# ECOLOGICAL STUDIES OF AQUATIC ORGANISMS IN THE MACKENZIE AND PORCUPINE RIVER DRAINAGES IN RELATION TO SEDIMENTATION

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and

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# ABSTRACT

Rosenberg, D. M., and N. B. Snow. 1975. Ecological Studies of Aquatic Organisms in the Mackenzie and Porcupine River Drainages in Relation to Sedimentation. Fish. Mar. Serv. Res. Dev. Tech. Rep. 547: 86 pp.

A review of recent literature on the effects of increased sedimentation on aquatic biota is presented. Timber harvesting, forest fires, road construction and operation, and channelization of rivers and streams were identified as the major possible sources of unnatural increases in suspended and settled sediments in northern watersheds. Detrimental effects of increased suspended and settled sediments can result, singly or in combination, from a reduction in light penetration, mechanical abrasion, toxicants adsorbed to sediment particles, and changes in substrate. Specific detrimental effects, due to a variety of watershed disturbances, on flora and fauna are discussed. Recovery rates of flowing waters from increased sedimentation vary from a few days to not at all and depend, basically, on characteristics of the river or stream, the severity of sediment addition, and availability of undamaged areas as sources of recolonization. It would appear from the literature that unnatural increases in suspended sediment concentrations of most flowing waters should not result in a concentration >80 mg liter$^{-1}$ to ensure protection of aquatic life. A flowing-water habitat should always be able to carry away an increased sediment load to prevent permanent sedimentation of the substrate. Future research needs on the effects of unnatural increases of sediment on aquatic biota include a standardization of measurements and methods used, quantitation of terms such as "adverse", "detrimental", "deleterious", and "damage", and laboratory experimentation complementary to descriptive and experimental field data.

A natural retrogressive-thaw flow slide on Caribou Bar Creek, northern Yukon, added an estimated 2000-2600 metric tons of sediment to the Creek. Standing crop of benthic invertebrates was reduced immediately by 70% and qualitative changes in proportions of benthic-invertebrate taxa were evident. Recovery of benthic invertebrate populations occurred within a month. Although the mudslide was intermittently active during the following year, no apparent effect on the benthic invertebrate fauna resulted. The difficulties in using all but the most specialized forms of Chironomidae as indicators of unnatural increases in sedimentation are discussed.

Crossings of the Martin River by the Mackenzie Highway right-of-way slash, winter road, and temporary bridge resulted in no significant effects on benthic invertebrate and fish populations, and physical and chemical parameters of the water in the first year after construction activities began. The study is continuing. The Dempster Highway crossing of Campbell Creek, N.W.T. appeared to have prevented upstream migration by northern pike and broad whitefish in spring of 1973. From visual observations, the site has received increased sediment supply, likely from roadfill and erosion of adjacent disturbed terrain. However, physical and chemical parameters of the water showed no major differences

above and below the crossing and bottom substrates had only a slightly higher proportion of fine sediments at the downstream stations than those upstream of the crossing. Benthic invertebrate populations downstream of the crossing tended to be typical of areas disturbed by sedimentation. However, these data were not conclusive. This could have been due to differences in substrate above and below the crossing which made the area difficult to sample adequately. Also, the full effect of hydrologic complexity of the Campbell Creek watershed on benthic invertebrate populations is unknown.

Experimental as well as descriptive approaches to the study of the effects of suspended and settled sediments on aquatic biota are necessary. To this end, the drift responses of invertebrates in the Harris River, N.W.T. to additions of known amounts of bankside sediment were studied. River invertebrates were categorized into macrobenthos, zooplankton, and total (= macrobenthos + zooplankton) invertebrates in order to measure response to the added sediment. Macrobenthos showed a positive percent increase in drift at all intended concentrations of suspended sediment used (10-500 mg liter$^{-1}$) but zooplankton and total invertebrates did not. No relation existed between percent increase of macrobenthos drifting and suspended sediment concentration, total weight of sediment added, or theoretical weight of sediment added per unit area of stream bottom. Analyses of variance done for the macrobenthos showed a significant difference between numbers drifting during control and sediment addition periods and among sediment loads. No relationship could be found between sediment loads and numbers of macrobenthos drifting. Similar results were obtained from analysis of the percent increase data. Preliminary results have shown that individual taxa of macrobenthos showed different responses to sediment addition. Analyses of variance done for zooplankton and total invertebrates showed a significant difference in numbers drifting among sediment loads but no significant difference between numbers drifting during control and sediment addition periods or the interaction between sediment load and numbers drifting. Separation of the river invertebrates into three types revealed the sensitivity of the macrobenthos to increased sedimentation.

Maximum numbers of macrobenthos leaving per m$^2$ of experimental channel bottom as a result of sediment addition over a 15 min period in the Harris River ranged from 25.5 to 129.6. The minimum number per m$^2$ was 1.9 for a 15 min sediment addition period. The maximum percent of the resident macrobenthos population caused to drift by sediment addition was estimated to be 2.6 while the minimum was estimated to be 0.04%. Based on a number of assumptions, depletion of 50% of the standing crop of macrobenthos would occur in 7 hours at the maximum rate of exit and 18 days at the minimum. A model illustrating drift dynamics for an undisturbed section of river and one affected by sediment addition is presented.

# RÉSUMÉ

Rosenberg, D. M., and N. B. Snow. 1975. Ecological Studies of Aquatic Organisms in the Mackenzie and Porcupine River Drainages in Relation to Sedimentation. Fish. Mar. Serv. Res. Dev. Tech. Rep. 547: 86 pp.

On fait ici la revue des récentes publications sur les effets que produit sur la biote aquatique l'accroissement de la sédimentation. On a relevé comme principales causes de l'augmentation artificielle des sédiments en suspension et en dépôt dans les bassins hydrographiques du nord, les coupes de bois et les incendies de forêt, la construction et l'utilisation des routes et la canalisation des cours d'eau. Les effets dommageables de l'accroissement des sédiments en suspension et en dépôt proviennent de l'action, simple ou conjuguée, du troppeu de lumière, de l'usure mécanique, d'agents toxiques absorbés par les particules de sédimentation et de la modification des substrats. On discute des effets caractéristiques mauvais que produisent sur la flore et la faune divers bouleversements de bassin. La rapidité avec laquelle les cours d'eau récupèrent de cet excès de sédimentation varie entre quelques jours et aucun, et elle est surtout fonction des caractères des cours d'eau, de l'importance des sédiments qui s'y ajoutent et de la présence de bassins non encore altérés pouvant servir à une nouvelle colonisation. Il découle de la lecture des publications que l'accroissement artificiel des concentrations de sédiments en suspension dans la majorité des cours d'eau ne devrait pas dépasser >80 mg litre$^{-1}$ si l'on veut assurer la protection de la vie aquatique. Dans un cours d'eau, le courant devrait toujours être capable de charrier l'excès des sédiments pour empêcher que les substrats ne se couvrent d'une sédimentation permanente. On souhaite pour l'avenir que les recherches sur les effets que produit sur la biote aquatique l'augmentation de sédiments portent sur la normalisation des mesures et des méthodes employées, sur l'appréciation quantitative de ce qu'on entend par les termes "défavorable", "dommageable", "délétère", et "dommage", et sur les expériences faites en laboratoire pour compléter les données descriptives et expérimentales recueillies sur le terrain.

Dans le ruisseau Caribou Bar situé dans le nord du Territore du Yukon, un éboulement naturel dû à un dégel et à une crue tardifs a déversé entre 2,000 et 2,600 tonnes métriques de sédiments. On constata que le peuplement stable d'invertébrés benthiques avait immédiatement diminué de 70% et que des changements qualitatifs étaient survenus dans les rapports entre espèces d'invertébrés benthiques. Les peuplements benthiques récupérèrent en moins d'un mois. Quoique le glissement de boue se répétât par intermittence au cours de l'anneé suivante, on constata que celle-ci n'avait eu aucune conséquence sur la faune des invertébrés benthiques. On discute des difficultés qui surgissent lorsqu'on se sert uniquement des formes hautement spécialisées de chironomidés comme indicateurs de l'augmentation artificielle des sédiments.

Le fait qu'on ait enjambé la rivière Martin en construisant une bande

de passage pour l'autoroute Mackenzie, un chemin d'hiver et un pont temporaire n'a eu, au cours de l'année qui suivit le début des travaux, aucun effet appréciable sur le peuplement des invertébrés benthiques, sur celui des poissons, ainsi que sur les paramètres physiques et chimiques de l'eau. Les études à cet égard se poursuivent. Au printemps 1973, dans les Territoires du Nord-Ouest, il semble que la construction d'un pont de l'autoroute Dempster sur le ruisseau Campbell ait empêché le grand brochet et le grand corégone de faire leur migration. On a pu établir par de simples observations visuelles que l'emplacement avait reçu une augmentation de sédiments provenant vraisemblablement des graviers du chemin et de l'érosion des terrains adjacents qu'on avait remués. Toutefois, les paramètres physiques et chimiques de l'eau ne révélèrent à l'examen aucune différence appréciable entre les eaux en amont et les eaux en aval de l'endroit traversé; les substrats du fond analysés par les stations situées en aval contenaient une concentration de sédiments fins légèrement plus élevée que celle contenue dans les substrats analysés aux stations en amont. On a noté que les peuplements des invertébrés benthiques trouvés en aval tendaient à ressembler au type que l'on retrouve dans les milieux altérés par la sédimentation. Toutefois, les données recueillies ne sont pas probantes. Cela était peut-être dû à la nature différente des substrats en aval et an amont, ce qui rendait l'échantillonnage difficile. De plus, on ignore toute la portée de l'action qu'exerce la complexité hydrologique du bassin du bassin du ruisseau Campbell sur les peuplements.

Nous devons de toute nécessité étudier selon des méthodes expérimentales aussi bien que descriptives les effets que produisent les sédiments en suspension et en dépôt sur la biote aquatique. À cette fin, on a étudié ce qui est arrivé au mouvement des invertébrés dans la rivière Harris (T.-N.-O.) lorsqu'on y a déversé des quantités données de sédiments provenant de la berge. Aux fins de l'expérience, on a divisé les invertébrés de la rivière en trois groupes: le groupe macrobenthos, le groupe zooplancton et le groupe des invertébrés qui représente la somme des deux premiers groupes. On a que le macrobenthos, à tous les degrés de concentration de sédiments en suspension (10-500 mg litre$^{-1}$), a accusé une certaine augmentation de déplacement appréciable en pourcentage; par ailleurs, le groupe zooplancton et le groupe des invertébrés n'ont laissé voir aucun changement. Dans le cas du macrobenthos, on n'a pu établir aucun rapport entre l'accroissement du déplacement et le degré de concentration de sédiments en suspension, qu'il s'agisse du poids total des sédiments ajoutés on qu'il s'agisse du poids théorique des sédiments ajoutés par unité de superficie du lit de la rivière. Les analyses de variance faites pour le macrobenthos ont révélé une différence marquée entre les quantités d'invertébrés se déplaçant au cours des périodes de contrôle et d'addition de sédiments, et les charges de sédiments habituelles. On n'a pu trouver aucune relation entre les charges de sédiments habituelles et les quantités de macrobenthos en déplacement. On a obtenu des résultats analogues en analysant les données d'augmentation en pourcentage. Des résultats préliminaires ont révélé que certains représentants du groupe macrobenthos ont réagis différemment à l'addition de sédiments. Les analyses de variance faites pour le groupe zooplancton et le groupe des invertébrés ont permis de relever une différence marquée dans les quantités qui se déplaçaient parmi les charges de sédiments habituelles, mais aucune différence appréciable entre les quantités en déplacement au cours des périodes de contrôle et d'addition de sédiments, ni aucun rapport entre les charges de sédiments habituelles et les quantités en déplacement. En divisant les invertébrés de la rivière en trois groupes, on a pu constater que le macrobenthos est sensible à un accroissement de sédimentation.

Le nombre maximal de macrobenthos qui ont été déplacés sur le fond du chenal expérimental de la rivière Harris pendant la période de 15 minutes où l'on a ajouté des sédiments a varié entre 25.5 et 129.6 par $m^2$. Le nombre minimal a été de 1.9 par $m^2$ pour une même période de 15 minutes. On a estimé que le pourcentage du groupe macrobenthos stable forcé de se déplacer par l'addition de sédiments n'a pas été supérieur à 2.6 ni inférieur à 0.04. En se fondant sur un certain nombre d'hypothèses, on a pu déterminer qu'on pourrait évacuer en 7 heures 50% du groupe macrobenthos actuel au taux maximal d'évacuation, et en 18 jours au taux minimal. On présente un tableau illustrant la dynamique du déplacement appliquée à un tronçon de rivière qui n'a pas été troublé, et à un autre tronçon où l'on a ajouté des sédiments.

# I. REVIEW OF CURRENT LITERATURE ON THE EFFECTS OF INCREASED SEDIMENTATION ON AQUATIC BIOTA

## A. Introduction*

A number of noteworthy papers have appeared since the review by Brunskill *et al.* (1973). Those dealing with patterns of erosion, the dynamics of sedimentation and sediment transport, and the effects of the presence of sediment on physical factors of natural waters along the route of the proposed pipeline and elsewhere have been discussed above (see Brunskill *et al.*, 1975).

## B. Sources of unnatural increases in suspended and settled sediments in northern watersheds

Soil loss by sheet erosion from agricultural lands, the greatest source of man-caused suspended sediment in southern areas, is not a major problem in the north. However, timber harvesting is done in the north and can result in increases in suspended sediments in northern watersheds. Rice, Rothacher, and Megahan (1972) have concluded that most of man's activities in forested watersheds will cause an increase in erosion. In their appraisal of the erosional consequences of timber harvesting, Rice *et al.* (1972) and Megahan (1972) pointed out that the road systems built in connection with timber harvesting have a far greater effect than logging or fire as a cause of accelerated erosion.

In fact, road construction can be a major source of unnatural additions of sediment to waterways. Sedimentation is the most severe of the nine pollutional effects attributed to highways by Scheidt (1971). Caused by erosion of soil exposed during construction, a substantial amount of sediment reaches stream and river channels where it covers the beds, fills navigation channels and reservoirs, and adversely affects aquatic biota. Studies in Maryland have shown that rural areas which normally contributed 518 metric tons of sediment $km^{-2}yr^{-1}$ contributed 2616 to 313,390 metric tons $km^{-2}yr^{-1}$ (Scheidt, 1971) when under urban development. The construction of divided lane highways which require exposure of 6.5 to 22.7 ha $km^{-1}$ of highway during construction can produce 4830 tons of sediment $km^{-1}$ (Scheidt, 1971).

Adam's (1973) timely review of winter roads was done from an engineering point of view and, unfortunately does not devote much space or detail to the effect of winter roads on freshwater biota although other environmental considerations (mainly terrestrial) composed a large part of the review. Adam concluded that ice bridges could be an environmental problem if approaches were not well-constructed and maintained (mud flows and sedimentation could result from permafrost regression and thermal erosion); if the use of corduroy and sawdust in the construction of ice bridges and blasting for their removal is not eliminated; and if, in the case of shallow streams, care is not taken to prevent freezing to the bottom

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* The third in a series of 13 technical reports on ecological studies of aquatic systems in the Mackenzie and Porcupine drainages in relation to proposed pipeline and highway developments.

thus disturbing resident and/or migrating fish populations. He recommended the immediate study of efficient methods for the removal of ice bridges and snow road switch-backs at river crossings: ones which would prevent damage to the banks or bed and not interfere with water flow. Adam cited no actual data on the effects of winter roads on freshwater biota. Neither have we ever seen any in the literature. However, the possibility of indirect environmental effects such as oil and gas spills is identified in Adam as well as Scheidt (1971). Of interest is the transcript of sometimes conflicting opinions in interviews held with representatives of industry, university, and government regarding installation, removal, and inspection of winter stream and river crossings which appears in Adam (1973).

Although channelization of streams and rivers is used in some highway construction, it is more commonly undertaken for agricultural purposes, flood control, navigation, and hydroelectric development. It can result in unnatural increases in suspended sediment that can detrimentally affect the flora and fauna of freshwater ecosystems. In the "News and Comment" section of the magazine "Science", Gillette (1972) gave examples of the extreme effects of channelization. A survey of at least six states in the U.S.A. showed reductions of local populations of fish, plant life, and ducks by 80 to 99%. The now famous Crow Creek case of channelization was used by Gillette as an example of the creation of a biological waste-land probably incapable of recovery. Pro-channelization groups in the U.S.A. feel that streams recover from channelization quickly. This view was supported by a consulting group hired by the Council for Environmental Quality to investigate the economic and environmental costs and benefits of stream channelization. However, most evidence would point to a less than rapid recovery in many situations and no recovery in sight for cases like Crow Creek.

C. Mode of action of suspended and settled sediments

The mode of action of unnaturally increased quantities of suspended and settled sediments in the flora and fauna of freshwaters takes several different forms. Oschwald (1972) has reviewed the subject.

1. Reduction of light penetration: This may restrict or eliminate photosynthesis. Sediments on leaf surfaces are likely to interfere with photosynthesis. All food chain levels would therefore be affected.

It is likely that a reduction in dissolved oxygen concentration is not directly due to reduction of photosynthesis but rather to the introduction (and subsequent decomposition) of organic matter with the suspended sediment (Ritchie, 1972).

Naturally occurring photochemical reactions (e.g. the photo-decomposition of toxic substances such as chlorinated hydrocarbon insecticides) may be delayed by the effect of suspended sediment on light transmission, enabling these substances to persist (Grissinger and McDowell, in Oschwald, 1972).

2. <u>Abrasion:</u> Sometimes the abrasive effects of suspended sediments can be combatted by physiological adaptations (e.g. mucous secretions by fish) or behavioural ones (e.g. reduced filtration rates in mussels) (Oschwald, 1972). However, sessile organisms can be adversely affected. For example, filter feeders can suffer gill clogging, impairment of proper respiratory and excretory functioning, and impairment of feeding activity (Cairns, in Sherk, 1971). From data reported in Sherk (1971), it would appear that suspended sediment concentrations of 0.1 g liter$^{-1}$ can reduce pumping rates of adult oysters more than 50%. Toxic substances adsorbed to the sediment particles can stimulate pumping activity or growth at suspended sediment concentrations of 0.1 g liter$^{-1}$ (Loosanoff, in Sherk, 1971). However, other species of marine bivalves do not show such sensitivity to suspended sediment (Sherk, 1971). Additionally, retention of a substance by filter feeders is dependent on the size of the particles and on the species of filter feeder (Sherk, 1971).

Fish that are found in highly turbid waters generally show structurally altered gills (Alabaster, 1972; Hynes, 1973). Fish that died as a result of exposure to >100,000 mg liter$^{-1}$ montmorillonite for 7 days or more showed silt-clogged gill cavities (Wallen, in Oschwald, 1972). Cause of death therefore could have been abrasion and suffocation. Paul (in Ritchie, 1972) recorded mechanical abrasion of fish due to suspended sediment. The fish become more susceptible to microorganism infections as a result. Nuttall (1972) associated a low incidence of plants and macroinvertebrates in the River Camel with the instability of sand sediments rather than turbidity or abrasion caused by particles in suspension. Nuttall and Bielby (1973) attributed the effects of china-clay wastes on plants and macroinvertebrates in the British rivers of their study to the deposition of fine particles rather than turbidity and abrasion caused by suspended particles.

3. <u>Adsorbed toxicants:</u> Sediment particles may adsorb or release nutrients (e.g. see Golterman, 1973a), pesticides (e.g. see Morris and Johnson, 1971), heavy metals (e.g. see Alabaster, 1972; Golterman, 1973b), and radionuclides (e.g. see Hubbard and Striffler, 1973; McHenry, Ritchie, and Gill, 1973). Alabaster (1972) reported that about 50% of the total concentration of heavy metals (including copper, zinc, nickel, cadmium, and chromium) may be adsorbed on suspended sediments in the River Trent in Great Britain. Golterman (1973b) reported that the Rhine transported the following amounts of heavy metals, "probably mostly adsorbed on the silt": Hg, 85; Pb, 1500; As, 1000; Cu, 2900; Cd, 200; and Zn, 9000 tons yr$^{-1}$. Morris and Johnson (1971) noted a correlation between turbidity and pesticide levels in streams. They claimed that chlorinated hydrocarbon pesticides reached Iowa streams in solution and adsorbed on eroded soil particles from treated farmlands. In their study, approximately half of the chlorinated hydrocarbon pesticide load was carried by suspended sediments which gradually settled to the bottom (especially if the stream was impounded) and stayed there for long periods of time. Feltz and Culbertson (1972) reported that concentrations of DDT and its metabolites were sometimes

directly correlated with suspended sediment concentrations in studies of pesticide runoff in central Pennsylvania. Furthermore, pesticide residues associated with sediments depended on both particle size distribution and organic matter content of the sediment. Therefore, pesticide concentrations could vary with variability of suspended sediment concentration and composition in a stream cross-section.

Pollutants (heavy metals, pesticides, radionuclides) sorbed on sediment may be ingested, adsorbed, and concentrated by aquatic organisms (Oschwald, 1972). Durant and Reimold (1972), who anticipated a kill of fish and shellfish from the dredging of toxaphene-contaminated sediments presented reasons why the kill did not occur. One of the reasons given was that the toxaphene was bound to clay particles and was not available to the aquatic biota. However, Morris and Johnson (1971) found that bottom feeding fish exposed to sediments coated with dieldrin (see above) accumulated larger amounts of dieldrin than species which had feeding habits less directly dependent on bottom sediments. Gannon and Beeton (1971) described laboratory methods for the evaluation of the possible consequences of open lake disposal of polluted, harbor sediment dredgings. The authors found that sediments dredged from Rouge River, Cleveland, Buffalo, Calumet, and Indiana harbors resulted in the highest mortalities of the benthic amphipod, *Pontoporeia affinis*, and therefore should not be dumped into the open waters of the Great Lakes.

Short- and long-term effects of sorption characteristics in sediment-water interactions are important. The concentration of a pollutant in water may be decreased by sorption mechanisms over the short term but the long-term effect may be deposition and retention of pollutants by sediments, and consequential ingestion and assimilation by aquatic organisms. Equally possible are movements of contaminated sediments to other areas, or burial by subsequent deposits before they can affect flora and fauna (Oschwald, 1972).

4. Changes in substrate: Flora and fauna can be adversely affected by shifting, unstable substrates or by gross changes in the particle size distribution of the substrate. For example, Lewis (1973) postulated that two factors would retard the colonization of coal-polluted streams by the aquatic moss, *Eurhynchium riparioides*: 1. formation of an unstable substrate due to the settling out of larger particles of coal dust; and 2. the reduction of light penetration by the coal particles. Instability of sand deposits as the cause of a low abundance of flora and fauna (Nuttall, 1972) has been discussed above. Accumulation of fine sediment on the bottom of a stream in Oregon was likely the cause of a change in algal flora reported by Hansmann and Phinney (1973).

Nuttall and Bielby (1973) and Hynes (1973) pointed out that most stream macroinvertebrates live in interstices between stones in gravel substrates, or attach themselves to the surfaces of these stones. An increase in fine sediment occupies the interstices and coats attachment sites, thus rendering the habitat unusable to many animals. Filling of these interstices also eliminates storage areas for organic matter on which many stream invertebrates are dependent for food. Those invertebrates that filter food from the water (e.g. filter feeders such as blackflies; net spinners such as hydropsychid caddis larvae) and the flatworm *Polycelis felina* (which traps prey on mucous strings) usually cannot maintain themselves in areas of increased sedimentation.

5. Integration of the effects of increased sediment supply to watersheds: The mode of action of suspended and settled sediments can be due to one or a combination of the effects described above. For example, changes in the fish fauna of sediment-polluted rivers can occur in a number of ways (Alabaster, 1972):

a) through the direct effect of the particles on survival, growth, resistance to poisoning, disease of the eggs, larvae, and/or fish themselves; and by affecting fish feeding behaviour (the visibility of food [Oschwald, 1972; Hynes, 1973]), natural movements, and migrations.

b) by indirect effects such as reduction of food supply from reduced productivity of plants due to the attenuation of light and substrate instability; and from detrimental effects on fish food organisms.

Ritchie (1972) concluded that the ecological effects of sediment on aquatic ecosystems is probably greater than the direct physiological effect on fish, but that the combined ecological and physiological stresses could cause qualitative and quantitative changes in fish populations thereby altering the original state of the aquatic ecosystem.

D. Effects on flora and fauna

1. Reviews: Hynes (1973) has reviewed our knowledge of the effects of turbidity and sedimentation by inert solids on plants, benthic invertebrates, and fishes and their eggs. Alabaster's (1972) review dwelt on field and laboratory studies of the effect of suspended solids (china-clay wastes), other chemically inert material, and wood fibre on fish (and to a certain extent benthic invertebrates). Ritchie (1972) reviewed the older literature pertaining to the effects of sediment on fish and fish habitat. He summarized sediment and/or turbidity effects on aquatic ecosystems in general, and, in particular, discussed effects on fish populations.

2. Flora: Samsel (1973) reported a decrease in numbers of genera of algae (from 24 to 16) in a small recreational impoundment suffering from sedimentation. Seven of the 24 genera were found in the areas of our studies in the Mackenzie and Porcupine River drainages (Brunskill *et al.*, 1973; Vol. II, App. V). Productivity decreased by 50% and dissolved nutrients such as $NH_4$, $SiO_2$, and $PO_4$ increased. Hansmann and Phinney (1973) reported a change in algal flora immediately following a yarding operation on a stream in a clearcut watershed in Oregon. The predominantly peri-

phyton-type community (mostly diatoms) changed to green algae. *Sphaerotilus natans* and large mats of green algae colonized the mud and the forest debris in the stream. Two-thirds of the diatoms still present in the stream appeared to be dead. Neither the filamentous mats nor the forest debris and mud accumulations were observed in the patch-cut or control streams in the study. Two of the species of diatoms identified as dominants by Hansmann and Phinney (1973) (*Achnanthes minutissima* and *Cocconeis placentula*) are also found in the areas of our studies. Lewis (1973) described the effect of suspended coal particles on the life-forms of the hardy aquatic moss *Eurhynchium riparioides*. In field studies, she observed that the gametophyte plant could survive in concentrations of coal dust as high as 5000 mg $liter^{-1}$ but that the growth form and distribution were restricted in areas of high concentration. The results of laboratory experiments showed that germination of spores was lowest (42%) at the highest concentration of coal dust used (5000 mg $liter^{-1}$) but increased with decreasing coal dust concentration. Rhizoidal growth occurred at every concentration used (5000, 2000, 1000, 500, 100 mg $liter^{-1}$ and a control with no coal dust) including the highest concentration but the development of new side shoots only occurred below 500 mg $liter^{-1}$.

3. Fauna (macroinvertebrates and fish): Rose (1973) reported a 57% mortality of oysters (*Crassostrea virginica*) in the vicinity of a dredging operation compared to 17% in other parts of the lease. He estimated that mortality due to the increased sedimentation alone (i.e. disregarding other mortality-inducing factors) was 48% and concluded that damage to oyster populations in the vicinity of dredging operations was dependent on factors such as sediment size, presence or absence of toxic materials (see Gannon and Beeton, 1971; Durant and Reimold, 1972), hydrographic conditions, time of year, and size and clutch type of oyster. Nuttall and Bielby (1973) have reviewed the effects of china-clay wastes on benthic invertebrates in rivers in Great Britain and described the findings of their own study. They reported the absence of rooted aquatic vegetation in high sediment supply areas; 36 times the density of macroinvertebrates in control areas than in areas of greatly increased sedimentation; and double the number of macroinvertebrates in control areas than in stations receiving reduced levels of china-clay. The abundance and number of species of macroinvertebrates was low in clay-enriched sediments. Several species had been eliminated or reduced in abundance by china-clay additions to the ecosystem. A statistically significant increase occurred in the abundance of *Baetis rhodani*, *Perlodes microcephala*, Tubificidae, Naididae, and Chironomidae in clay-polluted areas. Absence of or a statistically significant reduction in *Hydrobia jenkinsi*, *Dicranota* sp., Simuliidae, *Sericostoma personatum*, Limnephilidae, *Hydropsyche instabilis*, *Ephemerella ignita*, *Rhithrogena semicolorata*, *Leuctra fusca*, and *Polycelis felina* was found at stations receiving china-clay wastes. Representatives of many of these genera and higher taxa occur in the areas of our studies (Brunskill *et al.*, 1973; Vol. II, App. V).

Peters (1972) found that longnose and white sucker populations declined substantially in a part of a Colorado stream treated to reduce additions of sediment from agricultural land. Mountain sucker, flathead chub, and longnose dace populations were also reduced but not as much as the previous two species. Brown trout populations were thought to have increased but results were inconclusive. No changes in growth occurred in brown trout as a result of the sediment control measures but adult longnose suckers increased in length. White and mountain suckers, and flathead chub decreased in plumpness. This could have resulted from a reduced ability of these species to compete for food because of the lowered suspended sediment concentrations. It is important to note that all of the species of fish discussed in Peters (1972) are found in the Mackenzie Valley and/or the northern Yukon (see McPhail and Lindsey, 1970; Bryan, 1973; Stein *et al.*, 1973).

However, most other sediment-related changes are adverse to fish in fresh waters. Etnier (1972) reported the effects on fish and benthic invertebrates of the annual rechannelling of Middle Creek, Tennessee for flood control. Unfortunately, none of the species of fish discussed occur in the areas of our studies; however, several of the genera do. *Hypentelium* populations remained stable but could have represented upstream migrants from another river. The presence of five other fish species also may have been due to upstream migration. *Etheostoma kennicotti*, a darter, was rare but specimens were taken before and after rechannelling. *E. blennioides* and *Cottus carolinae* were present, although in low numbers, in swift deep riffles of the study area before rechannelling but not after. *Compostoma anomalum*, always abundant, and *Notropis stramineus* formerly rare, increased in dominance after rechannelling. *Etheostoma stigmaeum jessiae*, a darter of limited geographic distribution, quickly disappeared from the stream after rechannelling. *E. simoterum*, the most abundant darter in the area continued to persist in the altered stream although its numbers were drastically reduced. Etnier felt that substrate instability and decreased variability of physical habitat were the most significant factors involved in the change in fish fauna. Chironomidae and Oligochaeta continued to be abundant in the study area but Ephemeroptera, Trichoptera, and Plecoptera abundance and diversity was reduced after rechannelling. The decrease in hydropsychid caddis larvae probably had a significant effect on the decreased stability of the substrate in riffle areas. The decrease in diversity of benthic invertebrates probably contributed to the changes in fish fauna as well. Hansen (1971) reported the following differences between channelized and unchannelized portions of the Little Sioux River, Iowa:

a) greater daily fluctuations in water temperature in summer in the channelized section;

b) higher turbidities in the channelized section;

c) Although composition of bottom fauna was similar in the two sections, more macroinvertebrates colonized artificial substrates in the channelized section suggesting a lack of suitable attachment sites there;

d) higher numbers of macroinvertebrates drifting in the channelized section which supported conclusion (c);

e) more fish species in the unchannelized section;

f) more large channel catfish in the unchannelized section and greater numbers of smaller channel catfish in the channelized section during late summer and fall; and

g) no drastic differences in standing crops of fish between the two areas because of possible downstream movement from the unchannelized to the channelized section.

Alabaster (1972) cited the study of the Rivers Fal and Par in Great Britain which carried 1000 and 5000 mg liter$^{-1}$ of china-clay respectively. Control streams in the neighborhood, free of china-clay, and the River Camel containing 60 mg liter$^{-1}$ of suspended sediments had normal brown trout populations, while the two clay-enriched rivers did not. Contributing to the reduction of trout populations was a reduction in bottom invertebrate fish food fauna in both rivers. The few fish found were feeding mainly on drift and were suspected of being immigrants from clearer tributaries. Likely spawning beds were covered with sediment and were avoided. Buck (in Oschwald, 1972), found lower production of largemouth bass (*Micropterus salmoides*), bluegills, (*Lepomis macrochirus*), and redear sunfish (*Lepomis microlophus*) in turbid ponds (>100 mg liter$^{-1}$) than intermediate (25-100 mg liter$^{-1}$) and clear (<25 mg liter$^{-1}$) ponds. The latter had high production of fish (180.9 kg ha$^{-1}$ at the end of the second growing season as compared to 105.3 and 32.8 kg ha$^{-1}$ for the intermediate and muddy ponds respectively). The occurrence of largemouth bass and redear sunfish was much lower in the muddy ponds than in clear ponds. Spawning of largemouth bass was severely reduced by suspended sediment concentrations greater than 100 mg liter$^{-1}$. Spawning bluegills and largemouth bass avoided ponds receiving large amounts of highly turbid water (Swingle, in Oschwald, 1972).

Survival of rainbow trout (*Salmo gairdneri*) kept in the laboratory for several months in 810 and 270 mg liter$^{-1}$ of suspended china-clay was reduced by more than 50%. Little effect on mortality occurred at 90 mg liter$^{-1}$ and none at 30 mg liter$^{-1}$. The time of mortality varied from weeks to months (Herbert and Merkens, in Alabaster, 1972 and in Ritchie, 1972). Therefore, sustained china-clay concentrations that might be regarded as safe would be between 60 and 220 mg liter$^{-1}$ (Alabaster, 1972). Data for survival of various species of fish in concentrations of types of suspended solids other than china-clay are similar (Alabaster, 1972). Because Alabaster only gave common names for these fish it is difficult to tell whether or not they are species present in the areas of our studies. None of the five species of fish discussed previously (*S. gairdneri, S. trutta, L. macrochirus, L. microlophus*, and *M. salmoides*) occur in the Mackenzie Valley and Northern Yukon so the above discussion has rather limited direct use for the areas of our studies.

4. <u>Recovery</u>: Recovery rates of stream ecosystems from increased

sedimentation due to human activity (e.g. quarrying, mining, dredging, logging, road construction, removal of sand and gravel from streams) varies considerably. Gammon (1970) reported that zoobenthos populations required only a few days to decrease significantly or return to normal when subjected to intermittent additions of sediment from a rock quarry located on a small stream in Indiana. He reported that the response of fish was more complex and depended on the season and the species involved. However, he concluded that recovery to normal in the affected area of stream would not be achieved under the observed conditions. We will present data below to show that the effects of sedimentation on zoobenthos in some of the watersheds of our studies were relatively short-lived. Hynes (1973) cited several studies which reported recovery of stream ecosystems after a few years from logging, placer mining, and road construction that caused increased sedimentation. Irreversible damage has been claimed for Crow Creek on the Alabama-Tennessee state line by Gillette (1972) although he presented no data to substantiate his claim.

Recovery rate mainly depends on the physical, chemical, and biological characteristics of the receiving stream (including water velocity, discharge, and seasonal variation of the waterway); the severity, duration, and timing of the sediment addition; and the availability of undamaged areas to serve as sources of recolonizing organisms (Cairns *et al.* 1971). There is a general feeling in the literature that drift from undamaged upstream areas is the most important source of recolonizing benthos (e.g. see Cairns *et al.* 1971; Hynes, 1973). Insufficient attention has been paid to the hyporheic habitat in the immediate vicinity of a sediment disturbance. This habitat has been shown to harbor larger populations of zoobenthos than the surface substrates (e.g. see Coleman and Hynes, 1970; Bishop, 1973) and could act as a reservoir for re-populating zoobenthos.

E. Concentrations of suspended sediments in freshwaters adequate for the protection of aquatic life

Alabaster (1972) reported that the critical concentration of chemically inert suspended sediments for the presence or absence of fish in rivers in the U.K. appeared to be around 100 mg liter$^{-1}$, which agreed well with other field and laboratory studies. The European Inland Fisheries Advisory Commission's (E.I.F.A.C.) water quality criteria are: 1. in the absence of other pollution, less than 25 mg liter$^{-1}$ suspended solids should be no harm to fisheries; 2. 25 to 80 mg liter$^{-1}$ would allow good or moderate fisheries; 3. at 80-400 mg liter$^{-1}$ good fisheries would not likely be found; and 4. only poor fisheries, at best, would exist over 400 mg liter$^{-1}$ (Alabaster, 1972). Applicability of these criteria to Arctic and subarctic aquatic ecosystems needs study. The former U.S. Water Pollution Control Federation recommended that turbidity due to sediment discharges should not exceed 50 and 10 JTU in warm- and cold-water streams respectively, and 25 and 10 JTU in warm- and cold-water or oligotrophic lakes respectively (U.S.W.P.C.F., 1968). (Unfortunately, these values were not expressed in mg liter$^{-1}$, a more useful measure than JTU). Hynes (1973) concluded:

"Concentrations of inert silt, sand or clay that do not often exceed

> 80 mg/l are unlikely *seriously* to damage a fishery, although they may reduce growth rates and abundance. If the load is such as to result in any permanent siltation of the substratum the habitat will be damaged. The stream should therefore be able at all times to carry away the load imposed upon it."

F. Research needs

Sherk (1971) has presented the most comprehensive list of research needs of any author. He pointed out that the determination of threshold levels or limiting conditions of suspended sediments to benthos is difficult because of the differing sensitivities of life stages, not only to suspended sediment, but to other physical and chemical aspects of their environment (e.g. temperature, oxygen concentration, etc.) as well.

The "...lack of quantitative expression on permissible limits [of suspended sediments] merely reflects large gaps in knowledge, especially with respect to natural conditions which are to be modified, in the literature from which the recommendation drew its information. On the one hand, there has been a notable lack of research effort on this problem most probably due to the difficulty in maintaining experimental sediment levels....and to the difficulty in maintaining laboratory stocks of experimental organisms and at least some of their life stages. On the other hand, the data that do exist on suspended load and turbidity effects on estuarine organisms from various studies (both field and laboratory) are difficult to compare because they have measured different aspects of particles in suspension which may reflect a lack of understanding of the sedimentation problem" (Sherk, 1971, p. 47).

Of the research needs identified by Sherk, the following are the most important:

1. comparability of measurements and methods. Responses of organisms may not be due to measured turbidity or suspended sediment concentrations (expressed as tons day$^{-1}$, mg liter$^{-1}$, JTU, extinction values, etc.) but rather to the number of particles in suspension, their shapes, sizes, and densities, the presence of organic matter, and the sorptive properties of the particles. These characteristics should be known along with concentration to make comparisons of field data easier, for more accurate reproduction of field values in the laboratory, and for accurate assessment of particle characteristics most important to evoking a certain biological response.

2. quantitation of the terms "adverse, detrimental, and deleterious effects", and "damage" as related to what they imply: changes in growth, survival, reproduction, and ultimately energy flow. In other words, basic quantitative information is required, first on basic relationships of organisms to their environment and then on how these relationships are affected by environmental changes.

3. laboratory experimentation complementary to descriptive and experimental field data. The difficulty of maintaining adequate controls in the field and the normally high variance inherent in field data make

it imperative that complementary laboratory data be collected. Appropriate laboratory experimental results can be combined with other data generated for a system under stress to determine the real effects that are produced. The degree of predictability of the effects of sedimentation should then increase.

Ultimately the result of the data generated by careful field observation, field experimentation, and laboratory experimentation should assist in 1. defining the ranges of tolerance of environmental change for any one species (for a variety of life functions); 2. predicting what effects environmental changes will have to guide pre-project planning; and 3. adequately managing freshwater systems.

## II. THE EFFECTS OF A MUDSLIDE AND TWO HIGHWAY CROSSINGS ON THE AQUATIC ORGANISMS OF FLOWING WATERS IN THE MACKENZIE AND PORCUPINE RIVER DRAINAGES

### A. Introduction

We are investigating the effects of increases in suspended and deposited sediments on northern freshwater biota and have studied the following aspects of this problem:

1. distribution, abundance, and diversity of aquatic invertebrates in relation to various natural concentrations of and catastrophic (natural) increases in sediment;

2. effects of man-made disturbances resulting in increased supplies of sediments to rivers and streams (i.e. the effects of highway crossings on river and stream biota); and

3. the response of selected components of benthic communities to experimental additions of sediment.

The study of natural occurrences of benthic organisms has provided much needed data on the responses of benthic invertebrates to different concentrations and rates of transport of sediment. Natural landslides into clear streams enabled us to measure the response and recovery time of aquatic communities to this type of disturbance. Studying streams and rivers crossed by the Mackenzie and Dempster Highways (Martin River near Ft. Simpson and Campbell Creek near Inuvik, respectively) provided information on the aquatic ecological effects of actual man-induced sedimentation on the aquatic biota. Experimental sediment addition studies have given a measure of control not possible in the previous two observational approaches. The results of the experimental studies are valuable as a quantified response of northern stream invertebrates to additions of known amounts of sediment. The results of our observational studies are reported in this section; those of the experimental studies are treated in Section III. Observational and experimental approaches together with information from the literature will be helpful in setting tolerance levels for increases in sedimentation caused by man's activities in the north.

### B. Natural occurrences of macrobenthic organisms in relation to increased sedimentation

1. Previous results: Our results to date, as reported in Brunskill *et al.* (1973) can be summarized as follows:

a) In general, clear waters (<20 mg of suspended sediment liter$^{-1}$) had higher standing crops of benthic invertebrates than turbid waters

(100-2000 mg of suspended sediment liter$^{-1}$).

b) Headwaters of streams carrying low concentrations of suspended sediment suffered greater reductions of benthic invertebrate standing crops when subjected to increased sediment loads than did more turbid downstream regions of the stream.

c) Mackenzie Delta lakes which were clear (<5 mg suspended sediment liter$^{-1}$ ) had 41-98 times the standing crop and five times the number of taxa of benthic invertebrates than did turbid lakes. Standing crop of zoobenthos was reduced as much as 50% when clear lakes were flooded with sediment-laden Mackenzie River waters in spring.

d) A series of regression-equations were obtained by plotting benthic invertebrate standing crop data from
(i) rivers in the northern Yukon
(ii) the Mackenzie River and its tributaries
(iii) Mackenzie Delta lakes
against Secchi depth or suspended sediment concentration. The data from the Mackenzie River tributaries and the Delta lakes, when plotted arithmetically, indicated a great decrease in zoobenthos standing crop above 10-15 mg suspended sediment liter$^{-1}$.

e) A natural mudslide (more specifically, a retrogressive-thaw flow slide, according to Hughes *et al.* [1973] or a bi-modal flow landslide, according to McRoberts & Morgenstern [1973]) occurred on Caribou Bar Creek (tributary to the Porcupine River, northern Y.T.) in mid-August 1972. This addition of sediment resulted in an increase in concentration of suspended sediment from 3.8 mg liter$^{-1}$ to 10.6 mg liter$^{-1}$ and caused a 70% reduction in standing crop of benthic invertebrates. Qualitative changes in the proportions of zoobenthos taxa were also evident.

2. New data from the Caribou Bar Creek mudslide: During the 1973 field season, studies of occurrences of zoobenthos in relation to natural increases in sedimentation were centered on the Caribou Bar Creek mudslide (Figs. 1[a] and 1[b]).

## Methods

Chemical and biological methods used were essentially the same as for the 1972 field season and have been described in Brunskill *et al.* (1973). Water samples were taken approximately monthly and the following parameters were measured above and below the mudslide: temperature, conductivity, pH, Secchi visibility, suspended sediment, particulate carbon, particulate nitrogen, particulate phosphorus, dissolved oxygen, total dissolved nitrogen, total dissolved phosphorus, dissolved Si, $Cl^-$, $HCO_3^-$, $SO_4^=$, $Ca^{++}$, $Mg^{++}$, $Na^+$, and $K^+$. Zoobenthos samples were taken at the same time also above and below the mudslide. Three samples were taken

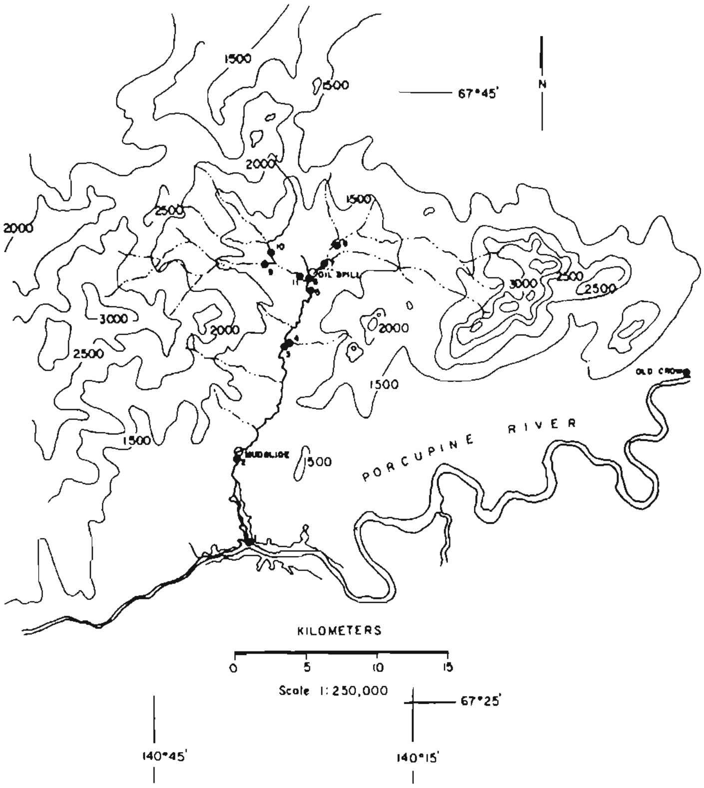



Figure 1(a). Location of natural retrogressive-thaw flow slide on Caribou Bar Creek, Y.T. (from Brunskill *et al.*, 1973).

Figure 1(b). The natural retrogressive-thaw flow slide on Caribou Bar Creek, Y.T. (The mudslide occurred between August 13 and 15, 1972. The photograph was taken on August 15, 1972).

at equidistant intervals across the width of the stream bed.

Results and Discussion

An estimated 2000-2600 metric tons of sediment was released during the initial activity of the slide (G.J. Brunskill, personal communication). The mudslide was visibly active intermittently throughout the 1973 open-water season (May to September). However, no significant physical or chemical differences were found in comparisons upstream and downstream of the mudslide except for particulate carbon, nitrogen and phosphorus, suspended sediment, and Secchi visibility on June 9 (Table 1). Water samples were not taken above the mudslide on this date so comparisions have been made to adjacent stations (Fig. 1[a]). The results show that the slide was measurably active at this time. Chemical data are similar for the last three sampling dates upstream and downstream of the mudslide (Table 2). Therefore, we have concluded that the mudslide ceased to supply a significant sediment load to the creek from July to August 1973.

Standing crops of major invertebrate taxa (i.e. those usually occurring as 2% or more of the total abundance) above and below the mudslide for September 1972 and the 1973 sampling dates are shown in Table 3. Activity of the mudslide during the June 9, 1973 sampling apparently did not affect the macrobenthos adversely. Major differences in standing crops of taxa above and below the mudslide have been underlined. Of these major differences, the occurrence of more Simuliidae below the mudslide on July 8 and more Chironomidae above the mudslide on August 2 and 27 are contrary to the predicted effects of increased sedimentation. The higher standing crop of Oligochaeta below the mudslide on July 8 and the lower standing crop of Trichoptera below the mudslide on August 27 are expected results of increased sedimentation (Hynes, 1973; Nuttall and Bielby, 1973). The lack of a uniform response as well as the temporary nature of the differences in occurrence of these four taxa reduces the possibility that they were reacting to the aftermath of increased sedimentation. Major faunal differences between stations above and below the mudslide did not exist as shown by the results of a two-way analysis of variance (Dixon and Massey, 1969) on the data: a) No significant difference was found between numbers of invertebrates of each taxon above and below the slide ($F = 0.008$ for 1 and 56 df; $P > 0.05$); b) Fluctuations in a taxon above and below the mudslide were equivalent (interaction term $F = 0.717$ for 3 and 56 df; $p > 0.05$); and c) As would be expected, seasonal differences in number of invertebrates per taxon were significant ($F = 9.136$ for 3 and 56 df; $p = < 0.05$).

Fig. 2 summarizes standing crops and percent composition of the major invertebrate taxa for the duration of the study. Size of each circle is proportional to the average standing crop of macrobenthos in the samples which appears below each circle. The magnitude of the differences among standing crops above and below the mudslide in September 1972 and the 1973 sampling dates is far less than in the first

Table 1. Particulate carbon (PC), particulate nitrogen (PN), particulate phosphorus (PP), suspended sediment (SS), and Secchi visibility below the mudslide (Station 2) and at adjacent stations (1, 5, and 6) on Caribou Bar Creek, Y.T. (see Fig. 1 [a]).

| Station | Date of sample (all '73) | PC | PN | PP | SS | Secchi |
|---|---|---|---|---|---|---|
| | | (mMoles $m^{-3}$) | | | (mg $liter^{-1}$) | (m) |
| 2 | June 9 | 142.0 | 9.57 | 0.95 | 42.8 | 0.28 |
| 1 | June 10 | 26.7 | 1.93 | 0.48 | 10.9 | 0.49 |
| 5 | June 9 | 55.9 | 4.57 | 0.37 | 10.4 | 0.84 |
| 6 | June 9 | 41.7 | 2.64 | 0.45 | 9.8 | 0.73 |

Table 2. Particulate carbon (PC), particulate nitrogen (PN), particulate phosphorus (PP), suspended sediment (SS), and Secchi visibility above (A) and below (B) the mud-slide on Caribou Bar Creek, Y.T. for 1973.

| Date (all 1973) | PC | | PN | | PP | | SS | | Secchi | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (mMoles $m^{-3}$) | | | | | | (mg $liter^{-1}$) | | (m) | |
| | A | B | A | B | A | B | A | B | A | B |
| June 9 | NT* | 142.0 | NT | 9.57 | NT | 0.95 | NT | 42.80 | NT | 0.28 |
| July 8 | 10.0 | 10.8 | <0.21 | 0.86 | 0.10 | 0.06 | NT | 1.83 | >1.00 | >1.00 |
| Aug. 2 | 13.3 | 7.5 | 2.21 | 0.93 | 0.07 | 0.20 | 0.85 | 1.44 | >1.00 | >1.00 |
| Aug. 27** | 27.5 | 23.3 | 1.79 | NT | 0.13 | 0.14 | 4.20 | 4.50 | 0.82 | NT |

* Not taken. See Table 1.

** Values for this date are above normal because of heavy rains at this time.

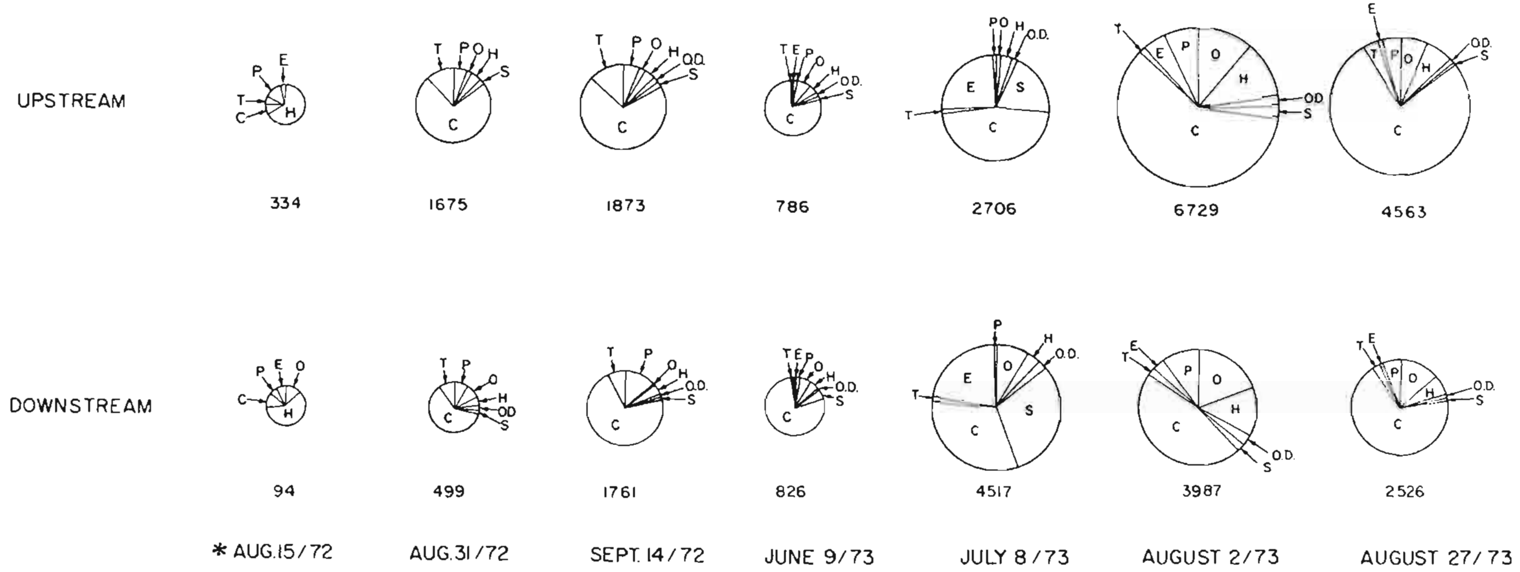
Table 3. Standing crops (number $m^{-2}$) of major* taxa of invertebrates above (A) and below (B) the Caribou Bar Creek, Y.T. mudslide in September 1972 and for all 1973 sampling dates. (Numbers are means of three Surber samples. Broken lines indicate major differences).

| TAXON | DATE | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | September 14, 1972 | | June 9, 1973 | | July 8, 1973 | | August 2, 1973 | | August 27, 1973 | |
| | A | B | A | B | A | B | A | B | A | B |
| Plecoptera | 118 | 243 | 18 | 11 | 25 | 11 | 492 | 413 | 190 | 165 |
| Ephemeroptera | 0 | 0 | 4 | 4 | 660 | 983 | 326 | 126 | 25 | 7 |
| Trichoptera | 248 | 126 | 4 | 8 | 22 | 39 | 75 | 75 | 147 | 57 |
| Chironomidae | 1353 | 1281 | 631 | 635 | 1277 | 1421 | 4051 | 1873 | 3513 | 1737 |
| Simuliidae | 22 | 4 | 18 | 65 | 538 | 1417 | 151 | 68 | 11 | 4 |
| Ceratopogonidae | 0 | 0 | 7 | 14 | 25 | 65 | 79 | 50 | 14 | 18 |
| Hydracarina | 100 | 86 | 39 | 39 | 90 | 190 | 818 | 553 | 304 | 176 |
| Oligochaeta | 25 | 7 | 16 | 36 | 47 | 373 | 700 | 761 | 323 | 355 |

* Usually occur as 2% or more of total abundance.

Figure 2. Standing crops (number $m^{-2}$) and percent occurrence of major taxa of invertebrates above and below Caribou Bar Creek mudslide in 1972 and 1973. (Number below each circle is standing crop which is the mean of 3 Surber samples. A "major taxon" usually occurred as 2% or more of total abundance).

LEGEND
P = PLECOPTERA
E = EPHEMEROPTERA
T = TRICHOPTERA
C = CHIRONOMIDAE
S = SIMULIIDAE
H = HYDRACARINA
O = OLIGOCHAETA
O.D = OTHER DIPTERA ( INCLUDES TIPULIDAE CERATOPOGONIDAE AND EMPIDIDAE




* Aug. 15/72 downstream circle is shown twice actual size.

two sampling dates of 1972 when 70% reductions in macrobenthos standing crop occurred as a result of the addition of sediment from the mudslide (Brunskill *et al.*, 1973). Standing crop above the mudslide on August 15 and 27, 1972 was approximately 3.5 times higher than below the mudslide. Standing crop was nearly equal in September 1972 one month after the mudslide started. In 1973, higher standing crops were recorded below the mudslide in the June and July samplings and above it in the two August samplings. Standing crop never differed by more than 1.8 times above and below the mudslide for the September 1972 and the 1973 sampling dates.

On August 15 and 31, 1972 sampling dates the Trichoptera were absent or showed a severely reduced occurrence downstream of the mudslide whereas the Oligochaeta were present or had a much increased occurrence (Fig. 2). These data reflected the influence of increased sedimentation due to the mudslide. However, one month later (September 14, 1972) diversity and abundance of macrobenthos were similar above and below the mudslide. The Trichoptera continued to have greater numbers above the mudslide, but the Oligochaeta were more common above than below (Table 3). As previously discussed, Fig. 2 shows no major, consistent faunal differences above and below the mudslide for the 1973 data.

As can be seen in Fig. 2, standing crops in 1973 were generally considerably higher than in 1972. Similar results were obtained at other stations on Caribou Bar Creek. This difference is likely due to normal year-to-year variations in standing crops but in the absence of long-term baseline data this must remain speculation.

A breakdown of the most abundant and diverse group of benthic macroinvertebrates in Caribou Bar Creek, the Chironomidae, further illustrates faunal changes caused by increased sedimentation due to the mudslide, and the recovery by the fauna after the slide. The data are for 1972. Data from 1973 is unavailable at this time. Standing crops of Chironomidae of various subfamilies are shown in Table 4. The cause of the low standing crops on August 15 is not clear. The Chironomidae (Tanytarsini) and Orthocladiinae were common and consistently occurred throughout the sampling period. Both showed a drastic reduction (64% and 75% for the Tanytarsini and Orthocladiinae respectively) downstream of the mudslide on August 31 and a recovery to near control levels by September 14. The Diamesinae were present in consistently low densities and seem to have been unaffected by the slide. Densities of Chironomidae for which species designations were available are shown in Table 5. Using trends in the numerical abundance of each species as a measure of their responses to the increased sediment, species were arbitrarily grouped into four classes: indeterminate (no clear trend, not considered further here), positively affected (increase in number downstream from sediment source), negatively affected (decrease in number downstream from sediment source), and unaffected. The results for the last three classes are shown in Table 6.

Known species of the nine genera listed in Table 6 are distributed over the world in a wide variety of habitats from very productive, warm,

Table 4. Standing crops (number $m^{-2}$) of subfamilies of Chironomidae larvae above (A) and below (B) the mudslide on Caribou Bar Creek, Y.T. (Taken by Surber sampler in 1972).

| SUBFAMILY | DATE (all 1972) | | | | | |
|---|---|---|---|---|---|---|
| | August 15 | | August 31 | | September 14 | |
| | A | B | A | B | A | B |
| Tanypodinae | 0 | 7 | 0 | 0 | 25 | 7 |
| Podonominae | 0 | 0 | 4 | 0 | 0 | 0 |
| Chironominae (Tanytarsini) | 0 | 0 | 327 | 119 | 324 | 216 |
| Orthocladiinae | 18 | 4 | 809 | 143 | 983 | 975 |
| Diamesinae (Diamesini) | 0 | 0 | 4 | 4 | 4 | 7 |
| Total | 18 | 11 | 1144 | 266 | 1336 | 1205 |

Table 5. Species designations* and standing crops (number $m^{-2}$) of Chironomidae larvae above (A) and below (B) the mudslide on Caribou Bar Creek, Y.T. (Taken by Surber sampler in 1972).

| TAXON | DATE (all 1972) | | | |
|---|---|---|---|---|
| | August 31 | | September 14 | |
| | A | B | A | B |
| Tanytarsini | | | | |
| *Cladotanytarsus* sp. 1 | 72 | 65 | 83 | 86 |
| *Micropsectra* sp. 1 | 18 | 4 | 36 | 22 |
| *Rheotanytarsus* sp. 3 | 97 | 7 | 18 | 7 |
| *Stempellina* sp. 2 | 29 | 0 | 29 | 0 |
| *Tanytarsus* sp. 3 | 111 | 43 | 158 | 97 |
| Total | 327 | 119 | 324 | 212 |
| Orthocladiinae | | | | |
| *Cricotopus* sp. 6 | 251 | 75 | 753 | 502 |
| *Eukiefferiella* sp. 3 | 4 | 0 | 0 | 0 |
| *Eukiefferiella* sp. 6 | 86 | 0 | 36 | 126 |
| *Eukiefferiella* sp. 7 | 4 | 0 | 0 | 22 |
| *Heterotrissocladius* sp. 1 | 0 | 0 | 0 | 4 |
| *Psectrocladius* sp. 1 | 7 | 0 | 4 | 0 |
| *Pseudosmittia* sp. 1 | 11 | 25 | 11 | 14 |
| *Synorthocladius* sp. 1 | 25 | 0 | 0 | 11 |
| Total | 388 | 100 | 804 | 679 |
| Diamesini | | | | |
| *Diamesa* sp. 2 | 4 | 4 | 4 | 7 |

* Being done by Biosystematics Research Institute, Ottawa. These designations should be regarded as provisional. We are currently attempting to assign species identifications to the specimens.

Table 6. Responses of various species of Chironomidae to the mudslide on Caribou Bar Creek, Y.T. in 1972.

| SPECIES | RESPONSE Positive | Negative | Unaffected |
|---|---|---|---|
| *Pseudosmittia* sp. 1 | • | | |
| *Micropsectra* sp. 1 | | • | |
| *Rheotanytarsus* sp. 3 | | • | |
| *Stempellina* sp. 2 | | • | |
| *Tanytarsus* sp. 3 | | • | |
| *Cricotopus* sp. 6 | | • | |
| *Psectrocladius* sp. 1 | | • | |
| *Diamesa* sp. 2 | | | • |
| *Cladotanytarsus* sp. 1 | | | • |

standing waters high in suspended organic matter to cold, clear, fast-flowing waters of low productivity (e.g. see Thienemann, 1954; Lehmann, 1971). In the absence of absolute species identifications, no certainty can be attached to a discussion of the responses of the designated species in Table 6 to increased sedimentation. The discussion must, therefore, be general. Nevertheless, a general consideration is illustrative.

*Pseudosmittia* are mainly terrestrial and semi-aquatic (Thienemann, 1954), some of whose member species have reverted to a fully aquatic existence, especially in the Arctic (O.A. Saether, personal communication). Body structure of the species in Caribou Bar Creek is typical of the terrestrial species. It is possible that specimens of *Pseudosmittia* sp. 1 were carried into the creek by the mudslide or, the increased sedimentation could have resulted in a substrate which encouraged colonization by *Pseudosmittia* sp. 1. Either or both of these possibilities could explain the positive response of this species to the mudslide.

*Diamesa* sp. 2 and *Cladotanytarsus* sp. 1 were unaffected by the mudslide. The former genus is found in fast-flowing, cold water streams (Elgmork and Saether, 1970) and is characteristic of glacial-melt streams (Thienemann, 1954). Such streams generally have high suspended sediment concentrations. Thus, the lack of response to increased sedimentation by *Diamesa* is expected. Also, Steffan (1971) reported that *Diamesa* species inhabit an extreme biotope: low water temperatures, small temperature amplitudes, high stream velocity, and (important to our interpretation of its response to the mudslide) an unstable substratum. The distribution of species of *Cladotanytarsus* is, however, not as distinct. It occurs in waters of a variety of different trophic states (Thienemann, 1954). Some species are typical of organically polluted waters (O.A. Saether, personal communication). *C. mancus* has been recorded from waters rich in suspended organic matter (Thienemann, 1954). Without knowing the actual species in Caribou Bar Creek, no further analysis can be made.

Six of the nine genera listed in Table 6 were adversely affected by the mudslide. Most species of *Rheotanytarsus* and *Stempellina* and some *Tanytarsus* are filter feeders (O.A. Saether, personal communication; Thienemann, 1954). For example, *T. gregarius* is described as being a filter feeder and *R. anomalous* builds a net at the end of its case to capture algae (Thienemann, 1954). Presumably, larvae pursuing such a way of life would be adversely affected by increases in suspended sediment, especially if the sediment had a poor food content. Hynes (1966) pointed out that *Tanytarsus* are favored by an increase in the amount of fine sediment on a river bed but he did not mention species. *Micropsectra*, too, are found in a variety of habitats (Thienemann, 1954; Lehmann, 1971) but are generally typical of oligotrophy (O.A. Saether, personal communication). Elgmork and Saether (1970) stated that *Micropsectra* of mountain brooks are especially found in sand, silt, and mud with a few species in aquatic moss, and none in stony substrates. *Micropsectra* in their study were hygropetric. Providing the species of *Micropsectra* found in Caribou Bar Creek is one of these, the negative effect of the mudslide can be readily understood. Nothing can be said about *Psectrocladius* sp. 1 without having a species determination. Of all the genera listed in Table 6 *Psectrocladius* is probably the most eurytopic. *Cricotopus* also has a wide range of habitat. It is generally associated with plants in standing waters (Thienemann, 1954). *C. microcornis*, however, has been taken from high alpine springs and in glacial runoff streams (Thienemann, 1954). Most of the species dealt with by Lehmann (1971) are from fast, cold waters as well. It is possible that the species of *Cricotopus* from Caribou Bar Creek, a fast cold stream, was of this group of species and this is the reason for its response to the mudslide, although the presence of *C. microcornis* in glacial runoff streams makes this explanation less plausible.

Scott (1958), in his work on the Great Berg River in South Africa, listed a number of chironomid species which he bred from a variety of habitats. By way of summary, the species of some of the genera shown in Table 6 have been listed in Table 7 which not only shows the plasticity of the occurrence of species within the same genus to different habitats but also indicates the plasticity of occurrence of the same species to different habitats. Thus, it can be seen that relating a change in Chironomidae with an environmental disturbance is difficult except for the most specialized chironomid larvae (e.g. the Diamesinae).

In conclusion, the invertebrate populations affected by a natural mudslide in mid-August 1972 had recovered by mid-September 1972, a month's time. We will herein define "recovery" as the return of the macrobenthic fauna to an abundance and diversity comparable to that shown by an adjacent undisturbed or control area. Although the slide appeared to become active intermittently through the 1973 sampling season, the invertebrate fauna remained unaffected. Recovery (see Section I, part D.4) was probably due to the following factors in the creek: a) adequate water velocity (velocity for June to August 1973 was 0.219-0.895 m $sec^{-1}$) which served to clean the fine sediments added by the mudslide out of the bottom substrates; b) the relatively small sediment load added and the short duration of the period of maximum activity of the mudslide; and c) the availability of nearby undamaged areas to serve as sources of recolonization.

C. The effects of highway construction on the aquatic biota of watersheds in the Mackenzie Valley

1. Previous results: Our studies of the effects of highway crossings on river biota have included: a) The culverted crossings of the Poplar River and b) Campbell Creek, by the Ft. Nelson and Dempster Highways respectively; and of c) the Martin River by the Mackenzie Highway right-of-way slash, winter road, and temporary bridge. Results of the Poplar and Martin River studies have been reported in Brunskill *et al.* (1973) and Porter, Rosenberg, and McGowan (1974) and can be summarized as follows:

(i) Poplar River (Fig. 3): Grayling fry were found in abundance below the bi-culverted crossing but none above the culverts in the spring of

Table 7. Habitats of various species of Chironomidae in the Great Berg River (from Scott, 1958). (See original paper for definition of habitats).

| | Stony runs & stickles | Stony backwaters | Sandy bottoms* | Marginal vegetation | From *Scirpus digitatus* in fast current |
|---|---|---|---|---|---|
| *Cladotanytarsus capensis* | o | | o | o | |
| *Cladotanytarsus nilicola* | | | o | | |
| *Cladotanytarsus reductus* | | | o | | |
| *Cricotopus albitibia* | | | o | | |
| *Cricotopus flavozonatus* | o | o | | | |
| *Cricotopus kisantuensis* | o | | | | |
| *Cricotopus obscurus* | | | o | | |
| *Psectrocladius viridescens* | | o | | | o |
| *Rheotanytarsus fuscus* | o | | | | o |
| *Stempellina*? sp. n. | | | o | | |
| *Tanytarsus aterrimus* | | o | | o | o |
| *Tanytarsus pallidus* | | o | | o | |

* variable current speed

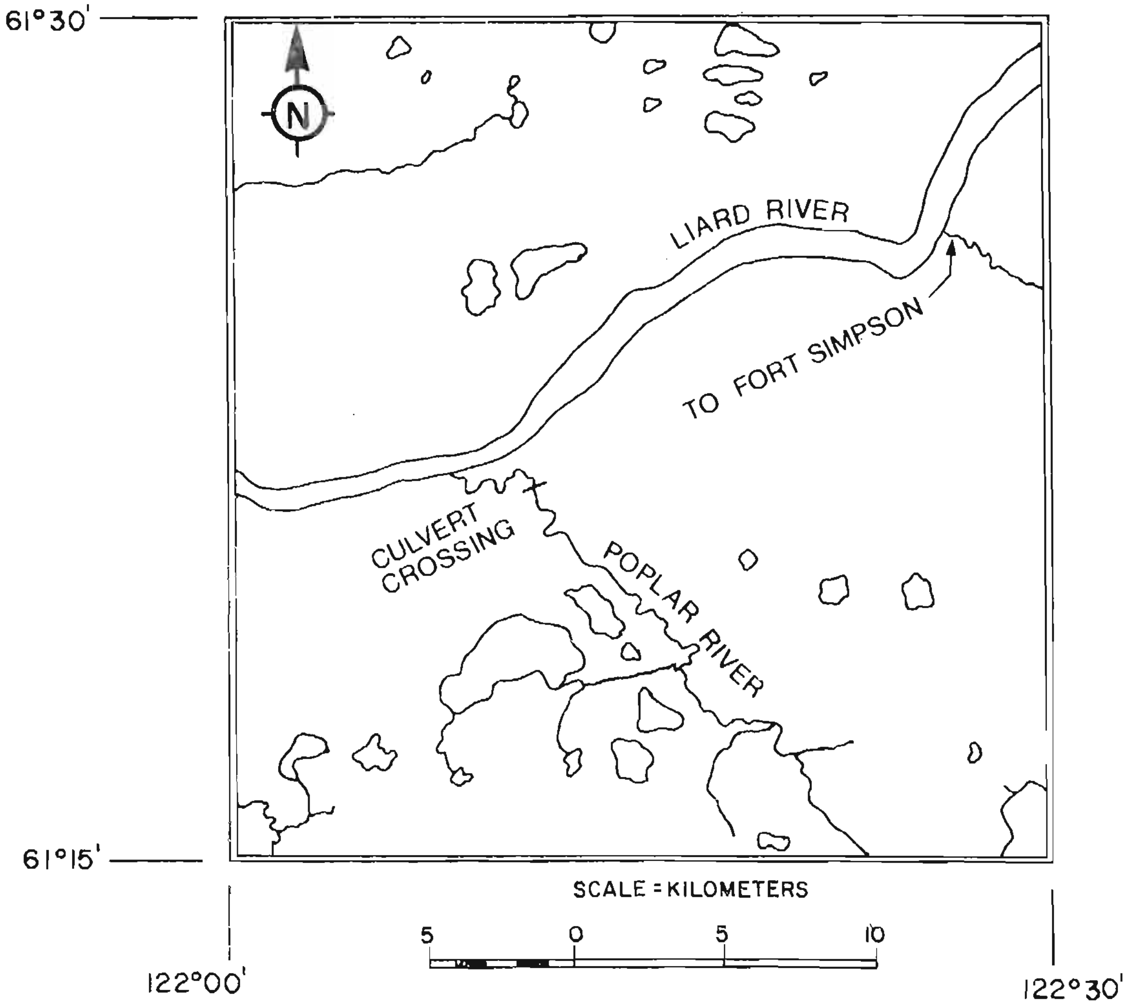



Figure 3. Location of the bi-culverted crossing of the Poplar River, N.W.T.

1972. In the spring of 1973 thousands of fish of various species were seen swimming in the pools downstream of the crossing but not above. Velocity of water coming out of one culvert was 1.1 m $sec^{-1}$ and approximately 2.5 m $sec^{-1}$ at the other culvert in fall of 1972. The downstream end of the latter culvert was a meter above the river bed. Pools, formed upstream and downstream of the culverts, were littered with logs during the fall of 1972. Combined with the normally low water levels in fall the debris could effectively act as a barrier to upstream migration by fall-spawning fish. Benthic invertebrate drift studies done above and below the crossing showed the influence of the pools at the downstream end of the culverts. Oligochaeta and Cladocera formed a higher percentage of the total fauna downstream and, in general, the downstream samples showed a lower diversity when compared to those taken upstream. Lower diversity is often indicative of a disturbed habitat.

(ii) Martin River (Fig. 4): Study of the river above and below crossings of the right-of-way slash (completed by mid-September 1972), a winter road (in place by early November 1972), and a temporary bridge (constructed by the end of March 1973) showed slightly higher suspended sediment concentrations when compared to the upstream control station. Dissolved oxygen concentrations at two stations (4 and 5) downstream of highway activities in March 1973 were low enough to be lethal to fish whereas concentrations upstream (station 6) were not as low. No other differences in physical and chemical parameters were detected in the study area. Zoobenthos and fish appeared to have been unaffected by construction activities. During the winter of 1972-1973, Porter *et al.* (1974) showed that three common species of fish (*Catostomus catostomus*, *Cottus cognatus*, and *Percopsis omiscomaycus*) in the Martin River were bottom feeders. Porter *et al.* (1974) emphasized the importance of keeping this habitat free of fine sediment. Little fish movement was detected from January to March 1973. It was therefore recommended that this represented a safe period for in-stream highway construction activities.

2. <u>New data from studies of the effects of highway crossings on Mackenzie Valley watersheds</u>: We have continued to observe the Martin River crossings and now have data available on the Campbell Creek highway crossing.

Martin River studies

a) <u>Methods</u>

Chemical and biological methods for the study of the Martin River highway crossings were as described by Brunskill *et al.* (1973), Stein *et al.* (1973) and Porter *et al.* (1974). Sampling was done at monthly intervals during the open-water period and approximately once every two months during the period of ice cover. Physical and chemical parameters measured were the same as for the Caribou Bar Creek mudslide study (see Section 11:B2 this report). These parameters were measured at stations 1, 4, 5 and 6 (Fig. 4). Suspended sediment concentrations were measured

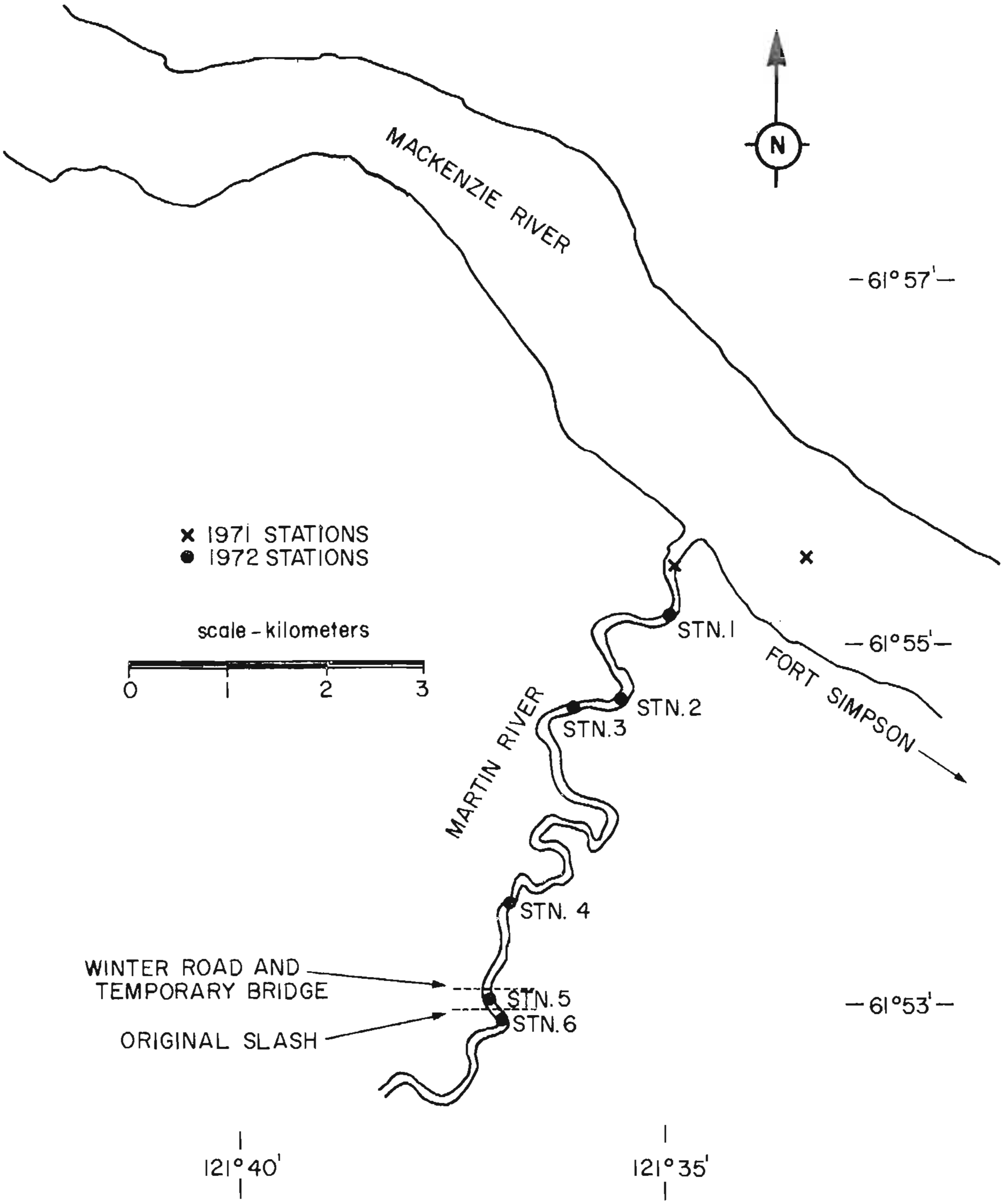



Figure 4. Station locations for studies of the Mackenzie Highway crossings of the Martin River, N.W.T.

at upstream and downstream ends of the pool at each station to determine whether significant amounts of sediment were settling. This is much simpler than trying to measure bottom sedimentation directly. Macrobenthos standing crop estimates were obtained during the open-water period by Surber sampler at stations 4 and 6 (Fig. 4). Artificial substrates (chicken barbeque basket type; Mason, Anderson, and Morrison, 1967) were placed in pools at all stations and macrobenthos were allowed to colonize them for at least four weeks before the substrates were removed. Substrates were placed in pools on the assumption that settling sediment would affect the abundance and diversity of macrobenthos colonizing the substrates. Three Surber samples and three artificial substrates were removed at approximately equal distances across the bottom substrate at the sampling site. A series of 24 hr driftnet samples were taken during a 1972-1973 winter study of the Martin River (Porter *et al.*, 1974). The locations of these driftnets were different than those shown in Fig. 4 and are shown in Fig. 5. Two stacked 10 x 10 x 76 cm, 200μ mesh nets were staked into the stream bottom in areas with current fast enough to distend the nets. Complete details can be found in Porter *et al.* (1974). Fish were sampled by beach seine at stations 6 and 4 (see Fig. 4) during the 1972 and 1973 open-water periods (Stein *et al.*, 1973; Porter *et al.*, 1974). (Species level determinations of macrobenthos are not yet available for the Martin River and Campbell Creek studies. Discussions of the effects of increased sedimentation therefore must be limited to higher taxa.)

b) Results and discussion

As in the 1972 open-water period and during the 1972-1973 winter no major differences occurred in the selected physical and chemical parameters at stations 1, 4, 5, and 6. However, when particulate carbon concentrations are examined over the entire study period, a trend to an increase in concentration and rate of transport of particulate carbon between stations 6 and 5 is obvious (Table 8[a], [b]). Suspended sediment concentrations and rates of transport of the three stations in the area of the crossings during the 1973 open-water period continued to show lowest levels at station 6 and highest at station 5 (Table 9[a],[b]) but, as in the previous data (Brunskill *et al.*, 1973; Porter *et al.*, 1974), the differences were not significant. No dissolved oxygen depletion was observed like that described during the winter period (Porter *et al.*, 1974).

Results of Surber samples taken during the 1972 and 1973 open-water periods upstream and downstream (stations 6 and 4 respectively; see Fig. 4) of the right-of-way slash are presented in Figs. 6(a), (b) as percent composition by each of the major invertebrate taxa (i.e. those ≥1% of total abundance). The size of each circle is proportional to the value of the standing crop (number of invertebrates $m^{-2}$) which appears below each circle. The following differences are evident between the two stations for 1972 (Fig. 6[a]):

(i) Consistently higher standing crops of macrobenthos occurred at station 6 (upstream control) compared to station 4 (downstream of highway construction).

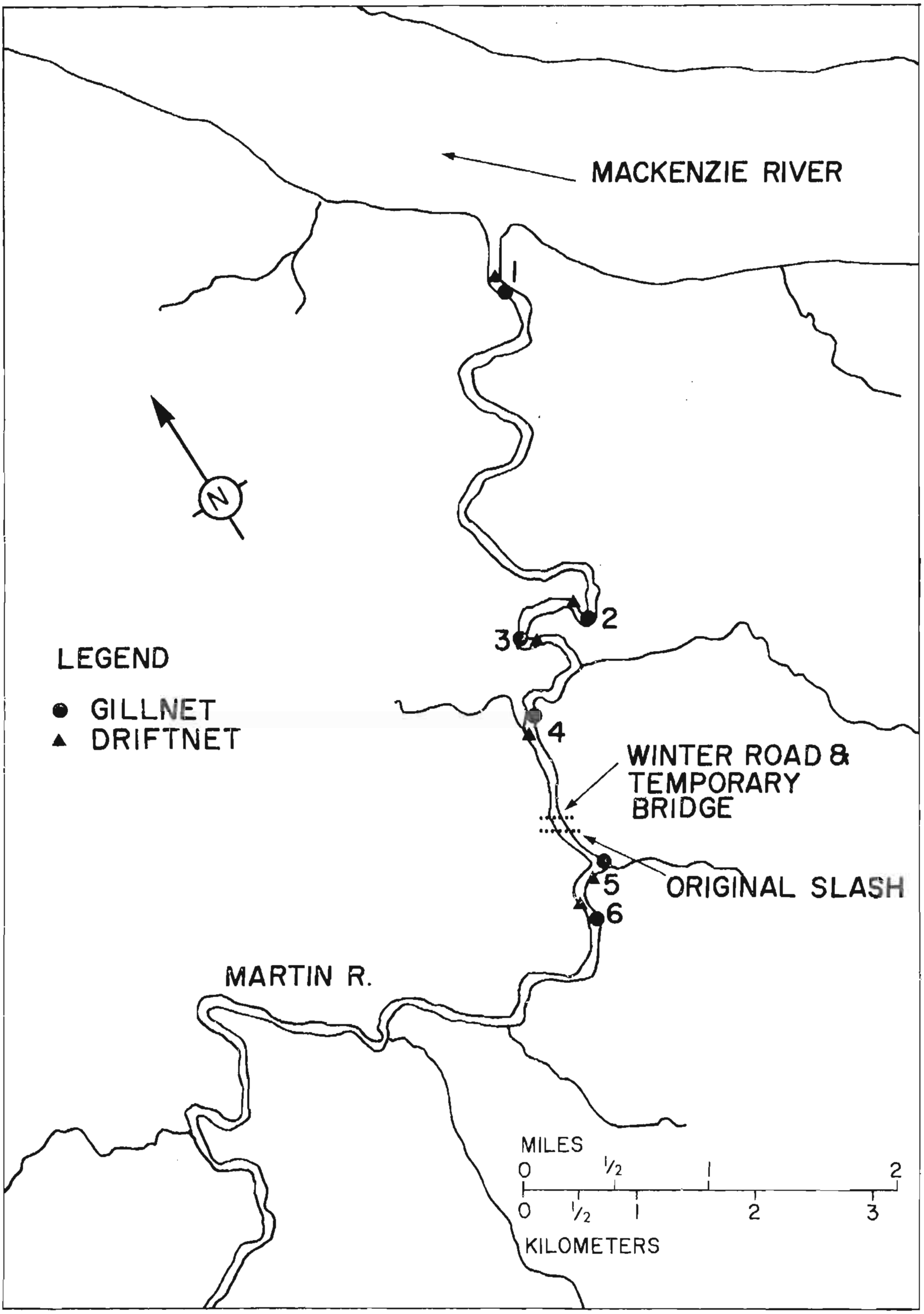



Figure 5. Station locations for the 24 hr driftnet samples taken on the Martin River, N.W.T. (from Porter *et al.*, 1974).

Table 8(a). Particulate carbon concentrations for the entire Martin River study period. (Broken line signifies highest values for that sampling date).

| DATE | STATION 6* | 5 | 4 | $1^+$ |
|---|---|---|---|---|
| | flow → (mMoles $m^{-3}$) | | | |
| July 20, 1972 | 81.7 | 132.5 | - | 98.6 |
| August 17, 1972 | 96.7 | 115.9 | - | 114.0 |
| September 14, 1972 | 103.8 | 87.2 | - | 138.0 |
| November 29, 1972 | 279.0 | - | - | 270.0 |
| February 3, 1973 | 350.0 | 380.0 | 41.7 | 379.0 |
| March 28, 1973 | 232.0 | 247.0 | 254.0 | 176.0 |
| July 19, 1973 | 10.0 | 32.5 | 30.8 | 29.2 |
| August 20, 1973 | 30.0 | 35.8 | 25.8 | 28.3 |
| September 12, 1973 | 15.8 | 20.8 | 15.0 | 13.3 |

Table 8(b). Rates of transport (concentration in mMoles $m^{-3}$ x discharge in $m^3$ $day^{-1}$) for entire Martin River study period. (Broken line signifies highest values for that sampling date).

| DATE | STATION 6* | 5 | 4 | $1^+$ |
|---|---|---|---|---|
| | flow → (moles $day^{-1}$ x $10^3$) | | | |
| July 20, 1972 | 10.87 | 17.63 | - | 13.12 |
| August 17, 1972 | 31.67 | 37.95 | - | 37.33 |
| September 14, 1972 | 21.43 | 18.01 | - | 28.50 |
| November 29, 1972 | 9.40 | - | - | 9.10 |
| February 3, 1973 | 5.14 | 5.58 | 0.61 | 5.57 |
| March 28, 1973 | 3.41 | 3.63 | 3.73 | 2.59 |
| July 19, 1973 | 3.30 | 10.73 | 10.17 | 9.64 |
| August 20, 1973 | 21.20 | 25.30 | 18.23 | 20.00 |
| September 12, 1973 | 2.54 | 3.34 | 2.41 | 2.14 |

* upstream of all construction
\+ at mouth of river
} see Fig. 4

Table 9(a). Suspended sediment concentrations for the 1973 Martin River open-water study period.

| DATE | STATION 6 | STATION 5 | STATION 4 | STATION 1 |
|---|---|---|---|---|
| | (mg $liter^{-1}$) | | | |
| July 19 | 3.39 | 3.67 | 3.53 | 6.58 |
| August 20 | 5.81 | 6.19 | 5.77 | 7.41 |
| September 12 | 1.17 | 1.96 | 1.69 | 3.44 |

Table 9(b). Rates of transport (concentration in mg $liter^{-1}$ x discharge in $m^3$ $day^{-1}$) for the 1973 Martin River open-water study period.

| DATE | STATION 6 | STATION 5 | STATION 4 | STATION 1 |
|---|---|---|---|---|
| | (kg $day^{-1}$) | | | |
| July 19 | 1118.9 | 1211.3 | 1165.1 | 2171.7 |
| August 20 | 4106.2 | 4374.8 | 4077.6 | 5237.0 |
| September 12 | 188.0 | 315.0 | 271.6 | 552.8 |

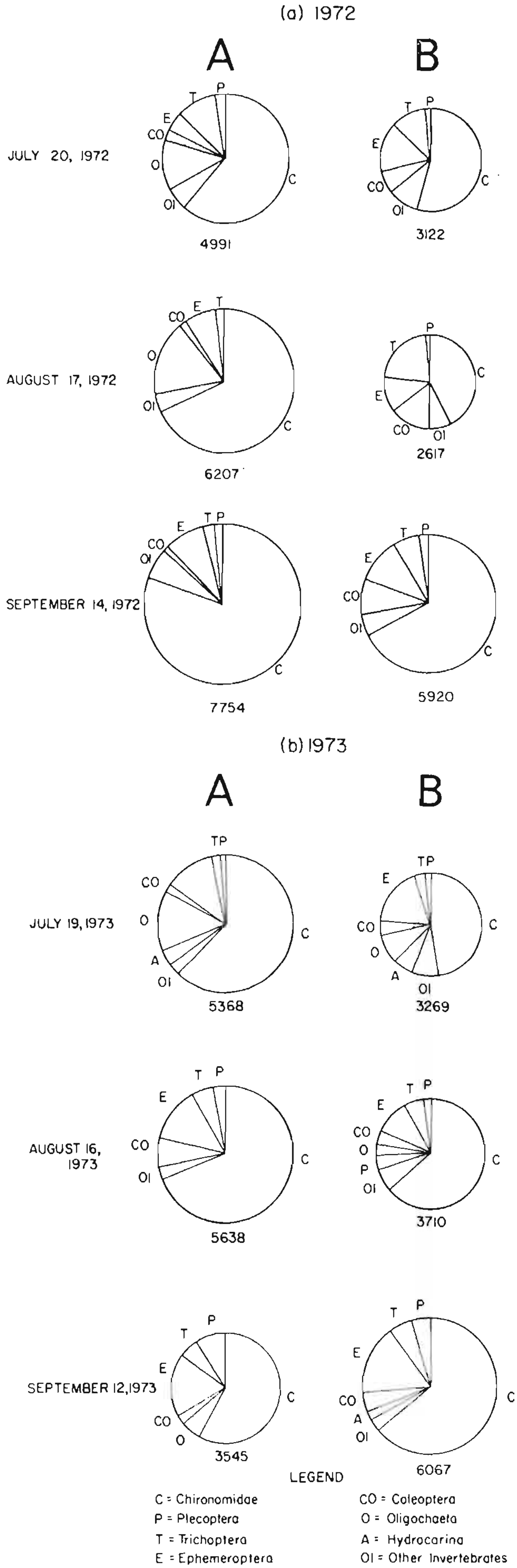



Figure 6. Standing crops (number $m^{-2}$) and percent composition of major taxa of invertebrates above (A) and below (B) the highway crossings of the Martin River, N.W.T.

(ii) A greater percent occurrence of Chironomidae and Oligochaeta was found at the upstream station, and Trichoptera, Ephemeroptera, and Coleoptera occurred more frequently at the downstream station. The pattern was not as clear in 1973 (Fig. 6 [b]). Standing crops of macrobenthos were again higher above the crossing but only on the July and August sampling dates. The September 12, 1973 sampling showed a higher standing crop downstream of the crossing. Chironomidae, again, had a higher percent occurrence at the upstream station in July and August (as in 1972) but not in September. Oligochaeta, too, had a higher percent occurrence above the crossing in July (as during the 1972 season), but were absent from the upstream station in August and from both stations in September, unlike in 1972. They composed only a small proportion of the macrobenthic fauna at the downstream station in August. Trichoptera showed a similar percent occurrence throughout the 1973 open-water period upstream and downstream of the crossing whereas in 1972 they always had a higher percent occurrence at the downstream station. Coleoptera and Ephemeroptera, which had a higher percent occurrence at the downstream station than the upstream station in 1972, showed the same trend in July and September 1973 but not in August 1973. As in 1972, however, the downstream station appeared to have a more equitable abundance (and higher diversity) of taxa.

The effects of increased sedimentation[1] on macrobenthos have already been discussed (see Section I). Increased sedimentation can cause a reduction in standing crop. Numbers of sensitive groups such as Trichoptera and Ephemeroptera are usually reduced but taxa such as Chironomidae and Oligochaeta which inhabit fine sediment usually show an increase in numbers.

Porter *et al.* (1974) also found fewer invertebrates at station 4 than upstream of the highway construction during the winter of 1972-1973. Lower standing crops at station 4 on five of the six sampling dates during the two open-water periods were a reflection of lower numbers of Chironomidae, a result not consistent with the likely effects of increased sedimentation predicted from the literature. The abundance of Chironomidae was higher at the downstream station only on the September 12, 1973 sampling date. The more frequent occurrence of taxa of fine sediments such as Chironomidae and Oligochaeta at station 6, of typically sediment-sensitive taxa such as Trichoptera and Ephemeroptera at station 4, and a more equitable distribution of numbers of organisms among different taxa at station 4 are further evidence that the highway crossing did not cause changes in the macrobenthic fauna. This conclusion is supported by the lack of great differences in physical and chemical parameters above and below the disturbed sites.

The difference between stations 4 and 6 is due to the different nature of the two riffle areas from which the samples were taken (the only two

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1 We are assuming that the major effect of an ecologically detrimental highway crossing is increased sedimentation. See discussion in Section I of this report.

riffle areas within many kilometers of the highway crossings). The riffle at station 6 is a wide (≈30 m), shallow (≈13 cm) shoulder of the main channel. Water flow is relatively slow (≈0.2 m $sec^{-1}$) which allows sediment deposition. Consequently, sediment is visibly admixed within the poorly-sorted silt to boulder-sized bottom substrate. The riffle at station 4 is part of the main channel and is narrow (≈10 m), deeper (≈25 cm), and has a greater water velocity (≈0.5 m $sec^{-1}$) than the upstream riffle. The bottom sediments are mainly gravel and because of higher water velocity, less sediment would settle here than in the upstream riffle. Because of the higher water velocity, the substrate would tend to be less stable. Also, less organic detritus would be deposited in the area.

The results of our study of the highway crossings by sampling of benthic invertebrates with artificial substrates during the 1972 open-water period and the winter of 1972-1973 are presented in Figs. 7 and 8 respectively. Artificial substrates were not installed at stations 5 and 6 until July 21, 1972, approximately one week after the site of the right-of-way slash became known. Thus, controlled data are available only for the August and September 1972 sampling dates. Artificial substrate data for the 1972 open-water period are complete as represented in Fig. 7. Insufficient numbers of artificial substrates were recovered from the March 28, 1973 sampling to include the data in Fig. 8. Artificial substrates at station 4 were installed when the winter road crossing site became known (November 28, 1972) and therefore the first samples were removed at this station during the February 2, 1973 sampling trip. Note that due to extremely heavy icing conditions (the ice was >2 m thick) at station 6 after the November 28, 1972 sampling, no artificial substrates could be recovered from this station. Thus, the February 3 sampling has no control data.

For the 1972 open-water period (Fig. 7), no major differences in mean numbers of invertebrates of any of the taxa examined could be detected between stations 6 and 5. In general, numbers of Chironomidae, Plecoptera, and Trichoptera were higher at station 5 (downstream of the right-of-way slash). Ephemeroptera were present in approximately equal numbers at both stations. Numbers of organisms were distributed relatively equitably among the major taxa (Chironomidae, Plecoptera, Ephemeroptera, Trichoptera, Simuliidae, and Acarina) at these stations. These results indicated that station 5, like 6, has not been affected by increased sedimentation. Generally higher mean numbers of invertebrates at stations 3, 2, and 1 is likely due to the longer colonization time available to the artificial substrates at these stations (see Mason *et al.*, 1973).

Mean numbers of Chironomidae, Plecoptera, Ephemeroptera, and Gastropoda are similar for stations 6 and 5 on the November 28, 1972 sampling date (Fig. 8). However, the Trichoptera are present in noticeably low numbers at station 5 when compared to the control station. The high mean number of Trichoptera at station 6 was caused by the occurrence of over 300 Trichoptera in one of the three artificial substrates. In view of the similarity in mean numbers for the other taxa at these stations and be-

Figure 7. Mean number of major taxa of invertebrates on three artificial substrates above and below the highway crossing on the Martin River for the open-water period of 1972.* (A "major" taxon occurred as 1% or more of total abundance).

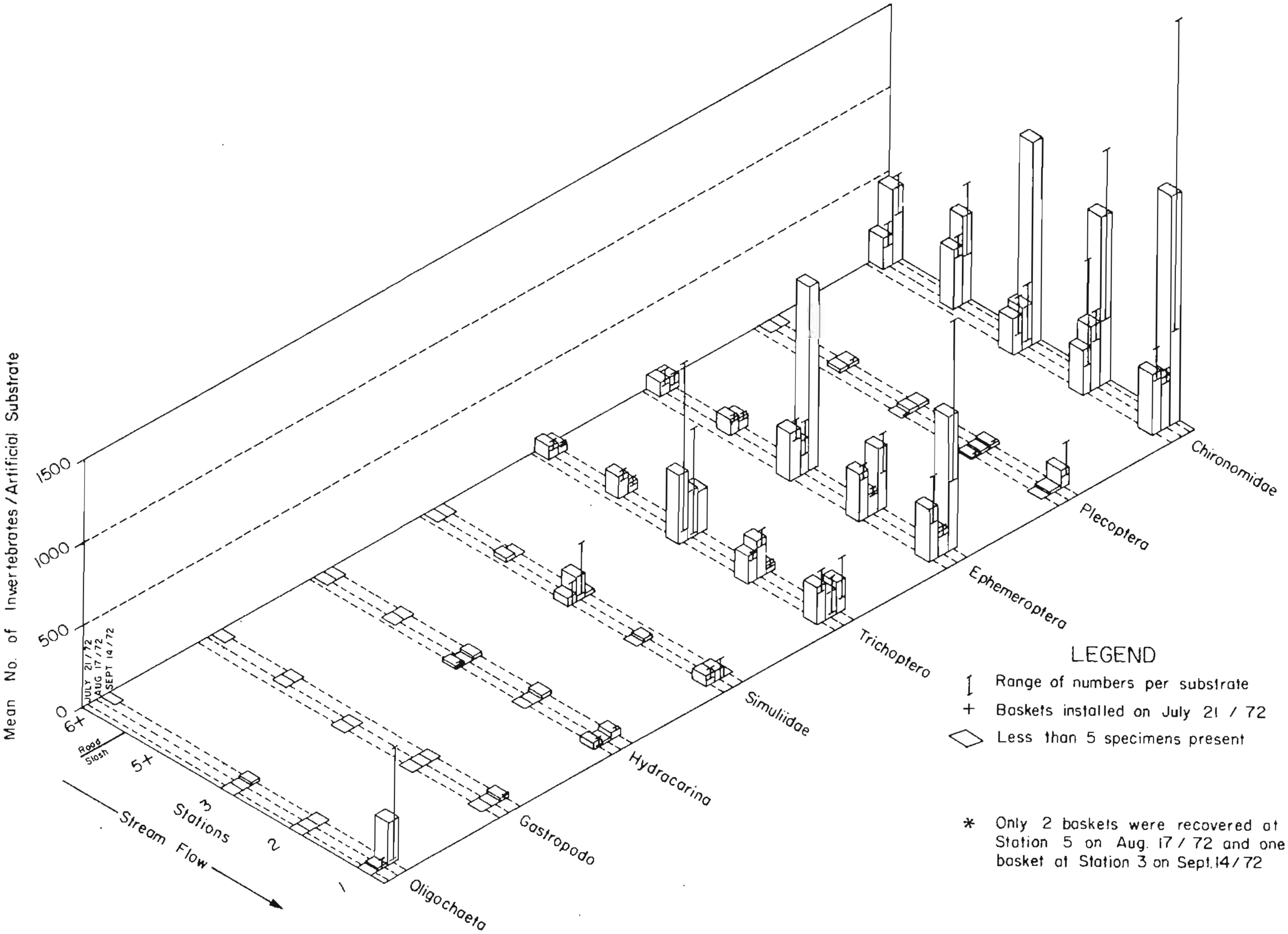
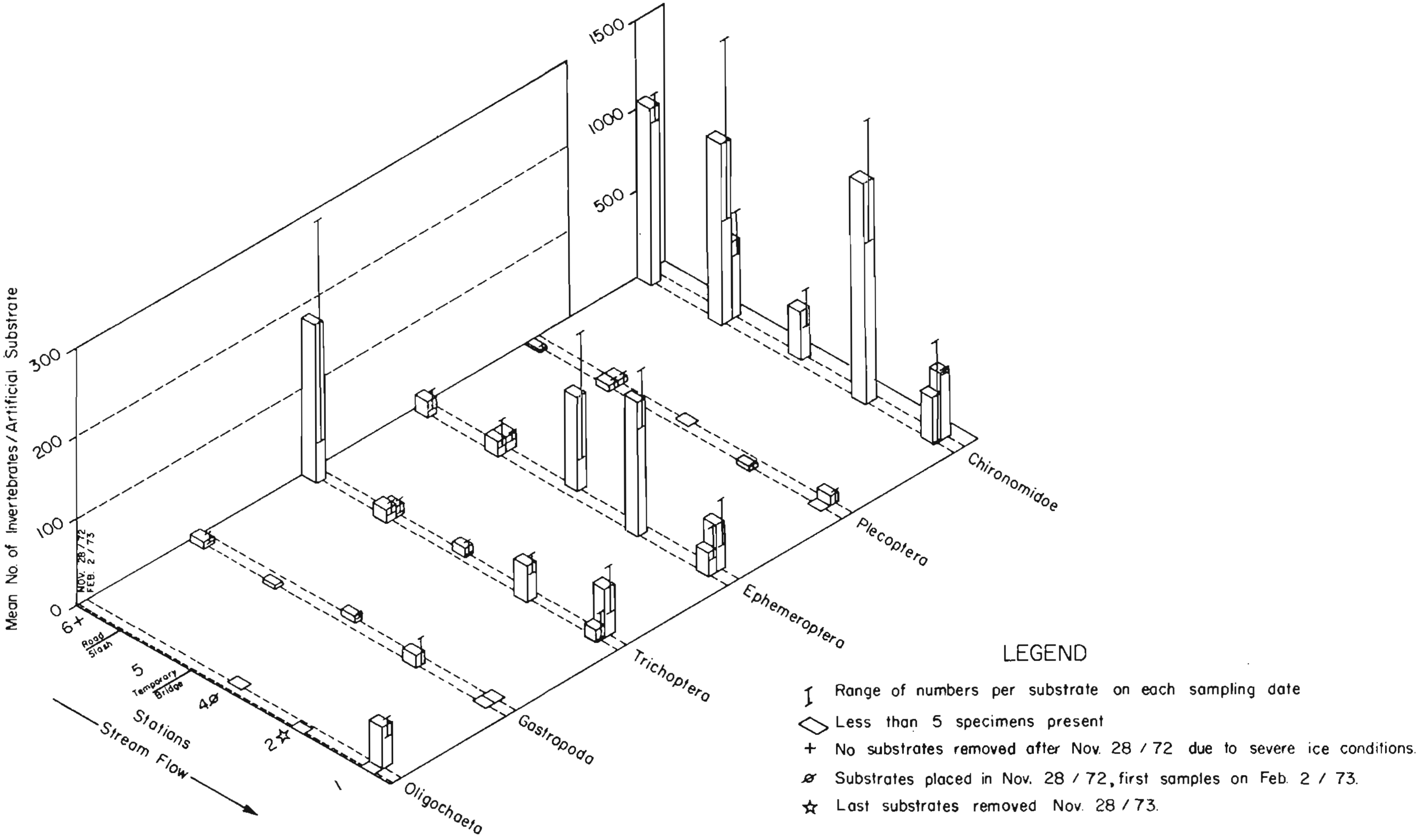


Figure 8. Mean number of major taxa of invertebrates on three artificial substrates above and below the highway crossings on the Martin River for winter of 1972-1973.* (A "major" taxon occurred as 1% or more of total abundance).




* Only 2 baskets recovered at Stations 1 and 4 on Feb. 2/73

cause of the similarity in mean numbers of Trichoptera among stations 5, 2, and 1, the high value at station 6 is likely due to the sampling of an abnormally high number of Trichoptera. Thus, the lower mean number of Trichoptera at station 5 was not likely due to a highway-related disturbance. In the absence of control data for the February 2, 1973 sampling date not much can be said about the possible effects of the highway crossings other than spectacular differences did not exist between station 1, the station farthest downstream and least likely to be affected by construction, and stations 2, 4, and 5.

Final evidence that the Martin River highway crossings have not disturbed the benthic invertebrate community is drawn from a series of 24 hr driftnet samples taken during the 1972-1973 winter study (Porter *et al.* 1974). The results are shown in Fig. 9. Because the samples were not always taken simultaneously at all stations on the same day, the samples were grouped in time intervals of two weeks or less for presentation. Numbers of invertebrates collected by the driftnets over the 24 hr period are given on or near each "coin", the size of which is proportional to this number. Percent composition of taxa in each sample is also shown by each coin. Station numbers are according to Fig. 5. The following patterns can be seen:

(i) Taxa predominating in these driftnet samples are different from the ones collected by Surber sampler (see Fig. 6[a], [b]) and artificial substrate (see Figs. 7, 8) because a different macrobenthic habitat was being sampled.

(ii) Downstream stations (1 to 4) generally have lower total numbers of drifting invertebrates than the upstream control stations (5 and 6). Sediment addition has been shown to increase the numbers of macrobenthos drifting (Gammon, 1970; Section III, this report) so, obviously, the downstream stations are not suffering from sedimentation. Also, the stations below the crossings show a higher diversity of taxa than the control stations. Ephemeroptera, a group usually intolerant of fine sediment, are present in larger numbers at downstream stations than upstream stations. Large numbers of planktonic Copepoda have inflated the numbers of invertebrates collected at the upstream stations. This indicates a difference in habitat between control and downstream stations, rather than an effect of disturbance.

(iii) The cause of the inordinately low numbers of invertebrates collected at station 4 in the third and fourth sampling periods (the second and third week of December 1972; the third week of January 1973) is not clear. Total numbers collected during the first sampling period (981 in the third week of November 1972) did not differ significantly from numbers collected at other stations at that time. A total of 3,015 invertebrates were collected in a sample taken during the fourth week in November (not shown in Fig. 9). Almost all of the collection taken in the third sampling period was Ephemeroptera. Populations immediately downstream from station 4 on the two sampling periods in question are more similar to the control than those at station 4. If station 4 was being affected by the crossings, the effect was very

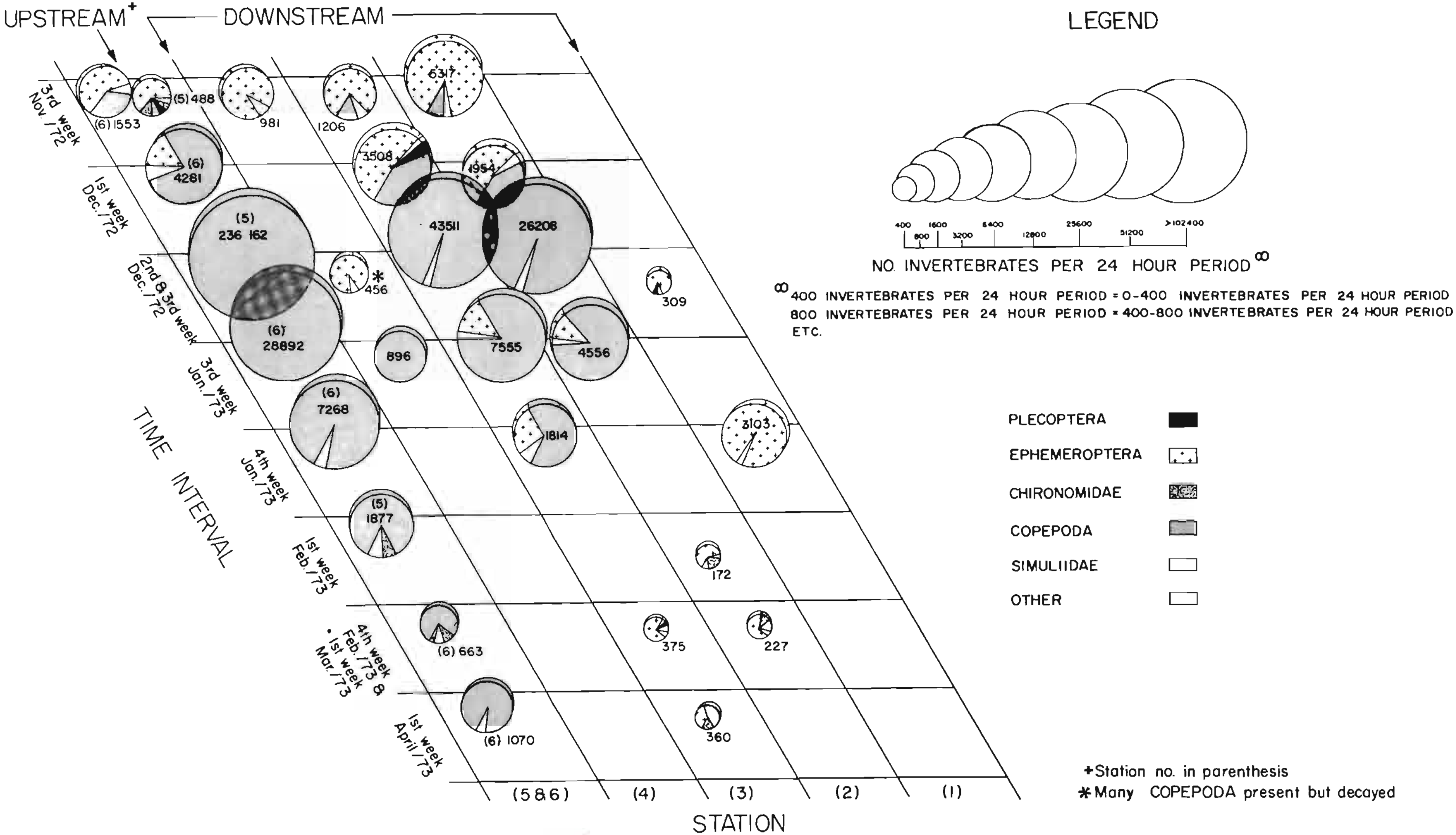



Figure 9. Total number per 24 hr period and percent composition of major taxa of invertebrates caught in driftnets upstream and downstream of highway crossings of the Martin River in winter 1972-1973. (A "major" taxon occurred as 4% or more of total abundance).

localized. Therefore, in the absence of data for station 4 after the fourth sampling period, it must be concluded that the low numbers were not due to effects of the crossings.

(iv) Stations below the highway crossings continually showed a higher occurrence of Ephemeroptera than the upstream, control stations. This is not an expected response for areas disturbed by excessive sediment supply.

In summary, these drift samples showed no significant effects due to either the actual highway crossings or highway-related activities (see Porter *et al.*, 1974) on the invertebrate fauna of the Martin River during the winter of 1972-1973. These results support the conclusions already made for invertebrates taken in the Surber samples and by artificial substrates.

In general, the number of species of fish and the number of individuals of fish were similar above and below the highway crossings (Table 10). *P. omiscomaycus*, the most commonly caught fish had an almost equivalent abundance upstream and downstream of the crossings for the three sampling periods (Table 11). Further statistical analyses were impossible because of insufficiencies in the data. *Catostomus* spp. and *Cottus* spp. showed a definite trend to greater abundance downstream of the crossing. Since the suspended sediment concentrations are similar above and below the highway crossings on the Martin River, the higher number of fish at the downstream station would appear not to be due to differences in suspended sediment concentration and is therefore probably a natural occurrence. Peters (1972) reported that longnose and white sucker populations were reduced substantially in a part of a Colorado stream which was treated to reduce suspended sediment. Nothing was said about the response of such populations to increased suspended sediments.

We have concluded that the crossings have had no effect on the fish populations. A similar conclusion was reached by Porter *et al.* (1974) for the 1972-1973 winter period.

Campbell Creek studies

a) Introduction

The first major watershed to be crossed by the northern section of the Dempster Highway was Campbell Creek, approximately 25 km southeast of Inuvik (Fig. 10). This watershed drains low relief taiga and tundra and flows southwest into Campbell Lake. At peak discharge, a connection with Sitidgi Lake may exist via Norris Creek to the northeast.

Two circular section culverts of 2.4 m diameter and approximately 30 m long were installed across Campbell Creek in the winter of 1971-1972. The crossing area probably is normally subject to spring flooding because the relief is low in the area and because ice from Campbell Lake goes out much later than from the Creek. The road was not consolidated when spring flooding occurred in early June 1972. Considerable surface erosion

Table 10. Numbers of all species* of fishes captured in seine hauls+ above (A) and below (B) the highway crossings on the Martin River, N.W.T.

| DATE (all 1973) | NO. OF SPECIES A | NO. OF SPECIES B | NO. OF INDIVIDUALS A | NO. OF INDIVIDUALS B |
|---|---|---|---|---|
| July 18-19 | 6 | 4 | 241 | 378 |
| August 20-21 | 6 | 4 | 129 | 144 |
| September 12-13 | 4 | 4 | 51 | 75 |

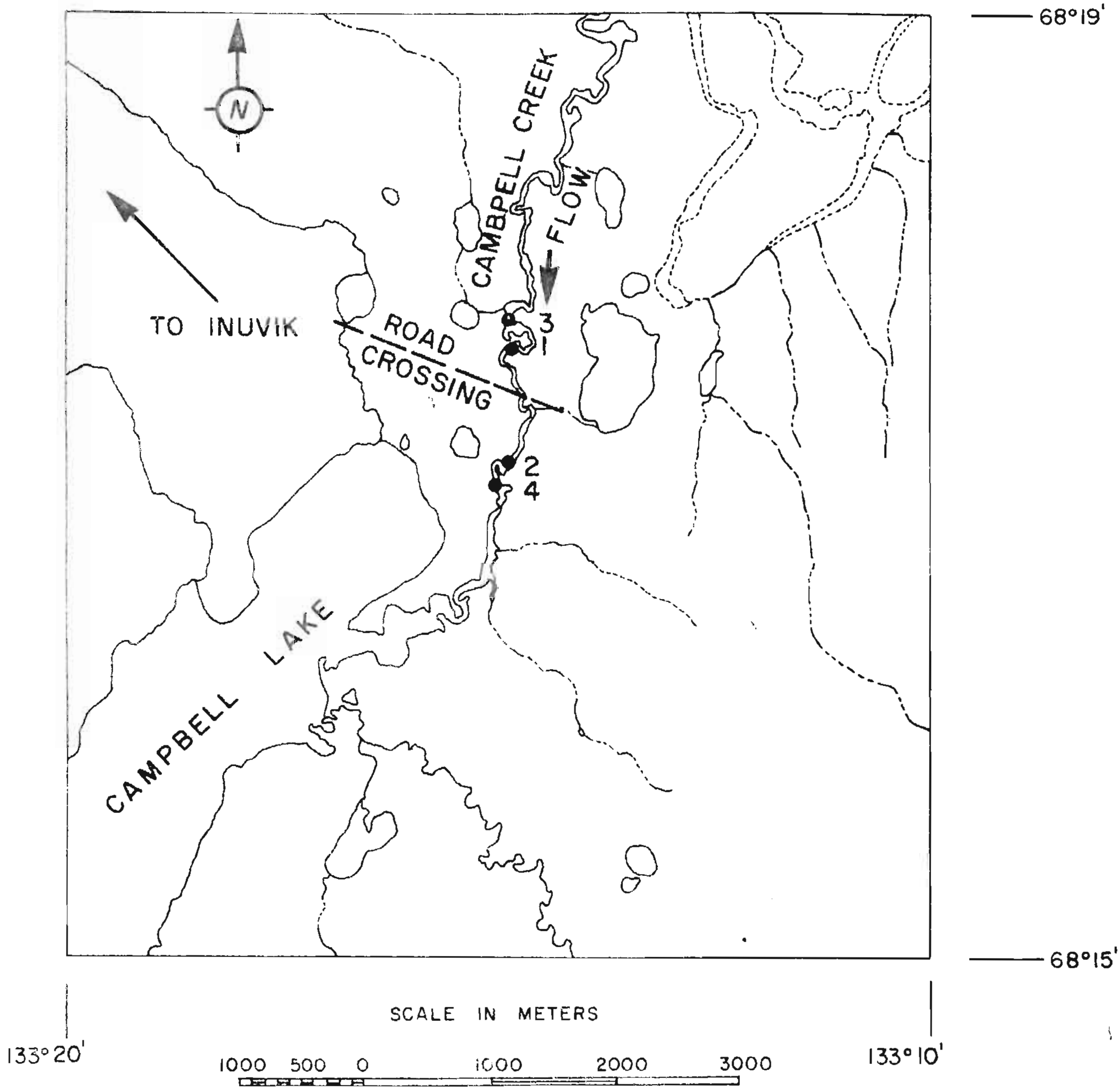
* *Catostomus* spp.
*Cottus* spp.
*Couesius plumbeus*
*Esox lucius*
*Lampetra japonica*
*Percopsis omiscomaycus*
*Rhinichthys cataractae*
*Stizostedion vitreum vitreum*
*Thymallus arcticus*

\+ Numbers are totals of 4 samplings taken in a 24-hour period at approximately the same times above and below the crossings. Three seine hauls were taken in each sampling at each location in July and two in August and September.

Table 11. Numbers of common species of fishes captured in seine hauls above (A) and below (B) the highway crossings on the Martin River, N.W.T.

| SPECIES | DATE (all 1973) | | | | | |
|---|---|---|---|---|---|---|
| | July 18-19 | | August 20-21 | | September 12-13 | |
| | A | B | A | B | A | B |
| *Percopsis omiscomaycus* | 211 | 130 | 119 | 132 | 47 | 54 |
| *Catostomus* sp. | 16 | 239 | 2 | 7 | 1 | 8 |
| *Cottus* sp. | 1 | 6 | 1 | 2 | 2 | 12 |

Figure 10. Station locations for studies of the Dempster Highway crossing of Campbell Creek, N.W.T.



occurred to the highway itself. During the summer of 1972, the roadbed was built up approximately 5.5 m above the culverts and rip-rapped with boulder-sized dolomite. In the spring of 1973 water levels had risen to within two feet of the top of the culverts by the third week of May. By the end of that month the creek had overflowed the highway causing surface erosion and also carrying parts of the road away. At this time the Creek was 4 to 5 times its mid-summer width which is approximately 10 m. Within a week, waters had subsided and most of the flow occurred through the culverts again.

In 1972 and 1973, when the flood waters subsided, water velocities through the culverts were too fast to be measured with a Gurley Pygmy flowmeter but were estimated, in early June 1973, to be at least 3.5 m $sec^{-1}$ just after peak flooding had occurred. By early July 1973 water velocity through the culverts was .06 m $sec^{-1}$. High water velocities through the culverts just after peak flood period aggravated erosion of flattened areas of fill adjacent to the crossing. Large vortices were evident approximately 6 m from the point of discharge of water from the culverts. The fill areas still had not stabilized by spring of 1973 and visible amounts of sediment were being introduced into the water downstream of the crossing. The upstream stations had substrates composed of gravel with some finer sediments. Downstream, a visibly silty layer covered the creek bed.

During the 1973 flood period, the Creek at the crossing was exposed to considerable angling pressure. Interviews of anglers revealed that no fish were being caught upstream of the culverts but that large numbers of pike (most of which had mature gonads) were being taken downstream, along with smaller numbers of broad whitefish. By mid-June, large numbers of broad whitefish were observed in eddies from the downstream vortices. By the third week in July, pike were caught in gillnets above and below the culverts but no whitefish were taken.

b) Methods

Sampling stations were set up at 500 m and 800 m above the crossing (station numbers 1 and 3 respectively) and 500 m and 800 m below the crossing (station numbers 2 and 4 respectively) (Fig. 10). Water samples were taken at stations 1 and 2 throughout the study (July 1972 to September 1973) and at stations 3 and 4 on some of the 1973 sampling dates. Determinations were made of the same physical and chemical parameters as outlined for the Caribou Bar Creek and Martin River studies above.

Benthic invertebrates were sampled by Burton-Ekman grab (Burton and Flannagan, 1973) and sometimes by Ponar grab[2] at either or both of the

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[2] The Burton-Ekman grab was used when the substrate was composed of fine sediment and the Ponar was used when the substrate was mainly gravel. We have assumed that each grab worked at 100% efficiency in each type of substrate.

stations established at 500 and 800 m upstream and downstream of the crossing. Three samples were taken at equal intervals across the width of the creek bed and combined. The samples were live-sorted under an illuminated magnifier and the specimens preserved in 70% ethyl alcohol. The sediments remaining were sent to our Winnipeg laboratory for particle size determinations (Jenning, Thomas, and Gardiner,1922) and analysis of organic matter (Jackson, 1956).

c) Results

Table 12 shows suspended sediment concentrations above and below the highway crossing. Only July 14, 1972 shows a considerable difference between stations. Most of the suspended sediment transport likely occurred during the spring flood period in May and June. Table 13 gives a particle size analysis of bottom sediments above and below the crossing. Stations 2 and 4 below the crossing show a slightly higher proportion of fine sediments (as reflected in the mean value of 64.06%) than stations 1 and 3 above the crossing (mean of 58.48% fine sediments). The presence of more fine sediments at stations below the crossing can be seen better on the dates for which samples were taken simultaneously above and below the crossing (September 19, 1972; June 25 and 27, 1973; and August 20, 1973). The fine sediment observed covering the stream bottom below the crossing and detected in the particle size analyses likely originated from the road fill and adjacent disturbed areas.

Bottom sediments contained approximately the same percentage of organic matter above and below the crossing (mean values of 11.20 and 9.40% respectively; see Table 13). Other physical and chemical parameters were similar above and below the crossing as well.

The results of macrobenthic sampling are shown in Tables 14 and 15. The creek was not sampled during the 1972 flood period. The 1973 flood period (May 31) showed higher numbers of Oligochaeta, Gastropoda, Chironomidae, and Pelecypoda downstream from the crossing. Pelecypoda require a soft bottom in which to burrow (e.g., see Gale, 1971). Increases in numbers of Oligochaeta and Chironomidae are likely responses to increased sedimentation as described by Hynes (1973) and Nuttall and Bielby (1973). Reports of the effects of increased suspended and settled sediments on the occurrence of Gastropoda are scarce. Nuttall (1972) stated that *Lymnaea pereger* occur in high numbers in organically rich muds. The occurrence of high numbers of Gastropoda below the crossing is likely a result of the silty and organically rich substrate at the downstream station. The relationship, however, is not clear. Gastropoda are usually browsers so they would be affected by decreases in organic matter (e.g. periphyton and macrophytes) in the substrate rather than by changes in the particle size distribution of the substrate. The distribution of periphyton and macrophytes is generally adversely affected by increases in suspended and/or settled sediments (see Section I, and also Edwards, 1969).

The results for all other sampling periods for three of the four major

Table 12. Suspended sediment concentrations (mg liter$^{-1}$) above and below the Dempster Highway crossing of Campbell Creek, N.W.T.

| DATE | CONCENTRATION | |
|---|---|---|
| | Above | Below |
| July 5, 1972 | 9.15 | 12.00 |
| July 14, 1972 | 2.40 | 28.20 |
| August 11, 1972 | 2.45 | 2.85 |
| September 19, 1972 | 7.30 | 8.92 |
| November 23, 1972 | 17.50 | 18.00 |
| May 31, 1973 | 13.30 | 11.20 |
| June 27, 1973 | 9.31 | 7.72 |
| August 20, 1973 | 6.00 | 7.70 |
| September 17, 1973 | 6.93 | 4.17 |

Table 13. Particle size distribution of bottom sediments above and below the Campbell Creek highway crossing.

| DATE | STATION | PERCENT COMPOSITION+ | | | |
|---|---|---|---|---|---|
| | | Above | | Below | |
| | | Coarse* | Fine° | Coarse | Fine |
| July 17, 1972 | 2 | | | 23.41 | 73.20 |
| August 11, 1972 | 2 | | | 53.71 | 44.00 |
| September 19, 1972 | 1 | 62.29 | 32.80 | | |
| September 19, 1972 | 2 | | | 31.58 | 58.00 |
| November 24, 1972 | 2 | | | 34.23 | 57.00 |
| June 25, 1973 | 1 | 14.81 | 57.19 | | |
| June 27, 1973 | 3 | 32.13 | 59.20 | | |
| June 27, 1973 | 2 | | | 18.95 | 59.60 |
| June 27, 1973 | 4 | | | 10.17 | 80.00 |
| August 20, 1973 | 1 | 16.03 | 76.00 | | |
| August 20, 1973 | 3 | 26.04 | 67.20 | | |
| August 20, 1973 | 2 | | | 11.78 | 80.00 |
| August 20, 1973 | 4 | | | 8.51 | 79.20 |
| Mean values | | 30.26 | 58.48 | 24.04 | 66.34 |

+ % $H_2O_2$ loss on ignition (i.e. % organic matter) = 100.00 - (% coarse + % fine)

* Includes sand (2 to 0.05 mm) and larger diameter particles

° Includes silt (0.05 to 0.002 mm) and clay (<0.002 mm) fractions

Table 14. Standing crops (number $m^{-2}$) of commonest invertebrates above (A) and below (B) the Dempster Highway crossing of Campbell Creek, NWT.[α]

| DATE | TAXON | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Oligochaeta | | Gastropoda | | Pelecypoda | | Chironomidae | |
| | A | B | A | B | A | B | A | B |
| July 17, 1972 | 630 | 112 | 4228 | 224 | 378 | 798 | 308 | 182 |
| August 11, 1972 | 280 | 434 | 112 | 56 | 126 | 1204 | 98 | 476 |
| November 24, 1972 | 126 | 0 | 210 | 700 | 70 | 2520 | 28 | 1246 |
| May 31, 1973[+] | 120 | 434 | 0 | 742 | 0 | 98 | 63 | 252 |
| June 27, 1973 | 357 | 405 | 63 | 49 | 763 | 1106 | 182 | 56 |
| August 20, 1973* | 63 | 79 | 32 | 104 | 466 | 186 | 82 | 209 |
| September 17, 1973 | 147 | 56 | 553 | 126 | 1897 | 1001 | 273 | 189 |

α Values are means when more than one station was involved above or below crossing.

\+ All "A" samples taken by Ponar grab.

* All samples taken by Ponar grab.

Table 15. Standing crops (number $m^{-2}$) of less frequently-occurring invertebrates above (A) and below (B) the Dempster Highway crossing of Campbell Creek, NWT.[α]

| DATE | TAXON | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nematoda | | Hirudinea | | Odonata | | Ephemer-optera | | Trichoptera | | Ceratopo-gonidae | | Hydracarina | |
| | A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| July 17,1972 | 28 | 0 | 14 | 0 | 14 | 0 | 0 | 0 | 112 | 14 | 742 | 0 | 224 | 14 |
| August 11,1972 | 0 | 0 | 518 | 0 | 14 | 0 | 56 | 0 | 28 | 14 | 14 | 0 | 0 | 14 |
| Nov. 24,1972 | 0 | 140 | 0 | 0 | 0 | 0 | 0 | 0 | 14 | 0 | 28 | 294 | 14 | 0 |
| May 31,1973[+] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 |
| June 27,1973 | 26 | 14 | 7 | 0 | 0 | 0 | 0 | 0 | 49 | 0 | 0 | 0 | 0 | 0 |
| Aug. 20,1973* | 0 | 25 | 13 | 0 | 0 | 0 | 0 | 3 | 0 | 9 | 0 | 6 | 13 | 3 |
| Sept. 17,1973 | 0 | 0 | 28 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 14 |

α Values are means when more than one station was involved above or below crossing.

\+ All "A" samples taken by Ponar grab.

* All samples taken by Ponar grab.

taxa (Table 14) are difficult to interpret. Only the Pelecypoda, which require a fine sediment bottom, occur in consistently higher densities downstream of the crossing, except for the last two sampling dates.

Like the taxa of most frequent occurrence, those of lesser frequency show trends toward a sediment-disturbed fauna but the results are once again inconclusive (Table 15). The Nematoda, Ephemeroptera, and Ceratopogonidae do not show clear trends in frequency of occurrence or standing crop. The Hirudinea always occurred above the crossing. Little information as to the effects of suspended sediment on leeches is available from the literature. However, Nuttall (1972) noted that *Glossiphonia complanata* and *Erpobdella octoculata* often occur in high numbers in organically rich muds. Like the Gastropoda, the situation is not as simple as that. Both occurrences of Odonata were above the crossing and not below. The Odonata are strictly predaceous and hunt by sight. Reduction in the abundance of their prey[3] by increased sedimentation and reduced visibility in turbid waters would adversely affect dragonfly larvae. The Trichoptera occurred more frequently and usually were more abundant above the road crossing. Hynes (1973) reported decreases in abundance of caddisflies due to increased sedimentation. Nuttall and Bielby (1973) reported absences or significant reductions of the species of Trichoptera of their study concerning china-clay sedimentation. Three species of Trichoptera were eliminated by sand deposition which had no effect on a third (Nuttall, 1972). In general, Trichoptera are extremely sensitive to most environmental disturbances (e.g. see Brunskill *et al.*, 1973); thus, the scarcity of Trichoptera below the crossing is a typical reaction for this group. The Hydracarina occur a similar number of times above and below the crossing but standing crops of water mites are usually higher above the road crossing. Nuttall and Bielby (1973) recorded a decline in the numbers of Hydracarina in clay-polluted stations of their study.

From visual observations, the site has been subjected to obvious increased sediment supply from road fill and erosion of adjacent disturbed terrain. However, although the benthic invertebrate fauna does show trends typical of responses to increased sedimentation, these trends are not consistent. The sometimes extreme fluctuations in benthic invertebrate standing crops suggest that the area is naturally unstable. Benthic invertebrate communities may be in the process of recovery, only to be interrupted by another flood. It should be noted that the area was extremely difficult to sample adequately for benthic invertebrates because of the differences in substrate above and below the crossing. Also, the watershed is very complex hydrologically. For example, East Channel water during high discharge periods flows into Campbell Lake, raising the lake level and causing water to back up into Campbell Creek. The effect of this hydrological complexity upon the benthic macroinvertebrate fauna is not understood.

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3 "... dragonfly larvae are facultative feeders on whatever is palatable, most readily available, and of a suitable size ..." (Corbet, 1963; p. 64).

## D. Summary

1. A retrogressive-thaw flow slide which occurred in mid-August 1972 added an estimated 2000–2600 metric tons of sediment to Caribou Bar Creek, Y.T. Analyses of physical and chemical parameters of the water from May to September 1973 showed that the mudslide was measurably active in June but not for the rest of the open-water season. Benthic invertebrates had recovered from the effects of the mudslide by mid-September 1972, approximately one month after it occurred, and were not affected by the mudslide during the period May to September 1973. The use of Chironomidae as indicators of the increased sedimentation in Caribou Bar Creek is discussed.

2. Ecological studies of the impact of the right-of-way slash, winter road, and temporary bridge crossings of the Martin River, N.W.T. by the Mackenzie Highway were continued during May to September, 1973. This completed approximately 14 months of continuous study of the crossings. Analysis of physical and chemical parameters of the water and populations of benthic invertebrates and fishes showed that the crossings continued to have no adverse effects on the river ecosystem.

3. A bi-culverted crossing of Campbell Creek, N.W.T. by the Dempster Highway appeared to have prevented upstream passage by populations of northern pike and broad whitefish. Fine sediment, seen to cover the Creek bottom downstream of the crossing, probably originated from road fill and adjacent disturbed areas. Physical and chemical parameters of the water showed no major differences above and below the crossing. However, bottom substrates had a slightly higher proportion of fine sediments at the downstream stations than those upstream of the crossing. Benthic invertebrate populations downstream of the crossing tended to be typical of areas disturbed by increased sedimentation. The inconclusive data on benthic invertebrates is likely due to the hydrologic complexity of the Creek in the vicinity of the crossing.

## III. THE EFFECT OF CONTROLLED SEDIMENT ADDITION ON MACROINVERTEBRATE DRIFT

### A. Introduction

The value of zoobenthos as indicators of disturbances to aquatic ecosystems is widely accepted (e.g. see Aston, 1973; Brundin, 1949; Goodnight, 1973; Liebmann, 1951; Olive and Dambach, 1973; Weber, 1973; Wiederholm, 1973). Zoobenthos are also important as elements of the food web of fishes (e.g. see Elliott, 1973; Hunt and O'Hara, 1973; Mundie, 1969; Waters, 1969). Zoobenthos are therefore an important part of the aquatic community to study with respect to environmental disturbance.

The term "drift" refers to the downstream transport of insects and other invertebrates in flowing waters (Waters, 1972) and is characteristic of these systems. The effects of disturbances such as flooding and application of toxicants (e.g. pesticides) on flowing water ecosystems are usually manifested by increases in the numbers of drifting organisms (e.g. see Elliott, 1967; Anderson and Lehmkuhl, 1968; Minshall and Winger, 1968). Besch (1966) suggested the use of drift to compare different reaches of polluted waters. Therefore, drift can be used as an indicator of disturbance to a stream ecosystem. Also, samples of drift are usually free of the debris associated with benthic samples and are thus easier and faster to process. This factor is an obvious advantage to studies such as this one.

We are here concerned with disturbances arising from pipeline and highway construction resulting in increases in concentrations of suspended sediments, and the effects on northern freshwater biota. The detrimental effects of increased sedimentation on freshwater biota have already been discussed in Section I. Such studies are usually descriptive (e.g. see Nuttall and Bielby, 1973). Experimental approaches to this problem are rare. It is clear that descriptive studies are self-limiting. To study the mode of action of suspended and settled sediments, and the responses of freshwater fauna to known concentrations of suspended and settled sediments, an experimental approach is necessary. One of the aims of our research will be to provide information useful in developing guidelines and setting tolerance levels of suspended sediment for streams, rivers, and lakes subjected to northern construction activities.

Alabaster (1972) and Hynes (1973) have reviewed the results of laboratory and field bioassays and sediment addition studies on different species of fishes, and Lewis (1973) has reported an experimental study on the effects of coal dust on an aquatic moss. These papers have already been discussed in Section I above.

The only recent experimental study involving zoobenthos was a sediment addition study by Gammon (1970) on a river in Indiana. The stream had stable flows from July through November which typically averaged less than 0.27 $m^3$ $sec^{-1}$. Substrate in the test section was composed of the following particle sizes (values are average percent by weight of several samples): >4 mm - 70.8%; 0.125 to 4 mm - 13.4%; <0.125 mm - 20.7%. The sediment added to the test section originated from one of the settling basins of the rock quarry which operated near the stream. Gammon did not give a particle size analysis of the sediment used, but for the effluent from the settling basins, the particle size distribution is shown in Table 16(a). Gammon reported some visible deposition of sediment by the end of some additions but did not identify the concentrations of suspended sediment involved. Gammon reported that the numbers of macroinvertebrates drifting increased in a roughly linear fashion with increases in sediment added to the stream up to approximately 160 mg liter$^{-1}$ (Table 16 [b]). He gave no explanation for the drop in numbers drifting at the two highest concentrations of suspended sediment used (154.5 and 271.3 mg liter$^{-1}$; Table 16[b]). The lower percent increases at these concentrations could be reflecting a depletion of the standing crop of benthic macroinvertebrates in the upper part of the stream substrate. Unfortunately he did not treat his data with a thorough statistical analysis. Also, it is difficult to understand his view that suspended rather than settled sediments caused the increase in drift. Most benthic macroinvertebrates inhabit the interstices between stones in the classical, gravel-bottomed stream substrate (like the one of Gammon's study and this one) and on the surfaces of these stones (Nuttall and Bielby, 1973; Hynes, 1973). Therefore, the sediment must settle first in order to evoke a response from the macroinvertebrates. (This assumption, of course, need not apply to filter feeders such as blackfly larvae.) Gammon also concluded that the entire benthic macroinvertebrate community was similarly affected by the added sediments because animals found in the drift during experimental and control periods were present in approximately the same taxonomic proportion as in the stream bottom. He did not present any data on percent composition or the taxa involved other than the observation that Chironomidae comprised 60% of the bottom and drifting macrobenthos.

The first of a series of experimental studies on the effects of artificially increased suspended sediment concentrations on various aspects of benthic macroinvertebrate life in northern flowing waters was carried out in the summer of 1973 on a small, northern river. This initial study dealt with the response of benthic macroinvertebrates, as measured by numbers of animals, taxonomic composition, and biomass in the drift, to addition of pre-determined concentrations of riverbank sediment. The effect on numbers of animals is reported herein.

## B. Methods

The Harris River is a brown-water river which flows southwesterly through low lying muskeg for about 50 km and enters the Mackenzie River directly east of Ft. Simpson (Fig. 11). Its total watershed area comprises about 740 km$^2$ and it lies in an area of discontinuous permafrost (Crampton, 1973). It is in sub-boreal forest of the northward extension of the interior plains biome (Burns, 1973). The river drains an area of low topographic relief (165-330 m) through silty-clay moraine (Crampton, 1973) of Devonian argillaceous shale and limestone. Total discharge of the river in 1973 was 16.8 x 10$^6$ m$^3$ (Water Survey of Canada, unpublished data). The river is covered by ice from October to April and, in

Table 16(a). Particle size distribution of quarry sediment as taken from quarry effluent (from Gammon, 1970). (Values are percent of material by weight finer than indicated size).

| DIAMETER | REPLICATE | | |
|---|---|---|---|
| (microns) | 1 | 2 | 3 |
| 125.0 | 95 | 98 | 98 |
| 62.5 | 91 | 96 | 97 |
| 44.2 | 88 | 91 | 95 |
| 31.2 | 87 | 85 | 85 |
| 22.1 | 85 | 46 | 39 |
| 15.6 | 56 | 2 | 1 |
| 11.0 | 8 | - | - |
| 7.8 | 2 | - | - |

Table 16(b). Percent increases in number of macroinvertebrates drifting caused by additions of known amounts of suspended sediment (from Gammon, 1970).

| ADDED SOLIDS (mg liter$^{-1}$) | % INCREASE IN NUMBERS DRIFTING |
|---|---|
| 18.6 | 25.9 |
| 54.3 | 32.0 |
| 84.3 | 45.7 |
| 104.7 | 89.5 |
| 135.5 | 118.5 |
| 154.5 | 101.7 |
| 271.3 | 88.8 |

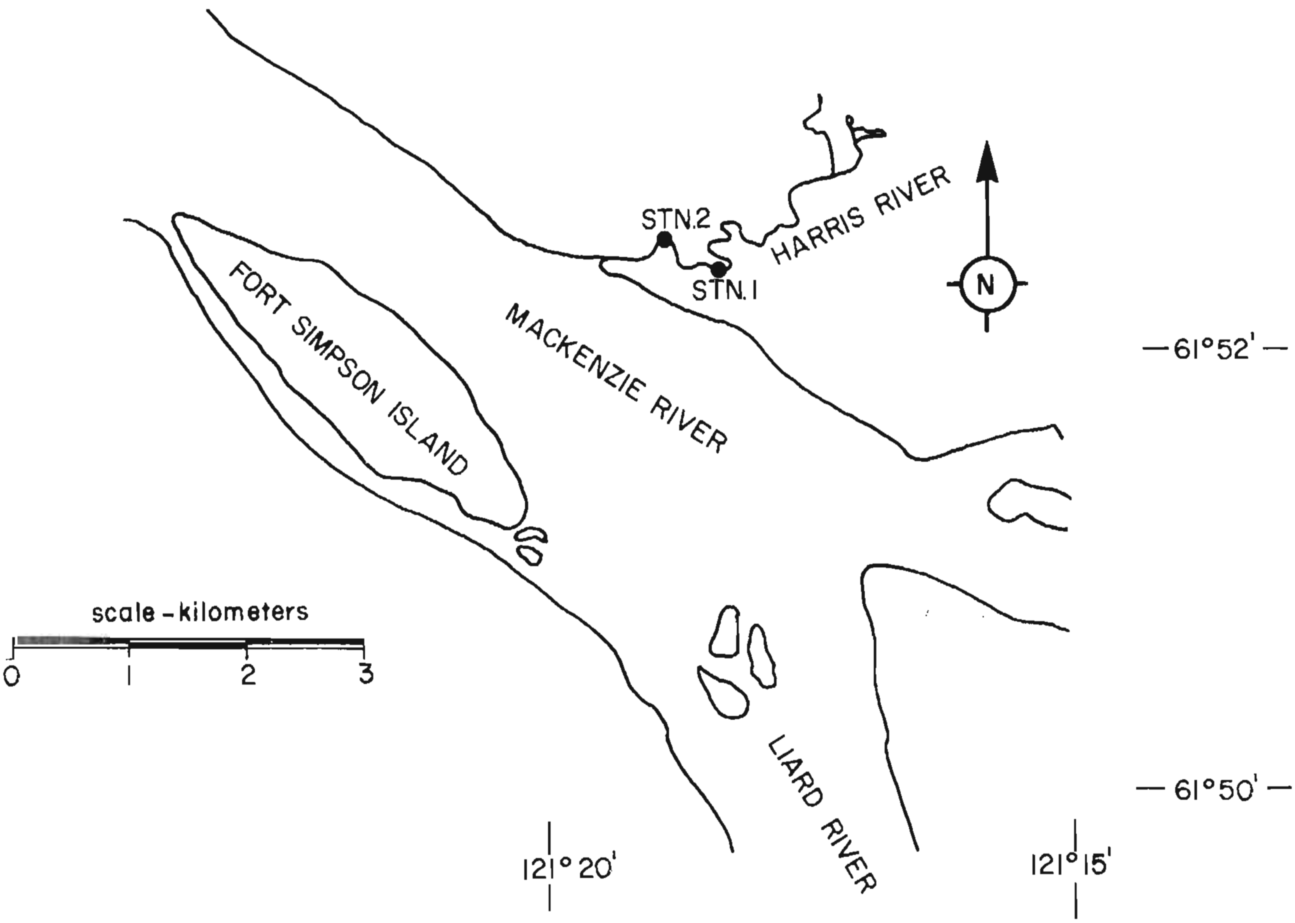



Figure 11. Location of the Harris River, N.W.T.

the experimental section, riffles and usually pools are frozen to a depth of several centimeters. Ranges for chemical and physical parameters are given in Table 17. Water depth in mid-channel ranges from 0-≃1.5 m. A more thorough description of the watershed area can be found in Northern Pipelines Task Force publications such as Brunskill *et al.* (1973), Burns (1973), Crampton (1973), Strang (1973), and Tarnocai (1973).

The Harris River was chosen as the site of the proposed experiments because it was sufficiently small to manipulate, a suitable source of sediment was nearby, and two years of chemical and biological background data had been collected for the river.

Experiments were done at Station 2 (61°52'N x 121°19'W) on the river (Fig. 11). Here the river is a pool-riffle-pool sequence. To the north, a cutbank, approximately 15 m high, rises abruptly from the water. The south bank, about one meter high, is separated from the main flow during periods of low discharge (July to September) by 5 to 10 m of dry river bed. This area is flooded during high discharge periods (May to June) or during storms. The riffle, during the period of experimentation, was 25 to 30 m long and 5 to 10 m wide. The experimental section was located at this riffle. River substrate at the riffle was mainly friable and fissile chloritic shale with admixtures of silt and finer particles, and fine and coarse gravels. A few boulders, not exceeding 0.5 m in diameter were also present. The soft, fragile nature of the shale made accurate particle size determinations of the bottom sediments difficult. However, two samples examined for silt and smaller sized particles yielded 16.80% and 18.49% by weight of these materials. One experimental sediment addition (65 mg liter$^{-1}$) was done approximately 0.2 km upstream of the riffle in an area of slower flow and more uniform shale bottom.

Seven separate sediment additions were carried out from July to September, 1973. The intended concentrations of suspended sediment used were 10, 20, 30, 65, 100, 250, and 500 mg liter$^{-1}$. To introduce a weight of sediment that would yield the desired concentration the following formula was used:

$$D = X \times A \times \bar{V} \times 60$$

where:
$D$ = addition rate (g min$^{-1}$)
$X$ = desired concentration (mg liter$^{-1}$)
$A$ = cross-sectional area of the test section (m$^2$)
$\bar{V}$ = mean water velocity of the test section (m sec$^{-1}$)

An experimental section 15 m long and 1 to 3 m wide (the latter was dependent on discharge) was delineated within the riffle for each experiment. Discharge of the test section was measured before each run (Brunkill *et al.* 1973) and D calculated for the sediment concentration to be used. Attempts were made to cease all instream activity one-half to one day prior to the experiment or were limited to areas downstream of the test section.

Two types of sediment dispenser were used:

1. Three garbage cans with square holes, 10 and 7.5 cm wide

Table 17. Some physical and chemical parameters near the mouth of the Harris River, N.W.T. (from Brunskill *et al.*, 1973).

| PARAMETER | RANGE |
|---|---|
| mean velocity (m $sec^{-1}$) | 0.133-0.653 |
| conductivity (μmho $cm^{-1}$ at 25°C) | 170-450 |
| temperature (°C) | 0-22.0 |
| dissolved oxygen (mg $liter^{-1}$) | 3.8-9.6 |
| pH | 7.3-8.1 |
| Ca (Moles $m^{-3}$) | 0.54-1.7 |
| Mg (Moles $m^{-3}$) | 0.29-0.88 |
| Na (Moles $m^{-3}$) | 0.16-1.8 |
| K (Moles $m^{-3}$) | 0.02-0.05 |
| $SO_4$ (Moles $m^{-3}$) | 0.27-0.76 |
| Cl (Moles $m^{-3}$) | <0.01-0.06 |
| $HCO_3$ (Moles $m^{-3}$) | 0.88-5.2 |
| total dissolved N (mMoles $m^{-3}$) | 10-74 |
| total dissolved P (mMoles $m^{-3}$) | 0.27-1.1 |
| Si (mMoles $m^{-3}$) | 35-87 |
| Fe (mMoles $m^{-3}$) | 0.20-5.9 |
| Mn (mMoles $m^{-3}$) | 0-0.50 |
| suspended sediment (g $m^{-3}$) | <0.20-5.6 |
| total suspended sediment (metric tons $day^{-1}$) | 0.0005-2.6 |
| Secchi depth (m) | 0.56->1.0 |
| color | red, brown |
| suspended C (mMoles $m^{-3}$) | 7.9-140 |
| suspended N (mMoles $m^{-3}$) | 0.68-21 |
| suspended P (mMoles $m^{-3}$) | 0.05-0.90 |

opposite one another at the bottom of the can were used for periods of higher discharge (Fig. 12[a]).

2. A 240 x 30 cm plywood trough with square holes 10 and 5 cm wide opposite to each other at the bottom of the trough and at 30 cm intervals along the trough was used for periods of lower discharge (Fig. 12[b]). The larger holes of both types of dispensers always faced upstream.

The sediment was added as a stream water slurry from buckets by people standing behind the dispensers on a plank suspended above the river bottom. The sediment used was obtained from the cutbank just below the experimental section (Fig. 12). Pre-weighed subsamples of the sediment used in each run were oven-dried at 105°C for 24 hr and a correction for moisture made before D was calculated. The subsamples were then sent to our Winnipeg laboratory for particle size determinations (Jenning, Thomas, and Gardiner, 1922) and analyses of organic matter (Jackson, 1956).

Temperature, conductivity, pH, dissolved oxygen, and $HCO_3^-$ concentration of the water were measured before and after each experiment according to methods described in Brunskill *et al.* (1973, App. VII). Two liter water samples for suspended sediment analyses were taken half-way through each sediment addition period at 0, 7.5, and 15 m distance downstream from the dispenser. Halfway through each control period, samples were taken 15 m downstream from the dispenser. Samples were collected from planks suspended above the river bottom so that sampling personnel did not walk on the experimental or control stream bed, or upstream of it. Bottom sediment samples for particle size and organic matter analyses were taken at upstream and downstream ends of the experimental sections, and above the experimental section after each experiment. Intervals between experiments were approximately one week. Experiments were started at 1400 hr.

An experiment consisted of six alternating 15 min periods of control and sediment addition (= runs). Driftnets (10 x 10 cm aperture, a 76 cm long 200μ mesh Nitex bag) were installed 15 m downstream from the sediment dispenser. Width of the experimental section was established by releasing a few short bursts of sediment from the dispenser and placing the outermost driftnets well within the plume at the downstream end. Driftnets were changed and emptied at the end of each 15 min period.

Invertebrate collections by three of the nets were destined for weighing and those of the other three for species composition determination. In addition, three Surber samples (200μ mesh, 0.09 $m^2$) were taken (Brunskill *et al.*, 1973) above the test section to determine biomass and species composition of benthos in the bottom substrate.

Because of recent findings that biomass determinations made on long-preserved zoobenthos are underestimates (e.g. Howmiller, 1972; Stanford, 1973) and the finding that no appreciable change in weight results if 100% formalin is used (O.A. Saether, personal communication), driftnet samples intended for biomass determination were preserved in 70% ethyl

Figure 12. Sediment dispensers used in the Harris River sediment addition experiments: (a) for high discharge periods; (b) for low discharge periods. Water flow is toward the viewer. Note cutback, from which sediment was obtained, to the side. Sediment dispensers and plank from which sediment slurry was poured are at the top of the channel. Water samples for suspended sediment analysis at 7.5 m were taken off the plank at mid-channel. Driftnets are at the lower end of the channel.

A

B

alcohol if they could be sorted immediately and in 100% formalin if they were to be stored for longer than a week before sorting. Species composition samples (the other driftnet samples and the Surber samples) were preserved in 70% ethyl alcohol. Sorting was done in the laboratory under a binocular microscope. Biomass samples will be dried at 105°C for 24 hr then ashed at 525°C for 24 hr. (Data from the Surber samples and the drift biomass samples are not yet available.)

The following hypotheses were being tested:

1. No significant difference exists between numbers of animals drifting during control and sediment addition periods.

2. No significant difference exists between numbers of animals drifting among the different sediment loads added.

3. No relationship exists between numbers of animals drifting and sediment load added.

4. No significant difference exists in percent increase of animals drifting during control and sediment addition periods.

5. No significant difference exists in percent increase of animals drifting during runs of each experiment.

6. No significant difference exists in mean percent increase of animals drifting among the seven sediment loads added.

7. No significant difference exists in mean numbers of animals drifting between control and sediment addition periods for each sediment load added.

The following statistical analyses were made:

1. Analysis of variance using a 2 x 7 factorial design (Steel and Torrie, 1960) to identify the significance of:

   a) numbers of animals drifting during control versus sediment addition (= treatment).

   b) numbers of animals drifting during different sediment additions (= loads).

   c) the interaction between numbers of animals drifting and sediment load.

These are tests of hypotheses 1, 2, and 3, respectively. Calculations were done on log transformations of the total number of animals drifting in the three replicates within each run.

2. A two-way analysis of variance (Steel and Torrie, 1960) to identify the significance of runs and treatments (tests of hypotheses 4 and 5, respectively). Calculations were done on the square root of the percent increase in numbers of animals drifting from control to treatment periods

(Steel and Torrie, 1960). Percent increase was calculated by the formula:

$$\frac{T_s - T_c}{T_c} \times 100$$

where: $T_s$ = sum (3 replicates for each run) of animals drifting during treatment period.
$T_c$ = sum (3 replicates for each run) of animals drifting during control period.

3. Tukey's Test (Steel and Torrie, 1960) to compare mean percent increases in drift among the seven sediment loads for significance (a test of hypothesis 6). Mean of the root of percent increases in the three runs within each sediment load was used.

4. Comparisons for significance of the mean numbers of animals drifting between control and treatment periods for each sediment load were done (a test of hypothesis 7). The following formula (Steel and Torrie, 1960) was used to calculate the value of 2 standard deviations for the data:

$$s_{\bar{x}} = \frac{\sqrt{\text{error mean square}}}{r} \times 2$$

where: r = number of replicates.

Log of mean number of animals drifting in the 3 runs for control and treatment periods was used. Error mean square was obtained from the factorial design analysis described above. Control and treatment means were considered significantly different if their difference exceeded the value of $2s_{\bar{x}}$.

In order to give an estimate of the range of total numbers of macrobenthic invertebrates drifting from the cross-sectional width of the experimental section and of the whole stream at the experimental section during control and sediment addition periods, the method of Elliott (1970) was used. Estimates of the range of percent of the total standing crop caused to leave the experimental section because of sediment addition were also made. Calculations were done using data from the sediment loads which yielded the least and greatest difference in mean numbers of macrobenthos drifting between control and sediment addition periods.

## C. Results and Discussion

During the experiments, discharge varied from 1.9330 to 0.0155 $m^3sec^{-1}$ for the entire riffle and from 0.4140 to 0.0155 $m^3sec^{-1}$ in the experimental section (Table 18). Mean water velocity of the experimental section varied from 0.545 to 0.075 m $sec^{-1}$ (Table 18). Temperature, pH, conductivity, dissolved oxygen, and carbonate did not show any change as a result of short-term sediment additions (Table 19).

Particle size distributions and percent organic carbon of the bankside

Table 18. Discharge of the riffle ($Q_T$) and the experimental section of the riffle ($Q_P$) and mean water velocity ($\bar{V}$) of the experimental section for sediment additions on the Harris River, N.W.T.

| DATE (all 1973) | $Q_T$ ($m^3$ $sec^{-1}$) | $Q_P$ | $\bar{V}$ (m $sec^{-1}$) |
|---|---|---|---|
| July 4 | 1.9930 | 0.3390 | 0.469 |
| July 13 | 0.7144 | 0.4140 | 0.480 |
| July 27 | 0.1599 | 0.1014 | 0.210 |
| August 3 | 0.0267 | 0.0267 | 0.090 |
| August 11 | 0.0155 | 0.0155 | 0.101 |
| August 17 | 0.0260 | 0.0260 | 0.075 |
| September 9 | 0.1426 | 0.0793 | 0.545 |

Table 19. Water chemistry done before and after each sediment addition experiment.

| DATE (all 1973) | INTENDED SEDIMENT CONCENTRATION (mg liter$^{-1}$) | TEMPERATURE (°C) | | pH | | CONDUCTIVITY (μ mho cm$^{-1}$ at 25°C) | | DISSOLVED OXYGEN (mg liter$^{-1}$) | | BICARBONATE (moles m$^{-3}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Before | After | Before | After | Before | After | Before | After | Before | After |
| July 27 | 10 | 23.0 | 23.0 | 7.92 | 7.90 | 245 | 246 | 6.52 | 6.48 | 3.10 | 3.14 |
| Sept. 9 | 20 | 13.0 | 13.0 | 8.80 | 8.20 | 305 | 320 | 9.10 | 9.20 | 3.82 | 3.64 |
| Aug. 3 | 30 | 21.0 | 21.5 | 7.93 | 7.94 | 300 | 340 | 5.60 | 5.60 | 3.72 | 3.76 |
| July 4 | 65 | 19.0 | -* | 7.90 | - | 260 | - | 7.00 | - | 2.26 | - |
| July 13 | 100 | 21.2 | 21.5 | 8.37 | 8.10 | 240 | 190 | 6.48 | 6.52 | 2.46 | 2.42 |
| Aug. 11 | 250 | 22.7 | 22.8 | 7.90 | 7.92 | 250 | 250 | 6.62 | 6.60 | - | - |
| Aug. 17 | 500 | 12.5 | 13.0 | 7.94 | 7.94 | 230 | 260 | - | - | 3.92 | 3.90 |

* not measured

sediment used are shown in Table 20. It can be seen that silt was the dominant component of the bankside sediment used. Sand-sized particles composed approximately 25% of the bankside sediment. Breakdown of the sand sizes revealed that almost half was included in the smaller size categories (0.25 to 0.05 mm diameter).

Technical problems (sampling and analysis) prevented the use of particle size determination data from the stream bottom samples taken at the end of each experiment. Analysis was extremely difficult because of the brittle nature of the predominantly shale bottom sediments and settled sediment was not distinguishable from disintegrated shale shingles after sampling.

No change in suspended sediment concentration of samples taken during the three control periods was evident (Table 21). Approximately 85% of the sediment added in each experiment had settled to the stream bottom after the first 7.5 m and 90% by 15 m (the end of the experimental channel). Only the 250 and 500 mg liter$^{-1}$ concentrations left noticeable residues of sediment on the stream bottom after the experiment had been completed. Only the 30 and 500 mg liter$^{-1}$ concentrations were reasonably close to the intended concentration (as measured just below the dispenser outfall) (Table 21). The main reasons for the disparity between intended and actual suspended sediment concentrations are likely:

1. inadequacies of the empirical formula used to determine application rate (e.g. particle size distribution of the sediment used and turbulence or other uneven flow patterns were not considered).

2. difficulties in standardization of application (pouring) rates of the sediment slurry, resulting in time variations in suspended sediment concentrations during the experiment. Sherk (1971, p. 47) identified "the difficulty in maintaining experimental sediment levels" as a research problem in studies of the effects of sediment on aquatic biota. Additions of sediment at more points along the test channel should produce a more even application in future studies.

If the experiments are arranged in the order in which they were done, distinct seasonal differences are apparent in mean numbers of zooplankton (mainly Copepoda, Cladocera, and Ostracoda) and macrobenthos drifting (Table 22). The same range of variation is not apparent in the data presented by Gammon (1970) over the period June 26 to October 12 for mean numbers of benthic invertebrates drifting in an Indiana stream. The influence of variation due to season was reduced as much as possible by the statistical analyses described above.

Differences, expressed as percent increase or decrease, in numbers of drifting organisms from control to sediment addition periods for macrobenthos, zooplankton, and total numbers of invertebrates (= macrobenthos plus zooplankton) are shown in Table 23.

The zooplankton probably originated in the many pool areas upstream of the experimental site and/or existed just above the bottom substrates and were able to persist in the river because of its low water velocity (Table 18).

Table 20. Particle size distribution and percent dry weight (105°C) organic carbon of bankside material used in sediment addition experiments.

| BATCH | PERCENT COMPOSITION | | | |
|---|---|---|---|---|
| | Sand (2 to 0.05 mm) | Silt (0.05 to 0.002 mm) | Clay (<0.002 mm) | Organic carbon (Moles $gram^{-1}$ dry wt) |
| 1* | 23.26 | 53.05 | 23.69 | 7.69 |
| 2 | 38.1 | 54.4 | 4.8 | 2.7 |
| | 24.8 | 39.2 | 26.4 | 9.6 |
| | 36.7 | 35.6 | 21.2 | 6.5 |
| 3 | 24.6 | 47.6 | 24.4 | 3.4 |
| | 29.4 | 21.7 | 43.2 | 5.7 |
| | 27.2 | 44.8 | 23.2 | 4.8 |
| 4 | 19.4 | 46.4 | 26.0 | 8.2 |

* Values provided courtesy of Dr. C. Tarnocai, Canada-Manitoba Soil Survey, Winnipeg.

Table 21. Total weight of sediment added, mean and range of suspended sediment concentrations at various distances below the sediment dispenser, and theoretical weight of sediment deposited per unit area of stream bottom. (No sediment was added during the control period. $M_A$ = theoretical weight of sediment per unit area of stream bottom).

| INTENDED SEDIMENT CONCENTRATION (mg liter$^{-1}$) | TOTAL WEIGHT OF SEDIMENT ADDED (g) | ACTUAL MEAN SUSPENDED SEDIMENT CONCENTRATION ACHIEVED* (mg liter$^{-1}$) DISTANCE BELOW DISPENSER (m) | | | CONTROL (@ 15 m) | $M_A$+ (g m$^{-2}$) |
|---|---|---|---|---|---|---|
| | | 0 | 7.5 | 15 | | |
| 10 | 3061.8 | 63.14(35.06-92.69) | 2.30(1.80-2.89) | 3.51(3.46-3.54) | 1.36(1.22-1.52) | 73.5 |
| 20 | 4616.9 | 36.59(7.39-63.22) | 13.87(7.36-18.05) | 5.88(4.24-7.19) | 0.58(0.43-0.68) | 260.9 |
| 30 | 2423.9 | 37.93(24.30-47.94) | 5.19(4.03-6.29) | 4.16(2.82-5.71) | 0.91(0.82-0.96) | 46.7 |
| 65 | 68890.5 | -** | - | 16.33(11.30-20.20) | 3.31(2.07-4.25) | 1635.0 |
| 100 | 126299.3 | 315.33(162.00-484.00) | 12.83(7.60-17.30) | 24.60(12.50-33.80) | 2.68(2.30-3.40) | 2898.6 |
| 250 | 11354.2 | 163.55(110.55-237.21) | 26.73(21.66-35.79) | 23.45(22.74-27.86) | 0.70(0.62-0.82) | 247.2 |
| 500 | 39803.4 | 478.06(435.33-530.29) | 106.95(70.41-130.14) | 61.60(56.59-71.12) | 0.95(0.80-1.05) | 944.7 |

* Range shown in parenthesis

\+ $M_A = \frac{W_T}{A} \times P_{\bar{x}}$

Where: $W_T$ = total weight of sediment added (g) during experiment (i.e. in 45 min)

$A$ = area of bottom used for the sediment addition experiment ($m^2$)

$P_{\bar{x}}$ = mean percent of sediment settled out. Calculated from suspended sediment concentrations at 15.0 m as a fraction of those at 0 m.

** not measured

Table 22. Seasonal differences in mean numbers of benthos and zooplankton caught in driftnets+ 15 m below the sediment dispenser(s) during control and sediment addition periods.

| INTENDED SUSPENDED SEDIMENT CONCENTRATION (mg $liter^{-1}$) | DATE OF EXPERIMENT (all 1973) | MEAN NUMBERS* | | | |
|---|---|---|---|---|---|
| | | MACROBENTHOS | | ZOOPLANKTON | |
| | | CONTROL | SEDIMENT ADDITION | CONTROL | SEDIMENT ADDITION |
| 65 | July 4 | 22.2(16-34) | 30.1(14-38) | 116.7(74-153) | 142.1(113-207) |
| 100 | July 13 | 21.1(14-34) | 34.0(20-48) | 83.3(71-104) | 99.4(81-114) |
| 10 | July 27 | 10.2(6-14) | 13.0(9-24) | 33.6(14-45) | 39.2(28-65) |
| 30 | Aug. 3 | 5.3(3-8) | 14.8(8-29) | 14.4(10-21) | 15.6(7-40) |
| 250 | Aug. 11 | 2.3(0-5) | 4.1(3-7) | 2.4(2-4) | 3.2(1-7) |
| 500 | Aug. 17 | 2.0(1-5) | 7.6(5-10) | 3.4(1-6) | 3.3(0-10) |
| 20 | Sept. 9 | 5.0(3-9) | 8.1(4-16) | 15.1(10-24) | 10.9(5-19) |

+ Total of 9 (i.e. 3 replicates in each of 3 control and sediment addition periods).

* Ranges given in parenthesis.

Table 23. Percent differences in macrobenthos, zooplankton, and total numbers of invertebrates caught in driftnets from control to sediment addition periods.+

| INTENDED CONCENTRATION OF SEDIMENT (mg liter$^{-1}$) | MACROBENTHOS | PLANKTON | TOTAL INVERTEBRATES |
|---|---|---|---|
| 10 | 27.5 | 16.7 | 19.2 |
| 20 | 62.0 | -38.5* | -11.6* |
| 30 | 179.3 | 8.3 | 54.6 |
| 65 | 35.6 | 21.8 | 23.9 |
| 100 | 61.1 | 19.3 | 28.2 |
| 250 | 78.3 | 33.3 | 54.2 |
| 500 | 280.0 | - 3.0* | 101.9 |

+ Percent increases were calculated using the formula $\frac{T_s - T_c}{T_c} \times 100$ and percent decreases by $\frac{T_c - T_s}{T_s} \times 100$.

See "Methods" section for explanation of terms.

* Numbers in control period exceeded those in the sediment addition period.

Table 24. Percent increase in macrobenthic drift for similar concentrations of suspended sediment and similar distances downstream of the sediment dispenser(s) for Gammon's (1970) and this study.

| SUSPENDED SEDIMENT CONCENTRATION IN GAMMON (1970) AT 12.5 m (mg liter$^{-1}$) | SUSPENDED SEDIMENT CONCENTRATION IN THIS STUDY AT 15 m (mg liter$^{-1}$) | | PERCENT INCREASE OF MACROBENTHOS DRIFTING | |
|---|---|---|---|---|
| | Actual | Intended | Gammon (1970) | This Study |
| 18.6 | 16.33 | 65 | 25.9 | 35.6 |
| 54.3 | 61.60 | 500 | 32.0 | 280.0 |

Note that they seemed little affected by the addition of sediment as compared to macrobenthos. The highest increase in zooplankton caught in the driftnets during sediment addition compared to the control period was 33.3% (at 250 mg liter$^{-1}$). Numbers of zooplankton caught in driftnets during the control period were higher than during sediment addition at 20 and 500 mg liter$^{-1}$. The response of zooplankton was more variable and less pronounced than that of macrobenthos for which sediment addition always produced larger numbers drifting than in the control period. Gammon (1970) reported a similar positive response for macrobenthos to sediment addition. Direct comparison of our studies is difficult. Sediment added to a stream will disperse and settle along a gradient according to particle sizes and density. When and where should samples be taken along the experimental channel? In fact, a measure of sediment settled on the stream bottom would be preferred (since the increase in drifting macrobenthos is likely caused by settled sediment). Length of the riffle used by Gammon for his sediment addition studies was 25 m. The sediment "dispenser was placed near the head of the riffle and the driftnets were placed at the foot of the riffle". Gammon measured suspended sediment concentrations halfway between the dispenser and the driftnets (i.e. approximately 12.5 m). Table 24 compares the percent increase in drifting macrobenthos for similar concentrations of suspended sediment at 12.5 and 15.0 m downstream of the dispenser for Gammon's and this study respectively. As can be seen, only two concentrations could be compared and the percent increases in macrobenthos drifting bear little resemblance between the studies.

The results of the two-way analysis of variance on total numbers of macrobenthic invertebrates drifting during control and sediment addition periods indicated a significant increase in drift with sediment addition (Table 25). Differences among sediment loads as a factor were also significant but this is a reflection of seasonal differences rather than response to sediment load. The interaction term is the true indicator of a different response to different sediment loads and this term is not significant. That is, it is not possible to distinguish among the responses to different sediment loads, although sedimentation clearly increased the numbers of macrobenthic invertebrates drifting.

Results of the two-way analysis of variance on percent increase in numbers of macrobenthic invertebrates with sediment addition show no significant difference among the three runs for each sediment load or among the sediment loads used (Table 26). These results verify the conclusions drawn from the non-significant interaction term in the factorial analysis (i.e. adding sediment increases drift but the amount added appears unimportant).

The value of $\omega$ for Tukey's test was 16.93. Mean (of three runs) square root percent increases ranged from 5.23 to 19.94 (for intended concentrations from 10 to 500 mg liter$^{-1}$). Therefore, no significant difference in percent increase of drift existed among sediment loads used. This result confirms earlier conclusions and questions the advisability of using percent increase as a measure of the intensity of effect of various sediment loads on macrobenthos, especially without further analyses.

The value of $2s_{\bar{x}}$ was 0.17. Differences between mean numbers of benthic

Table 25. Analysis of variance for 2 x 7 factorial design (total numbers of macrobenthos drifting). (Steel and Torrie, 1960).

A: Treatment totals

Correction term = C = 84.82
Total SS = 7.06
Treatment SS = 6.46
Error SS = 0.60

B: Main effects and interactions

| SOURCE OF VARIATION | DEGREES OF FREEDOM | SUM OF SQUARES | MEAN SQUARE | F |
|---|---|---|---|---|
| Treatment | 1 | 0.95 | 0.95 | 44.38* |
| Load | 6 | 5.23 | 0.87 | 40.91** |
| Interaction | 6 | 0.29 | 0.05 | 2.27+ |
| Error | 28 | 0.60 | 0.02 | |

* $F_{.01}$ value for 1 and 28 df is 7.64

** $F_{.01}$ value for 6 and 28 df is 3.53

\+ $F_{.05}$ value for 6 and 28 df is 2.44

Table 26. Two-way analysis of variance (percent increase in numbers of macrobenthos drifting). (Steel and Torrie, 1960).

| SOURCE OF VARIATION | DEGREES OF FREEDOM | SUM OF SQUARES | MEAN SQUARE | F |
|---|---|---|---|---|
| Total | 20 | 975.20 | | |
| Sediment load | 6 | 469.82 | 78.30 | 2.22+ |
| Runs | 2 | 83.87 | 41.93 | 1.19++ |
| Error | 12 | 421.54 | 35.10 | |

\+ $F_{.05}$ value for 6 and 12 df is 3.00

++ $F_{.05}$ value for 2 and 12 df is 3.89

invertebrates drifting in the control and treatment period for each sediment load used are shown in Table 27. Only the intended suspended sediment concentrations of 10 and 65 mg liter$^{-1}$ did not exceed this value. Therefore, the mean number of macrobenthic invertebrates drifting during control and sediment addition periods for these two sediment loads were not significantly different. This result cannot be further explained by analysis of the present data. It is possible, however, that different responses will be evoked by different sediment loads and that the magnitude of the response is not necessarily directly related to a linear increase in sediment load. Results of the factorial design analysis would support this conclusion.

Preliminary results of the investigation of the responses of individual macrobenthic taxa to various weights of sediment used showed that the number of Chironomidae in the drift always increased with sediment addition. However, the Ephemeroptera, Simuliidae, and Hydracarina were inconsistent in their responses to sediment addition. If substantiated by more thorough analyses, these results would conflict with the conclusion of Gammon (1970) that the entire macrobenthic community was similarly affected by sediment addition.

Analyses of variance, using the same designs, were done on zooplankton and total invertebrates caught in the driftnets. For zooplankton, results showed significance among loads ($F = 138.25$ for 6 and 28 d.f.) but no significant difference between control and sediment addition periods ($F = 0.14$ for 1 and 28 d.f.) and in the interaction term ($F = 0.87$ for 6 and 28 d.f.). This indicated that while a great deal of variability, probably seasonal, existed among experiments, plankton were unaffected by sediment addition. The zooplankton could be almost entirely from upstream and thus would be unaffected by sediment addition or, if they exist just above the bottom substrate in the experimental section, simply may not be affected by sediment addition. Zooplankton occur in Mackenzie Delta lakes of varying turbidities seemingly unaffected by the higher suspended sediment concentrations (N.B. Snow, personal communication). This observation reinforces the results obtained in these sediment addition experiments. Analysis of the total number of invertebrates caught in the driftnets showed similar results to the plankton: loads were significantly different ($F = 45.15$ for 6 and 28 d.f.) but control and treatment periods and the interaction term were not ($F = 3.34$ for 1 and 28 d.f.; and 0.44 for 6 and 28 d.f. respectively). Had an analysis of only the total invertebrates drifting been done, the effect of sediment addition on macrobenthic invertebrates would not have been detected.

It is now clear that seasonal effects had considerable influence on the results. This source of variance could be reduced by the use of a different experimental design. For example, the riffle area could be partitioned into discrete channels and a different sediment load simultaneously introduced to each channel. All sediment loads would thus be added at the same time.

It is of value to consider what would be the consequences to the standing crop of benthic invertebrates in an area if increases in drift of the order observed persisted. The least difference in mean numbers of macrobenthos

Table 27. Differences in mean numbers of macrobenthos drifting during control and sediment addition periods.+

| INTENDED CONCENTRATION (mg $liter^{-1}$) | DIFFERENCE |
|---|---|
| 10 | 0.11 |
| 20 | 0.22* |
| 30 | 0.42* |
| 65 | 0.14 |
| 100 | 0.23* |
| 250 | 0.29* |
| 500 | 0.65* |

+ Mean (of log transformation) of three runs used.

* $>2\ s_{\bar{x}}$

Table 28. $\chi^2$ values for significance of spatial variations in driftnet catches * (Elliott, 1970).

| INTENDED SUSPENDED SEDIMENT CONCENTRATION (mg $liter^{-1}$) | PERIOD OF EXPERIMENT | |
|---|---|---|
| | CONTROL | SEDIMENT ADDITION |
| 100 | 16.16 | 21.82** |
| 250 | 8.14 | 3.24 |

* $\chi^2_{.05}$ for 8 d.f. is 2.18 (lower level) and 17.53 (upper level).

** $P < 0.05$

drifting during control and sediment addition periods was at an intended suspended sediment concentration of 250 mg liter$^{-1}$. The greatest was at 100 mg liter$^{-1}$ (Table 22). Therefore data from these two sediment loads were used to calculate the total numbers of macrobenthos drifting from the experimental section of the riffle and the entire stream cross-sectional width at the downstream end of the experimental section in a 15 min period. $\chi^2$ tests for agreement with a Poisson series were done to verify a significant departure from a random distribution of drifting macrobenthos at different driftnet locations across the experimental section (Elliott, 1970). Calculations were based on the nine driftnets (three runs, three nets per run) used during the control and sediment addition periods. Driftnet catches for the 100 mg liter$^{-1}$ sediment addition period differed significantly from a Poisson series (Table 28). Total drift can be estimated from mean drift rate when agreement with a Poisson series is accepted for catches at different locations across the stream (Elliott, 1970). Thus, the arithmetic mean of the nine catches (= mean drift rate) was used to estimate total drift from the experimental section and the entire stream (Elliott, 1970). The three nets with catches which agreed with a Poisson series were treated by this method (Table 29). Data for the sediment addition period of the 100 mg liter$^{-1}$ experiment was also treated by this method as well as by another described by Elliott (1970) when agreement with a Poisson series is rejected for catches at different positions across the stream (Table 29). Two assumptions were necessary for this latter calculation:

1. Catches were proportional to the volume of water sampled by the nets.

2. Drift density is a Poisson variable.

A rough estimate can be made of the minimum and maximum percent of the population of macrobenthos in the surface sediments of the stream which leave due to sediment addition by:

1. assuming that the difference in numbers of macrobenthos drifting during sediment addition and control periods is the number caused to drift by the sediment addition.

2. using the maximum possible numbers for 100 mg liter$^{-1}$ and the minimum possible for 250 mg liter$^{-1}$ as a range.

3. knowing the actual area of the experimental section involved in producing the drift. (Since most [≃85%] of the sediment had settled in the first half of the channel, the area used will be the channel width x half the channel length.)

4. knowing an approximate value of the standing crop of the bottom sediments of the Harris River. (Surber samples taken in 1971 in a riffle just downstream of the experimental site had an approximate mean value of 5,000 macrobenthos m$^{-2}$ [Brunskill *et al.*, 1973; App. III]).

The two estimates of the maximum percent of the macrobenthic population leaving due to sediment addition are 0.5 and 2.6% (Table 30). These differ by a

Table 29. Total numbers of macrobenthos drifting out of the experimental section and the entire stream for intended suspended sediment concentrations of 100 and 250 mg liter$^{-1}$. (Values are for a 15-minute period. 95% confidence intervals are shown [Elliott, 1970]).

| INTENDED SUSPENDED SEDIMENT CONCENTRATION (mg liter$^{-1}$) | CROSS-SECTIONAL WIDTH | | | |
|---|---|---|---|---|
| | EXPERIMENTAL SECTION | | ENTIRE STREAM | |
| | PERIOD OF EXPERIMENT | | | |
| | CONTROL | SEDIMENT ADDITION | CONTROL | SEDIMENT ADDITION |
| 100 | 542.7±93.2 | 918.0±235.2*<br>2931.5±335.2** | 1668.3±286.4 | 2822.0±722.9*<br>5060.3±578.7** |
| 250 | 56.4±28.7 | 100.5±38.2 | 56.4±28.7 | 100.5±38.2 |

* Estimate of total drift from mean drift rate when agreement with a Poisson series is accepted for catches at different points across the stream.

** Estimate of total drift from drift density when agreement with a Poisson series is rejected at different points across the stream but the catches are proportional to volumes of water sampled by the nets, assuming drift density is a Poisson variable.

Table 30. Maximum and minimum percent of the population of macrobenthos in the surface sediments of the Harris River caused to drift because of sediment addition over a 15 min period.

| NUMBER OF MACROBENTHOS CAUSED TO DRIFT BY SEDIMENT ADDITION | | EFFECTIVE EXPERIMENTAL CHANNEL AREA ($m^2$) | | NUMBER OF MACROBENTHOS LEAVING PER $m^2$ OF EXPERIMENTAL CHANNEL BOTTOM AS A RESULT OF SEDIMENT ADDITION OVER A 15 MIN PERIOD | | ESTIMATED PERCENT OF MACROBENTHIC STANDING CROP | |
|---|---|---|---|---|---|---|---|
| | | INTENDED SUSPENDED SEDIMENT CONCENTRATION ($mg\ liter^{-1}$) | | | | | |
| MAXIMUM* | MINIMUM** | 100 | 250 | MAXIMUM | MINIMUM | MAXIMUM | MINIMUM |
| 517.3+ | 34.5 | 20.3 | 18.4 | 25.5 | 1.9 | 0.5 | 0.04 |
| 2630.8++ | | | | 129.6 | | 2.6 | |

* Data for 100 mg $liter^{-1}$: Absolute maximum number drifting during sediment addition minus absolute maximum drifting during control.

\+ 100 mg $liter^{-1}$, first estimate: 1153.2 - 635.9 (see Table 29).

++ 100 mg $liter^{-1}$, second estimate: 3266.7 - 635.9 (see Table 29).

** Data for 250 mg $liter^{-1}$: Absolute minimum number drifting during sediment addition (62.2) minus absolute minimum drifting during control (27.7) (see Table 29).

factor of about 5. The estimate of the minimum percent leaving is 0.04% which differs from the maximum by about 10 for the first estimate and 65 for the second. If 0.04% of the standing crop of macrobenthos exited in a 15 min period at a minimum and 2.6% at a maximum then it would take as many as 18 days and as little as 7 hr for 50% of the resident population to leave. The latter value could be cause for concern. Calculations of these figures are based on a number of dubious assumptions and should be regarded as only very rough approximations at best.

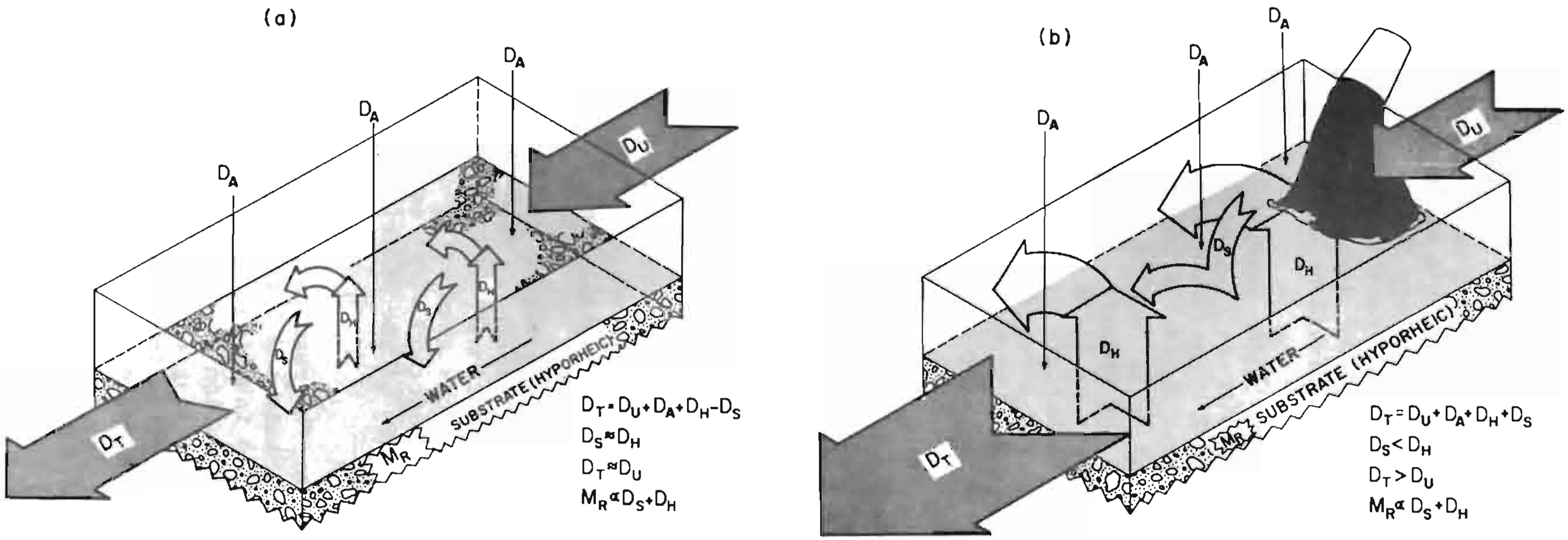
From the review given in Section I and from the results of this experiment, it is possible to construct a simple, hypothetical model of drift dynamics in a section of stream affected by sediment addition. Fig. 13(a) shows an undisturbed section of stream. $M_R$ is the population of macrobenthos resident in the substrate of that section. The main components of total drift leaving the section ($D_T$) are the numbers of macrobenthos entering in drift from upstream ($D_U$), the numbers settling in the section ($D_S$), the numbers entering the drift from the substrate in the section ($D_H$), and the allochthonous drift ($D_A$). From our observations, $D_A$ in the Harris River is inconsequential. We will assume that $D_S \approx D_H$. This assumption may not be a safe one (Waters, 1972) but we have no data from the Harris River to prove or disprove it. If $D_S \approx D_H$ then $D_T \approx D_U$ and $M_R$ remains the same. Fig. 13(b) shows the hypothetical effect of sediment addition to the same section of stream. $D_A$ and $D_U$ cannot be affected by sediment addition so their magnitude remains the same as in Fig. 13(a). Sediment addition fills interstitial spaces, covers attachment surfaces, and creates unsuitable conditions for filter feeding macrobenthos and the result is an increase of $D_H$. Invertebrates normally part of $D_S$ now do not settle. Therefore, $D_H$ and $D_S$ contribute to the increase in $D_T$ and $M_R$ is reduced.

None of the processes outlined can be quantitatively described at this stage. Quantitation will require further research. Also, the model is simplistic and no doubt other interactions are involved. However, the model can be changed as more information becomes available.

An investigation of the time required to cause $D_H$ to be reduced significantly will be done in the coming field season. Future field research will include studies of the relative contributions of $D_U$ and $D_H$ to $D_T$; the relative importance of organisms in the upstream drift and those from the substrate (hyporheic) in repopulating a section of stream denuded by sediment addition; and the effects on macrobenthos of the addition of fine sediment of different sizes.

It should be emphasized that the results generated in this study are applicable only on a short-term basis and for the range of sediment loads and size composition used. It is inadvisable to draw conclusions about the effects of long-term sedimentation from short-term experiments. Until experiments on the effects of long-term sediment addition and rates of recovery are completed, the guidelines set by E.I.F.A.C. and reviewed by Hynes (1973) will have to be followed.

Figure 13. Model of macrobenthic drift dynamics on the Harris River, N.W.T.
(a) undisturbed section of stream
(b) sediment addition




## LEGEND

$M_R$ = Resident population of macrobenthos

$D_A$ = Allochthonous (terrestrial) drift entering experimental section

$D_U$ = Upstream drift entering experimental section

$D_H$ = Drift entering experimental section from hyporheic of experimental section

$D_S$ = Drift settling into hyporheic of experimental section

$D_T$ = Total drift leaving experimental section

D. Summary

1. Short-term sediment additions varying from 10 to 500 mg liter$^{-1}$ of suspended sediment were made on a section of a northern river and the effects of this increased sedimentation on drifting invertebrates measured.

2. Short-term sediment additions did not affect the five water chemical parameters measured.

3. Approximately 85% of the sediment added settled out in the first 7.5 m of the experimental section and 90% by the end of the section.

4. A seasonal effect in numbers of macrobenthos and zooplankton drifting during control and sediment addition was detected.

5. A positive increase in drift was shown at all concentrations of suspended sediment by macrobenthic invertebrates but not zooplankton and total (= macrobenthos plus zooplankton) invertebrates. Magnitude of the positive percent increases was always less for zooplankton and total invertebrates than for macrobenthos. The percent increase of macrobenthos was not linear with increase in suspended sediment concentration, total weight of sediment added, or theoretical weight of sediment added per unit area of stream bottom.

6. For macrobenthos, analysis of variance showed a highly significant difference between numbers drifting during control and sediment addition periods. However, no relationship could be found between sediment load and numbers of macrobenthos drifting. Similar results were obtained from the analysis of the percent increase in drift. In individual comparisons, means of numbers of macrobenthos drifting in control and sediment addition periods for 10 and 65 mg liter$^{-1}$ were not significantly different. Preliminary results have shown that individual taxa of macrobenthos showed different drift responses to sediment addition.

7. For zooplankton and total invertebrates caught in the driftnets, analyses of variance showed a highly significant difference among intended sediment loads (probably due to seasonal variation) but no significant difference between control and sediment addition periods or the interaction between intended sediment load and numbers caught in the driftnets. The lack of effect on zooplankton could be due either to their origin outside the treatment area or their intrinsic resistance to increased sedimentation.

8. Use of total invertebrates alone would have masked the effect on the sensitive macrobenthic invertebrate community. These experiments verify the value of using the macrobenthic invertebrate community as an indicator of sediment pollution.

9. Total numbers of macrobenthos drifting out of the experimental section and the entire stream for intended suspended sediment concentrations which produced the greatest and least difference in mean number of macrobenthos drifting were calculated to provide an estimate of the range in

numbers of macrobenthos affected by sediment addition. The maximum number of macrobenthos leaving per $m^2$ of the experimental channel bottom as a result of sediment addition over a 15 min period ranged from 25.5 to 129.6. The minimum number per $m^2$ was 1.9 for a 15 min sediment addition period.

10. The maximum percent of the resident macrobenthic population caused to drift by sediment addition was estimated to be 2.6. The minimum was estimated to be 0.04%. Depletion of 50% of the macrobenthic standing crop was estimated to take 7 hr at the maximum depletion rate and 18 days at the minimum.

11. A model illustrating drift dynamics during control and sediment addition periods is presented.

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