.1 HSPF

The Hydrological Simulation Program - FORTRAN (HSPF) is a mathematical model developed in the mid to late 1970s for the EPA (Grimsrud et al. 1982; Johanson et al. 1984; Donigian et al. 1984). Its usefulness as a nonpoint source watershed model for NCASI has been recently investigated (Whittemore 1997). Its analytical features have application in planning, design, and operation of large and small (urban and rural) water resource systems, although HSPF has the greatest utility in large rural watersheds. The model also enables the use of probabilistic analyses in the fields of hydrology and water quality management by virtue of its time series management of inputs and calculated flows and water quality concentrations.

To simulate the processes that occur in a watershed, HSPF uses such information as the time history of rainfall, temperature, and solar intensity, and the parameters related to land use patterns, soil characteristics, and agricultural practices. The initial result of an HSPF simulation is a time history of the quantity and quality of water transported through various soil zones down to the groundwater aquifers, and then over ground flow to other surface waters. Runoff flow rate, sediment loads, nutrients, pesticides, toxic chemicals, and other quality constituent concentrations can be predicted. The model then takes these results, and information about the receiving water channels in the watershed, and simulates the processes that occur within these channels. This part of the simulation produces a time history of the water quantity and quality at any point in the watershed.

HSPF contains an in-stream water quality simulation capability as well, which should make it attractive here, and of all the models discussed in this section should be considered the most versatile. However, HSPF has extensive data requirements and is the most difficult to understand and use. Its lack of simple utility must be thoroughly examined before considering the use of HSPF as the logical next step in a detailed development of a stream assessment tool.

5.2 SMPTOX

The Simplified Method Program - TOXics (SMPTOX) performs waste load allocations for toxics, calculating water column and stream bed toxic substance concentrations resulting from point source discharges into streams and rivers (Goodwin 1995). The model predicts pollutant concentrations in dissolved and particulate phases for both the water column and bed sediments, as well as total suspended solids concentrations. Predictions are obtained by solving one-dimensional steady-state models for: (1) conservative or nonconservative total pollutant; (2) separate dissolved and particulate phase without bed interactions; and (3) separate dissolved and particulate phase having bed interactions. The approaches differ in their spatial and temporal variations, environmental media, and pollutant forms and behavior. In practice SMPTOX runs extremely rapidly, but needs detailed composition chemistry on the sprayed material to provide a useful result. Other inputs not readily available to the casual user would also need to be entered, which makes the model less attractive than originally thought.

5.3 OPUS

Opus (no acronym) is a computer model for the transport of material in soil and surface water (Smith 1992; Ferreira and Smith 1992). The model is a simulation tool for studying the potential pollution from various agricultural management practices. It simulates water movement that results from rainfall, and other weather inputs, affected by soil, crop, topography, and many types of management actions and water use influencing the surface conditions. Opus includes models for the growth of plants, development of cover, water use, uptake of nutrients, cycling of soil nitrogen, phosphorus, and carbon, transport of adsorbed pesticides and nutrients, interaction of surface water and soil water, runoff, and erosion. Opus allows the user to choose between a detailed simulation involving data on the time-intensity pattern of rainfall, or a more lumped approach using either recorded daily rainfall or stochastically generated rainfall. The model does not, however, contain a stream module, nor does it consider stream assessment.

5.4 BASINS

The Better Assessment Science Integrating point and Nonpoint Sources (BASINS) model (Lahlou et al. 1996) is a multipurpose analysis system configured to support environmental and ecological studies in a watershed context. Traditional approaches to watershed-based assessments typically involve many separate steps – preparing data, summarizing information, developing maps and tables, and applying and interpreting models. BASINS acts as a decision support system by providing all of these features in one program and enabling extensive mapping features and overlays. Point and nonpoint pollutant loading sources are modeled within BASINS by using the two models NPSM (NonPoint Source Model) and TOXIROUTE. NPSM simulates nonpoint source runoff, pollutant loadings, and dissolved oxygen levels in runoff for the selected watershed, but does not include the stream simulation models found in HSPF. TOXIROUTE uses a simple first-order decay solution to simulate the transport of selected pollutants in streams and rivers (not unlike the model found in SMPTOX). Later versions of BASINS will implement more HSPF approaches, while adding additional features and options. However, it is presently a watershed model and cannot be used to simulate the spatial distribution of aerially-released spray materials. Long-term, BASINS may actually expand to be the model of choice, but currently it is not.

5.5 EXAMS

The EXposure Analysis Modeling System (EXAMS) provides software for formulating aquatic ecosystem models and rapidly evaluating the fate, transport, and exposure concentrations of synthetic organic chemicals (pesticides, industrial materials, and leachates from disposal sites) (Burns et al. 1982; Burns 1997). EXAMS estimates exposure, fate, and persistence following release of an organic chemical into an aquatic ecosystem, and contains a set of process modules that link fundamental chemical properties in the parameters that control the kinetics of fate and transport in aquatic systems, and provides facilities for long-term (steady-state) analysis of chronic chemical discharges, initial-values approaches for study of short-term chemical releases, and full kinetic simulations that allow for monthly variation in mean climatological parameters and alternation of chemical loadings on daily time scales. Its inclusion of stream loading is particularly attractive here.

To support the usefulness of EXAMS in the present application, we have included the Export of those parameters extracted from an AgDRIFT® prediction that would seem to be needed to initialize a calculation in EXAMS. These data would then be used to run EXAMS and produce a detailed prediction of stream concentration decay, including the effects of chemistry. To understand EXAMS well enough to be able to set up a stream assessment problem and run it with confidence, then be confident of its results and an interpretation of them, would require an effort not undertaken in the present work.

Typical export to EXAMS file structure is shown in Table 6.1. The top portion of the file is a summary of the relevant input into the model, while the lower portion provides columns of initial conditions for time (at which the deposit enters the stream, in seconds, with the first entry always set to 0), distance downstream (at which the center of the deposit enters the stream, in meters, measured from the center of the field), and initial concentration of the deposit into the stream (in ng/L).

6.0 CONCLUSIONS AND RECOMMENDATIONS

This report offers a one-dimensional unsteady advection-diffusion equation as the basis for a stream assessment model interpreting the results of aerially-released spray material entering a stream downwind of a spray block. Accessed from within the existing deposition model AgDRIFT® through a toolbox option, this model provides a rapid prediction of downstream diffusion effects. It will form a part of all future releases of the AgDRIFT® model.

Stream assessment predictions have been confirmed in the near-field by comparison with available data, but require additional data – particularly to exercise the assumed Riparian Interception Factor, In-stream Chemical Decay Rate, and Recharge Rate – to validate use of the model for long stream distances. Its link to other, more complicated, watershed and stream models currently under development by the EPA has also been explored.

The one cautionary note regarding the development of the model is that it should typically be used for a scoping study, with a single use into a stream, for a relatively short distance downstream. Multiple sources, and multiple applications to the watershed, are not handled by this model. In these cases the user will have to investigate the use of EXAMS, BASINS, or HSPF. The model should probably also carry a restriction regarding the maximum distance it may be applied downstream of the insertion point.

A number of recommendations have been generated by this work.

- Additional model predictions with available field data are important, especially for the proposed Riparian Interception Factor, In-stream Chemical Decay Rate, and Recharge Rate. A field study collecting all pertinent data to make model comparisons would appear to be important. In an effort to make AgDRIFT® easier to operate, a separate document, compiling typical values for these inputs and giving specific instructions for using this toolbox option, should be considered as well.
- The Stream Assessment toolbox should be expanded to permit discrete insertion points for fresh water into the stream. This effect would generalize the Recharge Rate input.
- An operational understanding of the assessment model EXAMS should be considered, including attendance at an available training session. Reliable calculations with the model could then be undertaken.
- Results presented here, and the model behind them, should be presented at a conference and published in a peer-reviewed journal.
- BASINS and HSPF model development should be watched as potential long-term stream assessment tools.

Table 6.1. Structure of the Stream Assessment Export File into EXAMS

Title:	Untitled
Run ID:	1.07 00-00-0000 00:00:00
Drop Size Distribution Name:	Medium
Number of Drop Categories:	28
Spray Material Name:	Water
Nonvolatile Rate (lb/ac):	0.5
Active Rate (lb/ac):	0.25
Spray Rate (gal/ac):	2
Aircraft Name:	Air Tractor AT-401
Number of Nozzles:	42
Temperature (deg F):	86
Relative Humidity (%):	50
Release Height (ft):	10
Number of Spray Lines:	20
Swath Width:	60 ft
Swath Displacement:	1/2 Swath Width
Stream Width (m):	3
Stream Depth (m):	1
Stream Flow Rate (m3/s):	3
Spray Line Length (m):	1000
In-stream Chemical Decay Rate (1/day):	0
Recharge Rate (m3/s/km):	0

1	0.000000E+00	28.867510	834.156300
2	6.588530	39.426200	534.871100
3	13.177060	49.984900	380.342500
4	19.765590	60.543600	298.868600
5	26.354120	71.102290	250.865800
6	32.942650	81.660990	218.573300
7	39.531180	92.219690	195.050900
8	46.119710	102.778400	175.411700
9	52.708240	113.337100	158.692400
10	59.296770	123.895800	144.428100
11	65.885300	134.454500	132.480500
12	72.473830	145.013200	123.192800
13	79.062360	155.571900	115.284000
14	85.650890	166.130600	108.401700
15	92.239420	176.689300	102.967500
16	98.827950	187.248000	102.967500
17	105.416500	197.806600	102.967500
18	112.005000	208.365300	102.967500
19	118.593500	218.924000	102.967500
20	125.182100	229.482700	102.967500

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