# Effects of eroding oil sand and periodic flooding on benthic macroinvertebrate communities in a brown-water stream in Northeastern Alberta, Canada

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The portion of the Steepbank River which cuts through the Athabasca oil sands deposit supported a less diverse benthic invertebrate community than did upstream areas. The variety and relative abundance of Plecoptera and Trichoptera were consistently lower in the area of oil sand exposure. As a substrate for benthic invertebrates, oil sand appears to be analogous to bedrock, supporting about 60% as many animals per unit area as adjacent rubble substrates. Burrowing and negatively phototropic organisms were significantly less abundant on oil sand than on rubble. When high discharge of the Athabasca River flooded a riffle to form a pool near the mouth of the Steepbank, rheophilic forms, such as *Baetis* and *Simulium*, were largely eliminated from the riffle and benthic standing stocks were reduced by about 50%. The invertebrate community recovered quickly after riffle conditions returned.

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La portion de la rivière Steepbank qui traverse les sables bitumineux d'Athabasca supporte une communauté d'invertébrés benthiques moins diversifiée que la région en amont. La variété et l'abondance relative des plécoptères et des trichoptères sont toujours moins importantes dans la région où les sables bitumineux sont à découvert. Les sables bitumineux semblent avoir la même valeur comme substrat que la roche mère; en effet, la densité des invertébrés y est d'environ 60% de celle que supporte le substrat adjacent qui est formé de gros cailloux. Les organismes fouisseurs et les organismes à phototropisme négatif sont significativement moins abondants sur les sables bitumineux que sur les cailloux. Lorsque la crue de la rivière Athabasca a inondé les rapides pour les transformer en zone calme près de l'embouchure de la rivière, les formes rhéophiles telles *Baetis* et *Simulium* ont été éliminées en grande partie des rapides et la biomasse benthique a été réduite de moitié. La communauté d'invertébrés a vite récupéré après le retour aux conditions normales des rapides.

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## Introduction

The contamination of aquatic habitats resulting from accidental or experimental spills of crude and refined oils has been shown to cause changes in both the variety and density of various components of the flora and fauna (McCauley 1966; Roeder *et al.* 1975; Rosenberg and Wiens 1976; Parker *et al.* 1976; Burk 1977; Busdosh and Atlas 1977). Such studies have been concerned with single introductions of oil and the recovery of the biota over fairly short periods of time. The long-term effects of hydrocarbons on lotic communities have received very little attention (Parker *et al.* 1976).

In the Athabasca oil sands area of northeastern Alberta, many tributary streams of the Athabasca River have eroded down into oil sands deposits. Since oil sand is a cohesive mixture of fine sand, clay, and bitumen (about 5–15% of the oil sand by weight), organisms living in these streams are continuously exposed to low levels of hydrocarbons in the water or on the substrate. By sampling riffles above and below the point where one such stream, the Steepbank River, begins to erode oil sand, we were able to study the qualitative effects of long-term, natural exposure to hydrocarbons on the composition of the benthic invertebrate community. Since oil sand forms much of the streambed at the lower site, quantitive samples were collected to compare numbers of riffle macroinvertebrates living directly on the oil sand and on adjacent limestone rubble. During periods of high discharge of the Athabasca River this lower riffle area backed up, becoming a pool. Therefore, we also sampled an unflooded riffle to assess the effects of a fluctuating current regime on the abundance and composition of the fauna.

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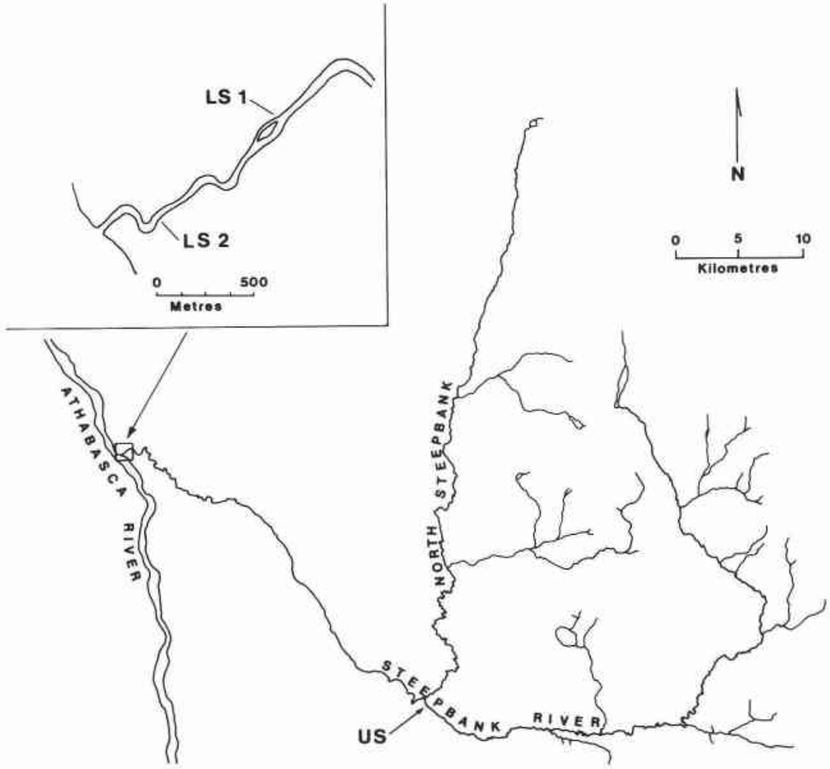


FIG. 1. The study area. US, study site upstream from oil sand; LS-1, LS-2, study sites within area of eroding oil sand.

## The Study Area

The Steepbank River is the first major tributary of the Athabasca River entering from the east downstream of Fort McMurray, Alberta (57°02′ N, 111°30′ W). For most of its 116 km length (Fig. 1), the Steepbank has a gradient of 2.4 m $km^{-1}$ and consists of riffles and pools with glacial gravel and boulder substrates. In its lower 20 km, the Steepbank has a gradient of about 5.7 m $km^{-1}$ and consists of a series of long riffles and runs with few true pools. This portion of the river cuts through the Athabasca oil sands and the underlying, extremely friable, Devonian limestone so that the bed of the stream resembles fine-grained asphalt pavement with patches of angular limestone rubble lying on, or embedded in, the surface. Seasonal ranges of selected chemical and physical parameters of the lower Steepbank River are given in Table 1.

The mean discharge of the Athabasca River in winter is about 200 $m^3 s^{-1}$ and in summer varies from about 570 to well over 1700 $m^3 s^{-1}$. This fluctuating discharge results in changes of 2–4 m in the elevation of the river surface over periods as short as a few hours.

When the discharge of the Athabasca River exceeds about 1130 $m^3 s^{-1}$, the water level of the lower Steepbank River rises and the current regime is altered in these lower reaches. If the discharge of the Steepbank is less than 7 $m^3 s^{-1}$ during such periods, current speeds are negligible as much as 500 m above the mouth and this former riffle area becomes a long pool where silts and clays are deposited. If the discharge of the Steepbank exceeds 7 $m^3 s^{-1}$ during high water episodes, a distinct current is maintained further downstream but the flow is much less turbulent than during low water. This alternation of riffle and pool conditions continues throughout the open water period. The Steepbank River generally freezes in late October and remains so until late April. Under the ice, water temperatures remain 0°C but, in summer, maximum (June–July) temperatures of 20°C may occur, with daily summer water temperature fluctuations of up to 8°C.

An upstream site (designated US), above the point where the river begins to erode through oil sand, was located 50 km above the mouth near the confluence of the North Steepbank (Fig. 1). Two riffles, 1000 and 400 m above the mouth of the Steepbank River, were chosen for the lower stream

TABLE 1. Seasonal ranges of selected chemical and physical parameters of the lower Steepbank River, 1977, from data collected by the hydrometric surveys group of Inland Waters Directorate, Fisheries and Environment Canada (only discharge was monitored in 1976)

| | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| | December–March | April–May | June–August | September–November |
| pH | 7.7–7.8 | 7.0–7.6 | 7.8–8.2 | 8.0–8.1 |
| Total alkalinity, mg L$^{-1}$ | 314–329 | 50–85 | 75–123 | 125–128 |
| Conductance, μΩ cm$^{-1}$ | 590–610 | 110–172 | 159–230 | 222–256 |
| Turbidity, J.T.U.* | 1.3–2.5 | 10.5–33.0 | 1.1–8.2 | 1.2–6.7 |
| Oil and grease, mg L$^{-1}$ | <0.1 | <0.1–1.7 | 0.1–1.4 | 1.2–2.4 |

*J.T.U., Jackson Turbidity Unit.

sites (designated LS-1 and LS-2, respectively). LS-1 was not affected by fluctuations in the level of the Athabasca River during 1976.

## Methods

The benthic fauna were compared at the upstream (US) and downstream (LS-1) sites on 22 July and 11 October 1976 and on 30 January, 1 May, and 22 July 1977. On each visit during the ice-free season, an effort was made to collect as many different taxa as possible from each site. Qualitative kick samples were taken from every apparent habitat along a 30-m reach of the river (i.e. riffle, pool, margin, oil sand, macrophytes) using a coarse-meshed dipnet (aperture 500 μm). The material so collected within 15 min was combined and immediately preserved in 10% formalin. An additional 10 to 15 min were spent examining further nettings as well as stones and debris collected by hand from which larger organisms were picked out and placed in 70% alcohol. In January, collecting was confined to holes cut through the ice near midstream in riffle areas.

In the laboratory, the kick samples were mixed thoroughly and a portion was withdrawn. All the animals in this portion were picked from the associated debris under 10 × magnification. Additional portions were examined, if necessary, until at least 300 animals were obtained. These organisms were identified and enumerated at the generic or specific level, in most cases, and the percentage composition of the fauna was calculated. The animals that had been handpicked in the field were not included in these calculations but were used to complete the faunal lists on a basis of presence or absence.

Rubble and oil sand as substrates and the effects of alterations in the current regime were studied at sites LS-1 and LS-2 using a Surber sampler which enclosed an area of 0.09 m$^2$ and was equipped with a 202-μm-mesh collecting bag. Oil sand substrates (i.e. patches of asphalt-like streambed not covered by stones or gravel) enclosed by the sampler were scrubbed clean with a vegetable brush. On rubble substrates (consisting of angular limestone pebbles up to 10 cm in maximum length with small amounts of gravel and sand), stones were removed by hand to a depth of 10 cm, or down to solid oil sand, and scrubbed. Any remaining finer sediments were agitated thoroughly to dislodge benthic organisms. When lentic conditions prevailed at site LS-2, 0.09-m$^2$ quadrats were sampled using an airlift equipped with a 202-μm-mesh collecting bag (Barton and Hynes 1978*b*). The quantitative sampling program is summarized in Table 2.

All samples were preserved with 10% formalin in the field and returned to the laboratory where macroinvertebrates were sorted from the associated debris under 10 × magnification. All

TABLE 2. Numbers of quadrat samples collected at downstream sites, 1976

| Date | LS-1 | LS-2 | Conditions at LS-2 |
|---|---|---|---|
| 23 June | NS | 4os, 4R | Riffle |
| 3 July | 4os, 4R | 2os, 2R | Pool |
| 4 August | 3R | 3os, 3R | Riffle |
| 22 August | NS | 3os, 3R | Pool |
| 15 September | 4R | 1os, 3R | Deep riffle |
| 4 October | 4R | 3os, 3R | Riffle |

NOTE: os, oil sand; R, rubble; NS, not sampled.

insects, except Chironomidae, were identified and enumerated at the generic or specific level. Chironomids were separated only to the level of subfamily or tribe as most specimens had globules of tar adhering to them preventing further identification. Attempts to remove the tar with acetone and xylene were unsuccessful. The broad groupings, Oligochaeta and Acari, were treated as individual taxa. Most of oligochaetes were Enchytraeidae and *Nais behningi* Michaelson.

Since variances tended to be large, the quadrat data from sites LS-1 and LS-2 were transformed as ln (number per sample + 1) (Elliot 1971). Student's *t*-test was used to test the significance ($p \leq 0.05$) of differences between sites and between substrates.

## Results

### *Upstream Site (US) versus Area of Oil Sand Exposure (LS-1)*

A total of 124 taxa were collected from the two sites. Of these, 17 were found only at the upstream site on two or more visits, and 7 only at the downstream site (Table 3). Three of 11 stonefly species and 8 of the 16 caddisflies were found only at the upstream site during these regular sampling visits. Three species of *Sigara* (Hemiptera) were found only at the downstream site. The number of taxa collected per visit was consistently greater at the upstream site (Table 4). The percent composition of the fauna at each site showed considerable variation between visits (Table 4). While the mean percent abundance of several groups differed greatly between sites, only the Plecoptera and Trichoptera were consistently more abundant at

TABLE 3. Taxa collected only at the site above (US) or within (LS-1) the area of eroding oil sand on two or more visits during the qualitative survey. Numbers in parentheses indicate the total number of taxa found at both sites in all qualitative samples (rare taxa collected only on one visit at either site have not been included)

| | US | LS-1 |
|---|---|---|
| Ephemeroptera (22) | *Ephemerella tibialis* | *Ephemerella inermis* |
| Plectoptera (11) | *Leuctra* cf. *sara*<br>*Claassenia sabulosa*<br>*Pteronarcella regularis* | *Isoperla fusca* |
| Trichoptera (16) | *Rhyacophila*<br>*Glossosoma* spp.<br>*Wormaldia gabriela*<br>*Arctopsyche ladogenesis*<br>*Ceraclea* spp.<br>*Micrasema* | |
| Corixidae (9) | | *Sigara bicoloripennis*<br>*S. conocephala*<br>*S. solensis* |
| Chironomidae (37) | *Microtendipes* cf. *pedellus*<br>Orthocladiinae A<br>*Heterotrissocladius* cf. *marcidus*<br>*Nanocladius* cf. *rectinervis*<br>*Synorthocladius* | *Ablabesmyia*<br>*Paramerina* |

TABLE 4. Percentage composition and number of taxa in qualitative collections from sites above (US) and within (LS-1) the area of eroding oil sand

| | 22 July 1976 | | 11 October 1976 | | 30 January 1977 | | 1 May 1977 | | 22 July 1977 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | US | LS-1 | US | LS-1 | US | LS-1 | US | LS-1 | US | LS-1 |
| Lower phyla | 0.2 | — | 3.9 | 0.6 | 3.9 | 8.4 | 2.1 | 8.0 | 2.5 | 4.3 |
| Oligochaeta | 0.3 | — | 1.5 | — | 4.0 | 1.4 | 5.3 | 5.8 | 13.7 | 4.2 |
| Ephemeroptera | 29.9 | 19.5 | 20.2 | 34.8 | 13.7 | 5.5 | 18.0 | 41.6 | 37.2 | 44.8 |
| Plecoptera | 2.7 | — | 13.1 | 4.3 | 2.7 | — | 1.3 | — | 4.9 | 1.5 |
| Trichoptera | 22.4 | — | 35.0 | — | 34.2 | — | 7.5 | — | 5.5 | 3.1 |
| Tanypodinae | 0.1 | 3.1 | 3.0 | 5.0 | 0.8 | 0.9 | 1.7 | 4.4 | 0.8 | 5.9 |
| Chironomini | 0.5 | 1.8 | 0.9 | 8.9 | 0.9 | 0.2 | 3.0 | 0.8 | 0.4 | 0.5 |
| Tanytarsini | 7.2 | 46.1 | 6.3 | 5.1 | 11.7 | 66.5 | 30.9 | 12.7 | 20.0 | 18.5 |
| Orthocladiinae | 34.8 | 14.3 | 6.0 | 8.8 | 14.9 | 1.4 | 18.0 | 12.9 | 11.5 | 7.6 |
| Other diptera | 4.7 | 14.4 | 7.2 | 11.5 | 11.0 | 15.0 | 2.5 | 11.7 | 1.6 | 7.0 |
| Other insects | 0.1 | — | 2.1 | 13.9 | — | — | — | 0.8 | 0.4 | 0.5 |
| No. of taxa | 46 | 18 | 58 | 32 | 47 | 14 | 48 | 37 | 47 | 42 |

the upstream site. Tipulidae and Empididae (which accounted for 90% of 'other diptera') were consistently more abundant at the downstream site.

### *Flooded versus Unflooded Sites*

During the first three months of 1976, the mean discharge of the Athabasca River was about 198 $m^3 s^{-1}$. In early April the river rose, cresting at 1700 $m^3 s^{-1}$ on 18 April, and was clear of ice by 19 April. Discharge declined rapidly in the week following breakup and then fell slowly until mid-June.

The discharge of the Steepbank River followed a similar pattern during the first half of 1976. After a winter mean of 0.45 $m^3 s^{-1}$, the river crested at 17.7 $m^3 s^{-1}$ on 15 April, was free of ice by 20 April, and fell steadily until late May. Flooding of the lower site, due to high discharge of the Athabasca, occurred from 26 June to 28 July and from 8 August to 17 September (Fig. 2). Lentic conditions existed at the lower site during the first period of high water and during the second until 27 August when an exceptionally heavy rainstorm caused the dis-

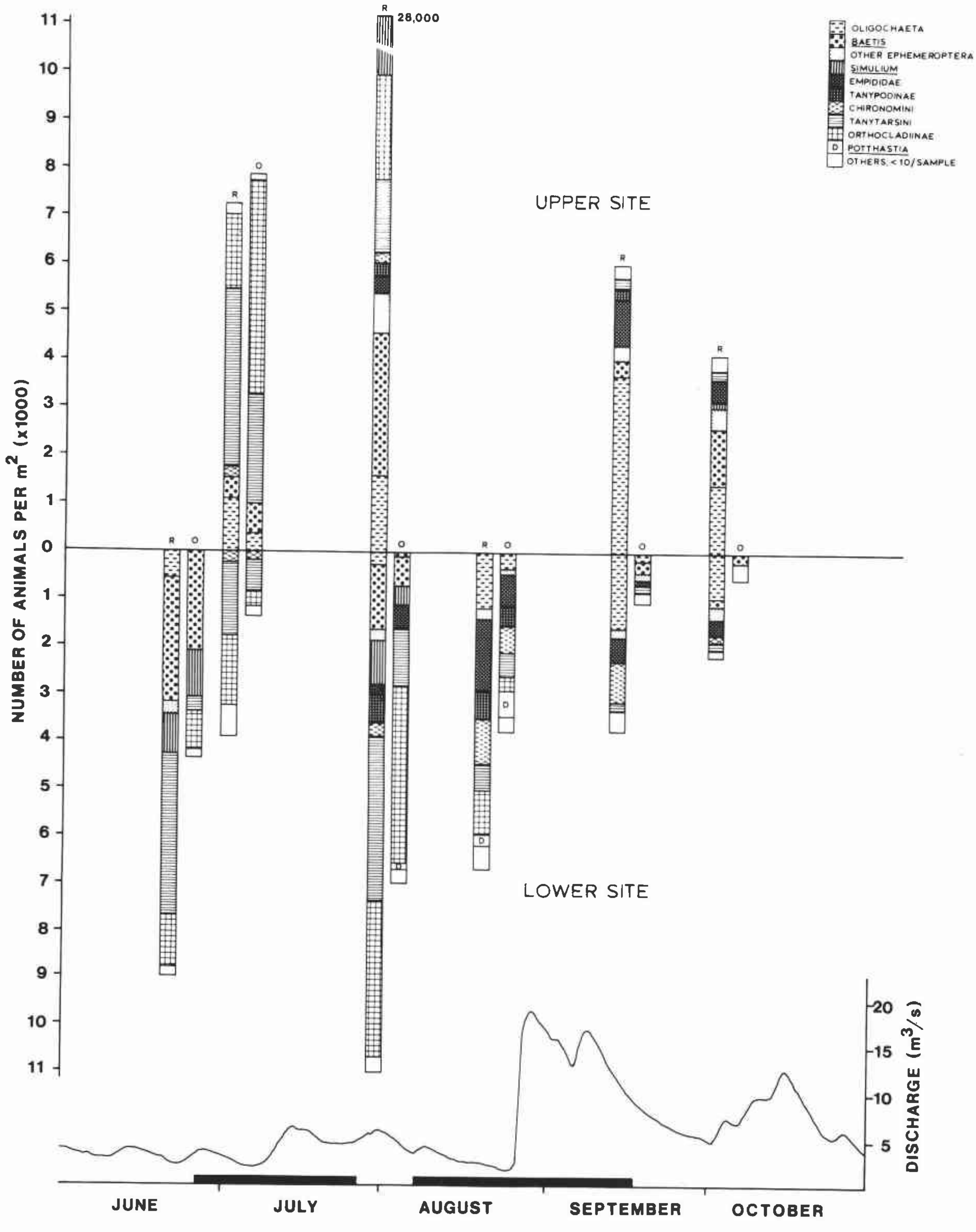


FIG. 2. Mean abundance of invertebrates on rubble (R) and oil sand (O) at the upper (LS-1) and lower (LS-2) downstream sites. The lower curve shows the discharge of the Steepbank River, with the horizontal black bars indicating periods of flooding at LS-2 (whenever discharge of the Athabasca River exceeded $1130 \, m^3 \, s^{-1}$).

TABLE 5. Mean numbers of taxa per quadrat (0.09 $m^2$) (excluding Chironomidae) collected at the lower riffle sites

| Site | Substrate | Date | | | | | | $\bar{x}$ | $t$ |
|---|---|---|---|---|---|---|---|---|---|
| | | 23 June | 3 July | 4 August | 22 August | 15 September | 4 October | | |
| LS-1 | Rubble | NS | 9.5 | 18.7 | NS | 12.0 | 12.2 | 12.3 | |
| | | | | | | | | | 0.14 |
| LS-2 | Rubble | 10.5 | 7.5 | 17.0 | 15.7 | 13.0 | 11.0 | 12.0 | |
| | | | | | | | | | 3.72** |
| LS-2 | Oil sand | 4.2 | 4.5 | 12.0 | 11.3 | NC | 6.3 | 7.4 | |

NOTE: NS, not sampled; NC, not calculated; **, $p < 0.01$.

charge of the Steepbank River to increase sufficiently to reinstate lotic conditions for the rest of the open-water season.

Because the discharge of the Steepbank River was greater than 8.5 $m^3 s^{-1}$ during April when the Athabasca was also high, the fauna at the lower site (LS-2) was exposed to lotic conditions continuously through the winter and spring. We have assumed, therefore, that the fauna sampled at LS-2 in late June was similar to that of other riffles in the lower Steepbank at that time and could be used to assess subsequent changes at both LS-1 and LS-2.

The total density of benthic invertebrates on rubble at LS-1 averaged 8300 animals $m^{-2}$ in late June and early July, rose to 28 000 $m^{-2}$ in early August, and declined in September and October (Fig. 2). The high densities recorded in early August were associated with the appearance of second generations of *Baetis* and *Simulium tuberosum* complex. The autumn decline in standing stocks was probably due to the completion of the emergence of many of the insect species and the scouring effects of the spate in late August and early September. The number of nonchironomid taxa per sample showed a similar peak in August but the late summer values were only slightly higher than those for June and July (Table 5).

Flooding and the imposition of lentic conditions at LS-2 was accompanied by a 50% reduction in the total benthic standing stocks in both July and August (Fig. 2). This was largely due to the elimination of such rheophilic forms as *Baetis, Simulium*, and *Rheotanytarsus*. Invertebrate density decreased in a pattern similar to that observed at the upper site following the spate of early September.

Total invertebrate abundance on rubble was significantly lower at LS-2 than at LS-1 on dates when both sites were sampled (Table 6). Among major groups of organisms, the mean densities of Oligochaeta, *Baetis*, and *Simulium* were significantly greater at LS-1 and Chironomini were significantly more abundant at LS-2 (Table 7). There was no difference between sites in the mean number of taxa per sample (Table 5) or in the total number of taxa collected on any given date.

*Oil Sand versus Rubble*

Both the variety and abundance of invertebrates on oil sand were significantly less than on rubble substrates (Tables 5 and 6). Since all but a few rare taxa were collected from both substrates, these differences appeared to be due to the physical structure of the substrate rather than any surficial toxicity of oil sand. Burrowing or negatively phototropic forms such as Oligochaeta, Plecoptera, the mayflies *Ephemerella, Heptagenia*, and *Rhithrogena*, and all Chironomidae (except Orthocladiinae) were significantly less abundant on oil sand while surface dwelling forms such as *Baetis* and *Simulium* were not (Table 7). Since Tanytarsini arrange their tubes to face into the current whether on the top, sides, or bottom of stones, their lower abundance on oil sand was probably due to the smaller total surface area available for attachment rather than the lack of a specific, preferred microhabitat.

During the more extensive sampling at the downstream sites (LS-1 and LS-2) small populations of several taxa were found which had been recorded only at the upstream site during the seasonal, qualitative study (Table 3). These include *Leuctra* cf. *sara, Glossosoma, Arctopsyche ladogenesis, Ceraclea, Lepidostoma, Micrasema, Microtendipes pedellus, Nanocladius rectinervis*, and *Synorthocladius*.

## Discussion

The effects of oil on freshwater benthos have been reported to be quite variable, depending on such factors as the type of oil, the season of exposure, and the nature of the receiving water, lentic or lotic (McCauley 1966; Parker *et al.* 1976). Several general trends are apparent, however. Lighter oils appear to be highly toxic to most benthic invertebrates but disappear rapidly through evaporation (Snow and Rosenberg 1975*a*). Certain Trichoptera, Chironominae, Plecoptera, and Ephemeroptera

TABLE 6. Mean numbers of invertebrates per quadrat (0.09 $m^2$) and results of $t$-tests comparing abundances on substrates at downstream sites

| Site | Substrate | Date: 23 June | 3 July | 4 August | 22 August | 15 September | 4 October | $t$ | df |
|---|---|---|---|---|---|---|---|---|---|
| LS-1 | Rubble | NS | 654.2 | 2527.3 | NS | 546.8 | 376.8 | | |
| | | | | | | | | 2.40* | 24 |
| LS-2 | Rubble | 805.2 | 344.5 | 974.0 | 599.7 | 335.0 | 194.3 | | |
| | | | | | | | | 4.38** | 28 |
| LS-2 | Oil sand | 392.0 | 121.5 | 626.7 | 336.7 | NC | 50.0 | | |

NOTE: NS, not sampled; NC, not calculated; *, $p < 0.05$; **, $p < 0.01$.

TABLE 7. Mean numbers of organisms per quadrat (0.09 $m^2$) in major groups and results of $t$-tests comparing sites and substrates (based on all samples collected)

| | Sites: LS-1 | Sites: LS-2 | Sites: $t$ | Substrates: Rubble | Substrates: Oil sand | Substrates: $t$ |
|---|---|---|---|---|---|---|
| Oligochaeta | 170.8 | 57.4 | 3.50** | 60.7 | 15.2 | 4.52** |
| *Baetis* | 97.6 | 34.4 | 3.27** | 86.6 | 63.0 | 0.50 |
| Other Ephemeroptera | 26.8 | 15.7 | 0.26 | 15.1 | 3.7 | 4.85** |
| Plecoptera | 4.7 | 2.4 | 0.91 | 3.8 | 0.5 | 5.32** |
| Trichoptera | 3.1 | 1.2 | 0.80 | 1.5 | 0.9 | 0.53 |
| *Simulium* | 340.4 | 18.5 | 1.79* | 31.3 | 25.0 | 0.40 |
| Empididae | 41.6 | 21.3 | 1.18 | 30.4 | 17.3 | 1.25 |
| Tanypodinae | 11.3 | 18.5 | 0.69 | 21.7 | 7.8 | 2.02* |
| Chironomini | 10.4 | 30.1 | 1.73* | 26.4 | 11.5 | 2.85* |
| Tanytarsini | 121.8 | 107.8 | 0.56 | 217.9 | 81.6 | 2.67* |
| Orthocladiinae | 124.2 | 94.4 | 0.52 | 129.7 | 161.8 | 0.39 |
| Diamesinae | 4.2 | 2.7 | 1.35 | 5.3 | 10.3 | 0.48 |

NOTE: *, $p < 0.05$; **, $p < 0.01$.

show a long-term susceptibility to heavier oil fractions, while other Diptera, especially Orthocladiinae, are very tolerant and may even increase in abundance on oiled substrates (Bengtsson and Berggren 1972; United States Environmental Protection Agency 1973; Snow and Rosenberg 1975*b*; Rosenberg and Wiens 1976; Barton and Wallace 1977, 1978). Oil tends to accumulate in lake sediments where its effects persist over long periods of time (Bengtsson and Berggren 1972; Snow and Rosenberg 1975*b*; Hare 1976), but is rapidly flushed from rivers (Chen *et al.* 1976) where the fauna may, at least partially, recover in a year or less (Snow *et al.* 1975; Rosenberg and Wiens 1976; United States Environmental Protection Agency 1973).

Bitumen, the hydrocarbon component of oil sand, is a heavy, tar-like substance that has been suggested to be the result of weathering and microbial decomposition of conventional crude oils (I. Rubinstein, O. P. Strausz, C. Spyckerelle, R. J. Crawford, and D. W. S. Westlake, unpublished data). The relatively small proportion of soluble light oils in the bitumen and their rapid evaporation from turbulent river water probably accounts for the apparent lack of a gross toxic effect from oil sand in the Steepbank River. However, our results show that the variety of benthic organisms inhabiting the portion of the river that cuts through the oil sands deposit is smaller than in upstream areas; qualitative sampling consistently yielded more taxa at the upstream site (US). Among the groups that appear to be most affected by exposure to oil sand, the Plecoptera and Trichoptera stand out, both in terms of a reduction in the variety of forms and in their numerical contribution to the entire fauna. Eleven taxa in these two groups were commonly collected only in the portion of the Steepbank River above the oil sand during the qualitative survey; only a few specimens of six of these were also found in the oily area during intensive quantitative sampling.

The physical behaviour of eroding oil sand is probably of primary importance in this regard, though there is evidence that oil is toxic to some species of caddisflies and stoneflies (Bugbee and Walter 1973; Snow and Rosenberg 1975*a*). Where streams erode banks of oil sand, some of the material breaks off as large chunks but some is also carried downstream as minute, tar-covered particles, especially during spring breakup, late summer, and autumn. (Both personnel and equipment immersed in the river during the open water season are quickly covered with minute specks of sticky tar.) The relatively small population of Trichoptera, especially the net-spinning Hydropsychidae and Philopotamidae, in the lower Steepbank is probably related, at least in part, to these suspended particles of oil sand. This material may interfere with the operation of the feeding nets or may be toxic if ingested by the larvae while cleaning the net. The different feeding mechanism of *Simulium*, the other dominant filter feeder in the Steepbank, may be less susceptible to fouling by particles of tar, allowing them to thrive in the absence of competition from caddis larvae (Davies 1950).

Larger chunks of oil sand, where there are no obstacles to hinder their movement, are moved downstream by the current and are worn into shapes identical to fluvial gravel and pebbles. If these come to rest on the stream bed, they are colonized by the benthic fauna. Large quantities of oil sand entering a stream, as from a major bank slippage, tend to fuse together and slowly flow downstream at a rate of a few centimetres per year. Such fusion and downstream movement leads to the formation of the impermeable pavement-like layers of oil sand that form much of the substrate in the lower Steepbank River.

As a substratum for benthic invertebrates, this layer of fused oil sand is analogous to bedrock where the density and diversity of the fauna is limited by the effective surface area available for colonization and the lack of sheltered surfaces and a hyporheic refuge (Williams and Hynes 1974). While we acknowledge the difference in the sampling techniques used, our mean of 3400 animals $m^{-2}$ (1400 if chironomids are excluded) is similar to the standing stocks on bedrock substrates reported by Pennak and Van Gerpen (1947) and Armitage (1961) in streams, and Barton and Hynes (1978) in large lakes. Such a comparison further emphasizes the apparent lack of an overall, long-term toxic effect from exposure to oil sands. Certainly the abundance of invertebrates on oil sand and bedrock are more similar to each other than to the mean standing stocks of 250 000 $m^{-2}$ in streams with porous substrates studied by Hynes (1974) and Hynes *et al.* (1976).

Scott and Rushforth (1959) hypothesized that large stones lying on the stream bed allow the development of larger benthic standing stocks since the large stones provide areas of reduced current, protection from vertebrate predators, accumulations of organic debris, and stability during spates. This is a specific example of the more general theory that habitat complexity and faunal diversity are directly proportional (MacArthur and MacArthur 1961). Our results support this theory: the less structurally complex habitat afforded by oil sand supported fewer animals of fewer kinds than did the physically more varied rubble substrates.

It was expected that the more stable current regime at site LS-1 would support a greater diversity of organisms than was found at site LS-2, which was subject to wide fluctuations in this environmental parameter (Klopfer 1959; de March 1976). This was not the case over the summer as a whole, although the number of species per sample is perhaps not the best measure of diversity (Wilhm 1967; de March 1976). Since the Chironomidae were seldom identifiable, calculation of more elaborate diversity indices was not considered appropriate. When considering the effects of alternating lotic and lentic conditions, the lack of an overall difference in the variety of animals between sites LS-1 and LS-2 suggests that while several strongly rheophilic forms such as *Baetis*, *Simulium*, and *Rheotanytarus* were largely eliminated by reductions in current speed, many of the species inhabiting the lower Steepbank River are capable of surviving severe changes in current velocity, at least for periods less than an entire season.

In summary, the variety and percentage composition of stream benthos were altered in the portion of the lower Steepbank River that cuts through the Athabasca oil sands deposit. The relative abundance and variety of Trichoptera and Plecoptera were smaller in this downstream section of the river. These differences in the benthic communities were probably largely caused by physical alteration of the substrate and the presence of particles of oil sand in suspension. The standing stocks of benthic invertebrates on oil sand substrates were about half as large as those on rubble and contained significantly fewer burrowing or negatively phototropic forms. Flooding of riffle habitat resulted in a 50% reduction in the abundance of macrobenthos but the community recovered rapidly upon the resumption of normal current conditions.

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ARMITAGE, K. B. 1961. Distribution of riffle insects in the Firehole River, Wyoming. Hydrobiologia, **27**: 152–174.

BARTON, D. R., and H. B. N. HYNES. 1978. Seasonal study of the fauna of bedrock substrates in the wave-zone of Lakes Huron and Erie. Can. J. Zool. **56**: 48–54.

——— 1978*b*. The wave-zone macrobenthos along the exposed Canadian shores of the Saint Lawrence Great Lakes. J. Great Lakes Res. **4**: 27–45.

BARTON, D. R., and R. R. WALLACE. 1977. Ecological studies on the benthic invertebrates of rivers in the A.O.S.E.R.P. study area, NE Alberta. Report AF. 2.0. Report of the Alberta Oil Sands Environmental Research Program. Edmonton, Alta.

——— 1978. Ecological studies of the aquatic invertebrates of the A.O.S.E.R.P. study area of NE Alberta. Report AF 2.0.1. Report of the Alberta Oil Sands Environmental Research Program. Edmonton, Alta.

BENGTSSON, L., and H. BERGGREN. 1972. The bottom fauna in an oil-contaminated lake. Ambio, **1**: 141–144.

BUGBEE, S. L., and C. M. WALTER. 1973. The response of macroinvertebrates to gasoline pollution in a mountain stream. *In* Proceedings of the Joint Conference on Prevention and Control of Oil Spills. Washington.

BURK, C. J. 1977. A four year analysis of vegetation following an oil spill in a freshwater marsh. J. Appl. Ecol. **14**: 515–522.

BUSDOSH, M., and R. M. ATLAS. 1977. Toxicity of oil slicks to arctic amphipods. Arctic, **30**: 85–92.

CHEN, E. C., B. E. KEEVIL, and R. O. RAMSEIER. 1976. Behaviour of oil spilled in ice-covered rivers. Inland Waters Directorate, Ottawa. Sci. Ser. No. 61.

DAVIES, D. M. 1950. A study of the black fly population of a stream in Algonquin Park, Ontario. Trans. R. Can. Inst. **28**: 121–159.

DE MARCH, B. G. E. 1976. Spatial and temporal patterns in macrobenthic stream diversity. J. Fish. Res. Board Can. **33**: 1261–1270.

ELLIOTT, J. M. 1971. Some methods for the statistical analysis of samples of benthic invertebrates. Freshwater Biol. Assoc. Sci. Publ. 25.

HARE, R. L. 1976. The macroscopic zoobenthos of Parry Sound, Georgian Bay. M.Sc. Thesis. University of Waterloo, Waterloo.

HYNES, H. B. N. 1974. Further studies on the distribution of animals within the substratum. Limnol. Oceanogr. **19**: 92–99.

HYNES, H. B. N., D. D. WILLIAMS, and N. E. WILLIAMS. 1976. Distribution of the benthos within the substratum of a Welsh mountain stream. Oikos, **27**: 307–310.

KLOPFER, P. H. 1959. Environmental determinants of faunal diversity. Am. Nat. **93**: 337–342.

MACARTHUR, R. H., and R. W. MACARTHUR. 1961. On bird species diversity. Ecology, **42**: 594–598.

MCCAULEY, R. N. 1966. The biological effects of oil pollution in a river. Limnol. Oceanogr. **11**: 475–486.

PARKER, B. L., J. D. BRAMMER, M. E. WHALON, and W. O. BERRY. 1976. Chronic oil contamination and aquatic organisms with emphasis on Diptera: status and bibliography. Water Resour. Bull. **12**: 291–305.

PENNAK, R. W., and E. D. VAN GERPEN. 1947. Bottom fauna production and physical nature of the substrate in a northern Colorado trout stream. Ecology, **28**: 42–48.

ROEDER, D. R., G. H. CRUM, D. M. ROSENBERG, and N. B. SNOW. 1975. Effects of Norman Wells crude oil on periphyton in selected lakes and rivers in the Northwest Territories. Environ. Can., Fish. Mar. Serv. Res. Div. Tech. Rep. No. 552.

ROSENBERG, D. M., and A. P. WIENS. 1976. Community and species responses of Chironomidae (Diptera) to contamination of fresh waters by crude oil and petroleum products, with special reference to the Trail River, Northwest Territories. J. Fish. Res. Board. Can. **33**: 1955–1963.

SCOTT, D., and J. M. RUSHFORTH. 1959. Cover on river bottoms. Nature (London), **183**: 836–837.

SNOW, N. B., and D. M. ROSENBERG. 1975*a*. Experimental oil spills on Mackenzie Delta lakes. I. Effect of Norman Wells crude oil on Lake 4. Environ. Can., Fish. Mar. Serv., Res. Div. Tech. Rep. No. 548.

——— 1975*b*. Experimental oil spills on Mackenzie Delta lakes. II. Effect of two types of crude oil on Lake 4c and 8. Environ. Can., Mar. Serv., Res. Div. Tech. Rep. No. 549.

SNOW, N. B., D. M. ROSENBERG, and J. MOENING. 1975. The effects of Norman Wells crude oil on the zoobenthos of a northern Yukon stream one year after an experimental spill. Environ. Can., Fish. Mar. Serv., Res. Div. Tech. Rep. No. 550.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY. 1973. Boone Creek oil spill. United States Environmental Protection Agency, Surveillance and Analysis Division. Athens, GA.

WILHM, J. L. 1967. Comparison of some diversity indices applied to populations of macroinvertebrates in a stream receiving organic wastes. J. Water. Pollut. Control Fed. **39**: 1673–1683.

WILLIAMS, D. D., and H. B. N. HYNES. 1974. The occurrence of benthos deep in the substratum of a stream. Freshwater Biol. **4**: 233–256.