# THE EFFECTS OF SEDIMENTATION ON THE AQUATIC BIOTA

by

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## ABSTRACT

A review of the effects of sedimentation on aquatic biota is presented. The detrimental effects of increased suspended and settled sediments on fish, bottom invertebrates, and primary productivity are documented. It is shown that the upper tolerance level for suspended sediment is between 80-100 mg/l for fish, and as low as 10-15 mg/l for bottom invertebrates. Recovery of the aquatic biota from increased sedimentation is dependent on the severity of sediment additions and the discharge level of the rivers or streams. Recovery from short-term additions of sediment is usually complete within one year.

The use of remote sensing and biomonitoring to locate sources of sedimentation is discussed. Remote sensing can generally be used to identify point sources of sedimentation, define flow patterns, choose sampling stations, interpret ground survey data, and maintain permanent records of changes in water quality. Biomonitoring can be used to monitor water quality, especially with regard to sedimentation, since alterations in the environment are reflected by the indigenous biota.

The sedimentation characteristics in the Alberta Oil Sands Environmental Research Program (AOSERP) study area are presented and observations are made on the potential for erosion and sediment production. The AOSERP study area is divided into twelve hydrological zones and each zone is classified for erosion potential. The zones having a high erosion potential are: (1) lower Ells basin and eastern slopes of Birch Mountains (Zone 1); (2) tributaries immediately north of Fort McMurray (Zone 6); (3) Christina River basin (Zone 7); (4) Hangingstone and Horse River basins (Zone 8); (5) MacKay River basin (Zone 9); (6) Dunkirk River basin (Zone 10); and (7) upper Ells River basin (Zone 11).

Road construction, pipeline construction, general construction (urban and industrial sites), vegetation removal, overburden removal, and pit excavation, tailing ponds, settling ponds, and diversion channels were identified as possible sources of unnatural increases in suspended

and settled sediments in the AOSERP study area. The effect of development activities on the hydrological regime and the aquatic biota is shown. The scale of the disturbance and the length of the recovery period are also predicted. Development activities such as road building and pipeline construction will affect a number of the watershed basins; therefore, they were classified as having regional effect and were considered to be of greatest concern.

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# 1. INTRODUCTION

The Alberta Oil Sands Environmental Research Program (AOSERP) study area (Figure 1) encompasses one of the most important industrial areas in the Province of Alberta (Jantzie 1977). From a biological standpoint, the area is also important (Jantzie 1977). Two major river systems (the Peace and Athabasca) merge within this region to form one of North America's major wetlands, the Peace-Athabasca Delta. Many of the lakes such as Athabasca, Namur, Gardiner, Gipsy, and Gregoire are known for their fisheries and/or recreational potential (Jantzie 1977). There are also many rivers in the area that are rated as being exceptionally important to the fisheries and/or recreation of the region: the Athabasca, Clearwater, Firebag, Ells, Steepbank, MacKay, and Birch (Jantzie 1977).

The potential for environmental damage within the study area as a result of sedimentation caused by technological development is continually present. Therefore, Renewable Resources Consulting Services Ltd. was retained to prepare a document based on the following objectives:

1. To review the published North American and European literature on sedimentation and provide a summary on the subject having special reference for the AOSERP study area;
2. To contact AOSERP Water and Land systems Research Managers to become familiar with their concerns;
3. To review the use of biomonitoring and remote sensing techniques and their applicability for the assessment of the effects of sedimentation on aquatic biota; and
4. To define relevant information gaps and propose research projects that will serve to overcome these deficiencies.

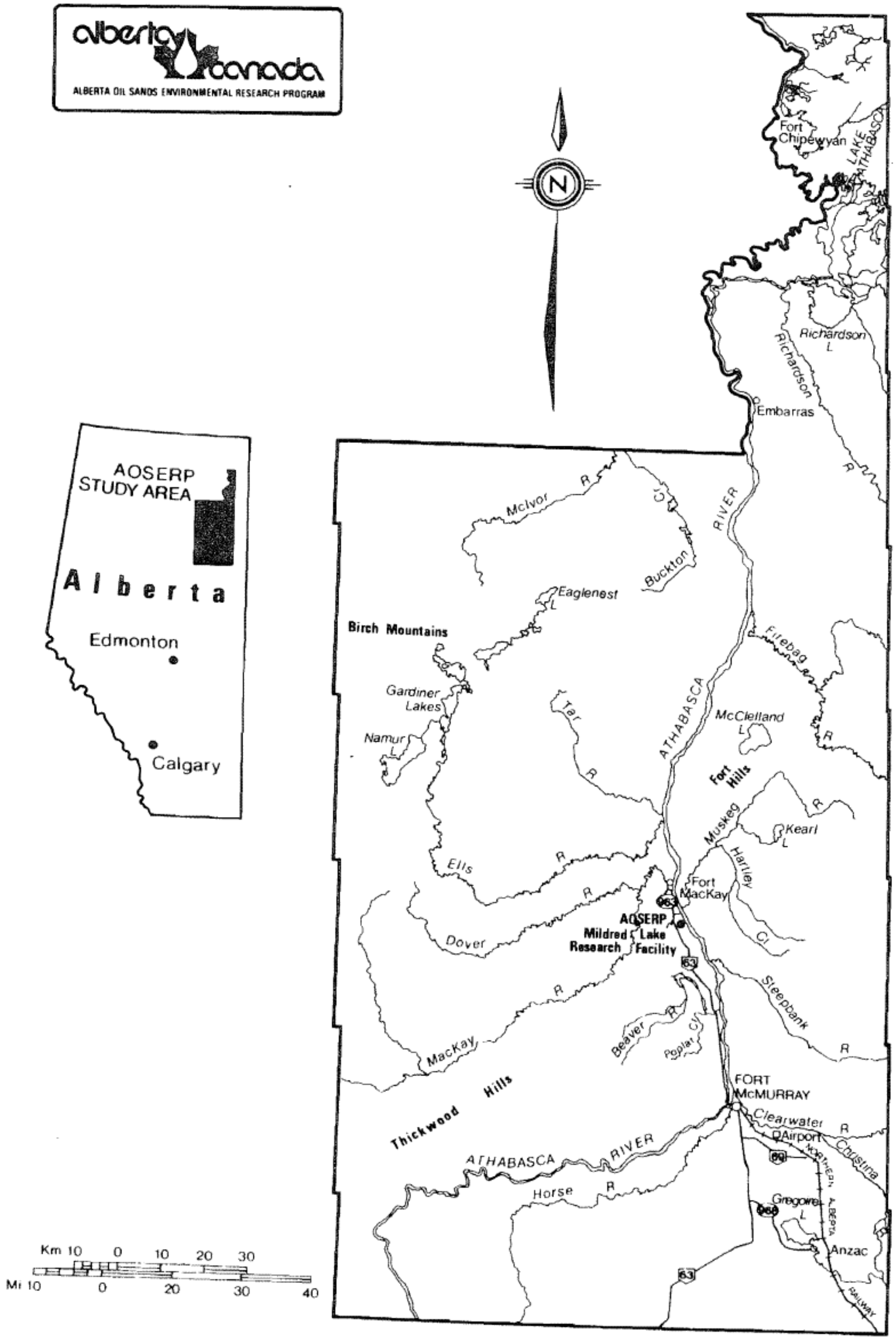


Figure 1. The AOSERP study area.

## 2. REVIEW OF THE EFFECTS OF SEDIMENTATION ON AQUATIC BIOTA

Increasing sediment loads have been shown to have major effects on aquatic biota. The purpose of this report is to review and summarize the available literature and to present this material with respect to the oil sands development in the AOSERP study area. The detrimental effects of increased suspended and settled sediments have been documented in recent review papers by a number of authors (Hynes 1973; McCart and deGraff 1974; Rosenberg and Snow 1975). A distinction between suspended material and siltation was made by Brown (1975); he concentrated on the effects of suspended sediment. Although he stated that the effects of suspended sediment and siltation are almost inseparable, he felt that "to include the effects of siltation, or deposition materials, in the present [his] analysis would only serve to perpetuate many of the misconceptions surrounding the possible effects of suspended solids . . . ." (Brown 1975:63).

In this report the effects on the aquatic biota of both suspended sediments and settled sediments have been discussed. Some confusion in terminology is apparent throughout the North American and European literature. Suspended sediment levels are identified by a number of synonymous terms: suspended solids, suspended load, suspended matter, suspended particles, solids in suspension, finely divided solids, and suspenoids. Turbidity is apparently often used as an analogous term even though " . . . the degree of turbidity is not equal to the concentration (or quantity) of suspended solids, but is an expression of only an effect of suspended solids upon the character of the water" (McKee and Wolf 1971, cited by Brown 1975:8). Similarly, settled solids are synonymous with silt, siltation, settleable solids, and sediment. The term "sedimentation" is taken to describe the active process of transport and deposition of suspended sediments and of sands, silts, and gravels by flowing water.

The sources of unnatural increases in suspended and settled sediments in Canadian northern watersheds have been outlined by

Rosenberg and Snow (1975). Road construction is considered to be a major source of sedimentation. Timber harvesting and stream and river channelization are also common contributors to the sediment load. Hynes (1973) has stated that human activities such as quarrying, mining, dredging, logging, and roadmaking have enormously increased the amount of siltation. He indicates that an undisturbed forested eastern watershed has a very low erosion rate (about 2.5 ton $km^{-2}$ $yr^{-1}$, Borman et al. 1969, cited by Hynes 1973), but human activity has increased sedimentation in the Great Lakes area by a factor of 50 (Ontario Department of Lands and Forests 1971, cited by Hynes 1973). Discussion on sedimentation, water quality, and changes in hydrology resulting from surface mining are given by Light (1975) and by Gleason and Russell (1976).

The mode of action of suspended and settled sediments has been outlined by Rosenberg and Snow (1975). Increases in the quantities of suspended and settled sediments are detrimental since they: (1) reduce light penetration, restricting or eliminating photosynthesis; (2) abrade biota, possibly damaging respiratory and excretory organs; (3) absorb toxicants, resulting in transport and concentration of heavy metals, pesticides, and nutrients; and (4) change the bottom substrate, resulting in infilling of interstices between stones and the formation of unstable substrate (i.e., sand beds, etc.). The following is a review of these effects on the aquatic biota. A number of reviews have appeared in recent years and elaboration on the information presented here can be obtained by referring to these papers. The most comprehensive recent papers are: Cordone and Kelley (1961); European Inland Fisheries Advisory Commission (EIFAC) (1965); U.S. Federal Water Pollution Control Administration (1968); Edwards (1969); Gammon (1970); Phillips (1971); Alabaster (1972); Oschwald (1972); Hynes (1973); McCart and deGraff (1974); Brown (1975); Rosenberg and Snow (1975).

## 2.1 EFFECTS ON FISH

Suspended sediment can act on a fish population either directly or indirectly. The direct effects are: (1) mortality of adult fish as a result of mechanical and abrasive damage; (2) impairment of reproduction, growth, and survival; and (3) increase in disease within the population. The indirect effects result from: (1) habitat modifications, (2) alterations in food sources and other biotic relationships, and (3) reduction of visibility.

Brown (1975), in a review prepared for the U.S. Army Corps on the effects of suspended particles on aquatic life, critically analysed the existing literature. He claims that because of inconsistent criteria and measurement, complexity of aquatic systems, and the multitude of interacting factors, most studies have at best produced questionable and non-comparable conclusions. However, he does cite some cases that have produced substantive evidence for certain effects.

Direct fish mortality because of suspended sediment is considered to have little direct supportive evidence in either historical comparisons, field studies, or laboratory experiments. Although many dramatic changes in fish distribution have been shown (Pfliger 1971, cited by Brown 1975) by historical records, and several species of rough fish have become more abundant in recent years, direct fish deaths are not implicated. The same conclusion was reached by Brown when he reviewed the field study and laboratory experimental literature. Cordone and Kelley (1961), the EIFAC (1965), Cairns (1967), and Koski (1972) are cited as reviews that support this contention.

Brown (1975) does cite two or three histories of direct fish mortality from suspended sediment, but he argues that these situations are abnormal since they present catastrophic events. One example is of significance to the AOSERP study area. Contamination of the Peace River in Florida in 1967 with 1,850,223 $m^3$ (1,500 ac-ft) of phosphate mine-wastes (montmorillmite clay) occurred when an earthern dike surrounding a 80.1 ha (200 ac) settling basin broke. Ninety-one percent of the fish (estimated at more than 983,000 fish) were killed along 122.4 km (76 mi) of riverbed (Ware 1969, cited by Brown 1975). Concentrations of suspended solids reached 8,400 to 59,750 mg/1 in the week following the break. Recovery of both the river habitat and fish populations was rapid (15 months) because of the flushing action of high stream flows in the summer of 1967.

In all of the other case studies cited by Brown (1975), no substantive evidence was presented that isolates suspended sediment levels as the causative factor of adult fish mortality. He generally felt that the combined effect of suspended sediment and pollution, toxins or eutrophication could not be separated.

Brown (1975) summarizes his review by stating that it was not possible to isolate suspended sediment as the causative factor of direct fish mortality. This has also been noted by Hynes (1973), who states that fish have the ability to move out of affected areas; therefore, large fish kills from suspended sediment are unlikely. Evidence of this ability to avoid heavy suspended sediment is given by Saunders and Smith (1965, cited by Hynes 1973) and by Gammon (1970). Gammon reported that several warm water fish species moved out of Deer Creek, Indiana, when suspended sediment levels (limestone) rose above 80 mg/1.

Although suspended sediments may not be responsible for large fish kills there is considerable evidence that high concentrations can eliminate or transform important freshwater fisheries by modifying survival rates, growth rates, resistance to disease, feeding behaviour, movement, and migration (Alabaster 1972; Hynes 1973; Brown 1975). The European Inland Fisheries Advisory Commission (EIFAC, 1965) have presented the following criteria for the maintenance of a freshwater fishery with respect to chemically inert suspended solids:

1. 25 mg/1 or less would not have a harmful effect on fisheries,
2. 25 to 80 mg/1 would maintain a good to moderate fishery,
3. 80 to 400 mg/1 are unlikely to support a good fishery,
4. above 400 mg/1 only a poor fishery would likely be found.

Evidence presented by Alabaster (1972) from Britain supports the EIFAC criteria. Alabaster (1972) concluded that a level of approximately 100 mg/1 of chemically inert suspended solids separates rivers containing fish and those that are virtually fishless. However, he also presents evidence that wood fibre, iron hydroxide, and other oxidizable solids (where there is a risk of deoxygenation of the water) may have acceptable levels that are lower than those presented by the EIFAC. Hynes (1973) also concluded that concentrations of inert sediment under 80 mg/1 were unlikely to seriously damage a fishery; however, growth rates and abundance may be reduced.

An alteration in the species composition from desirable game fish to rough fish because of heavy sediment loads is predictable (Brown 1975). The turbid environment presents a competitive advantage to those species that do not rely on good visibility to catch their prey. Phillips (1971) indicates that fishing success for trout and salmon declines once suspended sediment levels exceed 25 mg/1 since these species are dependent on sight feeding.

The effects of settled sediments on fish populations are more subtle but very destructive (Phillips 1971). Settled sediments usually act by modifying important spawning and rearing habitat or by reducing the food supplies available to adult fish. Phillips has reviewed the literature and listed the effects on early life history stages:

1. Sediment deposition in spawning beds reduces the survival of eggs and alevins by filling the interstices in the gravel substrate, thereby reducing the exchange

of oxygenated water and reducing the removal of metabolites. The reduced intergravel water flow results in the smothering of buried eggs and alevins.

2. Sediment deposition can act as a physical barrier that will block emergence of fry. Sediment blocks the interstitial spaces that provide the normal route of egress of the fry from the redd. Trapped fry starve to death after the yolk sac is absorbed.
3. The survival of the fry after emergence is lowered because of the elimination of their escape cover and food supply. Accumulation of sediment and the infilling of crevices and interstices in the gravel substrate are again implicated.

The adverse effects of settled sediment on the early life history stages of fish have an overall impact on the population recruitment. The size of spawning escapement has been used as an index of fish productivity in salmon streams in western Canada; streams with smaller sediment loads have higher spawning escapement (McNeil and Ahnell 1964 and Wickett 1958, cited by Phillips 1971), and a higher reproductive capacity. Cordone and Kelley (1961), in their comprehensive review of the literature up to 1960, concluded that "the effects of sediment upon alevins and especially eggs of salmonids can be and probably often is [*sic*] disasterous" (Cordone and Kelley 1961:204). They continued that settled sediment, even moderate deposition, is probably one of the most important limiting factors for natural reproduction of salmonids in streams.

A major effect of sedimentation on the carrying capacity of a waterbody and therefore on fish populations comes about indirectly. Many northern species such as Arctic grayling *(Thymallus arcticus)* and Arctic char *(Salvelinus alpinus)* depend on aquatic invertebrates for food, and reduction of this food source by sedimentation can adversely affect or reduce populations of these fish (McCart and deGraff 1974). Reduction in bottom fauna was also responsible for a reduction of trout populations in two English rivers (Alabaster 1972). High sediment levels (1,000 to 5,000 mg/1) reduced the standing crop of benthos from 692 g/100 $m^2$ in control streams to 36 g/100 $m^2$ in the heavily silted river. Fish still remaining in the polluted river were suspected of being immigrants from the clearer tributary streams and were generally found to be feeding on drift. Unfortunately, food would be a limiting factor for most of the year.

## 2.2 EFFECTS ON BOTTOM INVERTEBRATES

There is considerable evidence that the macroinvertebrate fauna of streams are sensitive to suspended and settled sediment levels (Cordone and Kelly 1961; Hynes 1973; McCart and deGraff 1974; Rosenberg and Snow 1975). They are generally adversely affected because of the loss of food supplies and shelter due to infilling of the interstitial spaces within the substrate. They can also be affected by the abrasive and clogging action of the silt on gills and on feeding devices (see Gammon 1970, for an example of the adverse effect on net spinning shadflies). Because of injury to the gills the effect from an increased silt load is further compounded (McCart and deGraff 1974). The aquatic macroinvertebrates are not able to adapt to the further reductions in water flow or oxygen levels in the intragravel habitats.

A change in habitat characteristics of lotic waters as a result of sedimentation usually results in a decline in important fish food organisms (Tricoptera, Ephemeroptera, Plecoptera) and their replacement with more tolerant species such as Chironomidae and Oligochaeta (McCart and deGraff 1974). In their study of the Mackenzie River area, Rosenberg and Snow (1975) indicated that the changes in invertebrate genera and higher taxa were similar to those cited in Nuttall and Bielby (1973). Nuttall and Bielby (1973:83) reported a change in the abundance and species composition of benthic invertebrates in rivers in Great Britain that were affected by china-clay wastes:

> On average, central stations supported 36 times more animals than clay polluted stations, and double the number of animals supported by stations on rivers receiving a reduced level of china-clay effluent. . . . The density of Naididae, Tubificidae, Chironomidae, *Baetis rhodani* and *Perlodes microcephala* increased significantly ($P<0.01$), whereas *Hydrobia jenkinsi*, *Dicranota* sp., Simuliidae, *Sericostoma personatum*, Limnephilidae, *Hydropsyche instabilis*, *Ephemerella ignita*, *Rhithrogena semicolorata*, *Leactra fusca* and *Polycelis felina* were either absent or significantly reduced ($P<0.05$) at stations associated with china-clay wastes pollution.

As representatives of these genera are also found in the AOSERP study area, these results may be indicative of potential effects of sedimentation in the oil sands drainages.

Because of their sensitivity to low levels (10 to 15 mg/l, Rosenberg and Snow 1977) of suspended sediment, the invertebrate populations are important as monitoring agents of environmental changes resulting from siltation. McCart and deGraff (1974) list the comparisons between disturbed areas and silted areas. Silted areas exhibit the following characteristics:

1. A reduction in the overall density of macroinvertebrates,
2. A replacement of sensitive species with more tolerant species, and
3. A reduction in the macroinvertebrate species diversity.

## 2.3 EFFECTS ON PRIMARY PRODUCTIVITY

The source of energy for all biological systems is photosynthesizing organisms. In most freshwater lakes and streams these are phytoplankton, benthic algae, and aquatic plants. These energy trapping organisms are the base of the food pyramid and as such are of critical importance to the productivity and success of the entire system. Their productivity is in turn controlled by a complex of interacting factors including light, nutrients, $O_2$ and $CO_2$ levels, temperature, currents, interspecific competition, and predation. Any change in the environment that affects these factors affects the productivity. An increased suspended particle load has the potential to alter light intensity, nutrient and $O_2$ - $CO_2$ levels, and the temperature of the waterbody.

The most commonly researched hypothesis is that increased suspended sediment levels reduce the amount of light reaching photosynthesizing algae and plants (Ellis 1936; Cordone and Kelley 1961; Rosenberg and Snow 1975). Brown (1975), in a critical analysis of the literature, cites many papers concerning this hypothesis and concluded that there is little evidence to support or dismiss it. Meyer and Heritage (1941) demonstrated an inverse relationship between turbidity and photosynthesis in *Cerathophyllum demersum*. They also postulated that the rate of photosynthesis could be further retarded by a coating of mud on the leaves of aquatic plants. Some preliminary experiments seemed to support this. This suggestion was also put forward by Phinney (1959) and Phillips (1960). Griffith (1955) also correlated turbidity in Lake Michigan with productivity, but concluded that because many interacting factors were involved it was difficult to draw decisive conclusions.

On the basis of a theoretical model developed by Murphy (1962), Plumb (1973) estimated that a 0.5 mg/l increase in suspended sediment levels because of the introduction of taconite tailings could result in a 50% reduction in primary production of Lake Superior phytoplankton. Murphy tested his model using the results of Buck (1956) from Oklahoma fish ponds and found that results agreed very well. However, no mechanisms were suggested and theoretical results must be interpreted with caution.

Productivity in rivers in relation to suspended sediment levels has been examined by Berner (1951), Williams (1964), Bartsch (1960), Martin (1968), and Minckley (1963). All studies demonstrated adverse effects on productivity, but suggested a large number of interacting factors, of which stream flow is the most critical, are responsible.

In a well documented paper on the effects of siltation on aquatic plants in South African river, Edwards (1969) cites severe changes in aquatic flora because of siltation. Besides the direct effects of smothering, siltation results in substrate changes. As many species are quite specific in habitat requirements, community structure is either altered or completely changed. Plant succession is also accelerated by siltation. Plants also suffer directly from the abrasive action of debris and small pebbles.

The effects of sedimentation on the productivity of a lake or stream are dependent on the duration of the increased sediment load, the currents and flow patterns of the waterbody, and the nature of the sediment. Where flow is fast and the sedimentation is of short duration, the current will scour the substrate and effects will probably be minimal. However, the sediment must be deposited somewhere and, depending on the quantity, may have serious consequences for a given area.

## 3. RECOVERY OF AQUATIC BIOTA FROM INCREASED SEDIMENTATION

Recovery is the return of aquatic biotopes after a disturbance to an abundance and diversity comparable to that shown by an adjacent undisturbed or control area (Rosenberg and Snow 1975). Recovery rates vary. Zoobenthos populations in a small stream in Indiana recovered in only a few days from sporadic additions of sediment from a rock quarry (Gammon 1970). During gold dredging operations on Powder River, Oregon, benthic invertebrate numbers dropped to almost nil; they showed complete recovery one year after dredging operations were closed (Oregon State Game Commission et al. 1955; Wilson 1957). Peterson and Nyquist (1972) also found, from studies on Goldstream Creek near Fairbanks, Alaska, that benthic invertebrate populations recovered one year after construction of a bridge upstream; they, along with other investigators (Saunders and Smith 1965; Sheridan and McNeil 1968) conclude that the effects of periodic sedimentation to invertebrates are minimal and short-term. In Caribou Bar Creek, Yukon Territory, numbers of Chironomidae (Tanytarsini) and Orthocladinae were reduced 64% and 75%, respectively, during a mudslide, but had recovered in only 14 days (Rosenberg and Snow 1975).

Several factors can assist the recovery of populations from increased sedimentation: water velocity and discharge, including seasonal variation of these characteristics; the intensity and duration of the sedimentation; and suitable substrates to enable recolonization (Cairns et al. 1971). Freshets, if not too severe, can serve to flush out fine sediments from gravelly substrates to allow for recolonization of benthic organisms (Wilson 1957; Rosenberg and Snow 1975). Aquatic invertebrate drift may also contribute to recolonizing (Gammon 1970; Cairns et al. 1971; Hynes 1973). The hyporheic habitat (i.e., the zone between the rocky substrate and the ground water) provides a refuge for a variety of stream invertebrates and could also be a source for repopulating an area (Coleman and Hynes 1970; Bishop 1973); the influence of this habitat on streams in general, however, has been little explored.

There is little information on the recovery rates of fish and aquatic plants, including benthic algae. According to Gammon (1970) fish response is more complex and is dependent upon the species and the season. In a case history outlined by Ware (1969, cited by Brown 1975) the Peace River in Florida recovered completely in 15 months from a 91% fish kill. The species involved were largemouth bass *(Micropterus salmoides)*, channel and white catfish *(Ictalurus punctatus)*, and endemic minnows (Cyprinidae).

# 4. THE USES OF BIOMONITORING AND REMOTE SENSING

## 4.1 BIOMONITORING

Variations of an indigenous biota can reflect alterations in the environment and organisms can be used to monitor water quality, especially with regard to sedimentation. Since aquatic organisms respond to their total environment they provide a better assessment of environmental disruption than that obtained using either chemical or physical parameters (Cairns et al. 1973). Biomonitoring programs involve sampling, counting, and identification of aquatic organisms, biomass measurement, measurement of bioaccumulation, measurement of biomagnification of pollutants, and data processing and interpretation (Weber 1973 *in* Cairns and Dickson 1973). Biomonitoring can be employed in two basic forms: *in situ* analysis and bioassay. *In situ* analysis equates indicator organisms, population trends, and diversity indices with water quality. A bioassay may be defined as "a test in which the quantity or strength of material is determined by the reaction of a living organism to it" (Quayle 1969, cited by Sprague 1973:75). Bioassays rely on laboratory techniques to show lethal and sublethal effects of a pollutant.

The normal 96 h, LC50 (lethal concentration for 50% of the individuals) bioassay may not be suitable for testing suspended sediment because fish mortality occurs only at extremely high concentrations (Wallen 1951 *in* EIFAC 1965). Because of this, bioassays of sublethal or chronic effects could be used to study responses such as growth, swimming performance, behaviour, and reproductive success (Sprague 1973 *in* Cairns and Dickson 1973).

Aquatic organisms are useful indicators of water quality since groups of plants and animals are often associated with a particular type of habitat (riffle, pool, backwater, etc.). Benthic macroinvertebrates are particularly useful because of their substrate requirements; substrate particle size is closely allied to the distribution of macrobenthos (Cummins and Lauff 1969). Hynes (1976) points out that worms (Oligochaeta), midges (Chironomidae), and burrowing mayflies (Ephemeridae, Potomanthidae, and Polymitarcidae) are generally associated with soft substrate while coarse substrates are normally inhabited by stoneflies (Plecoptera), caddisflies (Tricoptera), and free-living mayflies (Ephemeroptera). The latter three groups are generally associated with clean water. Benthic invertebrates in clean water use the interstitial spaces of coarse substrates for food gathering and cover (Hynes 1973). Accumulation of sediment within the interstitial spaces can severely limit the capabilities of the substrate to harbour a good diversity of invertebrates (Nuttall 1972). Ayers et al. (n.d.) found that diversity declines with reduced particle size and that the diversity of benthic invertebrate communities is largely dependent on substrate composition.

Since most gill-breathing benthic macroinvertebrates are adapted to silt free conditions, degradation of a gravel bottom will be reflected rather quickly by the community composition (Gaufin 1973 *in* Cairns and Dickson 1973). In general, then, the occurrence of aquatic insects that breath with gills can be related to the presence or absence of pollution (Gaufin 1973 *in* Cairns and Dickson 1973). However, the presence of indicator species in seemingly unpolluted water must be interpreted cautiously as Gaufin points out that no community is made up of entirely clean water representatives.

Indicator species are useful in giving a first-hand, qualitative evaluation of freshwater systems (silt bottom organisms versus coarse bottom organisms). However, this is usually a superficial assessment of water quality. The inherent difficulty in using an organism or a small group of organisms as indicators is that the degree of sedimentation in one area cannot be accurately measured or compared to other areas. Other reasons such as geographical location, size of the stream, and flight range of insects produce lack of agreement in indicator values (Gaufin 1973 *in* Cairns and Dickson 1973).

Evaluation of changes in community composition provide better indices of environmental degradation caused by sedimentation than results obtained by the use of indicator species. However, attempting to describe community structure and composition is cumbersome. Therefore, the use of diversity indices to summarize the large amounts of information about numbers and kinds of organisms is desirable (Wilhm 1967). Benthic invertebrates are most often used when developing diversity indices because "their habitat preference and low mobility cause them to be affected by substances which enter their environment. . . . Benthic macroinvertebrates can be indicative of present and past environmental conditions" (Wilhm 1967:1673). Wilhm (1967) explains several diversity indices that are widely used. King and Ball (1964a, cited by Wilhm 1967) used an index based on a ratio between the wet weights of one common organism (Tubificidae) and the wet weights of insects, in each sample; they showed that the ratio was reduced in polluted areas of the Cedar River, Michigan.

Burlington (1962, cited by Wilhm 1967) used the frequency of one taxonomic group and its mean diversity at collecting stations in the Wabash River, Indiana, to discern variations in populations of bottom macroinvertebrates. He found a correlation between the number of groups in common between two stations and the coefficient of similarity.

Keefe and Bergersen (1977) discuss the use of a sequential comparison index (SCI) to measure biological diversity. This procedure is designed for quick handling of large samples with a minimum of taxonomic expertise. However, the method is rather crude and the main criteria used to separate organisms are size, shape, and colour. Examples using benthic invertebrates and fish are given.

In biomonitoring with bioassays, two types of assays are normally used: (1) static bioassay (standing water test), and (2) continuous flow bioassay. The effect of a pollutant can be categorized as: acutely toxic (lethal), or chronic (sublethal)

(Sprague 1973 *in* Cairns and Dickson 1973). Bioassays can be short-term, to determine lethal levels, or long-term (over the life cycle of an assay organism) to determine chronic effects. Short-term bioassays have been employed primarily with fish and macroinvertebrates (Weber 1973 *in* Cairns and Dickson 1973). Bioassays using algae generally measure the effect of the pollutant in terms of reduced rates in growth and photosynthesis, and an increase in susceptibility to normal environmental stresses (Weber 1973 *in* Cairns and Dickson 1973). Algae and other photosynthetic organisms might be best suited for sediment bioassay because turbidity reduces productivity (Samsel 1973). Fish such as rainbow trout *(Salmo gairdneri)* and fathead minnow *(Pimephales promelas)* are frequently used in bioassays (Sprague 1973 *in* Cairns and Dickson 1973). Long-term (chronic) bioassays on fish may be more applicable than lethal bioassays, since Wallen (1951 *in* EIFAC 1965) found that extremely high concentrations (175,000 to 225,000 ppm) of sediment were necessary to cause mortality; it is unlikely that these conditions will ever exist even under the most extreme cases of sedimentation.

## 4.2 REMOTE SENSING

Terrestrial remote sensing is "the measurement of environmental conditions at or near the surface of the earth that is performed with sensors on airborne and space vehicles" (Syncrude Canada Ltd. 1974:1). Other forms of remote sensing may be used (e.g., underwater acoustics, underwater photography), though aerial photography seems to be the most versatile and applicable for hydrological studies.

Remote sensing techniques and their applications have been reported in papers presented at the *Proceedings of the Fifth Symposium on Remote Sensing of the Environment* (1968). Comprehensive remote sensing information is also available from the library files of the Alberta Remote Sensing Centre in Edmonton.

The use of remote sensing in the Athabasca Oil Sands area has been highlighted by Syncrude Canada (1974). The authors, in reviewing remote sensing materials and techniques, feel that remote sensing is necessary to integrate, on a local and regional basis, environmental information and to provide the proper data for future planning.

Remote sensing of suspended sediment has been documented by Bukata et al. (1974) and the use of remote sensing in the study of various hydrological and limnological conditions has been presented by Bukata and McColl (1973), Higer et al. (1969), and Whipple and Haynes (1970). Detection of turbidity and sedimentation is largely restricted to sensors using the visible spectrum (400 nm to 700 nm) such as black and white (panchromatic) photography, colour photography, and false colour (colour infrared) photography (telephone conversation of 17 February 1978 from C. Bricker, Administrator, Alberta Remote Sensing Centre, Edmonton, Alberta). Satellite sensing will not provide the necessary detail for detecting suspended sediment in the waterbodies in the AOSERP study area except perhaps in Lake Athabasca (C. Bricker pers. comm.). Aerial photography is useful in watershed surveys since it provides information on soils (organic versus mineral) topography, drainage systems, erosion, vegetation, surficial geology, and land use (Bird 1972). In the AOSERP study area, highly erodible soils could be identified by remote sensing. James (1975 *in* Raymond and Mosonyi 1975) reports that remote sensing can generally be used in identifying point sources of sedimentation, distinguishing various water masses, defining flow patterns, choosing *in situ* sampling stations, interpreting ground survey data, and maintaining a permanent record of changes in water quality. Aerial surveys over urban areas and plant sites can aid in locating sources of sedimentation and provide data on unstable areas and their rates of erosion (Robinove 1968). Aerial photographs provide information on size, shape, and position of objects as well as maintaining a constant record over time of changes in a watershed (i.e., increase in delta formation) (James 1975 *in* Raymond and Mosonyi 1975). Dye marker experiments can illucidate local flow patterns and suspended sediment levels can be measured by the intensity and composition of scattered light (Bukata et al. 1974; James 1975 *in* Raymond and Mosonyi 1975). General ranges of water depths can be measured by multi-spectral scanning (Higer et al. 1969); this could provide information on sediment deposition and be used to determine different substrate types.

Full photographic analysis of bottom characteristics is restricted by water transparency and season (Lukens 1968). Meteorological conditions and low light also restrict the use of multi-spectral scanning which operates the range of the visible spectrum (Thompson et al. 1974). In cases where aerial remote sensing is not feasible subsurface sensors can be used to collect data on light penetration, compensation depth for photosynthesis, water transparency, and light scattering (turbidity) (Cain 1966).

## 5. SEDIMENTATION CHARACTERISTICS IN THE AOSERP STUDY AREA

The term "sedimentation" is taken to describe the process of transport of sands, silts, and gravels by flowing water (e.g. in river channels); this definition is accepted by environmentalists but differs somewhat from that used by engineers.

AOSERP is concerned with the relationship between sedimentation and the aquatic biota in streams. More specifically, their interests lie in the ability of the biota to function within extremes of suspended sediment concentrations or bed load transport rates, particularly if these extremes are a direct or indirect consequence of oil sands mining development. An important first step in a study of this problem is a description of the sedimentation regime of streams in the AOSERP study area. At this stage there is little definitive information available, particularly for channels tributary to the Athabasca River. However, order-of-magnitude observations can be made and potential mining areas having a high potential for erosion and sediment production can be pointed out. This will provide the benefit, for example, of indicating "hot spots" or areas that might require establishment of special sedimentation research projects.

As shown in Figure 2, the Athabasca River generally bisects the AOSERP study area. Upstream of Fort McMurray the river passes over a series of rapids at an average gradient of about 0.094% as it cuts across the strike of bedrock outcrops. Bed material consists of boulders that likely experience only occasional transport; banks are relatively stable as the channel has become entrenched in bedrock. Frequent valley-wall slumps provide a source of easily erodible and transportable materials. Measurements of suspended sediment at Fort McMurray shows that the average annual sediment load upstream of the town is about 13.6 x $10^6$ tonnes/year (Thurber, Crippen, and Northwest Hydraulic Consultants 1975), 5% of which is assumed to be transported as bed load. The Clearwater River adds about 0.9 x $10^6$ tonnes/year to this amount at Fort McMurray. Concentrations of suspended sediment, as measured by Water Survey of Canada at their Fort McMurray station, reach several thousands milligrams per litre.

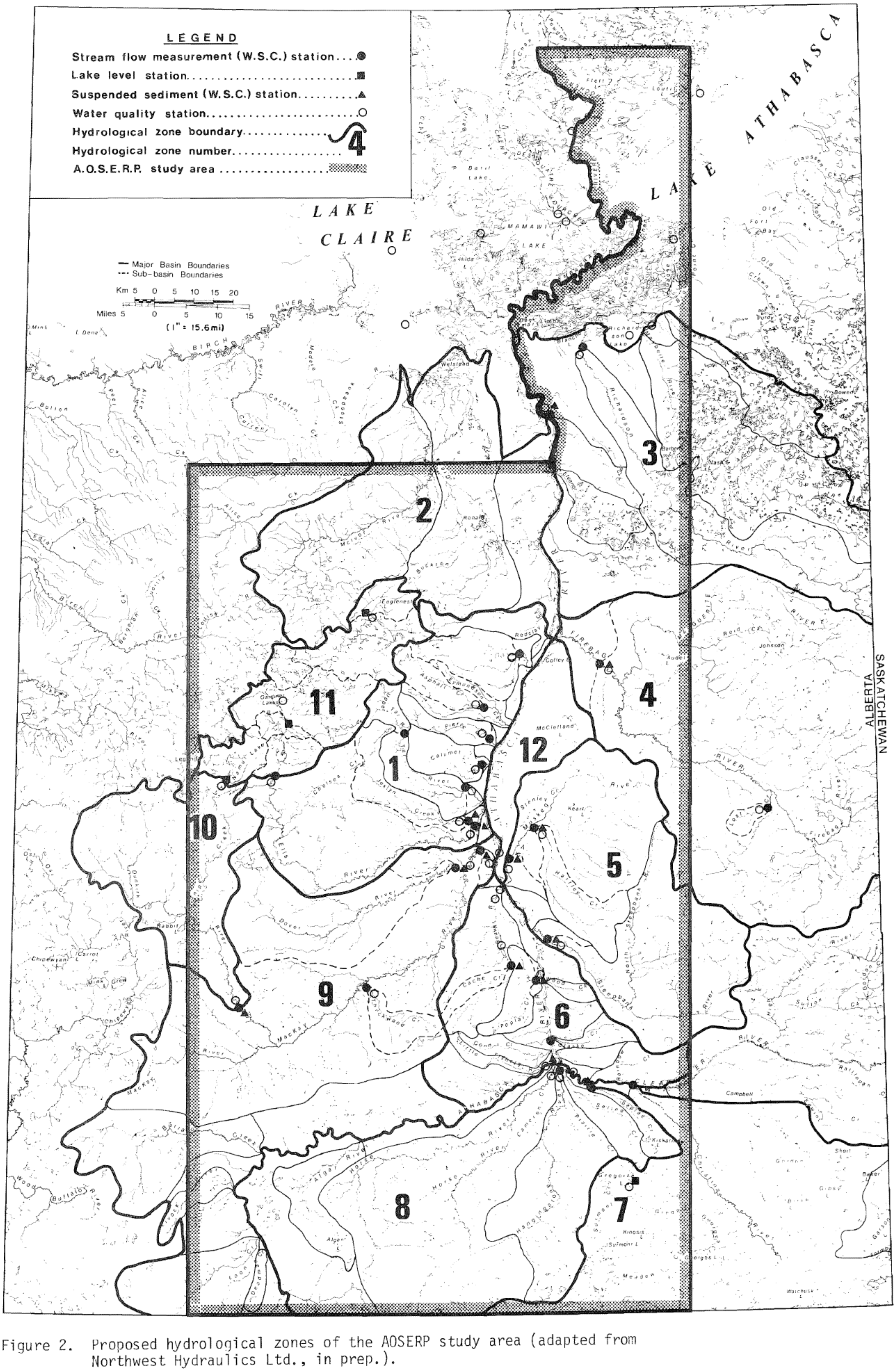


Figure 2. Proposed hydrological zones of the AOSERP study area (adapted from Northwest Hydraulics Ltd., in prep.).

Size analyses of the material being transported in suspension indicate that, on the average, it has the following composition: 26% clay, 50% silt, and 24% sand.

Downstream of Fort McMurray the Athabasca River has a dramatically reduced gradient of about 0.010% as it follows along the strike of underlying bedrock outcrops. The bed material is composed primarily of sand, and the presence of numerous mid-channel islands and bars indicates that the bed material is actively and frequently transported. Suspended sediment data are not available in the downstream reaches of the river to the same extent as at Fort McMurray, but based on the Clearwater River data, we estimate that the 22,000 $km^2$ of tributary inflow between Fort McMurray and the Embarrass channel, on the average, adds less than $0.9 \times 10^6$ tonnes of sediment per year to the Athabasca River. This indicates that the tributaries between these two points provide only about 5% of the sediment entering the present-day delta of Athabasca River.

River and stream channels that are tributary to the Athabasca and Clearwater rivers within the study area generally have their beginning in plains or upland regions and terminate within the Clearwater Lowland region. Incised valleys and entrenched channels are normally present where the channels have down-cut through the surficial glacial drift of the lowland region to meet the gradient of the Athabasca River; the exception is the Richardson and Maybelle rivers, which have formed within deposits of the Athabasca Delta in their lower reaches. Tributary channels can be classified as stable (i.e. low rates of bank erosion) for several reasons:

1. The watersheds have a dense cover of vegetation or muskeg resulting in low runoff rates and low flood peaks,
2. Stream banks have a dense vegetation cover particularly in the upper reaches of a basin (this offers resistance to erosion), and
3. The streams in their lower reaches have become entrenched in bedrock.

The exception to this generalized point of view is the area along the eastern slopes of the Birch Mountains. Extensive slumping in the higher and steeper reaches has resulted in considerable amounts of eroded material being carried downstream to where relatively large alluvial fans have developed in the lower reaches.

At present the sediment transported by streams in the AOSERP study area is the product of:

1. The action of sheet flow and erosion of exposed land surfaces in a watershed; the majority of this source of erosion material is likely derived from escarpments along the eastern slopes of the Birch Mountains.
2. Erosion of material in small gullies; likely the largest source of sediment; generally, the material derived from this action is fine grained and commonly referred to as wash load.
3. Erosion of material along exposed stream banks; likely minimal in the study area.
4. Transport of channel bed material; likely insignificant considering the small size of deltas formed at the mouths of the tributary channels.

Assessment of the tributary watersheds in terms of their natural sedimentation regimes and potential for severe impact caused by development is best initiated by determining whether unique or common sub-areas can be delineated in the study area. A particular set of sub-areas or zones developed as part of another AOSERP study (Yaremko in prep.), are shown in Figure 2. These zones have been based on physiographic and surficial material characteristics (see Appendix 9.1), as well as consideration of the potential for oil sands development in the given area. It is proposed that common sedimentation characteristics should occur within each of these zones. The approach has been to treat the larger channels separately within each zone, providing as much information as is available for each one, and then providing summary remarks with respect to erosion potential from development; the results of this are presented in Appendix 9.2.

The criteria established to grade erosion potential were very judgemental, and generally reflect a combination of character of surficial material, landslopes, and probable mode of oil sands development. A high potential, for example, might consists of a basin covered by fine-grained (non-cohesive) soil situated on the steeper land slopes in the area, and having the potential for *in situ* oil sands development. An improvement on this method of assessment would require the availability of terrain analysis information, a project which AOSERP apparently was pursuing at the time of study.

In some cases suspended sediment data are available at Water Survey of Canada stations near the mouths of tributary channels, and this provides some valuable information regarding base-line sediment concentrations. The channel hydraulic characteristics provided are *very* approximate, having been estimated primarily from interpretation of aerial photographs (Yaremko 1975), and represent what average flow conditions might be like.

The following comments summarize our findings:

1. Zone 1 (Lower Ells Basin and eastern slopes of Birch Mountains) -- The upper (western) area has the potential for *in situ* oil sands development, which suggests large-scale clearing of land for road, drainage ditch, and injection well construction. The surficial material contains a high percentage of clayey-till and as such might offer resistance to erosion. However, this will be offset by having to contend with steep terrain and rapid runoff; it is concluded that the potential for land erosion is medium to high. Also, care should be taken not to remove bank vegetation along channels in this area, as the potential for bank erosion is medium to high. The eastern half of the area will likely be surface mined. Even though the surficial material primarily consists of clayey-silt (outwash sands and gravels along the eastern edge) the potential for land erosion is likely small because of the type of development and flat terrain.

2. Zone 2 (Northern Slopes of Birch Mountains) -- There is little potential for oil sands development in this zone.
3. Zone 3 (Richardson River Basin) -- There is no potential for oil sands development in this zone.
4. Zone 4 (Firebag River Basin) -- A small proportion (<10%) of this zone (the area immediately to the east of McClelland Lake) has the potential for oil sands development. Primarily, the possibility for open pit mining exists in an area in which the surficial material consists of outwash sands and gravels. Measured suspended sediment concentrations have been relatively low. The potential for land erosion is considered low because of the flat terrain and the type development.
5. Zone 5 (Muskeg and Steepbank River Basins) -- This zone has high development potential (primarily surface mining) in areas covered by clay and silt till. Only within that portion of the Muskeg Mountain region is there a medium to high potential for land erosion because of the steeper terrain. The western half of this area has a relatively flat terrain and it is felt that little extra sediment should be produced as a result of development. Care will have to be taken in controlling surface erosion from spoil banks.
6. Zone 6 (Tributaries immediately north of Fort McMurray) -- This is the zone within which present development has occurred; further development will likely consist of open pit mining. Fairly high suspended sediment concentrations have been measured in Poplar Creek prior to the Beaver River diversion, which may be because of the steepness of the river. Generally, the potential for surface erosion is high because the basins tend to be long and narrow, resulting in a situation where connecting streams are steep; any disturbance of vegetation or increase in natural flows associated with development could result in rapid downcutting through the surficial silt and clay material.
7. Zone 7 (Christina River Basin)-- There is little potential for development in this zone; however, the area south and east of

Gregoire Lake could be developed by *in situ* mining. The potential for surface erosion south of this is high because of the steep terrain and silty till along the northern edge of the Stony Mountain Upland.

8. Zone 8 (Hangingstone and Horse River Basins) -- Most of this zone within the AOSERP study area has the potential for *in situ* mining. There is a high potential for land and bank erosion in the upper reaches of the Hangingstone basin, where the drainage courses traverse the northern edge of the Stony Mountains. The remainder of the zone is relatively flat and little land erosion should occur.
9. Zone 9 (MacKay River Basin) -- In this zone, surficial material is predominately clayey and silty till. The area in the western half of the zone is flat and covered with muskeg; therefore *in situ* development can likely occur with little additional land erosion. The eastern portion of the MacKay basin (upstream of the Dover River confluence) downcuts rapidly through the Algar Plain, and as a result lateral drainage channels also tend to be steep. Any widespread land clearing or increase in natural flows in these channels would likely result in high rates of land erosion and gully development. The Dover basin is somewhat different in that even though the gradient is similar to that of MacKay River, there is little development of steep lateral channels because the topography is generally lower in this area. The potential for land erosion in the lower Dover basin is correspondingly much less.
10. Zone 10 (Dunkirk River Basin) -- All of this zone within the study area has the potential for *in situ* mining. Surficial material consists of sand, gravel, and silt. Most of the area will be subject to high land erosion potential once disturbed.
11. Zone 11 (Upper Ells River Basin) -- This zone lies at the higher elevations in the Birch Mountains, an area that has a high concentration of lakes. Development (roads, land clearing) could result in high land erosion but products would only have a local

impact, i.e., sediment loads downstream of the Gardiner Lake system would probably not be affected.

12. Zone 12 (McClelland Lake) -- The terrain in this zone is flat; few channels have developed and there is no surface connection to the Athabasca River. It appears that there is little surface drainage. The potential for land erosion is low.

## 6. EFFECTS OF SEDIMENTATION FROM OIL SANDS DEVELOPMENT ACTIVITIES ON AQUATIC BIOTA

Oil and development is made up of four major activities:

1. Open pit mining,
2. *In situ* extraction,
3. Urban development, and
4. Industrial development (Northwest Hydraulic Consultants Ltd. 1975).

These major activities can be subdivided into a number of component parts that will cause changes in the hydrological regimes and increase erosion potential greatly. Table 1 outlines the direct development processes and indicates the probable effect of these activities on the hydrological regime and the aquatic biota. The scale of the disturbance and the length of the recovery period are also shown.

All of the development activities listed in Table 1 have the potential to create major, chronic sedimentation problems. If adequate control measures are not implemented the destruction of the aquatic biota for many decades is possible. Fortunately most of the development activities are site-specific and control is feasible. For example, although tailings deposits may alter surface and groundwater regimes and surface erosion from the tailings piles could result in the chronic sedimentation of the local watershed, this situation could be controlled by the use of dikes and by careful placement of the tailings piles. Some of the development activities such as road building, pipeline construction, etc., are more regional in nature, and control during the construction phase is rarely adequate. These sources of sedimentation are considered to be the greatest concern and will be discussed in further detail in the following text.

No attempt has been made to provide a comprehensive review of the literature for each technological development. Only a few papers are quoted in each section to give supportive evidence for the comments made in Table 1. Further coverage of these topics would tend to be exhaustive since the general effects of suspended and settled sediments have already been reviewed in an earlier part of this report.

Table 1. The probable effects of increases in suspended and settled sediment caused by types of development in the AOSERP study area.

| Activities that Increase Sedimentation | Probable Effect on the Hydrological Regime | Probable Effect on Biota of Suspended and Settled Sediment | Scale of Effect | Duration of Effect |
|---|---|---|---|---|
| Road Construction | Disruption of surface drainage patterns resulting in faster runoff, higher peak flows, increased surface erosion, unstable channels, and higher sediment loads in watercourses. | Increases in suspended sediment will reduce the standing crop of fish, reduce invertebrate numbers, and affect net-spinning caddisflies and mayflies. Heavy concentration of inorganic silt will scour the stream bed and suffocate both invertebrates and photosynthetic organisms. The egg and fry stages of fish will also be affected. | Regional effect: road systems are expected to traverse watersheds throughout the study area; including headwater areas of basins. | Site-specific effects are expected to be short-term. Recovery will be within one year. Regional effects will be long-term since the road network will be extensive. |
| Pipeline Construction | Same as above. | Same as above. | Regional effect: pipelines from *in situ* extraction may cross many watershed basins. | Recovery from pipeline construction should be rapid. Normal recovery should take place within one year. |
| General Construction<br>1) Paved street and parking lot construction.<br>2) Storm drain network construction.<br>3) Urban and industrial site development. | During construction phase lower retention capability of land and exposure of reworked soils would result in higher total runoff ($m^3$/s days) and higher peak flows. Suspended sediment yield (i.e., from 1-100 times that expected for undisturbed landscape) would be high during the entire construction phase. After the construction phase areas are impermeable; no infiltration is allowed, and very rapid response from precipitation results. | General construction is expected to have similar effects on the biota as those indicated for road construction. In addition, long-term reduction in the permeability of the landscape will result in chronic effects on the biota. Abnormal gravel scouring resulting in the loss of benthos, algae, fish eggs, and fish fry is predicted. Long-term increases in sedimentation will result in the widening of the watercourse and the loss of deep water living space. The overall effect will result in a change in the species composition for both teleosts and aquatic invertebrates. | Local effect: would affect only the portion of the watershed basin where the industrial or urban development occurs. | The affected watershed may not recover for many years because of the instability of the stream channel caused by the decreased permeability of the landscape, and the high flood peaks and low-base flow cycle. |

Continued...

Table 1. Continued.

| Activities that Increase Sedimentation | Probable Effect in the Hydrological Regime | Probable Effect on Biota of Suspended and Settled Sediment | Scale of Effect | Duration of Effect |
|---|---|---|---|---|
| Vegetation Loss by:<br>1) De-watering<br>2) Forest fire<br>3) De-foliation (from aerial toxins or (pollutants) | Lower retention capability of area would result in earlier response, faster rates of runoff, higher volumes of runoff and higher peak flows in watercourses. Combined effect would be unstable channels, increased soil erosion, higher sediment loads in watercourses and more delta formation. | Same long-term effect as above. | Regional effect: vegetation removal will be prevalent for all industrial, urban, and mining developments. Many watershed basins will be affected. | The affected watershed may not recover for many years because of the instability of the stream channel caused by the increased permeability of the landscape, and the high flood peaks and low-base flow cycle. |
| Overburden Removal and Pit Excavation | It is likely that infiltration amounts would be lessened, resulting in more surface runoff, high sediment loads, etc. Stockpiles of overburden will erode quickly and will result in higher sediment loads in watercourses if they are not well contained. The pit would act as catch basin for precipitation and groundwater. It would require continuous 'pump out' operations. | Sedimentation from mining will degrade the quality of the aquatic biota by reducing diversity and abundance of invertebrates and fish. Slight increases in suspended sediment levels result in higher macrobenthos drift rates. Heavy deposition of mining wastes depopulates riffles of insect larvae and impairs fish egg development. Turbid water near mining sites forces fish into cleaner water. | Local effect: each mining operation will only affect nearby watersheds. Sedimentation levels on a regional basis will parallel the degree of oil sand development. Overall impact could be regional. | Sediment input is expected to be higher than normal for a number of years, therefore, the problem will be chronic. |
| Tailing Ponds and Settling Ponds | Source of supply for contaminants, which by deep percolation of infiltration water would reach the groundwater regime, or by surface erosion would reach watercourses and lakes. Dike failure would be catastrophic. Extremely high levels of contamination would result. | Catastrophic contamination would result in a 90%-100% fish kill. Death would be by mechanical suffocation because of gill clogging. Benthos and photosynthetic organisms would likely be killed by suffocation. Spawning beds could be destroyed. Rapid sedimentation could also occur in the Delta, thereby causing changes in hydrological regime. | Local effect: could be regional if dike failure occurs. Athabasca River and Delta would be adversely affected by dike failure. | Turbidity would lower within 1-2 weeks but siltation of bottom substrate would not be scoured until major flooding occurred. Recovery could take 2-3 years. If settling ponds contains toxins recovery would be longer. |

Continued...

Table 1. Concluded.

| Activities that Increase Sedimentation | Probable Effect in the Hydrological Regime | Probable Effect on Biota of Suspended and Settled Sediment | Scale of Effect | Duration of Effect |
|---|---|---|---|---|
| Water Use | Use of local surface (stream or lake) sources could deplete water availability for downstream needs during low flow periods. | Water use will not directly cause an increase in either the suspended sediment or unsettled sediment loads. However, the reduction or depletion in water availability may reduce the sediment flushing capacity of a stream or river, thereby prolonging the recovery period of the biota within the system. | Local effect: could be regional if water use for *in situ* extraction is high; dependent on the number and distribution of injection wells. | The ability of a waterbody to recover from sedimentation is often dependent on the flushing rates of settled inorganic materials. Sedimentation events that would normally recover within one year could become chronic if water levels are severely reduced. |
| Waste Water Disposal | Act as a possible source of increased sedimentation if waste water levels of suspended solids or if excess water produces lateral and/or vertical instability in disposal channels. | If chronic, the biota in the affected portion of the watershed would undergo a change in species composition; mud-loving forms would have a competative advantage and would dominate. | Local effect: disposal channel and immediate drainage tributaries affected. | High levels of suspended sediment in waste water would produce a chronic situation. |
| Diversion Channels | Rerouting a watercourse would likely produce a diversion channel which is not in regime. Results could be lateral and/or vertical instability, hence higher sediment loads and more delta information. | Channelization will disrupt and eliminate aquatic biota for varying lengths of time. Long-term degradation will occur if substrata are unstable and incapable of insect recolonization. Bank instability will result in high silt loads and subsequent reduction in diversity and biomass of organisms. Erosion silt from ditches, dam faces, and general construction activities will have similar biological impacts as road construction and pipeline development. Suitable mitigative measures can improve habitat in new or existing channels. | Local effect: channelization will only occur on a site-specific basis and will only affect individual watersheds. | Recovery should be rapid (1-2 years). Benthic drift will colonize new channel sections if a suitable substrate is available. |

## 6.1 ROAD CONSTRUCTION

Road construction may contribute greatly to stream damage from erosion and sedimentation. Approximately 85% of the erosion can occur during the first year after construction and sediment production may range from 1 to 100 times greater in roaded areas than on undisturbed lands (Megahan and Kidd 1972). The Federal Water Quality Administration (1970, cited by Brown 1975) estimated that the average sediment yield from a highway construction site during a rainstorm was 200 times greater than from grass land and 2,000 times greater than from forested areas. Although recovery from road construction may be rapid at specific locations the overall impact of this development activity is expected to be extensive since continuing development of the Athabasca Oil Sands area will require an ever increasing network of roads.

Revegetation of road sites (cuts) should be initiated as soon as possible.

The initial effect of road construction will be an increase in the suspended sediment load downstream from the construction site. This will cause a drop in numbers and standing crop of fish just below the crossing site; fish tend to avoid high levels of suspended solids (Barton 1977). Little or no fish mortality would be expected (Ritchie 1972). Change in the species composition of invertebrates is also likely to occur in the affected section of stream. Net-spinning caddisflies and mayflies would be reduced and case-building caddisflies, chironomids, and water mites would increase. Reduction in invertebrate numbers in the affected zone would probably result from drift since invertebrate drift rate tends to increase with increases in suspended solids (Rosenberg and Wiens 1975).

High concentrations of inorganic material in the river will also scour organisms from the stream bed, and inorganic sediment settling on the stream bed may suffocate both invertebrate and photosynthetic organisms (King and Ball 1964b, cited by Wilhm 1967).

Peterson and Nyquist (1972) showed that subarctic streams in Alaska appeared fully recovered within one year. Barton (1977) reported that for an Ontario stream, the effects of highway culvert construction on riffle invertebrates and fish were short-term and that recovery took less than 8 months.

Sediment production will likely follow a scenario similar to that present by Megahan and Kidd (1972) for logging roads in Idaho (Figure 3). They noted that sediment production rates resulting from roads averaged 220 times greater than the rates for undisturbed lands during the 6-year study period. The overall impact would therefore be considered as regional in nature.

## 6.2 PIPELINE CONSTRUCTION

Pipelines will cross many watersheds and disturbance of the watersheds will result from both vegetation clearing and the laying of the pipeline. Disturbances of the stream bottom from trenching and backfilling operations and erosion of material along the pipeline right-of-way will increase sedimentation during the immediate post-construction period.

McCart and deGraff (1974) have reported the effects of disturbances from pipeline construction on the benthic fauna of small streams in the vicinity of Norman Wells, N.W.T. They concluded that "sediment loads resulting from pipeline construction will not reach lethal levels for a long enough period of time to cause mortality to juvenile or adult fish" (McCart and deGraff 1974:20). But, they also state that the most serious effect to the fisheries would result from the damage to egg and fry and through a reduction in available food from aquatic invertebrate losses. "The results conform to the generalization that active erosion adversely affects benthic invertebrate populations but that when conditions are stabilized, natural hydrological processes will tend to restore the original habitat and invertebrate populations will recover or, in unusual circumstances, even exceed the original level" (McCart and deGraff 1974:23-24).

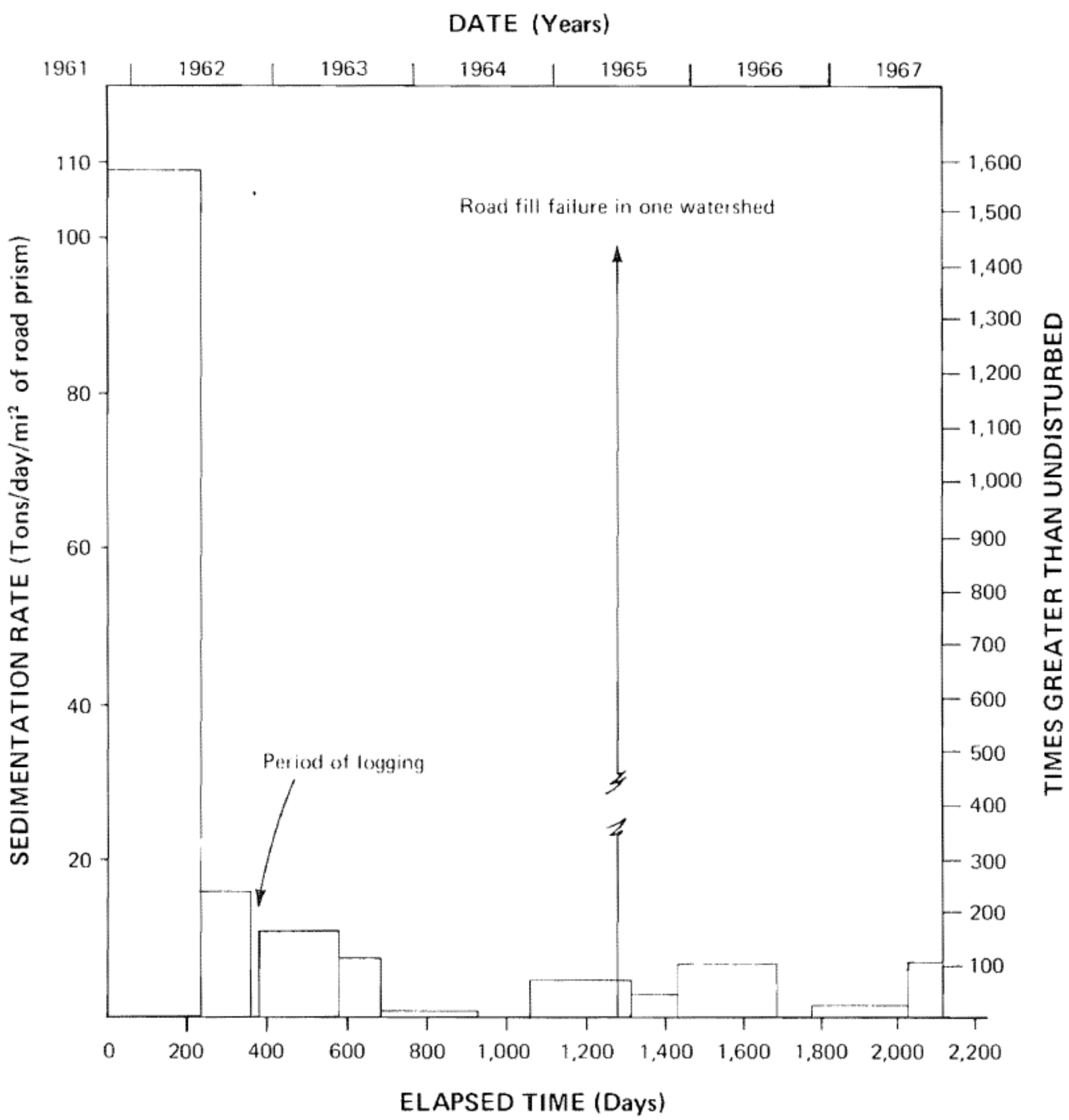


Figure 3. Sediment production over time from surface erosion on jammer roads (from Megahan and Kidd 1972).

## 6.3 GENERAL CONSTRUCTION -- URBAN AND INDUSTRIAL SITES

The effects of urbanization on the sediment loads in stream has been discussed by Evans (1977). He indicates that two factors will influence the change in sediment load: (1) during the initial construction phase reworked and exposed soils will erode rapidly, and (2) post-construction changes in the permeability of the urban or industrial landscape will increase flood peaks and decrease base flows, causing a deepening and widening of the stream channel.

An illustration of the effect of urban development on sediment yield is reported by Yorke and Davis (1971, cited by Evans 1977). This study shows the response of two similar storms, one before and one during development. The area of urban construction covered about 15% of the 437 ha (1,080 ac) drainage basin of the Bel Pre Creek in Maryland. The comparative data resulting from the two storms are shown in Table 2 and Figure 4. Yorke and Davis (1971, cited by Evans 1977) also indicate that the effect of construction was substantially greater than that indicated by the table (nine-fold increase in sediment yield) since the sediment yield from the construction site alone reached peaks of 90 times that expected from the undisturbed landscape.

The initial construction phase of development is expected to affect the aquatic biota adversely and conform to the pattern already presented for road or pipeline construction:

1. Fish will be reduced in standing crop because of avoidance of high levels of suspended solids;
2. No direct mortality of adult fish is expected but egg and fry stages may be killed; and
3. Invertebrate numbers will be reduced and the drift rate will increase and species composition may change.

Table 2. Comparative data for two storms in the Bel Pre Creek basin.[a]

| Period of Storm | Before Development 6-7 November 1963 | During Development 18-19 October 1966 |
|---|---|---|
| Total Runoff (cfs-days) | 40 | 35 |
| Peak Discharge (cfs) | 80 | 84 |
| Suspended Sediment Yield (tons) | 14.3 | 124.0 |
| Mean Suspended Sediment Concentration (mg/l) | 70 | 500 |

[a] Source: Adapted from Yorke and Davis (1971 *in* Evans 1977).

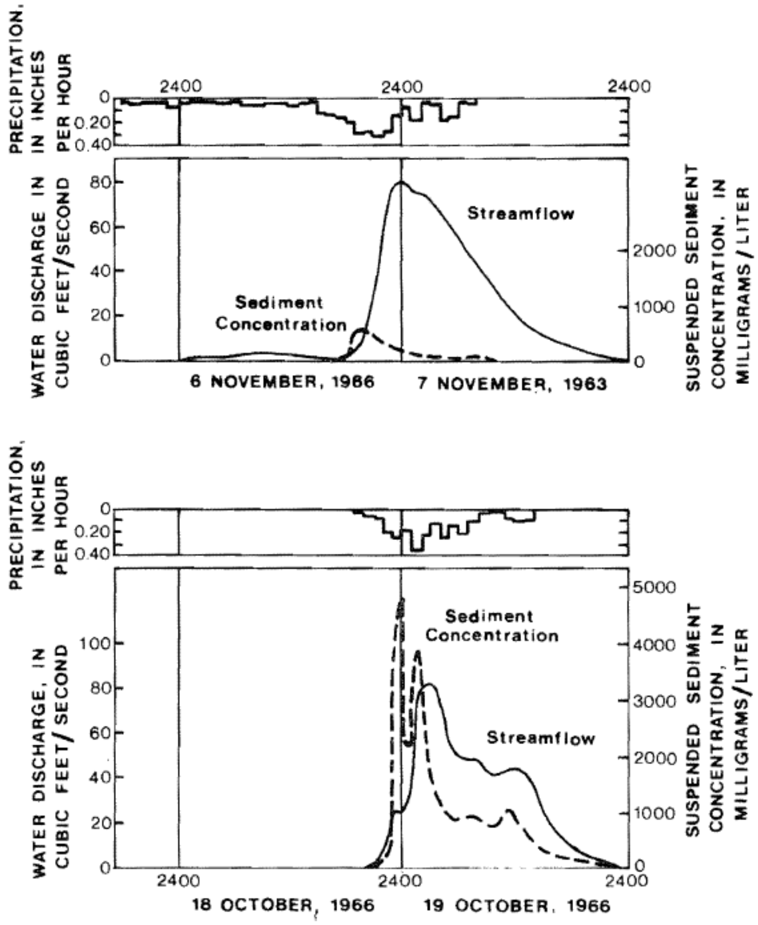


Figure 4. Variation of precipitation, sediment concentration, and water discharge during two storm-runoff periods for Bel Pre Creek, Maryland (adapted from Yorke and Davis 1971, cited by Evans 1977).

Unfortunately, recovery may not be as rapid as predicted since the increased flood peak and decreased base flow caused by decreased permeability of the landscape, may continue to affect the channel causing lateral and/or vertical instability and a continuation of increased soil erosion of bank materials.

The effect on the aquatic biota of increased sediment load and altered stream habitat could be quite extensive and of a longer duration than that for road or pipeline construction. The long-term effects of channel degradation and realignment should only occur in the portion of the watershed containing the development and may be confined to small portions of the AOSERP study area.

## 6.4 VEGETATION REMOVAL

Vegetation removal as part of the industrial development of the oil sands will be extensive. In many of the development activities described in this report (i.e., road construction, urban and industrial construction, etc.), vegetation removal is only one aspect of the overall "construction phase" of the development and as such the changes caused by the loss or removal of vegetation cannot be separated from the changes caused by the construction activity. However, within the AOSERP study area additional vegetation losses may occur because of:

1. The dewatering of extensive areas around the mining site,
2. A possible increase in the incidence of forest fires, and
3. A possible increase of aerial or surficial toxins or pollutants.

The removal of the vegetation is expected to result in accelerated erosion. The rate of erosion will vary considerably in relation to many site-specific factors such as slope, geology, soils, and climate. It is assumed that erosion from a well-forested watershed represents the minimum for that site (Rice et al. 1972). The death of trees by themselves does not significantly increase erosion, but the exposure of soils on steep unstable slopes may lead to increased mass, gully, rill, and sheet erosion. "However, observations leave little doubt that accelerated erosion is a common result of fire on forested lands. The most obvious effect of fire is the removal of ground litter" (Rice et al. 1972:325). Accelerated erosion is also caused by deterioration of forest areas by road construction and logging. It is not the cutting of trees that causes the problem, but their removal from the forest (Rothwell 1977 *in* Swanson and Logan 1977). Skidding of logs and haul roads cause most of the soil disturbance (Fredricksen 1970; Megahan 1972). Sediment loads from logged watersheds have been from 4-400 times greater than those from undisturbed watersheds (Fredricksen 1970; Megahan 1972). The effect of extensive vegetation removal and road construction in Alberta has been shown by Lengelle (1976) in the Swan Hills. He estimates that sediment removed during erosion processes on deforested lands in that area may reach 4.5 million Mg (5 million tons)/ year, 68,180 - 145,000 kg/ha (60,000 - 13,000 lb/ac).

Reduction of forest cover will significantly increase the flood peaks in the surrounding watershed since the retention capability of the area would be reduced. The increased peak flows will result in:

1. Vertical instability of the stream bed, and
2. Lateral instability of the stream channel.

The vertical instability will cause abnormal gravel shifting and scouring that will result in the removal of benthic algae and aquatic invertebrates and in the mortality of fish eggs and incubating fish embryos (Chapman 1962). Lateral instability of the stream channel (accelerated bank cutting) will result in an increased sediment level, and the widening of the stream. This will cause the loss of deep water living space that is especially important to the larger resident fish species (Chapman 1962). Vegetation removal also results in the increase of water temperatures in the affected streams. This has generally been found to be beneficial since higher temperatures may increase invertebrate production and increase carrying capacity in the stream of juvenile and adult fish (Burns 1972).

## 6.5 OVERBURDEN REMOVAL AND PIT EXCAVATION

The initial stages in the development of the Athabasca Oil Sands will involve site drainage, overburden removal, and mining of the bitumen impregnated sand. Site drainage of tamarack and spruce muskeg will take up to 5 years at any one mine site (Jantzie 1975). At present Great Canadian Oil Sands Ltd. (GCOS) drains the surface water by ditching; the excess water collects in ditches and lowland areas away from the pit. Future installations will likely use similar dewatering procedures. Presently there are no data available on suspended sediment levels in drainage ditch waters.

Because the muskeg remains highly saturated after drainage it must be removed while it is still frozen. Once the organic soils are removed subsurface layers are excavated and stockpiled or used to build tailings pond dikes. During pit excavation water draining into the pit will be pumped into tailings and settling ponds (Jantzie 1975).

The initial process of site drainage may result in increased flows in streams receiving waters, but this is dependent on the scheme used. Syncrude Canada Ltd. has drained one mine site by means of the Beaver River diversion. Even though flows in Poplar Creek have increased three- to four-fold (up to 165 cfs) sediment levels have not increased (telephone conversation of 17 February 1978 from J. Retallack, Limnologist, Syncrude Canada Ltd., Edmonton, Alberta). Siltation will not occur during removal of muskeg in the winter; however, rapid spring runoff and erosion may occur when the inorganic layers have been exposed. Erosion problems were not experienced at the Syncrude Canada site because of the relatively flat terrain on the lease.

During pit excavation, overburden stockpiles and tailings dikes will also be subject to erosion. Information on the rate of weathering, and erosion on spoil banks from coal strip mines in Kentucky is given by Curtis (1971a, b, c; 1973 *in* Hutnik and Davis 1973; 1974 *in* Natl. Coal Assoc. Bitum Coal Research Inc. 1974) and Farmer and Richardson (1976).

The nature and degree of erosion from oil sands mining will depend on: (1) the amount of inorganic soil exposed and the duration of exposure after the muskeg is removed; (2) the volume of overburden stockpiled; (3) and the size of tailings dikes. Extensive erosion will occur as a result of overburden removal and pit excavation on high gradient sections of any watershed as opposed to pit mining on flat landscapes. Brown (1975) maintains that erosion from 2 million acres of strip-mined land in the United States will produce an estimated 94 million tons of sediment/year. Brown (1975) states that active surface mines (total area 0.12 - 0.16 x $10^6$ ha; 0.3 - 0.4 x $10^6$ ac) in the U.S. will have erosion rates of 17,000 tonnes/$km^2$/year (48,000 tons/$m^2$/year).

In general, uncontrolled sedimentation from the oil sands mining will probably affect aquatic biota in the same manner as that produced by gravel crushing installations, quarry mining, placer mining, and coal strip mining. Gammon's (1970) investigations on a small eastern U.S. stream indicated that increases of 20 to 40 mg/l of suspended sediments from a limestone quarry reduced macroinvertebrate density by 25%. Increases of over 80 mg/l of suspended sediments and an increase in the deposition of settled solids caused a 60% reduction in density. Quarry sediments which settled out in riffle areas decreased the population density by 60%. Drift rate increased proportionally up to suspended sediment levels of 160 mg/l. Experiments by Rosenberg and Wiens (1975) also showed that increases in suspended sediment (30 to 500 mg/l) caused significant increases in numbers of drifting invertebrates.

Taft and Shapovlov (1935, cited by Smith 1940) reported that in the Klamath River, California, sediment deposition from placer mining reduced the average number of benthic organisms from 2,678/$m^2$ (240/$ft^2$) to 387 organisms/$m^2$ (36/$ft^2$). Experiments by Rosenberg and Snow (1975) indicate that short-term additions of silt can also affect invertebrate populations; 15-min. additions of 10 to 500 mg/l of silt resulted in zoobenthos losses of 25.5 organisms/$m^2$ to 129.5/$m^2$.

Aquatic invertebrate migration can also be affected by increased sedimentation. In a northern Idaho stream, sand accumulation from gem stone mining hampered upstream movement of aquatic insects (Luedtke and Brusven 1976). The authors concluded that pebble and cobble substrata were necessary for optimum colonization by benthic invertebrates they studied.

Branson and Batch (1972) found that coal strip mining in Kentucky raised sediment loads of the streams involved to 3,000 mg/l. Heavy sediment deposition eliminated most benthic macroinvertebrates; mayfly and crayfish numbers were reduced by 10% of the normal. Fish biomass and diversity were also reduced. In a clear stream, 17 species were common as opposed to only 12 species in turbid waters. Prior to mining, fish production in one stream was 17.0 kg/ha (15.4 lb/ac) after 11 months of mining the yield was reduced to 9.6 kg/ha (8.6 lb/ac).

Suspended sediments from gravel washing operations can also affect fish. A portion of the South Platte River, Colorado, which has suspended sediment levels of 90 to 100 mg/l, contained 15% to 40% as many fish as regions above a gravel pit (Gammon 1970).

Shaw and Maga (1943) showed that salmon eggs receiving 1,176 to 1,330 mg/l of mine tailings had an average yield of 1.6% fry as compared to the control values of 16.2% fry. They found that later additions of silt during incubation had less deleterious effects on hatching.

The extent of sedimentation and recovery time in any watershed will vary with different land use practices. Gammon (1970) showed that quarry wastes affected 2.6 km (1 mi) of stream below the sediment source and he felt that complete recovery would take more than 2 years, if at all. A coal mine in France produced sediments that raised suspended sediment levels to 570 mg/l and eliminated a cyprinid fish fauna; recovery did not occur until levels dropped to 100 mg/l (EIFAC 1965).

## 6.6 DIVERSION CHANNELS

Water diversions are necessary to direct surface waters away from proposed mine sites and to aid in overall surface drainage prior to pit excavation. Dams, diversion channels, receiving channels, interceptor ditches, and general construction activity (e.g., road construction) are all associated with water diversion. Each phase of construction presents the potential for increasing sediment loads to nearby watersheds.

The Beaver River diversion on the Syncrude Canada Ltd. lease (Zone 6), which was completed in the fall of 1975, diverts water from a dammed reservoir half way up Beaver River into Ruth Lake and finally into Poplar Creek. Interception ditches below the dam drain tributary flow to a lower portion of the Beaver River. Winter construction has reduced many of the potential erosion problems associated with the diversion; because diversion channels were cut into muskeg and glacial till, extensive sedimentation was not experienced. However, there has been some sedimentation from lateral erosion around ditches as well as erosion of spillway embankments (J. Retallack, pers. comm.). Sediment deposition is expected to occur in the Beaver River reservoir. More information will be available on the Beaver River diversion once the final copy of the report has been prepared by Syncrude Canada Ltd. In Poplar Creek, much of the fine bed material has been flushed and stabilization of the creek has minimized bank side erosion (J. Retallack pers. comm.).

Prior to diversion of the Beaver River into Poplar Creek the creek was a meandering stream with a gravel-sand-silt substrate (telephone conversation of 17 February 1978 from N. Chymko, Limnologist, Chemical and Geological Laboratories Ltd., Edmonton, Alberta). After the diversion was completed the diversity of the aquatic fauna increased and more clean water, gravel-type invertebrates were collected as well as nine additional species of fish (J. Retallack pers. comm.).

In the literature, however, channelization has generally been reported as having a negative impact on the aquatic biota. Gillette (1972, cited by Rosenberg and Snow 1975) has shown, from cases in at least six states of the U.S., that local populations of fish, plant life, and ducks were reduced by 80% to 99%.

## 7. KNOWLEDGE GAPS AND RESEARCH NEEDS

1. The European Inland Fisheries Advisory Commission (1965) and U.S. Federal Water Pollution Control Administration (1968) criteria for suspended solids in freshwater have been largely based on the effects of inert solids on salmonids in Europe. Usefulness of these criteria in the AOSERP study area is questionable because changes in base sediment loads and in fish species composition and behaviour relative to those areas studied may alter the recommended tolerance levels of suspended material. Application of these criteria should not be accepted without further documentation of their adaptability to the AOSERP situation.

   Laboratory experiments would be required to determine the real effects that are produced. Complementary information from descriptive and experimental field data may also be useful, but the difficulty of maintaining adequate controls in the field situation limits these approaches.

2. Non-standarized and constantly changing sampling techniques and instrumentation have severely restricted the usefulness of data on sedimentation (Sherk 1971; Rosenberg and Snow 1975; Brown 1975). Further assessment of the techniques recently adopted by Environmental Protection Agency (EPA) and/or the U.S. Army Engineer Waterway Experiment Station is required. Contacts should also be established with Canadian researchers active in this field to assure comparison of measurements and methodology.

3. A continuing monitoring program of the present industrial and mining developments in the AOSERP study area is recommended. This program would be the responsibility of the Alberta Department of the Environment and/or the industrial developers of the area (GCOS, Syncrude, etc.). Current water quality and water quantity monitoring data, available from AOSERP, should provide the baseline information source. However, programs involving the use of

remote sensing techniques should be considered for the near future. These techniques can be used to identify the point sources of sedimentation, interpret ground survey data, and maintain a permanent record of problem areas associated with the development. As already pointed out, aerial surveys over urban areas and plant sites can aid in locating sources of sedimentation and provide data on unstable areas and their rates of erosion. This information could then be applied using mathematical modelling techniques so that a predictive capacity for future planning is developed.

4. We recommend that AOSERP undertake a series of controlled sedimentation experiments to establish the effects of *chronic* sedimentation on the aquatic biota. We have indicated that many of the industrial activities and development plans for the AOSERP study area could lead to chronic sedimentation problems if control measures are not adequate. To date, attempts to determine the mode of action of suspended and settled sediments and the responses of the biota to known concentrations of suspended and settled solids by using an experimental approach have been limited. Recent work in Canada has been done by Rosenberg and Wiens (1975) on the Harris River, N.W.T. Unfortunately, this study was designed to assess short-term additions of sediment (one summer, 1973) and is of limited value in determining the effects of chronic sedimentation from the developments in the AOSERP study area.
5. It is well documented that construction of roads can result in extensive erosion along road ditches. The products of this erosion invariably enter natural drainage courses, often resulting in severe damage to the aquatic habitat. This type of impact has particular significance in those areas which will be mined by the *in situ* process. Field programs should be established using existing or specially constructed roads and

monitoring the rate of soil erosion over several years. The monitoring program would include assessment of the impact that the eroded material has on the aquatic biota in downstream channels. It is anticipated that road ditch design and reclamation and location criteria would be developed that are specific to the AOSERP study area as a result of this type of program.

6. Failure of containment dikes could result in a slug of sediment entering an adjacent watercourse. Analysis of impact necessarily must be site-specific, making it difficult to conceive broad-based research programs to deal with this potential problem. However, the presence of the GCOS settling pond dike adjacent to the Athabasca River provides an opportunity to carry out a site-specific study of the consequences to the Athabasca should this dike be eroded out or slump into the river channel. The objective of the study would be to determine whether the dike material would be transported downstream and, if so, at what rate. The impact of this event on the aquatic habitat would be a part of such a study.

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# 9. APPENDICES

## 9.1 PROPOSED HYDROLOGICAL ZONES WITHIN THE AOSERP STUDY AREA

The following tabulated information summarizes the average physiographic and surficial material characteristics in each of the proposed zones shown in Figure 2. In addition, the potential mode of oil sands development is indicated in the last column. The table was developed as part of a hydrological-water quality study for AOSERP (Yaremko in prep.), and was used in the present study to evaluate the sedimentation potential (see Appendix 9.2); the assumption being that this potential would be similar in each zone. The potential was defined simply in terms of low to high, an exercise which required consideration of the zone characteristics and considerable judgement.

Table 3. Proposed hydrological zones within the AOSERP study area.[a]

| Hydrological Zone | Physiographic Distribution | Surficial Material | Oil Sands Development Potential |
|---|---|---|---|
| 1 | Birch Mtns Upland<br>Algar Plain<br>Clearwater Lowland | Predominately clayey and silty till in upper regions; outwash sand deposits in lower regions | Nearly 100% developable similar proportions available for open pit and *in situ* mining |
| 2 | Birch Mtns Upland | " | <25% developable; *in situ* mining only |
| 3 | Athabasca Delta | Aeolian sands in the lower reaches; sands and gravels in upper reaches | 0% developable |
| 4 | Athabasca-Firebag Plain<br>Clearwater Lowland | Outwash sands and gravels | <10% developable; open pit to *in situ* mining possible |
| 5 | Muskeg Mtns Upland<br>Clearwater Lowland | Outwash sands in lower regions; clayey and silty till in the upper regions | 30-100% developable; negligible *in situ* mining potential |
| 7 | Methy Portage Plain | Clayey and silty till in the lower region; ground moraine composed predominately of sand | <10% developable; open pit to *in situ* mining potential |
| 8 | Algar Plain<br>Stony Mtn. Upland | Clayey and silty till | Nearly 100% developable; predominately *in situ* mining potential |
| 9 | Algary Plain | Predominately clayey and silty till | Nearly 100% developable; 80% potentially suited to *in situ* mining |
| 10 | Birch Mtns Upland | Hummocky moraine; drift of sand, gravel and silt | 100% developable; *in situ* mining potential only |
| 11 | Birch Mtns Upland | Hummocky moraine | 100% developable; *in situ* mining potential only |
| 12 | Clearwater Lowland | Outwash sands and gravels | 90% developable; primarily open-pit mining potential |

[a]Source: Northwest Hydraulic Consultants Ltd. (in prep.).

## 9.2 SUMMARY SHEETS OF HYDROLOGICAL AND SEDIMENTATION CHARACTERISTICS IN THE AOSERP STUDY AREA

Summary tables were prepared for each of the streams on which there are Water Survey of Canada hydrometric stations actively operating. In some cases miscellaneous suspended sediment samples have been collected, which afforded the opportunity of assessing natural sediment concentrations and the range of sediment sizes being transported. As well, comments have been provided which outline channel characteristics (Yaremko 1975); these offer very approximate descriptions, as the original information was based primarily on interpretation of aerial photographs.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Ells River

River or stream:
Ells River. Major tributaries are Joslyn Creek, and Chelsea Creek

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Birch Mountain Upland, Algar Plain, Clearwater Lowland. Hummocky moraine, drift of sand, gravel and silt in the upper reaches; clayey and silty till (alluvial and lacustrine materials) in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.0020 |
| Channel width: | 42.7 m in lower reaches, 24.4 m in upper |
| Average velocity: | 1.8 m/sec |
| Channel stability: | Stable |
| Bed material: | Sand and gravels |
| Bank material: | Silts to gravels |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 6-1498 ppm |
| (associated discharge): | 2.8.47 $m^3/s$ |
| Particle size ($D_{50}$): | 0.05 mm |
| Measured discharges: | 0.9.50 $m^3/s$ |
| Years of record (sed.): | 1976 |
| WSC station: | 7DA17 |
| Basin area: | 2,476 $km^2$ |

Summary Comments:

Sedimentation Potential:
- medium, a small delta has formed at the confluence with the Athabasca River.

Bank Erosion Potential:
- medium, particularly in the lower reaches where the river is confined by steep, unvegetated banks.

Surface Erosion Potential:
- low in upper reaches, river valley is wide, flat, and well vegetated.
- medium in lower reaches where surficial deposits are fine and the stream is entrenched below the surrounding terrain.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Ells River

River or Stream:
Joslyn Creek

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Birch Mountain Upland, Algar Plain, Clearwater Lowland. Hummocky moraine, drift of sand, gravel, and silt in the upper reaches; clayey and silty till (alluvial and lacustrine materials) in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.010 in lower and upper reaches, 0.003 in the middle reach |
| Channel width: | 4.6 m |
| Average velocity: | 1.2 m/s |
| Bed material: | Bedrock in lower reach, gravels and silt elsewhere |
| Bank material: | |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 37-1104 ppm |
| (associated discharges): | 0.1-16.2 $m^3$/sec |
| Particle silt ($D_{50}$): | 0.01 mm (medium silt) |
| Measured discharges: | 0.003-16.4 $m^3$/sec |
| Years of record (sed.): | 1975 and 1976 |
| WSC station: | 7DA16 |
| Basin area: | 249 $km^2$ |

Summary Comments:

Sedimentation Potential:
- medium, stream is steep. Noticeable suspended sediment load observed during a survey at a low flow (Sept. 1974)

Bank Erosion Potential:
- low in lower reaches, channel is incised in bedrock; probably medium in the steep upper reach

Surface Erosion Potential:
- medium in lower reach where surficial materials are fine

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Tar River

River or stream:
Tar River

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Birch Mountain Upland, Clearwater Lowland, Algar Plain. Hummocky moraine, drift of sand, gravel, and silt in the upper reaches; clayey and silty till (alluvial and lacustrine material)in the lower reaches.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 313 $km^2$ |
| WSC station: | 7DA15 |

Summary Comments:
Sedimentation Potential:
- medium as long as the vegetative cover, particularly in in the upper reaches, remains intact

Bank Erosion Potential:
- medium, because of fine-grained material through which the river has cut

Surface Erosion Potential:
- medium in the steep upper reaches (Birch Mountains); low elsewhere

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Calumet River

River or Stream:
Calumet River

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Algar Plain, Birch Mountain Upland. Predominantly clayey and silty till; outwash sand deposits in lower reaches.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 181 $km^2$ |
| WSC station: | 7DA14 |

Summary Comments:
Sedimentation Potential:
- medium as long as the vegetative cover, particularly in the upper reaches, remains intact

Bank Erosion Potential:
- medium, because of fine-grained material through which the river has cut

Surface Erosion Potential:
- medium in the steep upper reaches (Birch Mountains); low elsewhere

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Pierre River

River or Stream:
Pierre River

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Algar Plain, Birch Mountain Upland. Predominantly clayey and silty till; outwash sand deposits in the lower reaches.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 130 $km^2$ |
| WSC station: | 7DA13 |

Summary Comments:
Sedimentation Potential:
- medium as long as the vegetative cover, particularly in the upper reaches, remains intact

Bank Erosion Potential:
- medium, because of fine-grained material through which the river has cut

Surface Erosion Potential:
- medium in the steep upper reaches (Birch Mountains); low elsewhere

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Asphalt Creek

River or Stream:
Asphalt Creek; Eymundson Creek is the major tributary.

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Birch Mountain Upland, Clearwater Lowerland.
Predominantly clayey and silty till; outwash sand deposits in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.004 in lower reach, 0.017 in upper |
| Channel width: | 15 m in lower reach, 6 m above confluence with Eymundson Creek. |
| Average velocity: | 1.2 m/s in lower reach |
| Channel stability: | Stable |
| Bed material: | Sands and silts |
| Bank material: | Silt |

Suspended Sediment:
No measurement

| | |
|---|---|
| WSC station: | 7DA12 |
| Basin area: | 148 $km^2$ |

Summary Comments:

Sedimentation Potential:
- medium as long as the vegetative cover, particularly in the upper reaches, remains intact

Bank Erosion Potential:
- medium, because of fine-grained material through which the river has cut

Surface Erosion Potential:
- medium in the steep upper reaches (Birch Mountains); low elsewhere

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Unnamed

River or Stream:
Unnamed

Hydrological Zone No:
1

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Birch Mountain Upland.
Clayey and silty till in the upper reaches;
outwash sand deposits in the lower reaches.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurement

| | |
|---|---|
| Basin area: | 280 $km^2$ |
| WSC station: | 7DA11 |

Summary Comments:

Sedimentation Potential:
- medium as long as the vegetative cover, particularly in the upper reaches, remains intact

Bank Erosion Potential:
- medium, because of fine-grained material through which the river has cut

Surface Erosion Potential:
- medium in the steep upper reaches (Birch Mountains); low elsewhere

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Richardson River

River or Stream:
Richardson River

Hydrological Zone No:
3

Physiographic and Surficial Material Characteristics:
Athabasca Plain, Athabasca Delta, Clearwater Lowland. Sands and gravels in the upper reaches; aeolian sands in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope | 0.0005 in lower reaches, 0.003 in upper reaches |
| Channel width: | 21 m in lower reaches |
| Average velocity: | 0.9 m/s |
| Channel stability: | Moderately stable |
| Bed material: | Sands and silts |
| Bank material: | Sands and silts |

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 2,953 $km^2$ |
| WSC station: | 7DD2 |

Summary Comments:

Sedimentation Potential:
- medium, as evidenced by the large sand and silt delta at the mouth of the river.

Bank Erosion Potential:
- medium. The fine-grained sands, particularly in the lower reaches, offer little resistance to erosion.

Surface Erosion Potential:
- low. The large number of lakes and flat terrain, together with the sands of the surficial deposits which have high infiltration rates and a large groundwater storage potential, will result in low runoff rates.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Firebag River

River or Stream:
Firebag River. Marguerite River is the major tributary.

Hydrological Zone No:
4

Physiographic and Surficial Material Characteristics:
Firebag Plain, Clearwater Lowland, Muskeg Mountain Upland, Athabasca Plain.
Outwash sands and gravels.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.0004 in lower reach to 0.006 in middle reach |
| Channel width: | 67 m in lower reach, 49 m above confluence with Marguerite River |
| Average velocity: | 1.5 m/s |
| Channel stability: | Stable |
| Bed material: | Coarse gravel, except for lower reaches where sands and silts predominate |
| Bank material: | Sands and gravels |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 3-169 ppm |
| (associated discharge): | 20-67 $m^3$/sec |
| Measured discharges: | 5.5-238 $m^3$/s |
| Years of record (sed.): | 1974 and 1976 |
| WSC station: | 7DC1 |
| Basin area: | 6,035 $km^2$ |

Summary Comments:
Sedimentation Potential:
- low. The basin is characterized by a stable river flowing through predominantly coarse surficial deposits.

Bank Erosion Potential:
- low, except for medium in the lower reaches where materials are fine, though the vegetative cover in this region has a stabilizing effect.

Surface Erosion Potential:
- low, because of the flat terrain, well established vegetative cover, and the coarse surficial material.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Firebag River

River or Stream:
Lost Creek

Hydrological Zone No:
4

Physiographic and Surficial Material Characteristics:
Muskeg Mountain Upland.
Hummocky moraine, drift of sands, gravels, and silts.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 60 $km^2$ |
| WSC station: | 7DC2 |

Summary Comments:
Sedimentation Potential:
- low. Flat terrain of coarse surficial material.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Muskeg River

River or Stream:
Muskeg River. Hartley Creek is the major tributary.

Hydrological Zone No:
5

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Muskeg Mountain Upland.
Clayey and silty till in the upper reaches, outwash sands in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.004 in the lower and upper reaches; 0.0003 in the middle reach. |
| Channel width: | 20 m, 6 m above confluence with Hartley Creek. |
| Average velocity: | 0.6-1.5 m/s |
| Channel stability: | Relatively stable |
| Bed material: | Silts and sands |
| Bank material: | Silts |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 3-41 ppm |
| (associated discharge) | 0.9-15 $m^3/s$ |
| Measured discharges: | 0.14-42 $m^3/s$ |
| Years of record (sed.): | 1976 |
| WSC station: | 7DA8 |
| Basin area: | 1,455.6 $km^2$ |

Summary Comments:
Sedimentation Potential:
- medium. A small delta is evident at the mouth of this river.

Bank Erosion Potential:
- medium in the lower reaches where the river steepens; low elsewhere.

Surface Erosion Potential:
- medium in the upper reaches where the terrain steepens and superficial material is fine.
- low in the lower reaches.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Muskeg River

River or Stream:
Hartley Creek

Hydrological Zone No:
5

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Muskeg Mountain Upland.
Clayey and silty till in the upper reaches, outwash sands in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.002 |
| Channel width: | 6 m |
| Average velocity: | 0.3-0.6 m/s |
| Channel Stability: | Stable |
| Bed material: | Silts |
| Bank material: | Silts |

Suspended Sediments:
No measurement

| | |
|---|---|
| Basin area: | 349.6 $km^2$ |
| WSC station: | 7DA9 |

Summary Comments:
Sedimentation Potential:
- low. The area through which the river flows is primarily well-vegetated muskeg.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Steepbank River

River or Stream:
Steepbank River. North Steepbank River is the major tributary.

Hydrological Zone No:
5

Physiographic and Surficial Material Characteristics:
Muskeg Mountain Upland, Clearwater Lowland, Firebag Plain. Predominantly clayey and silty till.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.004; 0.002 above confluence with North Steepbank River. |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 6-741 ppm |
| (associated discharges) | 3.3-56 $m^3/s$ |
| Measured discharges: | 8.3-61 $m^3/s$ |
| Years of record (sed.): | 1975 and 1976 |
| WSC station: | 1975 and 1976 |
| Basin area: | 1,373 $km^2$ |

Summary Comments:

Sedimentation Potential:
- high. A large delta exists at the confluence with the Athabasca River.

Bank Erosion Potential:
- high. In places the banks are actively eroding and the formation of point bars is evident.

Surface Erosion Potential:
- medium. Terrain is not steep and a good vegetative cover exists, but surficial materials are fine grained.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Beaver River (see note)

River or Stream:
Beaver River. Cache Creek is the major tributary.

Hydrological Zone No:
6

Physiographic and Surficial Material Characteristics:
Algar Plain, Clearwater Lowland.
Clayey and silty till in the upper reaches. Outwash sands in the lower reaches.

Channel Hydraulic Characteristics:
0.001 in central reach, to 0.008 elsewhere

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 11-232 ppm |
| (associated discharges) | 0.2-4.3 $m^3/s$ |
| Measured discharges: | 0-18.5 $m^3/s$ |
| Years of record (sed.): | 1976 |
| WSC station: | 7DA18 |
| Basin area: | 435 $km^2$ |

Summary Comments:
Sedimentation Potential:
- high. Measured sediment concentrations at low flows are relatively high.

Bank Erosion Potential:
- medium. Bank erosion is evident.

Surface Erosion Potential:
- medium in the steeper upper reaches where surficial materials are fine grained.

Note: In July 1976 Beaver River was diverted into Poplar Creek.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Poplar Creek (see note)

River or Stream:
Poplar Creek

Hydrological Zone No:
6

Physiographic and Surficial Material Characteristics:
Clearwater Lowland, Algar Plain.
Predominantly clayey and silty till and lacustrine deposits.

Channel Hydraulic Characteristics:
Slope: 0.006

Suspended Sediment:

| | |
|---|---|
| Measured Concentrations: | 4-362 ppm |
| (associated discharges): | 0.2-2.6 $m^3/s$ |
| Measured discharges: | 0-5.5 $m^3/s$ (prior to July 1976) |
| Years of record (sed.): | 1974 and 1975 |
| WSC station: | 7DA7 |
| Basin area: | 150 $km^2$ |

Summary Comments:
Sedimentation Potential:
- high. As indicated by the high sediment concentrations.

Note: In July 1976 Beaver River was diverted into Poplar Creek.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Hangingstone River

River or Stream:
Hangingstone River. Saline Creek is a major tributary.

Hydrological Zone No:
8

Physiographic and Surficial Material Characteristics:
Algar Plain, Stony Mountain Upland, Methy Portage Plain, Clearwater Lowland.
Predominantly clayey and silty till.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.004 |
| Channel width: | 15 m |
| Average velocity: | 1.5 m/s |
| Channel stability: | stable |
| Bed material: | Sands and gravels. Occasional bedrock |
| Bank material: | Sands and gravels. Occasional bedrock |

Suspended Sediment:
No measurement

| | |
|---|---|
| Basin area: | 914 $km^2$ |
| WSC station: | 7CD4 |

Summary Comments:
Sedimentation Potential:
- medium. The upstream reaches are probably the major source of potential sediment.

Bank Erosion Potential:
- low. The river banks are stable.

Surface Erosion Potential:
- high in the reaches of the Stony Mountains where drainage slopes are steep. Low elsewhere.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Horse River

River or Stream:
Horse River. The major tributary is an unnamed stream.

Hydrological Zone No:
8

Physiographic and Surficial Material Characteristics:
Algar Plain, Stony Mountain Upland, Clearwater Lowland.
Predominantly clayey and silty till.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.004 in the lower reach, 0.001 above confluence with an unnamed stream |
| Channel width: | 43 m near the mouth, 15 m above the confluence |
| Average velocity: | 0.6-1.8 m/s |
| Channel stability: | Relatively stable |
| Bed material: | Sands and gravels |
| Bank material: | Sands and gravels |

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 2,180.8 $km^2$ |
| WSC station: | 7CC1 |

Summary Comments:
Sedimentation Potential:
- medium

Bank Erosion Potential
- medium. There is some evidence of bank erosion in the central reach.

Surface Erosion Potential:
- low. Drainage slopes are low.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
MacKay River

River or Stream:
MacKay River. Dunkirk River, a major tributary, is in Zone 10. Other tributaries are Dover River and Thickwood Creek.

Hydrological Zone No:
9

Physiographic and Surficial Material Characteristics:
Algar Plain, Birch Mountain Upland, Clearwater Lowland. Hummocky moraine, drift of sands, gravels, and silts in the upper reaches; clayey and silty till and lacustrine in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.002 |
| Channel width: | 46 m |
| Average velocity: | 1.2-2 m/s |
| Channel stability: | Stable |
| Bed material: | Sands and gravels |
| Bank material: | Sands and gravels, occasional bedrock |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 7-698 ppm |
| (associated discharge) | 9-158 $m^3/s$ |
| Particle Size ($D_{50}$): | 0.02 mm (coarse silt) |
| Measured discharge: | 0.03-3,033 $m^3/s$ |
| Years of record (sed.): | 1975 and 1976 |
| WSC station: | 7DB1 |
| Basin area: | 5,232 $km^2$ |

Summary Comments:
Sedimentation Potential:
- medium. Suspended sediment measurements indicate moderate concentrations.

Bank Erosion Potential:
- low. Banks are stable, often well-vegetated.

Surface Erosion Potential:
- high. River valley walls are steep.

SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS
IN THE
AOSERP STUDY AREA

Basin:
MacKay River

River or Stream:
Dover River

Hydrological Zone No:
9

Physiographic and Surficial Material Characteristics:
Algar Plain, Clearwater Lowland, Birch Mountain Upland
Hummocky moraine, drift of sands, gravels and silts in the upper reaches; clayey and silty till and lacustrine material in the lower reaches.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.003 |
| Channel width: | 20 m in lower reach, 8 m in upper reach |
| Average velocity: | 0.9-1.8 m/s |
| Channel stability: | Moderately stable |
| Bed material: | Sands and gravels |
| Bank material: | Sands and silts |

Suspended Sediment:
No measurement

| | |
|---|---|
| Basin area: | 956 $km^2$ |
| WSC station: | 7DB2 |

Summary Comments:
Sedimentation Potential:
- medium, particularly in the lower reaches of the river.

Bank Erosion Potential:
- medium. Some instability evident.

Surface Erosion Potential:
- medium. River valley walls are occasionally steep.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
MacKay River

River or Stream:
Thickwood Creek

Hydrological Zone No:
9

Physiographic and Surficial Material Characteristics:
Algar Plain
Predominantly clayey and silty till.

Channel Hydraulic Characteristics:

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 171 $km^2$ |
| WSC station: | 7DB4 |

Summary Comments:

Probably low sedimentation potential.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
MacKay River

River or Stream:
Dunkirk River

Hydrological Zone No:
10

Physiographic and Surficial Material Characteristics:
Algar Plain, Birch Mountain Upland
Hummock moraine, drift of sands, gravels, silts, and clays.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.0006 in lower reach, 0.003 in upper reach. |

Suspended Sediment:
No measurements

| | |
|---|---|
| Basin area: | 1,582 $km^2$ |
| WSC station: | 7DB3 |

Summary Comments:
Sedimentation Potential:
- high in the steep upper reach. Medium to low in the flat lower reach.

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Clearwater River

River or Stream:
Clearwater River

Hydrological Zone No:
Not applicable

Physiographic and Surficial Material Characteristics:
Predominant setting is the Saskatchewan Plain.
In the lower reaches alluvial sands and silts occur along the river valley surrounded by outwash deposits of sands and gravels, and clayey and silty till.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.0004 (in lower reach) |
| Channel Width: | 90-137 m |
| Average velocity: | 1.2-1.5 m/s |
| Channel stability: | Generally stable |
| Bed material: | Sands with some gravel |
| Bank material: | Sands and silts |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 2-2030 ppm |
| (associated discharge) | 30.3-708 $m^3/s$ |
| Particle size ($D_{50}$): | 0.01-0.07 mm (medium-coarse silt) |
| Measured discharges: | 30-711 $m^3/s$ |
| Years of record (sed.): | 1967-1976 |
| WSC station: | 7CD1 |
| Basin area: | 30,562 $km^2$ |

# SEDIMENTATION CHARACTERISTICS OF RIVERS AND STREAMS IN THE AOSERP STUDY AREA

Basin:
Athabasca River

River or Stream:
Athabasca River

Hydrological Zone No:
Not applicable

Physiographic and Surficial Material Characteristics:
In N.E. Alberta the Athabasca River passes from the high Alberta Plains through the Saskatchewan Plain to the Great Slave Plain. The river valley in the upstream reach of the region is predominantly outwash deposits of sands and gravels while the downstream reach is silts and clays.

Channel Hydraulic Characteristics:

| | |
|---|---|
| Slope: | 0.001 above, and 0.0001 below, Fort McMurray |
| Channel width: | 335-442 m |
| Average velocity: | 1 m/s (below Fort McMurray) |
| Channel stability: | Stable |
| Bed material: | Sands |
| Bank material: | Bedrock outcrops, silts, and clays |

Suspended Sediment:

| | |
|---|---|
| Measured concentrations: | 1-4,820 ppm |
| (associated discharges) | 108-701 $m^3/s$ |
| Particle size ($D_{50}$): | 0.01-0.03 (medium-coarse silt) |
| Measured discharges: | 97-701 $m^3/s$ |
| Years of record (sed.): | 1967-1976 |
| WSC station: | 7DA1 |
| Basin area: | 132,866 $km^2$ |

## 10. AOSERP RESEARCH REPORTS


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|---|---|---|
| 1. | | AOSERP First Annual Report, 1975 |
| 2. | AF 4.1.1 | Walleye and Goldeye Fisheries Investigations in the Peace-Athabasca Delta |
| 3. | HE 1.1.1 | Structure of a Traditional Baseline Data System |
| 4. | VE 2.2 | A Preliminary Vegetation Survey of the Alberta Oil Sands Environmental Research Program Area |
| 5. | HY 3.1 | The Evaluation of Wastewaters from an Oil Sand Extraction Plant |
| 6. | | Housing for the North--The Stackwall System |
| 7. | AF 3.1.1 | A Synopsis of the Physical and Biological Limnology and Fisheries Programs within the Alberta Oil Sands Area |
| 8. | AF 1.2.1 | The Impact of Saline Waters Upon Freshwater Biota (A Literature Review and Bibliography) |
| 9. | ME 3.3 | Preliminary Investigation into the Magnitude of Fog Occurrence and Associated Problems in the Oil Sands Area |
| 10. | HE 2.1 | Development of a Research Design Related to Archaeological Studies in the Athabasca Oil Sands Area |
| 11. | AF 2.2.1 | Life Cycles of Some Common Aquatic Insects of the Athabasca River, Alberta |
| 12. | ME 1.7 | Very High Resolution Meteorological Satellite Study of Oil Sands Weather, a Feasibility Study |
| 13. | ME 2.3.1 | Plume Dispersion Measurements from an Oil Sands Extraction Plant |
| 14. | HE 2.4 | Athabasca Oil Sands Historical Research Design (3 volumes) (in review) |
| 15. | ME 3.4 | Climatology of Low Level Air Trajectories in the Alberta Oil Sands Area |
| 16. | ME 1.6 | The Feasibility of a Weather Radar near Fort McMurray, Alberta |
| 17. | AF 2.1.1 | A Survey of Baseline Levels of Contaminants in Aquatic Biota of the AOSERP Study Area |
| 18. | HY 1.1 | Alberta Oil Sands Region Stream Gauging Data |
| 19. | ME 4.1 | Calculations of Annual Averaged Sulphur Dioxide Concentrations at Ground Level in the AOSERP Study Area |
| 20. | HY 3.1.1 | Evaluation of Organic Constituents (in review) |
| 21. | | AOSERP Second Annual Report, 1976-77 |
| 22. | HE 2.3 | Maximization of Technical Training and Involvement of Area Manpower ( in review ) |
| 23. | AF 1.1.2 | Acute Lethality of Mine Depressurization Water on Trout Perch and Rainbow Trout (in review) |
| 24. | ME 4.2.1 | Review of Dispersion Models and Possible Applications in the Alberta Oil Sands Area (in review) |
| 25. | ME 3.5.1 | Review of Pollutant Transformation Processes Relevant to the Alberta Oil Sands Area |

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|---|---|---|
| 26. | AF 4.5.1 | Interim Report on an Intensive Study of the Fish Fauna of the Muskeg River Watershed of Northeastern Alberta |
| 27. | ME 1.5.1 | Meteorology and Air Quality Winter Field Study in the AOSERP Study Area, March 1976 (in review) |
| 28. | VE 2.1 | Interim Report on a Soils Inventory in the Athabasca Oil Sands Area |
| 29. | ME 2.2 | An Inventory System for Atmospheric Emissions in the AOSERP Study Area |
| 30. | ME 2.1 | Ambient Air Quality in the AOSERP Study Area, 1977 |
| 31. | VE 2.3 | Ecological Habitat Mapping of the AOSERP Study Area: Phase I |
| 32. | | AOSERP Third Annual Report, 1977-78 |
| 33. | TF 1.2 | The Relationships between Habitats, Forages, and Carrying Capacity of Moose Range in the AOSERP Study Area |
| 34. | HY 2.4 | Heavy Metals in Bottom Sediments of the Mainstem Athabasca River System in the AOSERP Study Area |
| 35. | AF 4.9.1 | The Effects of Sedimentation on the Aquatic Biota |

These reports are not available upon request. For further information about availability and location of depositories, please contact:

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