PROJECT REPORT
2000-25
INTERIM PROJECT REPORT

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Pulp Mill Effluent Induced Coagulation and Flocculation in Receiving Waters

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ISBN 1-55261-085-3

Pulp Mill Effluent Induced Coagulation and Flocculation in Receiving Waters

by

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August 2000

ABSTRACT

Presented is the progress report for the SFM funded research project: pulp mill effluent induced coagulation and flocculation in receiving waters. It includes an introduction, progress report, major findings, significance of the study and a list of presentations and publications based on this study

ACKNOWLEDGEMENT

I would like to extend my utmost appreciation to Dr. Daniel W. Smith for his valuable guidance, patience, encouragement and financial support throughout the course of this research. I would also like to thank Dr. Gordon Putz and many graduate students for field surveys in the rivers, Frances Lally, Xinbo Ge, Stephanie Joyce (special thanks for considerable contribution to the biological factors portion), Maria Demeter, Nick Chernuka, Garry Solonynka, Debra Long and Stephen Craik for assisting with this study, and the Sustainable Forest Management Network Centres of Excellence for funding this project.

INTRODUCTION

Researchers have observed that pulp mill effluent (PME) results in floc formation, and deposition of an organic matrix and suspended sediments downstream of pulp mills in rivers (Krishnappan, 1994). This phenomenon is referred to in this study as Pulp Mill Effluent Induced Coagulation and Flocculation (PMEICF).

Impact of PMEICF on Receiving Waters

PMEICF is an essential process governing transport and fate of sediments and contaminants in rivers (Lau and Krishnappan, 1992). It may have a negative impact on aquatic ecosystems near the effluent discharge point. It may cause the buildup of fiberbanks, and increases the amount of contaminants in benthic sediments, fish or biota (Carlberg, 1986, 1988; Tavendale, 1996; Martinsen, 1994 and Judd, 1995). It may also threaten human health because of the ingestion of contaminated fish or biota (Adams, 1994). In addition, the resuspension of contaminated benthic sediments may release biodegradable chemicals, refractory compounds and even toxic materials into rivers. This may cause low dissolved oxygen and high toxicity in rivers. As a result, it may adversely affect aquatic habitats, biodiversity and reproductivity of bottom dwellers (Gifford, 1994; Maldiney and Mouchel, 1993).

Problem Statement

Thousands of PME-related chemicals and bacteria have been discharged into receiving waters. Some of them have affinity for ambient suspended particles, which are the sites for contaminant compounds to become lodged and transported. This may induce flocculation of suspended sediments and form settleable flocs. As previous research found that the phenomenon of PMEICF did not exist in all rivers, the occurrence of PMEICF was a debatable issue. No studies were carried out in attempt to postulate the mechanism for its formation; therefore, substances inducing the phenomenon of river flocculation were not identified, and the mechanism for its formation was not understood.

Although researchers were aware of the significance of PMEICF to the transport and fate of sediments and contaminants in the aquatic ecosystem; they have had difficulty including the effect of PMEICF in the transport models due to a lack of understanding of the mechanism for its formation, and uncertainties of substances causing and factors affecting the formation of PMEICF (Ng et al., 1996; Irvine et al., 1995; Ziegler and Nisbet, 1994). Thus, the majority of transport models were developed under the assumption that all particles behave as individual particles, and flocculation does not exist (Ongley et al., 1992). These models may not be adequate to use for rivers receiving PME. This is particularly true when a large percentage of sediments and contaminants are settled out instead of being carried downstream of the pulp mill outfall. This prompted us to conduct further research in an attempt to confirm the formation of PMEICF and to postulate the mechanism for its formation.

Objectives

The objectives of this study are to identify the conditions necessary for the formation of PMEICF, to evaluate factors affecting its formation and to postulate the mechanism for its formation. The results of this study are expected to be used to improve the transport models with the inclusion of PMEICF and floc deposition. This will facilitate efforts to effectively monitor long-term BOD, toxicity, dissolved oxygen, color and sediment impact, which are the most significant long-term issues related to river water management. In addition, the study results are expected to be used to adjust effluent treatment technologies or regulations, so that the potential threat to the environment by such materials will be reduced.

PROGRESS REPORT

The project was divided into two parts: confirmatory and mechanism studies. Numerical modeling was suggested.

Confirmatory Study

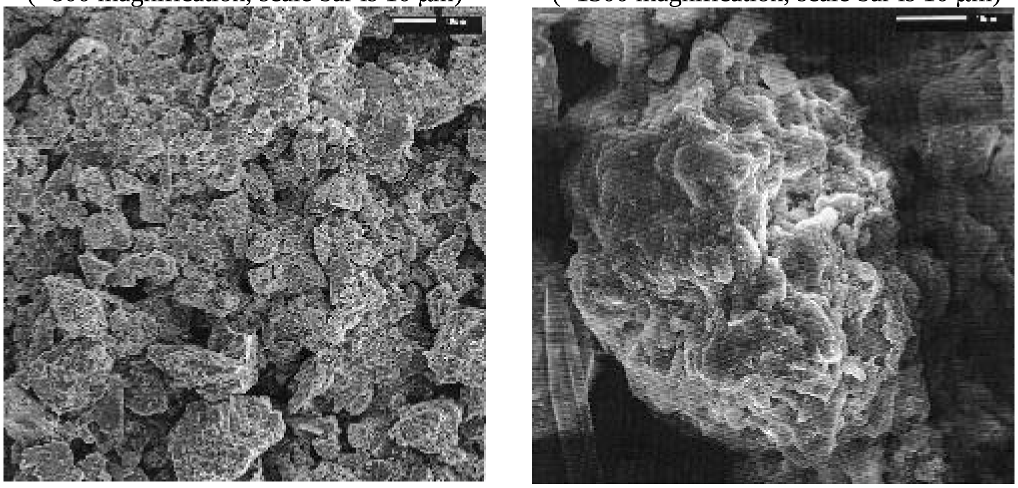
PMEICF has created much public concern and debate because of uncertainty, and inconsistent results from different rivers. This encouraged us to conduct further research to verify its existence. Confirmatory studies were conducted in the field and in the laboratory.

Field Confirmation

Field surveys were conducted on two major rivers in Alberta, which receive PME. The Athabasca River near Hinton receives PME from Weldwood, and the Wapiti River near Grande Prairie receives PME from Weyerhaeuser. The survey focused on river flow rate, COD, color and sediment flocs. The survey sites were selected 100, 300 and 1000 m upstream of the mill outfall, and 50, 100, 500, 1000 and 1500 m downstream of the outfall. Samples of river water and sediment flocs were collected from selected survey sites, and at the same time corresponding PME was taken from the outfall to compile samples for the flocculation study. An X-ray Scanning Electron Microscope (SEM) was used to observe floc morphology, and to determine the chemical composition of flocs. Field survey results demonstrated that sediments discreted upstream of the outfall, but flocs formed downstream of the outfall (Figure 1). A significant quantity of larger sized flocs formed from the outfall to approximately up to 1000 m downstream of the outfall. The size and amount of flocs decreased further downstream of the rivers. This suggests that physio-chemical reactions may play an important role in the formation of PMEICF in receiving waters. In addition, SEM images of field flocs show that fibers, fibrils from microorganisms, and aquatic organisms and plants (such as different types of diatom) are involved in floc formation. Examples of the flocs are presented in Figure 2.

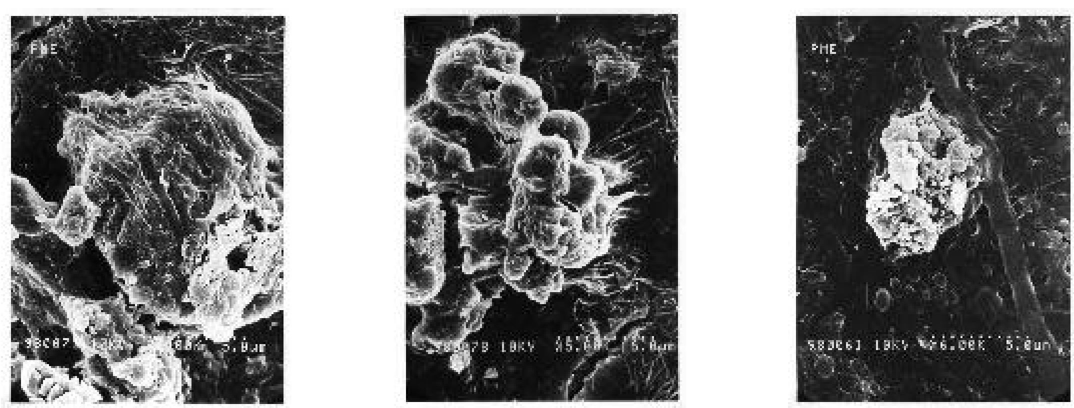
Upstream of the Outfall (×800 magnification, scale bar is 10 μm)

Downstream of the Outfall (×1300 magnification, scale bar is 10 μm)



a b

Figure 1: Sediment flocs from the Athabasca River near Hinton



a b c

Figure 2: Sediment flocs from Wapiti River near Grande Prairie

Laboratory Verification

In the laboratory, two mixing systems were used for verification of the occurrence of PMEICF. One was a standard jar testing apparatus (Hudson jar with a paddle mixer), the other was a vertically oscillating-grid mixing system as shown in Figure 3, which provided a uniform mixing environment.

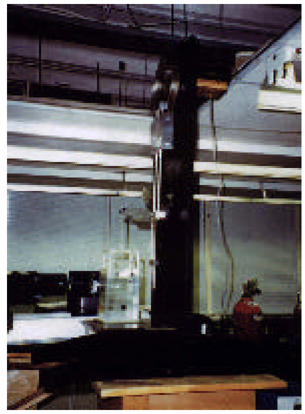


Figure 3: A vertically oscillating-grid mixing system

Samples used for most of the flocculation studies were mixtures of PME and river water. The samples of biologically treated PME were collected from the Weyerhaeuser pulp mill at Grande Prairie and the Weldwood pulp mill in Hinton. The samples of river water were collected from the Wapiti River at Grande Prairie and the Athabasca River near Hinton. Daily fresh and preserved samples (less than 11 days), and samples from different sites and seasons (from 1997 to 2000) were also used to estimate the temporal and spatial variations of PMEICF in receiving waters.

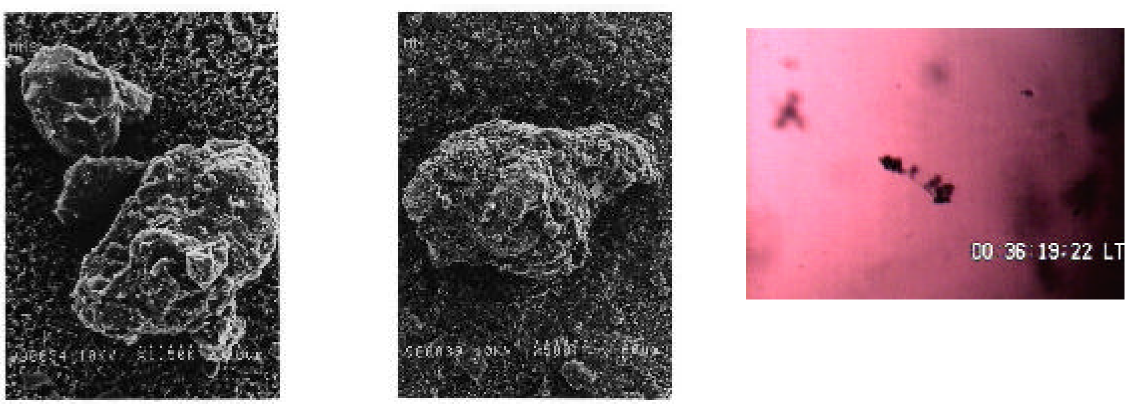
Turbidity and particle removal efficiencies (size less than 10 μm), and absorbance were the major parameters used for evaluation of flocculation performance. Total solids (TS), total suspended solids (TSS), total deposited solids, total organic carbon (TOC), chemical oxygen demand (COD), adsorbable organic halides (AOX), color, pH and conductivity were also monitored as the flocculation process progressed. An X-ray SEM was used to observe floc structure, and to determine the metal composition of flocs. An Inductively Coupled Plasma (ICP) spectrometer was used to determine the metal concentrations of PME and river water. High-Performance Size Exclusion Chromatography (HPSEC) was used to verify molecular weight distributions of components from the ultrafiltration fractionation of PME. The video microphotography system was used for on-line monitoring of floc formation. The IMAQ™ version software was used to determine floc size distributions from floc images.

Laboratory results showed floc formation (as shown in Figure 4), an increase in particle removal efficiency (Figure 5), and a decrease in both turbidity and total suspended solids of flocculated samples (Figure 6 to Figure 7 and Table 1). Figure 8 showed that flocs contain large numbers of bacteria and exocellular polymers, which played a role in the formation of flocs. The results suggest that PME can induce coagulation and flocculation in receiving waters.

Table 1: Variation for the characteristics of the samples of mixtures of Weyerhaeuser PME and Wapiti river water with a volume ratio of 1:1 (sample date: May to June of 1998; the results are averages of duplicates or triplicates

	Parameter		Result
	TS	(mg/L)	1145
	TSS	(mg/L)	208
	Turbidity	(NTU)	115.8
Before Mixing	Color	(CU)	586
	pH		7.3
	TC (measured)	(mg/L)	144
	TIC (measured)	(mg/L)	61
	TOC (calculated)	(mg/L)	83
	TS (top)	(mg/L)	1117
	TS (bottom)	(mg/L)	1113
After 100 h Mixing	TSS (top)	(mg/L)	15
At 2 mm/s	TSS (bottom)	(mg/L)	19
	Turbidity	(NTU)	5.37
After 20 h settling	Total Settled Solids	(mg/L)	233.6 (21% of the initial TS)
	Turbidity	(NTU)	6.08
	Color	(CU)	573
	pH		7.3
	TC (measured)	(mg/L)	156
	TIC (measured)	(mg/L)	63.5
	TOC (calculated)	(mg/L)	92.5

Note:
1. TS = Total Solids, TSS = Total Suspended Solids and TOC = Total Organic Carbon.
2. The increase of the turbidity after sedimentation was due to the disturbance of the suspension when the grid mixer was taken out.



a **b** **c**

Figure 4: Flocs formed in the laboratory from a mixture of PME and river water with a volume ratio of 1:1 at 2 mm/s for 100 h). Images of a and b from SEM and C from on-line microphotography system

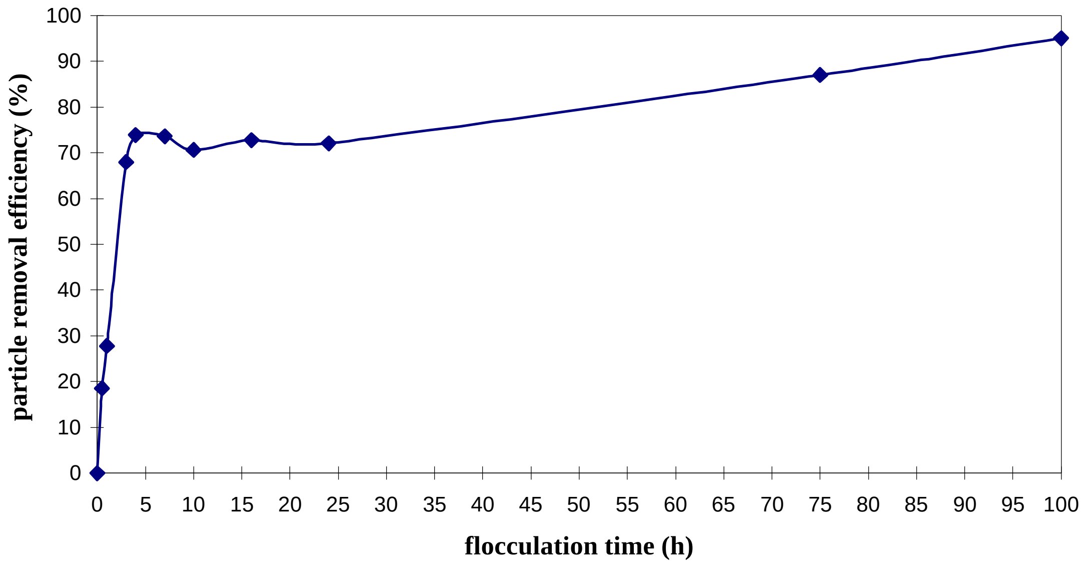


Figure 5: Effect of flocculation time on the particle removal efficiency of mixtures of pulp mill effluent and river water (V_{WHPME} : V_{ARW} = 1:1, sampling date: Aug. 19, 1998, V_{GS} = 2 mm/s)

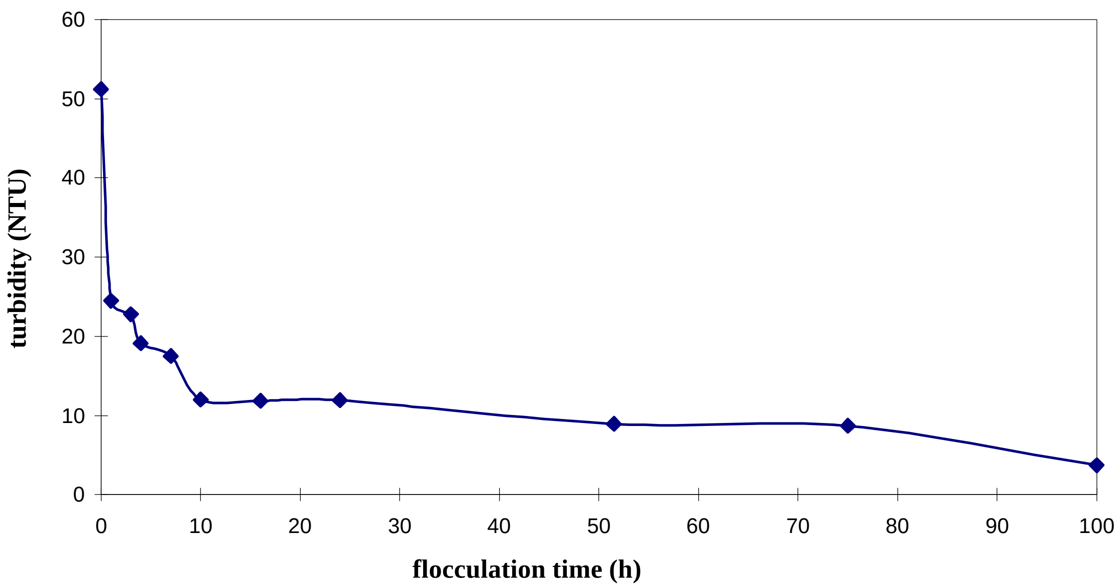


Figure 6: Effect of flocculation time on the turbidity of mixtures of pulp mill effluent and river water (V_{WHPME} : V_{ARW} = 1:1, sampling date: Aug. 19, 1998, V_{GS} = 2 mm/s)

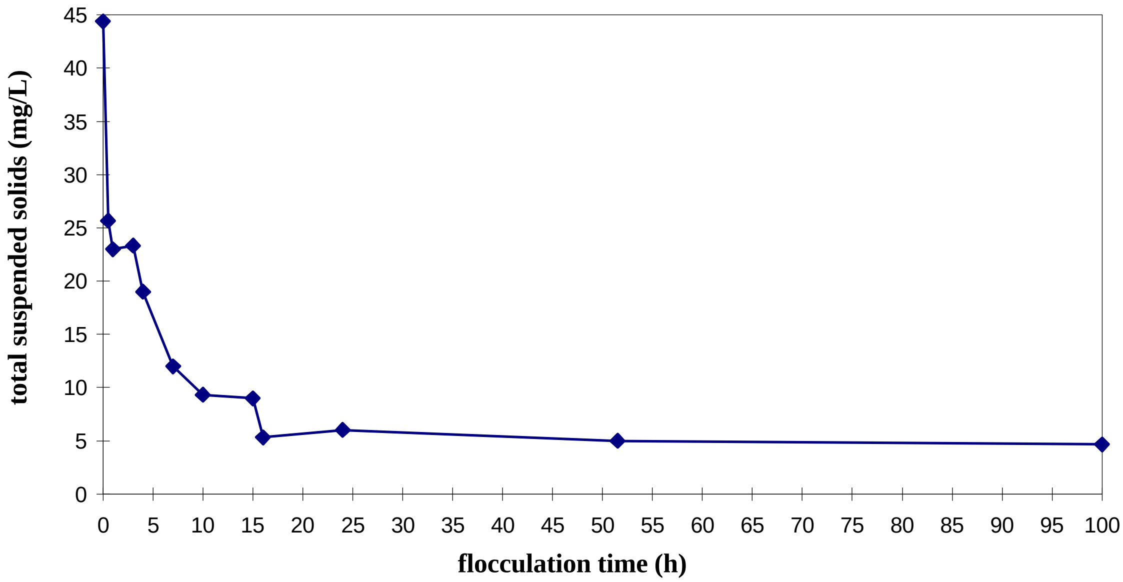
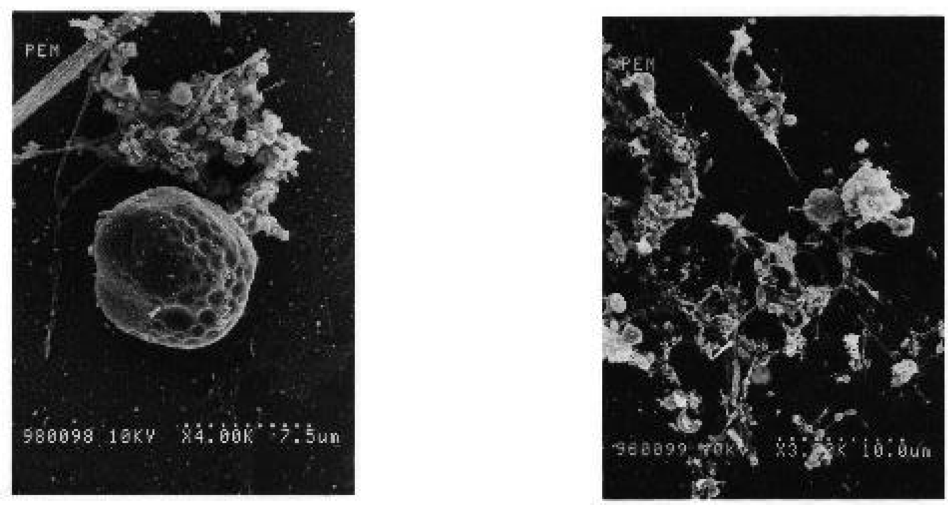


Figure 7: Effect of flocculation time on the total suspended solids of mixtures of pulp mill effluent and river water (V_{WHPME} : V_{ARW} = 1:1, sampling date: Aug. 19, 1998, V_{GS} = 2 mm/s)



a b

Figure 8: Flocs formed from a mixture of PME and river water with a volume ratio of 1:1

Mechanism Study

The mechanism study included characterizations of PME, river water and sediment flocs, and an evaluation of factors affecting the formation and the degree of PMEICF using daily fresh samples. The affecting factors evaluated included pH, alkalinity, temperature, mixing regime, dilution ratio, PME fraction from ultrafiltration, PME-related chemicals and microbial activities. Variation of the characteristics of preserved and fresh samples were evaluated over 11 consecutive days, which included AOX, COD, TOC, BOD, TS, TSS, pH, color, conductivity and absorbance. Two types of sampling methodology were used. T-tests were used to determine which method could actually simulate the situation in rivers. Temporal and spatial variations were evaluated for PMEICF, and molecular weight distributions were measured for PME fractions from ultrafiltration using HPSEC. Long-term BOD tests (more than 100 days) were conducted for samples of PME, river water and a mixture of both with a volume ratio of 1:1; samples were collected before and after flocculation tests. The floc formation process was monitored using an on-line video camera, and the floc morphology was observed using a Scanning Electron Microscope (HITACHI SEM-2500). Turbidity removal efficiency and particle removal efficiency (size $\leq$ 10 μm) were the major parameters used for characterizing flocculation performance. Absorbance, conductivity, TOC, COD, BOD, AOX, color, TS and TSS were also measured. The analytic methods are summarized in Table 2.

Results were all means of triplicates or duplicates. Where appropriate, single-factor ANOVA (analysis of variance) analysis was conducted to test the null hypothesis; there was no difference between the means of the two sets of experiments. If differences were detected, the statistical significance of the data was tested using a two-tailed t-test under equal variance assumptions. All statistical tests were carried out at the 5% significance level.

The experimental results show that all factors affected the formation and degree of PMEICF. A decrease in turbidity and total suspended solids for the mixture of PME and river water was observed. A greater number of flocs formed from the mixture of river water and PME than formed when river water or PME were used alone. Detailed results will be included in the overall report.

Extensive work was done to evaluate the effect of microbial activity on the formation and degree of PMEICF. This included: isolation of bacteria species from PME, river water and the corresponding mixture of both, identification of isolated bacteria using the Biolog™ system, and determination of floc-forming bacteria using both short-term and long-term bioflocculation tests. Negative-microplates yielded positive IDs for *Pseudomonas* spp., *Agrobacterium* spp., *Comamonas* spp., *Flavobacterium* spp., *Acidovorax delafieldii* and *Aquaspirillum metamorphum*. The results also indicated that all isolated bacteria species were Gram negative. Most were oxidase and catalase positive, and most could be classified as non-enteric (there were only two enteric isolates).

Bioflocculation results for the identification of floc-forming bacteria are provided in Table 3.

Table 2: Summarized analytical methods for the parameters

Analytical Parameter	Instrument	Method
PH	Accumet® - pH meter 50 (digital) (Fisher Scientific)	Section 4500-H^+ of Standard Methods (19th Edition, 1995)
Conductivity	Accumet® - pH meter 50 (digital) (Fisher Scientific)	Section 2510 of Standard Methods (19th Edition, 1995)
Color	Pharmacia Biotech Ultrospec® 3000 UV / visible spectrophotometer	The Canadian Pulp and Paper Association (CPPA) standard method H5.P (CPPA, 1974) with minor modifications (Facey, 1999)
Absorba7nce	Pharmacia Biotech Ultrospec® 3000 UV / visible spectrophotometer	(Mao, 1996)
Total Suspended Solids (TSS)		Section 2540 D of Standard Methods (19th Edition, 1995)
Total Solids (TS)		Section 2540 B of Standard Methods (19th Edition, 1995)
Turbidity	Orbeco-Hellige – Digital Direct – Reading Turbidimeter (Orbeco Analytical Systems Inc.)	Section 2130 of Standard Methods (19th Edition, 1995)
Particle Size Analyzer	A light-blockage particle size analyzer (HIAC/ROYCO MODEL 8000A)	P.S.A. Manual
Chemical Oxygen Demand (COD)	COD Reactor (HACH Company)	Section 5220 of Standard Methods (19th Edition, 1995)
Total Organic Carbon (TOC)	2100 Lab TOC Total Organic Carbon Analyzer - Astro Model 2100 (Zellweger Analytics Inc.)	Section 5310 of Standard Methods (19th Edition, 1995)
Adsorbable Organic Halide (AOX)	Euroglas (Delft, Holland) Total Organic Halide Analyzer	Euroglas BV Manual for Determination of AOX, POX and EOX
Biochemical Oxygen Demand (BOD)	Micro Oxymax V5.3 Respirometer (Columbus Instruments International Corporation)	Section 5210 of Standard Methods (19th Edition, 1995) and instrument manual
Alkalinity	Mettler DL25 Titrator (Mettler Instruments)	Section 2320 of Standard Methods (19th Edition, 1995)
Metal Ions	Inductively Coupled Plasma (ICP), Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)	EPA 6010 Analyzed by Maxxam Analytics Inc.
Molecular Weight Distribution	Shimadzu High Performance Liquid Chromatograph (HPLC), and Electrospray Mass Spectrometry (EMS)	*EMS was analyzed by the Department of Chemistry at the University of Alberta
SEM	HITACHI SEM-S2500	Standard SEM Methods analyzed by Department of Dentistry and Pharmaceutical Sciences, Electromicroscope Unit, Surgical and Medical Research Institute.
X-ray (SEM)	The JEOL-JSM-630 1FXV Scanning Electron Microscope (FACEY, 1999)	Secondary SEM Methods, analyzed by Department of Geology
On-line Floc Size Distribution	Microphotography system	

Table 3: Identification of floc forming bacteria

			$\overline{G_f}$ = 2 s^{-1}		$\overline{G_f}$ = 5 s^{-1}										$\overline{G_f}$ = 13 s^{-1}		Short-term Bioflocculation	Long-term Bioflocculation
			TRE	PRE	TRE			PRE			Absorbance				TRE	PRE	(up to 3 h)	(up to 96 h)
			with $CaCl_2$	with $CaCl_2$	with NaCl	with $CaCl_2$	without salt	with NaCl	with $CaCl_2$	Without salt	without salt		with $CaCl_2$		with $CaCl_2$	with $CaCl_2$		
ID	**Source**	**Biolog ID**									280 nm	340 nm	280 nm	340 nm				
HL	floc	no ID, *possibly Lampropedia hylina*	+	+					+	+			-	-	+	+	floc forming	floc forming
SE	1:1 mixture	no ID, likely *Pseudomonas* spp.	-	-					-	-			-	+	-	-	possibly floc forming	possibly floc forming
HJ	floc	*Pseudomonas echinoides*	+	+/-					+	+/-			-	-	+	+/-	floc forming	floc forming
SD	RW	no ID	+	+					+	+			-	-	+	+	floc forming	not floc forming
HK	floc	Aquaspirillum metamorphum	+	+					+	-			+	+	+	-	floc forming	not floc forming
SH	floc	no ID, likely *Pseudomonas* spp.	+	+/-					+	+			+	+	+	+	floc forming	possibly floc forming
HD	1:1 mixture	*Acidovorax delafieldii*			-	-	-	-	-	-	-	-					not floc forming	not floc forming
HB	1:1 mixture	*Achromobacter cholinophagum*			-	-	+	-	-	-	-	-					possibly floc forming	possibly floc forming
HH	RW	*Pseudomonas* spp.			-	-	-	-	+	-	-	-					possibly floc forming	floc forming
SF	floc	no ID, possibly *Aeromonas* spp.			-	-	-	-	-	-	-	-					not floc forming	floc forming
I	RW	*Pasteurella pneumotropica*			-	-	+	-	+	+	-	-					possibly floc forming	possibly floc forming
C	1:1 mixture	no ID, ressembles D in appearance and biochemical tests			-	-	-	-	+	-	-	-					possibly floc forming	not floc forming
HC	1:1 mixture	no ID, likely *Enterobacter* spp.			-	-	+	-	+	+/-	-	-					possibly floc forming	floc forming
A_2	1:1 mixture	no ID, ressembles D in appearance and biochemical tests			-	-	-	-	-	+	+	+					possibly floc forming	possibly floc forming
HG	1:1 mixture	no ID			-	-	+	-	-	-	-	-					possibly floc forming	possibly floc forming
D	1:1 mixture	*Agrobacterium* like-cystic fibrosis			-	-	-	+	+	+	-	-					possibly floc forming	not floc forming
B	floc	*Roseomonas* genomospecies 6			-	-	+	-	-	-	-	-					possibly floc forming	possibly floc forming
HF	1:1 mixture	Aquaspirillum metamorphum			-	-	+	-	+/-	-	-	-					possibly floc forming	possibly floc forming
SJ	1:1 mixture	no ID, likely *Pseudomonas aurantiaca*							+	+/-					+	+	floc forming	possibly floc forming
HI	PME	no ID, possibly *Aquaspirillum putridiconchylium*							+	+/-			-	-	+	+	floc forming	possibly floc forming
HE	1:1 mixture	*Acidovorax delafieldii*							+	+			-	-	+	+	formed good flocs	possibly floc forming

Note: + stands for floc forming bacteria
+/- stands for weak floc forming bacteria
- stands for non-floc forming bacteria

Numerical Modeling

Although an extensive literature review was conducted on models for coagulation and flocculation, numerical modeling will not be included in this research. It is suggested as a following-up study. The modified mathematical models for the transport and fate of sediments and contaminants in rivers should include the effect of river flocculation and floc deposition. The data for particle size and flow distribution in rivers should be collected. Then, mass balance should be conducted in a longitudinal direction from upstream to downstream in the river. The modified models are expected to provide greater accuracy in the prediction of the transport of sediments and contaminants in rivers.

RESULTS AND CONCLUSIONS

The experimental results will be discussed in detail in the overall report. The conclusions for a portion of the results are:

1. PME can induce coagulation and flocculation in receiving waters;
2. total solids from PME and particle removal efficiency for the mixture of PME and river water with a ratio volume of 1:1 increased with an increase in pH from 5 to 10;
3. optimum alkalinity leads to flocculation reaching its maximum degree;
4. $CaCl_2$, KCl, $MgCl_2$ and NaCl were identified using ICP to be the major pulp mill inorganic chemicals, which can enhance river flocculation;
5. fibers separated from PME (with or without acidic or alkaline surface treatment) were all capable of enhancing flocculation;
6. lignin, protein, sucrose, cellulose and starch (which are the major organic polymers in PME) enhanced flocculation, and to even a greater extent when salts, such as $CaCl_2$, KCl, $MgCl_2$ or NaCl were added to samples;
7. when using the Biolog Identification System, the following species were found to be present in the mixture of PME and river water: *Aquaspirillum* spp., *Acidovorax* spp., *Acidovorax* spp., *Pseudomonas* spp, *Enterobacter* spp., *Comamonas* spp., *Brevundimonas* spp., *Flavobacterium* spp., *Achromobacter* spp. *Pastuerella* spp. and *Aeromonas*.;
8. through a series of long-term (up to 4 days) bioflocculation experiments, it was found that *Pseudomonas* spp., *Enterobacter* spp. and *Comamonas testosteroni*. were involved in floc formation; possibly floc forming bacteria determined from long-term bioflocculation tests are listed in Table 3;
9. through a series of short-term (0.5 h to 3 h) bioflocculation experiments, it was found *Acidovorax delafieldii, Pseudomonas echinoides, Aquaspirillum metamorphum, and* some bacterica without IDs *(*likely *Lampropedia hylina, Pseudomonas* spp., *Pseudomonas aurantiaca and*

Aquaspirillum putridiconchylium) are floc-forming bacteria. Among them, *Acidovorax delafieldii* is the best at forming flocs;

10. images from an X-ray Scanning Electron Microscope (SEM) proved that some sticky polymers from bacteria (called extracellular polymeric substances) bridged suspended sediment particles and aided in the formation of flocs;
11. pulp mill chemicals with molecular weight MW < 1,000, MW < 5,000, MW < 10,000 and 5,000 < MW < 10,000 enhanced flocculation; components with MW > 10,000, 1,000 < MW < 5000 and MW < 1,000 + MW > 10,000 slightly enhanced flocculation, but insignificant flocculation occurred with the addition of components with MW < 5,000 + MW > 10,000;
12. dilution factor (PME was diluted using river water) had an impact on flocculation efficiency, the higher the dilution factor, the higher the flocculation efficiency; it was also found that dilution with a ratio volume of 1:1 was representative, this was used throughout the experimentation;

The aforementioned is only a portion of the conclusions drawn from this study. Further conclusions will be based on the results being analyzed.

SIGNIFICANCE OF THE STUDY

The research findings are expected to facilitate modification of sediment and contaminant transport models with the inclusion of the effects of river flocculation and floc deposition. The anticipated results will assist in effective long-term river water management. This will minimize the impact on the aquatic ecosystem and sustain biodiversity and productivity for future generations.

PAPERS AND PRESENTATIONS

Young, S. and Smith, D. W. Pulp mill effluent induced coagulation and flocculation in receiving waters. The Mechanical Wood-Pulps Network and Sustainable Forest Management Network Poster Session, the 86th Annual Meeting of the Pulp and Paper Technical Association of Canada, February, 2000 (poster presentation).

Joyce, S. and Smith, D. W. Biological Factors Affecting Pulp Mill Effluent Induced Coagulation and Flocculation in Receiving Waters. *Ph.D. Thesis*, University of Alberta, 1999.

Young, S. and Smith, D. W. Pulp Mill Effluent Induced Coagulation and Flocculation in Receiving Waters. The Sustainable Forest Management Network Conference Science and Practice: Sustaining the Boreal Forest, Edmonton, Alberta, February 14-17, 1999 (presentation made and paper published in proceedings).

Young, S. and Smith, D. W. Pulp Mill Effluent Induced Coagulation and Flocculation in Receiving Waters. SFM student workshop, Oct. 30, 1998 (presentation).

PAPERS TO BE PUBLISHED

Young, S. and Smith, D. W. Effect of pulp mill chemicals on river flocculation (to be published in IV-th International Conference, 16th National Conference: Water Supply and Water Quality, 11-13 September 2000, Kraków, Poland).

Young, S. and Smith, D. W. Verification of the occurrence of pulp mill effluent induced river flocculation. Part I: laboratory investigation (to be submitted to *Water Research* for publication).

Young, S. and Smith, D. W. Verification of the occurrence of pulp mill effluent induced river flocculation. Part II: field surveys on the Wapiti River near Grande Prairie and on the Athabasca River near Hinton (to be submitted to *Water Research* for publication).

Young, S. and Smith, D. W. Physical factors affecting pulp mill effluent induced coagulation and flocculation in receiving waters (to be submitted to *Water Research* for publication).

Young, S. and Smith, D. W. Chemical factors affecting pulp mill effluent induced coagulation and flocculation in receiving waters (to be submitted to *Water Research* for publication).

Young, S. and Smith, D. W. Biological factors affecting pulp mill effluent induced coagulation and flocculation in receiving waters (to be submitted to *Water Research* for publication).

Young, S. and Smith, D. W. Effect of the molecular size distributions of pulp mill chemicals on river flocculation.

Young, S. and Smith, D. W. Postulation of the mechanisms of pulp mill effluent induced coagulation and flocculation in receiving waters.

Young, S. and Smith, D. W. Evaluation of the effect of sample age on the degree of pulp mill effluent induced coagulation and flocculation in receiving waters.

Young, S. and Smith, D. W. Measurement of molecular weight distributions of ultrafiltration components from pulp mill effluent by high-performance size exclusion chromatography (HPSEC).

Young, S. and Smith, D. W. On-line measurement of floc size distributions by the video microphotography system.