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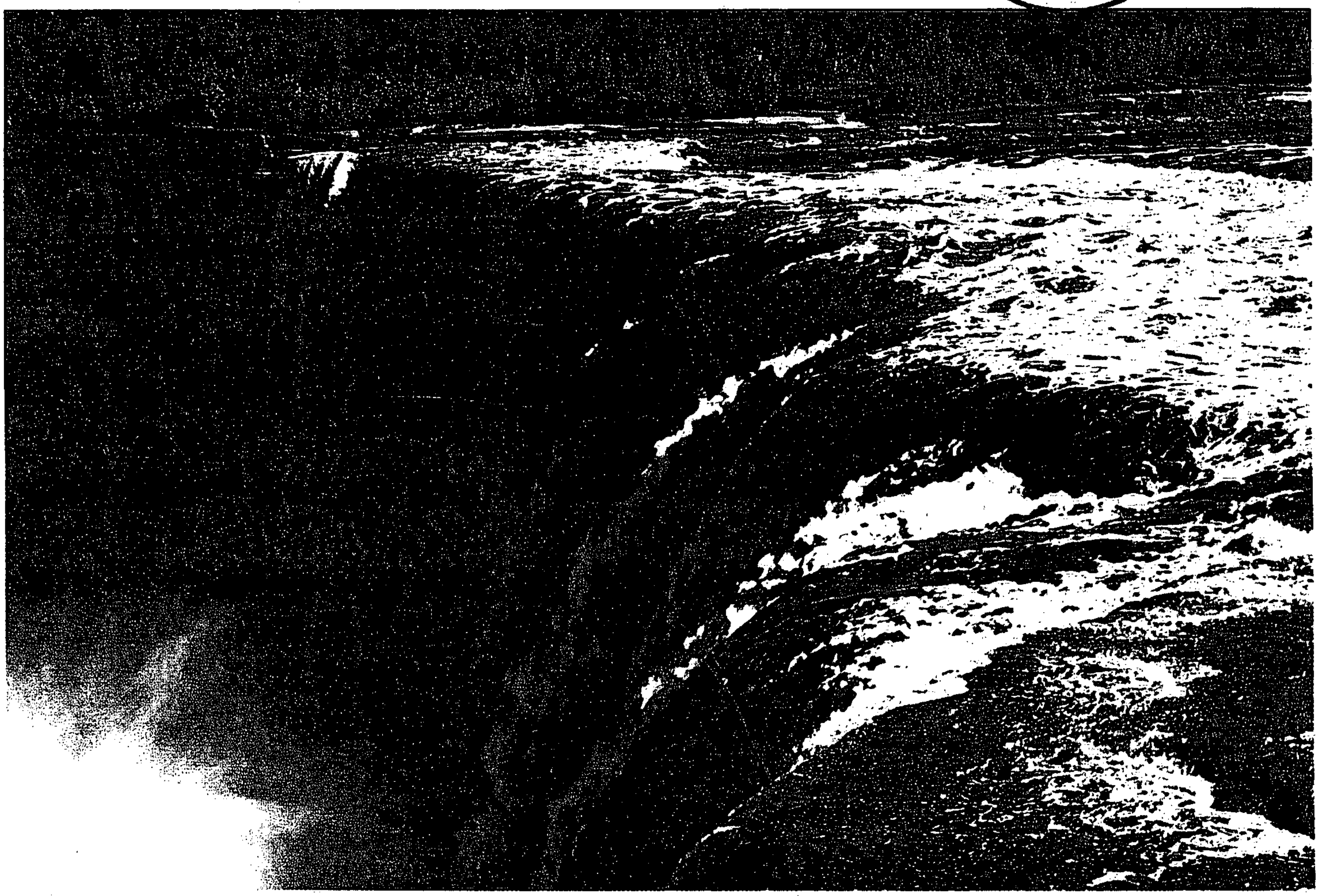
Variations and Mechanisms of Asbestos Fibre Distribution in Stream Water

H. Schreier and J. Taylor



TECHNICAL BULLETIN NO. 118

INLAND WATERS DIRECTORATE
PACIFIC AND YUKON REGION
WATER QUALITY BRANCH
VANCOUVER, BRITISH COLUMBIA

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Abstract

Asbestos fibre concentrations were determined in a ten-month study on the Sumas River in British Columbia and Washington State. An active landslide in a headwater tributary has exposed asbestos-rich serpentine bedrock, and this source influences asbestos fibre concentration of the entire downstream section of the river to the international border. Regional background levels were found to be somewhat lower than the water affected by the slide, but nevertheless the values were high, reaching concentrations of up to 10^{10} fibres/litre. Six stations were sampled during the major hydrologic events of the 1979-1980 season, and all showed seasonal fluctuations in asbestos concentration, some as high as four orders of magnitude. In addition, great differences in concentrations were also found between stations (10^8 -10^{13} fibres/litre). This suggests that occasionally collected grab samples provide an insufficient data base for asbestos analysis of stream water.

A laboratory settling experiment, which used stream bed sediments, was carried out to study the mechanism of transport of fibres. Evidence was produced to suggest that suspended asbestos fibres settle to the bottom in the absence of turbulence and water movement. The rate of settling decreases with time, and smaller fibres appear to remain in suspension longer than larger fibres. Some limited evidence of this process was also found in one stream station where the highest asbestos concentrations and the largest range in fibre size were observed during maximum streamflow and the lowest asbestos concentrations and smallest range in fibre size, during minimum streamflow. Unfortunately, this process could not be identified consistently, and particle interferences during the settling process are thought to be the cause of the more complex settling pattern of asbestos fibres.

No direct relationship was observed between water chemistry and asbestos fibre concentration. Distinct differences in water chemistry were apparent between the water samples from the landslide area and those unaffected by the slide. This indicates that chemical data can be used in the identification of source area location, but asbestos concentrations cannot be derived from the chemical data alone.

Résumé

Lors d'une étude de dix mois sur les eaux de la rivière Sumas en Colombie-Britannique et dans l'État de Washington, on a mesuré la concentration en fibres d'amiante. Un glissement de terrain dans un affluent d'amont a exposé la roche de fond, riche en serpentine, et cette source influence la concentration en fibres d'amiante de toute la partie inférieure de la rivière, jusqu'à la frontière internationale. Les teneurs normales dans la région étaient quelque peu plus basses que celles des eaux touchées par le glissement de terrain, mais elles restaient néanmoins élevées, avec des concentrations atteignant 10^{10} fibres/L. Pendant la saison 1979-1980 on a prélevé des échantillons à six stations lors de manifestations hydrologiques importantes. À toutes les stations on a constaté des fluctuations saisonnières de la teneur en amiante pouvant atteindre quatre ordres de grandeur. On a de plus noté de grandes différences entre les stations (10^8 à 10^{13} fibres/L). Ceci indique que des échantillons simples, prélevés occasionnellement, fournissent une base de données insuffisante pour mesurer la teneur en amiante d'un cours d'eau.

Une expérience de laboratoire a été effectuée avec des sédiments de la rivière pour mieux comprendre le mécanisme de sédimentation et de transport des fibres. On a constaté qu'en l'absence de turbulence et de mouvement de l'eau les fibres d'amiante en suspension finissent par se précipiter. Le taux de sédimentation diminue avec le temps et les fibres les plus petites semblent rester en suspension plus longtemps que les plus grosses. Quelques indications de ce phénomène ont également été constatées à une station où les plus fortes concentrations en amiante et la plus vaste gamme de dimensions des fibres ont été observées pendant la période d'écoulement maximal alors que les plus faibles concentrations et la plus petite gamme de dimensions des fibres étaient observées pendant les périodes de débit minimal. Malheureusement, ce phénomène n'a pu être observé de façon constante et l'interférence des autres particules pendant la sédimentation pourrait être la cause du mode plus complexe de sédimentation des fibres d'amiante.

Aucune relation directe entre la chimie de l'eau et la concentration en fibres d'amiante n'a été observée. Il y avait des différences marquées entre la chimie de l'eau des échantillons provenant de la zone du glissement de terrain et celle de l'eau provenant de régions non touchées. Cela signifie que les données chimiques peuvent servir à repérer l'emplacement de la source, mais qu'elles ne peuvent pas permettre d'obtenir la concentration en fibres d'amiante.

Variations and Mechanisms of Asbestos Fibre Distribution in Stream Water

H. Schreier and J. Taylor

PURPOSE AND SCOPE

The problems related to asbestos fibre concentration in receiving waters were reviewed in a recent report by Schreier and Taylor (1980). Few investigations have focused on determining the causes of asbestos fibre variations or the mechanisms of fibre transport in stream water. In view of the continuing concern about asbestos fibres in water supplies, it was felt that a study that focused on the examination of the spatial and seasonal variations in asbestos fibre concentration in stream water and on the identification of mechanisms of transport would be beneficial. This report contains the results of these investigations, which are the product of a one-year study in the Sumas River basin in Washington State and British Columbia.

A number of recent asbestos-related studies have been published that were not covered in the previous review. As many health and environmental protection agencies have become interested in the topic, an updated summary review has been provided which emphasizes asbestos-related literature published from 1977 to 1980. This is followed by a discussion of three topics:

(1) The sources and distribution of asbestos fibres in the Sumas River basin;
(2) The mechanisms of transport and fibre-sediment interactions; and
(3) The possible relationships between asbestos fibres and water chemistry.

REVIEW OF ASBESTOS FIBRES IN THE HYDROLOGIC CYCLE

General Background

Asbestos is the name given to two types of hydrated silicate minerals: serpentine asbestos (chrysotile) and amphibole asbestos (actinolite, tremolite, crocidolite, anthophyllite and amosite). The minerals are made up of heat-resistant fibres, which vary in size and which enter all parts of the hydrologic cycle. The fibres are transported by aeolian and hydrologic processes, and until the recent introduction of the transmission electron microscope, no reliable analytical method had been available to quantify the fibre content in water. Over the past four years methods have been developed that, by means of transmission electron microscopy (TEM), scanning electron microscopy (SEM), electron diffraction and dispersive X-ray analysis, permit accurate fibre count and identification of chrysotile and amphibole fibres (Flickinger and Standridge, 1976; Gravati *et al.*, 1978; Hutchison and Whittaker, 1979). A method involving a carbon-coated Nuclepore technique was found to be reliable from interlaboratory tests (Chatfield *et al.*, 1978; Chopra, 1978), and this method is currently used by U.S. Environmental Protection Agency (USEPA) and water resource scientists in the United States and Canada for water sample analysis of asbestos. A detailed review and description of the method are provided by Chatfield and Dillon (1979), Schreier and Taylor (1980) and the Committee on Asbestos Analysis (1977).

There is no general agreement within the scientific community on whether the quantification of asbestos fibres should be by weight, size, frequency or geometry. The fibre concentration (number of fibres per litre) and fibre length (micrometres) in water samples are usually reported, but it might also be of interest to know fibre weight and fibre diameter, particularly in the study of mechanisms of transport. Since the particles are micrometre-sized, such measurements are difficult to make, and no accurate techniques have yet been developed to study fibre weight or diameter. The fibre-counting procedure is tedious and time-consuming, and automatic counting methods are currently being assessed with mixed success (Pavlidis and Steiglitz, 1978; Dixon and Taylor, 1979). The question of what causes asbestos to be carcinogenic has yet to be determined, and consequently it is necessary not only to improve the current analytical methods (Hunsinger *et al.*, 1980) but also to examine physical, chemical and mineralogical aspects when assessing asbestos concentrations.

Asbestos Fibre Concentrations in Different Parts of the Hydrologic Cycle

Asbestos fibres from both point sources and non-point sources enter all parts of the hydrologic cycle. The various asbestos pathways are illustrated in Figure 1.

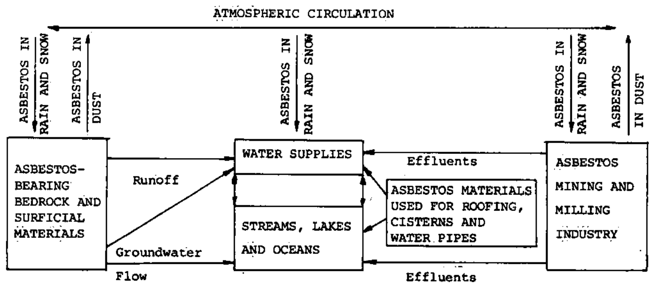

Figure 1. Asbestos pathways in the hydrologic cycle.

Although few data are available, Hallenbeck *et al.* (1977) and Hesse *et al.* (1977) have found significant asbestos fibre concentrations in rainwater, and Cunningham and Pontefract (1971) have found detectable levels in snow. Airborne emissions from industrial point sources have been the most extensively evaluated, and a level of approximately two fibres per cubic centimetre has been accepted as an international health standard (Charlebois, 1978). Most of the studies on asbestos fibre emissions have emphasized asbestos mining and milling operations, but emissions can also result from construction activities in asbestos-bearing bedrock (Rohl *et al.*, 1977); from off-road vehicle traffic in asbestos-rich surface materials (Kruse *et al.*, 1974; Cooper *et al.*, 1979a); and from automobile brake lines (Alste *et al.*, 1976). Cooper *et al.* (1979a) found substantial airborne asbestos concentrations in dust caused by recreational motorcycle traffic in a serpentine-rich area in California. Precipitation acts as a collector and thus introduces asbestos fibres into the hydrologic cycle. Unfortunately, too few measurements are available to determine the relative asbestos fibre contribution via the airborne collection process.

High asbestos fibre concentrations have been reported by Schreier and Taylor (1980) in several streams which are not influenced by asbestos mining and industrial activity. Stream contact with asbestos-bearing bedrock seems to be the cause of asbestos concentration in these waters. Similarly, groundwater originating in asbestos-rich aquifers has been found to contain high asbestos concentrations (Oliver and Murr, 1977). It is evident that natural asbestos contributions are much larger than originally anticipated, and some of the stream concentrations seem to exceed those found in asbestos industry effluents.

Asbestos is also used in a number of construction materials, particularly asbestos cement mixtures that are used in water storage and water transport systems. Asbestos cement water pipes are used extensively because of their supposedly high resistance to corrosion. A number of studies have been conducted to determine whether asbestos cement pipes release fibres into the water system (Olson, 1974; Oliver and Murr, 1977; Hallenbeck *et al.*, 1978; Tarter, 1979). All of these studies concluded that there is no significant increase in asbestos fibre concentration in the water after it has passed through asbestos cement pipes. Buelow *et al.* (1980), however, did produce evidence to indicate that fibres are released by drilling and tapping of asbestos pipes. More important, they showed that some waters are chemically aggressive enough to corrode asbestos cement pipes, thus causing asbestos fibre release. Tarter (1979) also noted that the distribution of asbestos fibre size changed in water before and after it had passed through asbestos cement pipes. Asbestos concentrations of up to 543×10^6 fibres/litre of water were also found in cisterns which collect water from asbestos cement tile roofing materials (Millette *et al.*, 1980).

Recently, national asbestos surveys have been completed for drinking water supplies in both Canada (Chatfield and Dillon, 1979) and the United States (Millette *et al.*, 1979), and similar conclusions were reached in both surveys. The majority of water consumers are not exposed to asbestos fibre concentrations exceeding one million fibres per litre. However, a small proportion of the population is exposed to levels of 100×10^6 fibres/litre, and in two Canadian water supplies, 2000×10^6 fibres/litre was recorded. It appears that the variability is generally greater in sample sites with high concentrations, and Chatfield and Dillon (1979) have suggested that rather than using single grab samples, pooling of samples over longer periods of time provides more reliability. A better alternative would be to examine several samples at different times to establish range and extreme values.

Most of the asbestos fibres in the water supplies are thought to enter from natural sources. It might be possible to differentiate between industrially processed and natural asbestos fibres in some of the water samples by using the dark field electron microscopy technique described by Seshan (1978). Chrysotile fibres tend to have microcrystalline fibre deformations as a result of the industrial milling and mixing process. Natural unprocessed fibres do not appear to have such deformations, and with this technique, some fibre source identification might be possible.

Finally, the most common asbestos fibre source is serpentinized ultrabasic bedrock. Fibres can be introduced directly into the water system by surface wash or groundwater flow. Serpentine-rich soils, which are generally alkaline and have low nutrient levels, are often poorly vegetated and are thus more susceptible to surface erosion, which facilitates asbestos fibre introduction into the water system. This is a particularly acute problem in the reclamation of asbestos mine waste (Moore and Zimmermann, 1975, 1977;

Meyer, 1980), where rapid revegetation could prevent much of the erosion problem.

Health Aspects of Water-Ingested Fibres

Asbestos fibres have been identified as a carcinogenic agent when inhaled (e.g. Selikoff *et al.*, 1964, 1972). However, health problems relating to ingested asbestos fibres are so far only poorly understood, and no conclusive evidence has yet been presented to suggest that ingested fibres cause gastrointestinal cancer (Olson, 1974; Levy *et al.*, 1976; Cunningham *et al.*, 1977; Wigle, 1977; Hallenbeck *et al.*, 1977; Meigs *et al.*, 1980). Recently, Cooper *et al.* (1979b) and Kanarek *et al.* (1980) did provide data which indicate a statistically significant association between asbestos levels in drinking water and certain types of cancer in the San Francisco area. The association was the most significant when stratified population data were used. Female gall bladders, digestive organs and the peritoneum were the most common cancer sites in the human body. More ongoing research is needed to identify direct cause and effect relationships conclusively. Moreover, a possible 15- to 40-year latency period between exposure and disease (Levy *et al.*, 1976) makes such studies particularly difficult. In response to the San Francisco study by Cooper *et al.* (1979b), the USEPA has produced water quality criteria for asbestos in drinking waters (EPA, 1980). Laboratory tests have shown that asbestos fibres (particularly chrysotile) are toxic to several types of cells and inhibit their growth (Neugut *et al.*, 1978; Mossman *et al.*, 1980; Reiss *et al.*, 1980a,b). In addition, Cook and Olson (1979) found that some fibres pass through the human gastrointestinal mucosa, while others accumulate in the body. Further work is needed, however, to determine whether the fibres are retained permanently and what health hazards they produce.

Medical researchers have suggested a range of causes of cancer, but at present, it appears that no agreement has been reached on this topic. Contamination of asbestos fibres by polycyclic aromatic hydrocarbons or trace metals, fibre geometry, and size and condition of fibre ends have been suggested as possible causes of cancer. In addition, Kanazawa *et al.* (1979) have suggested that asbestos can act as a catalyst, inducing neoplasia by stimulating virus activity, and Navratil *et al.* (1978) have noted that other factors can also interact with asbestos to cause cancer. The subject is obviously very complex, and as indicated by Shugar (1979), a more comprehensive assessment of the subject is necessary for conclusive evidence.

Summary

Asbestos fibres enter the hydrologic cycle both from natural sources (asbestos-rich bedrock and surficial materials) and from man-made sources (industrial mining and processing, and activities associated with surface disturbance of asbestos-rich soils). The fibres are very mobile and enter all pathways of the water cycle. The majority of the North American water supplies contain asbestos fibre concentrations of up to one million fibres per litre, and in asbestos-rich areas, concentrations of up to 200 million fibres have been measured. In contrast with the established health hazards related to inhaled asbestos fibres, water-ingested asbestos has not been shown to induce cancer. Only one study has so far indicated that a possible relationship may exist between high levels of asbestos in drinking water and cancer mortality (Cooper *et al.*, 1979b). However, long latency periods exist between exposure and appearance of the disease, and considerably more medical evidence is needed before concrete conclusions can be reached.

SOURCES AND DISTRIBUTION OF ASBESTOS FIBRES IN THE SUMAS RIVER BASIN

Introduction

The Sumas River has its headwaters on the western slopes of the Cascade Mountains in Washington State and it enters Canada near Huntingdon. The location of the Sumas River is shown in Figure 2.

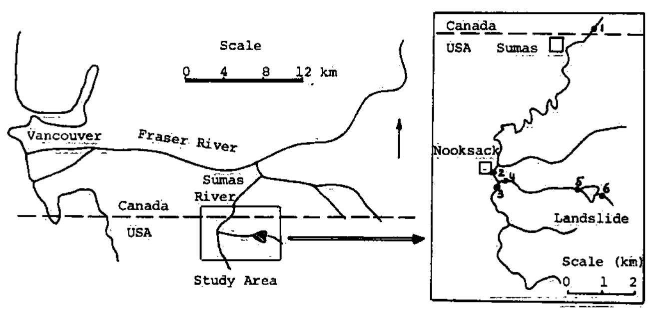

Figure 2. Location of study area. In key map the sampling stations are: *1* — Sumas River at international border; *2* — Sumas River at Nooksack; *3* — Sumas River above Swift Creek confluence; *4* — Swift Creek above Sumas River confluence; *5* — Swift Creek below landslide; *6* — Swift Creek above landslide.

Between January 1976 and December 1977, a number of water samples were collected from the Sumas River by the Pollution Control Branch of the government of British Columbia and the Water Quality Branch to determine asbestos fibre concentration, to examine possible sources of asbestos in the river basin, and to test analytical accuracy through interlaboratory asbestos determinations. Between June 1979 and February 1980, a new sampling program was initiated, in cooperation with the USEPA office in

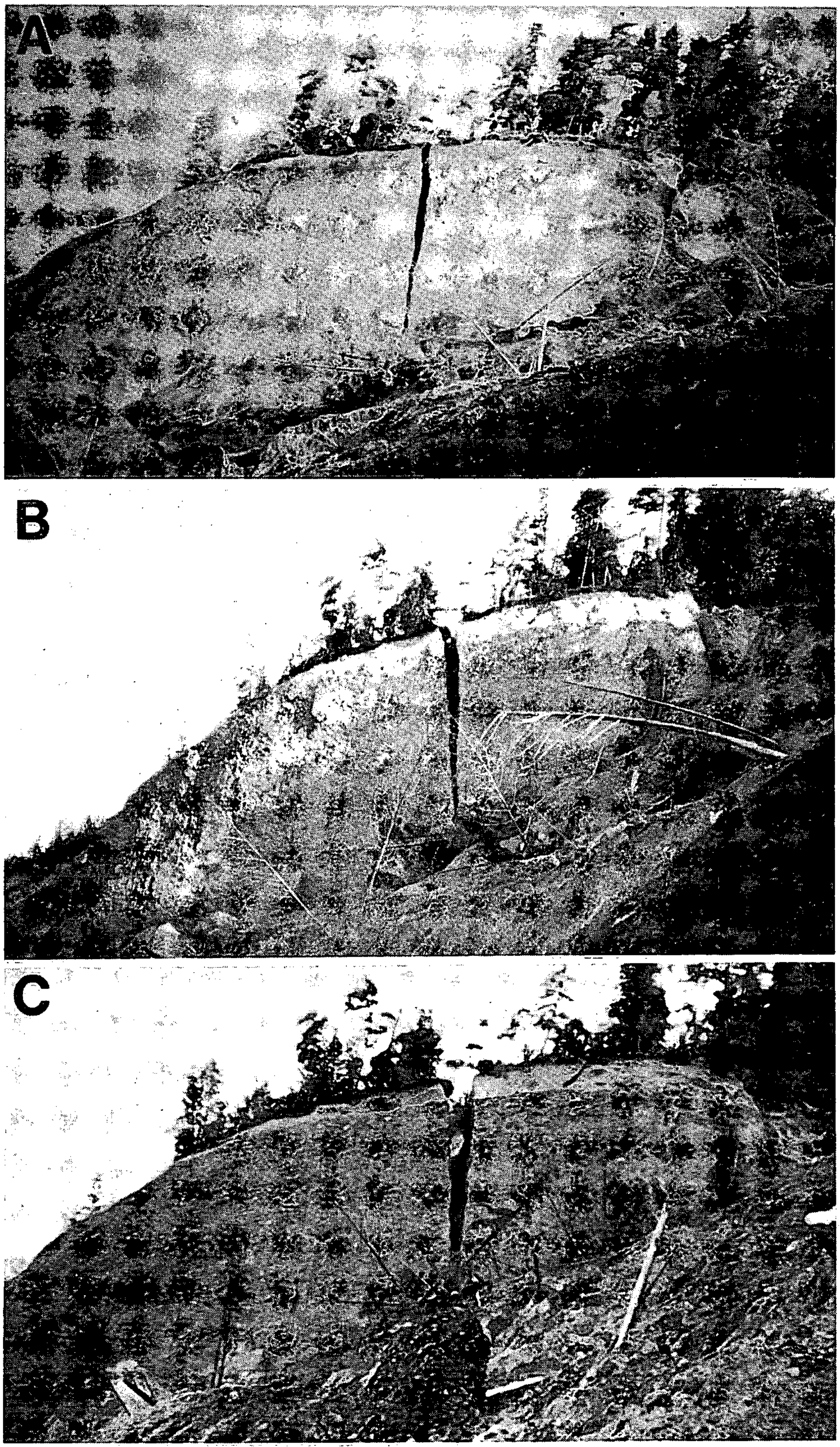

Figure 3. Active landslide in upper section of Swift Creek: ***A*** **– June 5, 1979;** ***B*** **– February 23, 1980;** ***C*** **– June 17, 1980.**

Seattle, to determine the spatial and temporal variations of asbestos fibres and to examine the mechanism of transport of the fibres in the river system. The Sumas River was chosen because of its potential transboundary pollution aspects with regard to water quality and because a natural asbestos source had been identified within the basin. A major landslide has exposed asbestos-rich bedrock in the upper section of the drainage basin where asbestos fibres are directly introduced into the stream. In addition, it should be noted that much of the headwater area is underlain by serpentinized rock, which can be considered a significant non-point source of asbestos fibres in the stream.

Landslide

The slide area is located in the headwaters of Swift Creek, a tributary of the Sumas River, and according to Converse, Davis, Dixon Associates Inc. (1976), it is a complex rotational slump-block slide which covers some 90 ha of exposed serpentinized bedrock. The instability probably occurred in postglacial times, and the landslide has been active for the past 35 years with frequent mass failures. The downslope movement over the past ten years has been estimated at 10 m/yr (Converse, Davis, Dixon Associates Inc., 1976), and the slide is considered to be the major sediment source for the Sumas River with an estimated erosion rate of 95 050 m^3/yr. The landslide activity was clearly evident during the study period and is illustrated by Figure 3, which shows the change in size of a wedge-shaped crack within the landslide area. In addition, a 150-m extension to the slide face occurred immediately after peak rainfall in December 1979. The slide area was included in the sampling program because it provided an excellent indicator for monitoring natural asbestos fibre release.

Sampling Program

Because of the great expense involved in the asbestos sample analysis, water quality sampling for this study could not be performed with conventional intensity. Instead, a sampling design was chosen to reduce the number of samples taken to a realistic minimum while maximizing the information value. This was accomplished by sampling the Sumas River in a way that represents the full range of streamflow conditions. Past discharge records (Water Survey of Canada, 1980) were used to determine the timing for sample collection. Six stations were selected in the watershed, and these were sampled five times during the 1979-1980 study period. Sampling occurred during the decreasing phase of the discharge in June, during minimal annual flow in August and October, during maximum annual flow in December and during late winter flow in February. The schematic illustration in Figure 4 indicates

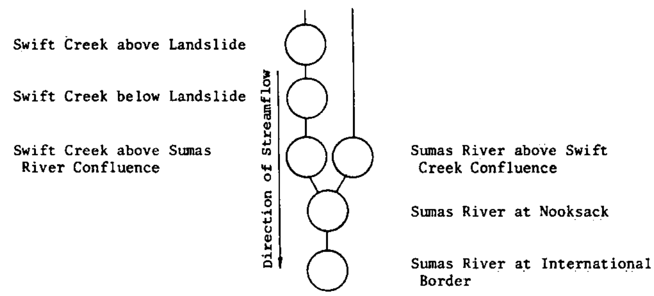

Figure 4. Schematic diagram indicating location of sampling stations in the Sumas River drainage basin.

the locations of the sampling stations, and Figure 5 presents the discharge record over the past four years with indications of the sample collection dates. The sampling stations on Swift Creek above the slide area and on the Sumas River above the Swift Creek confluence were selected because they are not influenced by the slide and could thus be used as control stations to determine regional background concentration of asbestos fibres.

Method of Asbestos Analysis

One-litre water samples were collected for both the asbestos fibre determinations and the water quality analysis.

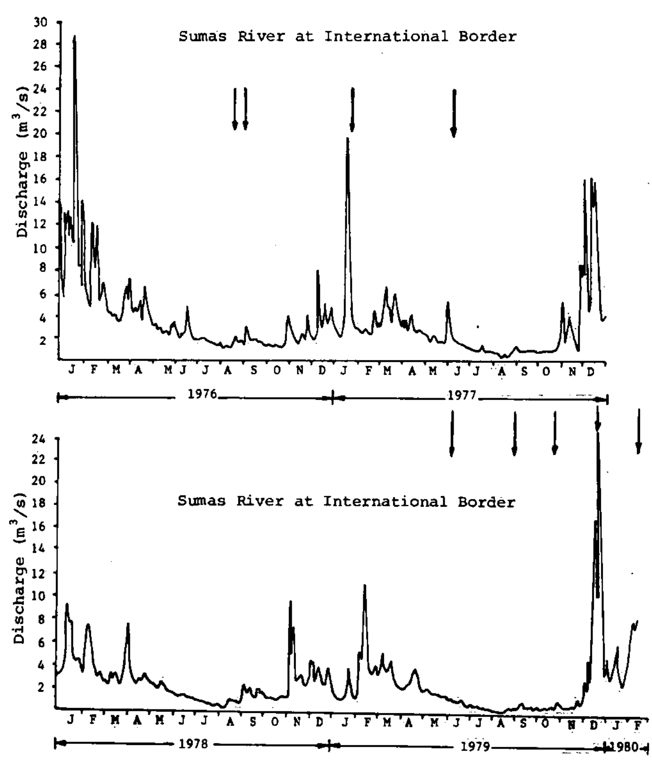

Figure 5. Sumas River discharge record and asbestos sampling dates. Arrows indicate sampling dates.

Mercuric chloride (1 mL of 2.7% $HgCl_3$) was added as a preservative to those samples to be analyzed for asbestos. The transmission electron microscopy technique developed by the Committee on Asbestos Analysis (1977) was used for the determination of the asbestos fibre concentrations and the identification of type and size of fibres. The technique is similar to the one used by the U.S. Environmental Protection Agency (Millette *et al.*, 1979) and has been reviewed by Schreier and Taylor (1980). Water samples were filtered through a Nuclepore filter (0.1-μm size); the samples were then carbon-coated, mounted on a grid and the filter paper was dissolved with chloroform. The morphology, size and frequency of the fibres were then examined with the transmission electron microscope using enlargements of 300 to 100 000 times. Tubular fibres belong to the chrysotile asbestos group and are distinct from amphibole fibres, which form solid rods. The abundance of fibres is measured in grid cells and a minimum of 100 fibres/cell is necessary to guarantee statistical reliability. Water samples with asbestos fibre concentrations in the range from 10^5 to 10^9 fibres/litre can be examined directly. Samples with higher concentrations require dilution.

The asbestos fibre analysis was performed in Vancouver by Levelton and Associates Ltd., who were previously involved in interlaboratory comparative analysis (Schreier and Taylor, 1980). The chemical analyses of the water samples were performed at the Water Quality Branch Laboratory in North Vancouver.

Spatial Distribution of Asbestos Fibres in the Sumas Drainage Basin

The asbestos fibre concentrations observed at all stations are summarized in Table 1, and schematic diagrams of the values are provided in Figures 6 and 7. From these figures, a number of statements can be made with regard to the spatial distribution of asbestos fibres:

(a) Very high asbestos fibre concentrations were observed in all the stations within the drainage basin.

(b) The highest asbestos concentrations were observed at the station immediately below the landslide and there is generally a decrease in concentration with distance from that source.

(c) The background levels observed at the two sampling stations not influenced by the landslide (Swift Creek above the landslide and the Sumas River above the Swift Creek confluence) were found to be substantial, particularly when compared with the asbestos fibre concentrations reported in other parts of Canada. However, the asbestos values from these two stations were

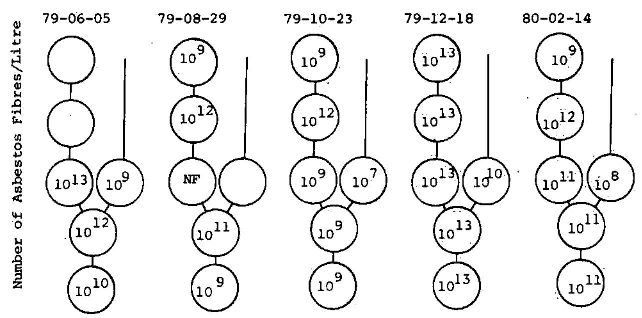

Figure 6. Distribution of asbestos fibre concentrations in the Sumas River basin. NF – No flow.

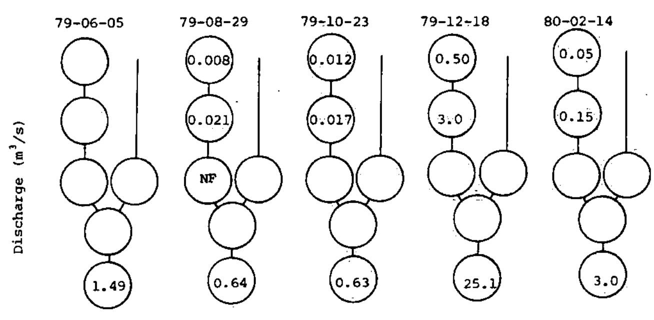

Figure 7. Discharge measurements during asbestos sampling in the Sumas River basin. NF – No flow.

Table 1. Asbestos Fibre Concentrations at All Sampling Stations (fibres/litre)

Date	Sumas River at international border	Sumas River at Nooksack	Sumas River above Swift Creek	Swift Creek above Sumas River	Swift Creek below landslide	Swift Creek above landslide
79-06-05	1.9×10^{10}	1.23×10^{12}	5.67×10^{8}	1.1×10^{13}	–	–
79-08-29	7.5×10^{8}	2.9×10^{11}	–	–	1.5×10^{12}	3.4×10^{9}
79-10-23	4.6×10^{9}	4.1×10^{9}	4.5×10^{7}	2.7×10^{9}	4.7×10^{12}	4.9×10^{9}
79-12-18	1.2×10^{11}	2.05×10^{13}	1.9×10^{10}	2.2×10^{13}	3.0×10^{13}	1.0×10^{13}
80-02-14	1.0×10^{11}	9.2×10^{10}	2.8×10^{8}	3.2×10^{11}	6.0×10^{11}	3.2×10^{9}

generally lower than those found in other sampling stations in the Sumas River. Although the pattern was not entirely consistent, it indicates that the influence of the landslide on asbestos fibre concentrations is evident despite the high background levels in the control stations. An interesting observation was made during the sampling trip on December 18, 1980. On that date, the asbestos fibre concentrations on Swift Creek above the slide reached levels equal to those below the site. This was the only incident in which the background concentration was not significantly lower than those found immediately below the slide. The explanation for this phenomenon is that the sampling took place on the day of maximum annual discharge following a major seven-day rainfall event. Within hours after the sampling, a mass failure occurred on the face of the slide, which resulted in total obliteration of the control sampling station. A new control station had to be established some 400 m above the old station for the remaining sampling period. It appears that during the sampling on December 18, 1979, upwelling and changes in the subsurface hydrology had already taken place prior to slope failure, thus contaminating the water with asbestos fibres.

(d) On August 29, 1979, Swift Creek did not have any surface flow near the Sumas confluence, and groundwater contributions from Swift Creek were probably small during that time period. Despite this, high asbestos fibre concentration was observed in the Sumas River station at Nooksack. This may suggest that a lag time exists in the clearing and dilution of the stream system, but it seems more probable that resuspension of deposits below the confluence, occurring over an extended period of time, is influencing these levels and masking any new contributions and fluctuations from Swift Creek. In this context, one should note that the dilution effect below the Swift-Sumas confluence is not very pronounced even though the discharge from the Sumas headwaters is at least seven times greater than that from Swift Creek.

(e) Variations between stations were not constant throughout the year, suggesting that site conditions and temporal events have an effect on concentrations.

(f) Finally, the asbestos fibre concentrations in the Sumas River are influenced by a major point source (landslide) and a non-point source (bedrock geology). The latter is responsible for the high background concentrations found in the upper sections of the river. To establish the proportional bedrock contribution clearly is slightly more difficult, and other sampling stations would have to be selected in accordance to major changes in the bedrock geology within the basin. Only with such a network would it be possible to establish regional asbestos levels and to partition the various source area contributions.

Temporal Distribution of Asbestos Fibres in the Sumas Drainage Basin

Based on the data provided in Figure 6, asbestos fibre concentrations appear to fluctuate over time. In the study of all of the available asbestos data in the Sumas River basin, a seasonal fluctuation in concentration was found to exist at all Sumas River sampling stations (Fig. 8). Maximum asbestos fibre concentrations were observed during peak discharge conditions, while the lowest values were measured during late summer when streamflow was minimal (Figs. 6 and 7).

These fluctuations are consistent even at the Sumas River station that is not influenced by the landslide. The data for the stations on Swift Creek above and below the landslide are plotted in Figure 9, and the associated discharge values are given in Figure 10. They indicate a positive association between discharge and asbestos fibre concentrations.

A correlation analysis between discharge and asbestos fibre concentration did not produce evidence of a significant

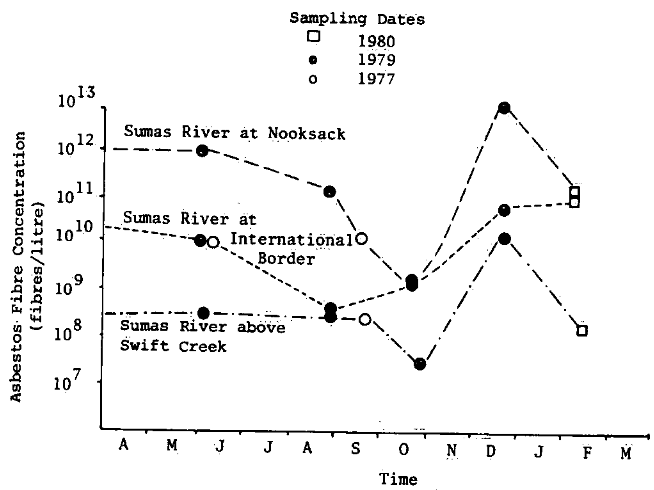

Figure 8. Seasonal distribution of asbestos fibres in the Sumas River.

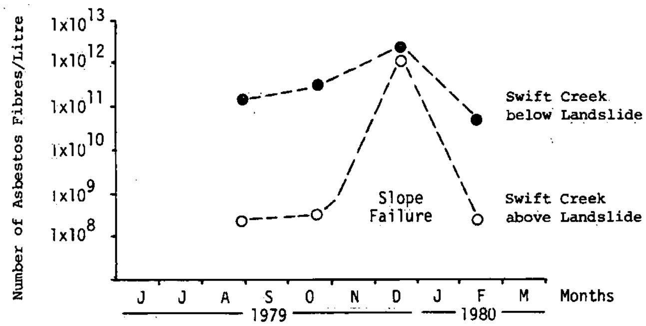

Figure 9. Seasonal distribution of asbestos fibres in Swift Creek.

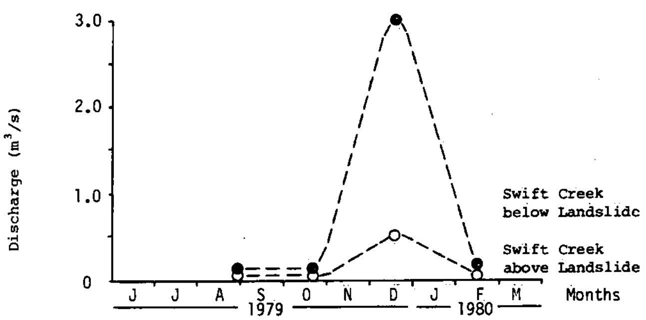

Figure 10. Mean discharge in Swift Creek.

relationship when all of the data from all of the sites had been pooled. Although an increase in discharge at any one site is usually accompanied by an increase in asbestos fibre concentration, it is probably not the amount of discharge but rather the increase in turbulence or velocity which is associated with fibre concentration. This is clearly illustrated in Figure 11, which shows relationships between discharge and asbetos fibre concentrations at three levels of discharge, each with approximately one magnitude of difference.

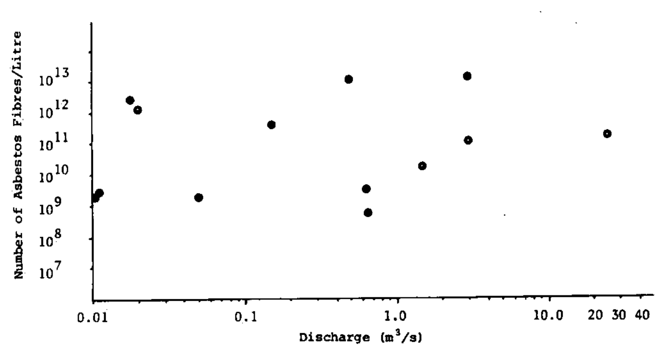

Figure 11. Scatter diagram between discharge and asbestos fibre concentrations.

Regardless of the discharge level, an increase in discharge causes an increase in fibres; this is probably related to a resuspension of fibres which have accumulated in the sediments. The relationship was further investigated with sediment samples in a small laboratory experiment and is discussed later.

Comparison between Spatial and Temporal Variations in Asbestos Fibre Concentrations

The spatial and seasonal variations are compared in Figure 12, showing the seasonal range in concentrations for each station and the spatial variation during the five sampling periods. From this figure it is clear that variations are significant in both space and time, showing that occasionally collected single grab samples are not sufficient to determine concentrations accurately. In the Sumas River study, spatial differences of up to five orders of magnitude and temporal differences of up to four orders of magnitude were observed.

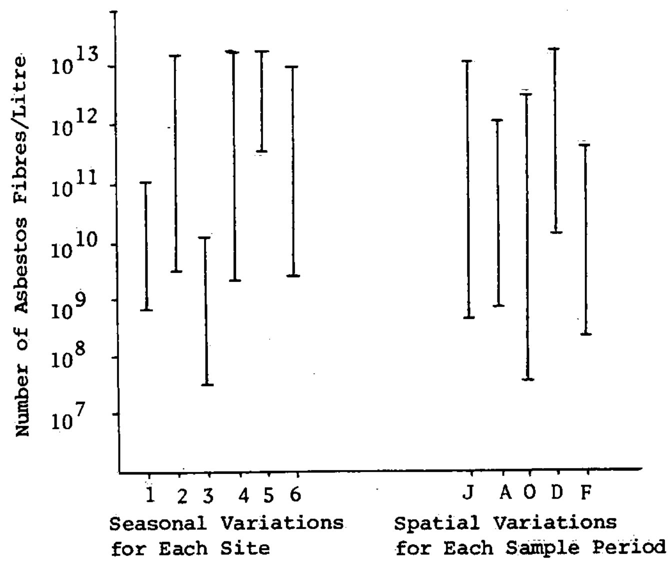

Figure 12. Comparison between temporal and spatial variations in asbestos fibre concentrations. Locations: *1* — Sumas River at international border; *2* = Sumas River at Nooksack; *3* — Sumas River above Swift Creek; *4* — Swift Creek above Sumas confluence; *5* — Swift Creek below landslide; *6* — Swift Creek above landslide. Time: *J* — June 5, 1979; *A* — August 29, 1979; *O* — October 23, 1979; *D* — December 18, 1979; *F* — February 14, 1980.

MECHANISMS OF TRANSPORT AND FIBRE SEDIMENT INTERACTION

Laboratory Settling Experiments with Bed-Sediment Samples

It was first postulated that despite their small size, asbestos fibres behave much like other sediment particles and, in the absence of water movement, settle to the bottom of a container. The only difference is that the settling rates might be slower and any small disturbance might resuspend the fibres. The examination of different settling rates by hydrometer and pipette methods (Day, 1950) is widely accepted as a means of determining particle size in soils and sediment studies. The method is based on Stokes' law, which states that settling rates of a falling particle are directly proportional to its size squared and which assumes that particles do not interact with each other during the fall.

Two bed-sediment samples were collected in the Sumas River at Nooksack and one was collected in Swift Creek above the Sumas confluence. In each case, the water was decanted from the sediments and the samples were divided into equal portions for moisture determination and settling experiments. A duplicate experiment was conducted with the Nooksack sample, while a single Swift Creek sample was examined for comparative purposes. The three samples were subjected to three long-term settling experiments. A sediment sample of 32.5 g (dry weight) was prepared for the replicate experiment with the Nooksack sample, while 19.5 g (dry weight) of sediment was used from the Swift Creek sample. Each sample was suspended in a 1-L measuring cylinder with 1-L of asbestos-free distilled water. The sediments were thoroughly mixed with a Teflon plunger, and 50-mL water samples were removed from the top 5 cm of the cylinder surface with a pipette after a settling time of 0, 24, 72 and 144 h. Care was taken to prevent any disturbance while inserting and removing the pipette to minimize resuspension of the already settled fibres. Both the duplicate sample sets (Nooksack sediments) and those from Swift Creek were analyzed for asbestos, and the results of the settling experiment are provided in Figures 13 and 14.

Adequate agreement was attained between the two replicate experiments. The small discrepancy observed after 144 h of settling can be attributed to physical limits within the experiments. At that stage, particles of less than 10 μm in size, as predicted by Stokes' law, are dominant, and surface charges and microturbulence could have a significant effect on the settling and suspension process.

A smaller amount of sediment was used for the Swift Creek sample experiment because of higher asbestos con-

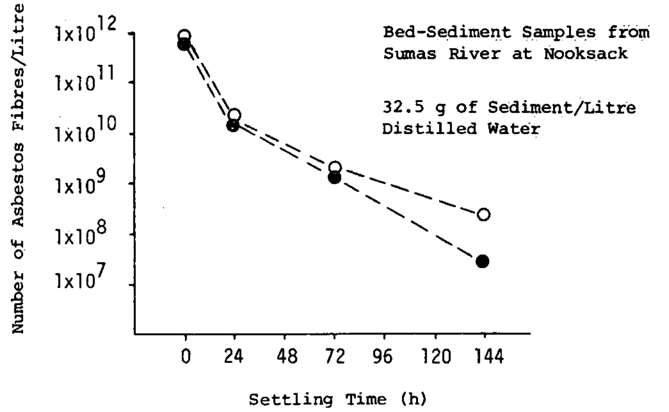

Figure 13. Replicate settling experiment of bed sediment from Sumas River.

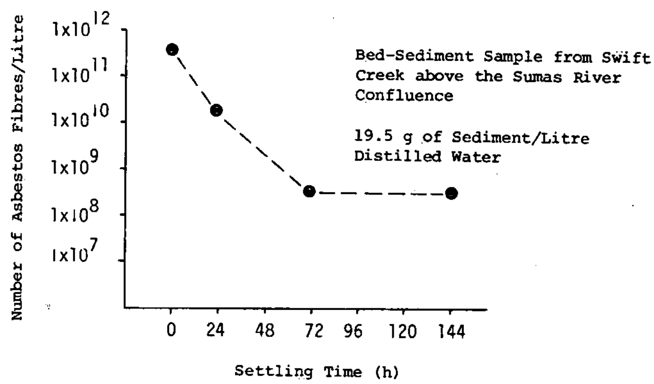

Figure 14. Settling experiment of bed sediment from Swift Creek.

centrations in the water. Again, as in the previous experiments, the same general trend was observed. This suggests that an exponential relationship exists between asbestos fibre concentrations and settling time.

According to Stokes' law, the particles smaller than 2 μm are not expected to settle within the first 24 h. However, the decrease in fibre concentration was much more pronounced during the initial 24 h and was followed by a more predictable settling rate between 24 and 144 h. The rapid initial settling of fibres can result from several causes: silt- and clay-sized sediment particles trap and remove asbestos fibres from the suspension during the settling phase; variable fibre shape affects settling rates and settling particles scavenge others with opposite surface charges; fibres often combine to form bundles which alter the size-settling relationship; or differences in specific gravity of particles of equal size can affect settling patterns. As a result, the correlation of settling time and fibre size is not expected to be very good, which is confirmed in Figure 15 where the average fibre size of the analyzed samples is

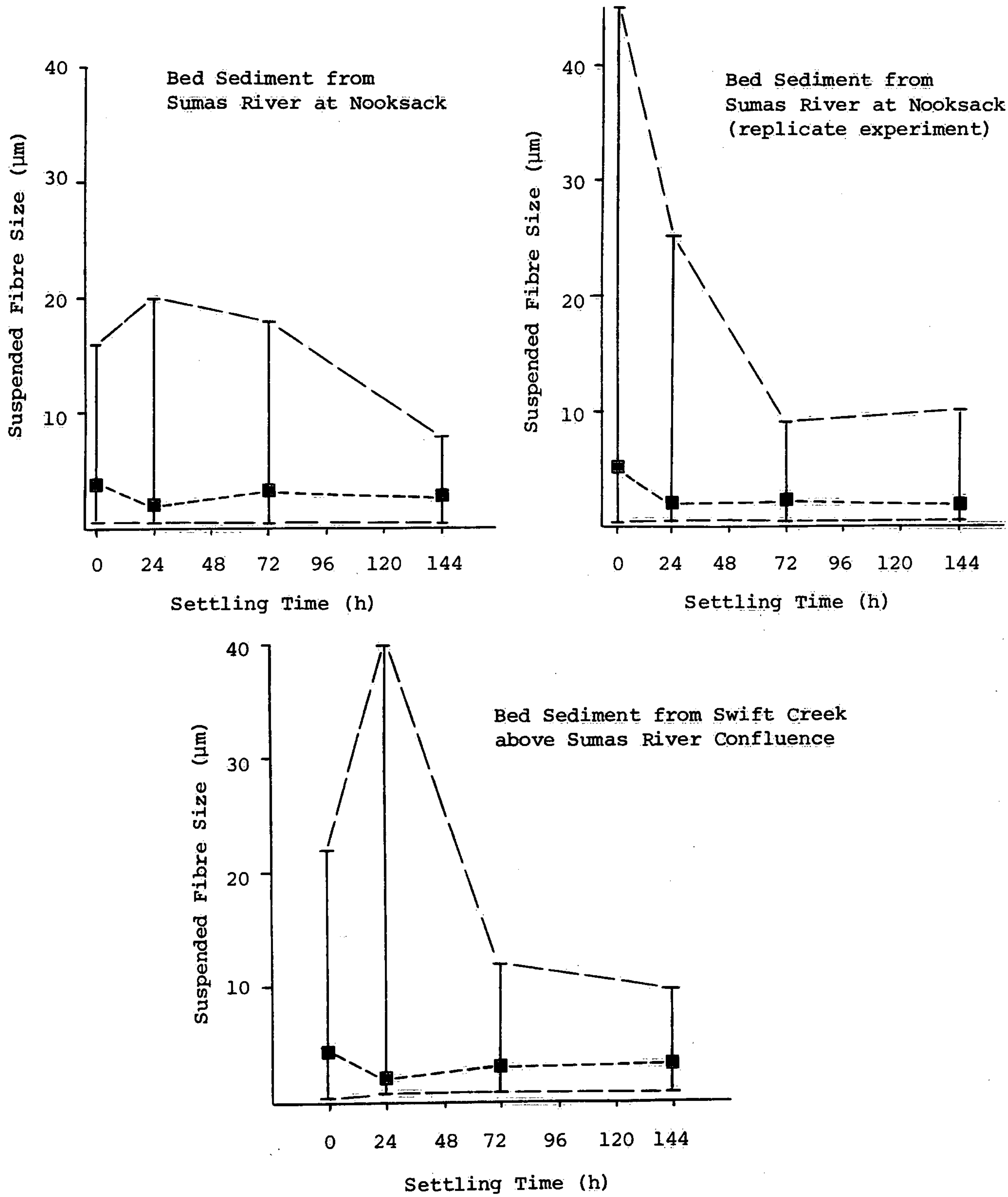

Figure 15. Relationship between asbestos fibre size and settling time.

Table 2. Downstream Variations in the Sumas River at Maximum Discharge on December 18, 1979 (longitudinal cross section)

Sampling stations	Asbestos fibre concentrations (fibres/litre)	Average asbestos fibre size (μm)	Discharge (m^3/s)
Swift Creek below landslide	2.97×10^{13}	4.0	2.4
Swift Creek above Sumas confluence	2.17×10^{13}	4.0	–
Sumas River at Nooksack	2.05×10^{13}	3.0	–
Sumas River at international border	1.25×10^{10}	2.0	25.1

plotted against settling time. The average fibre size did not show a consistent decrease with settling time, but at least the range in fibre size decreased over the longer time intervals in all three settling experiments. This suggests that the underlying principles of Stokes' law are present, but that some of these processes interfere and partially obliterate the size-settling time relationship.

Relating Laboratory Results to Stream Data

If asbestos fibres settle according to fibre size, then one would expect to find greater average fibre size in water samples of maximum discharge and greatest turbulence, and smaller fibres would then dominate during low flow periods when large fibres settle to the river bed. At two of the six stations, the highest annual mean fibre size was found in the samples collected during maximum flow. In addition, the Swift Creek station above the Sumas River confluence showed a fibre size distribution related to the discharge pattern (Fig. 16). This was not only the case for average fibre size but also for the entire fibre size range in each sample. Unfortunately, the other stations did not show the same pattern, and it is possible that other factors such as channel geometry, turbulence, and pool and ripple sequences influence the fibre concentration, size and discharge relationships.

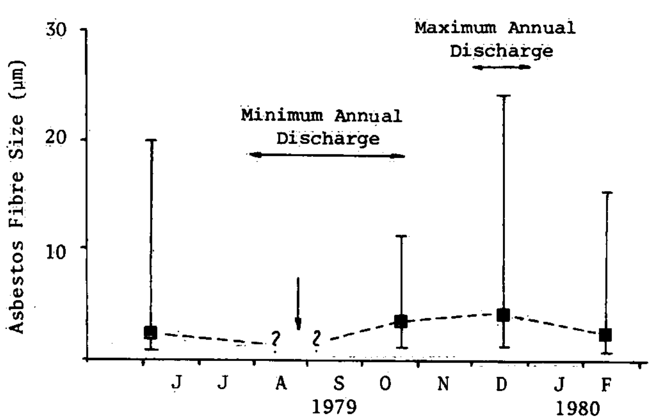

Figure 16. Seasonal differences in asbestos fibre size in Swift Creek above Sumas River confluence.

The evidence provided from the laboratory experiment and the stream data in Figure 16 suggest that some relationship exists between asbestos fibre size and settling time, but the correlation is inconsistent and complex, particularly when compared with the settling pattern of larger sized particles. Also resuspension appears to be related to seasonal increases in stream velocity and turbulence rather than to absolute discharge values (Tables 2 and 3).

Table 3. Differences in Asbestos Concentration between the Swift Creek and Sumas River Control Stations

Sampling date	Swift Creek above landslide (fibres/litre)	Sumas River above Swift Creek confluence (fibres/litre)
79-10-23	4.9×10^{9}	4.5×10^{7}
79-12-18	1.04×10^{13}	1.9×10^{10}
80-02-14	3.2×10^{9}	2.8×10^{8}

At the highest discharge levels in December, a decrease in average fibre size and fibre concentration was observed in the downstream direction from the landslide to the international border despite increases in discharge downstream (Table 2). Since the gradient and velocity in the upper section of the Swift Creek are considerably greater than downstream, settling is less likely in the upper portion than farther downstream.

In comparing the two control stations (Swift Creek above the landslide and Sumas River above the Swift Creek confluence), it is evident from Table 3 that there is a considerable difference in concentrations. It can be attributed to two possible causes: geological difference in the distribution and an abundance of serpentinized rock in the headwater region or variations in turbulence, velocity and discharge between the two stations.

The discharge in the Sumas River control station is at least seven times greater than discharge levels at the Swift Creek control station. The turbulence and velocity, however, are considerably higher in the Swift Creek station because of excessive gradient. Consequently, one would expect that most fibres remain suspended in Swift Creek. This results in higher fibre concentrations than in the Sumas River headwaters. Therefore it should follow that the range of fibre size would also be larger at the Swift Creek control station than at the Sumas control station. Actual data on fibre size, however, did not confirm this hypothesis, and based on the water quality data discussed later, it appears that the variations in regional geological conditions also contribute to the differences in asbestos fibre size and concentration between the two control stations.

No difference in fibre size could be observed between the stations, which indicates that the differences in concentration could largely be caused by variation in the regional geology, and the size of the stream and discharge rates have a less significant effect on suspended and settling fibre size. A significant correlation was found between asbestos fibre concentrations and total suspended sediments ($r = 0.93$). However, the use of simple linear regression techniques to predict asbestos fibre concentrations from suspended sediment concentrations was inadequate, giving poor predictive accuracy (large standard errors). The problems of differential particle settling are thought to be the cause of poor predictability.

RELATIONSHIP BETWEEN WATER QUALITY AND ASBESTOS FIBRES

The spatial and seasonal variations in water quality can be observed from Figures 17 to 19. The landslide has had a profound influence on the overall chemistry, and values for magnesium, iron and pH were usually significantly higher at the landslide station than at all other stations. In contrast, values for silica, potassium and calcium were all significantly lower at the landslide station than at the remaining stations. Some of these differences occurred throughout the year. A comparison of the most important chemical parameters in Swift Creek with those of the Sumas River is provided in Figure 20. These differences clearly reflect the serpentine-rich environment of Swift Creek.

Soils and water in serpentine-rich environments are known to be high in magnesium and iron and low in nutrients and, as reviewed by Proctor and Woodell (1975), the infertility of serpentine soils is thought to be caused by high magnesium, nickel, cobalt and chromium values and low calcium concentrations (Moore and Zimmermann, 1977; Meyer, 1980). The three trace metals that are commonly present in asbestos (Roy-Chowdhury *et al.*, 1973) were not measured in the water, but the magnesium values exceeded calcium values in Swift Creek at all times of the year (Fig. 20) and confirm results from other parts of the world. Magnesium, which is one of the main constituents of all types of asbestos, can be leached, and iron can replace magnesium in the structure by a process known as isomorphic substitution. The presence of iron and magnesium in high concentrations could thus be a reflection of serpentine weathering and mineral substitution.

To show the difference between Swift Creek and the Sumas River, the percentages of the combined magnesium, silica and iron concentrations in water were calculated and plotted in a ternary diagram (Fig. 21). On the basis of this information, it is evident that the samples from Swift Creek come from a chemical environment that is different from that of the Sumas River. However, neither individual nor

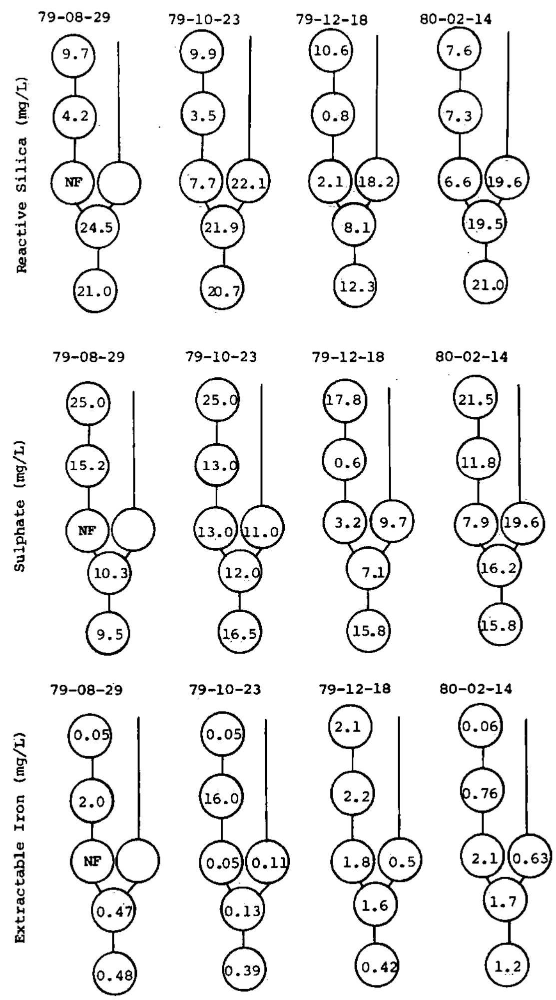

Figure 17. The SiO_2, sulphate and iron variability in the Sumas River basin. NF — No flow.

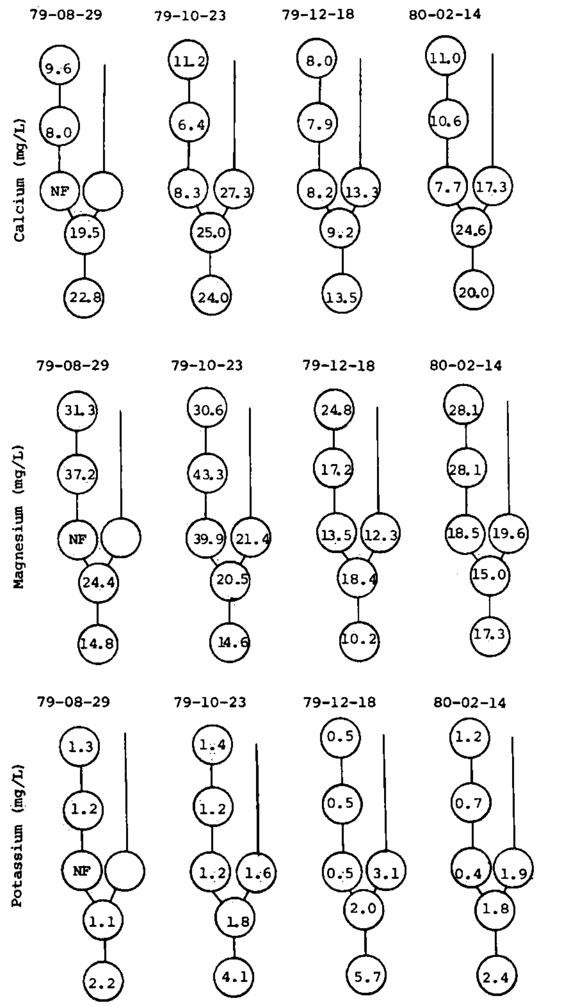

Figure 18. The calcium, magnesium and potassium variability in the Sumas River basin. NF — No flow.

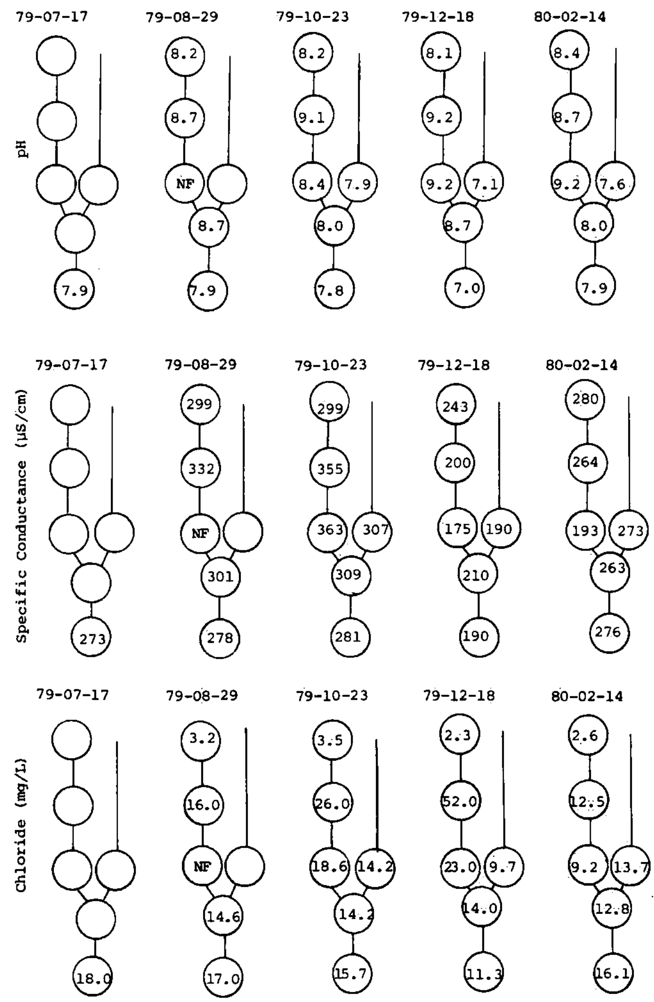

Figure 19. The pH, specific conductance and chloride variability in the Sumas River basin. NF — No flow.

combined chemical parameters correlated with asbestos fibre concentrations, and it is obvious that asbestos fibre concentration cannot be predicted from water chemistry. Instead, water chemistry can be used for separating different geochemical sources, and thus it can be useful in identifying locations of source materials.

CONCLUSIONS

Spatial Variations in Asbestos Fibre Concentrations

Asbestos fibre concentrations ranging from 10^7 to 10^{13} fibres/litre were found within the Sumas River drainage basin. The highest levels were measured immediately below an active landslide on Swift Creek, a tributary of the Sumas River. The landslide was identified as a major point source of asbestos, which influences concentrations all the way downstream from the landslide to the international border. Two control stations, which were upstream and unaffected by the landslide, showed consistently lower values than those found at the border. Nevertheless, the control stations reached concentrations as high as 10^{10} fibres/litre, which is considered substantial and probably results from the abundant asbestos-bearing bedrock in the region. Thus a stabilization of the slide could theoretically eliminate the extreme values of asbestos in Swift Creek but could not reduce substantially the generally high values found in the remaining portions of the watershed.

Temporal Variability in Asbestos Fibre Concentrations

Seasonal fluctuations of up to four orders of magnitude were observed at all of the stations, with the highest concentrations occurring during peak flow periods and the lowest concentrations occurring during late summer when the streamflow is at a minimum. No universal relationship

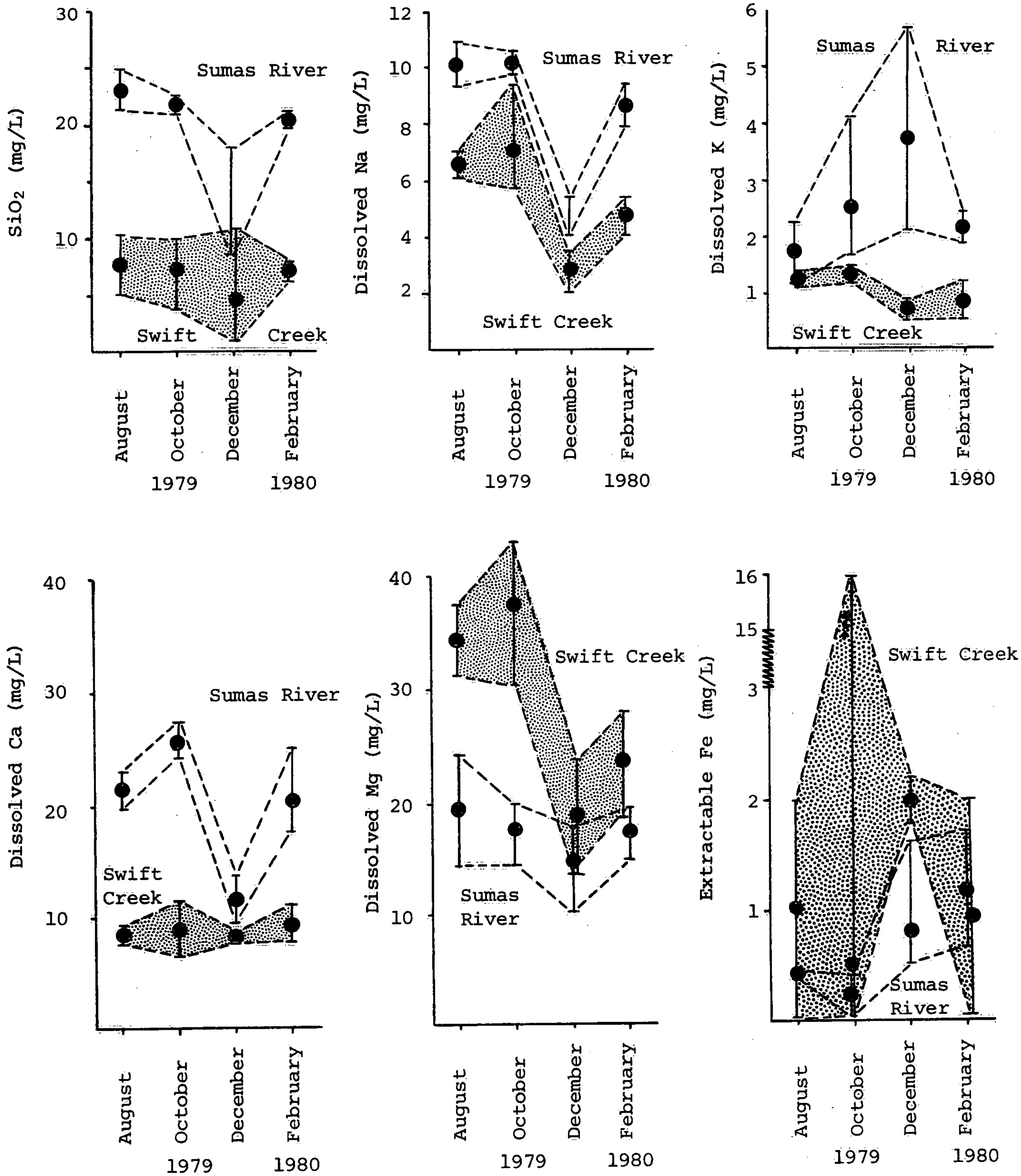

Figure 20. Comparison in water chemistry between Swift Creek and the Sumas River.

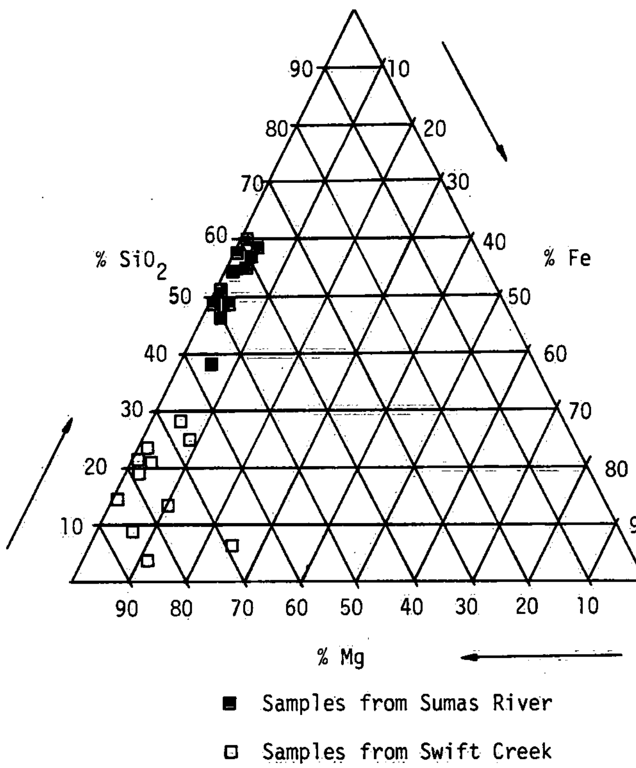

Figure 21. Ternary diagram of Mg, Si and Fe showing differences in water chemistry between Swift Creek and the Sumas River (proportional representation).

was observed between asbestos fibre concentrations and stream discharge values. Instead, site specific changes in relative velocity and turbulence appear to control fibre concentrations.

Comparison between Spatial and Temporal Variations

Both types of variation are significant, and because of the asbestos point source in the basin, spatial variations were found to be slightly greater (up to five orders of magnitude between some stations) than seasonal variations (up to four orders of magnitude at the Sumas River station at Nooksack during the 1979-1980 season). This clearly demonstrates that the occasional collection of grab samples is insufficient in determining background asbestos fibre concentrations in rivers.

Possible Mechanisms of Transport

Some asbestos fibres do not remain suspended in water at low velocity and turbulence, and although there is some evidence to suggest that fibre size decreases with settling time, the pattern is complex and inconsistent. Data from the Swift Creek station above the Sumas River confluence indicate that the smallest fibres were found during minimum river discharge and the largest, during maximum discharge in December. The range in fibre size and, to a lesser degree, the mean fibre size decreased with increasing settling time, which is expected according to Stokes' law. Unfortunately, this pattern is not consistent and often poorly developed, suggesting that other processes interfere. Settling particles probably scavenge other particles, particularly when opposite surface charges are present. Fibres are known to combine into bundles, which change the size-settling rate relationship, and differences in fibre shape and specific gravity of particles of equal size can also influence the settling process. All these processes are probably responsible for the poor and inconsistent size-settling relationship.

Relationships between Water Quality and Asbestos Fibre Concentration

No direct relationship exists between water quality and asbestos fibre concentrations, and individual elements cannot be used to predict asbestos concentrations. However, water quality data can be used to identify chemical differences in source areas, and in the present example, stations influenced by the landslide showed higher asbestos concentrations and dissolved magnesium and iron values than stations unaffected by the slide, which showed lower asbestos levels and dissolved magnesium and iron concentrations.

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