USFS Fire Retardant Misapplication Calculator (FRMC):
User Guidance, Assumptions, and Basic Methods

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Disclaimers

Version 1.0 of the U.S. Forest Service (USFS) Fire Retardant Misapplication Calculator (FRMC) is intended for beta testing by the USFS and other federal agencies. The calculator has been tested over a wide range of scenarios encompassing typical misapplications. If users encounter issues in functionality or suspect the calculator is producing erroneous results, please contact the authors for guidance. Upon satisfactory completion of the beta testing period, the calculator and source code will be publicly released via the web.

Although FRMC was developed in collaboration with the U.S. Geological Survey (USGS), no warranty, expressed or implied, is made by the USGS or the U.S. Government as to the accuracy and functioning of the program and related program material nor shall the fact of distribution constitute any such warranty, and no responsibility is assumed by the USGS in connection therewith.

Installation

The USFS FRMC v1.0.1 is provided to users as a stand-alone executable for use on personal computers with the Windows operating system. Place the 'USFS_FRMC.exe' file in a directory on your computer's hard drive (it does not have to reside in any specific directory, but network drives are not recommended). Users can create a shortcut on the computer's desktop by browsing to the directory where the executable file is located, right clicking on the file, and selecting "Send to" → "Desktop (create shortcut)".

Assumptions

The following assumptions are made in calculating the length of the affected reach and maximum exposure time in the USFS FRMC:

1. The affected reach is the part of the stream in which the concentration of the contaminant exceeds a toxicity value at some point. The toxicity value is taken as 10% of LC50, the concentration required to kill 50% of the population, for tests with a 96-hour exposure time. The LC50 concentrations for specific chemicals are taken from test results provided by the U.S. Forest Service.
2. All of the misapplied retardant chemical within the misapplication area as defined by the 'Errant drop shape' enters the water.
3. No reaction or decay of the retardant chemical is included.
4. The chemical is assumed to be well mixed across the stream's cross section and distributed evenly over the greatest dimension of the misapplication area.
5. When channel slope is not entered by the user, the shear velocity is assumed to be 1/8 of the mean channel velocity. If channel slope is entered, the shear velocity is computed by assuming rough turbulent flow in a rectangular channel.
6. The dispersion coefficient is computed from a weighted average of dispersion coefficients computed from eleven empirical formulas, and dispersion coefficients below 0.2 m^2/s are omitted.
7. The stream network and channel geometry downstream of the misapplication site are estimated using a stream order approach (Strahler 1957) and characteristics of streams and rivers of different order from around the world (Downing et al. 2012; Leopold 1962).
8. Discharge is assumed to double for every increase in stream order and remain constant within a reach of uniform stream order. Input from smaller tributaries is neglected.

Implications of Assumptions on Length of Affected Reach

The first assumption follows the practice from the previous spill calculator. Because concentrations decrease as the contaminant cloud moves downstream and spreads, choosing a smaller toxicity value would produce longer affected reaches. In one-dimensional transport of a conservative tracer, the peak concentration decreases approximately as $x^{-1/2}$, where x is the distance downstream of the spill. Therefore, in a channel with constant downstream properties, decreasing the toxicity value by a factor of two will increase the affected length by approximately a factor of four. However, when downstream growth of the stream is considered (see discussion of assumptions 7 and 8), the increase in affected length will be smaller. The choice of the toxicity value as 10% of LC50 produces conservative (i.e., high) estimates of the affected length and represents a desire of the USFS to account for sub-lethal effects on salmonids.

The second and third assumptions give conservative estimates of the affected length. Because the affected length is determined as the distance beyond which the concentration of retardant does not exceed the toxicity value, any assumption that leads to high estimates of concentration will give a high estimate of the affected length. By assuming that all the misapplied retardant enters the water and ignoring mechanisms of loss such as decay, the FRMC provides conservative estimates of both concentration and the affected length. In principle, assuming that the misapplied retardant is well mixed over the spill length (assumption 4) will give a low estimate of the affected length because initial concentrations are lower than if the spill were more concentrated; however, if the affected length is much greater than the largest dimension of the misapplication area, the affected length computed with assumption 4 will not substantially differ from a length computed by assuming that the misapplied retardant is concentrated at one point in the stream.

The fifth and sixth assumptions affect the dispersion, or spreading, of the contaminant cloud, but their effect on the affected length is unclear. If the cloud spreads faster, the concentrations also decrease faster, and the length of the affected reach will be smaller. Many empirical formulas are available to compute the dispersion coefficient K, but no clear guidance on choosing a particular formula exists. Therefore, to protect against inaccuracies in any one formula, the FRMC computes a weighted average of the estimates of K from eleven formulas and ignores any estimate below 0.2 m^2/s, the minimum value reported in Rutherford (1994). These formulas typically involve the channel geometry and flow parameters such as the mean velocity U and the shear velocity u_*, which is a measure of the shear stress on the bottom of the channel. If the channel slope—which was not used in the previous spill calculator—is known, then the shear velocity can be computed with reasonable assumptions. If the slope is not known, then the ratio U/u_* is assumed to be 8, the mean value of a range from 0.8 to 24 (Rutherford 1994). With $U/u_* = 0.8$ and current weighting scheme, affected lengths are 0.75 to 1.38 times the lengths computed with $U/u_* = 8$ for the test cases provided by the USFS, and with $U/u_* = 24$, the lengths are 0.5 to 2 times the lengths computed with $U/u_* = 8$. Although the different dependences of the empirical formulas on U/u_* and the weighting in calculating an average value of K make quantifying the effect of changing U/u_* in a particular case difficult, using the mean value of 8 will provide an estimate within a factor of 2 (likely much closer for many cases).

The seventh assumption arose from relaxing the assumption from the previous spill calculator that the channel geometry and flow does not change with distance downstream. When the geometry and flow were assumed to be constant, the advection-dispersion model, described in the Basis section, produced unreasonably large estimates of the affected length. In other words, the lengths were large enough that tributaries must have entered the stream and changed the width, depth, and discharge. The stream order approach of assumption 7 is an attempt to represent the growth of the stream (and dilution of the contaminant) with the limited information available from reports of misapplications. Because this approach replaces actual stream geometry with means of lengths and widths taken from a large dataset, the effect on the estimates of the affected length is not clear. Relaxing this assumption would require more detailed information on the stream geometry and network downstream of a misapplication.

The eighth assumption is related to the seventh because a change in stream order requires a tributary of the same order to enter the stream. At the confluence the flow will increase, and the contaminant cloud will be diluted. The FRMC assumes that the flow doubles—that is, the two meeting streams have not only the same stream order but also the same discharge. In principle, the larger the dilution ratio, or the ratio of the discharges downstream and upstream of the confluence, the smaller the affected length because any process that reduces the concentration will reduce the affected length, as described above. In practice in several of the test cases, the chemical concentration fell below the toxicity value at the sharp drop in concentration at a confluence. In these cases, while a smaller dilution ratio might lead to a larger affected length, larger dilution ratios could affect the FRMC's predictions only when the stream order changes more than once.

Operation

The USFS FRMC was designed to replicate the input data requirements and workflow of the previous calculator as much as possible (fig. 1). User inputs are colored in orange, while results (output) from the calculator are colored in blue (white output boxed are intermediate computations). We recommend opening a new calculator at the beginning of each session and checking to ensure the version being used is the most recent. Double click on the 'USFS_FRMC.exe' file or desktop shortcut icon to open the calculator. The calculator may take a minute or two to open (especially at first use), so please be patient. If Windows Defender tries to block the unknown application, please choose 'Run anyway'. The version number can be found in the 'Information' menu under 'About' (fig. 2). The 'Information' menu also includes a disclaimer and list of assumptions made in the calculator.

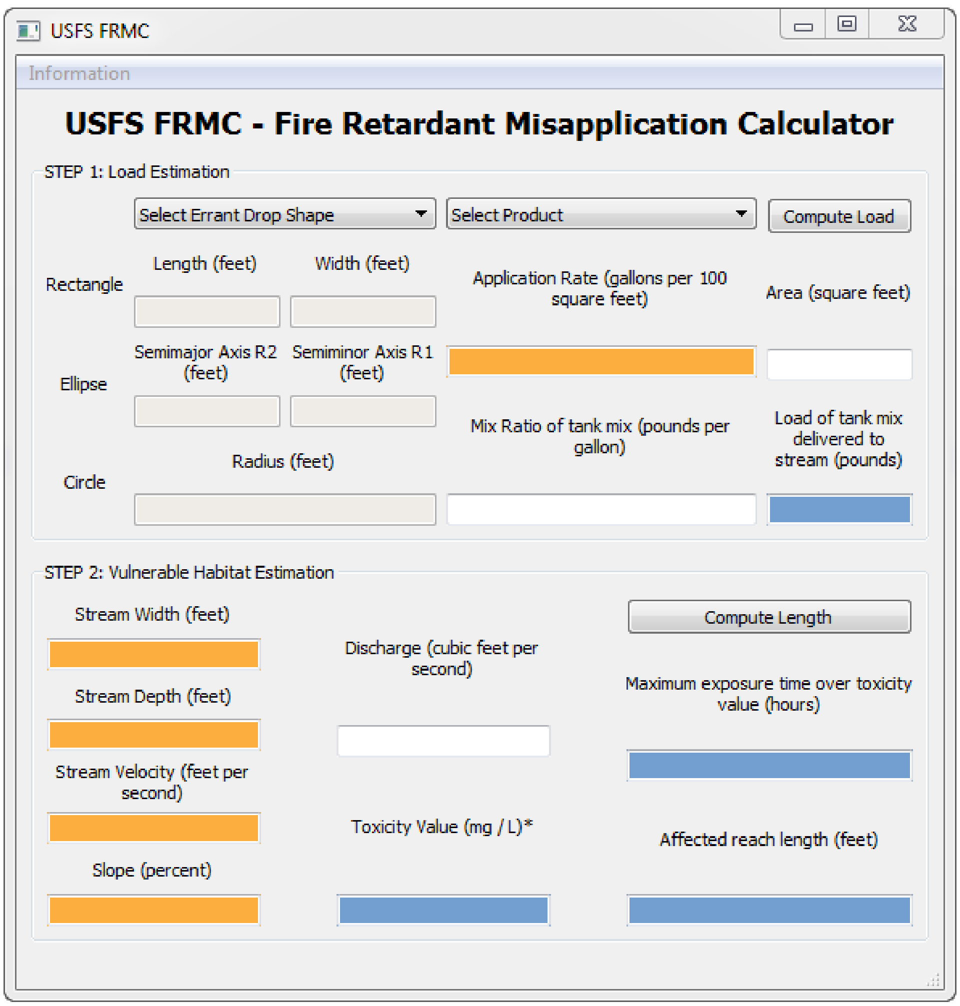


Figure 1. A screen capture of the USFS FRMC v1.0.0 graphical user interface.

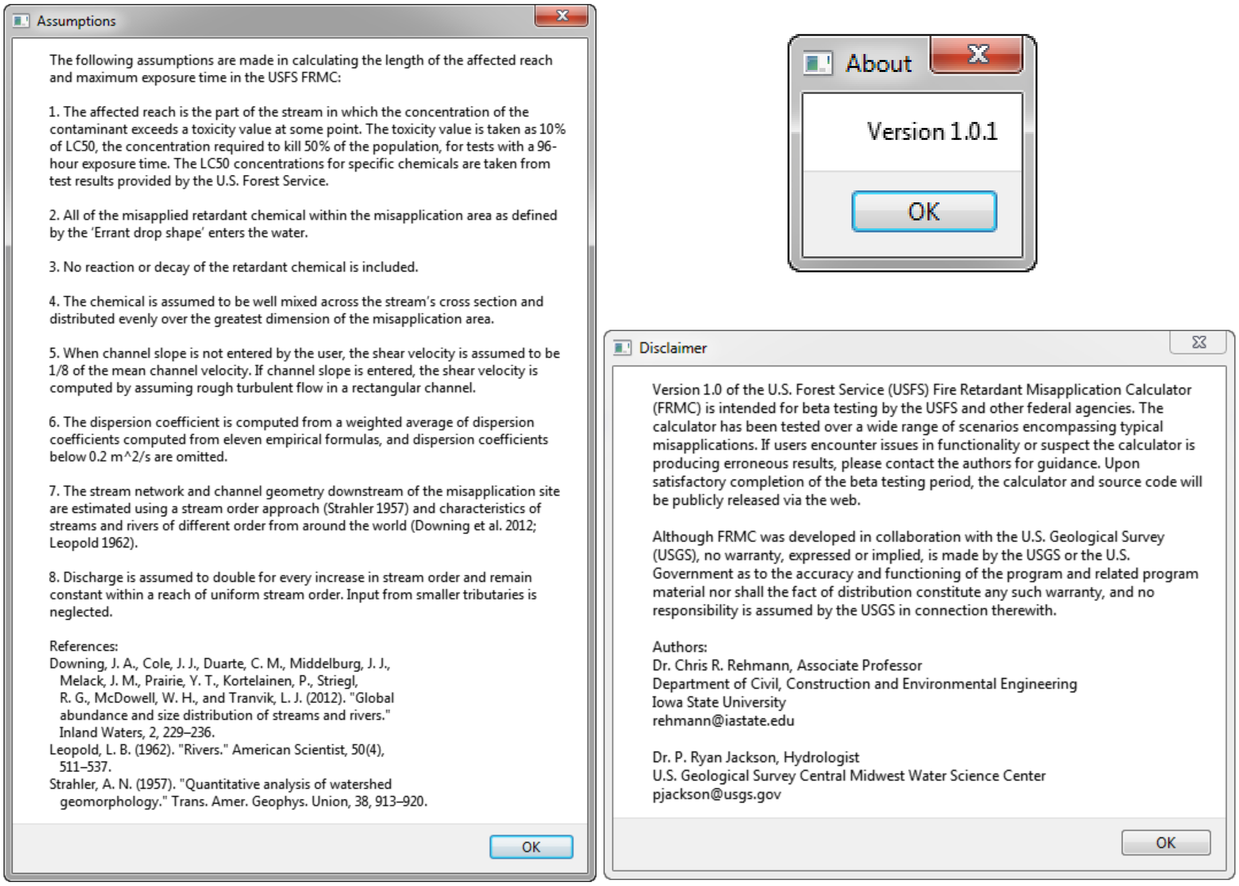


Figure 2. Screen captures of the items in the 'Information' menu.

Table 1. Input values for example misapplication (Buck fire, Bearskin Creek; data provided by the USFS) and output from the USFS FRMC v1.0.0. For comparison, the affected reach length computed using the previous spill calculator (spill calculator V. 1.9 Beta) is 4,201 feet.

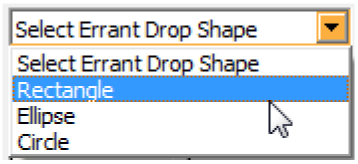
Description	Value
Input	
Errant drop shape	Rectangle
Length of misapplication area (feet)	22
Width of misapplication area (feet)	2.5
Retardant product	Phos-Chek LC-95R
Application rate (gallons per 100 sq. feet)	8.5
Stream width (feet)	2.5
Stream depth (feet)	0.6
Stream velocity (feet per second)	0.5
Output	
Load (pounds)	8.84
Affected reach length (feet)	13,037
Maximum exposure time (hours)	0.87

The workflow comprises two steps: (1) Load estimation and (2) Vulnerable habitat estimation. The calculator interface is divided into two panels, one for each of the two steps. The workflow is demonstrated below using data from a misapplication to Bearskin Creek during the Buck Fire (Table 1; data provided by the USFS).

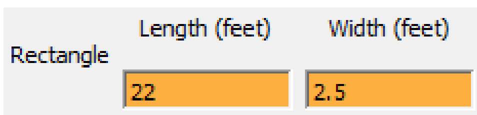
With the calculator open, complete the following steps to estimate the affected reach length from a misapplication:

<u>Step 1: Load estimation</u>

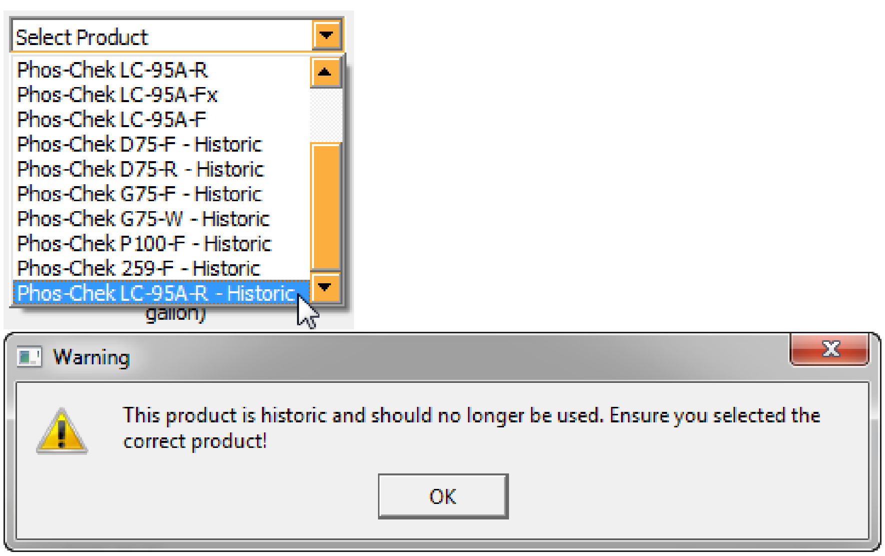
a. Select the errant drop shape from the dropdown list



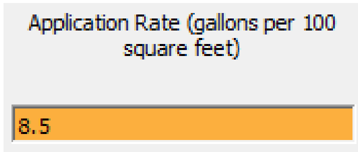
b. Enter the dimensions of the shape in the associated input box or boxes. Note: The narrowest dimension of the shape should not exceed the stream width entered in step 2. The narrowest dimension is twice the semiminor axis (2*R1) for an ellipse and twice the radius (or diameter) for a circle.



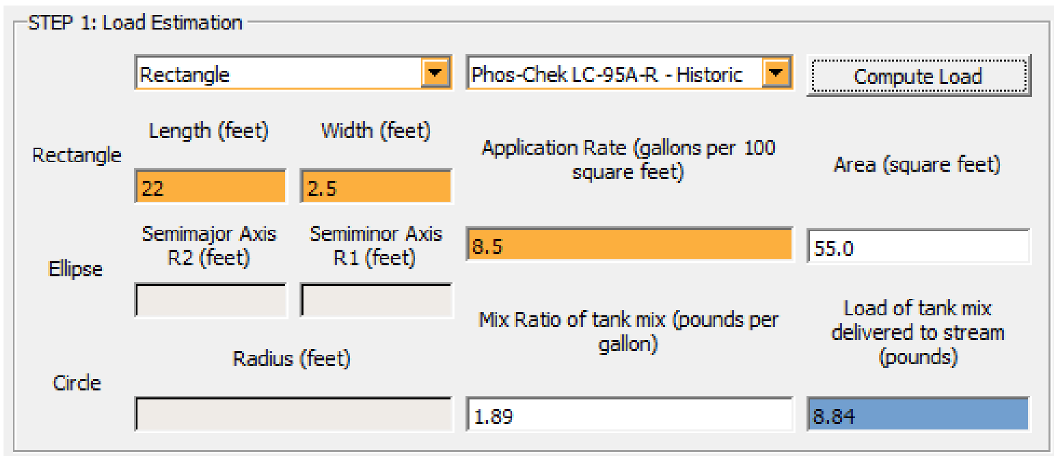
c. Select the product from the dropdown list (historical products no longer in use are available, but will generate a warning to ensure the user is aware they are choosing a historical product)



d. Enter the product application rate in gallons per 100 square feet



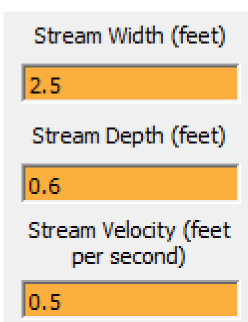
e. Press the 'Compute Load' button (the step 1 result boxes will populate)



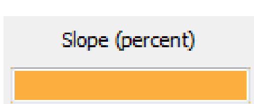
NOTE: If any edits are made to the step 1 input boxes (orange) after the load is computed, the results will disappear, and the user must recompute the load by pressing the 'Compute Load' button again.

<u>Step 2: Vulnerable habitat estimation</u>

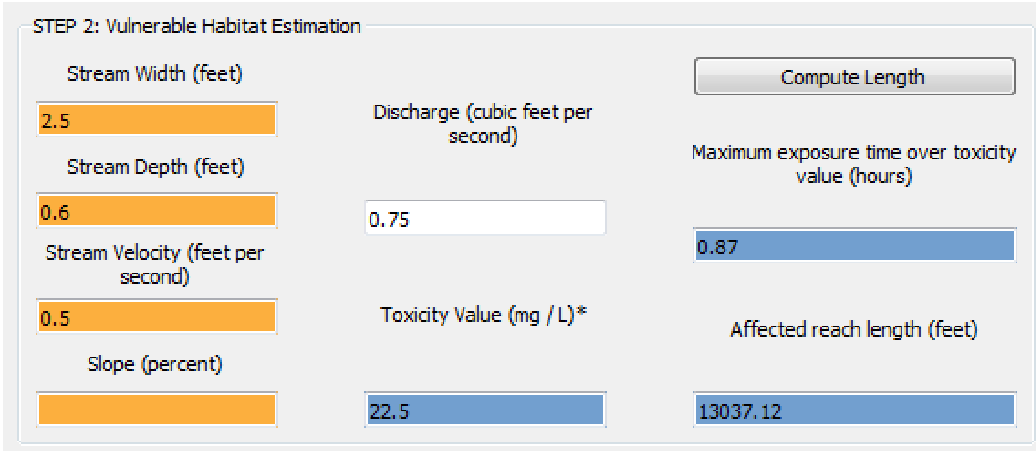
a. Enter the observed or estimated stream width (in feet), depth (in feet), and velocity (in feet per second) at the misapplication site



b. Enter the channel slope (in percent) at the misapplication site if known (optional; leave blank if unknown)



c. Press the 'Compute Length' button (the step 2 results boxes will populate)



NOTE: If any edits are made to step 2 input boxes after the reach length is computed, the results will disappear, and the user must recompute the reach length by pressing the 'Compute Length' button again.

Interpreting the Results

The spill calculator produces three primary results: (1) the load of tank mix delivered to the stream, (2) the affected reach length, and (3) the maximum exposure time over the toxicity value. The *load of chemical delivered to the stream* is straightforward, but it is important to understand that the load is computed assuming all the chemical in the misapplication area defined by the errant drop shape and dimensions enters the stream. Therefore, the smallest dimension of the errant drop shape should be no larger than the width of the channel. Failure to meet this requirement will result in overestimation of the load because chemical that falls on land adjacent to the stream will be included in the computed load.

The advection-dispersion model used in the calculator allows the computation of concentration versus time curves for many points downstream of the misapplication (fig. 3). The *affected reach length* is defined as the length of reach downstream of the misapplication site (in feet) where the peak concentration of the specified chemical is greater than or equal to the toxicity value for the chemical. Fish downstream of the affected reach length should not be exposed to concentrations of the chemical at or above the toxicity value (provided all model assumptions are valid).

The *maximum exposure time over the toxicity value* is defined as the maximum duration of exceedance of the toxicity value (in hours) within the affected reach. Fish within the affected reach should not be subject to chemical concentrations above the toxicity value for durations longer than the maximum exposure time. The maximum exposure time is computed from the width of the concentration versus time curves at the toxicity value (fig. 3). It is important to note that the maximum exposure time will rarely, if ever, occur at the beginning or the end of the affected reach. Maximum exposure times less than 18 minutes will display as 0.00 hours in the calculator due to rounding.

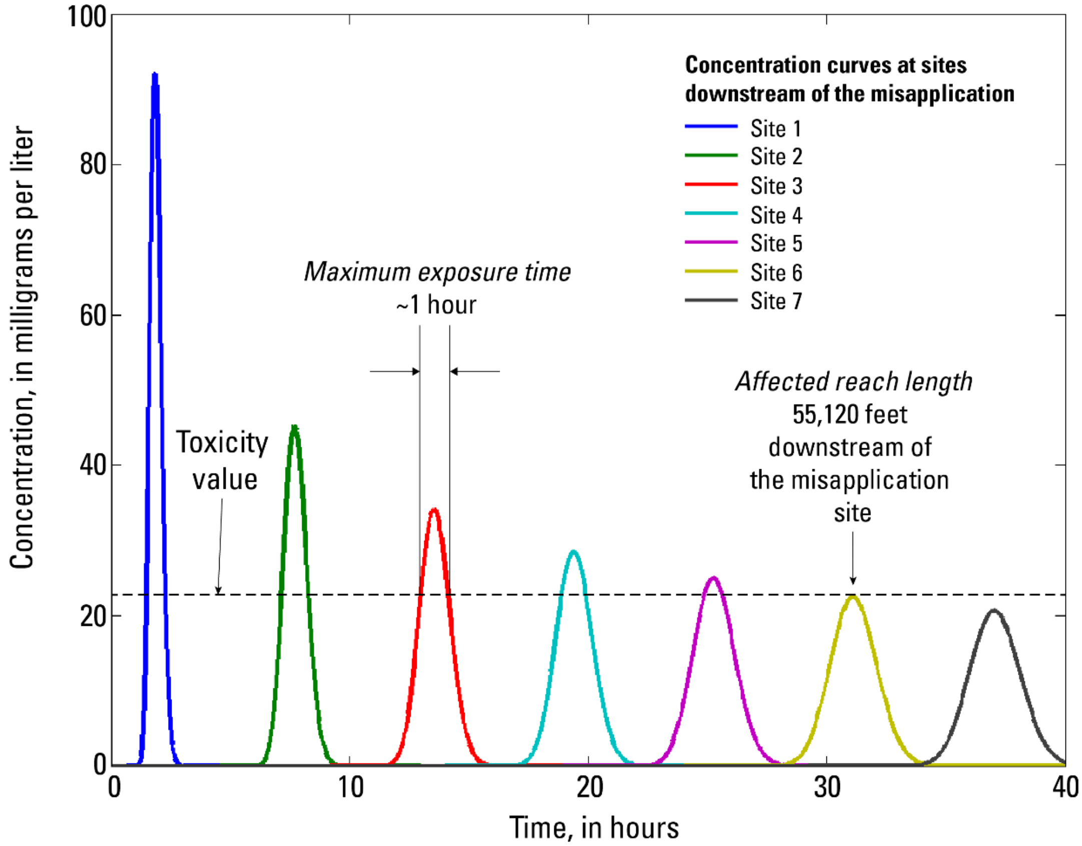


Figure 3. Concentration as a function of time at seven sites downstream of a misapplication. These curves, along with the toxicity value, are used to compute the affected reach length and maximum exposure time (both shown for reference).

Basis

The spill calculator computes the affected length of the stream using solutions of the one-dimensional advection-dispersion model (e.g., Fischer et al. 1979). Therefore, it accounts for advection, or carrying by the flow, at a mean velocity U and dispersion, or the spreading that occurs by several mechanisms, with dispersion coefficient K. The contaminant is assumed to be well mixed across the stream's cross section and distributed evenly over the length L_s of the misapplication area. The first estimate of the affected length is computed by assuming that the parameters of the stream geometry and flow do not change downstream. Then the concentration C of the contaminant can be computed as a function of downstream distance x and time t using

$$C = \frac{C_0}{2}\left[\operatorname{erf}\left(\frac{x-Ut}{\sqrt{4Kt}}\right) - \operatorname{erf}\left(\frac{x-L_s-Ut}{\sqrt{4Kt}}\right)\right] \quad (1)$$

where erf(z) is the error function (Andrews 1992, section 3.2) and $C_0 = M/L_sBH$ is the initial concentration of the spill of mass M (i.e., the load) distributed over the length L_s, width B, and depth H. If a toxicity value C_t is specified, then the affected length—or the downstream distance beyond which the concentration never exceeds the toxicity value—can be computed.

In some cases, the affected length produced by this procedure is large enough that the assumption of constant stream geometry and flow is questionable. To allow for the stream to grow as it moves downstream, the concept of stream order is used (Strahler 1957). The stream order of the point of the misapplication is determined by comparing the stream's width to the widths classified from 418 streams and rivers of different order compiled by Downing et al. (2012). If the initial estimate of the affected length puts it beyond the mean length corresponding to the stream order (Leopold 1962, Downing et al. 2012), the contaminant cloud is assumed to enter a reach of the next stream order and mix with a tributary of equal flow (i.e., a dilution ratio of 2). For example, downstream of a confluence of two order 1 streams, the stream order increases to 2, the discharge doubles, and the chemical concentration decreases by a factor of 2. Inflow from smaller tributaries is ignored.

This diluted concentration cloud is used as input to the next reach. If the location of the confluence is x_1 and the concentration at the end of the previous reach, divided by the dilution ratio (2 in this case), is $C(x_1, t) = f(t)$, then the concentration in the next reach is given by

$$C(x,t) = \int_0^t f(t-\tau)\frac{x}{\sqrt{4\pi K}\tau^{3/2}}\exp\left(-\frac{(x-x_1-U\tau)^2}{4K\tau}\right)d\tau \quad (2)$$

The mean channel velocity, depth, and width are assumed to increase with discharge following empirical relations derived by Leopold (1962) for the Yellowstone-Bighorn River system in Wyoming. Rates of increase of these parameters vary across rivers, but Leopold (1962) showed that variations in these rates are small. Once the parameters are computed, the new affected length is computed from equation (2), and the procedure is repeated until the affected length and stream order are consistent.

As noted in the previous section, the user specifies conditions at the misapplication site: the width and depth of the stream, the mean velocity, the load, contaminant type, and the length of the misapplication area along the stream. Therefore, applying equations (1) and (2) requires estimating the dispersion coefficient K. Most empirical formulas, and the ones used in this version of the FRMC, express the dispersion coefficient as a function of the stream width, depth, mean velocity, and shear velocity u_*, which is a measure of the shear stress on the bottom of the channel. The shear velocity can be estimated from a measure of the channel roughness and the longitudinal slope. In this version of the spill calculator, a value of $U/u_* = 8$ is assumed. This value is the approximate mean of 168 values, which have a minimum of 0.8 and a maximum of 24, from data in Rutherford (1994).

Even with a good estimate of the shear velocity, values of the dispersion coefficient are uncertain because of scatter in the predictions from the empirical formulas. Many formulas are available, and predictions from the formulas can differ by an order of magnitude or more (e.g., Carr and Rehmann 2007). Eleven empirical formulas were used in the calculations. The formulas, which produce the predicted dispersion coefficient K_p, were evaluated by using measured dispersion coefficients K_m in Rutherford (1994) to compute the discrepancy ratio DR = $\log_{10}(K_p/K_m)$, which should be zero if the predictions match the measurements (i.e., $K_p/K_m = 1$). Values less than 0.2 m^2/s, the minimum value reported by Rutherford (1994), were ignored, and a weighted average of the dispersion coefficient, using the reciprocal of the root-mean-square DR as the weight, was used to compute the affected length.

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