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An Evaluation of Gleams-Driver for Estimating Concentrations of Pesticides in Surface Water
Final Report

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ABSTRACT

Gleams-Driver is a computer program that can be used to estimate concentrations of pesticides in surface water (streams or ponds) associated with common forestry and agricultural applications of pesticides. Gleams-Driver itself is little more than a shell that serves as a pre-processor and post-processor for GLEAMS. GLEAMS is an edge-of-field and bottom-of-root-zone model developed by USDA/ARS that can be used to examine the fate of chemicals in various types of soils under different meteorological and hydrogeological conditions. Gleams-Driver post-processes GLEAMS output using a relatively simple set of algorithms that permit substantial flexibility in the specification of the characteristics and location of the stream or pond. In this process, Gleams-Driver relies heavily not only on GLEAMS but also on other USDA programs including Cligen, a weather generator developed and maintained by the USDA's Agricultural Research Service (USDA/ARS), as well as the Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/), an online program developed by the USDA's Natural Resources Conservation Service (USDA/NRCS).

While GLEAMS, Cligen, and the NRCS soil survey are mature models and tools that have been subject to extensive review and evaluation, Gleams-Driver is new program. This analysis is the first systematic attempt to evaluate the reliability of Gleams-Driver. Because of the simplifications required to support the flexibility of Gleams-Driver, this evaluation focuses not only on the ability of Gleams-Driver to estimate pesticide concentrations in surface water but also on the ability of Gleams-Driver to estimate flow rates in streams and water volumes in lakes. The latter evaluations are based on USGS data on stream flow at a monitoring site on Bull Creek near Cascadia, Oregon and the water volume of Lake Gregory in Crestline, California. In both cases, Gleams-Driver is able to model the gross hydrology of these water bodies reasonably well.

This evaluation of the ability of Gleams-Driver to model pesticide concentrations in surface water is based on two pesticide applications near streams. One study involves a USGS experimental application adjacent to Bull Creek in which sulfometuron methyl was applied twice, once to assess pesticide loss after artificial rainfall and again to assess pesticide loss after natural rainfall. The artificial rainfall component of the study was used to calibrate GLEAMS to the site. Gleams-Driver adequately modeled runoff from the treated site under natural rainfall, and, consistent with the monitoring data from USGS, Gleams-Driver projected concentrations in Bull Creek that were below the limit of detection. The other study involves a field application of hexazinone to a catchment on the Stanislaus National Forest. Two sets of Gleams-Driver simulations were conducted. The first simulation relied on standard default values for soil and chemical properties from the database that is distributed with Gleams-Driver. The second simulation involved additional refinements of input parameters based on a fuller use of the data available on hexazinone as well as a more detailed consideration of site characteristics based on the NRCS soil survey. In both cases, the Gleams-Driver simulations approximated concentrations of hexazinone monitored in the stream over a 4-year post-application period. The more refined analysis, however, provided more accurate central estimates and more protective and plausible upper bound estimates of concentrations of hexazinone in the stream.

1. INTRODUCTION

Gleams-Driver is a Windows program for estimating concentrations of pesticides in surface water. Gleams-Driver serves as a pre-processor and post-processor for GLEAMS. Gleams-Driver prepares input files for GLEAMS, runs the GLEAMS program, and then reads and processes the output from GLEAMS to provide estimates of pesticide concentrations in surface water (streams and ponds).

GLEAMS is a root zone model developed by USDA/ARS that can be used to examine the fate of chemicals in various types of soils under different meteorological and hydrogeological conditions (Knisel and Davis 2000). GLEAMS is a DOS program written in Fortran. While it can and has been used by some USDA personnel to perform exposure assessments in support of USDA program activities, it is not widely used by Forest Service personnel because of the difficulties in both running the model and manipulating the output.

GLEAMS is an edge-of-field and bottom-of-root-zone model. This is to say that GLEAMS models pesticide movement within the field to which the pesticide is applied and estimates the amount of pesticide lost from the treated field via runoff, sediment, and percolation. In past Forest Service risk assessments, a set of relatively simple equations were used to estimate concentrations of pesticides in ponds and streams based on GLEAMS outputs of pesticide losses in runoff water, sediment, and percolate as well as the volumes of water in runoff and percolate (SERA 2004a).

Gleams-Driver is very different from the previous generic approach used with GLEAMS (SERA (2004a) in that the intent of the Gleams-Driver program is to allow the user to estimate concentrations in ambient water (lentic or lotic) for a specific site and application. The primary purpose of the current effort is to evaluate the ability of Gleams-Driver to provide estimates of concentrations in streams and ponds that are plausible.

Version 1.0 of Gleams-Driver was initially released in May 2006 (SERA 2006). Subsequently, the Forest Service requested two additional efforts: one to enhance Gleams-Driver based on feedback from Forest Service personnel and the other to evaluate the performance of Gleams-Driver based on appropriate field studies. Under the enhancement effort, several revisions to Gleams-Driver have been made and the current release is Version 1.7 (Durkin and Knisel 2007). While Gleams-Driver can be viewed as an extension and formalization of earlier uses of GLEAMS in Forest Service risk assessments, Gleams-Driver is a new program. The current analysis is the first systematic effort to determine if Gleams-Driver is likely to provide plausible estimates of pesticide concentrations in surface water bodies after specific field-level applications.

The primary approach to the evaluation is to compare the results from Gleams-Driver to field studies of pesticide applications that are similar to those used in Forest Service programs. This effort is detailed in Section 2.2. Because of the simpler post-processing algorithms used in Gleams-Driver relative to more complex modeling tools such as EXAMS (Burns 2000), the evaluation of Gleams-Driver also addresses ability of the model to estimate the gross hydrologic behavior of surface water, specifically the water volume of lentic systems (i.e., ponds or lakes) as well as the water flow rates of lotic systems (i.e., creeks and streams). Thus, prior to the evaluation of field studies involving pesticides, Section 2.1 summarizes case studies evaluating the capability of Gleams-Driver to model lake volume and stream flow rates.

2. ANALYSES

2.1. Modeling Stream Flow and Pond Volume

2.1.1. General Considerations

Gleams-Driver has a number of assumptions and simplifications that are intended to be inherently conservative. Initially, the application of GLEAMS to estimate concentrations of pesticides in surface waters for Forest Service risk assessments was based on modeling pesticide losses via erosion, runoff, and percolation but did not consider the contribution of water from runoff and percolation to the body of water being modeled. This approach is similar to the use of the "static pond" in ecological exposure assessments conducted by the U.S. EPA (Burns 2006). Not considering water added to the pond or stream is a conservative assumption in that runoff and percolate water, which transports the pesticide to the water body, is not considered in the dilution of the pesticide in the water body.

Gleams-Driver has been designed to more flexibly (but still conservatively) address the impact of runoff and percolate water on the volume of a pond or lake and the flow rate of a stream. While static systems can still be employed by ignoring water balance, the default behavior of Gleams-Driver is to consider water balance under the assumption that the pesticide as well as the accompanying runoff and percolate water are transported to the water body on the day that rainfall generates the pesticide loss. For very small and well drained fields, this immediate loss of pesticide and water may sometimes be reasonable. In general, however, there will be a delay and perhaps a substantial delay at least in the movement of percolate from distant sections of the field to the water body with associated degradation of the pesticide in either the channel or subsurface delivery system.

Some modeling systems, such as PRZM-EXAMS (Burns 2006), address this issue directly. One of the primary functions of EXAMS (Exposure Analysis Modeling System) in the PRZM-EXAMS system is to model the specific processes that are involved in the advective (lateral) transport of both pesticide and water from soil to the water body (Burns 2000).

A much simpler approach is taken in Gleams-Driver involving the use of a reservoir for percolation. The percolation reservoir is treated as a first-order open compartment in which the pesticide and water enters the reservoir on the day of the rainfall event that generates the pesticide and water loss from the field. Transfer from the reservoir to the water body is governed by first-order loss rates. Separate loss rates can be specified for the water as well as the chemical. In addition, first-order degradation of the pesticide can occur in the reservoir, and the proportion of the chemical and water that may be transported from the reservoir to the water body may also be specified.

The reservoir for percolation may be necessary for comparing the results of field studies to Gleams-Driver simulations. If Gleams-Driver does not model the basic dynamics of the water body – i.e., flow rates for streams and water volumes for ponds or lakes – then modeled estimates of the concentrations of pesticides in the water body are not likely to reflect monitoring data after field applications.

2.1.2. Selected Sites

To evaluate the ability of the percolation reservoir in Gleams-Driver to model water volumes in ponds or lakes as well as stream flow rates, data were obtained from the USGS web site at http://waterdata.usgs.gov/nwis/qw. This web site provides a detailed and extensive compilation of data on flow rates of streams and rivers and water volumes of ponds and lakes.

One lentic water body (i.e., a pond/lake) and one lotic water body (i.e., a stream or river) were selected for analysis: Lake Gregory in Crestline, California and Bull Creek near Cascadia, Oregon. The USGS web site contains flow data on numerous streams with varying flow rates and geographic locations. Bull Creek was selected because it is also the site of a monitoring study (Wood 2001) involving sulfometuron methyl, which is considered in more detail in Section 2.2.1. The USGS web site also contains data on numerous lakes. Most of the lakes, however, have relatively large drainage areas. Because GLEAMS is a field scale model, an attempt was made to identify a lake with a relatively small drainage area. The USGS web site has only seven lakes with drainage areas less than 5 sq miles. Lake Gregory was selected because it has a drainage area of only 2.66 sq miles and is located in a National Forest – i.e., the San Bernardino National Forest.

Table 1 summarizes the information and key model input parameters for each of the two sites. A different modeling approach was taken with each of the two sites. The approach used with Bull Creek was relatively crude and intended to mimic the use of the Quick Run facility in Gleams-Driver. As discussed in Section 4 of the Gleams-Driver User Guide (Durkin and Knisel 2007), the Quick Run utility in Gleams-Driver is a very simple interface that allows the user to specify general site characteristics. A more elaborate modeling procedure was used with the Lake Gregory site using the Full Run facility in Gleams-Driver. As discussed in Section 5 of the Gleams-Driver User Guide, the full run facility is less user-friendly than the Quick Run facility and requires many more input parameters. It does, however, allow the user much more direct and transparent control over how the simulation is conducted.

2.1.2.1. Bull Creek

The Bull Creek site is characterized as having silt loam soil textures (Wood 2001). Thus, all of the soil inputs for the site, as specified in Table 1, are based on the default values for silt loam soils in Gleams-Driver. The longest flow path and average slope were estimated from satellite images using Google Earth.

Weather files were generated using the WEPP (Water Erosion Prediction Project) interface for Cligen as discussed in Section 6.1.2 of Durkin and Knisel (2007). For Bull Creek, a Cligen weather file was generally based on the specific latitude and longitude of the site given by USGS using interpolation of nearby weather stations.

The only other sensitive input parameter for the Bull Creek modeling is the basal flow rate. Gleams-Driver requires a basal flow rate as an input parameter for streams, and the flow rate of the stream is not allowed to fall below this value. The value of 30,000 L/day used in the simulation for Bull Creek is about ½ of the 5th percentile of the flow rates contained in the USGS data for this stream.

For Bull Creek, 200 Gleams-Driver simulations were conducted with each simulation covering a 2-year period. The initial year was used only to allow the transfer factor for the percolation reservoir to approach a pseudo-steady state. As discussed in Section 2.2 (Modeling Results), Bull Creek required only a relatively modest transfer factor for percolate loss, and exploratory analyses indicated that the 1-year period was adequate to reach a pseudo-steady state. Only the second year of each simulation was used for comparing the Gleams-Driver simulations to the USGS monitoring data. While Gleams-Driver allows for Monte Carlo analyses with many of the input parameters, all of the input parameters were fixed in the modeling of the flow rate in Bull Creek. Thus, the only variability used in the comparison to the monitoring data on stream flow involved the variations in weather patterns from the Cligen simulation.

2.1.2.2. Lake Gregory

For the Lake Gregory site, most model inputs where obtained for the site through the USDA's Natural Resources Conservation Service (NRCS) web site at http://websoilsurvey.nrcs.usda.gov/app/. This web site allows the user to select a specific geographic site and obtain information on soils and other site characteristics through an easy to use graphic interface. Using this interface, a roughly triangular area (mimicking the shape of Lake Gregory) was defined and most soil characteristics for the Lake Gregory site specified in Table 1 are based on the data from the NRCS web site. In general, however, the values reported for the Lake Gregory site by NRCS do not differ substantially from the default values used by Gleams-Driver. The SCS curve number (CN2) is not included in the data at the NRCS web site. The CN2 of 74, identical to that used from the Bull Creek site, seems appropriate for the loam soil texture and surface conditions at the Lake Gregory site. The slope of 0.36 is based on an averaging of the slopes reported by NRCS. Lake Gregory is in a mountainous area, and the actual slopes range from 2% to 75%. While Gleams-Driver is capable of modeling different field areas around a water body and this approach could have been used, the averaging of the slopes appears to be sufficient to at least crudely mimic the water volumes of Lake Gregory, as detailed in the Section 2.1.3.2.

As with the Bull Creek site, linear interpolation of nearby weather stations was initially used for Lake Gregory but this approach resulted in highly misleading weather files due to the proximity of low elevation/high temperature sites such as San Bernardino, California. As noted in Table 1, Lake Gregory has an elevation of 4,553 feet and the temperature and rainfall patterns for the region near Lake Gregory are substantially different from locations in lower elevations. While there is a weather station in Crestline – i.e., the Lyman/Leistra Weather Station – this weather station is not included in Cligen. As an alternative, a Cligen weather file was generated based on the weather station at Lake Arrowhead, California. Lake Arrowhead is about 3.5 miles to the east of Lake Gregory, and, based on summary statistics from the Lyman/Leistra Weather Station in Crestline, the average temperature and rainfall in the Lake Arrowhead region are about 93% and 94%, respectively, of the corresponding values in Crestline.

Similar to the basal flow parameter for stream modeling, Gleams-Driver requires an initial water depth, minimum water depth, and maximum water depth. The values used for these parameters, specified in Table 1, are based on the USGS monitoring statistics. Internally, the depth values are used by Gleams-Driver to calculate water volumes based on depth and the specified surface area of the lake. The Gleams-Driver simulations are started with the initial water volume based on the initial depth specified by the user. For the Gleams-Driver simulations of Lake Gregory, each simulation was conducted over a 5-year period in order to give the reservoir sufficient time to reach a pseudo-steady state. Only the last year of the simulation was used for comparison to the monitored values reported by USGS. Thus, the initial water volume has no impact on the analysis.

The minimum depth was set at 4.9 meters. The surface area of Lake Gregory is 84.3 acres (341,162 m^2). Thus, the initial depth resulted in a minimum water volume of about 1.7 million m^3 or 1.7×10^9 liters. This value was selected to be below the minimum volume for Lake Gregory based on the data reported by USGS. The minimum water volume reported in the USGS data file for Lake Gregory over the period from 1989 to 1993 is 1900 acre-feet. This value is equivalent to 6.19×10^8 gallons (1 acre foot = 3.258×10^5 gallons) or about 2.34×10^9 liters (1 gallon = 3.785 L). Thus, the expectation in setting the minimum water volume for modeling at a factor of about 70% of the minimum volume reported by USGS is that the minimum would not be reached in the Gleams-Driver simulations.

The maximum depth for the Gleams-Driver modeling was set at 8.3 meters, equivalent to a water volume of about 2.83×10^9 liters [8.3 m x 341,162 m^2 x 1000 L/m^3] or 2,296 acre-feet. This value was selected to be only slightly higher than the maximum recorded values of 2,290 acre-feet in the USGS data on Lake Gregory.

For Lake Gregory, 100 Gleams-Driver simulations were conducted with each simulation covering a 5-year period. Because of the larger drainage area of Lake Gregory (1,700 acres) relative to Bull Creek (420 acres), it was anticipated that a longer period of time might be required for the transfer factor for percolation to approach a pseudo-steady state. Only the last year of each simulation was used for comparing the Gleams-Driver simulations to the USGS monitoring data. As with the Bull Creek simulation, all model input parameters were held constant and the only variability among the simulations involved the different weather patterns from Cligen.

2.1.3. Modeling Results

The comparison of the Gleams-Driver modeling to the USGS monitoring data are illustrated in Figure 1 for Bull Creek and Figure 2 for Lake Gregory. These two figures illustrate that comparison in slightly different ways because of the differences in the available monitoring data from USGS.

2.1.3.1. Bull Creek

The stream flow data on Bull Creek spans a 13-year period from 1994 to 2006. Rather than plotting each of the 13 years for which monitoring data are available, the monitoring data for Bull Creek are illustrated in Figure 1 with thin solid lines illustrating the median value and the 5th and 95th percentiles. The modeled estimates from the 200 Gleams-Driver simulations are illustrated with thick dashed lines also indicating the median value and the 5th and 95th percentiles. As noted in Table 1, this simulation of stream flow used a first-order loss rate of 0.05 day^{-1} for the percolation buffer. In other words, the percolate (water lost below the root zone) was added to the percolation reservoir each day and then 5% of the total water in the percolation reservoir was added to that day's stream flow. The 0.05 day^{-1} loss rate was estimated by visual examination of the output from exploratory runs (typically involving 20 simulations).

For the most part, the Gleams-Driver simulations reflect the observed patterns in stream flow rates based on median values (i.e., central estimates). The greatest discrepancies in the central estimates occur during the fall, from about October 1 to mid-November. During this period, the median observed values tend to be less than the median modeled values but the magnitude of the difference is within a factor of 5. At the extremes, Gleams-Driver tends to overestimate the lower 5th percentile over much of the year (i.e., from about October to May), and the difference can reach nearly a factor of 8 in early March. At the upper limit of flow (the 95th percentile), Gleams-Driver underestimates stream flow from about mid-June to early October, and the magnitude of the difference can approach a factor of 10.

2.1.3.2. Lake Gregory

The comparison of Gleams-Driver simulations of the water volume in Lake Gregory to the observations reported by USGS is given in Figure 2. For Lake Gregory, the USGS reports data only over the 4-year period from 1989 to 1992. Consequently, Figure 2 illustrates the daily water volumes for each of the 4 years reported by USGS (dashed lines) along with median daily water volume and 5th and 95th percentiles of the daily water volumes modeled by Gleams-Driver (solid lines).

As noted in Table 1, the Gleams-Driver simulations illustrated in Figure 2 for Lake Gregory are based on a percolation loss rate, 0.0075 day^{-1}, which is lower by a factor of about 6.6 than the loss rate that was used for Bull Creek (0.05 day^{-1}). Intuitively, this difference is to be expected because of the differences in the area of the two water sheds, with the water shed for Lake Gregory (1702 acres) greater than the watershed for Bull Creek (422.4 acres) by a factor of about 4.

As with the Bull Creek sites, the percolation loss rate of 0.0075 day^{-1} was estimated from exploratory model runs, typically involving about 20 simulations per run. These exploratory runs clearly indicated that the percolation loss rate needed to be much lower than the corresponding value for Bull Creek, which is not surprising since the size of the drainage area for Lake Gregory is much larger than that for Bull Creek. Initially, the exploratory runs were conducted over a 2-year period in order to determine if this was adequate for pseudo-steady state between the reservoir and the lake. These exploratory runs suggested that this might not be the case. Based on the plateau principle (SERA 2007a, Eq. 3-8, [$X_0/X_{Inf} = 1-\exp(-k\ \Delta t)$]), uniform rainfall patterns would be expected to reach only a proportion of 0.93 of an eventual steady-state plateau at a loss rate of 0.0075 day^{-1}.

Natural rainfall patterns are, of course, not uniform and it was apparent that 2 years would not be an adequate period for the simulation. Consequently, the simulations for the final run illustrated in Figure 2 are based on 5-year runs in which only the last year is used for comparison to the USGS data. Again using the plateau principle, a 4-year period would be expected to reach a fraction of 0.99998 of an eventual pseudo-steady plateau. Consistent with this application of the plateau principle, a visual examination of the output of exploratory model runs suggested that the 5-year period for the model runs was adequate, which was confirmed by the final simulation.

Like most ponds and lakes, Lake Gregory has a peak water volume because excess water flows from the lake to a creek. This characteristic is particularly prominent for Lake Gregory because Lake Gregory is an artificial lake whose water level is regulated by a dam on the northern shore of the lake. Because of this artificial system, the median and 95^{th} percentile water volumes modeled by Gleams-Driver tend to be very close to each other over most of the year, diverging substantially only from late spring to early fall.

Nonetheless, the range of modeled water volumes between the 5^{th} percentile and median values encompass the 4-year set of observed water volumes from the USGS data. There are obvious and substantial differences in the reported values from USGS among the 4 years. The last 2 years (1991 and 1992) involve consistently greater water volumes than the first 2 years (1989 to 1990) from about April through January. The 1991 and 1992 water volumes from the USGS data are very well mimicked by the median values from Gleams-Driver. Water volumes for the first 2 years, are encompassed by the median to 5^{th} percentile values form Gleams-Driver. Water volumes from January to about April follow a more scattered pattern but again are encompassed by the 5^{th} percentile to median values from Gleams-Driver.

As noted in Section 2.1.2.2, the minimum water volume used as an input to the Gleams-Driver simulation was set at 1.7×10^9 liters (below the minimum volume from the USGS data) under the expectation that water volumes modeled by Gleams-Driver would remain above this minimum value. Consistent with this expectation, the water volumes for Lake Gregory modeled by Gleams-Driver are well above 1.7×10^9 liters.

2.2. Field Studies Involving Pesticide Applications

As discussed further in Section 3.1, many field studies have been conducted to evaluate GLEAMS. These studies primarily involve controlled applications of pesticides with measurements of pesticide concentrations in runoff water, percolate, and sediment. Most field studies on pesticide contamination in ponds and streams, however, involve either direct application to water (e.g., aquatic herbicides) or cases in which ponds or streams are contaminated by misapplication (e.g., spills) or drift from aerial applications.

While contributions from drift are accommodated by Gleams-Driver, the primary focus of the current exercise is to assess the post-processing of the output from GLEAMS. For the current evaluation, two field studies were selected: Wood (2001) and Frazier and Grant (2003). The

Wood (2001) study is relevant because it provides detailed information on runoff from roadside applications of sulfometuron methyl. Wood (2001), however, did not detect sulfometuron methyl in the stream. The Frazier and Grant (2003) report involves stream monitoring data from the Stanislaus National Forest after the application of hexazinone. This report is less controlled than the Wood (2001) study in that monitoring reported by Frazier and Grant (2003) was associated with an actual reforestation project as opposed to a smaller scale and more controlled experimental application as in the Wood (2001) study. The monitoring study from the Stanislaus National Forest, however, did detect hexazinone in streams over a prolonged period, approaching 5 years.

2.2.1. Bull Creek Application of Sulfometuron Methyl (Wood 2001)

2.2.1.1. Study Summary

The USGS conducted a study on the potential impact of roadside herbicide applications to water quality in streams (Wood 2001). The study was conducted near the intersection of Bull Creek and Highway 211 near Colton, Oregon. Wood (2001) involves the roadside application of four pesticides: diuron, bromacil, glyphosate, and sulfometuron methyl and measures concentrations in runoff after artificial irrigation (to simulate both natural rainfall as well as runoff from the roadway) and natural rainfall.

The first application was made on May 19, 1999 and involved simulated rainfall; the second application was made on September 28, 1999 and involved natural rainfall. As noted by Wood (2001), analyses of water samples at very low pesticide concentrations can be very imprecise. Moreover, the results reported in the publication … *are semiquantitative in nature*… and … *can be relied on only for order-of-magnitude representations of concentrations*.

Only sulfometuron methyl is included in the current evaluation of Gleams-Driver. As discussed by Wood (2001), both diuron and bromacil were found in both treated as well as control areas indicating other confounding sources of these herbicides. Glyphosate is not considered because glyphosate was detected only in runoff from the road side after artificial irrigation. No glyphosate was detected in a drainage ditch next to the application site or in the stream after natural rainfall. As discussed below, the artificial rainfall/irrigation phase of the Wood (2001) study is used to calibrate Gleams-Driver so that runoff, ditch, and stream contamination can be estimated.

In the simulated rainfall experiment, the herbicides were applied to three specially designed 5-foot by 10-foot areas from which runoff water could be collected (see Figure 3, p. 10, in Wood 2001). The soil in the treated areas is characterized as *"almost entirely sand and gravel"* (Wood 2001, p. 9). No slope is specified. Based on the cover illustration to the report, a slope of 0.02 is used in all Gleams-Driver simulations. The targeted application rate was 0.26 kg a.i./ha for sulfometuron methyl. Based on absorbent monitoring sheets, the actual application rate for sulfometuron methyl was 0.15 kg a.i./ha (0.13 lb a.i./acre). For the evaluation of Gleams-Driver, only the measured application rate is used.

After the May 19 application in the simulated rainfall phase of the study, each of the three test plots were subject to simulated rainfall at the rate of 0.3 inches per hour. In addition, perforated hoses were used to simulate runoff from the adjacent road to the test plots. The simulated rainfall was applied on three occasions at one week intervals starting one day after the application of the herbicides.

The Wood (2001) study does not specify the total amount of simulated rainfall and runoff at each of the three test plots. Wood (2007) was kind enough to provide this information for the current analysis, and the volumes of irrigation water applied to and the volumes of runoff collected from each of the three test plots are summarized in Table 2. GLEAMS considers rainfall but does not directly accommodate runoff water from adjacent sites such as the roadway in the Wood (2001) study. Therefore, estimates of artificial rainfall and artificial runoff were combined and treated only as rainfall.

2.2.1.2. Model Calibration

GLEAMS and hence Gleams-Driver require many specific input parameters for site and soil characteristics as well as weather (Durkin and Knisel 2007). Most monitoring studies, including Wood (2001), do not provide the specific detailed information on site characteristics and soil properties that must be used as model inputs. Consequently, the data on runoff concentrations from experimental plots with artificial rainfall were used to calibrate Gleams-Driver. In other words, the general description of the site – i.e., location, areas, and soil characteristics – were used to guide model inputs; however, the inputs were adjusted to reflect the differences among the three sites in a manner that reflected the runoff concentrations from the experimental plots.

As noted by Wood (2001), the road shoulder consisted primarily of sand and the surrounding soil consisted primarily of well-drained silt loam. Sand will typically have a low runoff potential and would be classified as Hydrologic Group A. Preliminary simulations with Gleams-Driver using default soil parameters indicated that predominantly sand soil textures would not result in any runoff under the conditions used in the artificial rainfall study. For a roadside application conducted by Wood (2001), however, substantial runoff is apparent and the runoff is probably associated with compaction of the soil during road construction. While the three test plots were similar to each other in the type of soils and general plot descriptions, Wood (2001) notes that test plots 2 and 3 were more highly vegetated than test plot 1. In addition, test plot 1 consistently exhibited greater runoff volumes than test plots 2 and 3 by factors of about 2 to 4 (Table 2). Vegetative cover would indicate more root activity on plots 2 and 3 that would result in higher porosity and less runoff than on plot 1.

In order to calibrate Gleams-Driver to the test plots from the artificial rainfall study by Wood (2001), adjustments were made to some default soil parameters (Table 3) and site parameters (Table 4). To reflect the general site characteristics described by Wood (2001), all simulations were conducted using two soil horizons, a top 12 inch layer of sand and a bottom 48 inch soil layer of silt loam. Wood (2001) does not discuss the depth of the sand soil layer, and 12 inches was selected to represent a plausible layer of sand that would be used in road construction. The 48 inch depth of the silt loam soil layer reflects the 60 inch total root zone used as a default in Gleams-Driver.

The adjustments to the soil parameters involved changes to the SCS curve numbers, porosity, and organic matter. All other soil parameters were treated as fixed values from the defaults for sand and silt loam soil textures used in Gleams-Driver (Table 3).

The SCS curve numbers were adjusted to values that are generally associated with Hydrologic Group D – i.e., soil with a high runoff potential. As summarized in Table 3, test plot 1 was calibrated to SCS curve numbers of 93 to 100 and test plots 2 and 3 were calibrated using somewhat lower SCS curve numbers to reflect the lower fractional runoff noted by Wood for these sites (Table 2). Wood (2001) observed that herbicide concentrations in runoff … *exhibited random variability rather than a trend with time* (Wood 2001, p. 16). Gleams-Driver does accommodate Monte Carlo analyses, and the range of SCS curve numbers given in Table 3 for each site is based on exploratory simulations using point estimates (single SCS curve numbers), which reflects the central estimates of runoff concentrations followed by preliminary simulations with ranges of SCS curve numbers that reflect the variability observed by Wood (2001). A similar approach was taken to adjustments in soil porosity – i.e., preliminary runs using point estimates are followed by preliminary simulations to reflect the variability observed by Wood (2001). Both SCS curve numbers and values for porosity were modeled with uniform distributions.

A somewhat different approach was taken to modeling organic matter in the soil. As discussed in SERA (2006b), the USDA/ARS Pesticide Properties Database (USDA/ARS 2006) contains information on numerous pesticides, including the percent organic matter in several soils. A total of 43 unique values are available for sand, and 55 unique values are available for silt loam. Using the standard approach for converting organic matter to organic carbon (e.g., Knisel and Davis 2002, p. 30), the organic matter values for sand and silt loam were converted to organic carbon and the distribution of these values was found to fit a lognormal distribution (SERA 2006b, Table 6). As indicated in Table 3, these distributions were used in both the calibration to the artificial rainfall studies as well as the simulation of the natural rainfall monitoring.

Adjustments to site parameters involved the GLEAMS parameters designated as CFACT (soil loss ratio), PFACT (contouring factor), and Manning's "n" (Table 4). These values were adjusted to reflect that qualitative description in Wood (2001) concerning the differences in vegetative cover between test plot 1 and test plots 2 and 3. As detailed in Knisel and Davis (2001), these factors primarily impact sediment loss. In measures of sulfometuron methyl in runoff, Wood (2001) used filtered water in which most of the sediment would be removed. In addition, Gleams-Driver simulations indicated that sediment losses were negligible (less by factors of about 10,000), relative to runoff loss. Thus, the adjustments in the site parameters had relatively little impact on the concentrations modeled in runoff water.

In addition to uncertainties in site and soil parameters, uncertainties exist in estimates of chemical properties for sulfometuron methyl (Table 5). In terms of modeling with Gleams-Driver, the most important parameters are the Koc and soil half-life. The reported Koc values for sulfometuron methyl do not vary over a wide range (SERA 2004b). For the current analysis, the Koc values for sulfometuron methyl were modeled with a triangular distribution using a mode of 78 mL/g (Knisel and Davis 2000) and bounds of 61-122 mL/g from the USDA/ARS

Pesticide Properties Database (USDA/ARS 2006). The same approach was used for modeling uncertainties in soil half-lives with a mode of 20 days (Knisel and Davis 2000) and a range of 20-100 days from the USDA/ARS Pesticide Properties Database. While the Koc values and soil half-lives are incorporated into the Monte Carlo analysis to reflect the variability noted by Wood (2001), these parameters are not part of the calibration. In other words, the Koc and soil half-lives are based on experimental observations and are not further adjusted to fit the observations by Wood (2001) in the artificial rainfall component of the study.

The Cligen weather files were generated using the approximate location of the treatment site (45.106 latitude and -122.29 longitude) and a random number seed of 1. For the artificial rainfall component of the study, the first year of the Cligen weather file was manually edited to reflect both the artificial rainfall/runoff on May 20, May 26, and June 3 as well as the naturally occurring rainfall on May 25 (0.02 inches) and May 30 (0.22 inches). The same year – i.e., the first year in the Cligen file – was used to generate separate weather files for each of the three plots. Thus, the only differences in the artificial rainfall simulations among the three test plots are the different amounts of water applied to each plot as specified in Table 2. The modified Cligen text files were then imported to a properly formatted Microsoft Access database, using the Cligen Import utility in Gleams-Drivers (Durkin and Knisel 2007, Section 6.1.1). As with the chemical properties, the rainfall files are not varied or otherwise adjusted to calibrate Gleams-Driver other than to reflect the irrigation and natural rainfall events in the Wood (2001) study.

The treated area is taken at 0.00092 acres based on the description of the treated area of the experimental plots in Wood (2001) – i.e., 10 ft x 4 ft = 40 sq ft, acre = 43560 sq ft., 40/43560 = 0.0009183 acres. For estimating runoff concentrations from the experimental plots in the artificial rainfall component of the study, the size of the untreated area does not matter because only the treated area is modeled.

For the simulated rainfall experiments, 200 simulations were conducted for each test plot. The weather sets did not vary in these simulations – i.e., the simulated rainfall as well as the reported natural rainfall were held constant to the values reported by Wood (2007). Thus, the variability in the results are based only on the variability in soil parameters (Table 3), site parameters (Table 4) and chemical parameters (Table 5).

The results of the calibration of Gleams-Driver to the artificial rainfall study by Wood (2001) are illustrated in Figure 3. The experimental observations are taken from Figure 4 in Wood (2001) and imported into GrafReader, an EXCEL utility for converting graphical data to coordinate values. A copy of this utility is available at www.sera-inc.com.

For Week 0 (the day after application), the median values as well as the 5^{th} and 95^{th} percentiles from the Gleams-Driver simulations closely approximates the median values and ranges of observations reported by Wood (2001). For week 1 after treatment, the median of the simulations for test plot 2 are also relatively close to the median value reported in Wood (2001). The median concentrations are slightly overestimated for test plot 1 (an observed median value of about 49 ppb versus a modeled median value of about 84 ppb) and slightly underestimated for test plot 3 (an observed median value of about 35 ppb versus a modeled median value of about 22 ppb). The magnitude of these differences is less than a factor of two which is relatively small compared to the variability reported by Woods (2001) as well as the variability modeled by Gleams-Driver. For week 2 after treatment, the simulations based on Gleams-Driver encompass the range of values reported by Wood (2001). The differences between the median modeled and median monitored values at week 2 are somewhat more substantial – i.e., a factor of about 3 for plot 1, 1.6 for plot 2, and 2.9 for plot 3. Further adjustments to the soil and site parameters could have been made to more closely calibrate the Gleams-Driver simulations to the test plots; nonetheless, the results summarized in Figure 1 are sufficient for the calibrating the Gleams-Driver model to the observed duration of natural rainfall (Section 2.3.3).

2.2.1.3. Simulation of Natural Rainfall Events

For the natural rainfall component of the study, the site parameters and soil parameters were taken as a composite of the values used to calibrate Gleams-Driver to the artificial rainfall component of the study. It should be noted that GLEAMS is written to accommodate a homogenous field – i.e., a field with only one set of site and soil parameters. For example, only a single SCS curve number (CN2) can be used in a single GLEAMS run even though different parts of a field may have different runoff characteristics.

The uncertainties and limitations involved in modeling a homogenous field are well illustrated in the Wood (2001) study with artificial rainfall. The three experimental plots were close to each other and along the same road shoulder with similar gross site characteristics. However, as illustrated in the artificial rainfall component of the study by Wood (2001), each site required somewhat different parameters in order to calibrate Gleams-Driver.

In the natural rainfall component of the study, a 0.7 mile length of the road shoulder was treated, and this area included the three test plots. As detailed in Table 2 (soil parameters), the SCS curve numbers and values for soil porosity used in simulation of the natural rainfall component of the Wood (2001) study are taken as uniform distributions that encompass the range of values used in the calibration of Gleams-Driver to artificial rainfall component of the study with only minor modification. All other soil input parameters are identical to those used in the model calibration.

The only adjustments made to the site parameters (Table 4) involved the specifications of the total area treated with sulfometuron methyl and the size of the untreated area. For the natural rainfall study, the treated area is taken as 0.68 acres. This is based on the description in Wood (2001) that the total treated area was approximately 4 feet by 0.7 miles (see Wood 2001 Table 4 for the width and p. 11, column 2, paragraph 2 for the length). For one side of the road, this 0.7 mile length corresponds to about 0.34 acres – i.e., 4 ft x 0.7 miles x 5280 feet/mile = 14784 ft^2 x acre/43560 ft^2 = 0.34 acres. Since both sides of the road were treated, the total treated area was about 0.68 acres.

Wood (2001) provides measures of the water flow rate in Bull Creek (Table 12, p. 20 in Wood 2001). In the study, the values for stream flow rates are expressed in units of ft^3/s. Gleams-Driver provides estimates of stream flow in units of liters per day (L/day). Units of ft^3/s were converted to units of L/day using the conversion factor of 2,446,848 L/day per ft^3/s [ft^3/s x 28.32 L/ft^3 x 86,400 s/day = 2,446,848 L/day]. In Gleams-Driver, modeled flow rate is based on the total size of the total drainage area – i.e., the area of the treated field as well as the area of the untreated field that drains into the body of water. The total size of the drainage area for the stream is taken as 3200 acres (Table 4). The size is based on the description in Wood (2001) that the total size of the watershed for Bull Creek at the treated site is about 5 square miles – i.e., 5 sq miles x 640 acres/sq mile = 3200 acres. Gleams-Driver allows the user to specify the proportion of percolate that contributes to stream flow. Wood (2001) provides no information that is useful for assessing this parameter. For the simulations of natural rainfall, the default value in Gleams-Driver, 100% of percolate, was used.

For the natural rainfall component of the study (Section 2.1.3), a 1000-year weather simulation was generated using the Cligen 5.2 file. This simulation was imported into Gleams-Driver, and a random number seed of 1 was used, as done with the artificial rainfall file and all other simulations.

A total of 200 simulations were conducted in which the soil and chemical parameters varied as in the artificial rainfall simulations and the climate simulations from Cligen were also varied with each simulation. No sulfometuron methyl was detected in stream water at the level of detection in the Wood (2001) study. Thus, Gleams-Driver can be evaluated only in terms of whether or not concentrations would have been expected to exceed the detection limit over the course of the simulations.

The monitored and modeled estimates of sulfometuron methyl in the natural rainfall component of the Wood (2001) study are illustrated in Figure 4. In this phase of the study, sulfometuron methyl was applied on September 28 but the first monitoring occurred on October 27. Because no monitoring data are available prior to October 27, the modeled estimates of the concentration of sulfometuron methyl in runoff water shortly after application are not illustrated in Figure 4.

Two sets of monitored concentrations are given in Figure 4. The diamond shaped symbols represent concentrations of sulfometuron methyl in runoff water from the roadside. These concentrations are analogous to the runoff concentrations given in the artificial rainfall component of the study. The triangle symbols represent concentrations in the drainage ditch immediately adjacent to the road shoulder.

As illustrated in Figure 4, the concentrations in the runoff from the road shoulder are quite similar to the concentrations in the ditch below the road shoulder. While not detailed in the current report, Wood (2001, Figure 6) also noted similar concentrations of diuron in both the road shoulder and the adjacent drainage ditch. In discussing these similarities, Wood (2001, p. 19, col. 2) notes that most of the water entering the drainage ditch adjacent to the roadway came from the roadway itself rather than the untreated area on the other side of the drainage ditch. A preliminary set of simulations using Gleams-Driver were conducted on this untreated area based on vegetated silt loam with properties similar to the silt loam soil layer detailed in Table 3. Consistent with the observations of Wood (2001), the simulations indicated no runoff water from the silt loam soil based on median values.

In Figure 4, the median modeled values from the Gleams-Driver simulation of the natural rainfall component of the Wood (2001) study are represented by a solid line, and the 5^{th} and 95^{th} percentiles are represented by dashed lines. All monitored concentrations are encompassed by the 5^{th} and 95^{th} percentiles. The median values for the simulation somewhat overestimate the monitored concentrations on October 27, very closely approximate the monitored concentrations on November 16, and only modestly underestimate the concentrations for the later dates – i.e., November 26 to January 10. While the median modeled values are somewhat erratic, reflecting essentially random differences in rainfall patterns from day to day, it is interesting to note that the monitored values indicate very little change in concentrations. Furthermore, this plateau is also reflected in the median values from the Gleams-Driver simulation over the period from about November 16 to January 10. This plateau in concentrations during the natural rainfall phase of the study is in contrast to the generally steady declines in monitored and modeled concentrations in the artificial rainfall study (Figure 3).

In terms of the practical use of Gleams-Driver for estimating concentrations in surface water, the stream data provided by Wood (2001) are most relevant. Wood (2001) provides data on both stream flow (Wood 2001, Table 12, p. 20) as well as the results of stream monitoring for sulfometuron methyl (Wood 2001, Figure 6, p. 21).

Gleams-Driver does not currently accommodate ephemeral or transient streams. The Gleams-Driver estimates of stream flow are based on a basal flow rate as well as the amount of water entering the stream from direct rainfall, runoff, and percolation. For the simulation of the Wood (2001) study, a basal flow rate of 1,000,000 L/day was selected. This basal flow rate is about one-third of the lowest flow rate reported by Wood (2001) – i.e., 1.2 ft^3/s or about 2,935,218 L/day. Figure 5 illustrates the flow rates modeled by Gleams-Driver relative to the reported flow rates in Wood (2001). Based on central estimates, Gleams-Driver substantially overestimates the initial flow rate of about 3 million L/day reported by Wood (2001) for November16. The stream flow rates modeled for November 25 and December 16 are virtually identical to values reported by Wood (2001), and the modeled stream flow rate for January 10 is slightly underestimated – i.e., a factor of about 1.9.

The initial flow rate for Bull Creek reported on Nov 16 is about a factor of 10 lower than the other reported flow rates measured on and after November 25. Based on the results of the Gleams-Driver modeling, the low flow rate reported by Wood (2001) for Nov 16 is well below the median value but within the range of expected values based on Cligen simulations.

The relatively small underestimates of stream flow from for these latter dates may be related to the actual rainfall patterns reported by Wood (2001), compared with the rainfall patterns simulated by Cligen. Wood (2001) reported a cumulative rainfall of 18.6 inches between October 29 and January 10, the period over which stream flow rates were measured. The Cligen 5.2 weather simulation for the Bull Creek site, however, estimates an average cumulative rainfall of about 37.4 inches over the same period. Thus, while the rainfall reported by Wood (2001) is not atypical and is encompassed by the variability in rainfall rates predicted by Cligen, the year in which the Wood (2001) study was conducted had a cumulative rainfall of about 2-3 inches less than the average rainfall simulated by Cligen.

Wood (2001) monitored water samples from Bull Creek down stream of the application site during November, December, and January and found no sulfometuron methyl at a detection limit of 0.06 ppb (Wood 2001, p. 20). As illustrated in Figure 6 of the current report, the failure to detect sulfometuron methyl at concentrations greater than the detection limit is consistent with the Gleams-Driver modeling. Based on the upper bound of peak concentrations of sulfometuron methyl modeled using Cligen weather files over the monitoring period for the downstream site (i.e., November 25 to January 10), the maximum expected concentration is about 0.017 ppb, below the limit of detection by a factor of about 3.5. The highest central estimate of the sulfometuron methyl concentration in the stream over this period was modeled at about 0.00045 ppb, which is below the limit of detection by a factor of over 130. Thus, the modeling of Bull Creek using Gleams-Driver calibrated to the experimental plots is consistent with the failure to detect sulfometuron methyl in the stream.

2.2.2. Stanislaus National Forest Application of Hexazinone (Frazier and Grant 2003)

2.2.2.1. Study Summary

The Stanislaus National Forest is located in the west-central region of California. As with many western forests, the Stanislaus is subject to wildfires. After a series of wildfires from 1987 to 1996, the Forest Service initiated a reforestation project covering 21,400 acres. Details of this effort are presented in a report by Frasier and Grant (2003). The reforestation effort involved the application of three herbicides – i.e., hexazinone, glyphosate, and triclopyr – as well as a monitoring program to assess levels of these pesticides in surface and ground water.

Two applications of hexazinone, one to a tributary of Moore Creek and the other to a tributary of Jordan Creek resulted in detectable levels of hexazinone in creek water over a period of several years. While the initial concentrations in the surface water may have been due to drift, the longer term concentrations can be most clearly associated with off-site movement due to rainfall – i.e., sediment loss, runoff, and percolation. Because of the long term monitoring program, these sites are well suited to the evaluation of Gleams-Driver.

The highest concentrations of hexazinone were observed in the Moore Creek tributary and reached approximately 600 ppb during the post-application period (Figure 7, p. 19 in Frasier and Grant 2003). This incident was investigated in detail, and the Forest Service noted a number of factors at this site, including very shallow soil layers, that may have contributed to the unusually high concentrations in stream water. The initial post-application concentrations in the Jordan Creek tributary peaked at substantially lower levels of about 67 ppb with maximum concentrations of about 36 ppb several months after application (Figure 9, p. 20 in Frasier and Grant 2003). While either site could have been modeled, the Jordan Creek tributary was selected because it presented an apparently more uniform set of field conditions.

A topographical map of the treatment area in the Jordan Creek tributary is given in Figure 7. The tributary itself is indicated by the thick solid line (blue). It is located in a well-defined 47 acre catchment (outlined in thick dashed red lines in Figure 7). The catchment drains into the west side of southern section of Jordan Pond. The monitoring station (referred to as 97-JD-T2 in report by Frazier and Grant) was located near the base of the tributary near a roadway on the western side of Jordan Pond.

The entire 47 acre catchment was treated with granular hexazinone at an application rate of 3 lbs a.i./acre by aerial application on March 17, 1997. The application involved Pronone 10 G, a granular formulation of hexazinone. As detailed in the Forest Service risk assessment for hexazinone (SERA 2005), Pronone 10 G contains 10% hexazinone and consists of insoluble clay-based material that is surface coated with hexazinone.

The monitoring data for the site is illustrated in Figure 8. Hexazinone was detected in the creek water on March 12 and 17, 1997 prior to application at low concentrations (about 0.14 ppb). During application, the concentrations of hexazinone in the tributary were monitored at 41-67 ppb indicating that at least some hexazinone was applied to the stream either by misapplication or drift. Prior to January 12, 1998, no hexazinone was monitored in the stream except for a 0.11 ppb concentration recorded on December 12, 1997. During a series of storms between January 12 and February 2, 1998, monitored concentrations ranged from about 5 to 36 ppb. Subsequent monitoring up to January 23, 2001, resulted in periodic detections of hexazinone that occurred primarily during storm events with the concentrations gradually declining over time. As in the monitoring study by Wood (2001), the concentrations of hexazinone in the Jordan Creek tributary on any given day were highly variable, spanning over one order of magnitude – i.e., concentrations monitored on February 2, 1999 ranged from 0.4 to 5 ppb.

2.2.2.2. Approaches to Gleams-Driver Simulations

The report by Frasier and Grant (2003) provides detailed information on the location of the site, herbicide application, as well as long term monitoring. Nevertheless, the Frasier and Grant (2003) study, like the Wood (2001) study, does not provide information on the many input parameters required by GLEAMS and Gleams-Driver.

For the evaluation of Gleams-Driver, two different modeling approaches were used that roughly correspond to the Quick Run and Full Run modes in Gleams-Driver. The Quick Run simulation relied primarily on default values for site, soil, and chemical specific inputs. The Full Run simulation made a greater effort to obtain site-specific information and to incorporate uncertainties in key chemical specific inputs.

Like Lake Gregory, the Jordan Creek site is in a mountainous area. In order to avoid problems associated with the interpolation of nearby weather stations in lower elevations, as was encountered in the modeling of Lake Gregory, a Cligen weather file was generated for the Yosemite National Park weather station that is included in the WEPP interface for Cligen. Yosemite is about 25 miles to the east of the Jordan Creek tributary. This weather file was used in both the Quick Run and Full Run simulations.

Table 6 summarizes the general site characteristics used in Gleams-Driver to model the Jordan Creek site. The site location was verified by Frasier (2007), and the gross site characteristics – e.g., field dimensions and slope – were estimated from satellite images.

The tributary for Jordan Creek is not included in the USGS database, and there is no detailed information regarding the flow rates for the tributary. Frasier (2007) kindly provided the following estimates:

> *Tributary JD-T2 is characterized as a small intermittent stream, running during the wet season (usually beginning in November-December) and continuing to flow into mid summer before drying up until the next wet season. … estimate average peak winter flow is probably 2-3 cfs and low flow in summer can drop as low as about .05 cfs (~20 gpm).* [2-3 cfs = 800 to 1200 gpm]

A flow rate of 20 gallons per minute is equivalent to 109,008 L/day. For the Quick Run simulation, the 109,008 L/day flow rate was used as the basal flow rate for the stream. In an effort to determine how well Gleams-Driver models the low flow characteristics of the tributary – i.e., drying up in mid-summer – the basal flow for the Full Run simulation was set at 10,900, a factor of 10 below the low flow estimate from Frazier (2007). This approach is taken in the Full Run because Gleams-Driver does not currently accommodate transient streams.

The peak flow rate 2-3 cfs (cubic feet per second) corresponds to about 4,900,000-7,300,000 L/day. These peak rates are not used directly in the Gleams-Driver but are used to assess the plausibility of the flow rates that are modeled by Gleams-Driver, as detailed below.

The information on the general soil classification – i.e., loam – was obtained from the NRCS web site at http://websoilsurvey.nrcs.usda.gov/app/. As summarized in Table 7, the Gleams-Driver default properties for loam were used in the Quick Run simulation. For the Full Run simulation, ranges were used for porosity and wilting point and the ranges were defined by the range between Gleams-Driver default values and the values reported by NRCS. This approach to approximating variability is admittedly crude; yet, the values reported by NRCS do not differ substantially from the Gleams-Driver defaults for loam. As illustrated by Wood (2001), measured values for soil properties at a particular location in a field might not reflect the soil properties at other nearby sites in a field. In the absence of specific information on the variability of the soil properties at the treated site, the range based on Gleams-Driver defaults and NRCS values is taken as an objective method to approximate variability in soil properties. Field capacity was not varied in the Full Run simulation because the value reported by NRCS (0.26 in^3/in^3) is remarkably close to the default value in Gleams-Driver (0.27 in^3/in^3). Similarly, the values for the percent of silt in soil differ very little between the Gleams-Driver default for loam (35%) and the value reported by NRCS (34%). There is a more substantial difference, however, between the Gleams-Driver default for the proportion of clay (20%) and the value reported by NRCS (30%). This range was not used in the Full Run simulation because Gleams-Driver does not accommodate Monte Carlo analysis of the proportions of clay, silt, and sand in soil.

While uniform distributions are used for most of the input parameters in the Full Run simulation, the proportion of organic matter in the soil is modeled using a lognormal distribution based on the analyses of 32 samples of loam soils in SERA (2006b).

A further complication in the modeling of the Jordan Creek tributary involves the use of a granular formulation. As detailed in the Forest Service risk assessment of hexazinone (SERA 2005), granular applications of hexazinone will differ from liquid applications in that the formulation of the hexazinone in a clay matrix may retard the release of hexazinone, relative to liquid applications. In the current application of Gleams-Driver, the granular application was mimicked in the same manner used in the Forest Service risk assessment. An incorporation depth of 1 cm was used and several of the soil characteristics for this top layer were set to the value for clay rather than loam. An exception to this adjustment involves the saturated conductivity of the soil. Because the Pronone particles do not blanket the soil to the extent that water flow is inhibited, the saturated conductivity of the top soil layer – i.e., the granules – was not adjusted.

The only other critical input parameter for the Gleams-Driver simulation involves the loss rate for the percolation reservoir. As noted in the discussion of the Bull Creek and Lake Gregory sites, the percolation transfer factors for these two sites were roughly proportional to the drainage areas – i.e., a factor of 0.05 for the 422 acre drainage area of Bull Creek and a factor of 0.0075 for the 1702 acre drainage area of Lake Gregory. The Jordan Creek tributary has a much smaller drainage area, 47 acres. By analogy to Bull Creek, the percolation transfer factor for the Jordan Creek tributary was set at 0.5 day^{-1} – i.e., a 10 fold greater percolation loss rate for an approximately 10 fold smaller area. As detailed in Section 2.2.3, this transfer factor proved to be adequate and no attempt was made to further refine this input parameter. The same percolation transfer factor was used for both water loss and chemical loss.

The application information and chemical properties for hexazinone used in the simulations of the Jordan Creek tributary are summarized in Table 8. The application rate and date are taken directly from the report by Frasier and Grant (2003).

As illustrated in Figure 8, some hexazinone appears to have been directly deposited into the stream during application. Although drift is peripheral to the current evaluation of Gleams-Driver, the initial attempt to model drift in the Quick Run simulation was based on default values of stream width in Gleams-Driver and drift proportion commonly used in Forest Service risk assessments (SERA 2007a). For the Full Run simulation, the width of the stream at the time of application was based on an estimate from Frazier (2007) and the proportion of drift was adjusted based on the results of the Quick Run simulation.

For the Quick Run simulation, the chemical properties for hexazinone were taken from the standard values in the Gleams-Driver database which are in turn taken from the Forest Service risk assessment. As noted in Table 8, there is substantial variability reported in the USDA/ARS Pesticide Properties Database for two sensitive parameters used in the Gleams-Driver modeling, K_{oc} and soil half-life. These ranges were used to define uniform distributions for Monte Carlo analyses in the Full Run simulation.

GLEAMS and hence Gleams-Driver require estimated proportions of pesticide applied to soil and vegetation. In order to mimic the granular application of hexazinone, the assumption was made that a proportion of 0.99 of the hexazinone was applied directly to soil and only 0.01 was applied to vegetation. Again, this is the same approach used in the Forest Service risk assessment on hexazinone.

Each simulation for the Jordan Creek tributary involved a 5-year period from 1997 to 2001. Thus, as with the simulations for Lake Gregory, which also involved a 5-year period, 100 Gleams-Driver simulations were conducted in both the Quick Run and the Full Run. Unlike the case with Lake Gregory, however, the high percolation transfer factor of 0.5 day^{-1} did not suggest a need to model an unused year. Again using the plateau principle, uniform rainfall patterns would be expected to reach only a proportion of greater than 0.99 of an eventual steady-state in only 10 days. This expectation was confirmed in exploratory runs. Given that application did not occur until March 17, 1997, the period from January 1, 1997 to the application day was more than sufficient for the modest percolation buffer to reach pseudo-steady state.

2.2.2.3. Quick Run Results for Jordan Creek

The results of the Quick Run modeling for the Jordan Creek tributary are illustrated in Figure 9. The monitored values, represented by diamonds, are identical to those illustrated in Figure 8 and are based on monitoring tables in the report by Frasier and Grant (2003). The median modeled values are indicated by solid blue lines; and the upper 95th percentile values are indicated by dashed red lines.

In interpreting this figure, it is important to bear in mind how the figures were generated. In the case of the Jordan Creek tributary, 100 simulations were run. Then, the median as well as the lower and upper 5th percentiles were calculated. Thus, while the lines plotted in Figure 9 appear to be relatively smooth, this is an artifact of the process of calculating the medians and percentiles for 100 simulations. The underlying individual simulations, similar to the monitoring data, reflected a very uneven and variable pattern associated with the occurrence of rainfall. The median and 95th percentile plots in Figure 9, simply reflect the most common concentration (the median) as well as an upper bound on the modeled concentration (the 95th percentile) for each day of the 100 simulations.

Given the lack of model calibration and the use of default values for most of the soil and chemical specific parameters, the Quick Run modeling appears to provide a reasonably close approximation to the monitoring data. As discussed above, the initial peak concentrations on March 17, 1997 were associated with drift and have little impact on the evaluation of Gleams-Driver. The assumption that drift was associated with a 1950 sq ft surface area is probably an overestimate but the assumption of drift ratios of 0.05-0.15 appears to be somewhat of an underestimate. As discussed in the following section (Full Run), these parameters are adjusted to better reflect the observed peak values. The ability to calibrate the model to a drift event, however, has nothing to do with the evaluation of the capability of Gleams-Driver to model rain-driven transport from the soil to the adjacent stream.

In terms of the post-application period, the modeled stream concentrations from Gleams-Driver generally reflect the monitoring data. The most prominent deviation occurs early in the post-application period on February 3, 1998. On this day, the upper 95th percentile modeled using Gleams-Driver was about 11.5 ppb while the monitored values ranged from 30 to 36 ppb, higher by a factor of about 3. In the period prior to February 3, 1998, however, the upper bound from Gleams-Driver is very close to the monitored values.

Over the period from about March 28, 1998 to January 20, 2000, the median values from Gleams-Driver are strikingly close to the monitored values. This correspondence is particularly evident in the cluster of points from March 11 to April 15, 1998, which are close to the median values modeled with Gleams-Driver. All but one of the monitored values on January 13, 1999 and February 13, 1999 are close to or below the median values modeled by Gleams-Driver. Albeit less detailed because of the fewer number of monitored values, a similar pattern is noted in the January 11 to January 18, 1999 period in which the median values modeled with Gleams-Driver are close to or above the monitored values.

In terms of a proportionate difference between modeled and monitored values, the greatest deviation occurs on July 14, 1999. On this day, Gleams-Driver modeled an upper 95th percentile concentration of about 0.01 ppb but Frasier and Grant (2003) report a concentration of 0.6 ppb in a single grab sample. Thus, even at the upper bounds of the modeled value, Gleams-Driver underestimates the concentration by a factor of 60.

The last monitored values reported by Frasier and Grant (2003) occurred on October 26, 2000 and January 23, 2001. These monitored values are at the upper bound of concentrations predicted in the Quick Run. These two monitored values, however, are 0.17 and 0.15 ppb, virtually identical to the 0.14 ppb concentration of hexazinone monitored on March 12, 1997 before hexazinone was applied to the catchment of the Jordan Creek tributary.

As noted above, Frazier (2007) provides plausible estimates of flow rates – i.e., a minimum flow rate of about 110,000 L/day during the summer and peak flow rates of about 4,900,000 L/day to 7,300,000 L/day during the rainy season. The flow rates modeled for the Jordan Creek tributary by Gleams-Driver are illustrated in Figure 10 along with the upper bound of the plausible flow rate suggested by Frazier (2007). As illustrated in Figure 10, the flow rate of 7,300,000 L/day was exceeded on only 3 of the 1825 days (<0.2 % of the modeled values).

2.2.2.4. Full Run Results for Jordan Creek

The results of the Full Run modeling for the Jordan Creek tributary are illustrated in Figure 11. The general pattern of the modeled concentrations of hexazinone in the Jordan Creek tributary is similar to those of the Quick Run (Figure 9). While the variability in the Quick Run is due entirely to differences in weather sets – i.e., no other input parameters were varied – the patterns in Figure 11 reflect both differences in the weather sets as well as the variability in several key input parameters, as detailed in Section 2.2.2.2.

The incorporation of this additional variability did create a clear shift in both the upper bound as well as the median concentrations. For the first two post-application years – i.e., 1998 and 1999 – the median modeled concentrations are much closer to the monitored values. In addition, all but two monitored values are encompassed by the 95th percentile modeled concentrations. As with the Quick Run, the concentration monitored on October 26, 2000 is marginally higher than the 95th percentile modeled concentration. This difference, however, is not substantial and occurs during a period in which the modeled concentrations are rapidly rising.

Also, as with the Quick Run, the monitored value of 0.6 ppb on July 14, 1999 is substantially above the 95th percentile of the modeled values. However, as illustrated in Figure 11, the maximum concentration modeled on this day in the Full Run simulation is 0.334 ppb, below the monitored value by less than a factor of 2.

The plausibility of the flow rates in the Full Run simulation can be better assessed than in the Quick Run simulation because of the use of a lower basal flow rate – i.e., about 11,000 liters/minute in the Full Run compared to about 110,000 liters/minute in the Quick Run. The stream flow rates modeled in the in the Full Run are illustrated in Figure 12. Unlike the corresponding figure for the Quick Run (Figure 10), Figure 12 is plotted on a log scale to more clearly show the peak and minimum flows. In Figure 12, the solid thick horizontal line is labeled as “Peak Plausible Flow”. This is the upper bound of the peak flow rate of 7,300,000 L/day given by Frazier (2007). The thick dashed horizontal line somewhat below the peak line is the lower range of the peak flow rate, 4,900,000 L/day, given by Frazier (2007). This line is labeled as “Typical High Flow”. This is not a term used by Frazier (2007) and is used here as a convenience to distinguish this line from the upper bound. Figure 12 also includes a line labeled as “Low summer flow”. This line is the 109,008 L/day flow rate that Frazier (2007) indicates would be characteristic of flows in mid-summer prior to the transient stream running dry. As noted above, Gleams-Driver does not accommodate transient streams – i.e., zero flow. The light dashed horizontal line somewhat above the x-axis in Figure 12 is a flow rate of only 10,900 L/day, the basal flow used in the Full Run simulation of the tributary.

In terms of peak flows, the Full Runs are consistent and virtually identical to the range of peak flows given by Frazier (2007). In each year of the simulation, the stream flow reaches and somewhat exceeds the typical high flow rate and occasionally reaches or is very close to the peak plausible flow. While the Full Run simulation did use a wider and perhaps more representative range of inputs that would impact the model stream flow rates, the simulation is still relatively crude in that no attempt was made to model or fully characterize any heterogeneous field characteristics. For example, the NRCS web site does identify two sets of soils in the drainage area for the stream. The two soil sets, however, are reasonably similar, and the input parameters for the Full Run are based on area weighted averages. Thus, the Full Run is perhaps more representative of the actual drainage area.

While the peak modeled flow rates correspond closely to the estimates from Frazier (2007), a limitation in the Full Run is illustrated in the examination of low flow rates in Figure 12. While detailed dates are not available, Frazier (2007) suggests that the low summer flow rate of 109,008 L/day should be reached in mid-summer followed by a presumably rapid decrease in flow rate to near zero values. The modeled estimates from the Gleams-Driver Full Run do not correspond to Frazier's values in terms of time-frame. In each of the simulation years (involving a total of 500 years), the 95th percentile of the expected flow rate reaches the low summer flow rate at about mid-May rather than mid-July. In addition, the modeled flow rate reaches the basal flow rate (a surrogate in the modeling for a dry stream bed) by mid-June to mid-July.

3. DISCUSSION

3.1. General Considerations

The evaluation of Gleams-Driver has focused on the post-processing of GLEAMS by Gleams-Driver in taking the estimates of sediment, runoff, and percolate losses at the edge-of-field from GLEAMS to estimate concentrations of pesticides in surface water. The specific algorithms used in this post-processing of GLEAMS outputs are detailed in the documentation for Gleams-Driver (Durkin and Knisel 2007, Section 7).

This approach to the evaluation of Gleams-Driver is appropriate because GLEAMS itself is a mature model that has been evaluated using data from numerous field studies over the past several decades. GLEAMS was initially developed in the late 1980's (Leonard et al. 1987) as an extension of another field-scale root zone model, CREAMS (Knisel 1980). GLEAMS was most recently updated to Version 3 in 2000 (Knisel and Davis 2000). GLEAMS has been tested extensively for modeling pesticides (Cohen 1996; Connolly et al. 2001; Garnier et al. 1998; Leonard et al. 1988; Sichani et al. 1991; Truman and Leonard 1991), and results from GLEAMS are generally comparable to PRZM (Pesticide Root Zone Model), another root zone model that was developed and is used by the U.S. EPA (Jones and Mangels 2002; Ma et al. 1988, 1999; Mueller et al. 1992; Parrish et al. 1992; Smith et al. 1991).

While GLEAMS has been used since the early 1990's to estimate concentrations of pesticides in surface water (e.g., Abbott 1993), these efforts involved DOS runs using GLEAMS followed by project-specific computer programs to post-process the GLEAMS output. This approach was adopted and extended in various Forest Service risk assessments from the late 1990's using GLEAMS combined with simple post-processing algorithms to estimate pesticide concentrations in ponds and streams (SERA 2000, 2004a). The GLEAMS-based estimates, however, were not site specific. Instead, a number of generic runs were conducted for sites with clay, loam, and sand soil textures at rainfall rates ranging from 5 to 250 inches per year. A major limitation in these estimates involved rainfall pattern. Because of the generic nature of these previous assessments, rainfall was assumed to fall in consistently even amounts on every tenth day.

While there was no expectation that these generic GLEAMS-based estimates would reflect pesticide concentrations in surface water after a specific field application in a specific site, the generic GLEAMS-based estimates generally encompassed reported monitoring studies. This is demonstrated in many risk assessments posted on the USDA/Forest Service web site (i.e., http://www.fs.fed.us/foresthealth/pesticide/risk.shtml). In addition, for many pesticides considered in Forest Service risk assessments, the U.S. EPA had modeled expected concentrations in ponds and/or reservoirs based on PRZM/EXAMS. EXAMS is essentially a post-processor for PRZM (just as Gleams-Driver is a post-processor for GLEAMS) that is linked to PRZM and uses output from PRZM to estimate concentrations in surface water. When such estimates were available in the preparation of Forest Service risk assessments, the estimates from EPA were compared to the estimates based on GLEAMS, and the GLEAMS-based estimates consistently appeared to encompass those from the U.S. EPA. This correspondence, however, could be attributed to the wide range of rainfall rates as well as the extreme values for chemical, soil, and site input parameters that had been used in the GLEAMS-based assessments.

3.2. Stream Flow and Pond Volume

The emphasis on the ability of Gleams-Driver to replicate stream flow rates and lake water volumes reflects a concern with the very simple post-processing algorithms used in Gleams-Driver, relative to the more complex hydrologic processes modeled in EXAMS. As detailed by Burns (2000), EXAMS considers several individual processes – e.g., advective water flow and sediment transport, as well as individual degradative processes including photolysis, hydrolysis, and microbial degradation. As with the general approach taken in GLEAMS, Gleams-Driver lumps all degradative processes into a single half-life in water and considers the partitioning between water and sediment to be instantaneous.

While somewhat peripheral to the evaluation of Gleams-Driver, it is worth noting that the relative simplicity of the Gleams-Driver post-processing algorithms is an intentional compromise to reduce the number and complexity of input parameters required from the user of Gleams-Driver. User-friendly interfaces such as EXPRESS (Burns 2006) are available for PRZM/EXAMS. EXAMS, however, requires detailed site-specific information in order to model the hydrology of a specific site. This complexity is addressed in the EXPRESS interface and in most other applications of PRZM/EXAMS by the U.S. EPA through limiting the application of PRZM/EXAMS to two water bodies, a standard 1-hectare farm pond with a 10-hectare drainage area and a 13-acre standard reservoir (referred to by the U.S. EPA as an Index Reservoir) with a 427-acre watershed. While EXAMS accommodates the modeling of other types of water bodies, including streams, constructing the input files for specific water bodies requires a substantial amount of data and effort. By simplifying the approach to GLEAMS post-processing, Gleams-Driver allows the user to specify the type of water (lentic or lotic) with relatively few input parameters.

The flexibility and simplicity of Gleams-Driver are of little use, however, unless the outputs from Gleams-Driver are reasonably reliable. In the current evaluation, both the Quick Run and Full Run capabilities have been examined in terms of the ability of Gleams-Driver to model gross hydrology (Section 2.1) as well as pesticide concentrations in surface water (Section 2.2.). The Quick Run simulations are all based on the use of general information regarding site characteristics and default values in Gleams-Driver databases. The Full Run simulations are based on the more detailed use of information regarding site characteristics (i.e., soil properties) as well as a fuller use of information about the variability and uncertainties in site and soil input parameters.

The Quick Run approach is used to model stream flow rates in Bull Creek (Section 2.1.2.1). No attempt is made to acquire site-specific soil information, and the weather patterns are based on a general interpolation of several nearby weather stations using Cligen. As illustrated in Figure 1, Gleams-Driver was able to reasonably, if not exactly, model the stream flow rates for Bull Creek recorded in the USGS database. While not attempting to minimize the observed deviations between Gleams-Driver simulations and the recorded values of stream flow from USGS, there should be no expectation that environmental fate and transport models will perfectly emulate historical data. In the Gleams-Driver simulations illustrated in Figure 1, the only source of variability comes from differences in rainfall patterns in weather files from Cligen. There are obviously many other uncertainties in this simulation associated with simplifications in the modeling (i.e., a single soil layer), uncertainties in many of the soil parameters used as inputs, as well as possible differences in the weather patterns simulated by Cligen versus the actual weather patterns in and around Bull Creek during the period over which monitoring data are available (1994 to 2006). These matters are not explored further in the current analysis because the purpose of the comparison is to assess whether or not the Quick Run facility in Gleams-Driver will reasonably estimate stream flow patterns. For the Bull Creek site (Figure 1), modeled stream flow rates well-reflect the magnitude and seasonal variability in the USGS data.

For the modeling of water volumes in Lake Gregory (Section 2.1.2.2), a Full Run approach was used by acquiring site-specific and soil-specific information from the Natural Resources Conservation Service (NRCS) web site as well as location-specific weather simulations based on a nearby weather station using Cligen. While this is a more refined analysis than that conducted on the Bull Creek site, the analysis does incorporate a number of simplifications including a single homogeneous soil layer and a single homogeneous field. The NRCS web site does provide information that could be used to model multiple soil layers as well as multiple field segments. The analysis of the water volume in Lake Gregory that is illustrated in Figure 2 had been designed initially as the first of a series of progressively more refined analyses. The relatively clear correspondence between the modeled values and the USGS data on Lake Gregory, however, suggest that a further refinement to the analysis is not necessary.

3.3. Concentrations of Pesticides in Surface Water

3.3.1. Bull Creek Application of Sulfometuron Methyl (Wood 2001)

The two field studies on pesticide applications involve two very different applications of Gleams-Driver. The study by Wood (2001) is essentially an exercise in the calibration of GLEAMS using the artificial rainfall component of the study (Section 2.2.1.2) followed by a Gleams-Driver simulation based on the GLEAMS calibration (Section 2.2.1.3).

One of the most useful aspects of the analysis of the Wood (2001) study involves the consideration of site heterogenicity. As detailed in Section 2.2.1.2, Wood (2001) examined three fundamentally adjacent plots along the roadway. Despite this proximity, the three plots evidenced marked differences in runoff characteristics. These differences are most pronounced in runoff volumes but are also evident in the runoff concentrations of sulfometuron methyl (Figure 3). In a standard application of Gleams-Driver, each of the three plots would be modeled as sand, the soil texture specified in the Wood (2001) study. As evidenced in the data on runoff volumes (Table 1), these three plots displayed differences in the proportion of runoff by factors of about 2 to 4 over the three weekly irrigation periods. In terms of applying Gleams-Driver, these difference required substantial adjustments in input parameters (Table 3) in order to reflect the differences in runoff concentrations (Figure 3).

Field heterogenicity is not a factor that is considered in most modeling exercises. GLEAMS as well as other field scale models such as PRZM assume a uniform field. The documentation for GLEAMS (Knisel and Davis 2000) as well as other sources will often give default or typical values for many soil input parameters, which are often used without further consideration. The study by Wood (2001) does illustrate that most environmental modeling exercises, including those presented in this paper, necessarily involve simplifications and assumptions of uniformity that will not reflect the complexity and variability of the site being modeled.

In this regard, it should be emphasized that the close correspondence between the monitored and modeled runoff concentrations illustrated in Figure 3 does not constitute an evaluation of GLEAMS or Gleams-Driver. Instead, the correspondence illustrates that GLEAMS can be calibrated to mimic the runoff concentrations. This calibration was necessary due to the lack of detailed data on soil and site characteristics in the study by Wood (2001). In terms of GLEAMS or Gleams-Driver as well as other environmental fate models, roadsides are highly artificial surfaces. In the process of road construction, soils are typically brought in from other locations to serve as a foundation for the road, and the shoulders of the road are intentionally compacted. Using "standard values" for sand and gravel, the soil texture of the road shoulder specified by Wood (2001), GLEAMS would not have predicted any runoff. Road shoulders are also atypical in that they may be subject to further compaction by traffic as well as the runoff of tire debris and other organics from the roadway. Thus, the artificial rainfall component of the study was needed to calibrate GLEAMS.

Even the correspondence in the runoff concentrations from the natural rainfall component of the Wood (2001) study, as illustrated in Figure 4, does not constitute an evaluation of Gleams-Driver. The runoff concentrations come directly from GLEAMS with no Gleams-Driver post-processing. Figure 4, however, does illustrate that GLEAMS is calibrated to the site.

The evaluation of Gleams-Driver is illustrated in the modeling of the stream flow rates (Figure 5) and in the estimates of the modeled concentrations of sulfometuron methyl in Bull Creek (Figure 6). It will be noted that the flow rate values reported by Wood (2001) for Bull Creek range from a low on November 16 of about 3000 m^3/day ($3x10^6$ L/day) to a high of about 50,000 m^3/day ($5x10^7$ L/day) on October 1, which is near the upper bound of the values given for Bull Creek based on the simulation of the USGS data (Figure 1). A direct comparison of these two simulations, however, is not appropriate because the USGS data are for a different location on Bull Creek with an upstream drainage area of only 0.66 square miles. The Wood (2001) study, however, was conducted further downstream in a location with a total drainage area of 5 square miles. Thus, the upper bound of the modeled values for the stream flow of Bull Creek in the area studied by Wood (2001), as illustrated in Figure 5, is about an order of magnitude higher than the modeled estimates for the USGS site on Bull Creek (Figure 1). These differences are to be expected based on differences in the two drainage areas – i.e., 0.66 square miles versus 5 square miles – which also approaches an order of magnitude.

As discussed in Section 2.2.1.3 and illustrated in Figure 5, Gleams-Driver overestimates the flow rate of Bull Creek for November 16, which may be associated with the failure to use a percolation buffer. For a 5 square mile area, about twice the drainage area for Lake Gregory, a very low percolation buffer with a low transfer rate could have better reflected the dynamics of the stream flow. As illustrated in Figure 1 for the USGS data on Bull Creek, there is likely to be a substantial increase in the flow rate of Bull Creek during the autumn. The percolation transfer factor was not used in the simulation of Wood (2001) study, however, because the area treated with sulfometuron methyl was very close to the stream and the focus of the simulation effort was on determining the maximum plausible concentration of sulfometuron methyl that might have occurred in the stream. As illustrated in Figure 6, the upper bound of plausible concentrations estimated by Gleams-Driver is substantially below the limit of detection. This estimate is consistent with monitoring data by Wood (2001), which detected sulfometuron methyl in both road runoff and the adjacent ditch but failed to detect sulfometuron methyl in the stream.

3.3.2. Stanislaus National Forest Application of Hexazinone (Frazier and Grant 2003)

In terms of assessing the utility of Gleams-Driver for its intended purpose – evaluating the potential consequences of pesticide applications in Forest Service programs – the report by Frazier and Grant (2003) is clearly the most relevant data set addressed in the current analysis. The pesticide, in this case hexazinone, was used in an actual forestry application (forest restoration) and the pesticide was detected in surface water over a prolonged period of time (Figure 8). With the exception of initial peak concentrations that are associated with drift or direct deposition, the monitored concentrations in surface water reflect the soil-to-surface water transport of the pesticide associated with the processes that Gleams-Driver is designed to model – i.e., erosion, runoff, and percolation.

Because the monitoring data from the Stanislaus application is highly relevant to the evaluation of Gleams-Driver, two separate simulations were conducted: one using the Quick Run facility and the other the Full Run capability of Gleams-Driver. Neither of these simulations involved any form of model calibration. Unlike the study by Wood (2001), no information is presented in the Frazier and Grant (2003) report that would support model calibration either in terms of the dynamics of stream flow or the site-specific chemical and soil parameters. While Frazier (2007) provides rough estimates of plausible flows for the Jordan Creek tributary, these can be used only to crudely assess the peak and minimum values modeled with Gleams-Driver. The monitoring data on hexazinone concentrations in the stream, however, are directly useful in assessing the performance of Gleams-Driver in modeling peak hexazinone concentrations as well as the dynamics of hexazinone concentrations over a period of several years.

The results of the Quick Run simulation are both encouraging and disturbing. As illustrated in Figure 9, the use of Gleams-Driver default parameters for the general soil type at the site as well as the default parameters for hexazinone resulted in a reasonably clear reflection of the concentrations of hexazinone in the tributary over a 4-year period. The modeled concentrations are at least “in the ballpark”. This correspondence of modeled to monitored values is obviously encouraging because of the very little detail used in the input parameters for the Gleams-Driver simulation.

The relationship of the modeled to monitored concentrations in Figure 9 is disturbing, however, because the Quick Run facility in Gleams-Driver is designed to yield modeled estimates that are conservative – i.e., the concentrations modeled by a Quick Run in Gleams-Driver, particularly the concentrations at the upper 95th percentile, are intended to provide estimates that are likely to exceed concentrations that will occur in a particular application. As clearly indicated in Figure 9, this expectation is not met in the results of the Quick Run. Some of the monitored concentrations on February 3 are above the median modeled values by more than an order magnitude and above the 95th percentile modeled values by a factor of about 3. In this respect, the Quick Run did not generate conservative estimates of concentrations.

The modeled concentrations in the Full Run (Figure 11), however, are consistent with the monitoring data. The median estimates from Gleams-Driver over the first 2 years after the application of hexazinone (1998 and 1999) are strikingly concordant with the monitored values. Over the entire 4-year post-application monitoring period, the 95th percentile concentrations encompass and typically exceed the monitored concentrations. In terms of realistic expectations in model performance, the performance of Gleams-Driver in the Full Run simulation is about as good as can be reasonably expected.

Additional analyses would be needed to more fully explicate the underestimated of concentrations from the Quick Run in the modeling the Jordan Creek tributary. While somewhat speculative, it is worth noting that the Quick Run facility in Gleams-Driver is currently (i.e., as of Version 1.7) configured to use central or best estimates of site, soil, and chemical properties. While the Quick Run facility in Gleams-Driver gives the user the option to use generic estimates of default variability, this option was not used in the Quick Run simulation of the Jordan Pond tributary because it would have obscured differences between the Quick Run and the Full Run simulations. In addition, the default variability option in the Quick Run is generally intended as a tool for entering place-holder distributions into the Gleams-Driver input database to facilitate the editing of the input database and refinement of the specific input distributions using the Full Run capabilities of Gleams-Driver.

In the application of Gleams-Driver to Forest Service risk assessments (e.g., SERA 2007b), central estimates based on Quick Run values are not used. Analogous to previous applications of GLEAMS-based modeling (SERA 2000, 2004a), three soil types are considered: clay, loam, and sand. For loam, central input values are used. For clay, the site, soil, and chemical input parameters are adjusted to favor runoff. For sand, the site, soil, and chemical input parameters are adjusted to favor percolation. As noted in SERA (2007b, Table 11), the parameter selections result in a range of modeled concentrations that are consistent with PRZM/EXAMS modeling conducted by the U.S. EPA based on central estimates from Gleams-Driver (91 ppb for PRZM/EXAMS and 100 ppb for Gleams-Driver). In addition, the upper bound of concentrations modeled by Gleams-Driver exceeds the estimate from PRZM/EXAMS by a factor of over 6 for peak concentrations and a factor of over 14 for longer term concentrations. Thus, the failure of the Quick Run of the Jordan Pond tributary to provide conservative estimates of hexazinone concentrations may not reflect an inherent flaw in the Gleams-Driver model but simply a characteristic of the parameter selections used in the Quick Run for the Jordan Pond tributary.

As noted in Section 2.2.2.2, a percolation loss rate of 0.5 day^{-1} is used for the 47 acre drainage area of the Jordan Creek tributary and this rate was selected intuitively as a starting value by analogy to the Bull Creek USGS site (Section 2.1.3.1) for which a loss rate of 0.05 day^{-1} is used to fit stream flow rates for a 422 acre drainage area. Given the reasonable fit of the initial simulations of Jordan Creek tributary, the loss rate of 0.5 day^{-1} was not adjusted further. For the much large drainage area of Lake Gregory (1702 acres), a much lower percolation loss rate, 0.0075 day^{-1}, is needed to reflect the time course of water volumes in the lake.

There is an apparent and intuitive inverse relationship between drainage area and percolation loss rate. The three pairs of loss rate/drainage area values covered in this analysis fit an exponential model and yield the following relationship:

$$k = 45.7 \times A^{-1.16}$$

where *k* is the percolation loss rate and *A* is the drainage area in acres. Although this equation is fit with only one degree of freedom, the fit could be considered statistically significant (*p*-value = 0.046). In the context of the use of the percolation loss rate in Gleams-Driver, *k* cannot exceed 1 – i.e., the maximum that can be lost from the percolation reservoir is the amount in the percolation reservoir. Thus, setting *k* to 1.0 and solving for *A*, the above relationship suggests that a percolation reservoir would not be needed or appropriate for drainage areas of about 27 acres (10.9 hectares) or less.

Given the minimal degrees of freedom in deriving the above equation, this discussion is intended only to suggest that analyses of additional sites may yield empirical support and guidance in the estimation of loss rates for the percolation reservoir in Gleams-Driver. It is also noteworthy that all of the sites used to derive the above equation consisted of predominantly loam soil textures. It seems reasonable to suggest that different relationships between the loss rate and drainage area are likely to be noted for different soil textures.

Gleams-Driver appears to have adequately modeled the concentrations of hexazinone in the Jordan Creek tributary over a prolonged period of time. While this is reassuring, the drainage area for the Jordan Creek tributary is relatively small and, as noted above, the percolation reservoir is associated with a relatively high loss rate, 0.5 day^{-1}. For larger drainage areas with proportionately smaller percolation loss rates, modeling the degradation of the pesticide in the reservoir could be increasingly important as the size of the drainage area increases. The failure to consider degradation in the reservoir would tend to overestimate pesticide concentrations in surface water and these overestimates could be substantial. This may not be a serious issue in the application of Gleams-Driver to general risk assessments (e.g., SERA 2007a) because the risk assessments address relatively small drainage areas (10 ha) and are intended to provide conservative estimates of exposure. Nonetheless, Gleams-Driver can accommodate a degradation rate for the pesticide in the percolation reservoir. For site-specific assessments involving large drainage areas, the degradation rate of the pesticide in the percolation buffer should be considered with care.

4. SUMMARY AND CONCLUSION

GLEAMS is a mature and well-evaluated program for modeling edge-of-field and bottom-of-root-zone pesticide loss. While GLEAMS output has been used for many years estimating concentrations of pesticides in surface water, Gleams-Driver is a new program designed to simplify the use of GLEAMS and provide substantial flexibility for modeling the concentrations of pesticides in surface water. The current analysis is the first systematic attempt of evaluate the reliability of the Gleams-Driver modeling.

Gleams-Driver is designed to operate in many different modalities. While not addressed in the current evaluation, Gleams-Driver can operate in a mode that ignores water balance. In other words, the chemical is transported from the application site to the surface water by rainfall through sediment loss, runoff, and percolation but the contribution of the rainfall, runoff and percolate water is ignored. This mode of operation is included only as a Tier 1 screening tool, similar to the GENEEC model used by the U.S. EPA (Burns 2007). In this mode, Gleams-Driver will provide upper bound estimates of pesticide concentrations in water. These estimates are likely to be conservative and probably grossly so.

The normal and intended mode of Gleams-Driver considers water balance but is still designed to provide conservative but plausible central and upper bound estimates of exposure. The current analyses of the studies reported by Wood (2001) as well as Frazier and Grant (2003) suggest that Gleams-Driver can provide reasonable estimates of concentrations in streams so long as appropriately conservative input parameters are used. The current Quick Run facility in Gleams-Driver, however, is programmed to use central estimates of site, soil, and chemical input parameters. Based on the Quick Run simulation of the Jordan Creek tributary using the monitoring study from Frazier and Grant (2003), Quick Runs may provide reasonable but not necessarily conservative estimates of concentrations of pesticides in streams unless appropriately conservative input values are used.

Gleams-Driver is designed to model concentrations in both streams and ponds. A major limitation in the current evaluation of Gleams-Driver is the lack of a monitoring study on a pond that involves forestry or agricultural applications suitable to evaluating Gleams-Driver. Many monitoring studies on ponds were reviewed in an attempt to identify a suitable pond study. None of the available studies, however, involve well-defined field applications in which the transport of the pesticide from the field to the pond can be associated primarily with sediment, runoff, or percolation over a prolonged period of time. The most relevant study encountered in the literature is the publication by Prichard et al. (2005) involving a border-check surface irrigation. This irrigation method is not used in Forest Service field applications and cannot be readily modeled using GLEAMS.

Studies used in the validation of EXAMS (Burns 2000) were also considered. EXAMS has been evaluated with studies of radon in Canadian lakes as well as nonpoint source contamination of a lake in Switzerland with 1,4-dichlorobenzene (Burns 2000). These studies, however, are not representative of field applications that can be modeled with Gleams-Driver. In the other field studies involving pond contamination reviewed as part of the current evaluation of Gleams-Driver, monitoring typically occurred over a short period of time, and the pond contamination was associated primarily with drift rather than the processes that GLEAMS directly addresses – sediment, runoff, and percolation. The lack of suitable pond monitoring study is a limitation that cannot be addressed further at this time.

Because of the simplicity of the post-processing algorithms in Gleams-Driver, substantial emphasis is placed on the evaluation of Gleams-Driver to model stream flow rate and lake volume. Based on the current analyses, the use of the percolation buffer in Gleams-Driver can reasonably approximate these gross hydrologic processes over simple catchments or drainage areas of up to at least 1700 acres (the largest area evaluated).

GLEAMS is a field scale model, and its capability to model water balance at the field level has been demonstrated (Knisel et al. 1991). Nonetheless, the watershed used in the evaluation by Knisel et al. (1991) covers only 0.35 hectares or about a 0.8-acre area. In the current evaluation, field areas used in the assessment of hydrologic processes vary from 47 acres (the drainage area of Jordan Creek tributary) to about 1700 acres (the drainage area for Lake Gregory). A field area of 47 acres is equivalent to about 20 hectares, about twice the size of the standard pond used in many U.S. EPA risk assessments (e.g., Burns 2007) as well as Forest Service risk assessments (e.g., SERA 2007b). The 1,700 acre area is about a factor of four greater than the 427 acre watershed used in the U.S. EPA Index Reservoir (Burns 2007). While the current evaluation suggests that Gleams-Driver may be able to reflect the gross hydrology of drainage areas up to about 1700 acres, the evaluation of monitored concentrations of pesticides in surface water (as opposed to non-detections) is limited to 47 acres. It is not clear from the current evaluation that Gleams-Driver can be applied with confidence at the scale of large water basins. Other models such as the Soil and Water Assessment Tool (SWAT, http://www.brc.tamus.edu/swat/) and the Annualized Agricultural Non-Point Source model (AnnAGNPS, http://www.ars.usda.gov:80/Research/ docs.htm?docid=5222) are available for modeling large water basins; however, the use of these tools is much more complex and data intensive than the use of Gleams-Driver.

The extent to which Gleams-Driver is a useful tool is clearly and obviously attributable to GLEAMS. GLEAMS and its predecessor CREAMS were developed over the course of many years by the USDA-ARS, Southeast Watershed Research Laboratory in Tifton, GA. While perhaps less obvious, the capabilities of Gleams-Driver are also based substantially on the use of Cligen, the climate generator developed and maintained by the USDA's Agricultural Research Service, National Soil Erosion Research Laboratory (USDA/ARS/NSERL) as well as the USDA's Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/), the online program developed by the USDA's Natural Resources Conservation Service (USDA/NRCS).

The above statements are intended both as acknowledgements of the contribution of these other tools as well as recommendations in the application of Gleams-Driver. Gleams-Driver is very simple to use. With Gleams-Driver, a user can select a chemical, designate an output file, and, literally in a matter of seconds, obtain modeled estimates of concentrations of a pesticide in a stream or pond. In some instances, such estimates may be sufficient. In any more refined use of Gleams-Driver, however, the proper understanding of GLEAMS as well as the use of tools such as Cligen and the USDA Web Soil Survey should be considered with care. While the information from USGS National Water Information System (http://waterdata.usgs.gov/nwis) is not used directly in Gleams-Driver, the current analysis illustrates the use of this resource in the application of Gleams-Driver.

This analysis is only the first systematic attempt to evaluate the performance of Gleams-Driver and is admittedly limited both in scope and by the available information. Nonetheless, the ability of Gleams-Driver to model lentic water volume and lotic water flow is apparent. In addition, Gleams-Driver can provide conservative estimates of pesticide concentrations in streams consistent with well-designed monitoring studies involving pesticide applications that are analogous (Wood 2001) or identical (Frazier and Grant 2003) to pesticide applications used in Forest Service programs.

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Table 1: Key Input Parameters Used in Gleams-Driver Modeling of Bull Creek and Lake Gregory

Parameter	Bull Creek	Lake Gregory
USGS Data [a]		
USGS Site Designation	14198400	10260640
Location	Near Wilhoit OR	At Crestline CA
Latitude	N 44° 57’42”	N 34°14'35"
Longitude	W 122°22’59”	W 117°16'22"
Elevation	1,680 feet	4,553 feet
Drainage Area	0.66 sq miles	2.66 sq miles
Other characteristics (see text for discussion)	Basal flow rate of 30,000 L/day	Surface area: 84.3 acres Initial depth: 6.5 meters Minimum depth: 4.9 meters Maximum depth: 8.3 meters
Weather Data	Cligen 5.2, Bull Creek Cascadia OR	Cligen 5.2, Lake Arrowhead CA
Soil Inputs [b]		
Soil Depth	60 inches	60
Soil Classification	Silt Loam	Loam
Clay (%)	20	20
Silt (%)	60	36
Organic Matter (%)	3.4	0.66
Porosity (cc/cc)	0.43	0.4
Field capacity(cc/cc)	0.32	0.2
Wilting Point(cc/cc)	0.12	0.1
SCS curve number (CN2)	74	74
Soil evaporation parameter (CONA)	4.5	4.5
Saturated Conductivity Below Root Zone (RC, cm/hr)	0.212	0.212
Saturated Conductivity within Root Zone (SATK, cm/hr	0.212	0.75
Field Characteristics [c]		
Field size	422.4 acres	1702 acres
Flow path (feet)	5280	8612 feet
Slope	0.1	0.36
Water Loss Rates Percolation Reservoir (day^{-1})	0.05	0.0075
Number of simulations	200	100
Number of years per simulation	2	5

[a] Data obtained at USGS National Water Information System: Web Interface, http://waterdata.usgs.gov/nwis/nwisman, except for elevation of Lake Gregory which is taken from Google Earth.
[b] Soil inputs for Bull Creek are taken from Gleams-Driver defaults for silt loam. Soil inputs for Lake Gregory are based on data from the USDA Soil Survey at http://websoilsurvey.nrcs.usda.gov/app/ where available. The SCS Curve runoff number is the default from Gleams-Driver for hydrologic Group B (moderate infiltration rates).
[c] The field size is taken from the drainage area specified by USGS for both sites. Other field characteristics are approximated from Google Earth.

Table 2: Amounts of irrigation and runoff applied to plots in study by Wood (2001)

	Total Volume of Water in Pavement Simulator	Total Volume of Water in Rainfall Simulator	Total Volume of Water Applied [1]	Runoff Volume	Ratio of Runoff to Total Water Applied	Rainfall Equivalent (mm)[2]
May 20th						
Plot 1	12	21.18	33.18	15	0.45	8.9
Plot 2	12	50.13	62.13	15	0.24	16.7
Plot 3	24	35.3	59.3	15	0.25	16.0
May 26th						
Plot 1	30.72	28.24	58.96	13	0.22	15.9
Plot 2	93.79	69.9	163.69	13	0.08	44.0
Plot 3	132.89	79.79	212.68	13	0.06	57.2
June 3rd						
Plot 1	16.80	20.47	37.27	15	0.40	10.0
Plot 2	81.60	58.6	140.2	15	0.10	37.7
Plot 3	72.00	52.95	124.95	15	0.12	33.6

[1] Data kindly provided by Tamara Wood via email to Patrick Durkin dated July 27, 2007.
[2] Conversion to mm of rainfall based on a 40 square foot treatment area.

Table 3: Soil Information Used in Modeling of Wood (2001)

Item	Value	Units	Note
Soil types, depth of soil horizons	Sand, 0 to 12 Silt loam, 12 to 60	inches	Soil types as described in Wood (2001).
SCS curve number (CN2)	Artificial rainfall Plot 1: 93 to 99 Plot 2: 88 to 95 Plot 3: 91 to 97 Natural rainfall 88 to 99		Plots 1, 2, and 3 calibrated to reflect observed runoff concentrations. Natural rainfall taken as composite value.
Soil evaporation parameter (CONA)	3.3		GLEAMS default for sand
Saturated conductivity (SATK and RC)	0.016	inches/hr	Gleams-Driver default for sites with a high runoff potential.
Porosity **Sand**	Artificial rainfall Plot 1: 0.1 to 0.7 Plot 2: 0.6 to 0.9 Plot 3: 0.2 to 0.7 Natural rainfall 0.1 to 0.9		Plots 1, 2, and 3 calibrated to reflect observed runoff concentrations. Natural rainfall taken as composite value.
Silt loam	0.4 to 0.46		No basis for varying among sites
Field capacity	0.16 (sand) 0.32 (silt loam)		GLEAMS defaults for sand and silt loam.
Wilting point (BR15)	0.03 (sand) 0.12 (silt loam)	at 15 millibars	GLEAMS defaults for sand and silt loam.
Clay	5 (sand) 20 (silt loam)	%	GLEAMS defaults for sand and silt loam.
Silt	5 (sand) 60 (silt loam)	%	GLEAMS defaults for sand and silt loam.
Organic matter	1.26 (SD 1.64), sand 2.96 (SD 2.56), silt loam	%	Mean and standard deviation for lognormal distributions. See Table 6 in SERA (2006b).

Table 4: Site Information for Artificial Rainfall Components of Wood (2001) Study

Item	Value	Units	Note
Treated Area Artificial rainfall	0.00092	acres	Treated area described in Wood (2001) as 10' x 4' = 40 ft^2. 40 ft^2/46560 ft^2 per acre = 0.00092 acres.
Natural rainfall	0.64	acres	4 ft x 0.7 miles (p. 11, col. 2, Para 2 for length; Table 4 for width) 4 ft x 0.7 miles x 5280 feet/mile = 14784 ft^2 x acre/43560 ft^2 = 0.34 acres. Both sides of road were treated: 0.34 acres x 2 = 0.68 acres.
Untreated/ Drainage Area	N/A (artificial rainfall) 3200 (natural rainfall)	acres	Drainage are for Bull Creek described in Wood (2001) as 5 square miles. 640 acres per square mile.
Field Width	4	feet	Application swath described in Wood (2001)
Slope	0.02		Estimated from cover photograph in Wood (2001)
Soil Erodibility Factor (KSOIL)	0.02		Gleams-Driver default for sand.
Surface Area of Clay	125	sq. m/g	Gleams-Driver default.
Soil Loss Ratio (CFACT)	Artificial rainfall 0.9 to 1 for Plot 1 0.6 – 0.75 for Plot 2 and Plot 3. Natural rainfall 0.6 to 1		Wood (2001) describes Plot 1 as having no or very little cover. Plots 2 and 3 are described as having more vegetative cover.
Contouring Factor (PFACT)	Artificial rainfall 1.0 for Plot 1 0.6 for Plots 2 and 3 Natural rainfall 0.6 to 1.0		
Manning's 'n' (NFACT)	Artificial rainfall 0.01 for Plot 1 0.012 to 0.015 for Plots 2 and 3 Natural rainfall 0.01 to 0.015		

Table 5: Chemical Input Parameters for Sulfometuron methyl

Item	Value	Units	Note
Application Rate	0.13	lb/acre	Wood (2001), Table 4, 0.15 kg/ha
Application Date	May 19 (artificial rainfall) September 28 (natural rainfall)		Wood (2001)
Water Solubility	300	mg/L	Gleams-Driver default
Foliar Half-life	10	Days	Gleams-Driver default
Foliar Washoff Fraction	0.65		Gleams-Driver default
Koc	Triangular(61 78 122)	mL/g	Central value recommended by Knisel and Davis (2000) and the upper and lower bounds are taken from the USDA/ARS Pesticide Properties Database.
Coefficient of transformation	1		Gleams-Driver default
Coefficient of uptake	0		Gleams-Driver default
Soil half-life	Triangular(10 20 100)	Days	The central value of 20 days from Knisel and Davis (2000) and the upper and lower bounds are taken from the USDA/ARS Pesticide Properties Database

Table 6: Site characteristics used for treated area at Jordan Creek tributary

Item	Value [a]	Units	Note
Latitude	37°45'45.41" N		Approximated from satellite image.
Longitude	120°04'48.19 W		Approximated from satellite image.
Treated Area and Drainage Area	47	acres	From Frazier and Grant 2003
Field Width	300	feet	Approximated from satellite image.
Elevation	3990	feet	Approximated from satellite image.
Slope	0.2		Average from USDA soil survey
Soil Erodibility Factor (KSOIL)	0.24		Average from USDA soil survey
Depth to restrictive soil layer	42	Inches	From USDA soil survey
Surface Area of Clay	125	sq. m/g	Gleams-Driver default
SCS curve number (CN2)	60		Central estimate for Group B soils in woods with fair hydrologic condition.
Soil evaporation parameter (CONA)	3.5		Gleams-Driver default for loam
Saturated conductivity below root zone (RC)	0.212		Gleams-Driver default
K Factor	0.24		Average from USDA soil survey
Cover Factor (CFACT)	0.5		Estimated from satellite image.
Contour factor (PFACT)	0.8		Table E-4 in Knisel and Davis (2000) for a slope between 21 and 25.
Manning's "n"	0.01		Estimate based on Table E-5 in Knisel and Davis (2000) using no surface depressions.
FOREST	2		Short leafed conifer/cedar option in GLEAMS.
Stream basal flow rate	109,008 [Q] 10,900 [F]	Liters/day	Flow rate for Quick Run based on estimate of early summer flow from Frazier (2007). Adjusted downward by a factor of 10 for Full Run.
Percolation reservoir loss rate	0.5	day^{-1}	Set by analogy to Bull Creek. See text for discussion.

[a] The [Q] and [F] entries indicated values that were used in the Quick Run and Full Run simulations, respectively.

Table 7: Soil Characteristics used for treated area at Jordan Creek tributary

Item	Granules [a]	Soil [b]	Note
Soil type	Clay	Loam	Clay used to simulate granular application.
Depth (inches)	0.4	42	From USDA Soil Survey
Porosity (in^3/in^3)	0.47	0.4 [Q] 0.4-0.49 [F]	Gleams-Driver defaults. USDA give a bulk density of 1.36 g/cm3 which would correspond to a porosity of 0.49. Use a uniform with a range of 0.4 to 0.48 in refined run.
Field capacity (in^3/in^3)	0.39	0.26	Gleams-Driver default. USDA soil survey gives a value of 0.27. Do not Monte Carlo in refined run.
Wilting Point	0.28	0.11 [Q] 0.1-0.15 [F]	Gleams-Driver default. USDA soil survey gives a value of 0.15. Use a uniform of 0.1 to 0.15 in refined run.
Clay (%)	50	20	Gleams-Driver default. USDA soil survey gives a value of 30.
Silt (%)	30	35	Gleams-Driver default. USDA soil survey give a value of 34.
Organic matter (%)	3.7	2.9 [Q] Lognormal: 2.87 mean, 2.69 SD [F]	Gleams-Driver default. USDA soil survey gives a value of 1.1. For refined run, use a log normal distribution with a mean of 2.87 and a standard deviation of 2.69 from SERA (2006b).
Saturated conductivity (in/hr)	0.212	0.212	These are central values for Group B soils. Do not adjust top horizon because pellets do not blanket the soil.

[a] A top clay horizon was used to mimic granular application. Values are taken from the defaults for clay in the Gleams-Driver documentation.

[b] The [Q] and [F] entries indicated values that were used in the Quick Run and Full Run simulations, respectively. Where a range is indicated for the Full Run, the range was used to define a uniform distribution. Data from the USDA Soil Survey are based on data for the site from http://websoilsurvey.nrcs.usda.gov/app/.

Table 8: Chemical properties and Application Data for Hexazinone used in Jordan Creek simulation.

Item	Value	Units	Note [a]
Application Rate	3	lb a.i./acre	From Frazier and Grant 2003
Application Date	March 17, 1997		From Frazier and Grant 2003
Drift, Quick Run	Drift proportion of 0.05 to 0.15 over a 6.5 foot (2 meter) width and 300 foot length.		Default values
Drift, Full Run	Drift proportion of 0.2 to 0.8 over a 1.6 foot (0.5 meter) width and a 700 foot length		Based on information from Frazier (2007) and results of Quick Run simulation.
Fraction applied to soil	0.99	Unitless	Based on monitoring study on granular application of hexazinone summarized in SERA (2005)
Water Solubility	33,000	mg/L	Gleams-Driver default
Foliar Half-life	30	Days	Gleams-Driver default
Foliar Washoff Fraction	0.9		Gleams-Driver default
Koc	54 [Q] 27-74 [F]	mL/g	Gleams-Driver default is 54. Values of 27 to 74 are summarized in USDA/ARS (2006)
Coefficient of transformation	1	Unitless	Gleams-Driver default
Coefficient of uptake	0	Unitless	Gleams-Driver default
Soil half-life	120 [Q] 27-216 [F]	days	Gleams-Driver default is 120. Values of 27 to 216 are summarized in USDA/ARS (2006)

[a] The [Q] and [F] entries indicated values that were used in the Quick Run and Full Run simulations, respectively. Where a range is indicated for the Full Run, the range was used to define a uniform distribution.

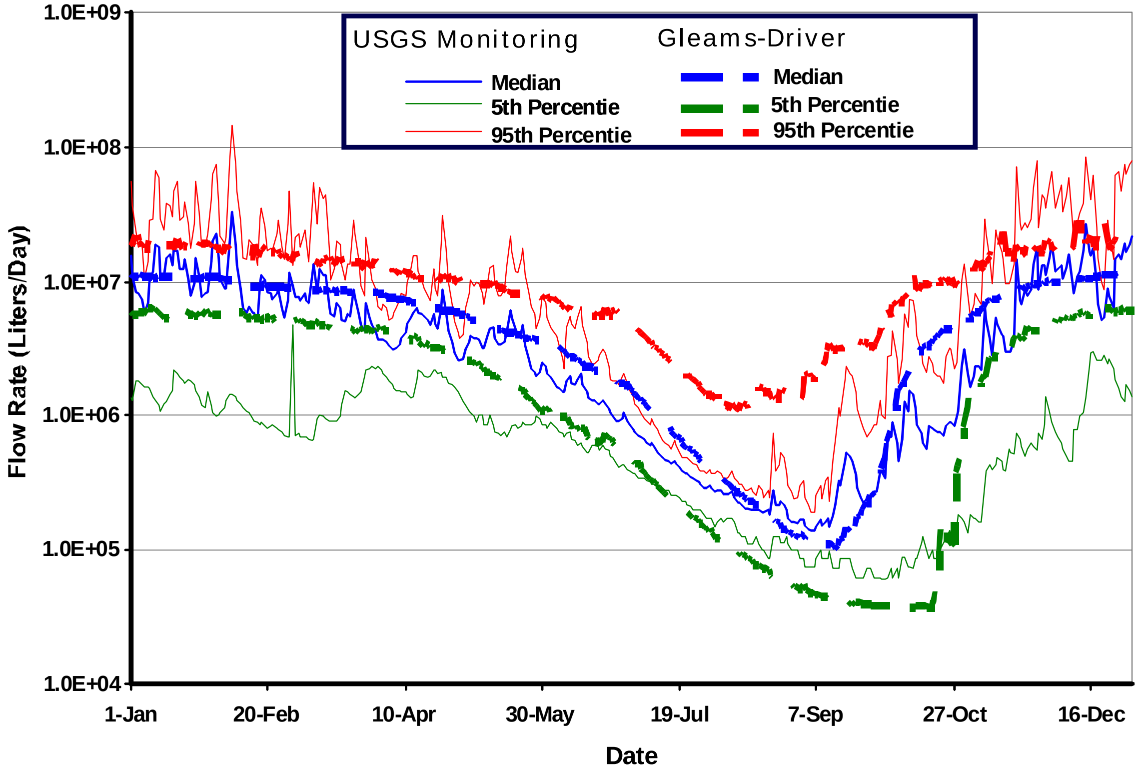

Figure 1: Monitored and Modeled Flow Rates in Bull Creek

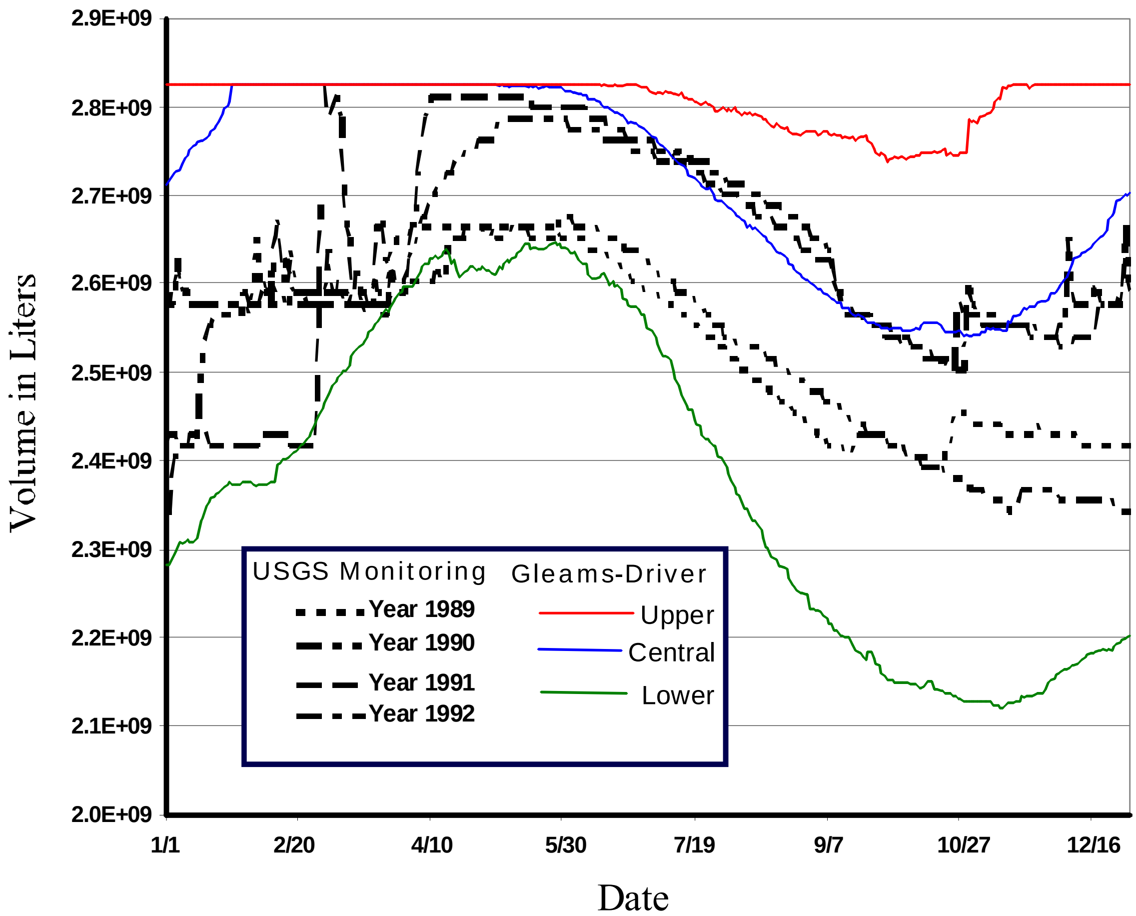

Figure 2: Monitored and Modeled Water Volume in Lake Gregory

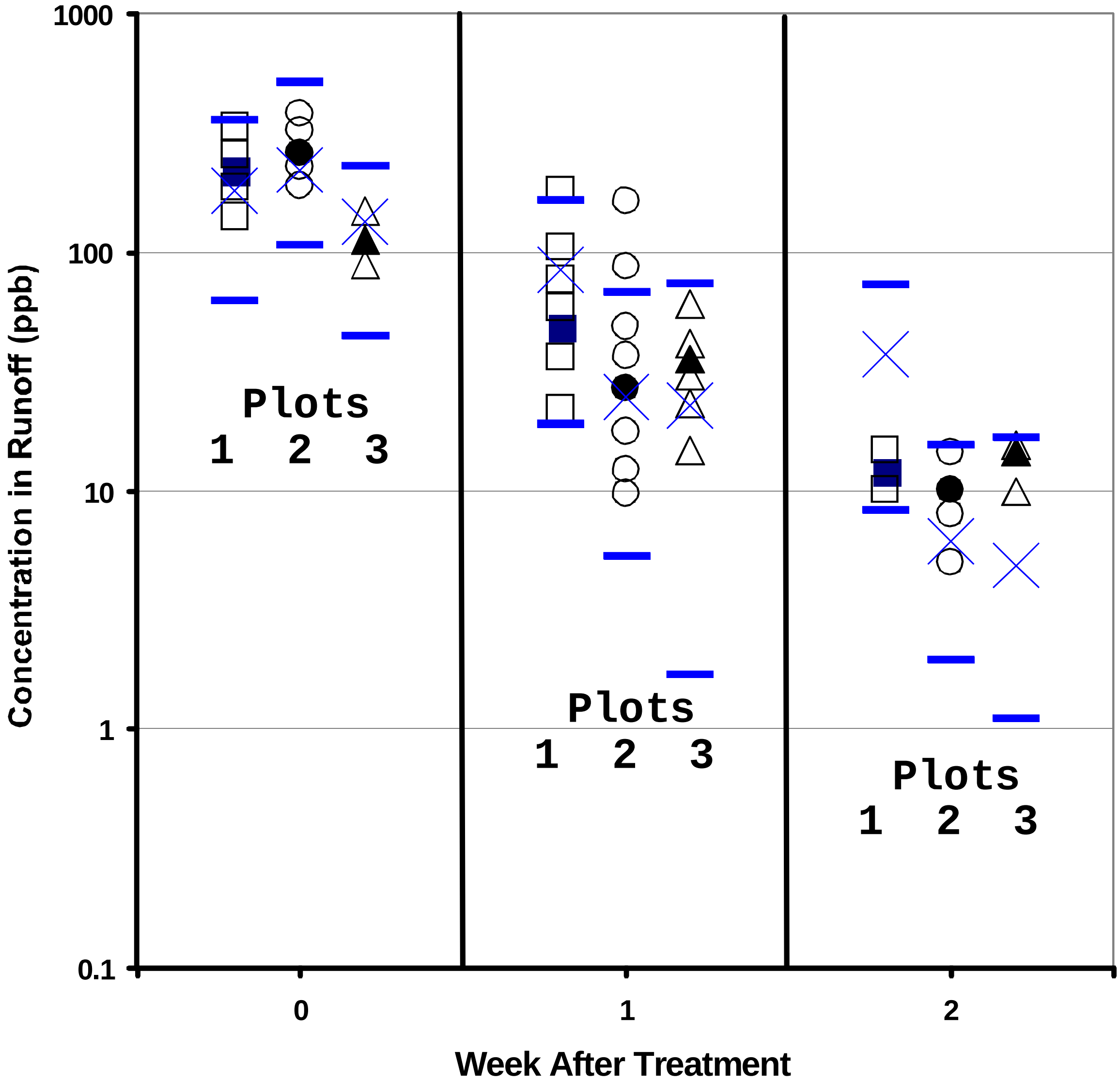

Figure 3: Calibration of Gleams-Driver to Bull Creek roadside plots based on concentrations of sulfometuron methyl (ppm) in runoff water from three plots after artificial rainfall

Measured data for Plots 1, 2, and 3 from Wood 2001, Figure 4. Open symbols are individual measurements and solid symbols are estimates of the median.

Modeled Values – Median (large X symbols) with 5th and 95th percentiles (large dashes)

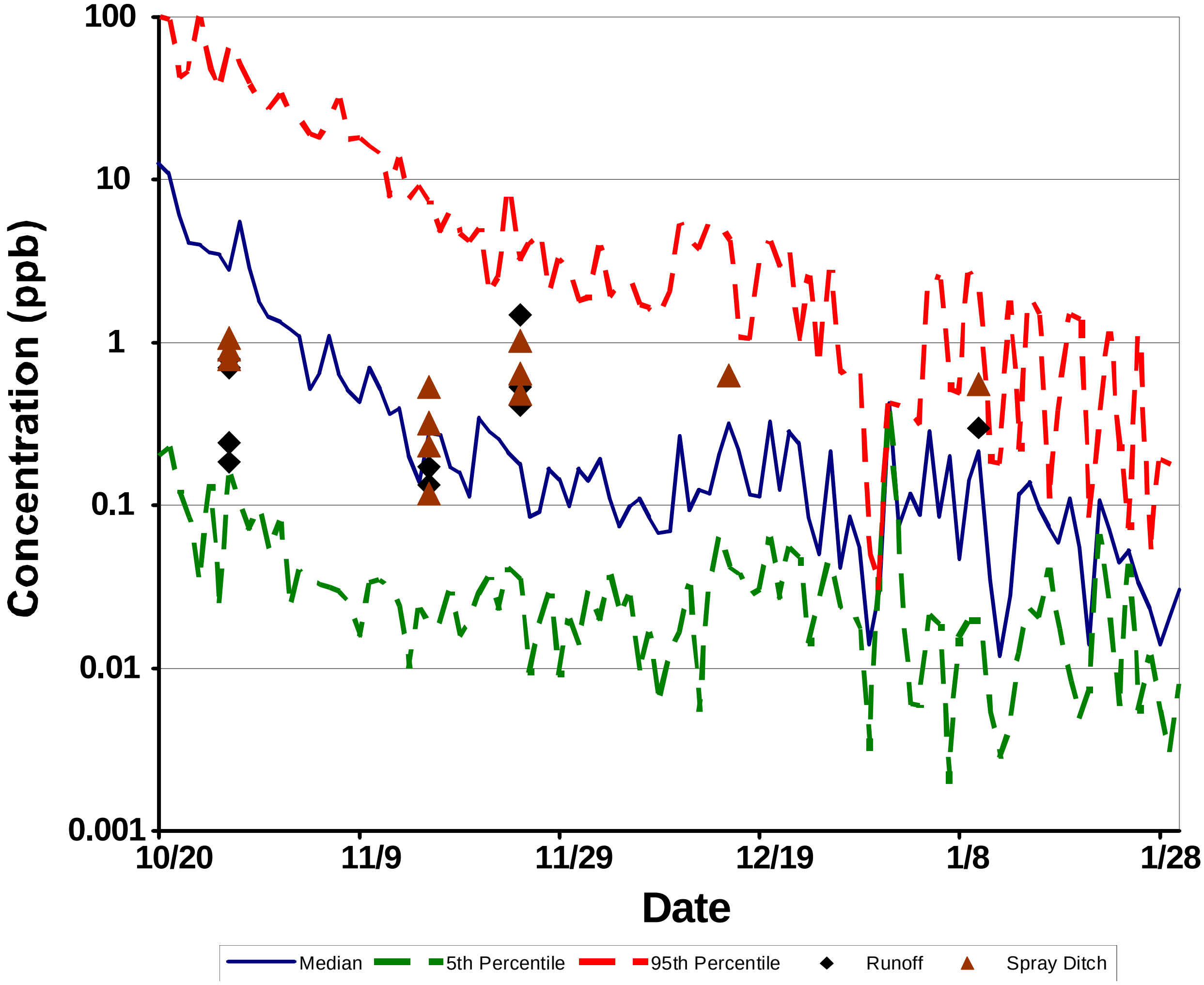

Figure 4: Concentrations of sulfometuron methyl in runoff after natural rainfall
Monitored data from Wood (2001). Gleams-Driver modeling based on calibration from artificial rainfall studies (see Figure 1).

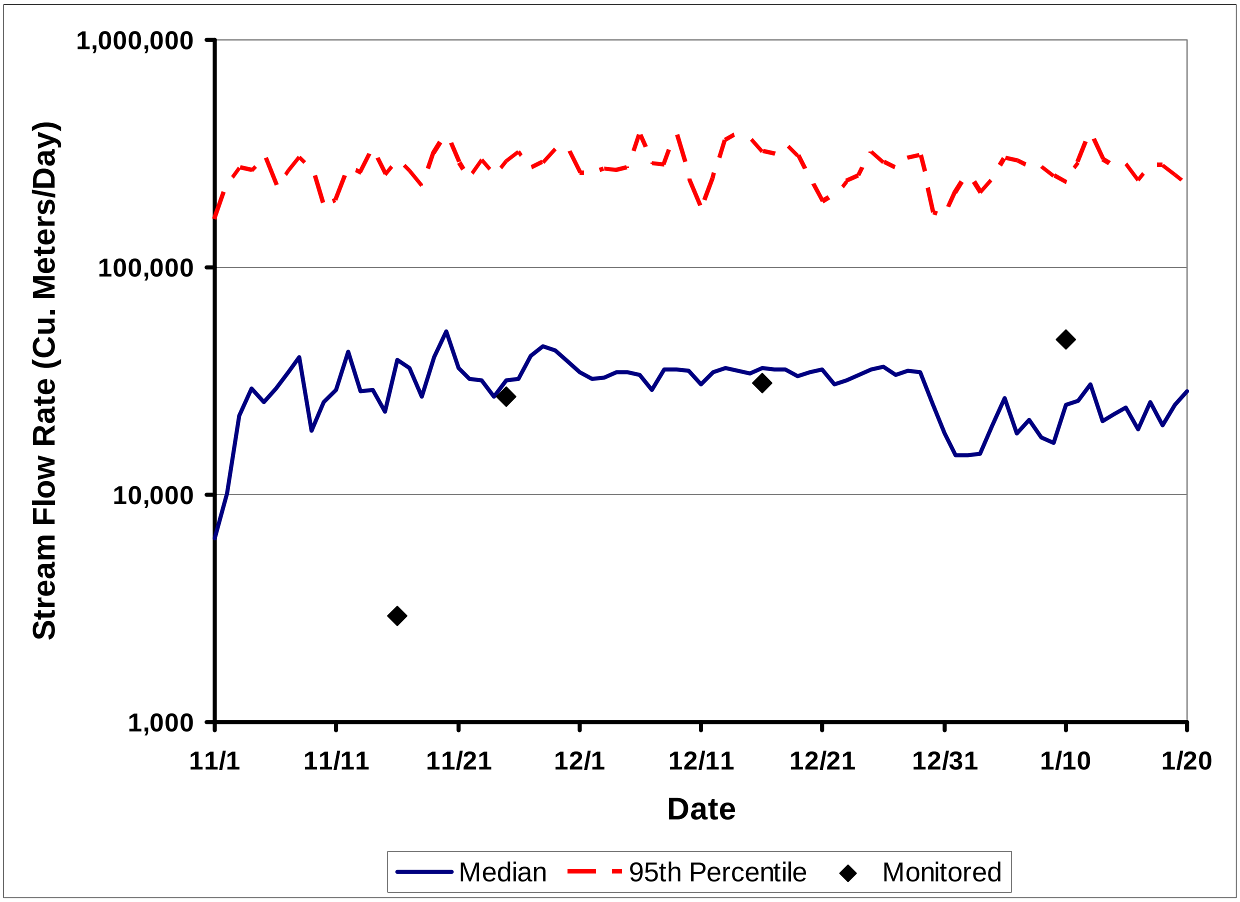

Figure 5: Modeled and monitored flow rates for Bull Creek
Monitored data from Wood (2001), Table 12, converted from ft^3/sec to m^3/day. Modeled flow rates from Gleams-Driver: median value as solid black line and upper 95th percentile as dashed red line.

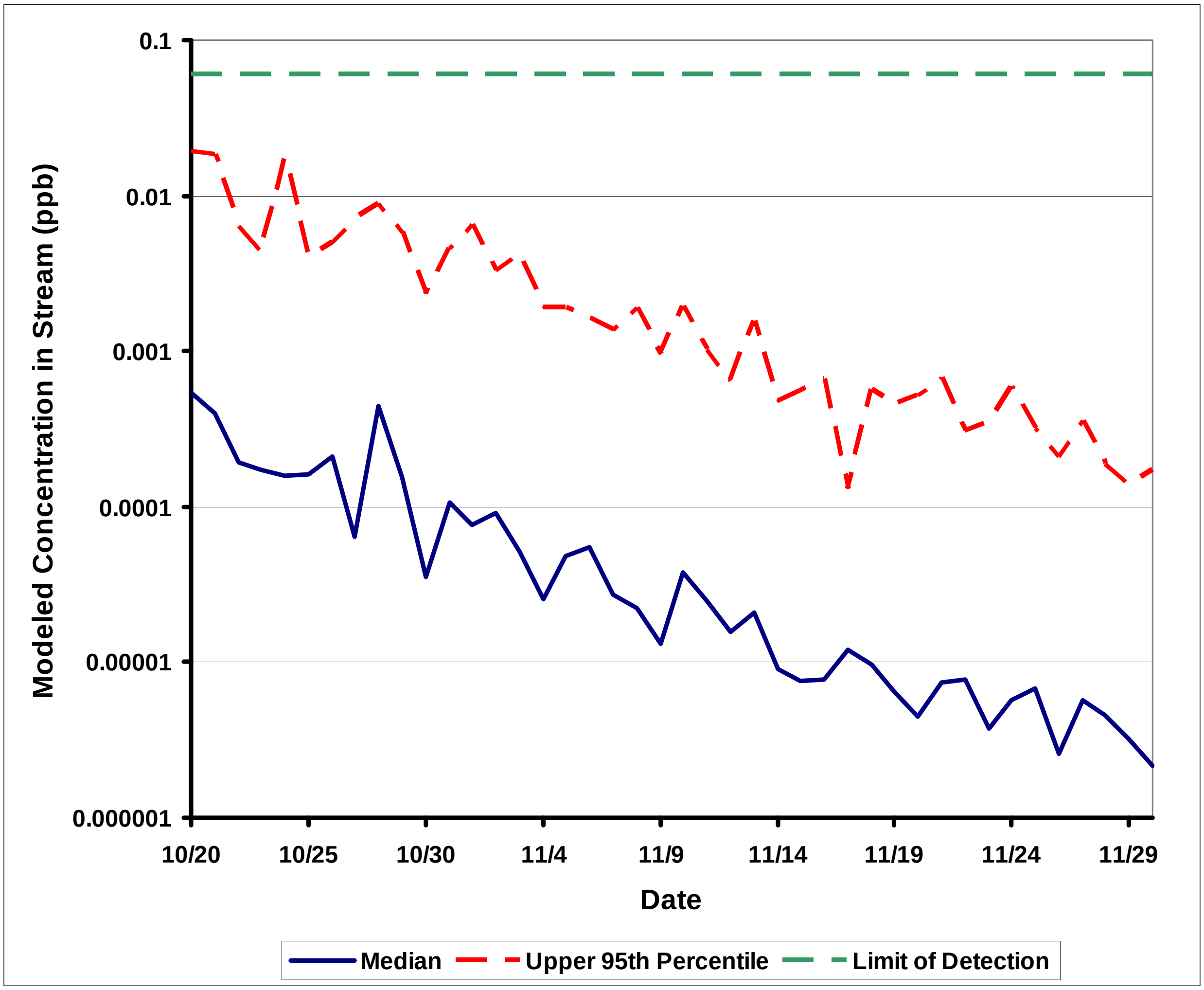

Figure 6: Modeled concentrations of and limit of detection for sulfometuron methyl in Bull Creek

Limit of detection of 0.06 ppb reported by Wood (2001, p. 20)

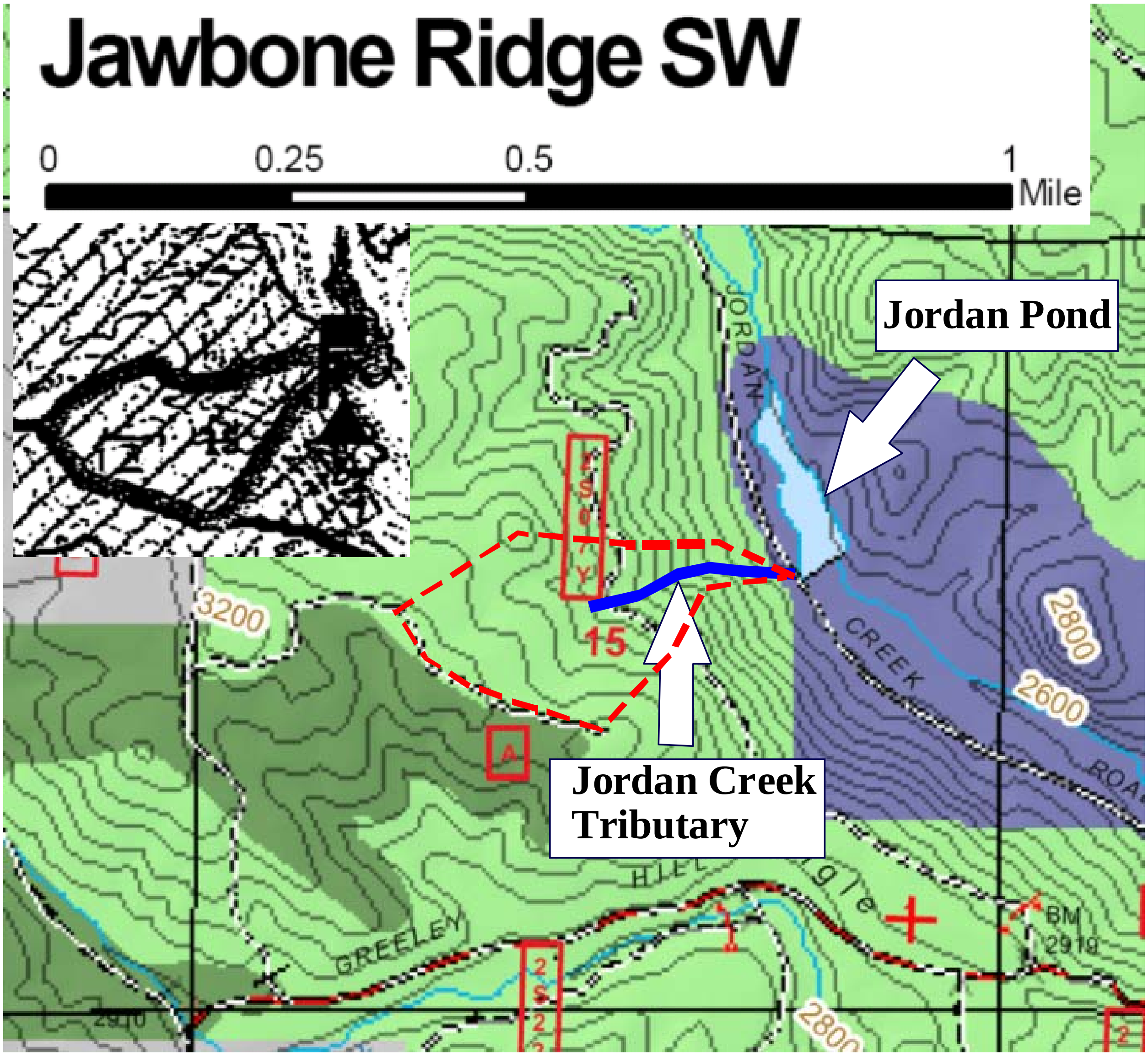

Figure 7: Map of Jordan Creek Area

The thick solid blue line indicates the approximate location of the tributary monitored by the USDA Forest Service.

The thick dashed red lines surrounding the tributary is the approximate area treated with hexazinone.

The black and white inset in the upper left region of the figure is taken from Figure 7 in Frazier and Grant (2003) indicating the location of the monitoring site and the treated area.

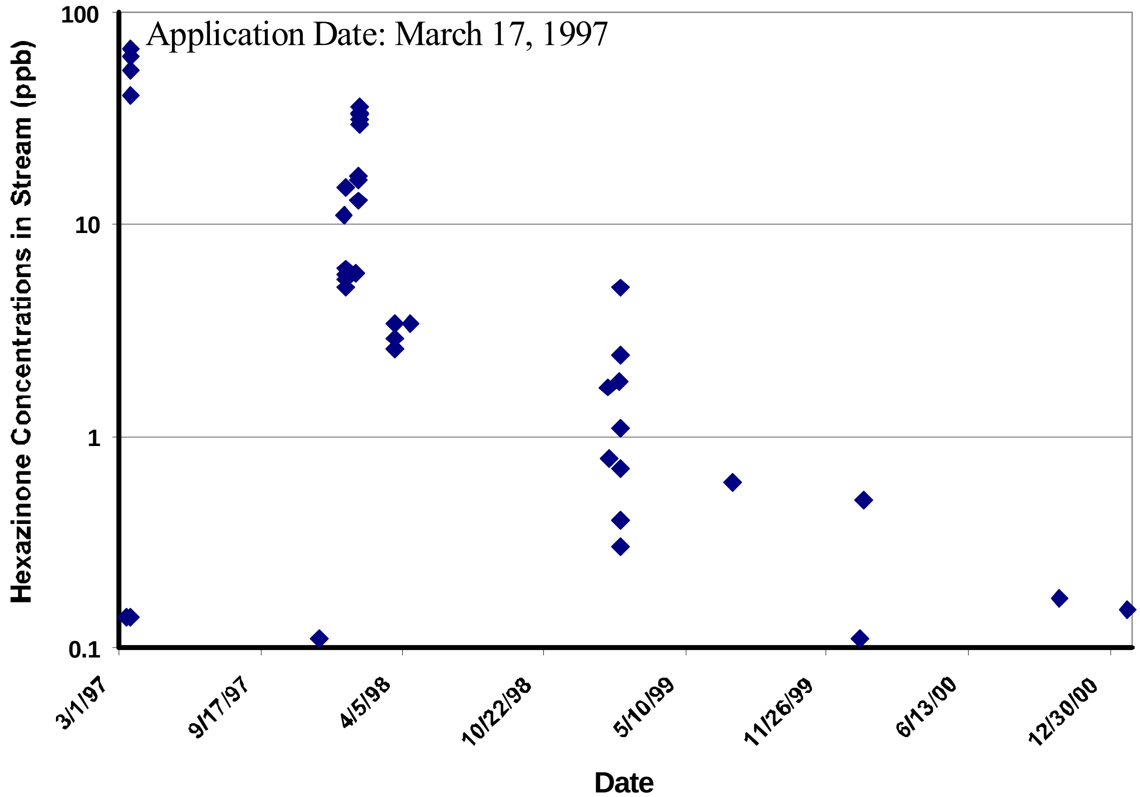

Figure 8: Monitoring data from the Jordan Creek tributary at the 97-JD-T2 location

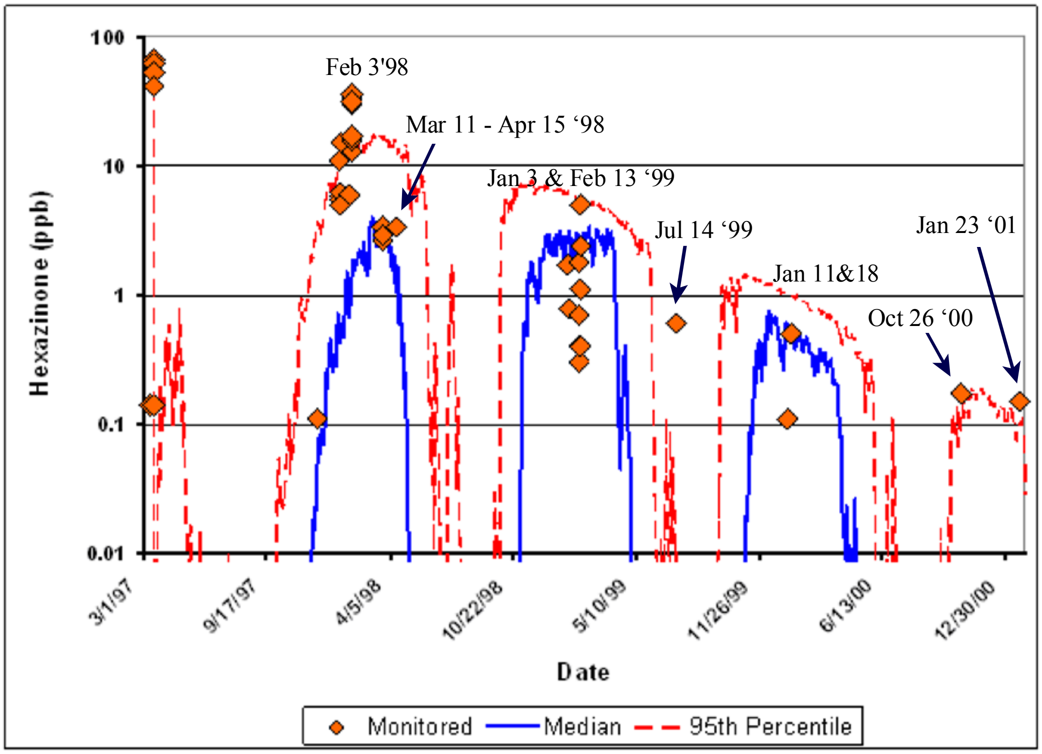

Figure 9: ***Quick Run*** **Gleams-Driver Modeling and Monitoring Data for Jordan Creek**

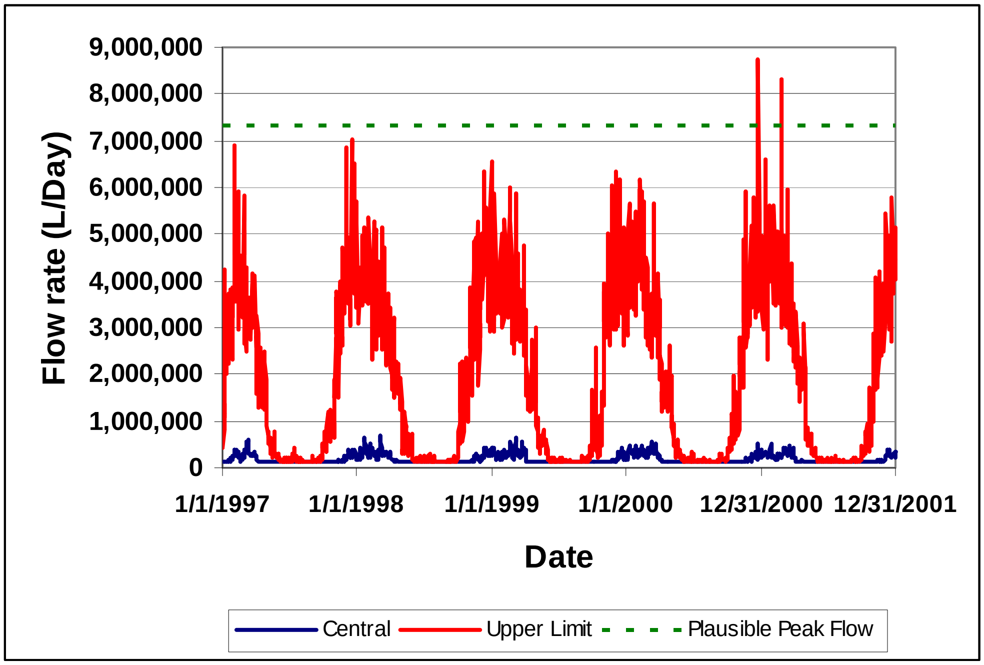

Figure 10: *Quick Run* Modeled Flow Rates for Jordan Creek Tributary

The dashed green line represents the upper bound of plausible flow rates estimated by Frazier (2007), USDA/FS Forest Hydrologist, Stanislaus National Forest.

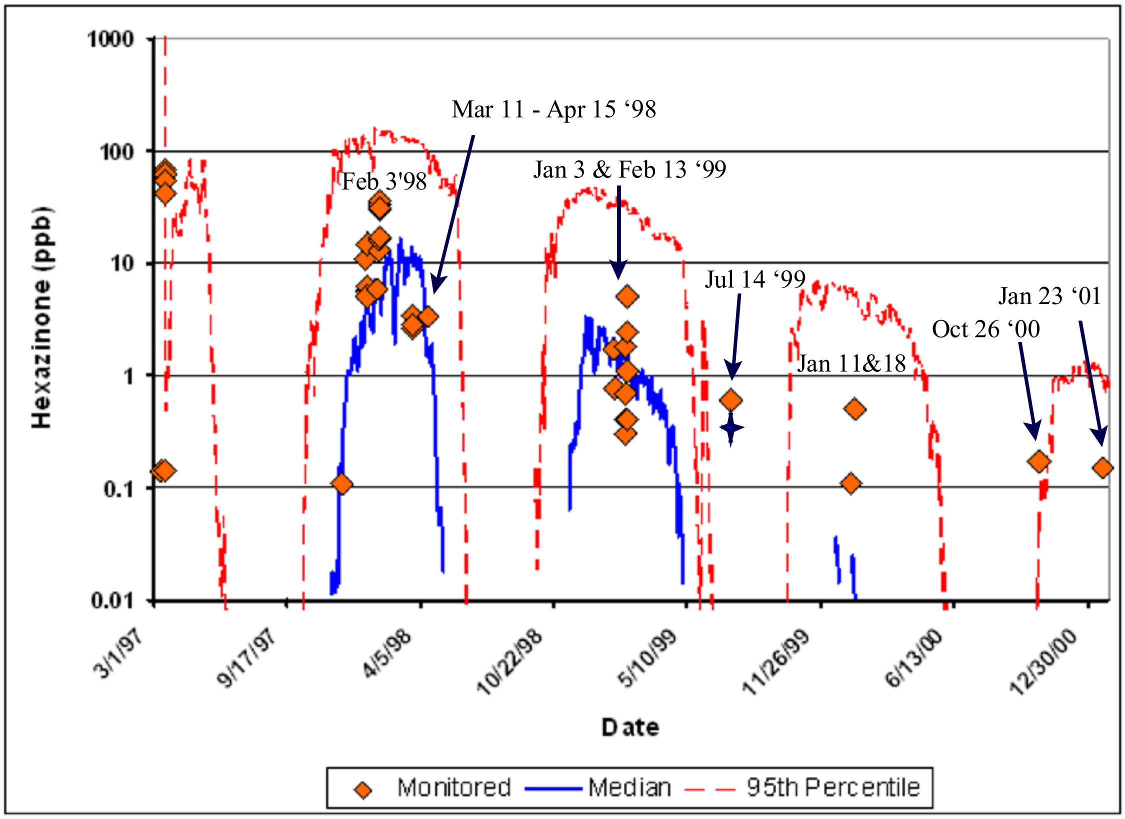

Figure 11: *Full Run* Gleams-Driver Modeling and Monitoring Data for Jordan Creek

The black star (✦) below the July 14, 1999 value is the maximum concentration for that day modeled in the 100 Gleams-Driver simulations.

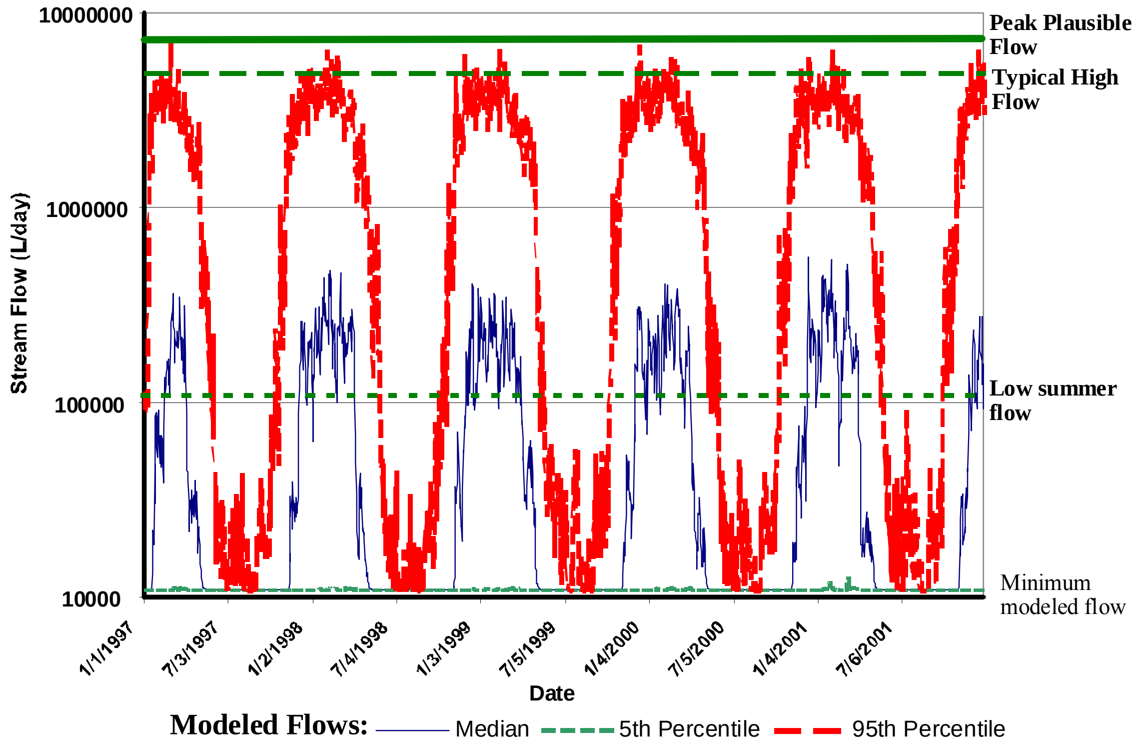

Figure 12: *Full Run* Modeled Flow Rates for Jordan Creek Tributary