Simulation of Flow Regimes to Reduce Habitat for *T. tubifex*

By Robert T. Milhous

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
Inch (in.)	2.54	centimeter (cm)
Inch (in.)	25.4	millimeter (mm)
Foot (ft)	0.3048	meter (m)
	Area	
Square foot (ft^2)	929.0	square centimeter (cm^2)
Square foot (ft^2)	0.09290	square meter (m^2)
	Volume	
Cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
Foot per second (ft/s)	0.3048	meter per second (m/s)
Cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Density	
Pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)
Pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
Vertical coordinate information is referenced to the insert datum name (and abbreviation) here for instance, "North American Vertical Datum of 1988 (NAVD 88)."
Horizontal coordinate information is referenced to the insert datum name (and abbreviation) here for instance, "North American Datum of 1983 (NAD 83)."
Altitude, as used in this report, refers to distance above the vertical datum.
Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).
Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

SI to Inch/Pound

Multiply	By	To obtain
	Length	
Centimeter (cm)	0.3937	inch (in.)
Millimeter (mm)	0.03937	inch (in.)
Meter (m)	3.281	foot (ft)
	Area	
Square meter (m^2)	10.76	square foot (ft^2)
Square centimeter (cm^2)	0.1550	square inch (ft^2)
	Volume	
Cubic meter (m^3)	35.31	cubic foot (ft^3)
	Flow rate	
Meter per second (m/s)	3.281	foot per second (ft/s)
Cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Density	
Kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
Gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
°F=(1.8×°C)+32
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8
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Simulation of Flow Regimes to Reduce Habitat for *T. tubifex*

By Robert T. Milhous[1]

Introduction

Whirling disease has had a significant impact on trout fisheries of the American west by reducing the numbers and quality of rainbow trout in infected streams. The life cycle of whirling disease is presented in figure 1. The figure is from a New Mexico Fish and Game publication distributed to fishermen. Of interest is that items 1 through 4 relate to the river bottom (sediment) or to worms that live in the sediment. A critical factor in the life cycle of the whirling disease parasite is the fine sediment that provides the optimum habitat for *Tubifex tubifex*, an oligochaete worm that acts as an intermediate host for the disease (Sauter and Gude, 1996; and Krueger, 2002). Oligochaete worms are used herein as an indicator of probability of the existence of *T. tubifex*. The assumption is that if habitat conditions are good for oligochaete worms in general, the habitat is also good for *T. tubifex*.

This report presents a model for the simulation of flushing flows required to remove undesirable fines and sand from a pool. Undesirable fines may also need to be flushed from runs, the surface layer (armour), and backwater areas. Well-defined links of specific particle sizes to oligochaete worm abundance is needed to justify the use of flushing flows to move sediment.

An analytical method for estimating the streamflows needed to remove the fine sediment is demonstrated herein. The overall steps to follow in removing fines from a stream are:

Step 1. Determine size of the sediment that is the habitat for oligochaete worms.

Step 2. Determine location of the sediment that is the habitat for oligochaete worms.

Step 3. Determine streamflows needed to flush (remove) the sediment that is the habitat for oligochaete worms.

The case study approach is used to present the method and to demonstrate its application. The case is derived from the sediment and oligochaete worm habitat of Willow Creek. Willow Creek is a tributary of the Upper Colorado River located in Grand County, Colo. Willow Creek Reservoir (an element of the Colorado–Big Thompson Project) controls the streamflows of the creek and is just above the study site.

[1] Hydrologist, Fort Collins Science Center, 2150 Centre Avenue, Building C, Fort Collins, Colo.

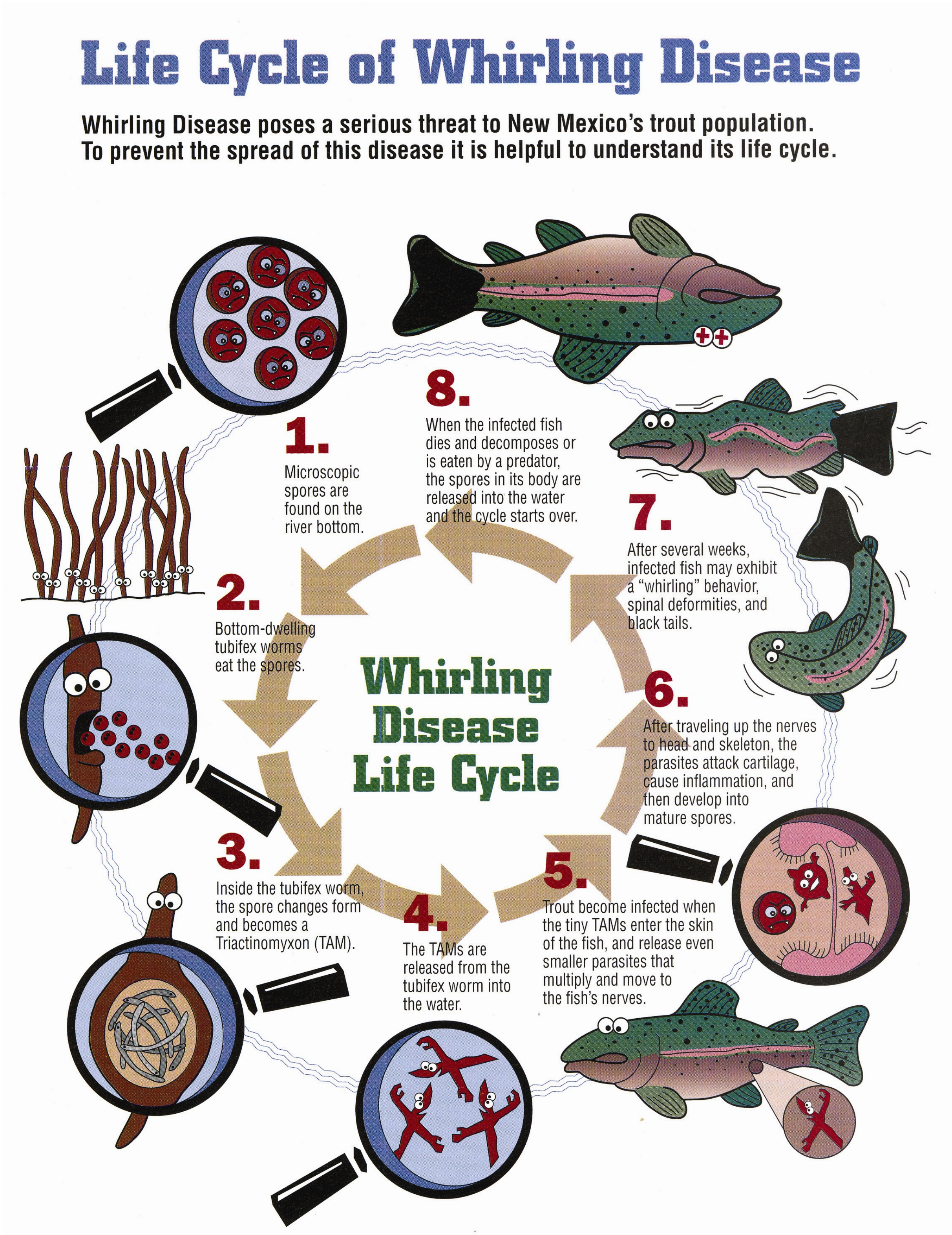

Figure 1. The life cycle of whirling disease (New Mexico Department of Fish and Game, 2003).

Willow Creek Case Study

Willow Creek, above Willow Creek Reservoir, where the watershed area is 329 km^2, had an average annual discharge of 2.0 m^3/s for water years 1955–1960. For the same period, the discharge below the reservoir (watershed area of 347 km^2) was 0.7 m^3/s. A map showing the location of the creek and the study reach is presented in figure 2. The study reach of Willow Creek is a gravel and cobble bed stream with runs, riffles, and pools. There is a section of bank where the creek is eroding a bank of fine sand, clays, and silt. Downstream of this bank is a pool with a deep deposit (about 0.3 m) of fine sand, silt, and clay on top of gravel and cobbles.

The pool analyzed in this case study is in the middle of the photograph presented in figure 3, and the bank on the left of the picture is the location of some of the deposited fine sediment.

A map of the study reach is presented in figure 4. Water flows from the upper part of the map to the lower part. Only the pool in the lower part of the study reach is considered in this report. A picture of the surface of the pool is given in figure 5. The plants on the surface are rooted in the fine sediments which should be removed from the pool in order to reduce the quality of the oligochaete habitat.

A discussion of the three steps in the analysis of environmental flows required to remove sediment in order to reduce the habitat for oligochaete worms follows.

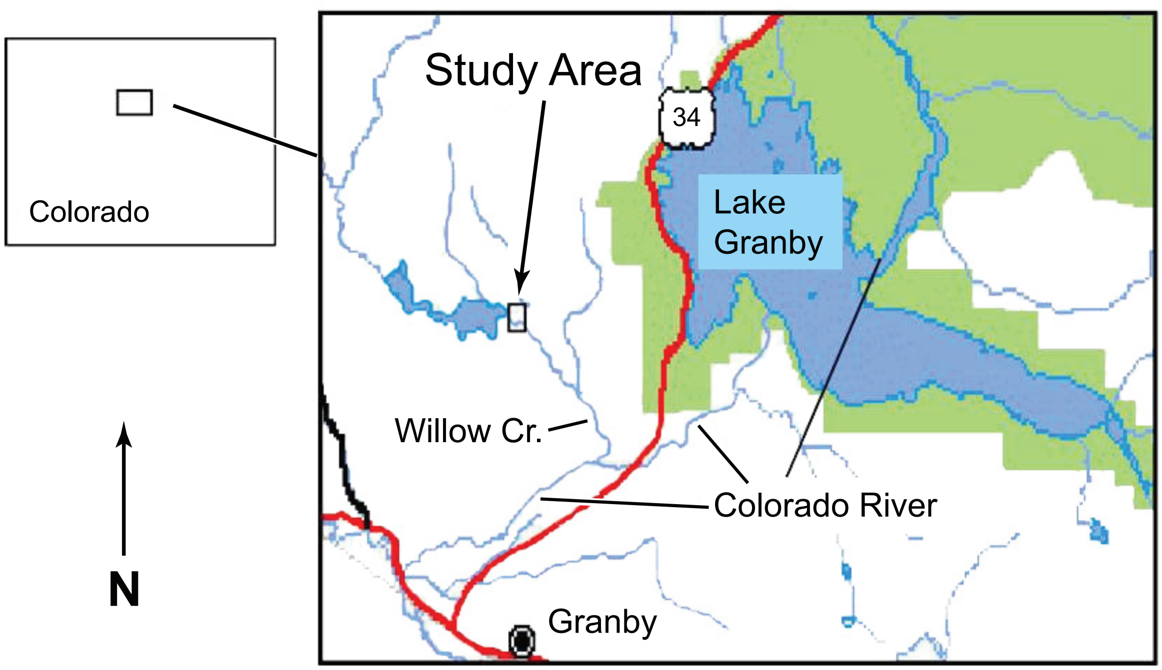

Figure 2. Location of Willow Creek, Grand County, Colo., and the study site which is just below Willow Creek Reservoir. Map courtesy of Terry Waddle, Fort Collins Science Center.

Figure 3. Picture of the pool section of the Willow Creek study site.

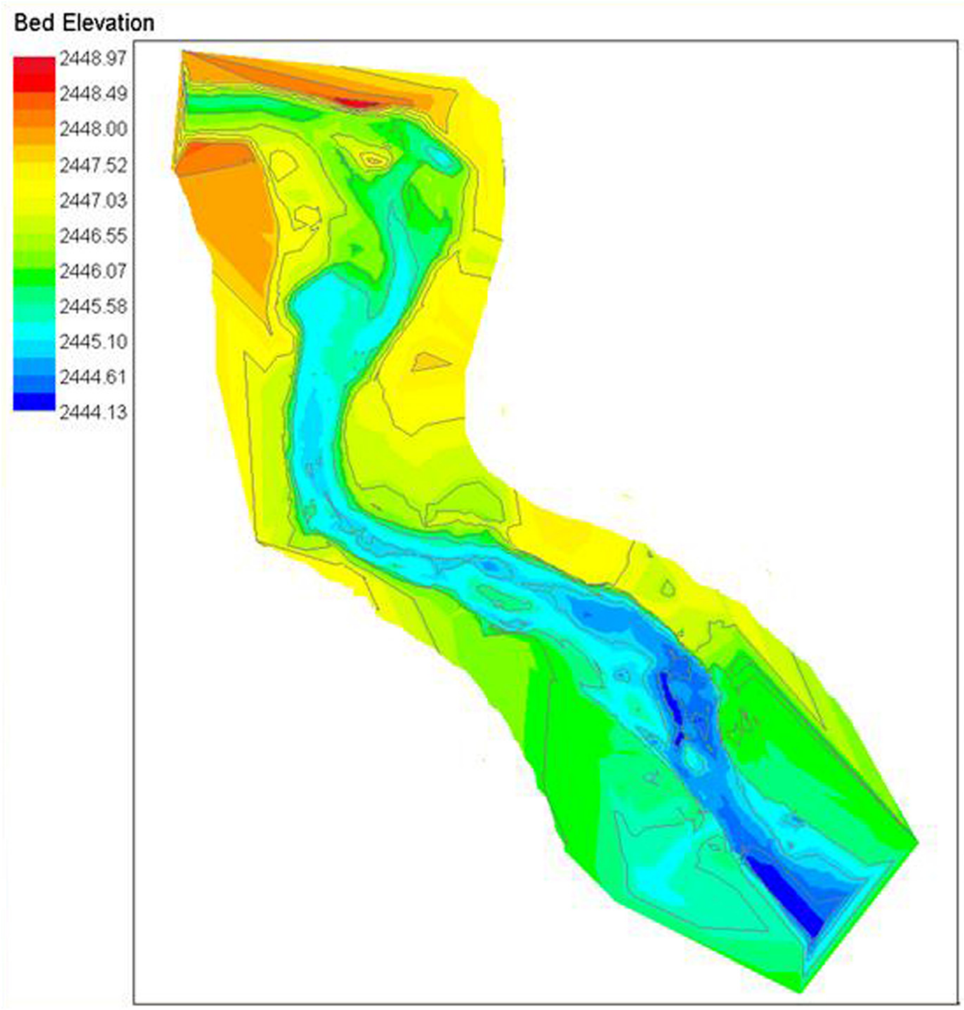

Figure 4. Map of the Willow Creek study reach. Bed elevations are in meters. Map courtesy of Terry Waddle, Fort Collins Science Center.

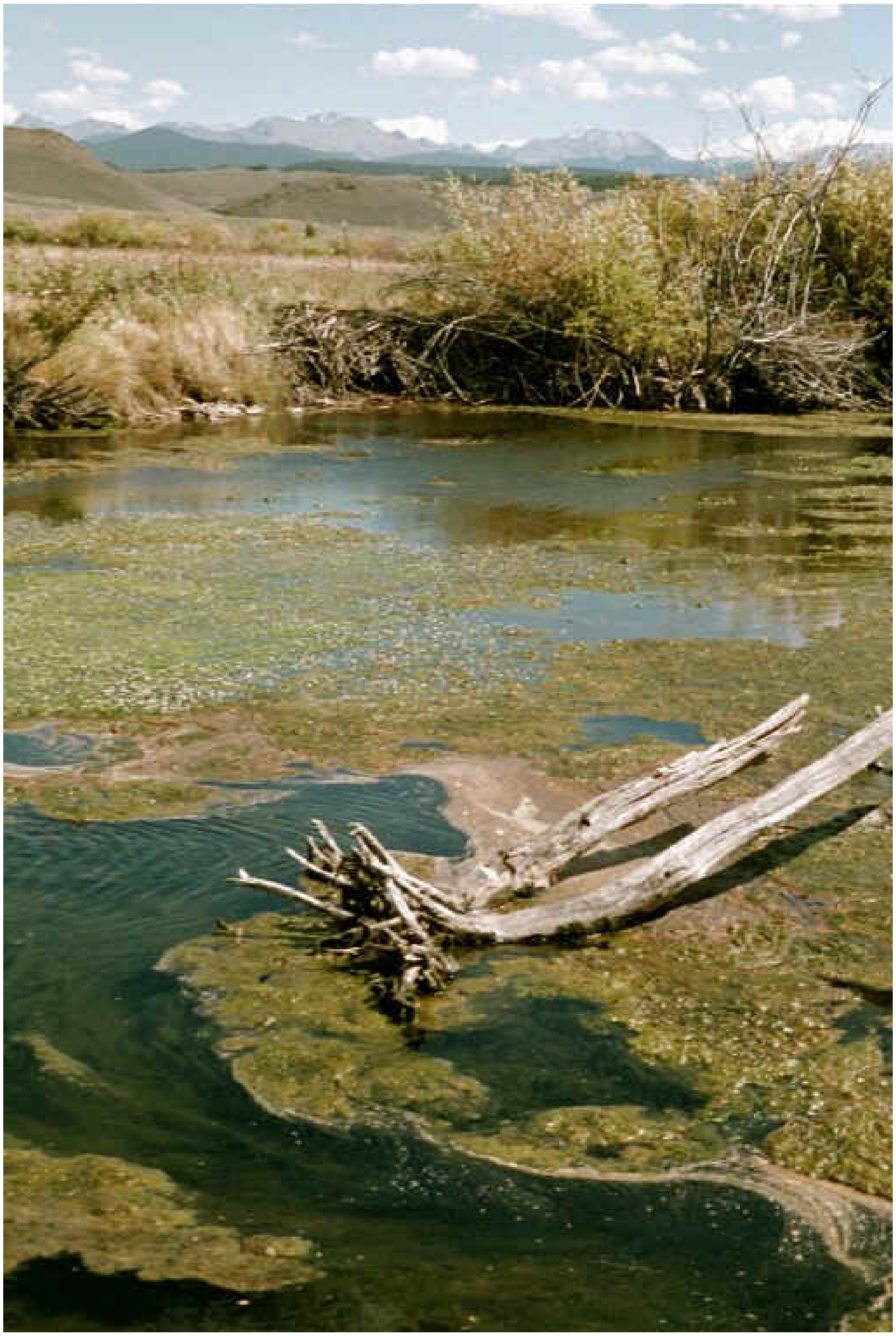

Figure 5. Picture of the surface of the pool used for the case study.

Step 1. Determining size of the sediment to be removed

The first step in the process of calculating the streamflows needed to reduce the habitat for oligochaete worms is to determine the size of the sediment that makes a habitat for the worms. A straightforward measure of the sediment characteristics of a stream is the median size (d50). The number of oligochaete worms in a sample of the substrate is used here as an index to the quality of the sediment for the worms. A relation between the median size of the sediment and the number of oligochaete worms in a sediment core is presented in figure 6. An expansion of the left side of figure 6 (d50 < 3 mm) is presented in figure 7. The objective of the expansions is to show the relation of the sizes of substrate that are high quality habitats for the worms. The diagram (figure 7) suggests median substrate sediment size of less than 1.35 mm produces good oligochaete habitat.

Another way of approaching the problem is to look at how the number of worms is related to the percentage of the substrate that is less than 1.35 mm. The relation between the percent of the sediment less than 1.35 mm and the number of worms in each sample is presented in figure 8.

We now have met the objective of knowing the size of sediment that needs to be flushed from Willow Creek in order to reduce oligochaete worm habitat. The flushing flow objective is to remove sediment deposits from Willow Creek where more than 50 percent of the substrate sediment is less than 1.35 mm.

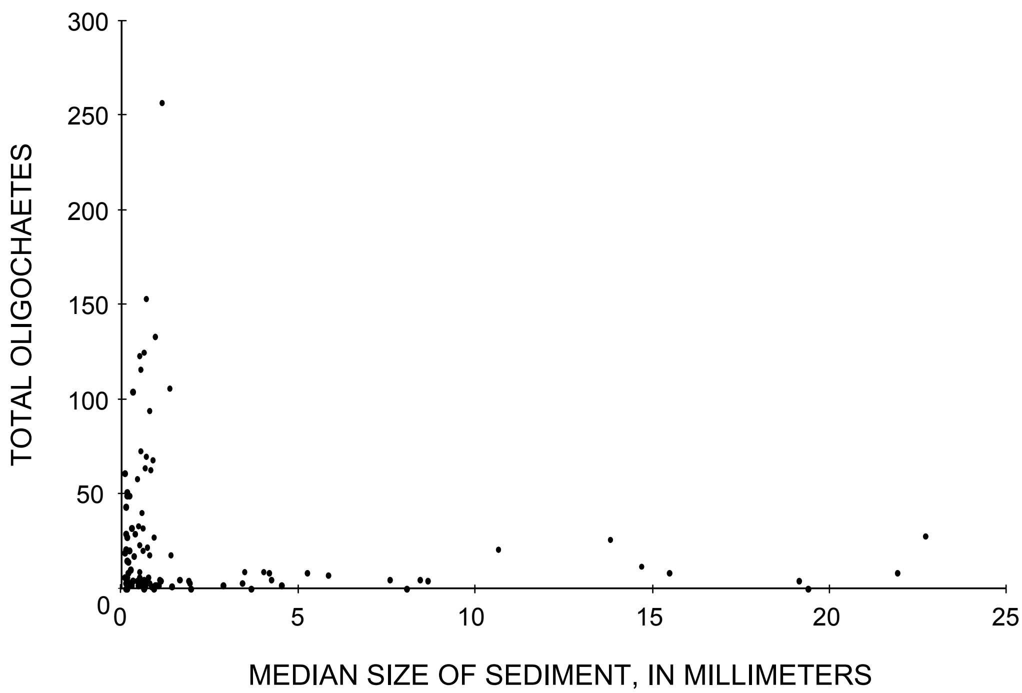

Figure 6. Number of oligochaete worms as related to the median size of the sediment in Willow Creek.

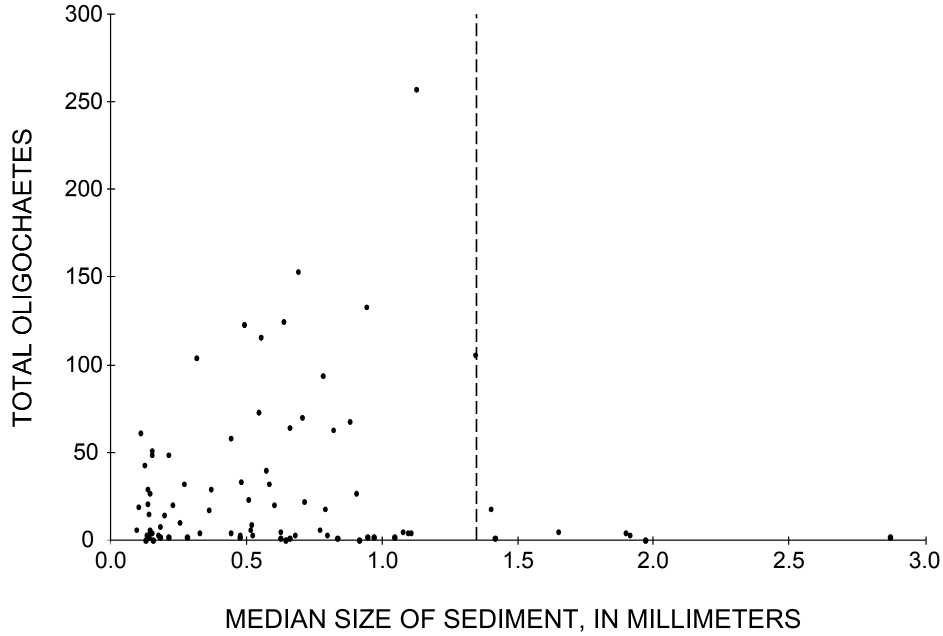

Figure 7. The number of oligochaete worms as related to median size of sediment, for a median size of 3 mm or less (expansion of the left side of figure 6).

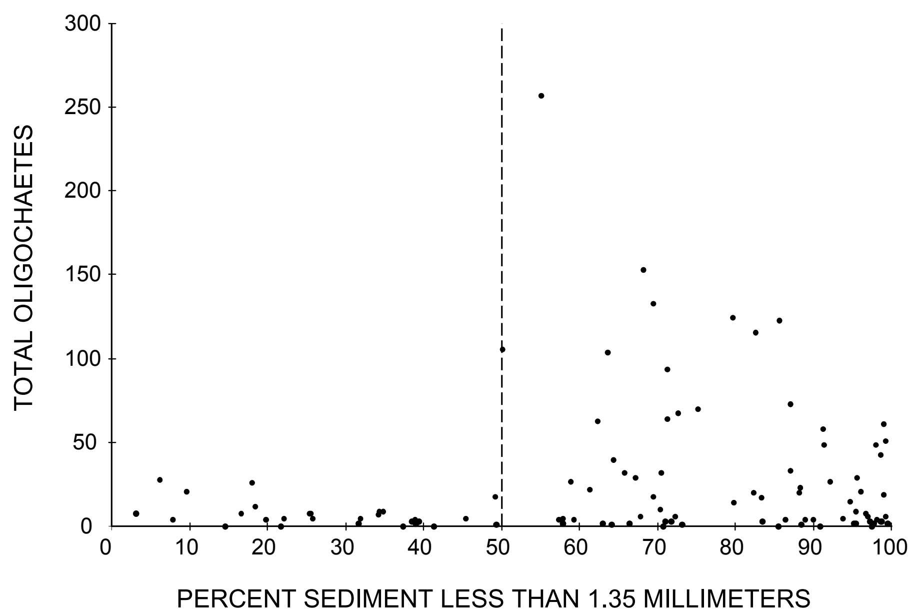

Figure 8. Number of worms in each sample as related to the percent of the sediment that is less than 1.35 mm.

Step 2. Determine location of the sediment to be flushed from the river

There are two locations within the study area with fine sediment: a backwater at the upper end of the study reach and a pool downstream of the eroding banks, shown in figure 3. Particle size distributions of the fine sediment found at two locations in the backwater area are presented in figure 9. The sample labeled "backwater" was not on one of the cross sections used in the study but was taken at a location that appeared to be representative of the sediment deposited in the backwater. The sample labeled C/S 16.5 was obtained at one of the cross sections used in the study. The vertical line on figure 9 marks a particle size of 1.35 mm. The vertical line intersects the relation for the backwater sample at the point were about 65 percent of the particles are finer, and the line for C/S 16.5 intersects that relation at the point where about 90 percent of the particles are finer. The results from step 1 indicate that the backwater area is prime habitat for oligochaete worms. The backwater area is probably not a natural riverine feature of the creek but caused by construction activities related to the construction of Willow Creek dam. A design for isolating the backwater is presented in Waddle and Terrell (2003). A berm isolating the backwater area was constructed in November of 2004.

The second location of fine sediment is the pool in the lower part of the study reach. The particle size distribution relation for three samples from the pool is presented in figure 10. The median size of the sediment is 0.96 mm. The lowest relation (shown by the dashed line) shows that 60 percent of the substrate in the pool is less than 1.35 mm—prime habitat for oligochaete worms. There are two ways to reduce the fines in the pool: (1) reduce the transport of fines to the pool by reducing the erosion from the banks, and (2) have streamflows remove the sediment from the pool. A combination of the two techniques would likely be the most successful for reduction of the pool's worm habitat.

Both the backwater area and the pool area have ample quantities of sediment that meet the worm habitat criteria. The objective pursued below is to remove fine sediment from the pool area.

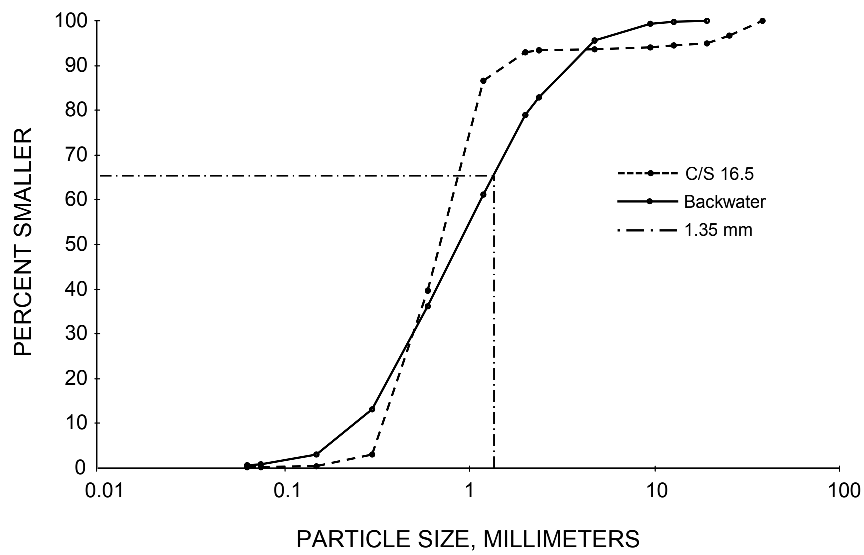

Figure 9. Particle size distribution of the fine sediment at two locations in the backwater area of the Willow Creek study reach. The dashed line shows the percent finer for a particle size of 1.35 mm.

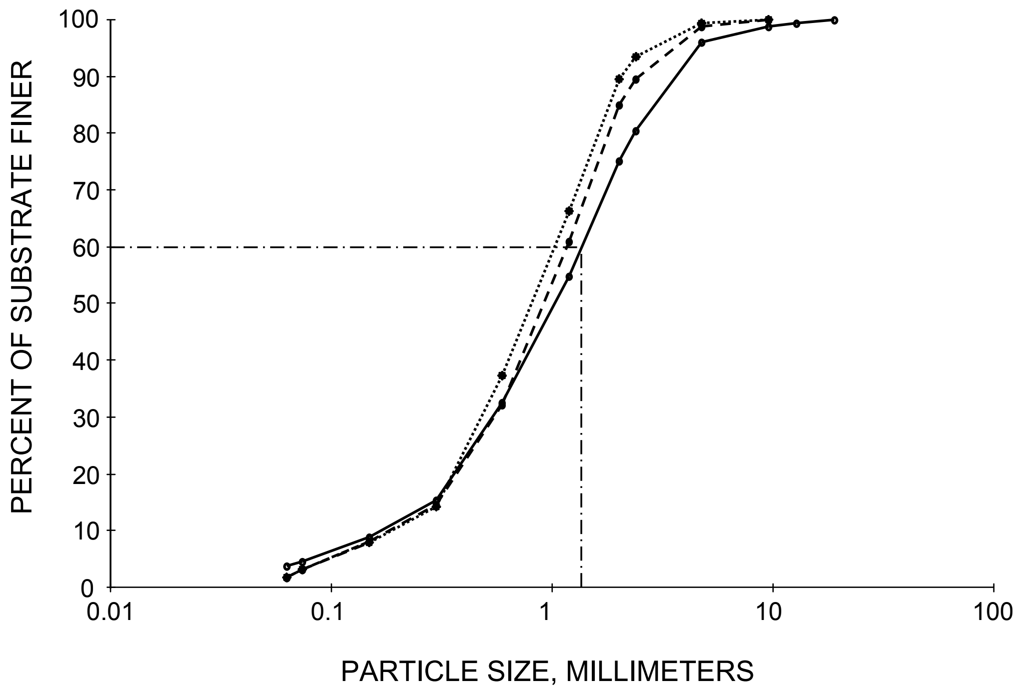

Figure 10. Grain size distribution of three samples of fine sediment in the pool.

Step 3. Determine flushing flows needed to remove the sediment

The equation used to calculate the shear stress on the stream bed required to move sediment is:

$$\tau_{crt} = k_s d_p (G_s - 1)\gamma \qquad (1)$$

where τ_{crt} is the shear stress required to move sediment particles of size d_p , G_s is the specific gravity of the particles, γ is the unit weight of water, and k_s is an empirical coefficient relating the downward force caused by the weight of the particles to the horizontal and uplift forces needed to move the particles. The logic (model) behind the equation is presented below.

The (hydraulic) driving force is down slope:

$$F_d = RS\gamma\left(\Pi d_p^2\right) \qquad (2)$$

where F_d is the driving force, R is the hydraulic radius, S is the energy slope, and the other terms are as defined above.

The resisting Force (sediment) is the weight of the particle acting downward:

$$F_r = \frac{(G_s - 1)\gamma(\Pi d_p^3)}{6} = \frac{d_p (G_s - 1)\gamma(\Pi d_p^2)}{6} \tag{3}$$

where G_s is the specific gravity of the sediment particles, F_r is the resisting force, and the other terms are as defined above.

The ratio of the driving force to the resisting force is:

$$\frac{F_d}{F_r} = \frac{RS}{d_p (G_s - 1)/6} \tag{4}$$

Typically the 1/6 factor is not used and the ratio

$$k_s = \frac{RS}{d_p (G_s - 1)} \tag{5}$$

is called the dimensionless shear stress.

For any value of k_s, a corresponding value of shear stress can be calculated using the equation:

$$\tau = k_s \left(d_p (G_s - 1)\right) \tag{6}$$

At the start of movement (critical):

$$\tau_{crt} = k_{s(crt)} \left(d_p (G_s - 1)\gamma\right) \tag{7}$$

and for continued movement of the sediment the required shear stress (τ_d) is:

$$\tau_d > \tau_{crt} > k_{s(crt)} \left(d_p (G_s - 1)\gamma\right) \tag{8}$$

As a reminder, k_s is the empirical coefficient converting the resisting downward stress to a resisting horizontal stress.

The selection of the empirical parameter (k_s) for the beginning of substrate movement must be selected (on a case by case basis) using judgment, as there is a wide range of values proposed in the literature. The range of values from the literature for k_s is between 0.021 and 0.047. There is also a required time dimension to the value of k_s required—the longer the flushing flow, the lower the acceptable value. Another way of looking at this is that the higher the flow, the more rapid the removal of the fines. In Willow Creek the duration is expected to be relatively short; hence, the selected k_S k_s should be relatively large (the upper limit). Once the material begins to move, it needs to be transported from the reach; for that reason, a value of 0.055 was selected for k_s.

In order to remove the sediment in the pool that has a median size of less than 1.3 mm, it is necessary to move the total mass of fines and sand found in the pool. The target size of the sediment to be removed from the creek bed is the size at which 90 percent is smaller than that size (d90). For Willow Creek, this is 2.79 mm (the average d90 for the three samples of the sediment found in the pool; see figure 10). The measured specific gravity of the deposit is 2.65.

Not all of the stream bed needs to be cleaned of fine sediment—just the bed area underwater during the portion of the year that the small fish can be infected by whirling disease. For Willow Creek, the period from May 1 to September 30 was selected. For the purposes of reducing the infection of fish by whirling disease, the streamflows during this period are used to determine a base flow. The selected base flow for each year used in this analysis is the discharge exceeded by 10 percent of the days. This discharge for each water year is presented in figure 11. In the Willow Creek streambed area, a streamflow on the order of 1.4 m^3/s would be a reasonable target area for the flushing of fines. During the winter and late fall the streamflow is on the order of 0.2 m^3/s, which would be within the stream area flushed if the streambed area at a discharge of 1.4 m^3/s was flushed of sand and fines. For the present analysis, the base flow was assumed to be 1.4 m^3/s, and the objective was to estimate the discharge required to remove the fine sediment in the part of the pool that is underwater at a discharge of 1.4 m^3/s. An example of the discharge in the river for water year 1982 is shown in figure 12. The streamflow pattern is probably typical of the variation during a typical water year, with long periods of nearly constant discharge and some periods with very low streamflows. In the case of water year 1982 the 10 percent discharge is 1.29 m^3/s. (In water year 1982, May 1 is day 241 and September 30 is day 365.)

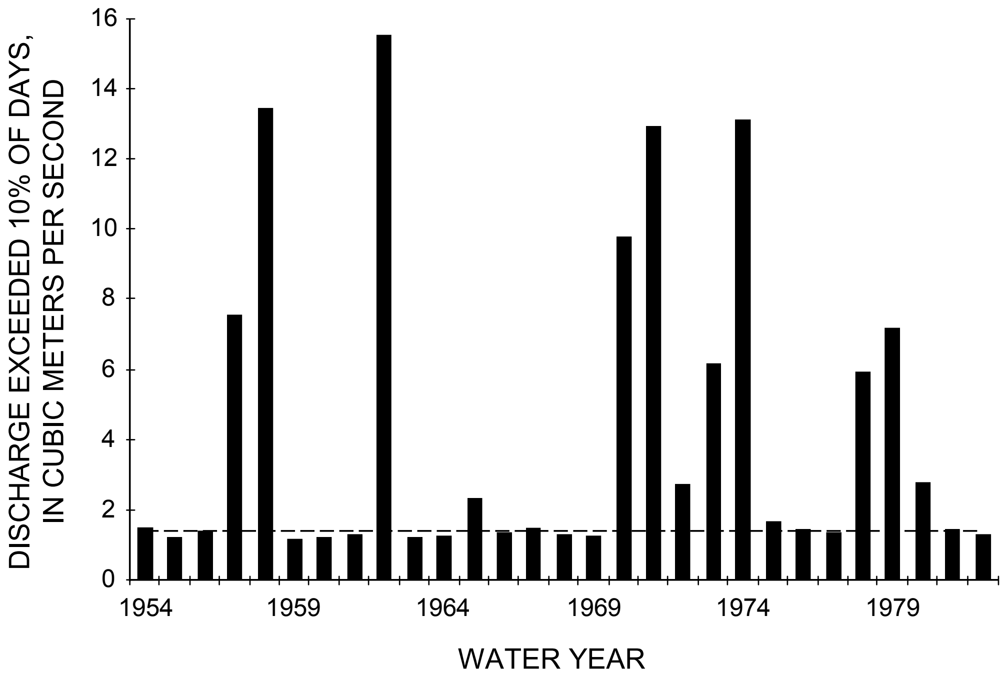

Figure 11. The daily discharge exceeded 10 percent of the days in each water year in Willow Creek below Willow Creek Reservoir, water years 1954–1982. The horizontal line marks a discharge of 1.4 m^3/s.

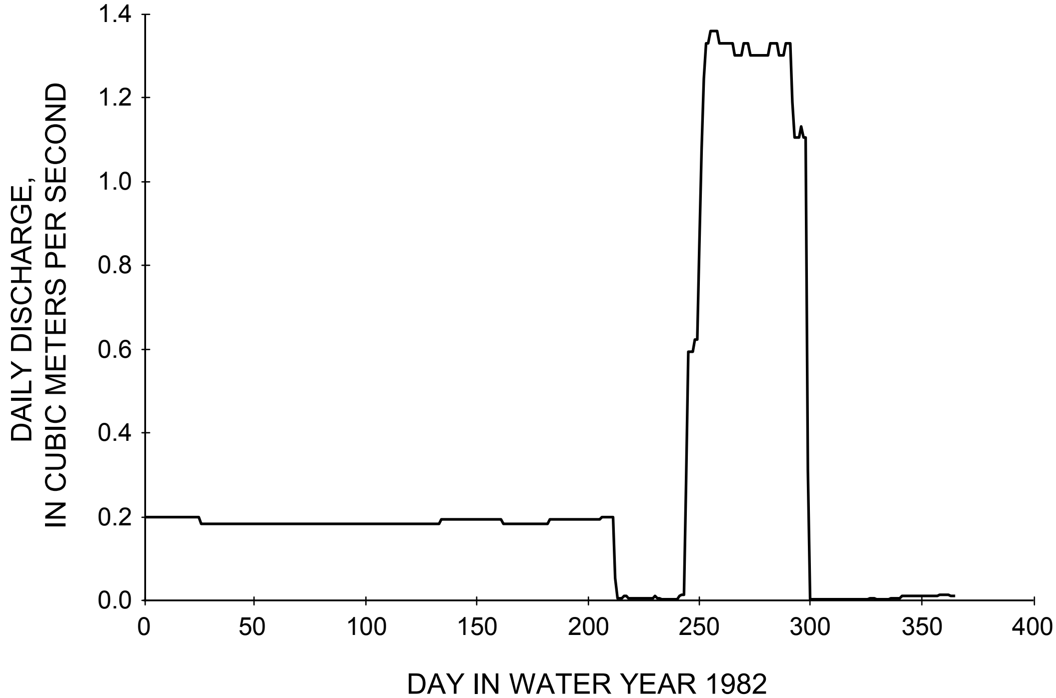

Figure 12. Daily streamflows in Willow Creek below Willow Creek Reservoir during water year 1982.

The shear stress is not uniform across a cross section for any discharge. There is a flushing discharge that would remove sediment from the area that is wet at the base flow, but for discharges less than that flow only part of the stream bed will be flushed. The Physical Habitat Simulation System (Milhous and others, 1989) was used to make the hydraulic calculations of the shear stress on the stream bed and the areas of the pool where flushing of the fines and sand will occur. The results of the flushing flow calculations are presented in figure 13.

The selection of a flushing flow using the information in figure 13 requires judgment. If, in the judgment of aquatic biologists, the river is adequately flushed of fines when 90 percent of the base flow stream bed is flushed, than the required flushing flow for Willow Creek is 7.32 m^3/s (the dashed line in figure 13).

The frequency of flushing flows is also important. The period of record available to the public is from 1954 through 1982. Using this data, the number of days in each water year that the discharge exceeds the flushing flow discharge of 7.32 m^3/s was determined for each water year. The results are presented in figure 14. A review of the data for the Colorado River above Grand Lake suggests the 29-yr period (1954–82) is probably representative of the last 60 years.

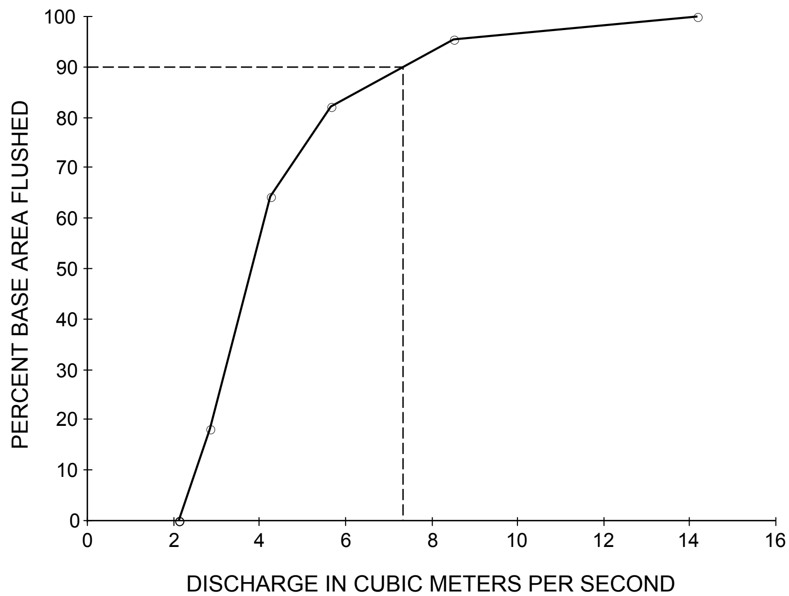

Figure 13. Percent of the base flow pool cross-sectional area flushed as related to stream discharge. The dashed line shows the flushing flow needed if 90 percent of the bed surface needs to be flushed.

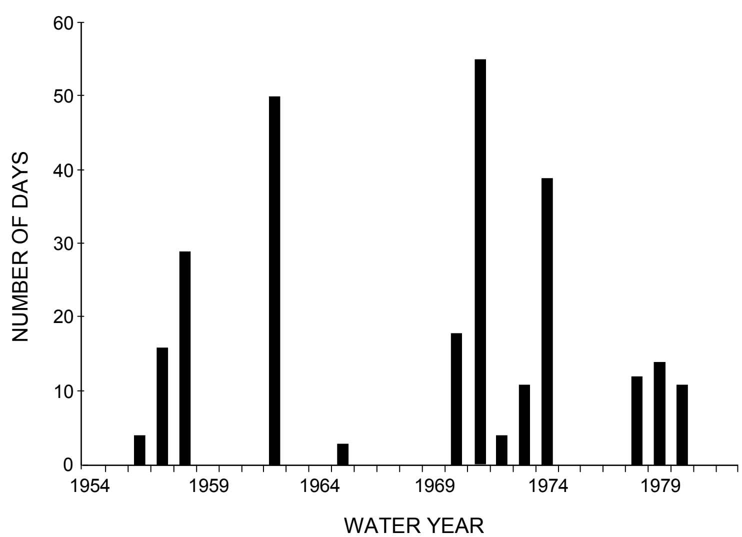

Figure 14. Number of days in each water year that the discharge was greater than or equal to the discharge required to move fines from 90 percent of the base flow pool cross-sectional area (7.32 m^3/s). Period of record was water years 1954–1982; the station is Willow Creek below Willow Creek Reservoir (09021000) and is just upstream of the study area. Data is from the records of the U.S. Geological Survey.

There is concern about the higher discharges eroding the banks just above the pool. Sediment is falling off the nearly vertical banks and forming a deposit of sediment at the bank toe just above the 1.4 m^3/s waterline. This deposit is easily eroded and may fill the pool as fast as the higher discharge removes sediment from the pool. For this reason, a design for bank protection works, which would protect those basks upstream of the pool at risk for erosion, was developed at the same time as the design to isolate the backwater (Waddle and Terrell, 2003).

The selection of a target sediment size for removal from the stream is critical. The analysis herein used the size at which 90 percent is smaller (2.79 mm). If the median size (1.1 mm) was used as the target size, the flushing flow analysis would yield different results. Results for a median sediment size of 1.1 mm are added to the diagram for the Willow Creek results to illustrate the difference (figure 15). The target discharge for removal of 1.1 mm sediment is 2.73 m^3/s compared to the 7.32 m^3/s used in the analysis above.

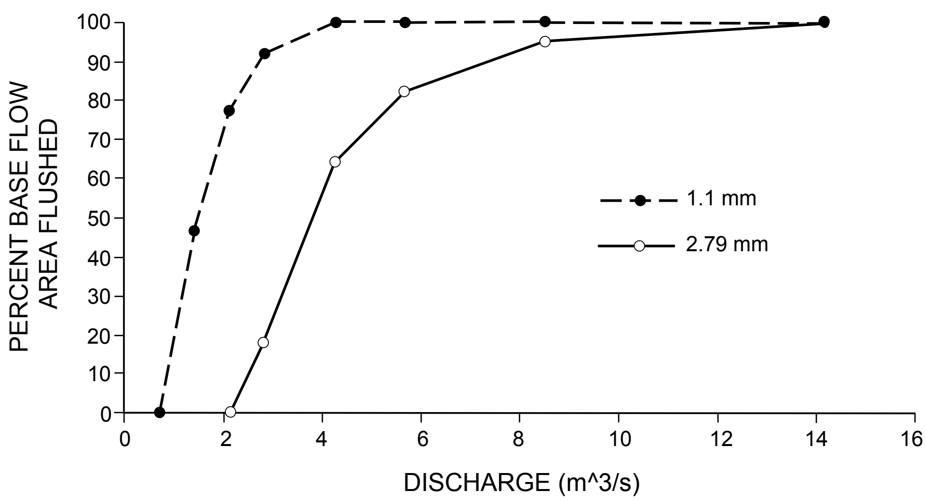

Figure 15. Percent of the base flow pool cross-sectional area flushed as related to stream discharge, for two different estimates for the size of sediment to be flushed from the river.

Discussion and Conclusions

The hypothesis of this paper is that one can determine a flushing flow that removes the sand and fines that are good habitat for oligochaete worms. Standard hydraulic calculations were used to accomplish this task. There are many issues associated with flushing flows other than determining the quantity of the streamflow. Among these other issues are the use of the water for other purposes and the impacts of the sediment flushing flows on other instream resources.

Key to the determination of a flushing flow is the knowledge of the relation between the quality of the sediment for oligochaete worms and the characteristics of the sediment.

Acknowledgements

The maps presented as figures 2 and 4 were created by Terry Waddle. The samples of worms and sediment used in the analysis for figures 6, 7, and 8 were collected by Jim Terrell, who also developed the protocol for the sampling. Sediment sample analysis was done by Julie Roth. Surveying and bed material sampling in the field was done by a team of Waddle, Roth, Terrell, and Milhous. This open file report is completely based on a presentation made at the 9th Annual Whirling Disease Symposium held in February 2003 in Seattle, Washington.

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