Effects of Fire Retardant on Water Quality[1]

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Abstract: Ammonium-based fire retardants are important in managing wildfires, but their use can adversely affect water quality. Their entry, fate, and impact were studied in five forest streams. Initial retardant concentrations in water approached levels which could damage fish, but no distressed fish were found. Concentrations decreased sharply with time after application and distance downstream, and there was no long-term entry. The numbers and kinds of stream insects were not affected. Simulations of retardant dispersal in streams showed fish mortality might occur from zero to more than 10,000 m below the point of chemical entry, depending on application parameters and stream characteristics. Guidelines to minimize adverse impacts from the use of fire retardants are suggested.

Chemical fire retardants play an important role in protecting forest resources from destructive fires. Their use has increased steadily since their introduction in the 1930's. Lowden (1962) reported that aerially applied fire retardant use in the U.S. increased from 87,000 liters in 1956 to more than 28 million liters in 1961. During 1970, 64 million liters of fire retardant were applied aerially to forest and rangeland fires (George 1971). USDA Forest Service aerially applied 55 million liters of fire retardant in 1977. More than 71 percent of this use was in California, Oregon, and Washington (Norris and others 1978).

Fire retardants have changed since their first introduction. Borate salts, the first retardants, were effective and long-lasting, but were also phytotoxic and soil-sterilants, and are no longer used (Fenton 1959). Bentonite clay in water is not as long-lasting or as effective as alternative materials (Phillips and Miller 1959). Ammonium phosphate, an effective fire retardant marketed in several formulations, is relatively long lasting, nontoxic and easy to apply (Douglas 1974). The ammonium-based fire retardants as a group account for nearly all chemical retardants used in controlling forest and range fires today.

The possible adverse effects of chemical fire retardants on the environment have received relatively little attention, probably because of the importance of these chemicals in fire control and their seemingly innocuous nature. However, even materials of inherent low toxicity can cause adverse environmental effects when organisms are exposed to toxic amounts. Research and development efforts have concentrated primarily on developing effective fire retardants, delivery systems, and strategies for use.

As the intensity of fire retardant use increased, incidents of misapplication or adverse environmental effects have begun to appear. There have been several reports of fish kills when retardants were applied directly into streams, but documentation is marginal. Fire retardants are alleged to have killed a number of trout in one stream in California, but the stream soon returned to normal. In 1969, a large number of juvenile salmonids and more than 700 adult salmon were killed in an Alaskan stream. While retardants were used near the river, the specific cause of death of the fish was not determined. Adult salmon entering the river 4 days later exhibited no toxic reaction (Hakala and others 1971).

As a result of these incidents, and concerns among resource managers that fire retardants may adversely affect the environment, an ad hoc interagency study committee was formed in 1970 (Borovicka 1974). The objective of the committee was to foster and coordinate research needed to evaluate the environmental safety of chemical fire retardants (primarily their effect on water quality and aquatic organisms). Toxicology research conducted by Fish and Wildlife Service, Bureau of Land Management, and National Marine Fisheries Service established dose-response relationships for use in evaluating the effects on fish of specific levels of fire retardants in streams (Blahm and others 1972; Blahm and Snyder 1973; Borovicka and Blahm 1974; Johnson and Sanders 1977). Forest Service scientists at the Northern Forest Fire Laboratory (Missoula, Mont.) conducted an initial simulation study of retardant distribution in streams (Van Meter and Hardy 1975).

The Pacific Northwest Forest and Range Experiment Station studied the behavior of retardant materials in streams, determined their effect on selected aquatic species in their natural habitat and (through simulation) estimated the effects of retardant application on fish mortality in streams of different characters. This paper draws heavily on the

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PNW research effort (Norris and others 1978), and suggests planning for resource managers concerned about minimizing fire retardant impacts on streams.

METHODS FOR FIELD STUDY

We applied an ammonia-based fire retardant to five streams in Oregon, Idaho, and California (Norris and others 1978). The application crossed a segment of four of the streams and was parallel (to within 3 m) on the fifth (table 1, fig. 1). The pattern of ground level application we used in the field studies (fig. 1B) is a simplified version of the pattern of retardant deposition resulting from operational aerial application (fig. 1A). Stream water samples collected periodically for up to 13 months after application at locations up to 2700 m downstream were analyzed for various forms of nitrogen and phosphorus. Samples of benthos and insect drift were also collected and evaluated for shifts in species diversity and abundance.

RESULTS OF FIELD STUDIES

Effects of Retardant on Stream Water Chemistry

The principal chemical species in the stream the first 24 hours after application were ammonia nitrogen (NH_3 + NH^+_4) and total phosphorus. Un-ionized ammonia (NH_3) is of primary importance because of its potential toxic effects on aquatic species. The amount of NH_3 relative to NH^+_4 is dependent primarily on pH (Trussel 1972). As the pH increases, the proportion of ammonia nitrogen present as NH_3 increases. The phosphorus may be important in downstream eutrophication. After 24 hours, nitrate (No^-_3) and soluble organic nitrogen are the primary retardant components in the stream. These are transformation products of the diammonium phosphate in the retardant mixture. Both nitrate and soluble organic nitrogen are low in toxicity and are natural components of aquatic ecosystems. Because NH_3 is most important, the results in table 2 and figure 2 emphasize ammonia nitrogen (NH_3 and NH^+_4) or un-ionized ammonia (NH_3).

Table 1--General characteristics of the study locations and streams

Stream and Location	Climate	Soil and parent material	Vegetation	Stream characteristics[1]		
				Width	Depth	Discharge
				(m)	(m)	(l/s)
Tohetie Oregon: representing Coast Ranges	High rainfall--cool, moist summers, winter snow rare	Inceptisol Andic Haplumbrept Siltstone and claystone	Douglas-fir, Sitka spruce Western Hemlock, Alder Salmonberry	5.4	0.03	2.3
Lewis Same	Same	Same	Same	2.8	0.20	13.7
Quartz Oregon: representing Cascade Range	Moderately high rainfall--warm, dry summers, occas. winter snows	Inceptisol Dystric Cryochrept Red breccia and basalt	Douglas-fir, Alder	2.4	0.18	35.4
Bannock Idaho: representing Intermountain Region	Warm, dry summers, winter snowpack	Mollisol Typic Cryoboroll Quartz monzonite (acid igneous)	Ponderosa pine	1.0	0.29	6.0
San Dimas Southern Calif.: representing areas of heavy chaparral	Hot, dry summers warm, moderately dry winters	Alfisol Mollic Haploxeralf Metamorphic and acid igneous	Chaparral	1.2	0.18	7.1

[1]Late summer, at time of application of fire retardant. All retardant applications crossed the stream (see fig. 1), except Tohetie Creek where the long axis of the application was parallel to the stream, with the edge of the distribution pattern 3 m or more from the edge of the stream.

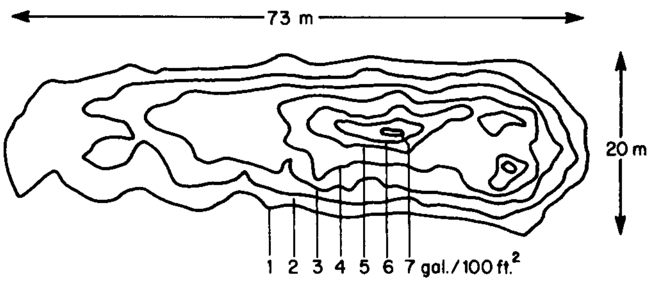
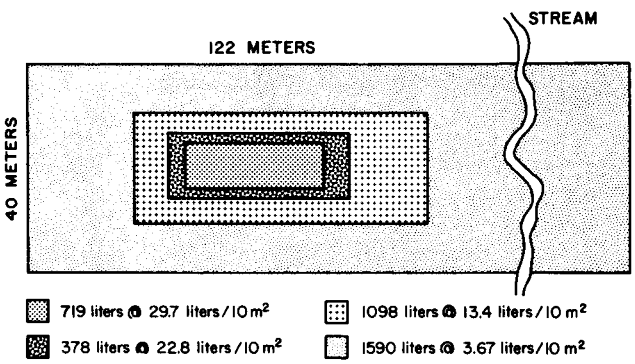


Figure 1--Retardant application patterns. A, Typical retardant application used in developing a pattern for the test applications (X 4.07 = liters/10 m^2).



B, Pattern of retardant application (applied with hoses at ground level) for cross-stream treatment at Lewis, Quartz, and Bannock Creek study sites. The same application pattern was used for Tohetie Creek except the long axis of the application was parallel to the stream and the edge was not closer than 3 m to the stream. A slightly modified pattern, applied by helicopter was used at San Dimas (Norris and others 1978).

Direct application of retardant to the stream surface produced the highest concentration near the point of application. Concentration decreased both with time after peak concentration and distance downstream (fig. 2, table 2). Detectable changes in stream water chemistry were noted up to 2700 m downstream. The changes we measured were of short duration and not important either toxicologically or with respect to eutrophication downstream. In our test, however, regulations required a low rate of application (maximum planned concentration 0.5 ppm NH_3), and only a single application was made on each stream. The effect of rate of application, vegetation density in the streamside zone, and other factors on retardant levels in streams are discussed in the section on results of simulation studies.

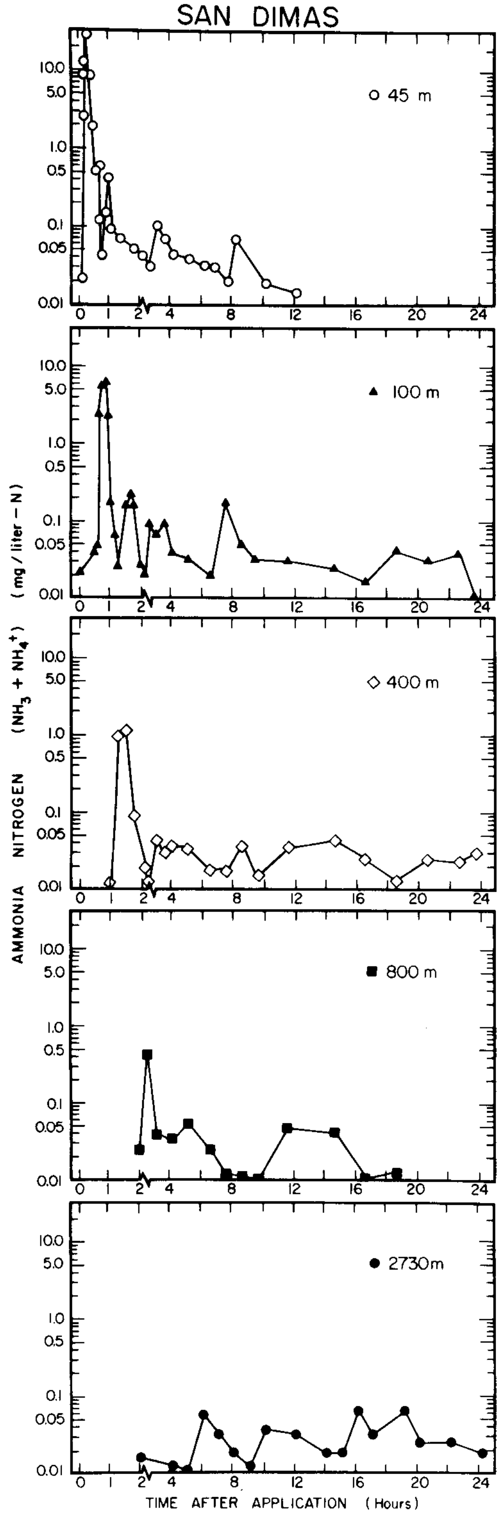


Figure 2--Concentration of ammonia nitrogen (NH_3 + NH_4^+) at various times after application and at five distances downstream from the application zone for East Fork San Dimas Canyon. The last samples were collected at 45 m and 800 m at 12 h and 18.5 h after the application.

Table 2--Effect of time and movement downstream on maximum concentrations (max. cone.) of ammonia nitrogen (NH_3 + NH_4^+) from retardant application zone (r.a. zone)

Study site[1]	Max. cone. NH_3 + NH_4^+ 45 m downstream from r.a. zone	Max. cone. NH_3 45 m downstream from r.a. zone[2]	Time for indicated dilution, 45 m downstream from r.a zone		Max. cone. at various distances below r.a. zone as percent of max. cone. at 45 m		
			10-fold	100-fold	200 m	400 m	800 m
	ppm-N	ppm-N	minutes		percent		
Lewis Creek	3.34	0.02	18	60	29	8	3
Quartz Creek	15.81	0.15	23	90	4	5	3
Bannock Creek	13.56	0.03	24	225	8	2	1
San Dimas Canyon	29.95	0.32	10	25	19	4	1

[1]Retardant applied directly to stream surface.

[2]Calculated from free ammonia concentration (Trussel 1972).

Direct application to the stream surface was the primary source of retardant components in the streams. Once initial residues cleared the stream system, only minor residues of retardant entered the streams from the streamside zone.

Relatively narrow untreated strips in the riparian zone are probably sufficient to largely eliminate movement of retardant from the land to the stream. Where the long axis of the application zone was parallel to the stream (Tohetie Creek, where the edge of the treated area was only 3 meters from the stream), we found no evidence of significant elevation of concentration of retardant components in the stream, even after periods of heavy precipitation.

Effects of Retardant on Stream Organisms

The experimental retardant application made in this study did not kill or incapacitate fish in the first 24 hours, or the density or diversity of stream drift or the stream benthic community in the first year after application (Norris and others 1978). This does not mean retardant application will not affect these organisms, only that they were not affected to a detectable degree by the rates of application used in these applications. The effects of higher rates of application on fish are dealt with in the section on simulation.

The high degree of natural variability in the biological communities in these streams (over both time and distance) is an important factor in masking small or temporary changes in community structure. This means fire or fire control-induced changes in stream community structure must be large to be detected without intensive sampling. Retardants which enter streams (even in high concentrations) are not expected to permanently alter community structure. As water quality returns to normal, repopulation is expected and community structure should shift towards pretreatment status.

METHODS FOR SIMULATIONS

Estimations of fish mortality following direct injection of retardant was obtained with a four-component model. First, a model of retardant dilution in streams was derived from dye dilution experiments in the field. This model was combined with another representing retardant application rates obtained from actual drop patterns(George and Blakely 1973), and a model predicting retardant interception by vegetation along the riparian zone (Anderson 1974). These three components, which predicted retardant concentrations in a variety of streams representing a wide range of mixing parameters, were linked to a model structured with fish mortality data taken from Blahm and Snyder (1973). Details of the model are in Norris and others (1978).

RESULTS OF SIMULATIONS

Simulations using the model had the objectives of (1) developing methods for predicting the concentration of retardant in streams when direct applications to the stream surface occur, (2) developing methods for describing the dispersal of retardant in streams, both with time after application and distance from the application, and (3) integrating these two techniques with data on toxicity to fish to evaluate the effects of retardant applications in various types of streams on fish mortality. The term "mortality zone" means the stream reach where fish mortality (0 to 100 percent) occurs. The mortality zone shifts downstream with time as the toxicant is carried with the stream water.

The simulation studies show that

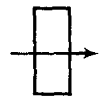
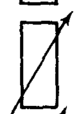
- Direct application of retardant to many streams is likely to cause fish mortality.
- The magnitude of the mortality and the distance over which it occurs varies with three elements: (1) the characteristics of the application, (2) the characteristics of the zone of application, and (3) the characteristics of the streamflow.

1. The characteristics of the application include orientation of the line of flight to the stream, size of load dropped, number of loads dropped, and the timing and placement of subsequent loads relative to the first load. For instance, a retardant application across and perpendicular to a stream produces a much smaller mortality zone than an application whose long axis is centered on the stream. If the rate of application is doubled (8000 instead of 4000 liters released over the same area) the mortality zone increases by a factor of 10 or more. We did not simulate the effects of multiple loads or the timing and placement of subsequent loads on the mortality zone, but believe the effects of additional loads will be at least additive to the effects of the first load. The characteristics of the application can be controlled by the fire control officer and the applicator to minimize the mortality zone (table 3).

2. The characteristics of the site. Several characteristics of the application site determine the initial concentration of retardant in the stream and the length of the fish mortality zone. Narrow, deep streams have a much lower initial concentration (therefore a shorter mortality zone) than shallow, wide streams (assumes equivalent flow properties; fig. 3). The more dense the vegetation canopy, the less chemical that falls directly on the stream and the shorter the mortality zone (fig. 4). These site characteristics can be recognized and retardant applications adjusted accordingly to minimize the size of the mortality zone.

3. Characteristics of streamflow. Streamflow characteristics influence the length of the mortality zone by determining the degree and speed of mixing and dilution of retardant with downstream travel. Simulation results show streams with a smooth channel have a longer mortality zone than those with many pools and riffles (assumes equal streambed gradient). Pools and riffles cause the peak of retardant concentration to spread out, thus reducing the magnitude of exposure. Increasing stream discharge with distance

Table 3--Fish mortality related to orientation of stream through retardant application zone, and to amount of retardant dropped (simulation results)

Application zone and stream direction	**Angle between long axis zone and stream**[1]	**Distance over which 100 pct mortality occurs**	
		Standard drop	**Standard drop times two**
	degrees	-------- **meters** --------	
	**90**	**50**	**480**
	**67.5**	**50**	**560**
	**45.0**	**100**	**1000**
	**22.5**	**240**	**>1000**
	**0**	**1000**	**>1000**

[1]At 90°, the long axis of the retardant application zone is at a right angle to the stream. The stream passes through the point of maximum retardant deposition in the retardant application zone.

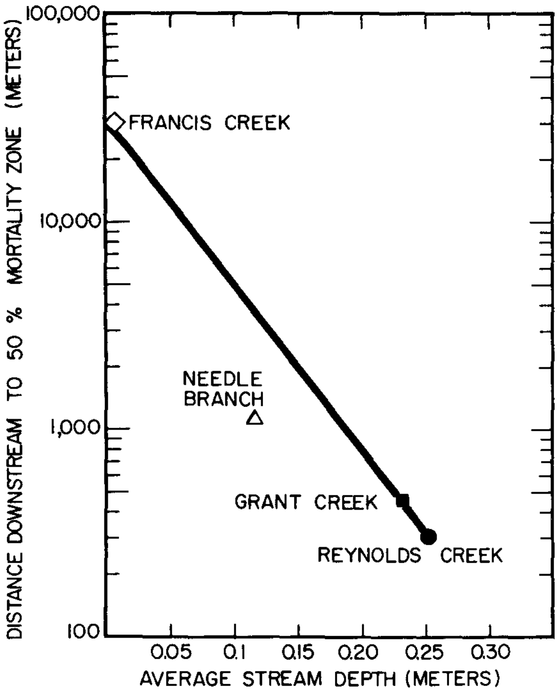


Figure 3--Effect of average stream depth on simulated length of fish mortality zone. See table 4 for stream characteristics.

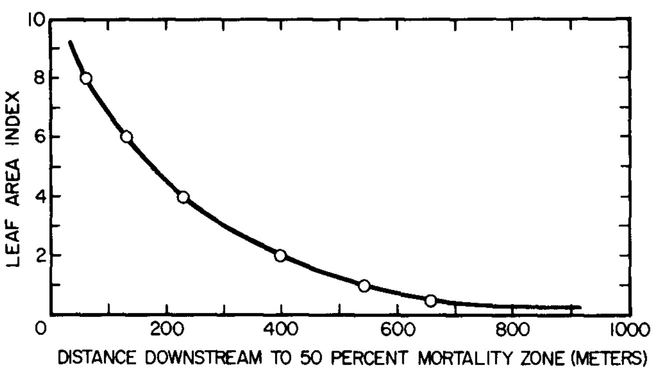


Figure 4--Length of simulated 50 percent fish-mortality zone as affected by density of streamside vegetation which intercepts retardant.

downstream (because of the inflow of groundwater and contribution from side streams) is also important as it increases dilution of the retardant. These characteristics of streamflow can be recognized by the manager.

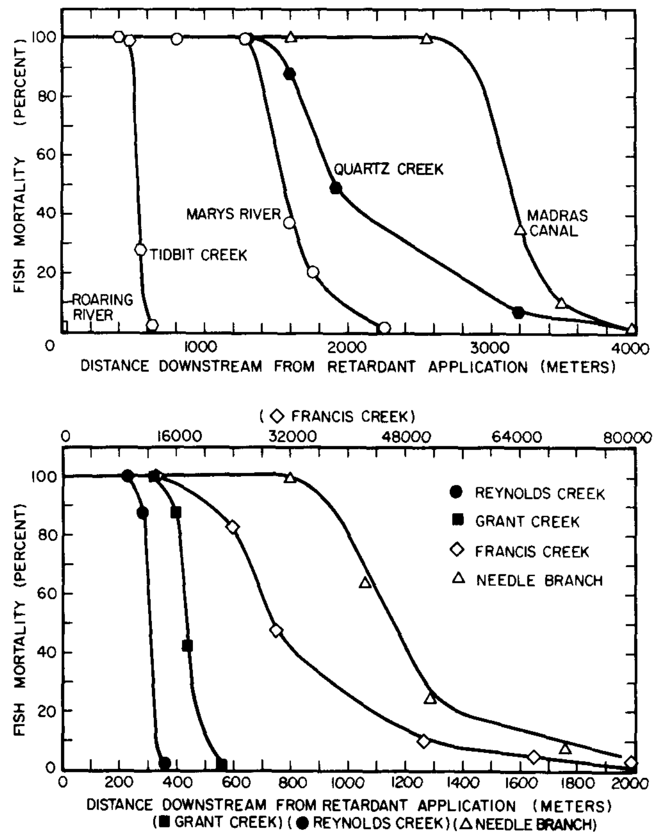


Figure 5--Simulated fish mortality at various distances downstream in several streams. Streams are oriented parallel with and through long axis of retardant application and have leaf area index of 1.0. See table 4 for listing of individual stream properties.

The results of simulation in a series of streams help illustrate the concepts (fig. 5, table 4).

PLANNING TO PROTECT STREAMS

Relatively large fires (more than 400 h) burning major portions of the watershed of perennial streams may have substantial effects on stream water quality and stream biological communities. Fire control practices such as bulldozing or hand clearing fire lines or the use of chemical fire retardants, can also impact streams. Fire control officers must use these techniques singly or in combination to achieve the appropriate balance between damage to the stream caused by fire and damage to the stream caused by fire control practices.

Our research indicates that applications of retardant that fall outside the riparian zone should have little or no effect on stream water quality. Fire control officers can plan on use of retardants away from the riparian zone with

Table 4--Description of mountain streams used in simulations

Stream	Stream characteristics	Width	Depth	Velocity[1]
		(m)	(m)	(m/hr)
Quartz Creek	Riffles and pools	4.23	0.19	206.9
Roaring River	Extremely fast and turbulent; no pools	9.45	0.49	4621.1
Marys River	Slow and channelled	5.79	0.31	388.8
Tidbits Creek	Riffles and pools	4.57	0.41	817.5
Madras Canal[2]	Rapid and channelled	1.5	0.17	1425.0
Reynolds Creek	Slow and channelled	2.23	0.25	450.9
Grant Creek	Slow and channelled	1.49	0.23	326.9
Needle Branch Creek	Riffles and pools	0.73	0.11	101.8
Francis Creek	Riffles and pools	0.94	0.04	258.9

[1]Velocity determined from dye dilution experiments. Mixing parameters are described in Norris and others (1978).

[2]An irrigation canal.

assurance that stream quality will not be significantly impaired.

When planning fire control with retardants near streams, attention needs to be given first to applications which may fall directly on the stream surface, and second to applications which fall in the riparian zone. Direct application to the stream surface is most likely to cause fish mortality. Applications in the riparian zone may affect water quality, but not to the point of causing major toxic effects. Potential impacts on downstream eutrophication need to be considered, however.

The key to successful applications (those that achieve fire control objectives and protect stream water quality) in each case is adequate planning before fire occurs (Borovicka 1974; Borovicka and Blahm 1974), including (a) identification of stream sections which need to be protected, and (b) development of retardant application plans to minimize adverse effects on the stream.

Identifying Streams for Protection

It may not be possible to do advance planning for protection of all streams. Therefore, it is necessary to identify streams that are of greater importance and are more likely to be affected by fire. Streams in high fire risk areas, for instance, should receive attention before those where the risk of fire is lower. Streams needing attention first include those which provide water for fish hatcheries, domestic use, or other special purposes. Streams that are particularly important for recreational use or fish production, or are habitat for rare or endangered species also need attention.

All parts of the stream system cannot be included in prefire planning. First order streams may be too small for effective protection. Streams in steep canyons where mechanical fire control is not possible, and where retardant must be dropped from higher than normal elevation, may also have to be excluded, at least from the first efforts to develop plans to permit retardant use while protecting streams.

Development of Applications Plans

Development of application plans must consider all the three elements important in determining the length of the zone of mortality discussed above. These are the characteristics of the site, the characteristics of streamflow, and the nature of the application. The most important site characteristics are the width and depth of the stream, and the leaf area index over the stream. The most important characteristics of streamflow are the ratio of pools and riffles, stream velocity, and degree of channelization.

These characteristics can be used in connection with the findings of the simulation studies to obtain an estimate of the initial level of retardant deposition to the stream--the level that will produce an acceptable mortality zone. Clearly, there are levels of deposition which will cause no mortality. When this level of protection is required, it can be achieved with good planning and careful execution. In those instances where a lower level of protection is adequate, this can also be achieved.

When an acceptable level of retardant deposition has been determined, the third element (the nature of the application) is considered. The procedures for estimating deposition developed in the simulation studies can be used to determine the size of load and orientation to the stream that will not cause a rate of deposition in excess of that determined to be acceptable. This information should then be cataloged and stored so it can be quickly retrieved when fire control operation commences in or near subject areas.

CONCLUSION

These methods require substantial subjective judgments on the part of the resource manager. However, they provide the logic and a process by which managers can plan fire control operations with retardants. Information presented in the report by Norris and others (1978) can be used to evaluate the impacts of retardant use on water quality as opposed to the impact of fire on stream chemistry or the impact of other methods of control. The development of GIS (geographic information systems) capabilities, the ready availability of aerial photos, and the expanding use of computers by managers make the type of prefire planning described above quite achievable. Further research and documentation of experience in the field are necessary to permit improvement of these preliminary guidelines and to help insure that the use of chemical fire retardants does not produce unexpected impacts on the aquatic ecosystem.

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