Mitigation of Fisheries Impacts From the Use and Disposal of Wood Residue in British Columbia and the Yukon

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1999

MITIGATION OF FISHERIES IMPACTS FROM THE USE AND DISPOSAL OF WOOD RESIDUE IN BRITISH COLUMBIA AND THE YUKON

by

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Samis, S.C., S.D. Liu, B.G. Wernick and M.D. Nassichuk. 1999. Mitigation of fisheries impacts from the use and disposal of wood residue in British Columbia and the Yukon. 2296: viii + 91 p.

This document, a companion to *Guidelines on Storage, Use and Disposal of Wood Residue for the Protection of Fish and Fish Habitat in British Columbia* (Liu *et al*. 1996), examines in detail the potential impacts on fish and fish habitat, including water quality, arising from operations involving the use, storage or disposal of wood residue in British Columbia and the Yukon. The chemical components of wood residue, mechanisms of degradation and leachate generation and strategies useful in the design of wood-residue storage and disposal sites are presented. Application of this information is intended to promote a consistent approach toward environmentally-sound use and disposal of wood residue so that detrimental effects on fish and fish habitat are prevented. Alternative technology is encouraged to divert wood residue from landfills to secondary uses such as energy generation or the manufacture of value-added products.

RÉSUMÉ

Samis, S.C., S.D. Liu, B.G. Wernick and M.D. Nassichuk. 1999. Mitigation of fisheries impacts from the use and disposal of wood residue in British Columbia and the Yukon. 2296: viii + 91 p.

Le présent document, qui constitue un complément aux *Guidelines on Storage, Use and Disposal of Wood Residue for the Protection of Fish and Fish Habitat in British Columbia* (Liu *et al*. 1996), examine en détails les impacts potentiels sur le poisson et son habitat, notamment sur la qualité de l'eau, des opérations relatives à l’utilisation, à l’entreposage et à l’élimination des résidus ligneux en Colombie-Britannique et au Yukon. On y traite des composantes chimiques des résidus ligneux, des mécanismes de dégradation et de lixiviation ainsi que des stratégies utiles pour la conception de sites d’entreposage et d’élimination des résidus ligneux. Ces informations visent à promouvoir une approche cohérente en vue d’une utilisation et d’une élimination des résidus ligneux respectueuses de l’environnement afin de protéger le poisson et son habitat. On encourage le recours à des technologies permettant des utilisations secondaires des résidus ligneux - qui autrement seraient éliminés dans des décharges - comme la production d’électricité ou la fabrication de produits à valeur ajoutée,

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1.0 INTRODUCTION

1.1 PURPOSE OF THE DOCUMENT

This document is a companion to the *Guidelines on Storage, Use and Disposal of Wood Residue for the Protection of Fish and Fish Habitat in British Columbia* (Liu *et al.* 1996). The *Guidelines* document contains a description of the regulatory review process pertaining to wood-residue disposal under the province of British Columbia's *Waste Management Act* and abbreviated sections on wood residue management strategies and the design of wood-residue landfills. This document provides more detailed technical information to proponents and regulators involved in the transportation, storage, use and disposal of wood residue in British Columbia and the Yukon.

The primary focus is the protection of fish and fish habitat, including water quality. Application of the information in this report is intended to promote a consistent approach toward environmentally-sound use and disposal of wood residue so that detrimental effects on fish and fish habitat are prevented. The report is also intended to be a reference manual for fish habitat biologists who may not be experts on wood degradation products, their respective toxicities and strategies for impact mitigation. Students, litigators, policy makers, regulators and project proponents may also find this information useful.

1.2 USER'S GUIDE

The document addresses four general categories of information:

1. Chapter 2 includes a description of the origin of wood residue in British Columbia, as well as an inventory of wood residue production. Currently, large volumes of wood residue are used in the generation of energy or the manufacture of secondary or value-added goods. However, significant amounts are still landfilled or burned without energy recovery. The development and adoption of alternative technologies will help reduce the quantity of wood residue that is wasted, which in turn will help minimize the potential for environmental degradation.
2. Chapters 3 through 6 describe the characteristics of wood residue, as well as the mechanisms of decomposition and leachate generation. The type and amount of the different chemical constituents in wood depend on a number of factors, including the tree species, tree part, age and the geographical area in which the tree grows. Chemical, biological and thermal processes (of which biological ones play the primary role) degrade wood-residue constituents and result in the by-products found in leachate.
3. The storage, use or disposal of wood residue near or in the aquatic environment can have serious consequences for fish and fish habitat. Chapter 7 provides a summary of the physical and toxicological effects of wood residue and leachate. The deposition of wood residue into or adjacent to the aquatic environment can result in the physical alteration, disruption or destruction of fish habitat (including spawning grounds and nursery, rearing and food supply areas). The leachate generated from wood residue can be acutely lethal to fish or to invertebrates comprising their food supply. Chronic or sub-acute toxicity causes behavioural, physiological or reproductive changes, all of which may ultimately be detrimental to the survival of the individual organism or the population.

4. In the event that wood residue must be stored or landfilled, different technologies may be employed to prevent detrimental effects on fish and fish habitat. Chapter 8 reviews several strategies, including: site selection; waste segregation or mixing; and leachate prevention, collection and treatment. Implementation of such strategies and the government review process outlined in *Guidelines on Storage, Use and Disposal of Wood Residue for the Protection of Fish and Fish Habitat in British Columbia* (Liu *et al.* 1996) will help ensure the protection of fish and fish habitat from wood residue impacts.

Appendix 1 provides an overview of the climatic conditions of British Columbia, as well as the salmonid life cycle and the importance of fish habitat. A glossary is included in Appendix 2.

2.0 ORIGIN, INVENTORY, DISPOSAL AND USES OF WOOD RESIDUE IN B.C.

2.1 ORIGIN OF WOOD RESIDUE GENERATED IN B.C.

Most wood residue comes from softwood trees, whereas hardwood volumes are small but increasing. Table 2.1 shows the most commonly harvested tree species in B.C. Lodgepole pine and white spruce are primarily harvested in the interior of B.C., while 78% of all the cedar harvested in B.C. in 1995 was from the south coast (COFI 1996). Most of the wood residue generated in the interior, therefore, is from pine and spruce and from western red cedar on the south coast.

Wood residue can be categorized based on its source of generation:

- Wood residue from **land clearing and timber harvesting** operations can include broken logs, decadent timber, foliage, stumps and tree limbs. In timber harvesting, only the bole or log is extracted from the forest while the crown (consisting of foliage and branches) and the stumps are considered to be wood waste. Between 6 and 9% of the dry weight of the bole consists of the foliage and between 10 to 15% is bark (McWilliams 1992).
- **Dredged wood residue** spoils removed from the bottom of a water body consist mainly of bark. Watercourses may also contain **floating wood debris**. In 1977, the Debris Management Board (formerly the Debris Control Board) established a permanent debris trap between Hope and Agassiz on the lower Fraser River to capture waterborne wood debris during freshet. The trap removes up to 90,000 m^3 of wood debris from the river, 80% of which is from natural sources. Downstream from the Agassiz trap, 20,000-30,000 $m^3 \cdot yr^{-1}$ of debris is collected by various Harbour Commissions, the forest industry and salvage operations. 80-90% of the debris collected below Agassiz is from forestry-related activities (Fraser Basin Council 1999).

Table 2.1 Most commonly harvested softwoods and hardwoods in B.C., in descending order of volume (1995).

Softwoods (conifers or evergreens)
lodgepole pine (*Pinus contorta*)
spruce (*Picea* spp.)
hemlock (*Tsuga* spp.)
true fir (*Abies* spp.)
Douglas-fir (*Pseudotsuga menziesii*)
western red cedar (*Thuja plicata*)
yellow cypress (*Chamaecyparis nootkatensis*)
western larch (*Larix occidentalis*)
western white pine (*Pinus monticola*)
ponderosa pine (*Pinus ponderosa*)

Hardwoods (deciduous trees)
trembling aspen (*Populus tremuloides*)
black cottonwood (*Populus trichocarpa*)
red alder (*Alnus rubra*)

Source: COFI (1996).

- Wood residue from **dryland sorting** operations can include bark and cull logs that are often mixed with rocks and earth. In a log yard or dryland sorting operation, each 100 m^3 of logs scaled will generate between 3 and 4 m^3 of debris for paved yard surfaces and between 5 and 6 m^3 for unpaved yard surfaces (McWilliams 1992).
- Wood residue from **wood processing** facilities can include chips, hogfuel, sawdust, shavings, bark, broken logs, reject wood and ends, edgings, knots, lathe cuttings, lily pads, panel trims, peeler cores, reject strips, sander dust, shake blocks, slabs, wood chunks and other wood fragments. Sawmills account for 80% of total hogfuel production in B.C. (Appleby 1988; Appleby 1989). Excluding chips, 9 million

bone-dry tonnes of mill residue were generated in the Province during 1989 (Stewart & Ewing Associates Ltd. *et al.* 1990); slightly less, an estimated 8.8 million bone-dry tonnes, was generated in 1994 (Holm 1995).

- **Demolition debris** includes broken lumber, pallets, particle board, pilings, plywood, poles, posts and ties.
- **Hogfuel** is a mixture of wood fibre, sawdust, bark and fragments of wood up to 10 cm in length produced when large pieces of wood residue not suitable for making into wood chips are "hogged" or cut in a mechanical shredder.
- Charred clinkers and **wood ash** are produced from the burning of wood residue.

Table 2.2 Types and amounts of mill residues generated in B.C. in 1989, excluding wood chips.

Type of Mill Residue	Quantity (MBDt*)
bark	4.60
sawdust	2.96
shavings	1.12
slabs/edging/trim ends	0.21
logyard debris	0.15
Total	**9.04**

*MBDt - millions of bone dry tonnes. "Bone" or "oven dry" refers to the weight of dried wood residue whereas "green" weight is the tonnage of undried wood residue.

Source: Stewart & Ewing Associates Ltd. *et al.* (1990).

In 1989, B.C. Ministry of Forests, in co-operation with the Council of Forest Industries (COFI), other forest industry associations, research organizations and private companies, established the Wood Residue Task Force. Table 2.2 summarizes the Task Force's findings on the types and amounts of mill residues that were generated in B.C. in 1989, excluding wood chips (Stewart & Ewing Associates Ltd. *et al.* 1990).

2.2 INVENTORY OF WOOD RESIDUE IN B.C.

The volume of forest and demolition debris generated annually in B.C. has not been estimated, so a total inventory of wood residue produced in the province cannot be given. Despite the current use of wood residue in conversion to energy or the production of secondary goods, there is a significant surplus of wood residue, much of which is burned without energy recovery or is landfilled.

2.2.1 Inventory of Surplus Wood Residue

There is an over-supply of wood residue in most areas of B.C. (Table 2.3). In the Vancouver Forest Management Region there was an estimated surplus of 0.447 million bone dry tonnes (MBDt) of mill residue for 1994 (Holm 1995). Excluding chips, an estimated 36% of mill-derived wood residue for the entire province was burned as refuse or deposited in landfills in 1994 (Holm 1995). Although most chips are utilized, surpluses can result from periodic market shifts or during labour disputes.

Approximately 98% of the surplus hogfuel produced on the south coast in the late 1980s was derived from softwoods, more than one-half of which consisted of western red cedar (Appleby 1988).

Table 2.3 Estimated surplus volumes of mill residue produced in 1994 (excluding chips) in the six provincial forest management regions of British Columbia.

Forest Management Region	Volume (MBDt) Produced	Volume (MBDt) Surplus	% Surplus
Vancouver	3.300	0.447	14
Prince George	2.015	1.391	69
Nelson	0.696	0.299	43
Cariboo	1.008	0.107	11
Kamloops	1.074	0.612	57
Prince Rupert	0.710	0.399	56
Total	**8.803**	**3.255**	**37 (Avg.)**

Source: Holm (1995).

2.3 DISPOSAL OF WOOD RESIDUE IN B.C.

2.3.1 Disposal of Wood Debris from Forestry Operations

Many dryland sorting and log yard areas are unpaved and the wood debris removed from such areas is usually mixed with a large percentage of soil and rock. As a result, this debris is unsuitable for burning and is currently dumped in landfills. A vacuum-drum separator is available in B.C. to demonstrate removal of rocks and other heavy objects from hogfuel and wood chips in a full-scale production situation (Bundalli 1991). Several log yards in the U.S. Pacific Northwest are processing log yard debris into hogfuel and soil amendments using innovative technology (McWilliams 1992). Many new log yards and dryland sorting sites are being paved to reduce the maintenance of ground surfaces and to decrease the volume of rocks and soil in the sorting debris.

Although slash burning is currently an accepted forest management practice, air pollution and other environmental concerns may lead to its curtailment. Dryland sorting debris suitable for incineration is commonly burned in the open with few environmental controls (i.e. leachate control; containment of debris, smoke and flyash) at many isolated locations. Log sorting debris is often stockpiled and burned near the high water mark of foreshore areas, resulting in the deposit of debris, leachate and ash into aquatic habitat. Pit incineration (i.e. with both underfire air and overfire air curtains) is an old technology for burning wood residue that reduces air pollution, but it is seldom practised in B.C.

A large proportion of the floating wood debris in the Fraser River originating from forestry operations is re-used or recycled (Fraser Basin Council 1999). The Coast Forest and Lumber Association has developed best management practices for forestry operations in the Fraser River basin. The BMPs address source control for a variety of activities such as log harvesting, sorting operations and log transportation (Coast Forest Lumber Association 1997).

2.3.2 Disposal of Surplus Wood Residue

Much of the surplus wood residue is burned as refuse in the open or in beehive burners, resulting in air pollution problems because of smoke and flyash. Primary breakdown facilities (such as sawmills) are permitted to landfill almost 900,000 green tonnes of wood residue per year. However, only an estimated 6% (or ~54,000 green tonnes) is landfilled while much of the remainder is burned due to the lower cost of incineration and the on-going environmental obligations associated with landfill sites (G.E. Bridges and Associates Inc. 1997). Mills in the Vancouver Forest Management Region account for almost 50% of the provincial surplus of wood residue deposited in landfills, whereas operators of mills in the Southern Interior landfill about 30% (G.E. Bridges and Associates Inc. 1997). The remaining four provincial forestry regions landfill very little wood residue, primarily because open burning remains an option. Although wood ash from the forest products industry can be used as a filler in aggregate materials, almost all wood ash (e.g. flyash and bottom ash) is currently deposited in landfills or is discharged with pulp mill process effluent.

The Wood Residue Burner and Incinerator Regulation of the *Waste Management Act* took effect in January 1996 and has resulted in the elimination of 42 beehive burners and unmodified silo burners to date. A further 34 were scheduled to be phased out by December 1997 and the remaining 4 by the end of 1998. The phase-out of burners in more remote locations has been extended to as late as 2005. The regulation also sets a province-wide standard for particulate emissions. The provincial government is encouraging operators to seek value-added opportunities for using wood residue in order to avoid the incineration of this resource. Airborne particulates are a concern in many communities around B.C. and in some locations burner operators are required by permit to meet more stringent emission levels than the provincial standard. Residential wood smoke is also a concern in many northern communities during the winter months and restrictions may be imposed on such operations in the future.

B.C. produced an estimated 2.4 million metric tonnes of municipal solid waste in 1989. The provincial government announced an initiative to reduce this volume by 50% by the year 2000 (Kinrade and Flegel 1990). Although almost twice as much surplus mill residue (i.e. not including forest debris and demolition wood residue) is produced annually compared to municipal solid waste, very few initiatives are in place to reduce the wood-residue surplus.

2.4 USES OF WOOD RESIDUE IN B.C.

Wood residue uses include the production of pulp and paper, energy generation and landscaping (Table 2.4). Mill wood residues in B.C. are used mainly for domestic pulp and paper production and steam/power generation in pulping (Appleby 1988; Appleby 1989). In addition, chips are exported to Japan and the United States in large quantities; in 1995, 340,000 tonnes were exported to the U.S. and 291,000 tonnes to Japan (COFI 1996). Prior to being shipped, chips are commonly stored in the open adjacent to foreshore areas. Some wood residue is used in the production of “value-added” products such as building materials and fire-logs.

The improper disposal of surplus wood residue and its over-use without appropriate controls have negatively affected the environment in B.C. Innovative means must be found to utilize surplus wood residue and appropriate disposal technology must be practised to prevent damage to fish and fish habitat, including water quality. In 1991, the Wood Residue Task Force published a report, *Toward improved utilization of forest industry mill residues in British Columbia* (Simons Strategic Services *et al.* 1991), identifying innovative technology under development or recently proven for the use of mill residues. Conventional uses as well as other research, pilot demonstrations and commercialization of processes using wood residue are discussed below.

2.4.1 Use of Wood Residue as Raw Material for Pulp Production

The economic viability of some sawmills depends on the sale of chips. Four pulp mills in B.C. (Elk Falls, Crofton, Powell River and Weyerhaeuser-Kamloops) have digesters that can use sawdust for pulp production. About 2.5 million green tonnes of chips (consisting of interior spruce, pine, fir and Douglas-fir) are shipped to Japan each year (Chew 1990). A small percentage of mill residue generated in B.C. is exported to Washington state pulp mills (Appleby 1990). Some wood species are not used extensively by pulp mills, however. For example, western red cedar wood chips are under-utilized by the pulp and paper industry because cedar wood extractive (Section 3.1.3.2) content necessitates use of comparatively large amounts of pulping chemicals. Cedar has, rather, been directed to other uses such as in the agricultural sector.

Table 2.4 Volume of mill residues used in B.C., in 1989 (excluding chips).

Utilization	Volume (MBDt)
energy generation	3.12
pulp furnish	0.76
landscaping and agricultural	0.24
board furnish	0.16
total utilization	**4.28**

Source: Stewart & Ewing Associates Ltd. *et al.* (1990).

The potential for the pulp industry to use chips generated from landclearing debris has been explored in a recent report (Pottinger Gaherty Environmental Consultants Ltd. 1997). Typically, demolition and landclearing debris has not been used as a source of wood for pulping because it is considered dirty. However, with the development of new sorting and chipping technologies, the use of landclearing debris in the pulp industry may become viable in the near future.

2.4.2 Use of Wood Residue in Manufacturing "Value-added" Products

Mill residues are also used in the manufacture of secondary or "value-added" products, including: particle board, medium-density fibreboard (MDF) and oriented-strand board (OSB) (B.C. MELP 1995a); roofing felt (Cheremisinoff *et al.* 1976); fire-logs (Appleby 1988); and wood-plastic composites that can be used in a variety of ways (Lavendal 1996). Many facilities producing "value-added" goods use self-generated waste to fulfil internal energy needs.

In 1991, a Vancouver-based company opened a facility in New Westminster to use wood residue to manufacture wood-fibre composite mats molded into a variety of shapes suitable for automotive and furniture applications. Other products include a "lawn-carpet" made from wood fibre and textile, sown with lawn seed and a similar product that can be used like a geotextile to prevent erosion and distribute seeds for revegetation (B.C. MELP 1995a). The company has also proposed to build a new facility in Williams Lake to manufacture fibreboard from wood residue.

The Institute of Wood Research at Michigan Technological University is developing a technology to produce molded-strand lumber products from wood residue that could eventually replace some metal products as a support material (Tunick 1992). The Alberta Research Council is currently developing the technology for producing the Canadian version called "wave board." In British Columbia, MacMillan Bloedel has created a similar product called "Parallam."

While the market for goods produced from wood-plastic composites is increasing, the amount of wood residue used in such products is modest compared to the surplus available. A larger amount of this surplus could be used in wood-plastic composite products that take the place of solid wood, much as particle board does (Glenn 1996). For example, many home builders find window and door frames made from the composites attractive because they are essentially waterproof, resulting in less warping and decay.

2.4.3 Incineration of Wood Residue and Energy Recovery

Although greenhouse gases are produced, burning wood residue may be a viable option if it can efficiently replace other fuels and be shown to reduce other environmental impacts (B.C. Round Table 1992). Burning wood residue as a fuel is generally encouraged by governments, provided appropriate air pollution control works are installed and residues of combustion are properly disposed of or recycled. For example, a federal-provincial committee was formed in 1989 to establish emissions guidelines for industrial boilers using various fuels, including wood residue. The result was the CCME National Emission Guideline for Commercial/Industrial Boilers and Heaters.

The energy efficiency of burning wood residue is directly related to the moisture content of the wood residue. This is one reason why mechanical debarking is favoured over hydraulic debarking. Research into economical and efficient dewatering of hogfuel is progressing. The potential for energy generation from wood residue is reduced for aged wood residue and, as a result, some mills commonly landfill such wood residue, as well as surplus, fresh wood residue. Ash and clinkers that result from the burning of wood residue are mainly deposited in landfills. A limited amount of wood ash was at one time discharged into the Greater Vancouver Regional

District sanitary sewer system from a sawmill in Port Moody. Alternatively, ash can be used in the production of fertilizers.

Large forest products operations commonly burn wood residue in industrial boilers or other energy recovery systems to supplement internal energy requirements (MacKay *et al.* 1979). Cogeneration is the term applied to the use of a fuel for simultaneous production of electrical/mechanical power and usable thermal energy (e.g. steam/hot air). Cogeneration projects require approval from the B.C. Ministry of Energy and Mines (formerly the Ministry of Energy, Mines and Petroleum Resources) through the Energy Project Certification process. New cogeneration facilities are located at Williams Lake and Port Mellon where wood residue is burned to produce energy for mill operations; excess electricity is to be sold to B.C. Hydro and Power Authority. The Port Mellon cogeneration project uses about 4,000 $m^3 \cdot d^{-1}$ of hogfuel (Strang 1998), a large proportion of the surplus wood residue from the south coast. A natural gas/wood residue cogeneration facility is also being installed in Castlegar.

Small (less than 5 MW) independent power producers (IPP) have always been able to sell their excess power to B.C. Hydro. Policy changes within B.C. Hydro in 1987/1988 allowed larger IPP to sell power to B.C. Hydro as well. The Provincial government established a series of environmental benefits programs around the same time as subsidized projects involving power generation from the burning of wood residue. However, in 1992 the Ministry of Energy and Mines announced a new policy requiring all IPP projects (i.e. gas, water, coal, thermal and wood residue) to be evaluated for acceptance on an equal basis. Environmental benefits are still included in this new evaluation process but subsidies or premiums are no longer available.

Due to the high capital cost, energy recovery systems (including the necessary air pollution control equipment) are generally only feasible at large mills. At smaller mills, the combination of increasingly high handling and transportation costs may curtail the utilization of wood residue for small scale energy generation and lead to an increase in the amount of wood residue being burned as refuse or deposited in landfills.

The European Community (EC) ban on the importation of green (non kiln-dried) lumber went into effect in June 1993. This ban has led to interest by some sawmills that ship lumber to the EC countries to explore wood residue as a source of energy for new kiln-drying facilities. Another incentive to sawmills using wood residue to fire drying kilns was instituted in 1998. Under the new two-year Greenhouse Gas Emissions Reduction Trading Pilot (GERT), the amount of wood burned for heat recovery is eligible for a credit. This credit can be offered for sale to a company whose options for controlling greenhouse gas emissions are much higher.

2.4.4 Fuel and Energy Production from Wood Residue

Many technical papers have been written on conversion of biomass into fuel (and other potential energy sources) under the Energy from the Forest (ENFOR) research and development program administered by the former Canadian Forestry Service. The ENFOR program is directed at securing knowledge and technical expertise that will expand the contribution of forest biomass to Canada's energy production in the medium to long-term. In 1983, the responsibility of the ENFOR program was transferred to the former federal Department of Energy, Mines and Resources (now Natural Resources Canada or NRCan) and integrated with related research, development and demonstration initiatives on biomass energy conversion as the Bioenergy Development Program. Since the early 1980s, NRCan has been promoting the development of alternative transportation fuels through programs such as initiatives under the former Green Plan and more recently, the National Biomass Ethanol Program.

Research world-wide into the conversion of biomass (including wood residue) into fuel and its additives (including oil, ethanol, octane enhancer and combustible gas) and energy has been on-going for decades. Many utilities in North America are currently burning wood residue and other biomass as a source of energy. A Canadian example is an Ontario utility operating three wood-residue-burning power plants at Chapleau, Cochrane and Kirkland Lake.

Ensyn Technologies of Ottawa uses Rapid Thermal Processing (RTC) to super heat wood residue, driving off a “soup” of chemicals; the “soup” is then rapidly cooled to retain it in a liquid phase. The resulting mix is 60-80% liquid or “bio-oil,” that can be used as a fuel. Twelve percent is a mixture of gases used to fuel the process and 13-28% is a high quality charcoal, that can also be used as a fuel, or it can be “activated” for use in water filtration (Anonymous 1994c). A Vancouver company producing bio-oil mixes the liquefied organic product with lime to form “Bio-Lime,” an additive used in coal-fired power plants and municipal waste incinerators to reduce emissions of nitrogen oxides and sulphur oxides (PGL Organix 1996).

Agriculture and Agri-Food Canada announced the National Biomass Ethanol Program in 1994. The purpose of the program is to “encourage firms to invest in the Canadian ethanol industry and encourage the production and use of renewable fuels where it is environmentally-sound and economically viable” (Agriculture and Agri-Food Canada 1994). The program will provide a re-payable, interest-bearing line of credit guaranteed by the federal government to applicants developing ethanol-from-biomass production facilities. The applicants must demonstrate that the removal of the federal excise tax exemption on fuel ethanol will impair their ability to meet scheduled long-term debt servicing commitments. Successful applicants may draw upon the line of credit between October 1999 and December 2005.

Ethanol is often used as an additive in gasoline to help engines work more efficiently and burn more cleanly. In Canada, most ethanol is produced from wheat. Because the inputs of fossil fuel energy are high in the production of this agricultural crop, the net CO_2 output from the use of wheat-derived ethanol can exceed that of gasoline (B.C. MELP 1995b). Alternatively, producing ethanol from “waste” materials such as wood residue and burning it as a fuel, will significantly reduce CO_2 emissions below levels generated by burning gasoline or diesel fuel. Research is on-going at the University of British Columbia (UBC) on ethanol production from wood and agricultural residues; a cold cycle Paszner process is being used to convert cellulose to usable sugar solutions (B.C. MELP 1995a).

Results of pilot studies of a modified simultaneous saccharification and fermentation (SSF) process that uses enzymes to convert cellulose into glucose for fermentation into ethanol, indicate that the yield of alcohol can be increased by 10 to 20% over conventional SSF technology. Sponsors are currently being sought to share the cost of a 51 to 102 $t \cdot d^{-1}$ demonstration plant through a U.S. Department of Energy co-operative research and development agreement.

A Vancouver company announced plans to build a facility to produce charcoal briquettes, fuel oils and activated carbon from wood residue (B.C. MELP 1995a). In co-operation with UBC, another private company is developing portable machines that will also convert wood residue into charcoal briquettes for use in wood stoves (PGL Organix Ltd. 1996).

Several B.C.-based companies are producing wood pellets from sawmill residues (B.C. MELP 1995a). The combustion of these pellets results in the production of a gas that can be used to fuel engines and generators and produce electricity (Parfitt 1990). A by-product of this process, activated carbon, is used by industry for the removal of organic contaminants from liquid and vapour streams.

2.4.5 Chemical Production from Wood Residue

Research into the production of other useful by-products from wood residue has also been on-going for decades. The potential for using wood residue, especially bark, as a chemical resource has been previously explored through various committees and organizations (MacKay *et al.* 1979; Venkatesh 1979; Maloney 1978; Mater and Mater 1976; Mater 1974; Van Vliet 1971; Mater *et al.* 1969). A 30-year study by a forest products company in the U.S. on the utilization of western hemlock bark was terminated in the late 1970's. Many useful products have been identified through this work but it has not been feasible to develop them commercially to date.

Tall oil can be produced from the terpene fraction of wood residue. A company in Prince George has been producing crude tall oil from pulp mill-derived black liquor soap skimmings since the 1960s. The oil was sold as a fuel to pulp mills until 1974; later, it was exported for refinement into other products. This company was recently expanded to produce depitched tall oil. A news release from UBC in December 1991 indicated that it was continuing research on finding new uses for tall oil, including preparation of insecticides.

The Department of Wood Science at the Virginia Technical Institute studied the use of lignin to make high-density insulating foams in 1988. Lignin has been tested for use as a phenol replacement in the adhesive market. In 1991, the New York State Energy Research and Development Authority awarded a research contract to a Kansas company to develop a facility to convert wood residue into chemicals used to produce tires, ink toner and industrial adhesives - products that are normally derived from petroleum. Under a contract with the former federal Department of Energy, Mines and Resources, a Vancouver company was identifying renewable sources of chemical feedstock, including sources such as wood residue (Longley 1991).

Extracts from cedar wood residue can also be used in the manufacture of pesticides, pharmaceutical products and deodorizers. A company in Washington state is currently marketing a deodorizer and pet shampoo made from western red cedar in B.C. Until 1989, a sawmill in B.C. was using cedar extractive for sapstain control. At present, western yew (*Taxus brevifolia*) bark is being exported from B.C. to the U.S. for the production of taxol, a drug used in the treatment of cancer.

2.4.6 Use of Wood Residue in Agriculture

Nursery operators use wood residue as a plant mulch and ground cover. Bark is beneficial as a mulch because it has inherent fungicidal properties that protect plant root systems from soil-borne disease, however, bark also has phytotoxic properties (i.e. toxic to plants). Catechin, a condensed tannin found in wood residue, is thought to be a germination and growth inhibitor in plants. Western red cedar wood residue is used preferentially in agriculture because of its slow rate of decomposition. However, research suggests that cedar extractives may be damaging to plant root systems; thus cedar wood residue is generally not placed near roots (Hon and Shiraishi 1991). Cedar bark is often composted for a month or more to reduce its phytotoxic effects (Hon and Shiraishi 1991).

Wood residue is a carbon source and “bulking” agent in composting operations. Shredded wood residue is used as a soil conditioner and amendment in composting, mulching and potting mixtures. Several businesses in B.C. are currently marketing composted sawmill residue and yard debris (B.C. MELP 1995a). Wood residue serves to retain moisture, retard erosion, inhibit weeds and hold warmth in the soil. However, wood residue has little fertilizer value and it will draw nitrogen from the soil as it decomposes. Nitrogen addition to a soil/wood residue mixture will promote microbial decomposition of the wood residue. A three-year collaborative project between the former Agriculture Canada and the Quebec Ministry of Agriculture, Fisheries and Food to develop compost from wood residue led to production of a soil amendment that was tested at a Quebec potato farm in 1991. Most research on composting is directed at the mechanics of composting (i.e. surveys of collection and composting operations, economic analyses, microbiology and composting methodologies), whereas little attention is paid to the environmental fate and effects of potentially harmful constituents of the composted materials (Kovacic *et al.* 1992).

Wood residue is used as an organic amendment for mineral soils at cranberry and blueberry farms because these crops are acid tolerant and have a high requirement for organic nutrients. There is no nutrient advantage in using wood residue at cranberry farms located in peat bogs since peat is already an organic nutrient source. However, large amounts of wood residue, mostly cedar, are deposited in peat bogs as road material and for dyke construction. Blueberry crops are generally grown in mineral soils and wood residue is added as an organic amendment. In established blueberry fields, mostly hemlock and/or fir sawdust is placed directly around each plant. Wood residue is not used at raspberry farms because this crop is not considered adequately acid-tolerant and its organic nutrient requirements are not high.

Shavings are used as a bedding material for animals and as an absorbent on farms. Cedar hogfuel is used in stables and as a base for riding rings. A Wood Residue Symposium was held in 1976 for the exchange of information on the utilization of wood residue as livestock feed (B.C. Ministry of Agriculture 1976). The consensus was that wood residue would have to be processed into a more digestible form for consumption by animals. Steam alters hardwoods so that much of the carbohydrates may be digested by ruminants (Anonymous 1994a). However, before implementing wood residue more fully as a feed supplement, further studies on the effects of the various chemical constituents of wood resins and wood extractives would be needed. Ponderosa pine foliage was reported to cause abortion in cattle (B.C. Ministry of Agriculture 1976), perhaps from the resin acids in the needles (Kubik and Jackson 1981). Wood residue is apparently not being used as a livestock feed in B.C. at the present time.

A $221,000 loan from Western Diversification was used in the development of a facility near Courtenay, B.C., for the production of soil-conditioning compost from fish-processing wastes and wood residue. One company in B.C. markets a mixture of aerobic, facultative anaerobic and thermophilic micro-organisms that secrete pectinases, cellulase and ligninase that can be used in composting organic wastes such as wood residue (Kam Engineering Ltd. 1991).

The volume of wood residue used on farms, nurseries and at equestrian facilities is of concern given that additional wood residue is regularly layered on top of older deposits. Often more wood residue is deposited than is necessary for agricultural or horticultural purposes and large quantities of wood residue are being used as fill at such sites. As a result, many existing agricultural uses of wood residue are causing pollution problems in places like the lower mainland of B.C. (Locken 1999).

2.4.7 Other Uses of Wood Residue

2.4.7.1 Treatment of Domestic Sewage

A pilot project to treat septic tank effluent with wood residue in Texas was implemented in 1993. Septic tank effluent was filtered through a layer of wood chips, reducing the total suspended solids (TSS) in the filtrate by 83 to 99% and the BOD to 360 $mg \cdot L^{-1}$. With this minimal treatment, the filtrate may be acceptable for some uses; in the event that a beneficial use is not available, the filtration process may serve as pre-treatment prior to treatment of the filtrate in a sewage treatment plant (Parten 1994). The spent wood chips and accumulated biosolids from this project are composted at a landfill.

In British Columbia, sewage is composted with wood residue at two locations. The Regional District of Comox-Strathcona uses wood residue diverted from landfills as a bulking agent in the composting process, the product of which is sold to local farmers or used in landfill capping. Composting is more cost effective than aerobic or anaerobic treatment and as much as 40% of the Regional District’s costs are recovered through sales of the composted wood residue (B.C. MELP 1995a). The City of Kelowna has been composting its sewage with wood residue for more than 10 years. The compost is used in local agricultural operations and for capping of landfills. The City is marketing “Ogo-Grow,” a soil amendment sold in bulk at nurseries and landscaping operations. The compost has also been used in provincial parks (B.C. MELP 1995a).

2.4.7.2 Fill Material in Construction

To make more usable land, wood residue is often dumped in environmentally-unsuitable and wet locations such as low-lying and foreshore areas, gullies, ravines and wetlands. Wood residue has been used as a substitute for granular fill material in septic tile-field systems. To allow construction of roads, highways, warehouses, industrial parks, houses and other structures on wetlands, wood residue is often dumped in huge quantities as a lightweight fill material rather than relying on the extraction of the peat and the use of an inert fill material. In recent years, large amounts of wood residue were deposited in the Lower Mainland of B.C. for development of residential properties. The construction of the Annacis and Westminster Highways in 1989 may have temporarily reduced the wood residue surplus in the province. However, the surplus volume is, at the time of printing, as high as prior to construction of these highways.

2.4.7.3 Landscaping

Wood residue is utilized as a foundation material in landscaped areas, pedestrian walkways, parks and trails. Wood residue is sometimes placed on race tracks for snowmobiles or cars. A company in Elko, B.C. bags landscaping bark; the company would reportedly prefer to use a Canadian supplier, but it has used a U.S. source for an adequate supply of wood residue (Anonymous 1994b).

2.4.7.4 Capping Material for Landfills

The use of wood residue as an intermediate cover or final capping material at municipal or industrial landfills can prevent the dispersal of debris by wind, restrict the access of wildlife to the contents of the landfill and reduce odour, however, wood residue does not present an impermeable barrier to gases or rainwater. Further, the eventual burial of such wood residue may result in additional generation of methane gas and leachate, thereby exacerbating the environmental impacts of the landfill. The acidity of wood-residue leachate may increase the leaching rate of other contaminants, such as metals, from municipal refuse. Although lysimeter tests at UBC implied that the use of hogfuel as a cover material at municipal landfills may not affect leachate quality (Cameron *et al.* 1975), the evidence was not conclusive.

2.4.7.5 Treatment of Acid Rock Drainage

The use of decaying wood residue has been suggested for the treatment of mildly acidic rock drainage (Gormely Process Engineering 1989; Murphey and Cowan 1978). Removal of heavy metals by precipitation as sulphides by sulphate-reducing micro-organisms is greatly enhanced in the presence of cellulose degradation by-products that the micro-organisms use as a carbon source. Some components of wood resins and extractives could also be removed by this process because they can form complexes with metal ions. The hydroxybenzene group of tannins chelates metals in acid mine drainage. However, problems associated with the collection, treatment and disposal of resultant leachates could present a significant obstacle to the use of wood residue in handling mine wastes. More research on this subject is required.

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3.0 CHARACTERISTICS OF WOOD RESIDUE

This section characterizes selected chemical constituents of wood residue and wood-residue leachate. Peat is included briefly because wood residue is often deposited as a lightweight fill material in peatland.

3.1 CHEMICAL COMPOSITION OF WOOD RESIDUE (WOOD, BARK AND FOLIAGE)

The composition of wood residue depends on which species of tree it was derived from and whether chemical contamination (e.g. antisapstain pesticide application) has occurred.

3.1.1 Elemental Constituents of Wood Residue

Wood is 51% carbon, 42% oxygen, 6% hydrogen, 0.2% nitrogen, 0.05% sulphur and less than 1% of the other elements on a dry-weight basis. Wood residue that has been exposed to sea water can have a higher sulphur content (Emcon Associates 1980).

3.1.2 Chemical Components of Wood Residue

Much of the current understanding of wood chemistry was derived from research on pulping technology and the development of wood-based chemicals. The chemical constituents of wood residue vary considerably between tree species. The type and amount of these constituents also depend on the age of the tree, the part of the tree and its geographic location. Chemical constituents in wood residue can be classified as water soluble, water insoluble (i.e. only soluble in organic solvents such as ether) or alcohol soluble. Alcohol soluble compounds generally exhibit some water solubility as well.

Wood residue is composed largely of water, organic compounds and a small amount of inorganic material. The organic compounds can be classified as carbohydrates, phenolic substances, terpenes, aliphatic acids, alcohols and proteins.

3.1.2.1 Water or Moisture Content

The water or moisture content (MC) of wood is generally expressed as the percentage of wet weight to dry weight (Cheremisinoff *et al.* 1976):

$$\text{MC} = 100\% \times \frac{(\text{green weight - dry weight})}{\text{dry weight}}$$

For some tree species, the MC can be as high as 200%. Considerable variation in MC can exist between trees of the same species and even between boards cut from the same tree (United States Forest Products Laboratory 1974). The MC of sapwood (composed of living wood cells) is almost always higher than that of heartwood (dead wood cells) from the same tree. The MC of cut wood and wood residue vary greatly, depending on weathering conditions. Table 3.1 shows the MC of freshly cut softwoods and hardwoods that commonly occur in B.C.

3.1.2.2 Carbohydrates

Carbohydrates consist entirely of carbon, hydrogen and oxygen and exist primarily as long chain water-insoluble polysaccharides and water-soluble wood sugars. Polysaccharides include cellulose, hemicellulose, starch and pectin. Holocellulose is the term used to describe the combined fractions of cellulose and hemicellulose. Cellulose is a polymer of several thousand glucose units, whereas the hemicellulose polymer consists of glucose and other sugars such as galactose, mannose, xylose and arabinose. Softwoods have an average carbohydrate content of about 70%, while hardwoods are about 80% carbohydrates, on a dry weight basis. The hemicellulose content in softwoods is 27±2% and the cellulose content is 42±2%, on a dry weight basis. In hardwoods, the hemicellulose content is 30±5% and the cellulose content is 45±2% (Smook 1990). Starch and pectin exist in minor quantities in wood. All carbohydrates are considered to be biodegradable because they can be metabolized by micro-organisms. Carbohydrates, especially hemicellulose and the short chain polysaccharides, can be easily hydrolyzed into shorter fragments and into simple wood sugars.

3.1.2.3 Phenolic Substances

Most of the decay resistance of living trees and cut wood can be attributed to the presence of phenolic substances in wood extractives with microbicidal and insecticidal properties. Phenolic substances consist mainly of water-insoluble lignin with minor amounts of water-soluble wood extractives such as tannins and alcohol-soluble wood extractives such as lignans. Excluding lignin, many of the other phenolic substances are “signature” compounds, present only in certain species of trees. Most of the phenolic compounds are aromatic and convey an odour species-specific to the wood residue. The presence of tannins and lignans is characteristic of heartwood, bark and foliage. Between 18% and 36% of the dry weight of wood consists of phenolic substances.

Taylor and Goudey (1992) reported high concentrations (up to 83 $mg \cdot L^{-1}$) of phenols in aspen leachate. Laboratory studies demonstrated that phenol is produced from the degradation of para-hydroxybenzoic acid (PHBA) that is associated with lignins and lignin precursors in certain hardwoods including poplar, willow, cherry and cranberry (Shariff *et al.* 1989).

3.1.2.3.1 Lignin

Lignin, a substance that bonds wood cells together into a rigid structure, is an amorphous polymer of several hundred phenylpropane units; its chemistry is complex and poorly understood in many respects. In addition to being relatively resistant to biodegradation, lignin is not readily susceptible to solubilization and extraction by solvents. Softwoods generally have a higher phenolic content than hardwoods due mainly to their higher lignin content; the lignin content of softwoods is between 25 and 35% dry weight and between 17 and 25% for hardwoods (Tsoumis 1968; Haygreen and Bowyer 1989). The highest lignin content occurs in *Thuja plicata* (33%) and *Tsuga* spp. (31%), whereas the lignin content in *Picea* spp., *Abies* spp., *Pinus contorta* and

Table 3.1 Average moisture content of green wood by tree species.

	Moisture Content (%)*	
Species	**Heartwood**	**Sapwood**
Douglas-fir	37	115
lodgepole pine	41	120
pondersoa pine	40	148
while pine	62	148
engelmann spruce	51	173
sitka spruce	41	142
western red cedar	57	249
western hemlock	85	170
grand fir	91	136
western larch	54	110
red alder	-	134
aspen	95	113
black cottonwood	162	146

* Based on oven-dry weight.

Source: United States Forest Products Laboratory (1974).

Larix occidentalis is between 24 and 29% (Sarkanen 1971). In softwoods, there is more lignin in sapwood than in heartwood. There are no consistent differences in the lignin content of the sapwood and heartwood of hardwoods.

3.1.2.3.2 Tannins

Tannins are mainly found in the bark, foliage and roots of softwoods, whereas heartwood contains lesser amounts. Tannins can be identified by the formation of blue- or green-coloured complexes in the presence of ferric salts and other coloured complexes in the presence of zinc, copper and manganese. Tannins have the ability to adsorb onto proteins and to form water-insoluble precipitates with proteins (e.g. the process that converts hides into leather known as tanning). Tannins are divided into hydrolyzable tannins and condensed tannins. Condensed tannins undergo progressive polymerization in the presence of heat and acid to yield mainly insoluble red- or dark-coloured substances. Hydrolyzable tannins are readily hydrolyzed by acids to phenol carboxylic acids and simple wood sugars or polyhydroxy alcohols.

Tannins found in the heartwood only occur in the condensed form. The condensed tannin content of western hemlock heartwood is only about 0.2% (dry weight). Douglas-fir heartwood generally contains less than 1% (dry weight) of the unpolymerized condensed tannin called dihydroquercetin that is also found in *Larix occidentalis* to a lesser extent. There is a lack of information on the tannin content of hardwoods.

3.1.2.3.3 Lignans

Lignans are made up of two phenylpropane units and can be found in roots, heartwood, foliage, fruits and exudates of both softwoods and hardwoods. Many lignans have fungicidal, insecticidal and anti-oxidant properties and may be associated with natural wood defence mechanisms. Lignans are only slightly soluble in cold water (solubility increases with increased temperature). Specific lignan molecules may be characteristic of tree genera. For example, lignans related to conidendrin are present only in *Tsuga* spp. and *Picea* spp. Lignans related to plicatic acids are only found in western red cedar, in which they comprise from 8 to 18% of the dry weight of the heartwood (Peters *et al.* 1976). There is some evidence to indicate that lignans are synthesized and deposited at the sapwood-heartwood boundary and in the cells of injured wood. The darker the heartwood, the more lignan content it will have. The lignan content of western hemlock heartwood is about 0.75% (dry weight). Little information is available on the lignan content of hardwoods.

3.1.2.3.4 Other Phenolic Substances

Significant amounts of para-hydroxybenzoic acid (PHBA) are found only in the sapwood and heartwood of poplar and willow (Shariff *et al.* 1989). Bark, foliage and root tissues of poplar and willow contain only a small amount of PHBA.

Tropolones are acidic, water-soluble, volatile phenolic substances (with seven carbon atoms in a ring structure) that are only found in the heartwood of western red cedar and species of the cypress family. Tropolones, including the methyl thujate and thujic acid forms, constitute between 0.5% and 2% of the dry weight of the heartwood of western red cedar (Peters *et al.* 1976). The concentration of tropolones in the heartwood decreases to almost zero near the centre of the heartwood. The darker the heartwood, the more tropolones it is likely to contain. The decay resistance of the heartwood of these species is due mainly to the presence of tropolones. Methyl thujate is responsible for the characteristic odour of western red cedar heartwood. Tropolones form red-coloured complexes in the presence of ferric salts and green-coloured complexes with copper acetate and metallic copper. Immersion of copper in western red cedar leachate is one way of collecting tropolones.

3.1.2.4 Terpenes

Terpenes are water-insoluble compounds that are largely absent from hardwoods. Up to 5% of the dry weight of softwoods consists of water-insoluble terpenes that can be divided into volatile (i.e. volatile oils) and non-volatile (i.e. resin acids) fractions. Oxygenation of some terpenes results in terpenoids. *Pinus* spp. have the most numerous and largest resin canals, concentrated in the heartwood, of the softwoods; consequently there are more terpenes in *Pinus* spp. than in other species. In *Picea* spp. the resin canals are evenly distributed between the sapwood and the heartwood.

3.1.2.4.1 Non-Volatile Terpenes

The non-volatile, or rosin fraction, of terpenes consists mainly of resin acids which are found only in resin canals of trees. Resin canals are normally only present in the bark and sapwood of pine, spruce, larch and Douglas-fir but traumatic resin canals caused by wounding can also occur in true fir and hemlock. The woody tissues in roots and stumps generally contain less resin acid than does the sapwood or heartwood of a tree. After a tree is harvested, resin acids can become oxidized by air or degraded by enzymatic hydrolysis. As these reactions proceed, resin acids become more water soluble. Solubility generally decreases under more acidic (i.e. lower pH) conditions.

Resin acids are synthesized by the living cells surrounding the resin canals in the sapwood and then exuded into the resin canals (and any damaged sites connected to these canals) throughout the sapwood and heartwood. The resin acid content of wood resins generally ranges from 25 to 50%. Resin acids constitute as much as 48% of Douglas-fir wood resins and between 30 and 40% of pine and spruce wood resins (Mutton 1962; Taylor *et al.* 1988). In contrast, western hemlock and alpine fir (*Abies lasiocarpa*) have relatively low resin acid content (Mutton 1962; Taylor *et al.* 1988).

3.1.2.4.2 Volatile Terpenes

The volatile terpenes, commonly referred to as the turpentine fraction, include mono-terpenes, terpenoids and other volatile oils. These constituents are found in the foliage of all softwoods and in resin canals. Volatile terpenes account for the characteristic odour of fresh wood and can be easily obtained by steam distillation of the wood residue. In a living tree, the volatile terpene fraction acts as a solvent, allowing resin acids and other constituents to flow to a wound. The extract from resin canals of *Pinus contorta* contains about 25% volatile oil which can be extracted as black liquor soap skimmings from kraft pulping processes and converted into turpentine and other products.

3.1.2.5 Aliphatic Acids

Aliphatic acids consist mainly of water-insoluble, long-chained saturated and unsaturated fatty acids. Aliphatic fatty acids are a source of stored energy for trees. Fatty acids are mostly concentrated in seed tissues (e.g. cones and fruits) but they are also found in the wood resins of all softwood and hardwood species. Fatty acid esters are also secreted in resin canals. Tree species may be characterized by a specific, predominant fatty acid ester. In a living tree both saturated fatty acids (e.g. palmitic, stearic, lignoceric) and unsaturated fatty acids (e.g. oleic, linoleic, linolenic) exist in their glyceride (or fatty) forms and only a small fraction exists as free acid. In cut wood, the glycerides are hydrolyzed into their free acid forms. The saturated fatty acids are stable while the unsaturated fatty acids are further oxidized and become polymerized. Between 1 and 5% of the dry weight of wood consists of aliphatic acids. Between 25 and 50% of the dry weight of wood resins in softwoods is fatty acids. Between 50 and 90% of the dry weight of wood resins in hardwoods is composed of fatty acids.

3.1.2.6 Other Chemical Constituents

The alcohol group includes the aliphatic alcohols and sterols that are formed from the esterification of fatty acids. Protein is most abundant in developing tissues but is seldom found in mature tissues of the wood and bark. Alcohols, proteins and inorganic minerals generally make up less than 1.5% of the dry weight of wood residue.

3.1.3 Wood Resins and Wood Extractives

Excluding water, the chemical constituents of wood residue can be separated into two groups according to their locations. The first group is the cell wall component, which includes carbohydrates and lignin. The second group is the extraneous component. The chemical constituents of the latter group are extractable with organic solvents and water at neutral pH. Extraneous components can be further subdivided into wood resins and wood extractives.

3.1.3.1 Wood Resins

Wood resins are oily constituents secreted and stored in the living cells of sapwood, bark and foliage. Wood resins provide the living tree with a defence against wood-boring insects. Wood resins contain long-chain fatty acid esters, sterols and terpenes. Wood resins are only slightly soluble in the acidic conditions characteristic of hydraulic debarker effluent and wood-residue leachate (Field *et al.* 1988).

3.1.3.2 Wood Extractives

Wood extractives result from natural chemical reactions and changes that occur after tree cells die (e.g. oxidation and hydrolysis). Extractives include long-chain fatty acid esters and phenolic substances that are stored in the heartwood, bark and foliage. Fatty acid esters are predominant in hardwood extractives. The wood extractive content of softwoods is approximately 5 to 30% (dry weight) and the content of hardwoods is 2 to 12% (Cheremisinoff *et al.* 1976; Tsoumis 1968; Haygreen and Bowyer 1989). Between 3 and 23% (dry weight) of western red cedar heartwood consists of hot water-soluble wood extractives. Heartwood in most species of softwoods is darker than the sapwood because of the higher extractive content in the heartwood. Heartwood and sapwood of spruce and fir have about the same white to pale yellow colour. There is no consistent difference between the colour of heartwood and sapwood of hardwoods.

3.1.4 Chemical Constituents of Bark

Bark makes up about 10 to 15% of the dry weight of a tree. The chemical composition of bark is more variable than that of wood and the presence of suberins (aliphatic acids) is a unique characteristic of bark. Bark contains much less carbohydrate than wood but the pectin fraction of carbohydrates is much higher in bark than in wood. Compared to sapwood and heartwood, bark generally has the same inorganic components but at higher concentrations. Extractives and wood resins are also more concentrated in the bark. The inorganic-minerals content of bark generally ranges between 2 and 5% dry weight. The wood resins and wood extractives in bark generally make up between 20 and 40% dry weight. Bark contains more protein than does wood and the protein content of bark varies during the course of the year. Considerably more phenolic materials, especially condensed tannins, are found in the bark than in the heartwood of a tree. Condensed tannins are acid insoluble and, under acidic conditions, these compounds polymerize into more complex substances, usually reddish in colour. The presence of larger amounts of hydrophobic (water-insoluble) compounds like lignin in bark than wood make the bark more resistant than the wood to biodegradation or insect attack.

Softwoods generally have a higher bark content than hardwoods. Douglas-fir bark volume is 30%, the highest overall volume of bark of all the softwoods, while lodgepole pine bark volume is about 11%. The bark of softwoods that have resin canals will also contain terpenes, mainly in the form of resin acids. Tropolones are not found in the bark of western red cedar. Softwood bark generally contains 30 to 40% holocellulose and 17 to 42% lignin, whereas the remainder is comprised of wood resins and wood extractives. The bark of western hemlock and Douglas-fir have relatively high condensed tannins contents: about 15% dry weight for hemlock and 8 to 18% for Douglas-fir. The content of dihydroquercetin, one of the main condensed tannins in Douglas-fir, was found to be about 5% by dry weight. The condensed tannin content of the bark of the *Pinus* spp., *Picea* spp. and *Larix* spp. is high compared to that of hardwoods.

3.1.5 Chemical Constituents of Foliage

One unique chemical characteristic in foliage is the presence of photosynthetic constituents (e.g. chlorophyll). The carbohydrate content is less in foliage than in wood. Considerably more protein, inorganics, terpenes and aliphatic acids are found in foliage than in wood, especially during the growing season. The foliage generally contains a large portion of the protein in the tree, particularly in summer. Foliage generally contains 32 to 36% cellulose, 33 to 37% lignin, 8 to 11% protein, 9 to 12% wood resins and extractives and 6 to 7% inorganic compounds. Wood resins and wood extractives in foliage include terpenes, lignans, tannins and fatty acid esters with the latter making up the largest portion.

Foliage terpenes are found in all trees. Terpenes are mainly volatile oils which convey the signature odour of a tree species. Foliage of many species of softwoods is very rich in terpenes (0.2 to 2% dry weight), especially during the period of new growth. In foliage, hydrolyzable tannins are found which, under acidic conditions, are converted into acids and wood sugars (mainly glucose).

3.2 CHEMICAL CONSTITUENTS OF WOOD ASH

Complete combustion of wood residue results in wood ash (largely composed of inorganics) weighing from 0.1 to 1.0% of the bone dry weight of unburned wood and from 1 to 3% of hog-fuel. In general, burning of hardwoods results in a higher ash content than burning of softwoods. The ash content of burned wood residue depends on many factors such as: tree species; soil type; climate; part of the tree burned; and the temperature of burning. The parts of a tree in the order of decreasing amounts of ash content are: foliage, bark, twigs, roots, branches, pith, early spring wood and juvenile wood.

The carbon content of wood residue ash can be divided into organic carbon and inorganic carbon. The inorganic carbon content of the ash resulting from complete combustion of wood residue is generally around 1%. Burning of wood residue at low temperatures will result in a high organic carbon content in the ash. Clinkers often result from incomplete combustion of wood residue (e.g. during open burning). The organic and volatile content of flyash is generally higher than that of bottom ash. Nitrogen and sulphur are largely absent from wood ash but they are found in foliage ash due to the higher protein content of foliage.

Other major components of wood residue ash include calcium, potassium, magnesium, phosphorous, manganese, aluminum, iron and sodium. Minor components of wood residue ash include arsenic, cadmium, chromium, nickel, lead, mercury, selenium, cobalt, antimony, barium, vanadium, zinc, boron, copper and molybdenum. Ash resulting from the burning of salt water-stored wood may also contain dioxin.

3.3 CHEMICAL COMPOSITION OF PEAT

A wetland is defined as an area that is saturated with water long enough to promote aquatic processes. Wetlands can be divided into organic wetlands or mineral wetlands. Organic wetlands are comprised of peat that is at least 40 cm thick. Bogs and fens are two types of organic wetlands. A mineral wetland is comprised of peat that is less than 40 cm thick. Swamps and marshes are two types of mineral wetlands. In B.C., most of the wetlands are classified as bogs and fens. Bogs are the predominant wetlands in the coastal areas of B.C. (including the Lower Fraser Valley), whereas fens predominate in the interior of the province. Bogs consist of poorly- to moderately-decomposed sphagnum moss and woody peat, with trees and shrubs usually present at the surface. Fens consist of well-decomposed sedge, with sedge, grass and moss usually present at the surface (Maynard 1989; Levesque *et al.* 1987).

The atomic composition of peat is not unlike that of wood. Peat is a partially-carbonized mass formed by the partial decomposition in water of various plant materials including grass, brush and trees. Peat is composed of about 80% water and 20% solids. The chemical composition of peat depends on the type of plant material, the extent of decay and the hydrogeologic conditions of the peat site over time. The solid portion of peat consists mainly of water-insoluble organic materials from plants and dead micro-organisms (Levesque *et al.* 1987; Fuchsman 1980). If the decomposing plant material contained trees, the organic substances could include lignin and other water-insoluble compounds such as terpenes, pectin, fatty acids, sterols and long-chain alcohols. Most of the water-soluble substances such as nitrogen, carbohydrates and proteins in the original plants are leached out or metabolized by micro-organisms in the decay process. Information on characteristics of peat water can be found in Section 6.3.

3.4 CONTAMINATED WOOD RESIDUE

Contaminated wood residue occurs at many forest-industry operations because it is commonly used as a spill absorbent for oils and chemicals. Waste chemicals and sludge are often dumped on wood residue in the belief that the contaminants will be diluted to non-detectable concentrations. However, if that is practised, contaminants may become more widespread in the environment during wood-residue storage and transportation.

Contaminated wood residue also results when wood that is treated with preservatives, fungicides, glues, paints or other toxic chemicals, is processed or taken out of service. Wood residue from wood preservation plants may be contaminated with toxic wood preservatives such as creosote, pentachlorophenol (PCP), chromated copper arsenate (CCA), ammoniacal copper arsenate

(ACA), or copper naphthenate. Wood residue from sawmills practising control of sapstain (i.e. fungal discolouration of freshly-cut lumber) may be contaminated with toxic fungicide formulations containing ingredients such as TCMTB, Cu-8, IPBC, DDAC, azaconazole and boron compounds. In addition, although all sapstain-control uses of PCP and TTCP were terminated by the former Agriculture Canada effective December 31, 1990, chlorophenol-contaminated wood residue from wood treated prior to this date may exist at sawmills. Sawmills and shake and shingle mills that cut cedar logs exclusively are unlikely to generate wood residue contaminated with toxic wood preservatives or fungicides. Wood residue from plywood, particle board and finger-jointing plants may be contaminated with glue resins, such as phenol formaldehyde. Used railway ties, utility poles, marine decking and other treated-wood products that are taken out of service will likely contain significant concentrations of toxic chemicals (e.g. creosote) remaining in the wood. Demolition debris often contains a significant portion of wood painted with toxic compounds or treated with preservative chemicals.

Wood residue that has been contaminated with an antisapstain chemical may qualify as a special (i.e. hazardous) waste. Contaminated wood residue should be subjected to a leaching (i.e. solid waste extraction procedure [SWEP]) test pursuant to the B.C. Special Waste Regulation. If a material is determined to be a special waste, the owner of that material must contact MELP for instructions on appropriate transport, storage and/or disposal. Wood residue contaminated with an antisapstain chemical cannot be used for mulch, residential fuel and wood residue contaminated with chlorophenols cannot be used as a fibre source in the pulp and paper industry (*Canadian Environmental Protection Act* Pulp and Paper Mill Defoamer and Wood Chip Regulations).

4.0 DECOMPOSITION OF WOOD RESIDUE

Decomposition of wood residue can occur via chemical, biological and thermal processes. Biological decomposition plays the major role in the degradation of wood residue constituents and intermediate by-products. Thermal decomposition includes degradation of wood residue by fire. Although a discussion on all decomposition by-products is beyond the scope of this document, it should be noted that these processes generally alter the original chemical constituents in wood residue to the decomposition products present in leachate.

4.1 CHEMICAL DECOMPOSITION

Immediately after tree harvesting, chemical decomposition of wood begins via oxidation and enzymatic hydrolysis. The resin acid content of white spruce chips stored for 6 months in the interior of a chip pile decreased by 80% and lodgepole pine chips by 38% (Rogers *et al.* 1971). Significant decreases in turpentine and fatty and resin acids were reported in spruce and pine chips aged for 26 weeks (PAPRICAN 1977a). The role of microbial and thermal decomposition in these losses was not documented.

4.2 BIOLOGICAL DECOMPOSITION

Biological decomposition of wood residue involves the utilization of its chemical constituents as a source of energy for growth and metabolism of micro-organisms. Some complex organic constituents of wood such as lignin, cannot be biodegraded by most micro-organisms. For decomposition to occur, physical factors (i.e. pH, temperature, osmotic pressure) and chemical factors (i.e. presence of water, carbon, nitrogen, trace minerals) must be satisfied; in addition, oxygen is sometimes required. Taken together, these factors determine the rate of biological degradation. Proliferation of bacteria and fungi in wood residue generally only takes place in the warmer seasons. Wood residue is a poor source of nitrogen, which is needed for rapid decomposition.

Bacteria and fungi are two important types of micro-organisms involved in the biological decomposition of wood residue. Visible mats of bacteria or fungi in leachate are indicative of the decomposition of wood residue and its constituents in the presence of an outside nitrogen source (e.g. seepage from a septic tank tile field). The proliferation of bacteria and fungi in leachate can have several effects. Fungal or bacterial mats can clog drainage pipes and promote the proliferation of other organisms such as tubificid and naidid worms. The metabolites and the decomposition of bacteria and fungi can produce strong odours. Methane and other gases (e.g. hydrogen sulphide) can be generated by some bacteria.

Although phenolic substances in wood have microbicidal and fungicidal properties, biological decomposition of wood residue does occur slowly. Biological decomposition can be aerobic (requiring oxygen) or anaerobic (in the absence of oxygen). Decomposition of wood residue generally goes through two phases, aerobic and then anaerobic. However, anaerobic decomposition may not occur on the surface of some wood-residue piles due to the presence of oxygen.

Aerobic decomposition is faster and produces 20 times more heat than anaerobic decomposition (Evans 1973). On a cold, wet day a fog-like condition over a wood-residue pile is a result of condensation of water in air warmed by wood residue decomposition, as it meets cold, ambient air. Biological oxidation can raise the temperature within a wood-residue pile or landfill to 60 to

85°C (i.e. not to the point of ignition). Organisms capable of carrying out biological decomposition cannot survive these extreme temperatures. Once the temperature declines, the aerobic decomposition cycle begins again. The final end products of aerobic decomposition are water and carbon dioxide.

The end products of anaerobic decomposition depend on the type of microbes involved but generally include carbon dioxide and hydrogen gases; methanol, ethanol and other simple alcohols; acetic, formic and other organic acids. Under strictly anaerobic conditions, methane-generating bacteria convert the products of anaerobic decomposition to methane. Sulphur bacteria use anaerobic decomposition products and convert inorganic sulphur compounds into hydrogen sulphide. Because wood residue has a high organic content, the amount of gas that can be generated is higher than that from most municipal refuse of the same volume.

4.2.1 Decomposition of Wood Residue by Chemoheterotrophs

Chemoheterotrophic organisms (e.g. *Sphaerotilus* spp.) are most commonly associated with decomposition of wood residue because they can utilize organic constituents such as carbohydrates as a carbon/energy source. Although many chemoheterotrophs can metabolize the simple organic constituents in wood residue, only a few of the aerobic chemoheterotrophs are capable of breaking down the more complex organic components, such as lignin.

Chemoheterotrophs convert the carbohydrates and other organic constituents into pyruvic acids, providing energy in a series of oxidation reactions. Other intermediary products, such as wood sugars (e.g. glucose, pentose, fructose, hexose) are released in this decomposition step. Pyruvic acids can be further metabolized via either respiration and/or fermentation pathways for additional energy generation.

Aerobic respiration, which utilizes oxygen, is the only energy generation pathway of aerobic chemoheterotrophs. Anaerobic respiration, which can only utilize inorganic substances (e.g. sulphate), is the only energy generation pathway of anaerobic chemoheterotrophs. Facultatively anaerobic chemoheterotrophs can use oxygen, when it is available, in aerobic respiration for energy production. In the absence of oxygen, such microbes use an organic molecule in aerobic or anaerobic fermentation processes (which do not require oxygen but sometimes occur in its presence); or use an inorganic molecule in anaerobic respiration.

Decomposition of pyruvic acid via aerobic respiration is generally faster than via anaerobic respiration or fermentation. More energy is generated from aerobic respiration than from aerobic or anaerobic fermentation. The amount of energy produced from anaerobic respiration is dependent on the type of organism and the inorganic substance that it utilizes. The product(s) of anaerobic respiration are dependent on the type of organism and the inorganic substances that it utilizes, but such a process is unlikely to occur because an inorganic receptor is needed.

Proliferation of algae such as *Draparnaldia glomerata* and blue-green algae, protozoa, insect larvae and other micro-organisms may be a secondary or indirect effect of the growth of chemoheterotrophic organisms in surface watercourses affected by wood-residue deposits.

4.2.1.1 Examples of Chemoheterotrophic Organisms

The growth of *Sphaerotilus* spp., strictly aerobic bacteria that form long grey, stringy slimes in water receiving wood-residue leachate, is enhanced in the presence of organic iron. *Sphaerotilus* was observed to grow rapidly on fresh bark using carbohydrates as nutrients (Servizi *et al.* 1970).

Escherichia coli, common bacteria in the human intestine, is a type of facultative anaerobic chemoheterotroph that can undertake anaerobic fermentation of wood residue. The products are acetic acid, ethanol, formic acid, lactic acid, succinic acid, hydrogen and carbon dioxide gases via pyruvic acid metabolism. Total (not faecal) coliform levels in waters receiving wood-residue leachate are higher than in uncontaminated waters.

Fungi are chemoheterotrophs that can be either aerobic or facultatively anaerobic. During the warmer seasons, large mats of fungi are commonly observed in surface waters receiving wood-residue leachate. Filamentous or thread-like bacteria such as *Actinomycetes* and fungi such as *Leptomituf* have been identified in waters adjacent to several wood-residue sites in B.C. Proliferation of free-living (non-parasitic) oligochaete worms have been observed in fungal mats in surface waters receiving wood-residue leachate. Strong odours from metabolites of fungi and their decomposition products are frequently reported from surface waters receiving wood-residue leachate.

White rot fungus (*Phanaerochaete chrysosporium*) is a chemoheterotroph that undergoes aerobic respiration. It produces ligninase, a lignin-degrading enzyme which can also degrade other complex organic molecules. This fungus may be useful for bioremediation of pentachlorophenol-contaminated wood residue.

4.2.1.2 Gas Formation and Decomposition by Chemoautotrophs

Gases other than carbon dioxide can be generated in large amounts from decomposing wood residue. Chemoautotrophs are micro-organisms that can use carbon dioxide (generated by the chemoheterotrophs) as their principal source of carbon and use inorganic chemicals as energy sources. Although chemoautotrophs are not generally expected to be commonly associated with decomposition of wood residue since it contains only a small amount of inorganic material, certain strains can play a significant part in methane and hydrogen sulphide gas generation during the anaerobic stages of wood residue decomposition. Gas migration could kill nearby vegetation by exclusion of oxygen from the root zones (Weiss 1974; Anderson and Dornbush 1967). Methane is a colourless, odourless and flammable gas that is explosive when present in air at concentrations between 5 and 15%. Hydrogen sulphide gas is toxic to man, plants and aquatic organisms; its rotten egg odour can be detected at about 5 parts per billion.

4.2.1.2.1 Methane Gas Generation

Methane is generated as a metabolic by-product of methanogenic bacteria. Methanogenic bacteria are strict anaerobes (i.e. oxygen is a toxicant) and generally chemoautotrophic. They can form methane either from oxidation of hydrogen and reduction of carbon dioxide or from the fermentation of simple acids and alcohols such as formate, acetate and methanol. The growth rate of methanogenic bacteria during wood residue decomposition depends on many factors such as temperature, pH, oxygen content, C:N ratio and moisture content. There is an abundance of metabolic precursors (such as carbon dioxide, simple acids and alcohols) for the methanogenic bacteria from the anaerobic phase of wood residue decomposition. Methane gas generation is considered as the last phase of wood residue decomposition.

Although methane can be generated at between 0 and 55°C, the optimal temperature range is 30 to 35°C; thus more methane gas generation is expected during summer. There is a significant drop in methanogenic activity at temperatures below 10°C. Substantial reduction in methane gas generation occurs with slight deviation from the optimal neutral pH; thus, leaching of resins and extractives from the wood residue can reduce gas production (Emcon Associates 1980). Methane generation will occur between a pH of 6.0 and 8.0 but the optimal range is from 7.0 to 7.2. If the pH drops below 6.0, the methanogenic bacteria may die off abruptly. The optimal moisture content is 60 to 80% for maximum methane production. The aeration of a decomposing wood-residue pile by physical movement or by infiltration of oxygenated water can also greatly reduce methane gas production. The C:N ratio of wood is about 200:1 while the optimal ratio for methane gas generation is about 16:1; without nutrient addition, methane gas generation in a wood-residue pile will continue at a reduced rate for many years. Assuming wood residue contains 75% carbohydrates, it was estimated that one bone dry tonne of wood residue can produce about 1215 m^3 of methane (Slagle 1976). Methods to calculate potential methane gas generation from landfills can be found in many references including Emcon Associates (1980). Environment Canada has used a model developed by the USEPA to estimate methane gas emissions from landfills (National Climate Change Secretariat 1998).

4.2.1.2.2 Hydrogen Sulphide Gas Generation

In most organic matter (e.g. wood residue, plant material, animal tissue, excrement) sulphur exists almost exclusively in the reduced organic form (i.e. S^{-2}) as a component of amino acid groups which make up protein. Anaerobic decomposition of organic matter by micro-organisms (e.g. pathogenic and putrefactive bacteria) can result in generation of significant amounts of hydrogen sulphide gas. However, the amount of hydrogen sulphide generated from wood residue decomposition is expected to be relatively small because wood residue contains only small amounts of protein and sulphur.

Significant amounts of hydrogen sulphide gas can be generated as an indirect consequence of decomposition of wood residue that has sunk to the bottom of a body of water. This is due to the abundance of sulphur bacteria in the sediments of water bodies, especially those in the marine environment. Sulphur bacteria include oxidizing and reducing varieties. Sulphur-oxidizing bacteria can change the reduced form of inorganic sulphur (such as elemental sulphur and monovalent [i.e. S^{-1}, as in pyrite] sulphur) to its oxidized sulphate form (i.e. SO_4^{-2}); this means sulphuric acid is generated by sulphur-oxidizing bacteria. Sulphur-reducing bacteria reduce sulphate and in doing so produce hydrogen sulphide.

Thiobacillus is an important group of sulphur-oxidizing bacteria commonly associated with wood residue decomposition. *Thiobacillus* bacteria are strictly aerobic and occur widely in marine and terrestrial environments, for example: mud, sewage, seawater, peat bogs, swamps, mine drainage, sulphur springs and polluted waters. These bacteria are mostly acidophilic; some can grow in environments with a pH of less than 2 and most cannot survive if the pH is greater than 6. These are strictly chemoautotrophic bacteria since they utilize carbon dioxide as the sole source of carbon and derive energy from oxidation of reduced inorganic sulphur compounds. The *Thiomicrospira* genus occurs mainly in marine mud; other sulphur-oxidizing bacteria are likely less commonly associated with wood residue decomposition.

The genus *Desulfovibrio* is an important group of sulphur-reducing bacteria associated with hydrogen sulphide gas generation during wood residue decomposition. *Desulfovibrio* bacteria are strict anaerobes and are widely distributed in nature, but only where anoxic conditions prevail. These bacteria have been found in sewage, polluted water, the sediments of lakes and seas, marine mud, anaerobic mud/sediment, oil wells and in the intestines of animals. *Desulfovibrio* bacteria are not strictly chemoautotrophic because some species cannot utilize carbon dioxide as the sole source of carbon. A substantial part of the carbon utilized is derived from an organic carbon source (e.g. from the decomposition of wood residue).

When wood residue is deposited in a location where reduced sulphur is present in abundance (e.g. sediment with high pyrite content), decomposition of the wood residue by chemoheterotrophs via aerobic respiration will generate carbon dioxide, promoting the proliferation of bacteria that oxidize inorganic sulphur minerals in the sediment into sulphate compounds. The acidic conditions created by sulphate compounds and wood-residue leachate enhances the growth of these sulphur-oxidizing bacteria. As more oxygen is consumed, the condition in and around the wood-residue deposit becomes anoxic; this will retard the metabolism of the sulphur-oxidizing bacteria but accelerate the metabolism of sulphur-reducing bacteria. Under strictly anaerobic conditions, the sulphur-reducing bacteria will proliferate by metabolizing the sulphate compounds into hydrogen sulphide.

When wood residue is deposited in a location where oxidized sulphur is present in abundance (e.g. marine sediments with high sulphate content), decomposition of wood residue by chemoheterotrophs via aerobic respiration will result in an anoxic condition in and around the wood-residue deposit. Under strictly anaerobic conditions, as noted above, the sulphur-reducing bacteria will proliferate by metabolizing the sulphate compounds into hydrogen sulphide. The hydrogen sulphide gas could become trapped within the sediment until the sediment is disturbed.

4.2.2 Role of Photoautotrophs

Decomposition of wood residue by chemoheterotrophs via aerobic respiration will generate carbon dioxide. Photosynthetic algae are one type of photoautotroph which use light as a source of energy and carbon dioxide as the principal source of carbon for photosynthesis. Proliferation of photoautotrophs can occur in surface waters receiving wood-residue leachate.

4.3 THERMAL DECOMPOSITION

Thermal decomposition of wood residue involves both combustion and pyrolysis. Combustion occurs in the presence of a flame, whereas pyrolysis occurs without a flame. Combustion and pyrolysis occur simultaneously in different zones of a burning pile of wood residue. With an increase in temperature, water will be initially driven out of the wood residue as vapour and subsequently volatile components will be released. Smoke, which consists of a complex mixture of solid and liquid residues of thermal decomposition, is more likely to be generated when moist wood residue is burned under restricted air flow conditions. Unless temperatures are measured inside a wood-residue pile, it may be difficult to determine if a foggy condition at a wood-residue site is generated as a consequence of thermal or microbial decomposition.

In the presence of a flame and adequate heat, complete combustion of wood residue and its volatile gases occurs. This will result in the formation of carbon dioxide, water and ash containing inorganic minerals and a small amount of carbon. Combustion processes are seldom complete in a situation where wood residue is burned in the open (i.e. at a low temperature) or when there is accidental fire in a wood-residue pile.

In the absence of a flame (i.e. under oxygen-deficient conditions), pyrolysis occurs and produces char (i.e. carbon), wood tars and gases (Hon and Shiraishi 1991). The yield and the type of these products depend on factors such as: the physical and chemical conditions of pyrolysis, the wood species and the parts of the tree involved. Pyrolysis at low temperatures (i.e. from 100 to 200°C) causes drying (i.e. water vapour is evolved). Rapid removal of hemicellulose occurs at about 140°C resulting in the formation of formic and acetic acids. Pyrolysis at 200 to 400°C results in more char than pyrolysis at lower temperatures. Compared to lower temperatures, pyrolysis at 400 to 600°C will result in greater destructive distillation of wood residue constituents into a complex mixture of wood tars and the formation of pyroligneous acids, formaldehyde, formic acid, acetic acid, ethanol and related compounds. Wood tar is a thick brown to black sticky, liquid mixture of hydrocarbons and their derivatives (including creosote) that has a distinctive odour. Wood tar can be divided into oils and pitches which can include resins, turpentine, oils/fats, acetic acid and organic acids, aldehydes, alcohols and hundreds of other complex chemical compounds. Pyrolysis above 600°C (i.e. above ignition temperatures for most components) will result in gaseous products reacting with char to form highly combustible products; this gasification process requires more water than that which is present in wood residue but may be available during fire fighting. Fire-fighting water should be contained on site if feasible because it is expected to contain constituents toxic to fish.

5.0 WOOD-RESIDUE LEACHATE GENERATION, MIGRATION AND MONITORING

5.1 LEACHATE GENERATION

Leachate generation at wood-residue sites is similar to the process of leachate generation at a municipal landfill. Many textbooks have been written about the mechanism of leachate generation and mathematical formulas and computer programs are used to calculate leachate production rates for different types of refuse materials under different conditions. Proponents seldom use these calculations in the selection process for a wood-residue site because of the complexity. Consultants who use these calculations often rely on incomplete or inadequate hydrogeologic data because of the high cost of obtaining the necessary data.

5.1.1 Mechanisms of Wood-residue leachate Generation

Although wood-residue leachate is more of a problem in the wet, coastal region than in the dry, interior region of B.C., leachate can be a problem wherever wood residue comes into contact with water. Leachate can be generated if water is allowed to percolate or flow through a wood-residue pile as a result of precipitation, irrigation, leachate recycling, fire fighting, or contact with infiltrating surface water or groundwater. Wood-residue leachate is generated as an exudate, or alternatively by the diffusion process. Diffusion is the movement of chemical constituents in a solution from an area of high concentration to an area of low concentration.

Exudates, containing wood resins and/or wood extractives, are forced out of “wounds” in wood (e.g. broken vessels, rays and wood cells) by atmospheric pressure or gravity immediately after tree harvesting or when the wood is cut. Shredding of wood residue into very small particles will increase the “wounded” area per unit of wood residue. Exudates are washed off as leachate when the wood residue comes into contact with water.

Freshly-produced wood residue has a moisture content (Table 3.1) and capacity to retain water that depends on the tree species. Wood residue is saturated if the wood fibre can absorb no more water. Leaching by the diffusion process begins when wood residue is saturated with water. Wood residue with a high fibre saturation point will have a relatively long wetting time before the initial generation of leachate by the diffusion process. Diffusion can take place through the minute pores in the wood cell walls and/or through “wounds.” In both cases, the diffusion rate is greater for water-soluble versus water-insoluble constituents. Diffusion rates through wood cells depend on cell wall pore size; smaller being slower. The following species are listed in order of decreasing cell wall pore sizes: pine, aspen, larch, spruce. Diffusion through the cell walls is slower than through “wounds” because cell pore diameters are smaller.

5.1.2 Leaching Rate and Concentration of Leachate

By submerging cedar blocks (volume = 22.7 L; surface area = 3.2 m^2) in a continuous flow of dechlorinated tap water (14.3 $L \cdot h^{-1}$), Peters *et al.* (1976) demonstrated that lignans are leached out rapidly (i.e. almost all leached out in 1 day). However, the concentration of tropolones recorded in the leachate from this experiment remained at 0.3 to 0.4 $mg \cdot L^{-1}$ throughout the 85-day test, reflecting a constant leaching rate for tropolones. Lysimeter test results indicated that the total mass of constituents leached from wood residue is proportional to the amount of precipitation. Three-tenths of a percent of the dry weight of the wood residue was leached out over two years with 37 cm per year of precipitation, while 1.5% leached out with 225 cm per year of precipitation (Cameron *et al.* 1975). Peters *et al.* (1976) also noted that 2.4 L of acutely toxic leachate could be leached from each gram of western red cedar heartwood.

The concentration of leachate generated from wood residue is dependent on the diffusion rate and solubility of organic and inorganic wood residue constituents. Initial leaching of wood residue generally produces a relatively concentrated leachate and can be exacerbated by a high proportion of finely-divided wood-residue particles. Water-soluble (e.g. wood extractives) and biodegradable constituents are expected to predominate in leachate initially. The concentration of less soluble, reactive and biodegradable constituents and metabolites of decomposition processes will increase over time and will ultimately reach a stabilized level.

If wood residue is exposed to a high rate of water exchange (e.g. it is deposited in a high rainfall area or in a stream), the concentration of leachate and the leaching rate are expected to be high initially, then decline relatively rapidly. Pulses of leachate containing high concentrations of soluble extractives can be generated when wood residue, stored in relatively dry conditions, is exposed to heavy rainfall or snow melt.

5.1.3 Termination of Leachate Generation

Constituents in wood residue will leach out whenever the wood fibre saturation point is reached and contact with water is continued. For the purposes of this document, leachate generation is considered to have stopped when the leachate quality is consistent with natural background water quality of surface waters. The length of time a given constituent will continue to leach out of the wood depends on:

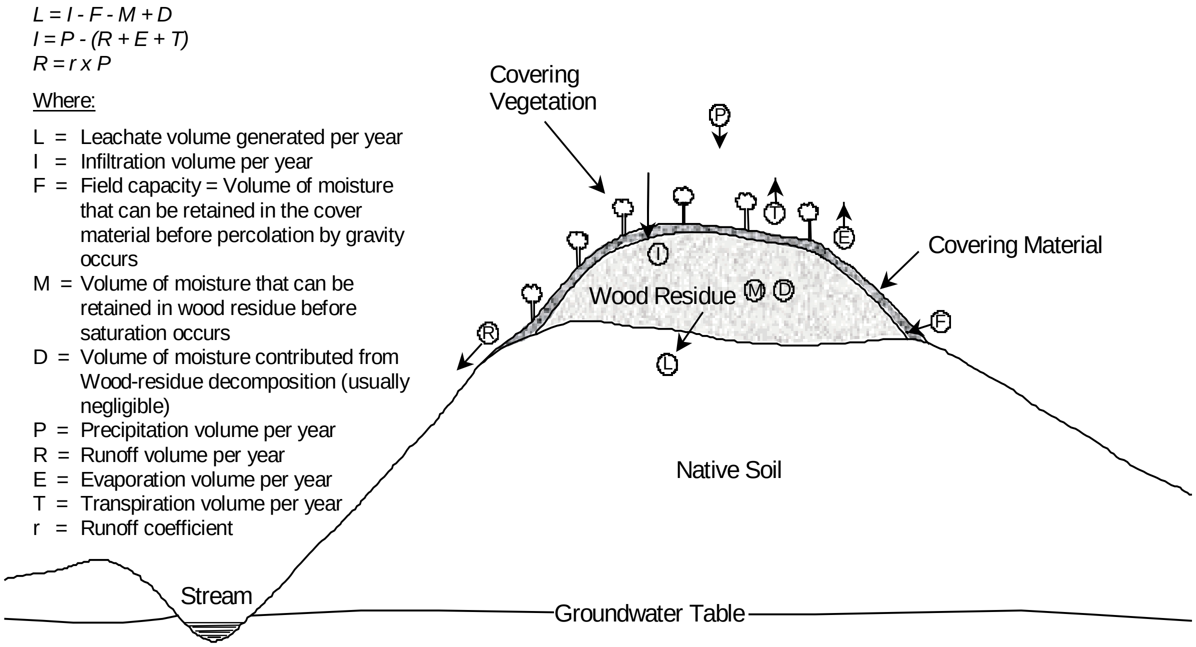
- the initial concentration of that constituent in the wood residue;
- the volume of water that has been in contact with the wood residue;
- the contact time between the wood residue and water; and
- the degree of biodegradation of that constituent.

Most estimates from accelerated leaching studies in the laboratory suggest that at least three years is required to complete the leaching of constituents from wood residue. At many wood-residue sites in B.C., leaching continued well after three years from the time of the original deposit. Leaching generally progresses over a relatively long time period in dry areas of the Province. Fresh leachate can be produced from old wood residue that has not been subjected to weathering. Since wood residue decomposition is a comparatively slow process, by-products can continue to leach out over many decades. Numerous factors, including the consistency and thickness of the wood-residue deposit, influence the length of time required to reduce soluble extractives and other constituents to negligible amounts. No specific time frame can be specified for leachate generation time because it depends on site-specific conditions.

5.1.4 Volume of Leachate Generation

Many mathematical formulas have been proposed to estimate the volume of leachate generation from municipal landfills (Lu *et al.*1985). Such formulas are typically based on water-balance equations which can be used to size leachate containment, collection and treatment systems for deposits of wood residue as well. The volume of leachate that can be generated per year within a deposit of wood residue in the simplified situation shown in Figure 5.1 can be estimated by the equations outlined in the same figure.

Figure 5.1 Leachate generation at wood-residue sites.



$L = I - F - M + D$

$I = P - (R + E + T)$

$R = r \times P$

Where:

L = Leachate volume generated per year
I = Infiltration volume per year
F = Field capacity = Volume of moisture that can be retained in the cover material before percolation by gravity occurs
M = Volume of moisture that can be retained in wood residue before saturation occurs
D = Volume of moisture contributed from Wood-residue decomposition (usually negligible)
P = Precipitation volume per year
R = Runoff volume per year
E = Evaporation volume per year
T = Transpiration volume per year
r = Runoff coefficient

The volumes of water derived from precipitation, evapotranspiration and runoff are directly dependent on the climate, topography and hydrogeology of the site. The precipitation data in Figure 5.2 dictate that coastal regions of B.C. that have the highest precipitation require special measures for leachate management. The equations suggest that leachate contamination of groundwater is likely occurring or has occurred at many wood-residue sites in B.C. because such operations rely on natural attenuation of leachate and because impermeable bottom liners or berms and covering materials are seldom used.

The field capacity of cover material is calculated by dividing the weight of water retained in the soil at saturation by the dry weight of soil, multiplied by 100%. Field capacity depends on soil characteristics (usually 5% for sand and 25% for clay loam). When field capacity is reached, water will percolate by gravity through the cover material and enter the wood-residue deposit. Leachate will be formed after the wood residue becomes saturated with the infiltrating water. Covering materials are not provided at many wood-residue sites in B.C.; this further increases the volume of leachate that is generated. Covering the wood residue with an impermeable material will minimize leachate generation.

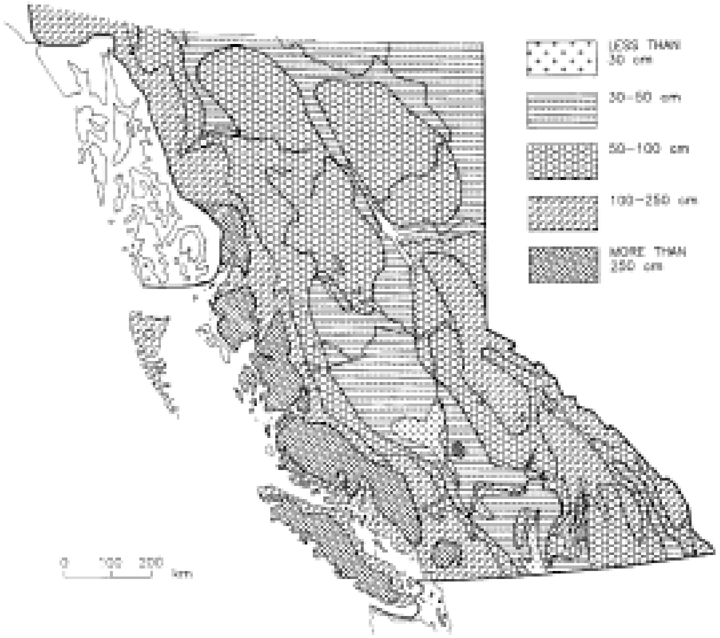
Other water balance equations must be used for scenarios where wood residue is deposited into the groundwater table and in contact with groundwater. In such cases, it is obvious that a large volume of leachate can be generated annually, especially with fast groundwater movement.

5.2 DIRECTION OF LEACHATE MIGRATION

Leachate, like water, migrates by gravitational percolation in the wood-residue deposit and the underlying soil via the path of least resistance. This usually means that leachate will migrate in a downward vertical direction. The installation of drain wicks, pilings or other structures within the wood-residue deposit or in underlying soil will promote the vertical migration of leachate. Increased lateral “channelling” of leachate within the wood-residue deposit or in the underlying soil can result from the presence of confining layers in the deposit or the soil. Confining layers can be formed by: compaction of the wood-residue deposit; compaction of underlying permeable soil by the weight of the wood residue or any overlying “preloads” or structures; or by the presence of a confining layer (e.g. impermeable soil) underlying the wood residue.

Once leachate is formed, it can appear as groundwater or surface water. Surface discharges of leachate at the base of wood-residue deposits can occur in areas characterized by highly compressible soils such as peat. Settlement and compression of peat by fill and preload can create an impermeable barrier that prevents downward migration of leachate and forces upwelling at the outer margins of the fill (Atwater 1980). Leachate will migrate into the groundwater if confining layers beneath the wood residue do not interrupt the flow. Leachate encountering a confining layer will migrate in a down-gradient direction and can appear in down-slope wells, springs, hill faces or streams. Surface leachate can only appears up-slope of a wood-residue site if an impermeable side-berm is keyed into an underlying confining layer.

Figure 5.2 Mean monthly precipitation at selected stations in British Columbia.



Source: British Columbia (1992).

If the wood residue is deposited in an area with a high groundwater table, leachate migration in the saturated soil is governed by percolation, but the migration rate is dependent on soil permeability, the hydraulic gradient and, to a lesser extent, by capillary diffusion and dispersion (Weiss 1974). Localized changes in the hydraulic gradient of the groundwater will alter the direction of leachate migration locally. However, the general direction of leachate migration away from the wood-residue site follows the same course as the groundwater movement surrounding the site.

Mathematical models are available to estimate the rate of leachate migration via chemical and physical means in saturated soil zones. Development of a single generic model for all situations is nearly impossible according to Lu *et al.* (1985). The use of models may be important in the selection process for a wood-residue site and in the associated monitoring requirements.

5.3 MONITORING WOOD-RESIDUE LEACHATE

Because monitoring practices at wood-residue sites are part of leachate control strategies, such practices are discussed in Section 8.8. There are no standardized procedures to sample for wood-residue leachate but the following information should be kept in mind during sampling or when specifying monitoring requirements.

5.3.1 Leachate Monitoring

Monitoring of leachate at wood-residue sites in B.C. is usually conducted on a monthly or quarterly schedule, mostly by visual observation. Inspection of a wood-residue site during a dry period often leads to the wrong conclusion that there is no leachate problem with the deposit. For practical reasons, it is nearly impossible to schedule inspections to coincide with the time when the fibre saturation point is reached in a deposit of wood residue, especially in remote areas of the Province. Unless wood residue is in contact with water all the time, there is no point in specifying a monitoring schedule that does not contain a proviso to conduct inspections during or immediately following a rainy period. Although visual inspections during rainy weather could be used to determine if surface leachate is present, (usually at the toe of the deposit), underground leachate is seldom detected due to the absence of any leachate collection works and monitoring wells at most wood-residue sites in B.C.

Monitoring of the leachate-receiving environment (e.g. streams or groundwater) is seldom practised in B.C. At a small number of wood-residue sites, receiving-environment monitoring is used to provide water-quality information on the unpolluted water (upstream of the leachate deposit) and the diluted leachate (downstream of the leachate deposit). Such receiving-environment monitoring cannot determine the localized effects of leachate seepage along the stream banks and bottom. In addition, monitoring of large streams will seldom yield test results that are of any real significance to the protection of biota, because survival of aquatic life is dictated not by average conditions, but by the extremes in the environment.

5.3.2 Leachate Sampling Locations and Procedures

Leachate should be sampled at the point where it exits the wood-residue deposit and be analyzed promptly (NCASI 1983). Concentrations of leachate constituents decrease because of degradation by micro-organisms and oxidation. In addition, dilution of leachate by surface and ground waters will lower the concentration of its constituents. Wood-residue leachate, which is generally anoxic within a wood-residue site, often becomes oxygenated when collected as a surface leachate sample. The further the leachate is sampled from its source, the more likely it is that the concentration of its constituents will have declined. For these reasons, it is important to understand the objectives of a leachate monitoring program before selecting sampling location(s).

Underground leachate can only be collected if a leachate-collection system and associated monitoring wells are installed at a wood-residue site. Leachate collected from groundwater monitoring wells is generally diluted with groundwater. If there is a high exchange of water in the groundwater (e.g. groundwater under tidal influence), test results will seldom yield results of any significance.

Specific leachate preservation and sampling techniques should be discussed with the laboratory analyst. The following points should be kept in mind when specifying wood-residue leachate sample collection procedures to satisfy specific objectives of a monitoring program.

5.3.2.1 Foam

Agitation of a liquid containing wood-residue leachate can result in foam formation. Such foam consists of toxic wood-resin constituents (e.g. resin acids and fatty acids). In an effort to fill a container completely with leachate, foam is often flushed out and not collected. If foam is not collected, the leachate sample will likely be less toxic.

5.3.2.2 Slicks

Surface slicks on stagnant wood-residue leachate are associated with toxic terpenes. Agitation of the leachate pool can quickly result in the disappearance (i.e. dispersion) of such a slick. Dipping the mouth of a sample container below the surface of a leachate pool will likely result in a sample that is less acutely toxic than if the slick is collected.

5.3.2.3 Sediments

Resin acids have an affinity for solids and tend to accumulate and persist in bottom sediments of receiving waters. Chelated, coloured metal complexes of tannins and tropolones settle on the bottom of leachate streams and receiving waters. Leachate sampling usually results in the disturbance and subsequent collection of some bottom sediment. The concentration of leachate constituents in such a sample (i.e. a sample containing liquid plus some sediment) should be higher than in an all-liquid sample.

5.3.2.4 Sample Agitation

As indicated above, agitation of the leachate or sample container could result in foam formation, dispersion of a slick and re-suspension of bottom sediments. Loss of dissolved gases such as carbon dioxide and aeration of the leachate will also result from agitation of the leachate or sample container. Field pH measurements of wood-residue leachate are often lower than those measured in the laboratory because of loss of carbon dioxide due to agitation and temperature changes during sample transport.

In instances where leachate cannot be collected, leachate can be generated using representative samples of the wood residue. Although standardized leaching procedures are not established to generate leachate from wood residue, the Department of the Environment (DOE) has followed a procedure that involves mixing wood residue and dechlorinated tap water at a ratio of 1:4 (w/w) with sufficient volumes to generate leachate for bioassay and chemical analyses. The mixture of wood residue and water is allowed to soak in a 45-gallon plastic barrel for 96 hours before the leachate is collected.

5.4 PARAMETERS FOR ANALYSIS IN WOOD-RESIDUE LEACHATE

Because some parameters such as pH change between field and laboratory, on-site analyses should be conducted wherever possible. However, many leachate constituents can only be identified using sophisticated laboratory techniques such as gas-liquid chromatography and infrared spectrophotometry.

Most laboratories are equipped to analyze specific classes of compounds or key parameters of concern in wood-residue leachate. Specific classes of compounds of concern in leachate include: tannins and lignin, phenolics, tropolones and resin acids. Analytical results for individual compounds and some of the classes of compounds can be meaningless given that specific environmental effects have not been correlated with many constituents of wood residue. The available information on fisheries impacts of wood-residue leachate constituents is summarized in Section 7. Parameters of concern for the protection of aquatic life include: pH, colour, dissolved oxygen (DO), total organic carbon (TOC), biochemical oxygen demand (BOD), chemical oxygen demand (COD) and toxicity. Table 5.1 shows the concentration of different parameters in a typical hogfuel leachate generated in a lysimeter study.

Although measurements of acidity, pH, colour, conductivity and oxygen demand have been used to estimate leachate strength and toxicity, experience has shown that such correlation is often unreliable. For this reason, chemical analyses are often accompanied by a bioassay test. Compared to chemical analyses, bioassay tests give a more reliable indication of leachate strength and toxicity because bioassays integrate the toxic effects of a combination of different constituents. Fish are usually used as test organisms in bioassays.

Aeration during a fish bioassay could affect the test result because aeration reduces oxygen demand (and increases the DO) of the sample and enhances degradation of some constituents in the leachate. Aeration beyond the condition prescribed in standard fish bioassay references is considered as a form of "treatment" of the leachate sample. Artificial adjustment of sample pH to neutrality could similarly reduce toxicity (Cameron 1982).

Acidity is a measure of the alkaline buffering capacity by some acids (e.g. carbonic, acetic and tannic acids) and some hydrolyzing metal salts that could be found in leachates. However, acidity is not a measure of the buffering capacity of many organic acids that are commonly found in wood-residue leachate (e.g. volatile fatty acids; fumaric, lactic, succinic, gallic and phthalic acids).

Since many of the chemical constituents in wood-residue leachate are electrolytes, specific conductance is often used as an indirect indicator of the amount of dissolved solids in the leachate and leachate strength. The use of specific conductance is not always reliable because it also reflects the presence of electrolytes (e.g. iron) leached from the soil.

The organic content of wood-residue leachate is usually estimated by BOD, COD or TOC. A BOD test will indicate the approximate oxygen requirements of micro-organisms which oxidize the organic material in the leachate. COD is an estimate of the chemical oxidization potential of organic material in the leachate. TOC is a measure of the organic carbon content of the leachate. Wood-residue leachate samples almost always have a greater COD than BOD or TOC.

Table 5.1 Characteristics of wood-residue leachate generated in a lysimeter study using hogfuel.

Parameter	Concentration (mg·L^{-1})[a]
COD	1100
BOD	550
NH_3 (as N)	0.4
total phosphorus	1
sulphide	1.5
tannin and lignin	1400[b]
arsenic	<0.2
cadmium	<0.002
copper	0.005
iron	16.1
lead	<0.02
manganese	1.9
mercury (µg·L^{-1})	<5
zinc	0.005
pH	3.5 – 6.5[c]

[a] Except pH which is pH units.

[b] Cameron *et al.* (1975). (leachate derived from western hemlock)

[c] Haygreen and Bowyer (1989).

Source: Birkbeck *et al.* 1990.

In terms of environmental effects, BOD is probably more appropriately used than COD since organic decomposition is mainly by microbial action. COD tests are not conducted on marine leachate samples because of interference by chloride ions. In the COD test, many but not all organic constituents in the leachate are oxidized. Straight-chain aliphatic compounds and aromatic hydrocarbons are not oxidized by the acids used in the COD test. The BOD:COD ratio can be used as a measure of biodegradability. A ratio of 0.5 suggests that the leachate is relatively biodegradable while a 0.1 ratio suggests low biodegradability (Crawford and Smith 1985). Peat water, containing fulvic and/or humic acids, generally has a low level of microbial activity and a low BOD:COD ratio.

The standard tannins and lignin analytical procedure relies on a colour reaction with the Folin phenol reagent. However, many reducing compounds can confound the result. Unless it is certain that there are no other reducing compounds present in the sample, the analytical result may have very little meaning. Analysis for phenolics is sometimes conducted in place of the standard tannins and lignin test. There are many different phenolic test procedures. The 4-aminoantipyrine colourimetric test method includes the analysis of para-hydroxybenzoic acid (PHBA), found in large amounts in aspen (Section 3.1.2.3).

Redox potential can give a rough indication of the presence or absence of oxygen. A low redox result generally indicates an anaerobic or reducing condition in the wood-residue site. Monitoring for carbon dioxide, methane, oxygen and total microbial count can also give an indication of the microbial activities at the wood-residue site.

6.0 CHARACTERISTICS OF LEACHATE

This section includes information on the characteristics of leachate derived from wood residue, wood ash and peatland. Information on wood ash and peatland are included because they are often associated with wood residue use and disposal in B.C.

6.1 WOOD-RESIDUE LEACHATE

Wood-residue leachate is a liquid generated through contact with precipitation, surface water and/or groundwater. Wood-residue leachate contains the dissolved and suspended chemical constituents of wood and the decomposition by-products of wood. The mechanism of leachate generation is outlined in Section 5.1. Wood-residue leachate is characterized by dark colouration, petroleum-like odour, white foam and in some cases, an iridescent sheen. Leachate is oxygen demanding, acidic and contains high levels of dissolved metals. Leachate from a landfill with biodegradable organic materials, such as wood residue, is generally anoxic.

When wood residue is in contact with water, its water-soluble constituents begin to leach immediately. These constituents include tannins, simple sugars, organic acids, short-chain alcohols, inorganic minerals and the by-products of microbial decomposition. Some of the water-insoluble constituents, including polysaccharides, fatty acids and resin acids, leach to a lesser extent. Other insoluble constituents, such as lignin, are not found in high concentrations in wood-residue leachate.

Hydraulic debarking and bark-pressing effluents have similar characteristics as those of wood-residue leachate except that the former have higher fibre content. Log-conditioning effluent (e.g. from veneer plants) contains a higher concentration of chemical constituents than that which occurs in leachate from wood-residue landfills. The higher concentration of chemical constituents results from the high temperature used in the log-conditioning process that increases the solubility of the chemical constituents.

Wood-residue leachate is acidic - its pH ranges from 3 to 6.5 pH units - largely due to the reaction of carbon dioxide (generated from biological decomposition) with water to produce carbonic acid. Organic acids in leachate, which contribute further to acidity, are derived from the soluble extractive components of wood residue. Peters *et al.* (1976) reported that leaching of plicatic acid from western red cedar heartwood was, at least in part, responsible for the sharp drop in leachate pH during the initial leaching phase. Leachate derived from bark is usually more acidic than that derived from wood of the same tree because of the higher concentration of tannins in bark than in wood (Haygreen and Bowyer 1989).

The dissolution and precipitation of specific metals follow unique pH equilibrium curves. Most metals exist in the solubilized form under acidic conditions and in the precipitated form under neutral or basic conditions. Many metal oxides (e.g. iron oxide) in soil can be solubilized upon contact with leachate. Dissolved metals in acidic wood-residue leachate originate primarily from soil or groundwater. If re-precipitation of dissolved iron occurs, sediments may become rusty; if reprecipitation of aluminum occurs, the sediments may be white in colour.

Wood-residue leachate that has not come into contact with soil or air is anoxic and has a dark colour. Rapid change of the anoxic leachate to black on exposure to air is caused by the oxidative condensation of tannins (Schermer and Phipps 1976). The chelation of tannins with naturally-occurring, dissolved iron from soil causes the formation of blue-black complexes in wood-residue leachate (Thomas 1977), an effect which is detectable at tannic acid concentrations as low as 0.4 $mg{\cdot}L^{-1}$ (Sweet and Fetrow 1975). The chelation of tropolones with dissolved iron causes the formation of red-coloured complexes in leachate from western red cedar heartwood. Tannins can also form other coloured complexes with other dissolved metals in the leachate. Many surface leachate streams may appear coloured but on closer examination, most of the colour is in the sediments, whereas the liquid portion is colourless. This phenomenon is the result of precipitation and settlement of coloured complexes or, alternatively re-precipitation of previously-dissolved metal ions such as iron, aluminum and manganese (Sweet and Fetrow 1975).

The petroleum-like odour of wood-residue leachate is primarily due to the presence of phenolic compounds and volatile oils (McNeeley *et al.* 1979). Different wood species can confer different, characteristic odours. Very foul odours have been reported at many wood-residue sites during the warm seasons. Such odours are caused by the metabolites and decomposition products of fungi and other micro-organisms that proliferate at certain times of the year. Except for hydrogen sulphide, most of the gases associated with the microbial decomposition of wood residue are odourless.

Much of the foaming that occurs when wood-residue leachate enters receiving waters is due to wood resin. Iridescent slicks on the surface of stagnant pools of wood-residue leachate or receiving waters are due to the presence of terpenes. Such slicks are seldom observed in free-flowing leachate streams or receiving waters because agitation causes slicks to disperse.

Wood residue and/or leachate will exert an oxygen demand when discharged into receiving waters because the organic constituents undergo aerobic microbial decomposition. The decomposition of dying micro-organisms may further lower the dissolved oxygen concentration in a receiving water body.

6.2 WOOD-ASH LEACHATE

Wood ash generated as a result of the combustion of wood residue may contain high concentrations of certain metals (e.g. sodium, potassium, magnesium and calcium) in either the oxide or hydroxide forms. Metal oxides react with water to form metal hydroxides and carbonates, which account for the high pH (>9) of water in contact with wood ash. Since metal solubilities follow specific pH equilibrium curves, the concentrations of metals in wood-ash leachate will not necessarily be proportional to those in wood ash.

When wood ash and wood residue are deposited together, two different types of leachate can result which, when combined, can exhibit a near neutral pH. Acidic wood-residue leachate can solubilize the metals in wood ash but the resulting metal ions will re-precipitate at near neutral pH, resulting in streaks of coloured sediment in the combined leachate streams.

6.3 PEATLAND LEACHATE

The chemistry of peat water depends on the characteristics of the peatland (Section 3.4), the sources of water and the depth of the water.

The chemical constituents of bog water are largely derived from the decomposition of the organic peat material. Bog water contains dissolved/suspended organic matter, carbon dioxide, minerals and nutrients (Monenco Maritimes Ltd. 1986; Fuchsman 1980). The organic constituents in peat water depend on the type of decomposed plants that are deposited in the peatland. Acid-insoluble humic acids are formed from reactions and decomposition of chemical constituents in plants and constitute a large component of peat and peat water.

Peat water in bogs that supported woody plants has similar characteristics to leachate generated from weathered wood residue. However, in peat water the concentration of water-soluble constituents in particular, will be lower than that in wood-residue leachate because the organic components have generally undergone extensive prior leaching and decomposition. In general, peat water darkens and its pH increases with increasing depth in the peatland. The pH of bog water (3 to 5) is usually lower than that of fen water. The sources of the acidity in bog water are organic acids (low molecular weight carboxylic acids: acetic and oxalic; high molecular weight/complex fulvic and humic acids). Precipitation is the primary source of water in bogs.

The chemical constituents of fen water are determined mainly by the characteristics of the inflowing surface and groundwater and to a lesser extent, from decomposition of organic peat materials. Other than precipitation, mineralized, alkaline groundwater and surface waters are primary sources of water for fens. Fen water is generally less acidic (i.e. pH 5.5 to 6.5), more mineralized and richer in nutrients than bog water.

The surface water in peatland may have dissolved oxygen concentrations similar to those of unpolluted receiving water bodies. Deep peat water is often anoxic (Levesque *et al.* 1987; Fuchsman 1980; Maynard 1989).

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7.0 IMPACTS OF WOOD RESIDUE AND LEACHATE ON FISH AND FISH HABITAT

7.1 BIOPHYSICAL IMPACTS OF WOOD-RESIDUE DEPOSITS

Fish habitat is defined in Section 34(1) of the *Fisheries Act* as:

> " . . . spawning grounds and nursery, rearing, food supply and migration areas on which fish depend directly or indirectly in order to carry out their life processes."

To make more land, wood residue has been deposited into foreshore areas, marine intertidal zones, marshes, riparian areas and near estuaries. Wood-residue deposits in fish habitat have also resulted from forest harvesting operations, log dumping, log sorting and wood processing (e.g. from log decks, bucking in water, discharge of hydraulic debarker effluent, improper storage of wood residue, scow loading). When deposited in water, wood residue will quickly absorb water and sink. The placement of wood residue into or adjacent to fish habitat can result in the physical alteration, disruption or destruction of the habitat. In addition, aquatic resources may be affected by the formation of leachate. Problems associated with the deposition of wood residue in fish habitat are discussed in detail in the Department of Fisheries & Oceans' (DFO) *Handbook for Fish Habitat Protection on Forest Lands in B.C.* (Toews and Brownlee 1981).

The impact of the aquatic deposition of wood residue has been investigated at a number of industrial log handling sites. Impacts include an overall decrease in species diversity, abundance and biomass, particularly with regard to the benthic invertebrate community. Most benthic organisms (e.g. fish-food organisms), particularly infaunal invertebrate species (i.e. those living within the sediments), cannot survive in the anoxic conditions that are often created by wood-residue deposition. Suspension-feeding bivalves, crustaceans and polychaetes which rely on unobstructed access to the water column are negatively affected by wood-residue deposits (Pease 1974; Conlan and Ellis 1979). The placement of wood residue in unstable areas, such as within marine intertidal zones or near estuaries, can result in the re-suspension of materials in the water column and subsequently, settling and smothering of benthic communities in adjacent areas. A continuous layer of wood debris in aquatic habitat presents a significant obstacle to the settlement and recruitment of benthic organisms. The net result can be an area of significantly reduced fish productivity.

In the extreme case, wood residue can present a physical barrier to fish migration in streams. In addition, wood residue can reduce critical living space for aquatic life in shallow, nearshore areas where juveniles typically rear. Wood residue deposited in streams, along lake margins or in marine foreshore areas may clog gravel and result in the permanent alienation of such areas (e.g. spawning beds) that are essential for fish production. Fish eggs, alevins and aquatic plants can be buried, displaced or asphyxiated by the deposition of wood residue. Interstitial water flow responsible for oxygen transfer to incubating eggs and developing alevins in stream gravels can be altered by wood-residue deposition. Such a reduction in oxygen supply may result in direct mortality or a decrease in the rate of growth. A delay in the emergence of fry, a condition that can reduce fish production, may result from exposure to sub-optimal environmental conditions such as temperature extremes and lower rates of water flow.

Temperature in a small receiving stream could rise appreciably as a result of the biological and thermal decomposition of wood residue and its leachate. Elevated concentrations of hydrogen sulphide and ammonia have been detected in the anoxic interstitial water of submerged bark deposits associated with marine and estuarine log handling facilities (Freese and O'Clair 1987). Wood residue that decomposes under anoxic conditions, especially in seawater, can produce methane and/or hydrogen sulphide gases. Such gases are soluble in water and can be acutely lethal to aquatic organisms, especially in poorly flushed areas. The disturbance of sediments containing such gases during dredging may result in toxic conditions in the overlying water. A number of fish kills have occurred during dredging of foreshore deposits of wood residue.

7.2 TOXICITY OF WOOD-RESIDUE LEACHATES TO FISH

When leachate is discharged into a watercourse, the plume may extend downstream into shallow, slow-flowing areas near shore, where juvenile fish rear. The response of fish to a leachate discharge depends on the fish species and its life-cycle stage. Most of the available studies on the impacts of wood-residue leachate to aquatic organisms were conducted in the 1970's. Researchers have studied toxicological effects using various bioassay methods that have involved the introduction of aquatic organisms to dilutions of wood-residue leachate or specific constituents for various periods of time. It is difficult to compare the test results of past studies because they were generally inconsistent in terms of the type of leachate used, the preparation methodology, bioassay procedure and/or organisms tested. The bioassay results presented in this section provide an indication of the toxicity of wood-residue leachate and constituents. However, the results are only strictly valid within the context of the relevant experimental conditions. Only studies on the toxicity of leachate to fish and invertebrates (e.g. fish-food organisms) are discussed here.

7.2.1 Acute and Sub-Acute (Chronic) Toxicity

In order to reduce experimental variability, **acute toxicity** is evaluated through the use of standardized bioassay procedures in which organisms (usually fish) are exposed to a test substance or mixture (e.g. leachate) under controlled conditions at specified concentration(s) for relatively short durations (usually 96 hours). The 96-h LC50 (i.e. median lethal concentration) value obtained in an acute toxicity test refers to the concentration of a substance that kills one-half the test organisms in a 96-hour period; the lower the test result obtained, the more toxic the substance. The LT50 (i.e. median lethal time) test result is the time to death of one-half of the test organisms in a specified concentration of a substance (usually 100%).

Chronic or **sub-acute toxicity** is defined as the toxic or harmful effects of a substance that may not be evidenced in an acute (i.e. short-term) bioassay test, but which, directly or indirectly, can be detrimental to the survival of the organism or the population. Sub-acute toxic impacts include behavioural, physiological or reproductive effects evaluated through long-term (i.e. greater than 96 hours) bioassay tests.

7.2.1.1 Toxicity of Whole Leachates

Acute lethality tests have been performed on the leachate derived from several wood species. Table 7.1 summarizes the results from a number of studies. The toxicity of the extract used in the acute toxicity bioassay conducted by Temmink *et al.* (1989) was attributed to the presence of tannins, which represented 50 to 60% of the total COD in the samples. As a result of exposure to

Table 7.1 Summary of findings from selected acute toxicity tests for leachate derived from various wood species.

Type of wood	Test	Concentration/ Lethal time	Test organism	Source
sitka spruce[a]	96-h LC50 in fw	25 – 40 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
western red cedar[a]	96-h LC50 in fw	35 – 45 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
western hemlock[a]	96-h LC50 in fw	75 – 90 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
yellow cypress[a]	96-h LC50 in fw	> 50 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
sitka spruce[a]	96-h LC50 sw	> 200 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
western red cedar[a]	96-h LC50 sw	> 200 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
western hemlock[a]	96-h LC50 sw	> 200 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
yellow cypress[a]	96-h LC50 sw	150 – 200 $mg \cdot L^{-1}$	pink salmon fry	Pease (1974)
western hemlock[b]	96-h LC50 sw	56 $mg \cdot L^{-1}$	pink salmon fry	Buchanan *et al.* (1976)
sitka spruce[b]	96-h LC50 sw	100 – 120 $mg \cdot L^{-1}$	pink salmon fry	Buchanan *et al.* (1976)
western red cedar[c]	LT50 in sw	18 – 25 h	coho salmon fry	Peters *et al.* (1976)
Norway spruce[b]	96-h LC50 (semi-static)	50 $mg \cdot L^{-1}$ (in terms of COD)	carp	Temmink *et al.* (1989)

[a] freeze-dried extract derived from intact log sections used.

[b] bark extract used

[c] heartwood blocks (22.7 L volume and 3.2 m^2 surface area) submerged in a continuous flow of dechlorinated tap water at 14.3 $L \cdot h^{-1}$ for 85 days. Approximately 2.4 L of acutely toxic leachate were produced per gram of heartwood.

fw – freshwater; sw – salt water

the extracts, the secondary gill lamellae of the fish completely fused. Subtle behavioural changes, including delayed feeding, surface swimming and contact with the side of the aquarium, were observed in carp exposed to sublethal concentrations of bark extracts from Norway spruce in a flow-through bioassay (Temmink *et al.* 1989). Changes in fish behaviour occurred at concentrations above 6.31 $mg \cdot L^{-1}$ total COD and increased in intensity with time over the 96-hour test period. Although the gills of these fish had lesions similar to those observed in the acute-exposure test, complete fusion of secondary lamellae occurred only rarely at the highest exposure level of 39.81 $mg \cdot L^{-1}$ COD. Such physiological changes can result in the eventual death of the fish.

In freshwater, flow-through experiments involving sockeye salmon, Servizi *et al.* (1970) observed no significant mortality from the egg to fry stage in fish incubated in gravel containing a 1% concentration of bark fragments derived from a mixture of fir, lodgepole pine (*Pinus contorta*) and Engelmann spruce (*Picea engelmannii*). They concluded that water velocities equivalent to those occurring in natural spawning grounds (i.e. 10 to 15 $cm \cdot h^{-1}$) likely prevented the accumulation of lethal concentrations of toxic substances. The increase in mortality that was observed at a lower water velocity (i.e. 5 $cm \cdot h^{-1}$) and at 10% concentration of bark fragments was attributed to localized clogging of the gravel rather than leachate toxicity.

7.2.1.2 Toxicity of Resin Acids Constituents

Research has shown that the toxicity of hydraulic debarker effluent generated from spruce, pine and fir is associated with dissolved rather than suspended solids. Fatty and resin acids in the effluent accounted for 90% of the toxicity (B.C. Research 1977). Using spruce and lodgepole pine, the fatty and resin acids in mechanical pulping effluent accounted for 60 to 90% of effluent toxicity (B.C. Research 1975). Resin acids have been linked to as much as 70% of the acute toxicity of mechanical pulping effluents (Leach and Thakore 1976).

Although it is not possible to make a direct comparison between pulping effluent and wood-residue leachate because the mechanical pulping process involves hot-water rather than cold-water extraction (Evans 1973), resin acids are known to play a significant role in the toxicity of wood-residue leachate. Seven resin acids identified in pulp mill effluent derived from softwood bark have been found to be toxic: abietic, dehydroabietic, isopimaric, neoabietic, palustric, pimaric and sandaracopimaric acids (McKague *et al.* 1977). Since Douglas-fir and species of pine, spruce and larch have relatively high resin acid content, the toxicity to fish of leachate derived from these species is of particular concern.

Table 7.2 Recommended surface water criteria for dehydroabietic acid (DHA) and total resin acids (provisional) for the Province of Ontario.[a]

	Concentration ($\mu g \cdot L^{-1}$)	
Receiving water pH[b]	DHA	Total Resin Acids
5.0	1	1
5.5	2	3
6.0	2	4
6.5	4	9
7.0	8	25
7.5	12	45
8.0	13	52
8.5	14	60
9.0	14	62

[a] based on criteria of 8 $\mu g \cdot L^{-1}$ for DHA and 25 $\mu g \cdot L^{-1}$ for total resin acids at pH 7.0.

[b] pH values < 6.5 do not meet Ontario Water Quality Objectives. Source: Taylor *et al.* (1988).

Taylor *et al.* (1988) published a resin acids criteria development document for the Province of Ontario; Table 7.2 summarizes Ontario's maximum resin acid concentrations for protection of aquatic life. These guidelines reflect the fact that the toxicity of resin acids increases with a decrease in pH from 7.0 to 6.4 (B.C. Research 1975).

Kruzynski (1979) reported 96-h LC50s ranging from 0.50 to 0.88 $mg \cdot L^{-1}$ for dehydroabietic acid in freshwater using sockeye salmon smolts (Table 7.3). The 0.50 $mg \cdot L^{-1}$ 96-h LC50 was attributed to a decrease in dissolved oxygen to 70% of saturation. In that study, when the dissolved oxygen level was maintained above 90% saturation, the 96-h LC50 remained above 0.79 $mg \cdot L^{-1}$ dehydroabietic acid. During this series of experiments, Kruzynski observed that smolts exposed to dehydroabietic acid exhibited a gradual deterioration in schooling and fright responses, followed by hypersensitivity to mechanical stimuli and abnormal swimming behaviour.

From a review of the available information, Taylor *et al.* (1988) predicted that the 96-h LC50 for any resin acid at circumneutral pH using rainbow trout would be in the 0.5 to 1.5 $mg \cdot L^{-1}$ range. Changes in other receiving water parameters such as salinity and temperature may be expected to influence the toxicity of soluble extractives of wood residue. Kruzynski (1979) observed that exposure of sockeye salmon smolts in freshwater to a sublethal concentration of dehydroabietic acid (0.63 $mg \cdot L^{-1}$) reduced their subsequent survival in clean sea water (salinity = 27 ‰). This result indicates that juvenile salmonids may be particularly vulnerable to exposure to the toxic components of wood-residue leachate immediately following their arrival in estuarine waters where they undergo physiological adjustment to saline conditions. Exposure to sublethal con-

Table 7.3 Summary of acute toxicity tests using various resin acids.

Resin Acid	Test	Concentration	Test species	Source
Dehydroabietic acid	96-h LC50	1.8 $mg \cdot L^{-1}$	coho salmon	Davis and Hoos (1975)
Isopimaric acid	96-h LC50	0.22 $mg \cdot L^{-1}$	coho salmon	Leach and Thakore (1977)
Dehydroabietic acid	96-h LC50	0.50 – 0.88 $mg \cdot L^{-1}$	sockeye salmon smolts	Kruzynski (1979)
Abietic acid	96-h LC50	0.2 $mg \cdot L^{-1}$	sockeye	Servizi *et al.* (1986)
Dehydroabietic acid	96-h LC50	2.1 $mg \cdot L^{-1}$	sockeye	Servizi *et al.* (1986)

centrations of wood-residue leachate could affect the survival of fish migrating from freshwater into sea water.

Resin acids have a relatively high affinity for solids. As a consequence, they tend to accumulate and persist in the bottom sediments of receiving waters. A half-life of 21 years has been estimated for sediment-bound dehydroabietic acid, the most common resin acid (Brownlee *et al.* 1977); whereas the half-life of dehydroabietic acid in water is estimated to be approximately 6 weeks.

7.2.1.3 Toxicity of Other Leachate Constituents

The high concentration of tannins in the bark of western hemlock and the presence of tropolones in western red cedar heartwood create significant concerns regarding the toxicity of the leachate derived from these species. Much of the toxicity of hydraulic debarker effluent and wood-residue leachate is attributable to tannins (Field *et al.* 1988). Tropolones are responsible for much of the toxicity associated with leachate derived from western red cedar.

The following discussion on toxicity of the terpene, lignan and tropolone components of western red cedar wood-residue leachate is derived from the bioassay work of Peters *et al.* (1976). A 96-h LC50 of 2.7 mg·L^{-1} was reported for coho salmon exposed to terpene extract. A 120-h LC50 using coho salmon ranged from 33 mg·L^{-1} for alevins to 60 to 64 mg·L^{-1} for fry that were exposed to lignan extract. A 96-h LC50 of 0.33 mg·L^{-1} was reported for an extract containing the four major tropolones and thujic acid using coho salmon. In contrast, eyed eggs survived an exposure to 2.5 mg·L^{-1} of tropolone extract over a 240-h period. Although fertilization of salmon eggs was inhibited at a tropolone concentration of 0.7 mg·L^{-1}, hatching was unaffected by concentrations as high as 7.0 mg·L^{-1}.

An increase in temperature from 10.5 to 18.5°C lowered the median survival time from 23.5 to 5.1 hours for coho salmon fry exposed to 1.25 mg·L^{-1} of western red cedar heartwood tropolone extract. This result indicates that aquatic organisms that inhabit shallow water bodies or surface water layers, where periodic extremes in temperature occur, may be particularly vulnerable to the toxic effects of tropolones and perhaps to other components of wood-residue leachate.

A 60-hour exposure to a sublethal concentration (i.e. 0.23 mg·L^{-1}) of western red cedar tropolone extract resulted in an increase in the tolerance of coho (i.e. the 96-h LC50 went from 0.31 to 0.72 mg·L^{-1}) to tropolone extract. This result indicates that acclimatized aquatic organisms could perhaps become more resistant to higher concentrations of tropolones and perhaps to other toxic components of the wood-residue leachate. However, further experimentation is required before such a conclusion can be made.

There are indications that the presence of metal ions may reduce the toxic effects of wood extractives, likely as a result of chelation. Peters *et al.* (1976) observed that a 1.25 mg·L^{-1} solution of heartwood tropolones from western red cedar was rendered non-acutely toxic to juvenile coho salmon in a solution with a total iron concentration of 0.43 mg·L^{-1} or greater. Further experimentation is required to assess the significance of this finding.

Very few studies have been conducted on the toxicity of hardwood leachate to fish. A relatively recent laboratory study revealed that water-soluble phenolic compounds are the main toxic constituents in leachate generated from aspen wood chips (Goudey and Taylor 1992).

7.2.1.4 The Effect of Other Wood-Residue Leachate Characteristics on Fish Survival

In addition to the toxic resinous and phenolic constituents of wood-residue leachate, several other characteristics of wood-residue leachate can effect fish survival. These include pH, BOD, COD and dissolved oxygen content. The characteristic dark colour and strong odour of wood-residue leachate may have an additional impact on fish feeding, migration and the utilization of certain aquatic habitats. Suspended solids in the leachate could bury fish food organisms and clog the gills of fish.

The discharge of wood-residue leachate may result in an increase in acidity (i.e. a decrease in pH) in the receiving waters, depending on the volume and concentration of the leachate and the available dilution. The pH of leachate significantly influences its toxicity (Haygreen and Bowyer 1989; McLeay *et al.* 1979; Cameron 1982). In most cases, the toxicity of wood-residue leachate declines as pH rises toward neutrality. Increased hydrogen ion concentration (i.e. lower pH) will result in precipitation of mucous on the gill epithelium and precipitation of proteins within the epithelial cells. The toxic actions of low pH may or may not be reversible, depending on the extent of damage that has occurred. In addition, the toxic actions of low pH will likely make the fish more susceptible to the effects of other toxicants, diseases and hypoxic conditions.

The presence of wood-residue leachate in fish habitat can result in localized depletion of dissolved oxygen and therefore may influence the distribution of fish and other aquatic organisms. Habitat shifts and other changes in fish behaviour occurring in response to sublethal concentrations of leachate may be associated with a variety of biophysical factors, such as reduced food availability and increased risk of predation, that ultimately determine the fitness and survival of fish. In general, most fish avoid aquatic habitats that are characterized by low levels of dissolved oxygen (Kramer 1987). Juvenile salmon, for example, have been observed to consistently avoid waters containing less than 7 to 8 $mg \cdot L^{-1}$ dissolved oxygen (Birtwell and Kruzynski 1989).

The avoidance by juvenile sockeye salmon of a log dump site in a protected bay off a narrow arm of Babine Lake in May 1985 was attributed to hypoxic conditions generated by the presence of leachate from floating logs (Levy *et al.* 1989). Limited water circulation and mixing during a period of rapid warming in the lake were thought to be responsible for maintaining and exacerbating these conditions. The concentration of leachate originating from a wood-residue landfill, however, would be expected to be considerably greater and therefore more toxic and associated with lower dissolved oxygen levels, than leachate emanating from a log dump site. Further, the impact of concentrated wood-residue leachate on BOD/COD levels would be accentuated in low flow conditions such as those encountered in shallow, slow moving streams or drainage ditches. Hypoxic conditions would be less likely to persist in areas subject to a high volume of water exchange.

Low levels of dissolved oxygen in the presence of toxicants, such as resin acids, may exacerbate the impact of those compounds on fish and other aquatic organisms (Kruzynski 1979; Werner and Robinson 1978; Davis 1975b). Hypoxic conditions generally induce metabolic stress that is typically associated with an increase in respiration rate, increased toxicant uptake and lowered resistance to toxicants (Davis 1975b). Fish exposed to resin acids have been observed to exhibit symptoms of respiratory distress characterized by coughing and increased gill ventilation (Taylor *et al.* 1988). This response may be of critical importance in situations involving exposure to wood-residue leachate. When exposed to the hypoxic conditions that are typical of receiving waters containing leachate, fish may be stressed to the point that they succumb to that which would ordinarily be a sublethal concentration of the toxicant (Kruzynski 1979).

Fungal and bacterial growths, which often accompany decomposition of wood residue and leachate, can also affect fish and fish habitat. Such growths can restrict water flow and oxygen exchange in a stream, affecting the survival of fish eggs and developing alevins. Microbial growth can physically impair the movement of juveniles fish in the water column. The micro-organisms could even grow directly on the gills, rendering the fish more susceptible to the previously-mentioned water quality or habitat changes caused by the wood residue and its leachate.

The dark colour of wood-residue leachate may also influence the distribution of certain aquatic organisms. One may expect that fish would avoid areas where their ability to detect prey is impaired. However, some fish species may actually be attracted to leachate plumes by the prospect or illusion of shelter that is offered by the dark waters. Moore (1990) observed schools of three-spine stickleback (*Gasterosteus aculeatus*) gathering in shallow watercourses contaminated with wood-residue leachate.

7.3 TOXIC EFFECTS OF WOOD-RESIDUE LEACHATE ON INVERTEBRATES

The toxicity of leachate to aquatic invertebrates is important because these organisms are used as food by fish. The availability of aquatic invertebrates may determine the distribution and survival of individual fish and fish populations.

The presence of wood-residue leachate may reduce the ability of aquatic plants to carry out photosynthesis and thus result in a decrease in primary production in fish habitat. This effect can result in reduced dissolved oxygen and disruption of benthic invertebrate community structure. Such impacts may be exacerbated by the toxic effects that wood-residue leachate appears to have on emergent vegetation.

Peters *et al.* (1976) investigated the effect of heartwood extractive of western red cedar on mayfly nymphs. A 120-h LC50 of 80 $mg \cdot L^{-1}$ was reported for lignan extract using mayfly nymphs. A 96-h LC50 of 4.4 $mg \cdot L^{-1}$ was reported for an extract containing tropolones and thujic acid. In another study, Buchanan *et al.* (1976) reported 96-h LC50s of 415 $mg \cdot L^{-1}$ for larval pink shrimp, 205 $mg \cdot L^{-1}$ for adult pink shrimp and 530 $mg \cdot L^{-1}$ for larval Dungeness crab exposed to extracts of sitka spruce bark.

Using 21-day chronic bioassays, Hensel (1990) observed the effect of wood-residue leachate on the timing of emergence and number of offspring produced by the cladoceran, *Daphnia magna* (water flea). Relative to the control, mean time to emergence in a 1% leachate solution of wood-residue leachate decreased from 12 to 9 days. In contrast, mean time to emergence in a 5% solution increased to 14 days. The number of total offspring produced increased from approximately 80 per female in the control and 0.2% solutions, to 115 in the 0.5% solution and 160 in the 1% solution. In the 5% solution, the number of offspring decreased to approximately 10 per female, all of which subsequently died.

Wood-residue leachate can have direct impacts on the survival of aquatic organisms other than fish, which can lead to effects on fish production. The dark colour and foam of leachate will reduce light penetration for the photosynthetic processes critical for aquatic plant production, which will in turn affect re-oxygenation of water and fish food production. Reduction or elimination of fish food organisms may render some habitat unsuitable for fish use.

7.4 BIOACCUMULATION POTENTIAL OF LEACHATE CONSTITUENTS

Recent scientific literature contains few references on the potential for bioaccumulation of, or the tainting (taste/odour) of fish tissue by, the components of wood-residue extractives. However, a description of the bioaccumulation of resin acids is contained in the scientific criteria document prepared for the Province of Ontario (Taylor *et al.* 1988).

Since resin acids are hydrophobic, they readily partition from water into the fatty tissues of fish following uptake across the surfaces of the gills (Kruzynski 1979). There is speculation that uptake may occur as a result of ingestion of contaminated food organisms. Since the ionized form of acids is less soluble in lipid than in water the rate of bioaccumulation decreases with increasing pH (McLeay *et al.* 1979; Oikari *et al.* 1983).

Resin acids are thought to be transported throughout the body via the bloodstream and transformed into water-soluble complexes in the liver. These water-soluble complexes are then transferred via passive diffusion from the blood to the bile and eliminated by excretion into the gut (Kruzynski 1979; Oikari *et al.* 1984). Resin acids bioaccumulate in the tissues of rainbow trout in the same proportions as they occur in the surrounding environment (Oikari *et al.* 1980; 1982). The bioaccumulation factor does not appear to vary significantly between different resin acids or with length of exposure.

The bioaccumulation of dehydroabietic acid in salmonids may reach an overall whole body tissue concentration of 20 to 30 times that of the surrounding water during short-term sublethal exposure (Fox *et al.* 1977). In contrast, bioaccumulation factors ranging from 30 to 996 have been recorded for major organs such as the kidneys, liver and the brain (Kruzynski 1979; Oikari *et al.* 1982). No information concerning either the rate of depuration or the effects of these accumulations on the behaviour or survival of contaminated fish was reported by Kruzynski (1979) or Oikari *et al.* (1980).

7.5 NON-FISHERY IMPACTS OF WOOD RESIDUE AND LEACHATE

Concerns other than impacts to fish and fish habitat can result from use and disposal of wood residue. Fire hazards, explosion hazards from methane gas formation, decomposition odours, contamination of drinking water supplies, aesthetics, dust problems and liquefaction during earthquakes are some of the concerns that a proponent may also have to address.

7.5.1 Impacts from Fungal and Bacterial Growth

Seasonal microbial growth in streams could result in aesthetically unpleasant sights and foul odours. Part of the foul odour could be caused by the metabolites, by-products and decomposition of micro-organisms. Higher than normal total coliform (but not *E. coli*) bacteria counts have been reported from samples of surface and groundwater that are contaminated with wood-residue leachate. The City of Richmond reported that mats of microbial growth washed from decaying wood-residue sites continuously clogged the debris screens at dyke pump stations that collect and discharge leachate-contaminated stormwater from the local ditches into the Fraser River (Zaharia 1991).

7.5.2 Fire and Explosion Hazards

There are indications that under certain conditions and in the presence of a metal catalyst, spontaneous combustion of a wood-residue pile or landfill can occur. Landfill fires have been attributed to the presence of metal fragments buried within a wood-residue pile. However, sparks, smoldering fragments (e.g. uncooled ash) and heat generated by outside sources constitute a greater risk of fire on the outside of a wood-residue pile or landfill than would spontaneous combustion of its interior (Blackerby 1963). Spontaneous combustion requires a supply of oxygen; compaction can reduce air flow through a pile of wood residue.

In B.C. there have been many reported incidents of fire at wood-residue storage and disposal sites. In November 1991, there were major fires in two large wood-residue landfills in the Lower Mainland. Aside from the fire hazards, toxic leachate is produced during fire-fighting operations; this leachate contains the thermal decomposition by-products described in Section 4.3. Placement of combustible refuse, such as wood residue, under power lines and in associated rights-of-way is not recommended due to fire hazard.

Explosion hazards are associated with the generation of methane gas during the anaerobic decomposition process. This concern is heightened where residential and commercial buildings are constructed over wood-residue landfills. The use of wood residue as construction fill at such development sites must also be carefully considered from an engineering point of view.

7.5.3 Groundwater Contamination

Groundwater contamination issues are seldom adequately addressed at wood-residue sites in B.C. and groundwater monitoring works are rarely implemented. In the Lower and Central Fraser Valley areas, there have been many public complaints received about the contamination of drinking well water and hobby ponds by leachate from relatively small quantities of wood residue that were deposited on neighbouring properties. In one civil litigation case, a complainant alleged that drinking the contaminated well water resulted in body rashes and diarrhoea. Published information regarding the human health aspects of wood-residue leachate has been compiled by Hausen (1981). Contaminated groundwater could also lead to fisheries concerns if the aquifer discharges into fish habitat.

7.5.4 Wood Dust

Complaints of wood dust deposition on properties adjacent to wood-residue sites have been made. A high sawdust content and windy conditions generally worsen the situation. Aside from being a nuisance, there may be potential health concerns from inhaling wood dust. It was reported that western red cedar can cause asthma but the responsible constituent was not identified (Hon and Shiraishi 1991). Irritating compounds are found mainly in wood resins and sensitizing compounds in wood extractives. Glenn (1988) reported that such compounds can be found in Douglas-fir, western red cedar, hemlock, pine, spruce and poplar. The Workers Compensation Board of B.C. recently amended exposure limits for wood dust to increase the level of protection of workers from wood-dust-related illnesses.

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8.0 DESIGN OF WOOD-RESIDUE LANDFILLS AND STORAGE FACILITIES

Many of the strategies that are used to prevent environmental impacts at municipal solid waste landfills (Bagchi 1990; Crawford 1985; Nobel 1976; Weiss 1974) are applicable at wood-residue sites. This section addresses technology intended to preclude impacts on fish and fish habitat from the transportation, storage, use and disposal of wood residue. Pre-proposal planning is the key to the successful implementation of these strategies. It is often a much more expensive proposition to try to mitigate environmental impacts after they have occurred than to plan ahead and avoid them. In some cases, the only practical solution to a problematic leachate discharge is to remove the wood residue. The B.C. Pollution Control Objectives (first published in 1977; reprinted without revision in 1989) state that "disposal sites must minimize . . . leachate pollution." Site selection, waste segregation/mixing, wood residue specification, leachate prevention, collection and treatment are worthwhile strategies reviewed here. Implementation of such strategies and the government review process outlined in *Guidelines on Storage, Use and Disposal of Wood Residue for the Protection of Fish and Fish Habitat in British Columbia* (Liu *et al.* 1996) should ensure protection of fish and fish habitat from wood residue impacts.

8.1 SITE SELECTION

The site selection process for wood-residue storage, use and disposal should be no different than that for a well-designed municipal solid waste landfill. In various jurisdictions, municipal solid waste landfills cannot be sited within a specified distance from water supply wells, lakes, ponds, rivers and wetlands, including fish habitat. Notwithstanding, much of the surplus wood residue in B.C. is deposited in unsuitable locations, like peat bogs, where adequate leachate control works are seldom installed. Examples of unsuitable sites can be found in an inventory of wood-residue sites in the Lower Mainland published by B.C. MELP (1992).

Site selection plays a key role in avoiding biophysical impacts from the deposition of wood residue. Such impacts can be easily avoided if wood residue is not deposited adjacent to fish habitat. Wood residue should not be deposited within estuarine areas, foreshore or riparian zones, sloughs, tidal flats, wetlands (e.g. marshes and swamps or peat bogs that drain into fish-bearing waters), streams and lakes. Siting should be avoided in areas within an active fault zone, floodplain (200-year level), or on a steep sidehill (greater than 15% slope) where wood residue can be carried by periodic landslides or water flows into fish habitat.

Site selection is also fundamental to avoiding impacts from wood-residue leachate. Climatologic, hydrogeologic and topographic conditions of a proposed site must be evaluated for the entire term of its operation, closure and potentially for years thereafter. Climatologic considerations include the precipitation and evapotranspiration rates at a site. Hydrogeologic considerations include the permeability of the soil, presence of adjacent water courses and groundwater level/movement. The potential for altering the hydrogeologic and topographic conditions at the site with the deposition of the wood residue must also be assessed. The extent of the assessments will be site specific, depending on the volume of wood residue involved and its proximity to fish habitat. Such assessments cannot be limited to cursory visual observations made during a dry period.

Wood-residue sites should ideally be located in areas where evapotranspiration rates are greater than rainfall rates. The site should be down-gradient (i.e. downhill) from wells and watercourses. It would be difficult to find such ideal sites in B.C.'s wet, coastal, mountainous regions. The B.C. Pollution Control Objectives describe the potential for leachate generation as significant at sites where "excess moisture" exceeds 85 $mm \cdot m^{-2}$ of refuse. Excess moisture is defined as the "average annual difference between precipitation and evapotranspiration." Without installing elaborate leachate-control works, siting is generally not acceptable within areas that typically collect surface water or groundwater and where such waters drain into fish habitat. Gullies, ravines, water-filled gravel pits and other areas with high groundwater tables, springs and surface water flows are unsuitable for the deposition of wood residue.

The depth to groundwater at a site can only be determined if a hydrogeologic assessment is carried out. A persistent surface flow or water ponding suggests the presence of a high groundwater table. The use of remote sensing instruments is preferred over drilling or excavation in the site-assessment process since the latter methods may inadvertently provide conduits for contact with groundwater. All test holes should be backfilled with the excavated soil. Measurements to find the highest groundwater table should be taken during the wet season. The provision of leachate control works may be required depending on the proposed site.

8.2 WASTE SEGREGATION AND MIXING

When industrial or municipal refuse is mixed with wood residue, there are effects on the leachate generated. Options to reclaim some wastes may be precluded if they are mixed with wood residue.

8.2.1 Segregation of Contaminated Wood Residue

Possible sources of contamination of wood residue by man-made chemicals are outlined in Section 3.5. Wood residue contaminated with antisapstain pesticides or other wood protection/preservation chemicals must not be mixed with uncontaminated wood residue or deposited where such chemicals will leach out and enter surface water or groundwater. Antisapstain chemicals and wood preservatives are very toxic to aquatic life and may be persistent in the aquatic environment. Leaching of a small amount of such chemicals (e.g. in the parts per billion range) from contaminated wood residue can lead to problems in site management. Similarly, the use of treated timbers in a wood-residue fill site could create complex leachate problems.

8.2.2 Segregation of Wood Residue from Other Refuse

Other refuse such as wood ash and metallic waste are sometimes deposited at wood-residue sites. A proponent is expected to provide analytical data in compliance with the B.C. Special Waste Regulation in order to deposit wood ash. When ash or metals are mixed with wood residue there can be chemical reactions that affect the characteristics of any leachate. The mixing of wastes can also impact on the operator's ability to later recycle materials such as metals.

Wood ash can have a high metals content and the leachate is usually alkaline. Mixing wood ash and wood residue or placing wood residue up-gradient of a wood ash deposit could result in leaching of metals from the wood ash by acidic wood-residue leachate. The combined leachate from the wood ash and wood residue would likely be more pH neutral than the individual leachates. Chelation of toxic wood residue components (e.g. tannins; tropolones) by metal wastes or dissolved metals from wood ash could reduce the toxicity of the combined leachates.

More information is required in this context. Wood ash intended for use in aggregates should be segregated from wood residue. Segregation of metallic wastes from wood residue allows for future salvage of scrap metals and avoids the possibility of spontaneous combustion in a wood-residue pile.

Gypsum wall board, which contains sulphur, should not be deposited at a wood-residue site since large quantities of soluble hydrogen sulphide could be released by microbial action and subsequently dissolve in the leachate. The dissolved sulphide will increase the acidity and toxicity of wood-residue leachate.

The deposition of wet waste materials such as dredge spoils, flyash or pulp mill clarifier sludge up-gradient of a wood-residue deposit will increase the amount of water that could come into contact with the wood residue.

Before decisions are made to mix refuse, discussions with regulatory agencies should occur so that the likelihood of unforeseen leachate problems is minimized.

8.3 SPECIFYING TYPES OF WOOD RESIDUE

8.3.1 Weathered Wood Residue

Wood residue from freshly cut trees will generate a more concentrated leachate initially than that from weathered wood residue. Leachate generated from weathered wood residue is expected to present fewer environmental problems than that from new deposits or from operations where wood residue is continually being replenished.

It has been suggested that fresh wood residue could be collected at regional centres in B.C. where intentional watering of the wood residue would be practised to speed the weathering process. This artificially weathered wood residue would be relatively inert in terms of leachate generation. The amount of weathering required would be dependent on the length of prior contact between the wood residue and any water (Section 3.1), as well as the specific conditions of the artificial weathering process used. Leachate generated from artificial weathering of wood residue must be collected and treated at the site of weathering before being discharged.

The loss of some microbicidal constituents may render weathered wood residue unsuitable as a construction fill material because microbial decomposition rates could be accelerated. Weathered wood residue may be best suited for use in the agricultural and horticultural sectors as an organic amendment or absorbent. There are no data on the availability of weathered wood residue in B.C.

Companies sometimes submit proposals claiming that only weathered wood residue will be deposited. Confirming data from suitable leaching tests should accompany such applications.

8.3.2 Coarse Wood Residue

In an effort to reduce volume and enhance compaction, coarse wood residue is often shredded into hogfuel-sized particles before it is deposited. However, reducing the particle size of wood residue increases the exposed wood surface area available for leaching (Section 3.1). Size reduction of wood residue should not be practised unless measures are in place to control problematic leachate generation.

8.4 MINIMIZING LEACHATE GENERATION

Leachate generation will occur whenever water comes into contact with wood residue that has reached its moisture saturation point. Water sources are precipitation, surface runoff, upwelling from underground springs and seepage from groundwater or effluents (e.g. from septic tank tile fields). In dry areas where the average evapotranspiration rate exceeds precipitation, periodic leachate generation can occur due to seasonal extremes in precipitation.

Proper measures to prevent leachate generation are seldom employed at wood-residue sites. Such measures may be impossible to implement once the wood residue is deposited. The cost of preventing leachate generation needs to be factored into the overall economic evaluation of a wood-residue-use proposal. Comprehensive references are available on the subject of controlling leachate generation at municipal landfills (Metry and Cross 1976; Lu *et al.*1985). With variation, some of these control measures have been used with limited success at wood-residue sites in B.C. Strategies to prevent/minimize wood-residue leachate generation are outlined in the following sections.

8.4.1 Configuration of Wood-residue Piles

The quantity of leachate generated as an exudate or by diffusion is reduced when the wood residue is deposited in a conical pile above the groundwater table. A conical pile of wood residue has a relatively small outer surface area compared to that of a flat pile. Under identical weathering conditions, wood residue in a conical pile would receive less precipitation, thus the wood fibre saturation point would be reached over a longer time frame compared to a low flat pile.

8.4.2 Diversion of Surface Runoff and Groundwater

The same strategies that are routinely practised at municipal landfills for the diversion of surface runoff and groundwater can be used at wood-residue sites. Any strategies must include the consideration of changes in the drainage pattern of a site due to the settlement and compaction of a deposit of wood residue. Long-term maintenance of surface water and groundwater diversion works is necessary to prevent clogging and to ensure that water infiltration does not occur after site closure. The B.C. Ministry of Environment, Lands and Parks and DFO must be contacted to determine the acceptability of any proposed water diversion works.

A good topographic map and a visual inspection of a site after heavy rainfall during the wet season are generally sufficient to determine if surface runoff diversion is needed and where it should be carried out. After a heavy rainfall a perched water table up-gradient of a site indicates that water is prevented from movement by the natural soil conditions and topography. In such cases the water will percolate through the subsoil (i.e. toward the site) or dissipate by evaporation and transpiration. Perched water should be drained and the area filled with inert soil to promote surface runoff. Installation of ditches and culverts are the two most cost-effective ways of diverting surface water away from a wood-residue site.

8.4.2.1 Ditches

Excavation of diversion ditches up-gradient and around a site is necessary to prevent infiltration and/or direct contact of the surface runoff with wood residue. A double ditch system may be required around the site - an outer ditch for runoff diversion and an inner ditch to collect leachate. The failure of a ditch to divert surface runoff can usually be traced to poor maintenance and inadequate flow-capacity design.

8.4.2.2 Culverts

If culverts are installed under a wood-residue deposit perforated pipes must not be used and joints of pipe sections must have water-tight seals. Failures of culverts can usually be traced to improperly-sealed joints, clogged pipes, or collapsed pipes caused by the weight of overlying materials. If feasible, it would be costly to repair a failed culvert system. Unrepaired, such systems act to collect large volumes of dilute leachate.

Groundwater can be collected and diverted by installing a perforated culvert system outside the lined perimeter of a wood-residue site (Section 8.4.3). Trenchless technology can also be used in the installation of underground drainage systems. Diversion of groundwater at wood-residue sites is not known to be practised in B.C. because it involves extensive trench excavation and permanent pumping systems. The cost of installing such works will preclude many areas from consideration as wood-residue storage and disposal sites.

8.4.3 Use of Liners

Liners are impermeable barriers or membranes used to separate water from a deposit of leachable material such as wood residue. Permeability is a measure of the rate of water passage through a liner; the permeability of a liner depends on its thickness and construction. Liners are usually constructed of synthetic material, or fine soil such as clay.

8.4.3.1 Soil Liners

Soils have a wide range of particle size and permeability. These characteristics are listed in Table 8.1 along with some textural descriptions. Excavated soils are expected to have a higher permeability than the same soils left in an undisturbed state. Indigenous soil is commonly used for liner material at wood-residue sites. The use of indigenous soil for a liner, even if it is a relatively impermeable material, can lead to leachate generation and loss. Factors that cause such failures are inadequate soil thickness, erosion, improper compaction, desiccation and cracking. Bentonite clay has extremely low permeability but it is not generally used as a liner at wood-residue sites because of its high cost.

Table 8.1 Porosity and permeability of selected soils and rocks.

Material	Typical porosity[a] (%)	Typical permeability[b] ($m \cdot d^{-1}$)
Top soil	>50	-
Clay	>40	10^{-2}-10^{-7}
Sand and gravel	20-47	2-2000
Sandstone	5-25	0.3-3
Limestone	5-25	10^{-4}-10^{-1}
Chalk	50	10^{-3}-10^{-1}
Granite	<1	10^{-3}

[a] Porosity = $\frac{\text{volume of voids}}{\text{total volume}}$ x 100

[b] Permeability = $\frac{\text{water flow}}{\text{hydraulic gradient x cross-sectional area}}$

Source: Crawford and Smith (1985).

Compacted and saturated clay with a relatively low vertical permeability of 5.8×10^{-10} $m \cdot s^{-1}$ or less is suitable for use as a liner material (Hoeks 1983). Clay must be kept moist to prevent shrinkage and cracking. A 15 to 30-cm thick layer of compacted clay is generally acceptable as a low-permeability liner. However, the permeability of a clay liner can be increased by freeze-thaw actions, desiccative cracks and damage during its installation (Bagchi 1990). Therefore, a 1.2 to 1.5-m-thick clay layer is recommended for use as a soil liner. Rip-rap, local soil and vegetation should be used to stabilize and protect a clay liner against erosion, cracking, or damage from compaction and settlement.

8.4.3.2 Synthetic Liners

A good synthetic liner is considered to be more impermeable than the most impervious soil liner. A synthetic liner is made of joined sheets of flexible geomembrane consisting of plastic polymers such as polyethylene or polyvinyl chloride (PVC). Since PVC deteriorates in ultraviolet light, the use of PVC geomembranes must be avoided if the liners will be exposed to sunlight. No information is available on effects of wood-residue leachate on geomembranes or on the anticipated life of synthetic liners in a wood-residue site. Geomembranes become useless when punctured or if the joints have been improperly sealed.

In B.C. synthetic liners are most often used where large volumes of wood residue are deposited at highway fill sites or major land development projects. Complete encapsulation of wood residue within a sealed geomembrane bag is the best way to prevent wood residue from contact with moisture, but venting of gases may be required. The installation of vents is described in Section 8.7. If pilings are driven into a wood-residue site, synthetic liners can be used to encase the wood residue in small bags which are then placed around the piles. Alternatively, liners could be fitted and sealed to caps on the top of each pile prior to the placement of the wood-residue fill. No data are available on the effectiveness or longevity of liner caps.

The permeability of different types of geomembranes does not differ significantly. Puncture resistance is the major factor in determining geomembrane thickness. Heavy gauge geomembranes, generally 60 to 80 mm thick, are commonly used at municipal solid waste landfills (Bagchi 1990). That thickness range is also suitable for synthetic liners to be used at wood-residue sites. Geotextile or other “cushioning” materials should be used on both sides of a geomembrane to give it protection from puncturing. Liner integrity is most vulnerable at the seams between adjacent geomembrane sheets. Proper seam sealing methods, including the use of adhesives, solvents, heat and/or extrusions, should be used. The quality of factory seals is always superior to that of seals made in the field. All field seaming should be carried out by an experienced installer, based on specific instructions from the manufacturer. “Sealing” by merely overlapping adjacent sheets of plastic liner material would not be effective in controlling leachate.

Effectiveness of liners in separating wood residue from moisture can only be demonstrated by conducting leachate/groundwater monitoring. Such monitoring in B.C. has shown that liners are seldom effective because they have been damaged or are of inadequate thickness. Damage to liners occurs when pile-supported structures, drain wicks, underground services, vents, or other structures are installed. These structures can also act as conduits for moisture to come into contact with the wood residue. The integrity of liners can be further compromised by compaction and differential settlement of the wood residue and any overlying fill. In addition, the build-up of hydrostatic and/or gas pressure can lead to liner rupture.

Because of the cost of excavating the fill to repair a ruptured liner, innovative practices such as the use of a multiple-liner system at wood-residue sites should be considered. The installation of leachate monitoring and collection works within multiple-liner systems is discussed in Sections 8.5 and 8.8. The use of bottom liners, berms and covers is discussed below.

8.4.3.3 Bottom Liners

A bottom liner is a confining layer that separates wood residue from the underlying groundwater at a site. A bottom liner, along with perimeter berms, can be used to prevent leachate generated within the wood-residue deposit from contact with groundwater. Provided that a hydrogeologic assessment shows that a bottom liner is continuous under the area to be filled, minimum separation distances (Section 8.6.1.4) could be waived at containment wood-residue sites. The use of containment wood-residue sites will generally be a requirement in wet regions of B.C. where the potential for leachate generation is high. Existing wood-residue sites in B.C. commonly do not have bottom liners, even though the groundwater table is often near the surface. Instead, most sites have a layer of permeable native soil that separates wood residue from groundwater. Such sites rely on the underlying soil to attenuate the leachate before it reaches the groundwater. Natural attenuation is discussed in Section 8.6.1.

8.4.3.4 Berms

Berms are generally installed around the perimeter of wood-residue sites to act as a buffer strip. Berms can also be used to divide a site into smaller cells. Dykes, walls, leavestrips and buffer zones can all be considered as berms. The design, construction and performance of berms may be dictated by the potential instability of a site, which in turn may limit the height, extent and rate of wood-residue deposition. Berms must be designed to be stable and effective under full operating conditions. The angle of side slopes is determined by the characteristics of the berm material, the precipitation rate and the availability of surface vegetation or rip-rap materials. The maximum side slope angle should not exceed 60° from the base.

Many wood-residue operations in B.C. use permeable soil for berm construction because it is the only readily-available native material. The width of such permeable soil berms is often determined arbitrarily by soil/land availability rather than soil characteristics. The existence of a soil berm does not imply works to minimize leachate generation are not necessary or that leachate treatment would not be required.

To be effective in preventing wood residue from contact with surface or groundwater, a berm must either be a geomembrane or be comprised of relatively-impermeable soil. To be effective, soil berms must be keyed into a bottom liner. Bentonite slurry walls have also been successfully used for leachate control works at the Port Mann and Premier Street municipal landfills in B.C. (Stringer 1991). Without a bottom liner, groundwater and surface water can infiltrate the wood-residue fill, or leachate can flow out via the path of least resistance at the toe of the berm.

8.4.3.5 Intermediate Covers and Final Caps

Wood residue at loading facilities, equestrian centres, farms and nurseries is generally exposed to the weather. In addition to precipitation, water for irrigation, dust and fire control is often applied to wood-residue piles. Under such circumstances, leachate generation is unavoidable, so plans for leachate collection and treatment must be developed prior to wood-residue deposition.

Intermediate and final covers can be used to reduce leachate generation at wood-residue sites. The use of permeable soil will not prevent water infiltration into underlying wood residue. The B.C. Pollution Control Objectives define intermediate and final cover materials as "earth exhibiting good workability and compaction characteristics and having a low-organic content which is used to cover a compacted refuse. Its purposes are to . . . control infiltration of surface waters into the refuse." Geomembranes, concrete and asphalt pavements have also been used as final capping materials at wood-residue sites in B.C.

8.4.3.5.1 Intermediate Covers

The operational phase of many wood-residue fill sites in B.C. lasts for many years or decades. Water accumulation within a site during the uncovered operational phase occurs if intermediate covers are not provided. Intermediate covers can effectively reduce the exposed surface area of wood residue at a site. The frequency of applying intermediate covers depends on the amount and frequency of precipitation at a specific site. Intermediate covers may not be necessary during the dry season and works where wood residue will be exposed should be scheduled during this period.

The B.C. Pollution Control Objectives specify that operators of sites with wood residue application rates greater than 230 m^3 per day are required to apply an intermediate cover once every week (i.e. Level A requirement). Operators of sites where wood residue is applied at rates up to and including 230 m^3 per day must apply an intermediate cover every 20 days of operation and at least once a month. Level A requirements must also be met at any site where the probability of leachate pollution is significant. In the Pollution Control Objectives, the probability is considered as significant when:

- the annual excess moisture at a site exceeds 85 mm per metre of refuse depth; or
- the refuse is less than 1.25 m above the highest groundwater level at a site; or
- the refuse is located near surface waters.

8.4.3.5.2 Final Caps

When using berms and bottom liners to separate wood residue from moisture, it is essential to also install a final cap to prevent the entry of surface water and the overflow of leachate. In wet regions, the permeability of the final cap material must be equal to or less than the bottom liner to prevent the leachate level from rising within the fill. Although clay has a relatively low permeability, it is difficult to compact clay in most situations and the tracks left by compactors cause rainfall to accumulate and infiltrate. Clay also has a tendency to form desiccation cracks. For these reasons, a clay cap should always be protected with an overlying layer of native soil.

In the preparation of a typical wood-residue fill site, the topsoil and subsoil that were stripped prior to filling should be retained as cover material to protect the final cap after site closure. Infiltration can be further minimized by planting vegetation with high a transpiration rate (e.g. reeds or rushes) in the cover soil. To allow proper drainage, the surface of the final cap should have a slope of at least 1°. Visual assessment of damage to the final cap should be made during and well after the closure of the site. Vehicular movement over the final cap may have to be restricted.

8.5 CONTAINMENT AND COLLECTION OF WOOD-RESIDUE LEACHATE

Although implementation of the techniques described in the previous sections will minimize leachate generation, there is no guarantee that leachate production will be eliminated during filling or following site closure. A proposal to minimize leachate production does not necessarily make a site suitable for wood-residue deposition. Prior to the operation of a site, a proponent must provide a plan to contain, collect and treat any leachate that would be generated. The cost of implementing the necessary leachate control works for a site should be factored into a development decision involving the storage, use or disposal of wood residue.

Liners, ditches and culverts are effective in containing and collecting leachate that is generated. Leachate collection can be a simple matter of installing over the bottom liner a collection tile field system, consisting of perforated collection pipes, culverts, clean outs/manholes and pumps. If approvals are received for the deposition of wood residue in environmentally-sensitive areas (e.g. adjacent to fish habitat), total containment of leachate would dictate the use of a double-bottom liner system. Primary leachate collection capacity is provided with the first layer of the liner, but there is also a secondary collection capacity between the liners. The second layer can act as a “witness drain” of liner integrity. Down-gradient monitoring is required to determine if leachate seepage is occurring and if further containment, collection and treatment works are needed.

The control works should be designed to ensure that only leachate is collected and uncontaminated surface water or groundwater will not add to the volume of leachate to be dealt with. The effects of settlement on the elevation and slope of the control works must be taken into account when deciding on the location for their installation. Failures of leachate collection systems can be traced to clogging and under-capacity designs. Geotextiles, filters, rock pits or other drainage materials may need to be installed around the collection pipes to reduce clogging and access should be provided for back flushing or cleanouts. Trenchless technology can be used in the installation of leachate-collection works at locations where disturbance of surface soil layers is undesirable.

The capacity of the collection system must be designed to handle the largest expected leachate volume. Large volumes of leachate can be generated during the working phase of an open wood-residue deposit before intermediate covers and a final cap have been installed. In such circumstances it may be necessary to utilize a temporary leachate-recovery system that has a higher capacity than the system that will be required over the long term. In any case, some form of surge capacity should be installed in order to accommodate seasonal variations in flow and any sudden increases generated during storm events.

At many farms, nurseries, equestrian facilities, golf courses and construction sites wood residue is deposited either directly over or near to an underground-drainage system. At farms ditches are often placed directly between the fields and wood-residue dykes. A portion of the leachate generated from the dykes is collected in the drainage system and ditches. In the dry seasons the leachate is effectively collected because the collection ditches are the source of water used in irrigation. Any leachate collected should be treated to acceptable levels prior to discharge into watercourses.

Containment works will be difficult to install unless they were built into the site prior to wood-residue deposition. Without such prior site design, leachate can escape unnoticed until it surfaces at down-gradient locations. Attempts to install leachate-collection works after site development can be difficult and expensive because a confining layer would need to be installed under the site to intercept all the leachate. Further, because works would not have been installed to separate uncontaminated surface water and groundwater from the wood residue, a much larger volume of dilute leachate would require handling. The job of locating, containing and collecting the leachate may require excavation or removal of a portion of the wood-residue deposit.

Although leachate can sometimes be collected in depressions existing at the toe of fills, deep trenches, drains, tile fields or extraction wells are often necessary to collect both the leachate and contaminated groundwater. In some cases the most reasonable solution to the problem is the removal of the wood residue.

8.6 LEACHATE TREATMENT AND DISCHARGE

It is inevitable that most wood-residue deposition will result in leachate generation. Wood-residue leachate may be toxic to aquatic life or otherwise degrade habitat for fish. In determining the economic viability of a project involving the storage, use or disposal of wood residue, proponents are advised to include the capital, operational and maintenance cost of leachate-treatment works. Proposals for leachate treatment should be accompanied with data to show that treatment can be expected to be effective. Field trials of unproven technologies will not be acceptable near a sensitive location. The discharge of treated leachate must be approved through application to the provincial Ministry of Environment, Lands and Parks. In the case of a discharge to the municipal sewage collection system, application must be made to the local sewerage authority. Surface water (and possibly groundwater) monitoring should be conducted at sites near sensitive locations. If the treatment systems do not perform adequately, removal of the deposited wood residue could be the only remedy.

There can be considerable variability in leachate volume and in the concentration of its chemical constituents within and among wood-residue sites. More concentrated leachate may have to be dealt with during the initial phase of wood-residue deposition. Seasonal variations in leachate volume may require a retention pond or treatment system that is “over designed” for most of the year. A treatment system may still be required years after site closure.

Wood-residue leachate treatment technologies are derived mainly from treatment processes for pulp mill effluents and municipal landfill leachate. Little or no research is currently being conducted on the treatability of specific constituents in wood-residue leachate. Ideally, a treatment process should produce a discharge with a quality similar to that of the receiving stream. Many treatment processes that are supposedly proven in laboratory studies have not performed adequately in the field or have been prohibitively expensive. Dilution and dispersion in a watercourse are not considered forms of treatment. Conventional biological and physical/chemical treatment processes are discussed in this section. This section also reviews the issue of natural attenuation and recirculation of wood-residue leachate and explains why these practices are generally not acceptable in dealing with wood-residue leachate in B.C.

8.6.1 Natural Attenuation

Natural attenuation may be defined as a process by which the load of toxicants and other leachate constituents is reduced by natural processes as the leachate permeates the surrounding soil. Attenuation depends on contact between the soil surface and the pollutants. Attenuation capacity of a given volume of soil is primarily related to soil porosity and water-retention capacity.

The movement of water into and within the soil depends primarily on the size and distribution of soil pores. Large soil pores result in rapid movement of water through soil and a relatively small surface contact area. One measure of moisture-retention capacity of soil is its “field capacity.” Field capacity is the amount of moisture held in the soil after the water has drained out of the large soil pores and downward movement of moisture has ceased. At field capacity, water remains in the small soil pores and is adsorbed onto the soil. The hygroscopic coefficient is a measure of soil's adsorptive capacity.

Soil at the saturation point or at field capacity cannot attenuate leachate because water will rapidly permeate such soil until a confining layer is encountered. Leachate attenuation is generally insignificant in coarse soil because of the existence of large soil pores. The field capacity of sandy soil is 5% moisture and for clay loam it is 25% moisture. Clay and humus have higher hygroscopic coefficients than sandy soil.

Dilution of leachate by groundwater or surface water is not considered as a natural attenuation process. Dilution does not immobilize or reduce the load of toxicants and other leachate constituents. The amount of dilution depends on the hydrology of the site and it varies greatly between different sites and during different times of the year.

8.6.1.1 Leachate Attenuation Mechanisms in Soil

Leachate attenuation mechanisms in soil include adsorption, ion exchange, precipitation, filtration and biological degradation (NCASI 1983). These mechanisms are discussed below.

8.6.1.1.1 Adsorption

Adsorption is a fixation process in which dissolved organic and inorganic constituents are attached to the soil surfaces by Van der Waals forces. The fixation process may be pH dependent and could be partially or totally reversible under certain circumstances. The adsorption force of mineral soils is very limited while organic matter, such as peat, is capable of strongly adsorbing dissolved organics in leachate that are hydrophobic (i.e. having a solubility of less than $10\ \mathrm{mg{\cdot}L^{-1}}$) or non-polar (NCASI 1983). Adsorption is probably the main attenuation mechanism for immobilization of constituents of wood-residue leachate. The adsorptive capacity of a given volume of soil is reached when all the available surface contact area is saturated with leachate. Until the adsorptive capacity of soil is renewed through biological decomposition of the fixed organic constituents on the soil surfaces, no further reduction in leachate constituents will take place.

8.6.1.1.2 Ion Exchange

Ion exchange operates on the principle of electrical attraction between opposite charges. In this process, an ion with a strong electrical charge in the leachate is preferentially attached to a soil particle with the opposite charge. This process causes release from the soil particle of an ion of the same charge as the leachate ion. Cation exchange takes place when the leachate ion is positively charged, whereas anion exchange occurs when the leachate ion is negatively charged. The rate of ion exchange is dependent on the soil pH. As soil pH decreases, the cation-exchange rate is reduced while the anion-exchange rate is increased. However, the anion-exchange capacity is not necessarily increased with acidic leachate because the acids will dissolve the hydroxide and carbonate minerals in the soil. As a result the soil pH is neutralized and the cation-exchange capacity is restored (Bagchi 1990).

Most soils have a predominant negative charge and therefore, a predominant cation-exchange capacity. Zeolites, containing mostly aluminosilicates, have the highest cation-exchange capacity (Crawford and Smith 1985). Humic soils, including peat also have a high cation-exchange capacity. Sphagnum peat has a relatively high permeability and a high pore space as well as high water-holding and cation-exchange capacities. Most of the organic constituents in wood-residue leachate that can exert a BOD or COD are nonionic. The dissolved ionic constituents are typically anionic. Accordingly, significant attenuation of wood-residue leachate by the ion-exchange mechanism in soil is not expected (Bagchi 1990). When the concentration of the permeating leachate becomes sufficiently weak, leachate constituents previously attached to the soil by ion exchange could be released. Therefore, ion exchange is considered to be a retardation mechanism rather than a removal process.

8.6.1.1.3 Precipitation

Precipitation involves the formation of an insoluble substance when the concentration of that substance exceeds its solubility limit or as a result of chemical reactions between different substances. The solubility of some constituents may also depend on their redox potentials and the temperature and pH of the leachate. Comparatively water-soluble constituents, such as tannins, are less likely to be precipitated than water-insoluble constituents, such as terpenes. However, tannins and tropolones can be precipitated as metal-chelated complexes when cations from the soil are dissolved by the acidic leachate. As indicated in the ion-exchange mechanism discussion above, leachate-saturated soil will eventually reach a neutral pH. At neutral pH, cations will not leach from the soil and further chelation will not occur.

8.6.1.1.4 Filtration

Filtration is the physical retention of suspended and settleable solids (including precipitated, chelated and “biological growth” materials) in the leachate by soil. Filtration efficiency of a given volume of soil depends on the pore size of the soil and the hydraulic gradient of the leachate. Compaction and settlement of the soil reduces filtration efficiency. Filtration is not considered to be a significant mechanism in leachate attenuation (Bagchi 1990).

8.6.1.1.5 Biological Degradation

Within each type of soil, there is a limited number of “sites” available to interact with and immobilize wood-residue leachate constituents on the basis of adsorption, ion exchange, precipitation and filtration. Immobilization is mainly a one-time phenomenon. Immobilization capacity is at its maximum when the soil is fresh and can quickly become saturated. Further immobilization of constituents in a leachate-saturated soil cannot occur unless the soil has been refreshed. Soil refreshment is accomplished by biological decomposition of the organic constituents immobilized in the soil. Natural biological activity occurs mainly in the soil layer above the water table. The rate of biological degradation is dependent on the factors described in Section 7.5.2. Biodegradation processes may eventually refresh leachate-saturated soil for further attenuation. However, such processes occur too slowly for the treatment of continuously-produced wood-residue leachate.

8.6.1.2 Laboratory Studies on Effectiveness of Natural Attenuation

Lysimeters (containers that hold wood residue and soil for experimental leachate generation) were used to conduct laboratory research on the effectiveness and capacity of various soils to attenuate wood-residue leachate. Cation exchange is thought to be the dominant attenuation mechanism in lysimeter studies (Griffin 1976). Attenuation research is reviewed in this section.

Cameron (1982) tested leachate flowing from a 47-cm-high lysimeter column filled with 4.5 kg of topsoil separating multiple 2.4-cm-thick layers of hogfuel. Bioassay tests confirmed that the leachate from the outlet of the lysimeter was toxic.

Schermer and Phipps (1976) reported tannin attenuation capacities of 0.32 $g \cdot g^{-1}$ of topsoil and 0.10 $g \cdot g^{-1}$ of gravel. Schermer and Phipps concluded that fine-grained, moderately-permeable organic soils are more effective for tannin attenuation than coarse-grained soils such as sand and gravel. He noted that any soil can quickly become saturated with leachate constituents and cease to be effective in natural attenuation. The limited attenuation capacity of soils is reflected in the estimated requirement of either 312.5 tonnes of topsoil or 1,000 tonnes of gravel to attenuate the tannin constituents in one tonne of western hemlock bark (assuming a 10% tannin content).

An early study of wood-residue sites and wood-residue leachate in B.C. (EconoTech Services Ltd. 1977) may have given the impression that leachate can be readily attenuated. However, test results from that study were inconclusive because the starting leachate strength was very weak and leachate samples were neutralized prior to the bioassay tests. The study showed that the toxicity of leachate from spruce and pine hogfuel is not attenuated by neutral or alkaline soils. The leachate that was passed through these soils was more toxic than untreated leachate.

In a 1990 study, Birkbeck *et al.* showed that when relatively weak wood-residue leachate was passed through a bed of unvegetated sand and gravel only 4% of the BOD and 19% of the COD were removed in the process.

Research on municipal landfill leachate has indicated that soil cannot adequately attenuate all the constituents in leachate, regardless of the thickness of the underlying unsaturated zone or the cation-exchange capacity of the soil (Bagchi 1990).

In summary, laboratory studies of natural attenuation are mainly based on removal of the tannin constituents of wood-residue leachate. Additional research is required to establish direct correlations between natural attenuation capacity of different types of soil to different constituents of wood-residue leachate. Laboratory research has shown that natural attenuation of wood-residue leachate in soil ranges from very limited to ineffective.

8.6.1.3 Field Studies on Effectiveness of Natural Attenuation

Field studies of the effectiveness of natural attenuation are rarely conducted because the necessary groundwater monitoring wells are seldom installed; adequate interpretation of results must be based on hydrogeologic information. Of the few field studies reported in the literature, one suggested that natural attenuation by sand and gravel would be effective at a log-storage yard (EconoTech Services Ltd. 1977). Another study concluded that passage of wood-residue leachate through soil and groundwater does not appear to remove tannins as effectively as shown in laboratory studies (Schermer and Phipps 1976). The field studies reported in the literature have not shown that natural attenuation is effective or practicable for treating wood-residue leachate.

8.6.1.4 Buffer Strip Distances for Natural Attenuation

In addition to the foregoing inconclusive findings, there are other problems with specifying buffer strip widths between wood-residue fill and sensitive areas (e.g. fish habitat). Establishing a buffer strip does not ensure that the available attenuation capacity of the soil within the horizontal and vertical planes of the area will be fully utilized. The installation of vertical conduits, such as perforated pipes, drain wicks and rock pits to alleviate local flooding will allow the leachate to bypass low permeability or highly-compacted soil and result in flow “channelling.” Channelling results in a portion of the soil becoming unavailable for natural attenuation. As indicated in Section 5.2, leachate tends to percolate downward in soils until an underlying, confining layer and/or the groundwater table are encountered. For this reason, the available soil within a buffer strip in the horizontal plane is seldom fully utilized for natural attenuation.

Nobel (1976) suggested that the required width and volume of soil for natural attenuation can be calculated by using the adsorption or ion-exchange capacity of the soil. However, there is virtually no data on the natural-attenuation capacity of different soils in relation to the various constituents of wood-residue leachate.

Jurisdictions within North America variously require or recommend different horizontal and vertical separation distances between landfills (including wood-residue sites) and downgradient surface waters/the highest groundwater table. A much wider separation distance is often required in the horizontal plane than the vertical plane.

In the U.S., the state government of Maine has specified minimum buffer distances of 91 m between wood-residue sites and surface water, whereas in Washington state the minimum buffer distance is 61 m. In B.C., minimum distances between wood-residue sites and watercourses are outlined in the provincial Waste Management Guidelines for Classification of Wood Waste Discharges and in the Code of Agricultural Practice for Waste Management (Section 2.2). The current B.C. Pollution Control Objectives for Municipal Type Waste Discharges state that "refuse shall not be placed in free water" and "in general no refuse other than inert refuse should be placed less than 1.25 m above the normal groundwater level measured at the fill area. Where excess moisture exceeds 85 mm per metre of refuse depth, the above distance should be increased to 2.5 m" (B.C. Pollution Control Board 1975).

Any minimum buffer distance serves only as a guide because site-specific factors may dictate more stringent protection. The following factors should be used in making site-specific buffer strip decisions: climatology; hydrogeology; the quantity of wood residue; characteristics and attenuation capacity of the surrounding soils; and the ground and surface water quality requirements for the aquifer and downgradient users.

8.6.1.5 Natural Attenuation at Wood-residue Sites in British Columbia

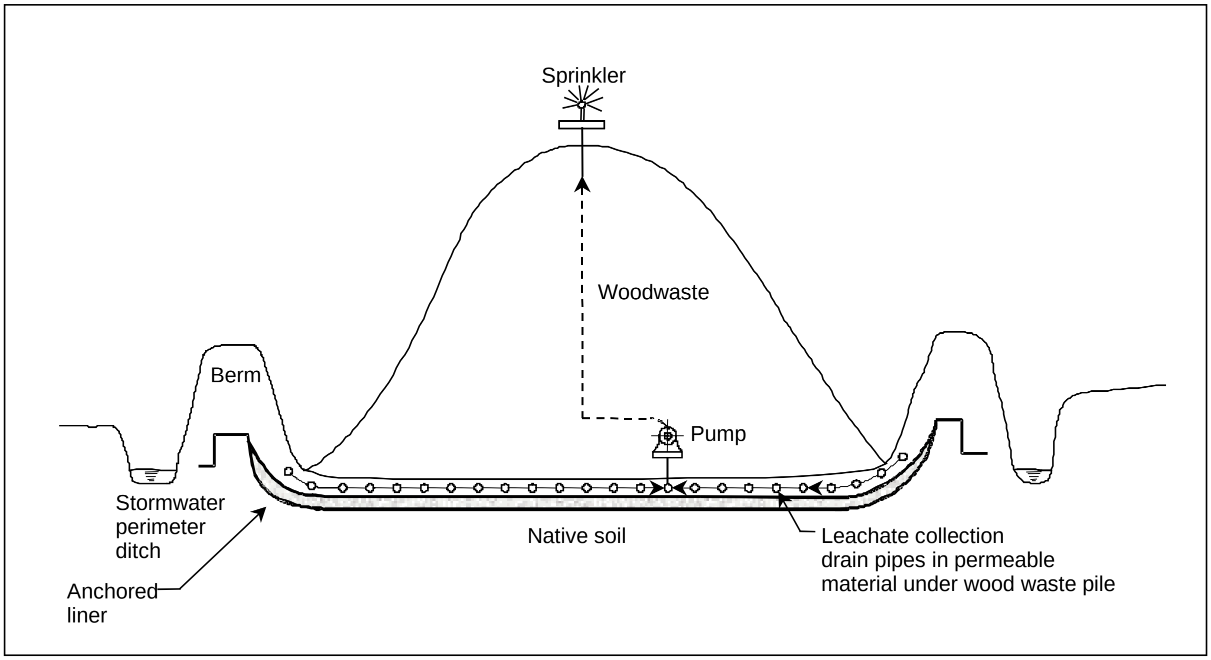
Natural attenuation of leachate occurs to some extent at wood-residue sites in B.C., but the attenuation capacity of soils can be easily exceeded. Until the attenuation capacity of a leachate-saturated soil is refreshed by the slow microbial process, such soil has no further attenuation capacity. At many of natural attenuation sites in B.C., dark coloured, anoxic and toxic leachate is observed. This problem is compounded when fresh wood residue is added to the site but leachate, groundwater and surface water are not monitored.

In practice in B.C., the effectiveness of natural attenuation for treating wood-residue leachate is unproven in some instances and grossly inadequate at some sites. Thus it is considered to be a very risky and unacceptable leachate-treatment option in wet areas near fish habitat. Approval for use of natural attenuation at wood-residue sites should be based on a demonstration by the proponent that the surrounding soils will be effective and have adequate capacity to contain and attenuate all the leachate that could be generated. Otherwise, natural attenuation should only be accepted as a viable form of leachate treatment in situations where a small volume of wood residue is stored, used or disposed of in dry areas of B.C., not adjacent to fishery waters.

8.6.2 Recirculation

Recirculation involves the collection and pumping of leachate onto the surface of a wood-residue site. The recycled leachate subsequently seeps through the underlying wood residue and is repeatedly collected. If a wood-residue site is not covered and it is located in an area where precipitation exceeds evapotranspiration, a net increase of leachate volume with time can be expected with recirculation. Little leachate treatment is provided in the recirculation process unless microbial decomposition of the organic constituents in the leachate is promoted in the underlying wood residue. In the case of a wood-residue landfill, the wood residue can be thought of as a crude anaerobic filter (Figure 8.1) and methane generation can be used to monitor microbial activity. Factors that will promote or terminate microbial decomposition of wood residue are listed in Section 4.2; biological treatment will be discussed in the next section. Spray irrigation of recirculated leachate will increase its oxygen content and thus enhance aerobic decomposition in the upper portion of a wood-residue deposit. Nutrient addition to recirculating leachate is usually necessary to promote microbial activity. Neutralization of recirculated leachate may be necessary to maintain anaerobic microbial activity. A large leachate retention pond may be needed to supply a steady flow of leachate throughout the year. Temperature extremes will terminate microbial activity. Once terminated, such activity requires considerable time to be reinitiated.

Figure 8.1 Leachate recirculation.



Lysimeter studies on recirculation have been largely based on leachate from municipal refuse. Cameron *et al.* (1975) and Cameron (1978) concluded that recirculation could increase biological activity and thus decrease the BOD content of wood-residue leachate. However, the effectiveness of toxicity removal was not reported. Some of the tests were conducted in lysimeters with a high soil/wood residue ratio (i.e. 4.5 kg of topsoil between each 15-cm-thick layer of wood residue), thus natural attenuation was likely augmenting the results of the biological activity.

Birkbeck *et al.* (1978) concluded that recirculation would not be an effective treatment option if acidic leachate terminates the biological activity and a consequential increase in BOD results. Jasper *et al.* (1986) showed that although a reduction in BOD, COD and TOC has been reported from lysimeter studies with recirculated wood-residue leachate, the same removal efficiencies may not be applicable in the field because the rate of simulated precipitation was sometimes exaggerated.

A full-scale recirculation system was reportedly successful in reducing oxygen-demanding substances and stabilizing the leachate quality at a bark landfill in Sweden when pH was maintained near neutrality (Rydin and Haglund 1981). However, there were no data given on treated leachate toxicity or other characteristics.

Spray irrigation is not usually practised as a leachate treatment method because of odour and respiratory health concerns. Generally at B.C. wood-residue sites where leachate is evident and attenuation is being used, recirculation is the first option implemented. Recirculation requires inexpensive pumping equipment, but passage of the leachate through the wood residue can be blocked by a build-up of fines, silt or microbial mats. Recirculation is generally considered to be ineffective at attenuation wood-residue sites in B.C. because of the following three problems:

- attenuation wood-residue sites do not typically have adequate leachate-collection works;
- leachate-pumping capacity is quickly overwhelmed in wet areas; and
- the rate of microbial activity is inadequate to effectively treat the leachate.

Leachate could be collected from underground drainage systems at farms and nurseries and recirculated as irrigation water. Before this is tested, perhaps investigations of the effects of wood-residue leachate on plant growth should be carried out because dead and dying grasses and other plants are frequently observed at sites affected by leachate.

Given its limitations and the lack of good data on its effectiveness, recirculation should not be accepted as a form of wood-residue leachate treatment in the wet regions of B.C. except as a short-term, stopgap measure for containment of leachate.

8.6.3 Biological Treatment

Wood residue and wood-residue leachate can be biodegraded by micro-organisms (Section 4.2). The use of a wood-residue deposit as a crude anaerobic filter in leachate recirculation is a form of biological treatment. Although all wood-residue sites probably undergo slow biological decomposition, true biological leachate-treatment systems require control of leachate volume, temperature, pH and nutrient content to maintain a stable microbial environment. Nutrients, such as nitrogen and phosphorus, should be added to leachate-treatment facilities (e.g. lagoons) to promote microbial growth. Oxygenation of the leachate undergoing treatment is also required so that aerobic micro-organisms will survive. A surge pond may be needed to reduce fluctuation in effluent volumes entering a biological-treatment system. Biological treatment is ideally operated at 35°C, but it will proceed more slowly at lower temperatures. This implies that biological treatment in cold regions may not be effective unless the leachate is pre-heated.

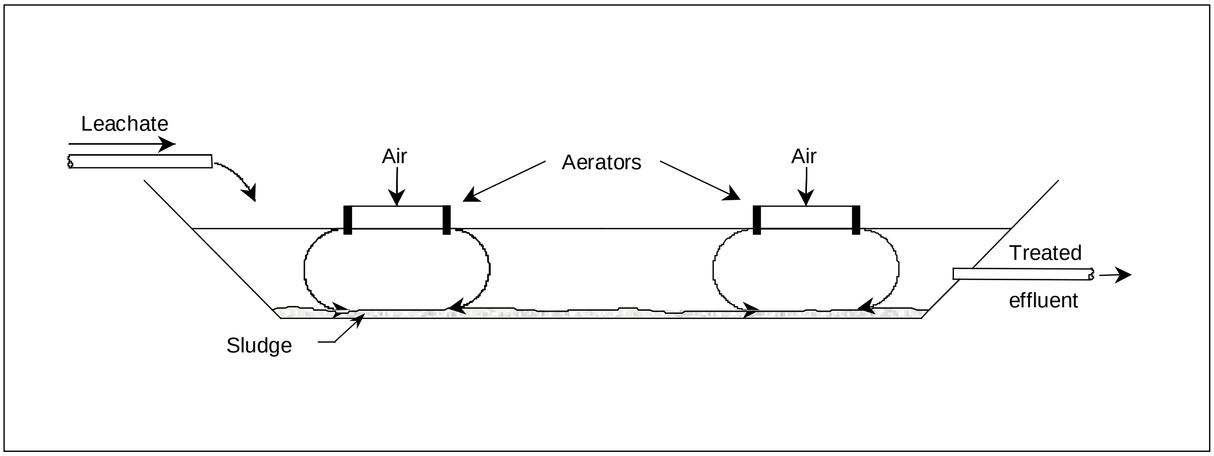
Biologically-treated leachate may need to be “polished” by physical/chemical processes to reduce constituents further and thus make a discharge acceptable. Because biological-treatment systems produce unpleasant odours, their use in residential areas without odour control may be unacceptable. One method of controlling odour involves the containment of all treatment equipment in a structure maintained at negative pressure. A fan is used to draw air through an odour-reducing bed with an adsorbent such as activated carbon. Alternatively, ozonation could provide an effective means of removing odours associated with wood-residue leachate. The growth of micro-organisms may also cause a problem with clogging of leachate-collection works. Provisions for sludge removal and disposal must be included in the plans for a biological-treatment system.

Most of the biological-treatment processes proposed for wood-residue leachate treatment are derived from pulp mill effluent treatment technology. Biological-treatment systems for wood-residue leachate including aeration lagoons, activated-sludge systems and artificial wetlands have demonstrated their potential value through laboratory studies (Birkbeck *et al.* 1990). However, biological treatment of wood-residue leachate is seldom practised in B.C. Selected biological-treatment technologies are discussed below.

8.6.3.1 Aeration Lagoons

Biological treatment can involve the passage of leachate through a series of two or more aerated lagoons in which the environmental conditions are optimal for the growth of micro-organisms (Figure 8.2). Eighty to eighty-five percent of the BOD in pulp mill effluent, which has chemical and physical similarity to wood-residue leachate, can be removed over a four-day period in aerated lagoons (Adamache 1991). In a laboratory study of a three-day-retention aeration lagoon system that treated relatively weak wood-residue leachate, Birkbeck *et al.* (1990) found that BOD and COD did not change significantly, but that the toxicity (as measured by a rainbow trout 96-h LC50) was reduced (Table 8.2).

Figure 8.2 Use of aeration lagoon systems.



The size of lagoons necessary to satisfactorily treat wood-residue leachate could not be readily accommodated at construction, mill or landfill sites. Because of the space requirements and high capital and maintenance costs, the use of aerated lagoons may only be feasible at sites where such facilities are already in operation to treat other types of effluent. Treatment of wood-residue leachate with aeration lagoons is currently only practised at a small number of B.C. pulp mills.

8.6.3.2 Activated Sludge

Activated-sludge treatment systems with high concentrations of micro-organisms and nutrients have the potential to reduce the space and time requirements for detoxification of wood-residue leachate. In a series of laboratory experiments, Birkbeck *et al.* (1990) examined the effectiveness of various activated-sludge systems in reducing BOD and COD concentrations of wood-residue leachate. The systems reported on included fluidized-bed, flow-through and sequencing-batch activated sludge (Figure 8.3). Experiments with a one-day-retention fluidized-bed system resulted in reductions of 31% of the BOC and 18% of the COD but the treated effluent remained toxic. A second experiment involving a sequential-batch system resulted in a 94% reduction in BOD and a 67% reduction in COD; in addition, the treated effluent was non-acutely lethal. When these authors compared sequential-batch systems with different retention times (i.e. two, five and ten days), there was almost no difference in removal efficiency for toxicity, BOD and COD. A third experiment involving a six-day-retention flow-through activated-sludge system, resulted in 97% reduction in BOD and 69% reduction in COD. The researchers noted that the quality of effluents produced by these activated-sludge systems could be expected to deteriorate during rainstorms if the mixed-liquor suspended solids concentration fell below the range that is necessary to promote effective treatment (i.e. between 2,000 and 4,000 mg·L^{-1}).

Table 8.2 Change in selected parameters at a 3-d-retention aeration-lagoon system that treated relatively-weak wood-residue leachate.

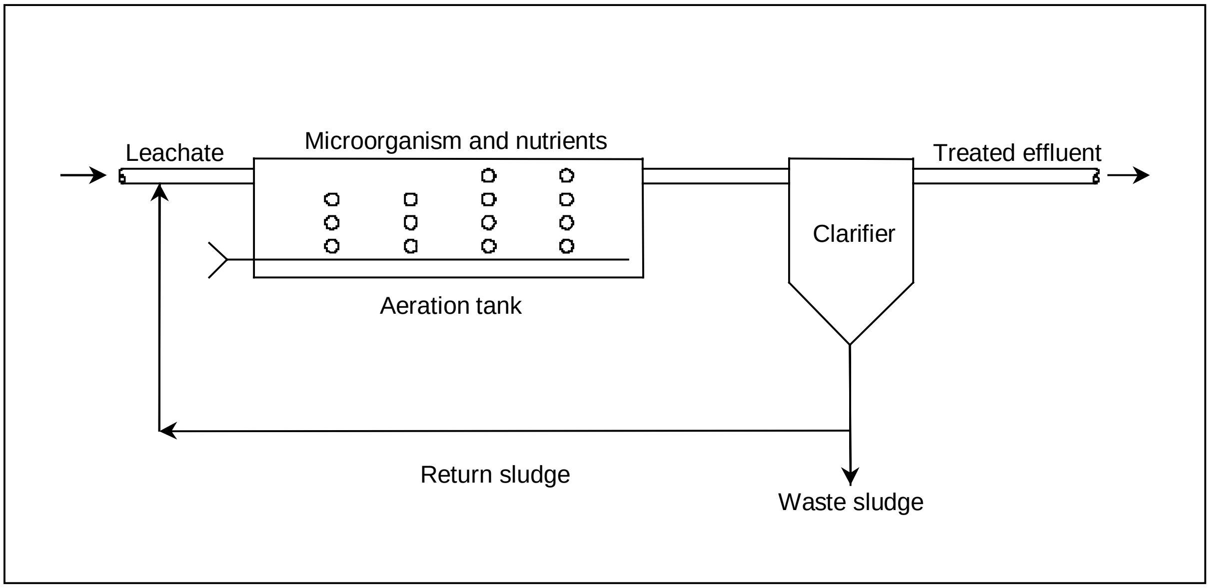
	BOD (mg·L^{-1})	**COD (mg·L^{-1})**	**Toxicity (96-h LC50)**
Influent	535	1726	40%
Effluent	555	1580	>100%
Removed	0%	8%	

Source: Birkbeck *et al.* 1990.

8.6.3.3 Natural and Artificial Wetlands

A definition of a wetland is provided in Section 3.4. In an early field study EconoTech Services Ltd. (1977) reported no reduction in the concentration of hogfuel leachate parameters over a 200-foot-wide swamp that received leachate. Dilution may be the only mechanism operating to

Figure 8.3 Use of activated sludge systems



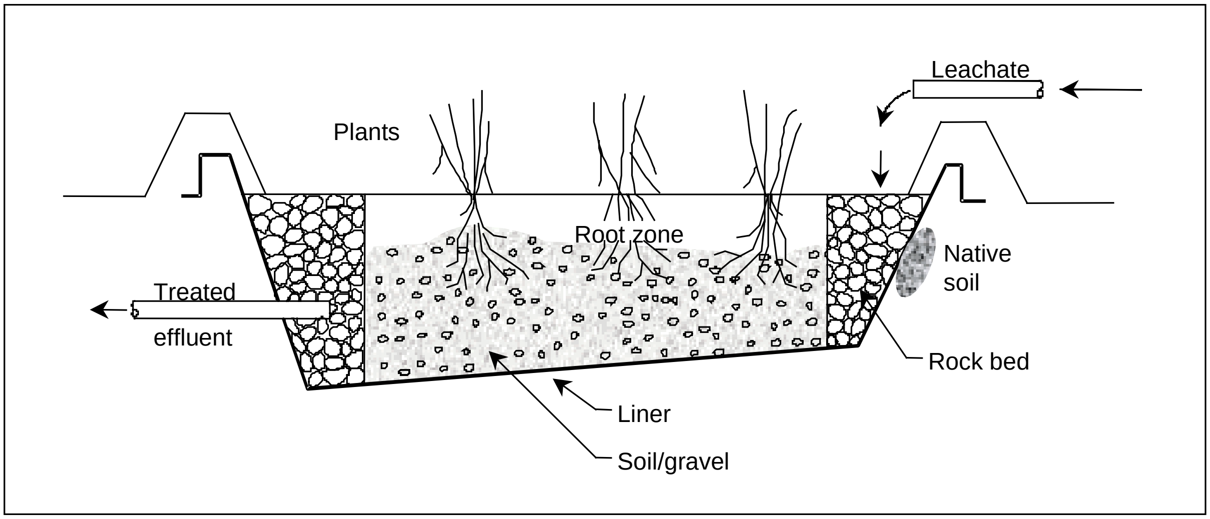
reduce leachate concentrations in some natural wetlands.

In the laboratory, Birkbeck *et al.* (1990) investigated the effectiveness of an artificial-wetland system (with planted vegetation) as a biofilter to remove organic and inorganic constituents of leachate (Figure 8.4). A short retention time led to ineffective removal of leachate toxicity. However, reduction in BOD and COD levels over a 10-day period was more effective if the initial levels of BOD and COD in the untreated leachate were kept relatively low. For example, a removal efficiency of 4% was achieved from an initial BOD level of 535 $mg \cdot L^{-1}$, whereas 43% was achieved from 463 $mg \cdot L^{-1}$ BOD. As well, a removal efficiency of 19% was achieved from an initial COD concentration of 1726 $mg \cdot L^{-1}$, whereas 29% was achieved from 1024 $mg \cdot L^{-1}$ COD. Birkbeck *et al.* concluded that the effectiveness of the treatment system could be enhanced by using more mature plants and longer retention times.

Kent (1990) reported the use of an "engineered marsh" in treating leachate that emerged along roads constructed over wood-residue fill in Richmond. Based on analyses of treated and un-treated leachate, the engineered marsh was reported to be successful in treating leachate over a two-year period.

Natural wetlands that flow directly into fish habitat, including fish-food-production areas, would not be acceptable for use in leachate treatment.

Figure 8.4 Engineered wetlands.



8.6.4 Physical/Chemical Treatment

Physical/chemical treatment methods including: aeration, carbon adsorption, chemical oxidation (e.g. using ozone, calcium hypochlorite, hydrogen peroxide or potassium permanganate), chelation, coagulation, ion exchange, neutralization, precipitation and reverse osmosis can be used singly or in combination to remove colour, selected organics and metals from wood-residue leachate. However, these technologies are not presently used at B.C. wood-residue sites because of the large operational costs. These methods may find use in specialized treatment applications such as: pretreatment; polishing to complement biological treatment; and where a small quantity of leachate must be treated quickly.

8.6.4.1 Carbon Treatment

Carbon can be used as an adsorbent to remove dissolved organic compounds, particulates and metals from wood-residue leachate. Carbon treatment involves a surface-adsorption phenomenon whereby ionic compounds in the liquid phase are accumulated and retained on the carbon surfaces. The BOD (as well as colour) of the treated leachate is reduced because oxygen-demanding organics are adsorbed onto the carbon particles. Activated adsorption, also known as chemisorption, involves electronic interactions between the carbon surface sites and solute molecules (Freeman 1989). During chemisorption, an actual adhesion force is generated between the carbon surface and the adsorbed compound. Sorption mechanisms are discussed in Section 8.6.1.1.

A large-scale carbon treatment of wood-residue leachate would involve use of one or more beds or columns of carbonaceous material. The number and volume of treatment cells would be determined in pilot studies. A redundant carbon column or bed can be installed at the end of each system if the treated effluent is to be discharged on a continuous basis (rather than in batches). Clogging of carbon beds by microbial growth or metallic complexes may occur, thus regular maintenance and backflushing is required. Due to the large concentration of organics in wood-residue leachate, any carbon beds or columns are likely to become quickly saturated. When the first carbon bed or column is saturated in a continuous-discharge system, it is taken out of service and replaced by the second bed or column and so on. A new redundant bed or column is subsequently added to the end of the system. The spent carbon may be regenerated/ reactivated by steam or high temperature incineration. The end products of these regeneration/ reactivation processes may include contaminated sludge, sediments, stack gases or a vapour stream, each of which poses its own discharge/disposal problems. As with all gaseous, liquid and solid wastes, the disposal of the spent carbon and its residues would require an approval or permit from the B.C. Ministry of Environment, Lands and Parks. The high cost and problems associated with carbon adsorption render it not economically feasible for wood-residue leachate treatment except in circumstances involving very small amounts of leachate. For these reasons, carbon adsorption is generally used as a “polishing step” after initial treatment by some other, less-costly processes.

Various carbonaceous materials have been used or evaluated for effluent treatment. Flyash was evaluated for treatment of pulp mill effluents (NCASI 1973). Ash from burning bark was found to be effective for detoxification of hydraulic-debarker effluents (PAPRICAN 1977b). Activated carbon has been used in the treatment of industrial effluents. Lignite or soft coal has been used in a large bed of filter media to treat municipal effluents. Wood ash and activated carbon have been used in treating log pond and hydraulic-debarker effluents in B.C. forest products operations but their effectiveness is not known since monitoring data are not readily available.

Activated carbon is the product of thermal activation (i.e. with an oxidizing agent) or chemical activation (i.e. with a hydrating agent) of any highly-carbonaceous raw material such as wood residue or lignite. Activated carbon contains a maze of cracks and crevices of varying sizes that contribute to its surface area. Due to its great porosity, activated carbon is one the few solids that can provide an extremely high ratio of surface area to mass at relatively low cost. Activated carbon is commercially available in powdered (i.e. < 150 mesh) or granular form. Powdered carbon is fed at a predetermined rate to a specified point in the effluent stream and the carbon is removed downstream. Granular carbon can be installed in beds or columns.

8.6.4.2 Other Physical/Chemical Processes

The effectiveness of other physical/chemical treatment processes on wood-residue leachate is less well understood than carbon adsorption. Before implementing any such processes, proponents should be prepared to conduct laboratory, pilot and field studies. There are indications that physical/chemical processes will not be cost effective except in situations where only a small volume of leachate has to be dealt with for a short period of time.

In addition to reducing toxicity, chemical oxidation may also be effective in removing colour, iron, odour and biological growths in leachate (Freeman 1989). The use of hydrogen peroxide as a chemical oxidant results in the generation of oxygen, thus anaerobic decomposition processes could be inadvertently terminated. The use of chlorine-containing compounds may add another pollutant that has to be dealt with before the treated leachate could be discharged. The use of coagulants like alum would be expensive and pH dependent. Sludge dewatering and disposal steps would be required with alum use.

8.7 CONTROL OF DECOMPOSITION GASES

Biological decomposition of wood residue will result in gas formation; aerobic decomposition could result in the formation of toxic and explosive gases such as hydrogen sulphide or methane (Section 4.2.1.2). Gases generated in the decomposition processes can either be dissolved in the leachate/water or be released into the atmosphere. The gas problem associated with dredging operations (e.g. dredging of wood residue) is outlined in Section 4.2.1.2.2. To prevent fish kills from the release of the toxic gases of decomposition and other impacts, the timing of dredging activities should not coincide with a time when fish or other marine life are present.

The control and safe venting of gases must be taken into consideration during design of wood-residue leachate-containment works. This is particularly important where low-permeability liners, foundations, slabs or large paved areas are constructed over wood residue. Efforts to control leachate production usually reduce the moisture content of wood residue and thus reduce the activity of methane-producing bacteria. The design of leachate-control works should also consider measures to prevent the passage of methane into underground “services” (e.g. sewer lines). A few small vents connected to above-ground stacks should be installed at regular intervals in liners encasing wood residue in order to prevent the build-up of carbon dioxide and methane that could lead to the eventual rupture of the liner and fire or explosion hazards. These vent stacks should be situated well above the groundwater table or surface water level. Alternatively, the vents could be connected to “riser” pipes that penetrate the surface of road bed margins. Consideration could also be given to the collection and use of methane gas from wood-residue-disposal sites. Landfill gas monitoring and control are outlined in GRCDA (1983) and Mooij *et al.* (1977).

8.8 LEACHATE MONITORING

The establishment of an effective monitoring program before, during and after the deposition of the wood residue is part of the strategy to prevent impacts on fish and fish habitat, including water quality. Leachate monitoring includes the sampling of leachate, surface runoff and groundwater at a wood-residue site. Cost is the major reason that “monitoring” activities at wood-residue sites in B.C. involve mainly visual observation for surface leachate. Another reason may be due to a false assumption that if there is no observable surface leachate, then there are no other concerns. Visual observation cannot determine if contaminated groundwater is migrating into fish habitat.

Surface leachate may wrongly be considered inconsequential, based on an assumption that natural attenuation will be effective. With surface leachate, the location, frequency and timing of leachate sampling are often poorly considered given that local climate and hydrogeologic conditions are important variables. Section 5.3 provides information on the monitoring, sampling and analysis of wood-residue leachate.

The only way to determine if leachate is being generated or migrating outside of containment and collection structures is by leachate and groundwater monitoring. However, such monitoring is seldom practised at wood-residue sites in B.C. although it is especially important at attenuation wood-residue sites. At containment wood-residue sites, leachate-collection systems could act as witness drains for liner integrity or as monitoring tools. Locations for installation of groundwater-monitoring wells must be determined after an evaluation of the local hydrogeology. Recommended procedures for design and implementation of a leachate monitoring program can be found in a publication by the former Fisheries & Environment Canada (Rovers *et al.* 1977).

8.9 SITE-SPECIFIC CONSIDERATIONS

The following sections provide additional guidelines to prevent impacts to fish and fish habitat at specific sites where wood residue is stored, transported, used and/or deposited. The hydrogeologic regime at a site can change during deposition of wood residue and after site closure. Site design should include a margin of safety for generation of a greater volume of leachate than predicted.

8.9.1 Timber Harvesting and Water Handling/Transportation of Logs

Practices at booming grounds and log dumps often result in deposits of wood residue in aquatic habitat. These deposits may dictate frequent dredging of foreshore areas. Strategies to prevent impacts on aquatic ecosystems from the water handling, transportation and sorting of logs is described in the DFO report, *Handbook for Fish Habitat Protection on Forest Lands in B.C.* (Toews and Brownlee 1981). The following points, taken from the handbook, are designed to minimize the impacts of log handling on the aquatic environment:

- Dry-land handling and sorting is preferred to water handling and sorting, although the location of dry-land facilities should not be in fisheries-sensitive zones such as estuaries, salt marshes, herring spawning areas or shellfish beds.
- The freefall, violent dumping of logs into water should not be practised since this is the major cause and point source of loose bark and other log debris.
- Easy let-down devices should be employed for placing logs in the water, thereby reducing bark separation and the generation of other wood debris.
- Positive bark and wood debris controls, collection and disposal methods should be employed at log dumps, raft building areas and mill-side handling zones. This would be required for both floating and sinking particles.
- Log dumps should not be located in rapidly-flowing waters or other water zones where positive bark and debris control cannot be effective.

- Accumulations of bark and other debris on the land and docks around dump sites should be kept out of the water.
- Whenever possible logs should not be dumped, stored, or rafted where grounding, particularly on sensitive habitats, will occur.
- Where water depths will permit the floating of bundled logs, they should be secured in bundles on land before being placed in the water. Bundles should not be broken again except on land or at mill side.
- The inventory of logs in water for any purpose should be kept to the lowest possible number for the shortest possible time.

8.9.2 Dryland-Sorting Facilities

Dryland-sorting facilities in B.C. are commonly located adjacent to watercourses. Paving of dryland-sorting sites is becoming a common practice. Compared with unpaved sites, pavement allows easier site cleanup because less soil and rock get mixed in with the dryland-sorting debris. Stockpiling and open burning of dryland-sorting debris should be conducted at sites well removed from the highest water mark. Brow logs or other control structures can be installed to ensure that debris is stockpiled within designated areas. Prolonged stockpiling should only take place during dry weather to minimize leachate generation. Sorting debris and burned residues should be frequently removed to a permitted refuse site. To avoid the deposit of flyash into watercourses, burns should be timed so that the prevailing wind blows away from watercourses. Leachate-control works, as described above, may be necessary if such problems occur.

8.9.3 Wood-Processing Facilities

The forest-products industry has improved its operational procedures in recent years with respect to the protection of fish and fish habitat but more needs to be done. At facilities that are located adjacent to watercourses, site-specific operational procedures, including staff training, can be implemented to further prevent deposits of wood residue and its leachate into watercourses. Wood-processing operations in water (e.g. log bucking) are not recommended because the wood residue and leachate cannot be effectively captured. Good housekeeping should be practised by mill operators to ensure regular and frequent removal of wood residue from under jackladders, log decks and log lifts. Properly maintaining and directing pneumatic wood residue conveyor systems will reduce wood-residue deposition in foreshore areas. The use of hydraulic debarkers should not be considered unless effective treatment works are in place to deal with the wood fibre content and toxicity of the debarker effluent. The timing of any dredging operations must be approved by the appropriate government agency to ensure there are little or no fishery activities in the area. Dewatering and dumping of dredge spoil must be conducted in permitted refuse sites only.

8.9.4 Wood-Residue Storage and Loading Facilities

Temporary storage is a term used to describe the open stockpiling of wood residue at farms, nurseries, shipping and wood-processing facilities. Temporarily stored wood residue is generally shipped or “used” within a few months. However, such stockpiling is really not temporary because the depleted piles are often renewed with fresh wood residue.

There are many abandoned, large wood-residue storage piles in B.C. that were built up over a decade or more. If outside storage of wood residue in large piles must be located adjacent to a watercourse, a buffer strip and control structures, such as bulk heads, should be installed between the water and the wood-residue pile so that erosion of the pile can be prevented. If wood residue is stored on piled structures overhanging the water, the integrity of the structures must be checked regularly and any repairs completed immediately. If wood residue is stored in overhead bins before being hauled away on trucks, these bins should be located well away from any watercourse.

To minimize leachate generation, the base of a wood-residue pile should be restricted to as small an area as possible (i.e. not spread out) and the surface should be shaped to create a moderate to steep slope (e.g. cone shaped). Surface runoff must be diverted around the piles and leachate control works may be necessary if problems occur or if water is sprayed on wood-residue piles for dust suppression or fire prevention

Wind blown wood-residue deposited into aquatic habitat is often the result of poor scow-loading practices and over filling of scows. Operators of wood-residue loading facilities are responsible for windblown deposits of wood residue into adjacent watercourses. Such losses can be reduced by installing enclosures for belt conveyors at critical locations and ensuring that outlet spouts are directed away from watercourses. A boom should be deployed around the scow to collect any wood residue that may have been blown into the adjacent waters. Boomed wood residue should be removed from the water frequently (i.e. before it sinks). Scow loading of wood residue should not be practised during windy conditions. To avoid slumping of wood residue into water, care must be employed when loading scows beyond the height of the side panels. Scow covers may be necessary if fine wood-residue particles, such as sawdust, are being transported.

8.9.5 Peatland Development

Peatland is generally low lying and wet but property value is increased if peatland can be developed for industrial, commercial, residential or recreational uses. Peatland development requires either extraction of the peat or the placement of a lightweight-fill material over the peat. Large quantities of wood residue are commonly used for peatland development in B.C. because it is the least-cost option. Since the use of wood residue as a construction fill is currently exempted from permitting requirements under the provincial *Waste Management Act*, many developers falsely believe they can have unregulated use of wood residue. The importance of undisturbed peatland in providing important wildlife habitat and its importance in ensuring good water quality and quantity in downstream fish habitat are often ignored in peatland development.

The protection of adjacent fish habitat, including water quality, from degradation by wood residue and leachate should be considered as part of the cost of the project before peatland is filled. Peat extraction and the use of more inert, lightweight materials should be considered. Strategies to protect fish habitat, including water quality, that are referenced in this section are comparatively difficult and expensive to implement in peatlands. The implications of a change in hydrogeologic regime should be of particular concern in areas characterized by peat soils where the weight of the overlying fill (e.g. wood residue and “preload”) may result in the compression of the underlying peat and the alteration of existing drainage patterns. Penetration of liners could occur if foundation piles are used to support heavy overlying structures or if drain wicks are installed to aid fill settlement. Differential settlement may be more of a concern in peatlands than in areas with mineral soil. Differential settlement exacerbates the potential for damage to the integrity of the liners and berms and other works installed to prevent contact of the wood residue with water.

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APPENDIX 1 CLIMATIC CONDITIONS AND FISHERY RESOURCES OF B.C.

A1.1 CLIMATIC CONDITIONS

Regional differences in mean precipitation are relevant to the determination of acceptable strategies for the use and disposal of wood residue. Mean annual rainfall can provide an important indicator of the suitability of a site for use as a landfill or wood-residue storage area. This is because the concentration/volume of wood-residue leachate that is generated is dependent on the volume of precipitation and ground/surface water that the wood residue comes into contact with. Groundwater contamination by leachate from wood-residue landfills is characterized by the lateral spread of a contaminant plume and can increase dramatically during wet months as a result of high levels of precipitation and a corresponding rise in the level of the water table, particularly in low-lying areas (Sweet and Fetrow 1975).

B.C.'s climate is governed by two major factors: the maritime influence of the Pacific Ocean and the orientation of the series of mountain ranges that parallel its coast. Throughout most of the year, moist, eastward-flowing oceanic air is forced over these mountains, resulting in high levels of rainfall on west-facing slopes. This pattern is especially evident in winter when the frequent occurrence of winter storms results in heavy precipitation in coastal regions. In winter, the build-up of a high pressure ridge is often associated with an influx of cold arctic air, resulting in periods of very cold, dry weather. Along the coast, the influence of the milder oceanic air periodically predominates, temperatures rise and precipitation occurs primarily as rainfall. In contrast, cold, dry conditions may persist throughout much of the winter in the interior and north-eastern portions of the Province. During summer, the normally strong eastward flow of air over much of the Province tends to weaken. This trend, in combination with the influence of persistent high pressure ridges that occur off the coast, diminishes the effects of passing frontal systems. As a result, summer is generally fairly dry throughout most of the Province.

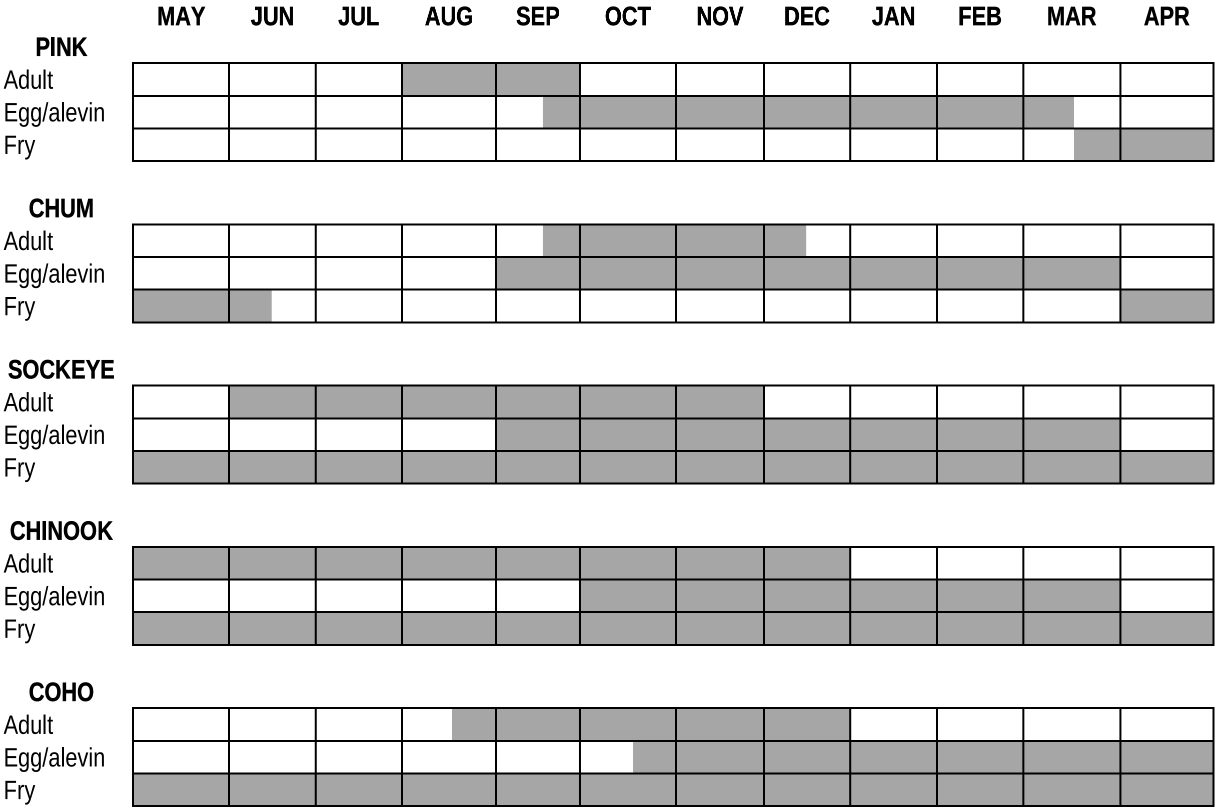
Weather systems from the Pacific have unobstructed access to Prince Rupert and Tofino and as a result these communities exhibit some of the highest levels of rainfall in the Province. Conversely, communities such as Summerland, located on the interior plateau, exhibit relatively low levels of precipitation. Monthly rainfall and temperature data, averaged over a 30-year period from 1951 to 1980, for 533 reporting stations in B.C. can be found in the "Canadian Climate Normals 1951-1980 for Temperature and Precipitation" (Atmospheric Environment Service 1980).

Figure 5.2 illustrates the mean annual precipitation and evapotranspiration rates in the different physiographic regions of B.C. Precipitation and evapotranspiration are natural processes controlling the amount of water that is available for recharging groundwater systems. The characteristics of these systems, in turn, may play an important role in determining the suitability of a site for the deposition or storage of wood residue. Because groundwater movements are dependent on site-specific conditions including slope, proximity to sources of surface water, soil type and degree of infiltration; these characteristics must be assessed on a site-specific basis.

A1.2 OVERVIEW OF THE SALMONID LIFE CYCLE

Because B.C.’s salmon populations support significant aboriginal, commercial and recreational fisheries, their life cycles are important. Five species of Pacific salmon, pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), chinook (*O. tshawytscha*), sockeye (*O. nerka*) and coho (*O. kisutch*) salmon occur throughout the Province in freshwater, estuarine and marine areas. Salmon and anadromous trout (i.e. steelhead - *O. mykiss* and sea-run cutthroat - *O. clarki*) annually migrate from marine waters to spawning grounds in their natal streams and lakes. Figure A1.1 illustrates the seasonal residency and utilization of freshwater habitats by Pacific salmon.

Figure A1.1 Life stages of Pacific salmon in freshwater.



Adapted from Samis *et al.* (1991)

Each species of Pacific salmon is made up of separate stocks originating in different river systems; each stock, in turn, consists of diverse races. Although each species is characterized by its own life history, all are anadromous, spending most of their adult lives in salt water and returning to natal streams to spawn. An exception is that of kokanee, a landlocked variety of sockeye salmon. Figure A1.2 illustrates the generalized life cycle of Pacific salmon. Juvenile salmon may spend up to 3 years in freshwater before migrating downstream to the ocean.

All species of Pacific salmon spawn in rivers and streams and sockeye salmon often spawn in suitable lake habitats. Pink, chum and coho salmon tend to return to coastal creeks, whereas the spawning grounds of chinook and sockeye salmon extend much further inland.

Figure A1.2 Generalised life cycle of Pacific salmon.

Source: Samis *et al*. (1991).

Eggs are deposited and fertilized in gravel nests or redds in autumn and incubate through the winter, undergoing a series of transformations from eyed egg to embryo. The young fish hatch as alevins in the spring and remain in the gravels that line the stream bed for several weeks prior to their emergence as fry. Throughout their development these fish are very sensitive to physical or chemical disruptions, including gravel movement or compression, sediment or debris deposition, fluctuations in water temperature and flow and changes in water quality.

During their downstream migration, juvenile salmon tend to swim in schools near the surface and seek shelter along the shallow margins of river channels where current is reduced and there is ample access to larval insect and other invertebrate prey. Since this migration usually coincides with spring freshet conditions, the fry of most species are swept along passively as they make their way downstream.

Once they reach the estuary, juvenile salmon may shelter in side channels, sloughs and nearshore marshes for several weeks while undergoing the physiological adjustments that precede their entry into salt water.

A1.3 IMPORTANCE OF FISH HABITAT

The environmental requirements characteristic of each stage of the salmonid life cycle play a critical role in determining the rate of survival of each species and stock. Salmon are physiologically sensitive, requiring a relatively narrow range of environmental conditions. This characteristic makes them vulnerable to physical and chemical disturbances, particularly in freshwater where they spawn and rear.

Prior to their return to freshwater, adult pink and chum salmon, as well as certain runs of sockeye, gather in shallow inshore waters near the mouths of major rivers, delaying their upstream migration for up to several weeks. The length of this delay seems to be related to the volume of river discharge. Because salmon rely on olfactory homing cues, it is possible that they are unable to detect the water from their natal streams until river discharges increase as a result of autumn rains. The effect of aquatic contaminants such as wood-residue leachate on the ability of fish to detect olfactory homing cues is unknown.

En route to their spawning streams, adult salmon exhibit a great deal of sensitivity to variations in water quality and changes in their physical environment. They are particularly vulnerable to obstructions and to conditions of low flow, both of which may seriously interfere with upstream passage. On the spawning grounds a certain range of temperature, gravel and flow conditions must be met before nest building, egg deposition and fertilization can proceed.

A productive salmon stream is characterized by several factors including appropriate gradient, gravel porosity and flow conditions. While the flow must be sufficient to provide a constant supply of water that regulates both stream temperatures and oxygen concentrations, it must not be so strong that it results in erosion of the stream bed and the disturbance of the gravel redds.

Developing salmon embryos are particularly intolerant of low dissolved oxygen concentrations. They rely on the percolation of water through the gravels of the stream bed for the continual re-oxygenation of the interstitial water. In salmon spawning habitats, the water column concentration of dissolved oxygen should be at or near 100% saturation (Davis 1975a). In rearing and migration areas, dissolved oxygen should be greater than 80% saturation, subject to seasonal dissolved oxygen variability.

Freshwater and estuarine habitats of fish provide for rearing space, shelter and the production of food. Juvenile salmon feed on aquatic insects and other invertebrates during their freshwater residence and while in estuaries. Areas that provide important habitat for juvenile salmon are frequently those which are most threatened by development, particularly in urban areas such as those adjacent to the lower Fraser River. Side channels and sloughs, which are often poorly flushed, are vulnerable to organic inputs such as wood-residue leachate that can significantly lower oxygen concentrations, affecting the survival of fish and other aquatic organisms.

Although these guidelines make specific reference to the protection of Pacific salmon species and their habitats, B.C. coastal and interior waters support diverse stocks of other fish and shellfish. Pacific salmon are recognized as being generally intolerant of habitat disruption and the degradation of water quality. Because salmon are relatively sensitive to pollutants, require access for migration, clean gravel for spawning and hunt by sight, measures for protection of salmon and salmon habitat from wood residue impacts should also ensure protection of other aquatic species.

APPENDIX 2 GLOSSARY

Absorption-The process of taking in liquids.

Acute Toxicity-A relatively short-term lethal or sublethal effect, usually defined as occurring within 4 days for fish and macro-invertebrates and within shorter times for smaller organisms.

Adsorption-Adhesion in an extremely thin layer of molecules of a liquid, gas or dissolved substance to the surface of a solid with which it is in contact.

Alevin-A stage of embryonic development of salmon or related species that refers to fish recently hatched from the egg, before absorption of the yolk sac and emergence from the spawning gravel have occurred.

Anoxic-Devoid of oxygen.

Antisapstain Chemicals-Compounds such as 2-(thiocyanomethylthio) benzothiazole (TCMTB); copper-8-quinolinolate (Cu-8); pentachlorophenates (PCP) and/or tetrachlorophenates (TTCP); iodo-2-propynyl butylcarbamate (IPBC), didecyl dimethyl ammonium chloride (DDAC); 1-((2-(2,4-dichlorophenyl)-1,3-dioxolan-2yl)methyl)-1H-1,2,4-triazole (azaconazole); and sodium borate (listed in order of decreasing toxicity to fish) which are used in the forest products industry to prevent the growth of sapstain fungus and mould that can cause aesthetic discolouration of freshly-cut lumber. (Although all sapstain control uses of PCP and TTCP were terminated by Agriculture Canada effective December 31, 1990, chlorophenol-contaminated wood residue from wood treated prior to this date may exist at sawmills.)

Benthic-Of, pertaining to, or living on the bottom of bodies of water.

Bioaccumulation-The uptake (includes both bioconcentration and ingestion) and storage in tissues of an aquatic organism of a chemical.

Bioassay-The use of an organism or part of an organism as a method for measuring or assessing the presence or biological effect of one or more substances, wastes or environmental factors under defined conditions.

Bioconcentration-The accumulation (where a passive equilibrium is reached with the ambient environment) in an aquatic organism of a chemical taken up directly from the water.

Biochemical Oxygen Demand (BOD)-The amount of oxygen required to oxidize the organic matter in water or effluent to a stable inorganic form via aerobic microbial decomposition. BOD is usually reported as the amount of oxygen consumed over a specified time period at a specified incubation temperature. A 5-day time period at an incubation temperature of 20°C is frequently used and reported as BOD_5 and usually expressed as milligrams of oxygen consumed per litre of sample (mg O_2 per litre).

Chelation-Chelation is the chemical process by which multidentate ligands attach to metal cations to form heterocyclic complexes containing the metal

Chemical Oxygen Demand (COD)-The amount of oxygen required for the complete chemical oxidation of organic material in water or effluent; usually expressed as milligrams of oxygen consumed per litre of sample (mg O_2 per L). COD provides an estimate of the amount of organic and reducing materials present in a sample.

Chronic Toxicity-Long-term effects that may be related to changes in growth, metabolism, reproduction, disease resistance and death. Chronic toxicity often signifies effects occurring over periods of at least one-tenth of the life span of the organism.

Excess Moisture-Average annual difference between precipitation and evapotranspiration (i.e. theoretical figure deduced from tables indicating on average what proportion of the rainfall and snowfall in an area seeps through to groundwater or runs off as opposed to evaporation and plant uptake (B.C. Pollution Control Board 1989).

Extract-Material separated from a liquid or solid mixture by a solvent.

Fibre saturation point (FSP)-The point at which the cell walls of wood remain saturated and all liquid water has been removed from the lumen of the cells. Below this point, the properties of wood are altered by changes in moisture content. The amount of moisture present in wood when used in environments that provide no contact with liquid water will always be less than the FSP.

Geomembrane-A synthetic liner made of plastic or rubber that is installed in contact with the ground and designed/sealed to prevent the loss of hazardous, polluting or valuable liquids into the aquatic and/or terrestrial environment.

Geotextile-A highly porous sheet of coarse screen made of plastic or rubber used as a support or protective covering for a geomembrane, or placed between layers of geomembrane as a permeable core to create a cavity to which a vacuum can be applied. Geotextiles are also used as filters on liquid collection pipes to reduce clogging.

Hogfuel-A mixture with varying amounts of wood fibres, sawdust, bark and other wood residues that are produced when large pieces of wood residue (not suitable for making wood chips) are “hogged” or cut in a mechanical shredder to produce uniform wood residue fragments, usually up to 10 cm long. Hogfuel is intended for use as a fuel in energy production.

Hydrophilic-Having an affinity for, attracting, adsorbing or absorbing water.

Hydrophobic-Lacking an affinity for, repelling or failing to absorb or adsorb water.

Hypoxic-Oxygen deficient.

Invertebrate-An animal lacking a backbone and internal skeleton. Macroinvertebrates are large enough to be seen without the aid of a microscopic.

Lethal Toxicity-Causing or able to cause death by direct action.

Median Lethal Concentration (LC50)-The concentration of an effluent or chemical that kills one-half of the test organisms usually within a defined time period. LC50 values are derived by exposing the test organisms to a range of concentrations of the pollutant in water and documenting the mortality, usually over 96 h. The final LC50 value describes the concentration of the substance at which the median death occurs.

Median Lethal Time (LT50)-The LT50 is the calculated lethal time to death of 50% of the test organisms at a specified concentration of a chemical or effluent.

Lignans-Optically active (i.e. possessing the ability to rotate the plane of polarized light due to molecular asymmetry), aromatic compounds that occur in the bark, roots, heartwood, foliage, fruits and resinous exudate of living trees.

Lignin-A naturally occurring, phenolic polymer that, together with cellulose, forms the woody cell walls of plants.

Permeability-1. The ability of a membrane or other material to permit passage of a substance. 2. Quantitatively, the amount of a substance that passes through a material under given conditions.

pH-A symbol for the degree of acidity or alkalinity of a solution. Expressed as the negative of the logarithm of the hydrogen ion concentration. A solution with pH equal to 7 is neutral. A solution with pH less than 7 is acidic. A solution with pH greater than 7 is alkaline.

Preload-Inert fill placed temporarily over wood residue or organic soil to cause its settlement prior to construction.

Riparian zone-The stream bank and floodplain adjacent to streams or other water bodies, with particular reference to the vegetation. The riparian zone provides a source of food through terrestrial insect drop; leaf litter, which is consumed by aquatic invertebrate detritivores; stream bank stability and stream channel integrity through the living root network; temperature buffering; and a source of large woody debris.

Sawdust-Particles of wood, approximately 5 mm in length, which are obtained from lumber during cutting.

Static bioassay-A method of testing acute toxicity in which organisms are placed in an effluent or chemical which is not replaced during the exposure period.

Sub-acute toxicity-A lethal or sublethal effect extending beyond an acute (short-term) period and which may become chronic.

Terpenes-Volatile oils that are found in plant foliage and are associated with the resin ducts of softwoods.

Tropolones-Volatile phenolic substances that are found only in the softwoods in the heartwood of decay-resistant conifers such as cedar and cypress.

Wick drains-Strips of conduit material inserted vertically through preload fill to promote infiltration and diffusion of surface water and the even settling of the preload and its underlying fill.

Wood-residue leachate-liquid that contains the dissolved and suspended chemical constituents of wood and its decomposition by-products leached from wood residue in contact with water.