PERGAMON

Marine Pollution Bulletin 44 (2002) 511–519

MARINE POLLUTION BULLETIN

www.elsevier.com/locate/marpolbul

Improvement of the sediment ecosystem following diversion of an intertidal sewage outfall at the Fraser river estuary, Canada, with emphasis on *Corophium salmonis* (amphipoda)

J.L. Arvai [a,*], C.D. Levings [b], P.J. Harrison [c], W.E. Neill [d]

[a] *School of Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210-1085, USA*
[b] *Department of Fisheries and Oceans, West Vancouver Laboratory, 4160 Marine Drive, West Vancouver, BC, Canada V7V 1N6*
[c] *Department of Earth and Ocean Sciences, The University of British Columbia, 6270 University Boulevard, Vancouver, BC, Canada V6T 1Z4*
[d] *Department of Zoology, The University of British Columbia, 6270 University Boulevard, Vancouver, BC, Canada V6T 1Z4*

Abstract

Primary treated sewage effluent from the city of Vancouver, Canada was deposited directly onto the intertidal ecosystem of Sturgeon bank, Fraser river estuary between 1962 and 1988. In response to the degraded sediment conditions an azoic zone developed near the discharge outfall. Effluent discharges into the intertidal zone were almost completely stopped in 1988 with the construction of a submerged outfall. Our studies, conducted between 1994 and 1996, showed considerable improvement in the environment of the mudflat ecosystem, including increased dissolved oxygen, decreased sediment chlorophyll, decreased organic material in the sediment, reduced heavy metals in surficial sediment and increased grain size. The amphipod *Corophium salmonis*, important in the food web for juvenile salmon and other fish species, recolonized the previously azoic location. At reference stations, *C. salmonis* density was similar to that observed in previous surveys two decades earlier. Our data strongly suggest that improvement of sediment conditions near the former sewage outfall was a major factor enabling colonization by *C. salmonis*.

Keywords: Improvement; Sewage; Pollution; Tidal flat ecosystem; *Corophium salmonis*; Secondary production; Fraser river estuary; Canada; Indicator species; Amphipods; Crustacea

1. Introduction

Estuaries located near major urban areas are often subjected to severe contamination from the disposal of sewage effluent. Estuarine disposal of these effluents results in the addition of nutrients and other contaminants (trace metals, solvents, other organic contaminants) to the surrounding waters and benthic habitats. The potential long-term effects of sewage effluent disposal include a combination of anoxia and hypoxia (pelagic and benthic), nutrient enrichment, trace metal and organic contaminant accumulation and toxicity, changes in sediment composition, and reductions in species diversity, density, and productivity (Pearson and Rosenberg, 1978; Waldichuk, 1984; Costello and Read, 1994). For 16 years (1962–1988) the greater Vancouver sewerage and drainage district (GVSDD) serving approximately 500,000 people in Vancouver, BC, Canada, discharged about 1.53×10^6 m^3 d^{-1} of primary treated sewage (stormwater, domestic, and industrial waste) directly into an intertidal ditch which drained the mud and sand flats of Sturgeon bank in the Fraser river estuary (Fig. 1). By 1974, an azoic zone several hectares in area had developed near the discharge outfall (Otte and Levings, 1975; BC Research, 1975; BC Research, 1977). In response to public and agency concern about sewage damage to this valuable ecosystem (e.g. Otte and Levings, 1975; Birtwell et al., 1983), the GVSDD constructed a subtidal outfall. Since April 1988, the effluent has been discharged at 100 m depth in the Strait of Georgia, about 5 km seaward of the original outfall. The old outfall is utilized in emergency situations only, with an average discharge of approximately 4177 m^3 y^{-1}, less than 0.01% of the annual discharge to the subtidal outfall.

* Corresponding author. Tel.: +1-614-292-2265; fax: +1-614-292-7432.

0025-326X/02/$ - see front matter
PII: S0025-326X(01)00264-8

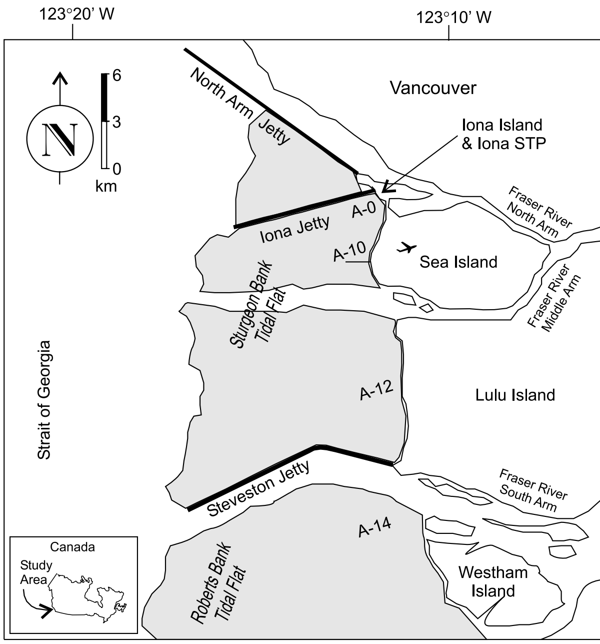

Fig. 1. Four sampling sites (A-0, A-10, A-12, and A-14) within the Fraser river estuary, BC, Canada. Shaded sections outline the Sturgeon and Roberts bank tidal flats at low tide.

In this paper we consider the improvement of the ecosystem of Sturgeon bank following the cessation of this stress, focusing on variables such as dissolved oxygen and sediment quality which had been measured in a number of earlier studies during the time when primary treated sewage contaminated the surrounding mudflats. Although a number of studies have investigated ecological changes related to the cessation of sewage dumping in shallow inshore waters (e.g. Moore and Rodger, 1991; Ueda et al., 1994; Underwood and Chapman, 1997), only a few papers present data on the improvement of sediment ecosystems in the intertidal zone (McLusky et al., 1993; Read, 1987). None of the studies deal with mudflats in estuaries of the northeast Pacific Ocean. To document a biological response from the intertidal fauna we utilized data on the density, production, and reproduction of an abundant estuarine detritivore, the tube-dwelling amphipod *Corophium salmonis*. The distribution and abundance of *C. salmonis*, which reproduces twice per year (in the early summer and fall), was studied both before (Otte and Levings, 1975; Levings and Coustalin, 1975; Otte, 1979) and after construction of the subtidal outfall (Arvai, 1997) with the latter work presenting detailed seasonal and interannual ecological data, including secondary production estimates.

In previous studies, *Corophium* sp. have been shown to prefer mud or muddy sand to coarser sediment but tended to avoid very shallow mud. Other sediment parameters have been shown to be important in limiting the distribution of *Corophium* sp. Organic content, porosity, permeability, and water content have all been shown to affect the distribution of this genus (Meadows, 1964; McClusky, 1968; Peer et al., 1986). For example, *C. salmonis* requires the presence of a sediment structure that is able to support the construction by the amphipod of a U-shaped tube from which it can collect sediment particles from the substratum surface during feeding (Miller, 1984; Icely and Nott, 1985). The construction of this tube requires a cohesiveness of sediments that supports the prolonged structural integrity of tubes.

In addition to its benthic and epibenthic inhabitants, the mudflat ecosystem on Sturgeon and Roberts banks supports about 50 species of fish including commercially important species such as salmon (*Oncorhynchus* spp.) and flatfish (e.g., starry flounder, *Platichthys stellatus*). The largest wild population of chinook salmon (*O. tshawytscha*) in the world uses the estuary as a nursery habitat (Levings, 2000). Crabs (*Cancer magister*) and shorebirds such as the great blue heron (*Ardea herodias*) are also abundant on the banks. Each of these top predators is directly or indirectly dependent on a food web based on crustaceans such as amphipods. As an example, *C. salmonis* is used as food by young chinook salmon. At high tide, the fish move into the mudflat habitats of Sturgeon bank. The amphipods leave their burrows when the sediments are submerged and hence become available as food for the young salmon (Levings and Coustalin, 1975).

2. Materials and methods

2.1. Study area

The north sector of the Fraser river estuary is characterized by Sturgeon bank, a large (approximately 83 km^2) tidal flat that extends south from the mouth of the North Arm to the South Arm of the Fraser river (Fig. 1). A small channel of the lower river drains directly onto Sturgeon bank, but during spring runoff of the river much of the fresh water on the bank arises from the Middle Arm, as the river's plume spreads to the northwest. Another major intertidal bank, Roberts bank (141 km^2) is located further to the southwest, across the South Arm of the Fraser. The northeast sector of Roberts bank is influenced directly by river discharge from the South Arm. The tidal range is up to about 5 m over chart datum. Both banks are characterized by brackish water and the overlying water at high tide is highly stratified with a salt wedge penetrating from offshore onto the tide flats (Tabata et al., 1971; Bendell-Young et al., 2000). At spring freshet, the surface water is typically 0 psu at high tide. However during low runoff, in winter, surface salinities on the banks are high ($>$ 25 psu; Levings and Coustalin, 1975).

The main contaminated site for pre- and post-improvement investigations was the area within approximately 200 m of station A-0 (49° 12.899′ N, 123° 12.488′ W, Fig. 1), a specific station within the azoic or severely polluted zone identified in the earlier studies (Otte and Levings, 1975; BC Research, 1975; Levings and Coustalin, 1975). station A-0 is located along the west shore of Sturgeon bank approximately 300 m from the former effluent release gate of the Iona Island STP (Fig. 1).

Three reference sites were investigated to compare the population ecology of *C. salmonis* with the contaminated site: A-10 (49° 11.501′ N, 123° 13.292′ W), A-12 (49° 09.14′ N, 123° 12.598′ W), and A-14 (49° 05.73′ N, 123° 12.35′ W; Fig. 1) (Arvai, 1997). These sites were sampled during earlier biological studies (Levings and Coustalin, 1975) but data were limited. It is important to note that these are not "control" sites. The concept of a control, in the sense of experimental procedure, is difficult to use in a field ecology study. Instead, we selected stations in the area at which we could make defensible comparisons with the contaminated site, A-0. Besides the fact that historical data are available, other considerations for their selection included their history in terms of previous effluent discharges and their location in relation to A-0 on the mudflat. Specifically, these three reference sites were not affected by effluent from the Iona Island STP due to the deflection of the sewage northward into the Strait of Georgia by tidal currents (Tabata et al., 1971) and because of the presence of the North Arm and Iona Jetties (Fig. 1). All four stations were located at approximately the same tidal height, namely −0.3 m relative to mean sea level, and were exposed to similar wave and current exposures (Feeney, 1995).

2.2. Sampling methods for *C. salmonis*

C. salmonis biomass and densities were determined from five replicate samples of 0.05 m^2 taken to a depth of 15 cm, using an aluminum box core. Visual inspections of the core contents indicated that all *C. salmonis* were present in the upper 10 cm. Sampling for *C. salmonis* began on 10 May, 1994, and continued monthly between September and April and bi-weekly between May and August. Monitoring was terminated in November 1996. All stations were reached at low tides

Table 1
Changes in sediment ecosystem variables and *C. salmonis* density in the azoic zone before and after diversion of sewage from the intertidal mud and sand flats on Sturgeon bank, Fraser river estuary

	DO range (mg l^{-1})	Chl a max (mg m^{-2})	Sediment grain size range (% < 63)	Mercury in surficial sediment (μg g^{-1})	Sediment LOI range (%)	*C. salmonis* density (no. m^{-2})	*C. salmonis* annual production (g m^{-2} y^{-1} AFDW)	Sediment appearance/quality
Pre-improvement (before 1988)	0.7–3.0[a]	772–1000[b]	81.8–94.1[a]	0.89[c]	7.4–8.6[d]	None observed[e]	None observed[e]	Blue–green algae dominant[b]; gel-like mud that would not hold the weight of a person
Post-improvement (after 1988)	4.4–6.1[f]	180[g]	25–52[h]	0.21–0.28[i]	3.9–5.0[j]	799[h]–1570[k]	0.50[l]	Pennate diatoms dominant[m]; highly cohesive sand and mud (Feeney, 1995)[n]

Only data from locations within 200 m of station A-0 are included.
[a] Otte and Levings, 1975; Otte, 1979 (high tide, 50 cm water depth, October 1974); Birtwell et al., 1983 (flood tide, surface, July 1980).
[b] BC Research, 1975; Otte and Levings, 1975.
[c] McGreer, 1979.
[d] Otte and Levings, 1975; Levings and Coustalin, 1975 (September 1973); Otte, 1979; BC Research, 1975 (stations A-1, A-3 in spring 1974; BC Research, 1977 (station A-3 in spring 1976).
[e] Levings and Coustalin, 1975 (September 1973); Otte and Levings, 1975; Otte, 1979 (June 1974).
[f] Nishimura et al., 1996 (high tide, 50 cm water depth, August 1995).
[g] Yin et al. submitted; (October 1994).
[h] Arvai, 1997 (summer and winter 1996).
[i] Levings and Bravender (from February 1992), Thomas and Bendell-Young, 1998 (from July 1995).
[j] Thomas and Bendell-Young, 1998 (from May and July 1995).
[k] This study, data from June and September 1994 and 1995.
[l] Arvai, 1997 (mean value for 1994, 1995, and 1996).
[m] Ross, 1998.
[n] Feeney, 1995.

using Canadian Coast Guard Search and Rescue Hovercrafts stationed at the Vancouver International Airport.

2.3. Laboratory and data analysis

A system of tiered sieves with mesh sizes of 1000, 750, and 500 μm were used to separate animals from finer sediments. All material retained in the sieve was fixed with 5% buffered formalin and stained with rose bengal. *C. salmonis* was then separated from other organisms and accompanying debris, sexed (according to Otte, 1975), reproductive condition assessed by verification of the presence of oostegites, and counted under a dissecting microscope. Annual production was estimated using cohort analysis (Crisp, 1971). Further details on methods are given elsewhere (Arvai, 1997).

2.4. Data sources for ecosystem variables

A number of previous studies investigated ecosystem variables affected by sewage discharge in the vicinity of station A-0, before and after construction of the subtidal outfall. These variables included dissolved oxygen at high tide, sediment grain size, chlorophyll, organic content, and heavy metals in the sediment.

3. Results

3.1. Ecosystem variables

Improvements in several of the variables which are considered to be important stressors from sewage were observed at station A-0 in our surveys (Table 1). This included an increase in dissolved oxygen of approximately 3.0 mg l^{-1}, an order of magnitude decrease in the standing crop of chlorophyll, an increase in sediment grain size as indicated by a 42% increase in the proportion of sand, a decrease in the amount of organic material in the sediment as estimated by loss-on-ignition (a 45% decline), and a decrease in sediment heavy metals, as indicated by mercury in surficial sediment (decrease of approximately 0.60 μg g^{-1}).

Direct observations during field trips by the authors corroborated these data. In 1974, sediments near A-0

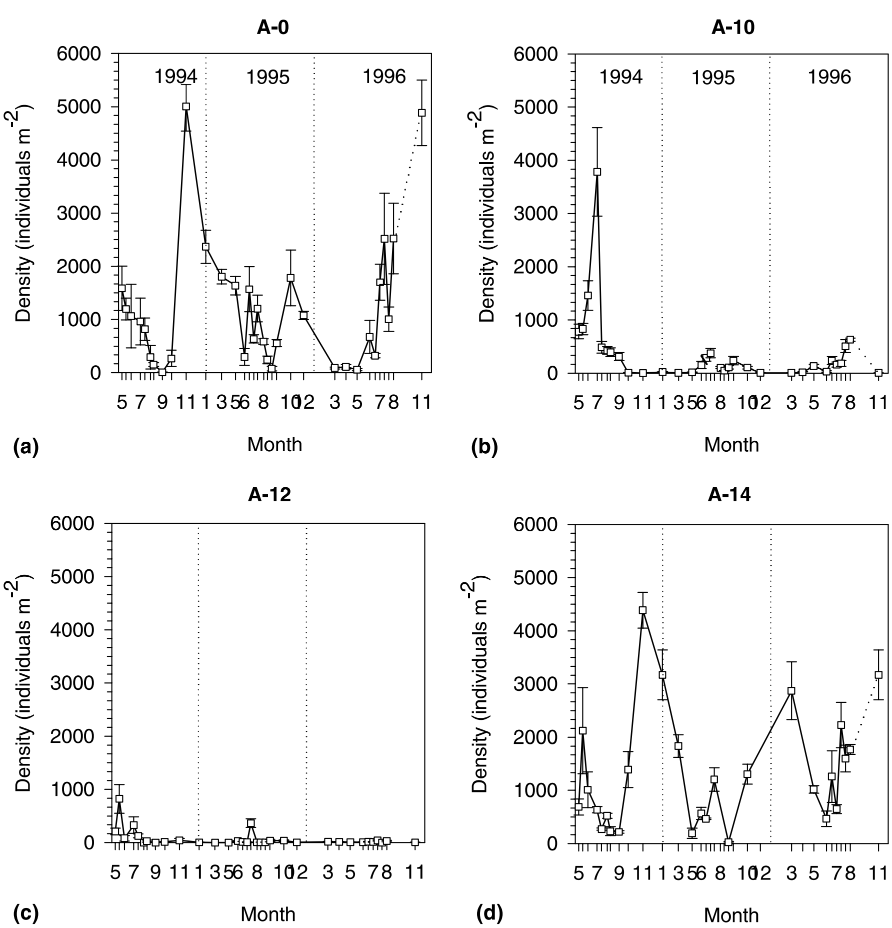

Fig. 2. Changes in density (m^{-2}) of the amphipod *C. salmonis* at four stations on Sturgeon (A-0, A-10, A-12) and Roberts (A-14) banks. Error bars represent ±1 S.E., $n = 5$.

were very soft, and persons attempting to walk on the flats at low tide sank into the mud at least 1 m deep but after improvement, investigators could easily traverse the intertidal area by foot. In addition, blue green algae, which were dominant on the sediment surface during the pre-improvement surveys, were not observed in the recent studies.

3.2. Increases in *C. salmonis* abundance and production at the previously azoic area

Survey data from 1994 to 1996 clearly indicated that the previously azoic area had been colonized by *C. salmonis* (Fig. 2). The peak density of *C. salmonis* for the entire study was observed at station A-0 (approximately 5000 individuals m^{-2}) on 22 November, 1996. Maxima were also observed in May 1994, October 1995, August 1996, and November 1996, indicating successful reproduction and recruitment of juveniles to the population in the area. This was confirmed by observations of reproductive condition, showing that ovigerous females were present at all sites, although in widely varying numbers (Fig. 3). Annual production was estimated at 0.50 g m^{-2} y^{-1} ash-free dry weight (AFDW) (Table 1).

3.3. Density of *C. salmonis* and ecosystem variables relative to reference stations in the pre- and post-improvement condition

The densities of *C. salmonis* at two of the three reference stations during the pre- and post-improvement period were similar, ranging from 361–572 individuals m^{-2} in the area of station A-10 and 381–430 individuals m^{-2} near station A-14 (Table 2). Densities at station A-12 were lower in the post-improvement era (Table 2). Only data on sediment grain size are available from the pre- and post-improvement periods. These data indicate that the percentage of fine sediment (< 63 μm) has shown a variation of < 9% at stations A-10, A-12, and A-14 (Levings and Coustalin, 1975; Arvai, 1997).

No seasonal data or information on the production of *C. salmonis* are available from before the time that the subtidal outfall was installed. However, the post-improvement data showed that the pattern of

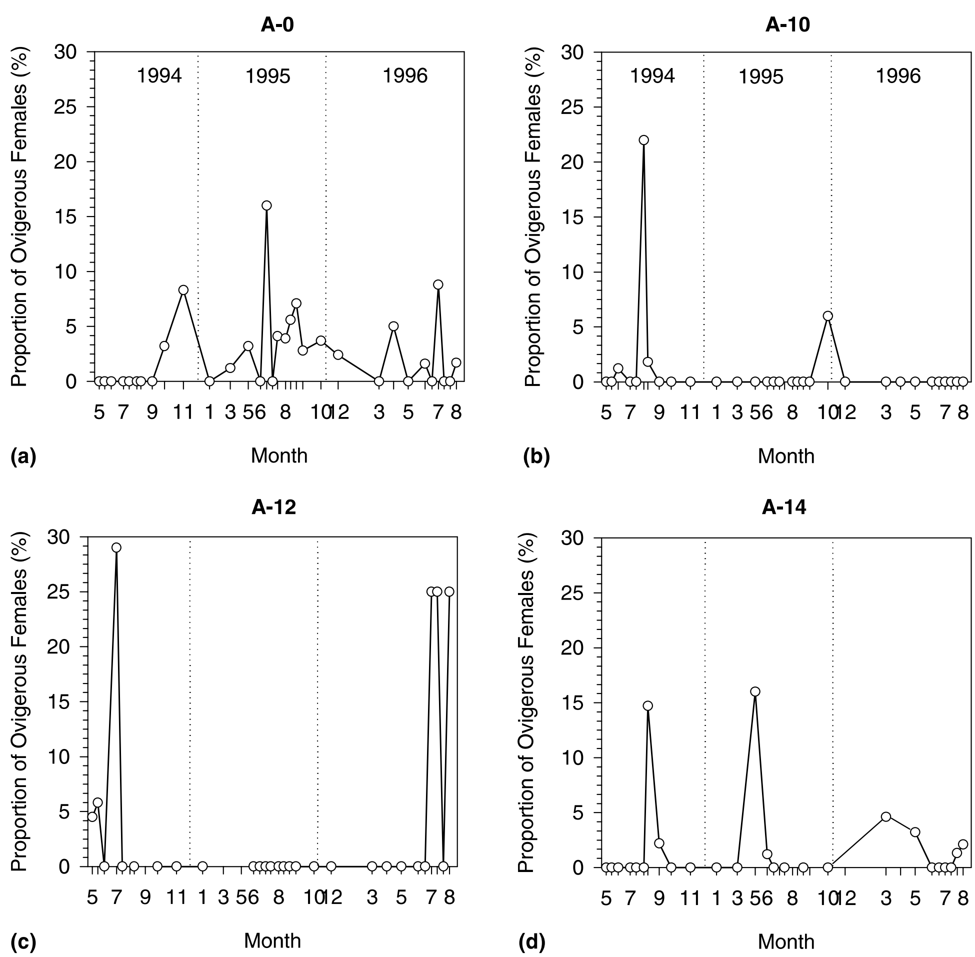

Fig. 3. Changes in the proportion of ovigerous females (%) of the amphipod *C. salmonis* at four stations on Sturgeon (A-0, A-10, A-12) and Roberts (A-14) banks.

Table 2
Densities (number m^{-2}; mean, range) and annual production (g m^{-2} y^{-1} ash-free dry weight) of *C. salmonis* at the three reference stations in the pre- and post-improvement conditions

	A-10*	A-12**	A-14***
Pre-improvement density (before 1988)	361; 20–1088[a]	902; 0–5600[b]	381; 16–1088[c]
Post-improvement density (after 1988)	572; 235–1460[d]	32; 0–80[d]	430; 26–1012[d]
Post-improvement annual production (after 1988)	0.46[e]; 0.07[f]	0.46[e]; 0.07[f]	0.54[g]

See footnotes for data sources.
* Station A-10 of Otte and Levings, 1975.
** Station FRAPER 12 of Levings and Coustalin, 1975.
*** Station FRAPER 14 of Levings and Coustalin, 1975.
[a] Based on data from 12 stations seaward of Sea Island (excluding station A-0) at a similar elevation to A-10 in September 1973 and June 1974; Levings and Coustalin, 1975; Otte and Levings, 1975; Otte, 1979.
[b] Based on data from seven stations seaward of Lulu Island at a similar elevation to A-12 in September 1973; Levings and Coustalin, 1975.
[c] Based on eight stations seaward of Westham Island at a similar elevation to A-14 in September 1973; Levings and Coustalin, 1975.
[d] This study, samples from June to September 1994 and 1995.
[e] Arvai, 1997; pooled data for 1994.
[f] Arvai, 1997; mean of pooled values for 1995 and 1996.
[g] Arvai, 1997; mean of pooled values from 1994, 1995, and 1996.

fluctuations in *C. salmonis* density were similar between stations A-0 and the three reference stations. Of particular interest were peaks in density observed during the winter months at stations A-0 and A-14 and the absence of similar peaks at stations A-10 and A-12 (Fig. 2). Consistently high densities were observed during the winter and spring, particularly in 1994 when densities ranged from 1804 (S.E. = 308.4) to 5007 (S.E. = 808.3) individuals m^{-2} at station A-0 (Fig. 2(a)) and 1835 (S.E. = 364.4) to 4385 (S.E. = 586.5) individuals m^{-2} at station A-14 between 29 November, 1994 and 21 March, 1995 (Fig. 2(d)). This trend was observed again during the winter of 1995 and spring of 1996 when densities were as high as 1076 (S.E. = 179.7) individuals m^{-2} at A-0 (22 November, 1995) and 2872 (S.E. = 943.8) individuals m^{-2} at A-14 (29 February, 1996). To help confirm the winter peaks in density, additional sampling was undertaken in November 1996 at all four sampling stations. At this time, density was again high at stations A-0 and A-14 (Figs. 2(a), (d)). Peaks in densities correlated with seasonal changes in numbers of ovigerous females, but data were extremely variable at stations A-10 and A-12 (Fig. 3). Annual production was 0.46 g m^{-2} y^{-1} AFDW at these two stations in 1994, and only 0.07 g m^{-2} y^{-1} AFDW in 1995 and 1996. At station A-14, production was similar to that at station A-0 (0.54 g m^{-2} y^{-1} AFDW) (Table 2).

4. Discussion

4.1. Factors enabling colonization by C. salmonis

The improvement in several physico-chemical factors in the previously azoic zone near station A-0 likely enabled *C. salmonis* to colonize the area. Laboratory experiments would be required to explicitly identify the factors, and the situation is complex because several likely co-vary. For example, organic content of the sediment is correlated with mercury concentration at the Fraser estuary (Thomas and Bendell-Young, 1998). There have been no lab experiments to identify specific toxic constituents of the sewage for *C. salmonis*. A related species (*C. insidiosum*) was reported to be an indicator species of "slight organic pollution" (Anger, 1977), so it is possible that *C. salmonis* is also somewhat pollution tolerant. Dissolved oxygen, sediment grain size, organic content of sediment and contaminant toxicity are some of the factors which could have influenced survival of the amphipod in the pre-treatment era (Costello and Read, 1994; Gamenick et al., 1996) and each has shown improvement. Stanhope (1983), working at the nearby Squamish river estuary in British Columbia, concluded from field studies that *C. salmonis* productivity was reduced in low oxygen conditions created by decomposing wood debris. The improvement of DO at station A-0 therefore may have influenced the survival and growth of *C. salmonis*. Sediment grain size is another key factor for *C. salmonis*, as discussed by Albright (1982) who concluded that sediment characterized by silt-sized particles are preferred by this species. In the pre-improvement condition, however, sediments near A-0 were dominated by an unstable silt and gel-mud which may have prevented tube-building by this species. An intact tube is required for sediment feeding by *Corophium* spp. (Miller, 1984; Icely and Nott, 1985).

4.2. Factors influencing contemporary amphipod production on Sturgeon and Roberts banks

Overall, density, biomass, and production were generally lower, especially at stations A-10 and A-12, characterized by sandy and unstable sediments, than values found for *Corophium* spp. in other areas. The sandy and unstable sediments at station A-10 and A-12 may restrict *C. salmonis* growth and productivity. Values were also relatively lower for *Corophium* spp. in comparison to intact and undisturbed habitats in other estuaries. For example, the density of *C. robustum* from a dredging-disturbed habitat in southwestern Russia ranged from 750 to 12,250 individuals m^{-2} (Bortkevitch et al., 1984). Grizzle (1984) also found higher densities of *C. ellisi* (max = 57,960 individuals m^{-2}, $\bar{x} = 16,234$ individuals m^{-2}) in organic-enriched, sewage disturbed sediments on the east coast of Florida. Mean biomass in a study in the upper Bay of Fundy ranged from 0.09 to 2.7 g m^{-2} DW (Hawkins, 1985) compared to 0 to 1.21 g m^{-2} AFDW in this study (Table 2).

The production of *C. salmonis* is also contingent upon food availability. Food availability is likely high at stations A-0 and A-14 because of high benthic microalgal biomass (Ross, 1998; Yin and Harrison, 2000) and increased organic content as a result of natural organic input and periodic sewage effluent discharges (as indicated by high loss on ignition, Table 1). On Sturgeon and Roberts banks, these take place as influxes of marsh detritus in fall and winter (Pomeroy and Levings, 1980). There are also relatively small occasional discharges of primary treated effluent from the Iona Island STP, mainly during volume-overload bypasses during periods of heavy rainfall, predominantly during the winter months. In 1994, nine such bypass events took place, spilling a total of 7.3×10^7 l of effluent near station A-0 on Sturgeon bank (Larson, 1995). On Roberts bank, station A-14 is thought to be influenced by discharges from the Annacis (3.7×10^5 m^3 d^{-1}) and Lulu Islands (5.1×10^5 m^3 d^{-1} STPs located upstream in the South Arm of the Fraser river (Moore, 1993). In 1995, Thomas and Bendell-Young (1998) found sediment organic levels ranged from 3.4% to 4.2% at this site as well as increased levels of metals in sediments.

Secondary production and secondary production to mean biomass ratios (*P*:*B*) of *C. salmonis* (which ranged from 0.89 to 2.05) at stations A-0 and A-14 were lower than those observed in several other estuaries (Table 3). These low *P*:*B* ratios and growth rates can be accounted for, in part due to increased longevity and latitude (Segerstråle, 1960; Ankar and Elmgren, 1976) as compared to other cold water *Corophium* spp. We may also have observed the effects of sublethal effluent-related toxicity related to the periodic effluent discharges from the Iona, Annacis, and Lulu STPs.

4.3. Ecosystem benefits of increased productivity of C. salmonis on Sturgeon bank

Because of the lack of detailed data on the ecology of Sturgeon bank before the sewage was diverted, it is difficult to give a quantitative perspective on improvement. However, we believe that the establishment of *C. salmonis* in the previously azoic area may have benefited secondary and tertiary consumers on Sturgeon bank. For example, up to 500,000 Western Sandpipers (*Calidris mauri*) utilize the tidal flats of the Fraser river estuary for feeding each day during their spring and late summer migration (Butler, 1994). It is expected that during their stay on the mudflats, Western Sandpipers remove a large amount of the available benthic production in the form of epibenthic and infaunal invertebrates from the intertidal as has been seen on temperate mudflats in the Bay of Fundy (Peer et al., 1986; Daborn et al., 1993). The arrival of migratory birds like the Western Sandpiper at these times likely partially accounts for the changes in *C. salmonis* density shown in Fig. 2.

As well, fish are now more abundant near station A-0 compared to the pre-improvement condition (Nishimura et al., 1996) and the increased amphipod production (0.5 g m^{-2} y^{-1} AFDW) is available for fish food energy flow. *C. salmonis* also becomes potentially available as fish food at high tide, when swimming amphipods are consumed by fish living in the water column such as juvenile salmon (Levings, 1985). Species such as starry flounder feed on *C. salmonis* emerging from the sediments even when the water is only a few centimetres deep. Some of the fish production in turn is used by predatory birds such as great blue heron and gulls. The

Table 3
Summary of published values of secondary production (*P*), and production to biomass ratios (*P*:*B*) measured for *Corophium* spp. in this and other studies

Species	*P* (g m^{-2} y^{-1} DW)	$P:\bar{B}$	Study site	Reference
C. salmonis	0.10	1.0	A-10/A-12	This Study (MIN.)
C. salmonis	1.55	1.7	A-14	This Study (MAX.)
C. salmonis	7.24	8.6	Grays harbor, WA, station 1	Albright (1982)
C. salmonis	21.44	7.6	Grays harbor, WA, station 2	Albright (1982)
C. salmonis	18.64	7.2	Grays harbor, WA, station 3	Albright (1982)
C. robustum	71.8	2.1	Ingulets river, Russia, station 1	Bortkevitch et al. (1984)
C. robustum	101.5	NA	Ingulets river, Russia, station 2	Bortkevitch et al. (1984)
C. spinicorne	0.78	2.4	Squamish estuary, BC, station 1	Stanhope (1983)
C. spinicorne	4.66	4.0	Squamish estuary, BC, station 2	Stanhope (1983)
C. sextoni	0.01	2.1	Torbay, UK	Hughes (1978)
C. volutator	3.17	NA	Pecks Cove, Bay of Fundy	Hawkins (1985)

NA = not available.

amphipod production is also available to invertebrate predators such as the Dungeness crab (*Cancer magister*) and predatory polychaetes such as nereids (*Eteone longa*) which now can use the area (Rebele, 1994).

5. Conclusions

The results of our study on *C. salmonis* strongly support the conclusion that the Sturgeon bank ecosystem at the Fraser river estuary has undergone significant improvement since 1988 when disposal of primary treated sewage into the intertidal zone ceased. As found in both intertidal and subtidal sediment ecosystems elsewhere (e.g., Moore and Rodger, 1991; Ueda et al., 1994; Underwood and Chapman, 1997), the removal of stress from sewage enabled changes toward an ecosystem which likely is more representative of conditions before the STP began operating. The evidence for the improvement in our study area includes increased dissolved oxygen levels, decreased sediment organics, increased grain size, decreased chlorophyll levels, decreased heavy metals and the finding of significant populations of the amphipod *C. salmonis* in an area where none were found when sewage was being discharged intertidally. In addition to improvement in the previously azoic zone, relatively high contemporary winter density, biomass, and secondary production of *C. salmonis* were observed at stations that were influenced by occasional or regular effluent discharges. This was likely due to ample food availability, optimum sediment grain sizes for feeding on organic material, and relatively low toxicity of the sewage discharged.

Acknowledgements

We wish to thank the Department of Fisheries and Oceans and Environment Canada for their financial and technical support, and particularly Dr. Colin Gray for his interest and comments on this study. We would also like to acknowledge the field support of Captains John McGrath and Mike Kelly, and the crews of the Canada Coast Guard Hovercraft Unit (Sea Island). Valuable research and technical assistance was provided by Ronalee Marsh, Kedong Yin, Christine Thomas, Mingxin Guo, Tim Parsons, Alan Lewis, Bruce Gillespie, David Jones, and Victoria Campbell.

References

Albright, R., 1982. Population structure and production of the amphipod *C. salmonis* stimpson in grays harbor, Washington. M.Sc. thesis, School of Fisheries, University of Washington, Seattle, 76 pp.

Anger, K., 1977. Benthic invertebrates as indicators of organic pollution in the western Baltic Sea. Int. Rev. Gesamt. Hydrobiol. 62, 245–254.

Ankar, S., Elmgren, R., 1976. The benthic macro- and meiofauna of the Askö-Landsort area (northern Baltic proper). A stratified random sampling survey. Contrib. Askö Lab., Univ. Stockholm 11, 1–115.

Arvai, J.L., 1997. The population dynamics and production of *Corophium salmonis* (S.) and *Macoma balthica* (L.) on an estuarine mudflat in response to effluent diversion from a sewage plant, Sturgeon bank, British Columbia. M.Sc. thesis, University of British Columbia, Vancouver, BC, 234 pp.

Bendell-Young, L., Yin, K., Thomas, C., Harrison, P.J., Feeney, T., Arvai, J., Levings, C.D., Ross, L., 2000. Biogeochemistry of the intertidal area of the Fraser river estuary. In: Groulx, B., Luternaer, J. (Eds.), Fraser Delta: Issues in an Urban Estuary. Geological Survey of Canada Bulletin, 57 p+tables, figs (in press).

BC Research, 1975. Environmental studies at Iona Island. Report No. 2, Project No. 1511/2. 162 pp.

BC Research, 1977. Environmental studies at Iona Island. Report No. 3, File No. 1-05-511. 47 pp.

Birtwell, I.K., Greer, G.L., Nassichuk, M.D., Rogers, I.H., 1983. Studies on the impact of municipal sewage discharged onto an intertidal area within the Fraser river estuary, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1170.

Bortkevitch, L.V., Khmeleva, N.N., Sadovskaya, N.I., 1984. Ecological characteristics, caloric value and production of *C. robustum* from the lower Dnieper. Hydrobiol. 2, 93–99.

Butler, R.W., 1994. Distribution and abundance of western Sandpipers, Dunlins, and Black Bellied Plovers in the Fraser river estuary. In: Butler, R.W., Vermeer, K. (Eds.), The Abundance and Distribution of Estuarine Birds in the Strait of Georgia, British Columbia. Canadian Wildlife Service Paper 83.

Costello, M.J., Read, P., 1994. Toxicity of sewage sludge to marine organisms. Mar. Environ. Res. 37, 23–46.

Crisp, D.J., 1971. Energy flow measurements. In: Holme, N.A., McIntyre, A.D. (Eds.), IBP Handbook No. 16: Methods for the Study of Marine Benthos. Blackwell Scientific Publishers, Oxford, pp. 197–279.

Daborn, G.R., Amos, C.L., Brylinski, M., Christian, H., Drapeau, G., Faas, W., Grant, J., Long, B., Paterson, D.M., Perillo, G.M.E., Piccolo, M.C., 1993. An ecological cascade effect: migratory birds affect stability of intertidal sediments. Limnol. Ocean. 38, 225–231.

Feeney, T.D., 1995. Physical controls on the distribution of contaminants on Sturgeon bank, Fraser river Delta, British Columbia. M.Sc. thesis, Department of Oceanography, University of British Columbia, Vancouver, 292 pp.

Gamenick, I., Jahn, I., Vopel, K., Giere, O., 1996. Hypoxia and sulphide as structuring factors in a macrozoobenthic community on the Baltic sea shore: colonisation studies and tolerance experiments. Mar. Ecol. Prog. Ser. 144, 73–85.

Grizzle, R.E., 1984. Pollution indicator species of macrobenthos in a coastal lagoon. Mar. Ecol. Prog. Ser. 18, 191–200.

Hawkins, C.M., 1985. Population carbon budgets and the importance of the amphipod *Corophium volutator* in the carbon transfer in a Cumberland Basin mudflat, Upper Bay of Fundy, Canada. Neth. J. Sea Res. 19, 165–176.

Hughes, R.G., 1978. Production and survivorship of epizoites of the hydroid *Nemertesia antennina* (L.). J. Mar. Biol. Assoc. UK 58, 333–345.

Icely, J.D., Nott, J.A., 1985. Feeding and digestion in *Corophium volutator* (Crustacea: Amphipoda). Mar. Biol. 89, 183–195.

Larson, D., 1995. Iona foreshore monitoring project: sediment bioassays using the bivalve *Macoma balthica*. Integrated Resource Consultants Inc., Richmond, 67 pp.

Levings, C.D., 1985. Juvenile salmonid use of habitats altered by a coal port in the Fraser river estuary, British Columbia. Mar. Pollut. Bull. 17, 248–254.

Levings, C.D., 2000. Fish ecology: current knowledge and its application to habitat management. In: B. Grouix and J. Luternaer (Eds.), Fraser Delta: Issues in an Urban Estuary. Geological survey of Canada Bulletin.

Levings, C.D., Coustalin, J.B., 1975. Zonation of intertidal biomass and related benthic data from Sturgeon and Roberts banks, Fraser river estuary, British Columbia. Environment Canada Fisheries and Marine Services Technical Report No. 468, 141 pp.

McClusky, D.S., 1968. Some effects of salinity on the distribution and abundance of *Corophium volutator* in the Ythan estuary. J. Mar. Biol. Assoc. UK 48, 443–454.

McLusky, D.S., Hull, S.C., Elliott, M., 1993. Variations in the intertidal and subtidal macrofauna and sediments along a salinity gradient in the upper forth estuary. Neth. J. Aquat. Ecol. 27, 101–109.

Meadows, P.S., 1964. Experiments on substrate selection by *Corophium* species: films and bacteria on sand particles. J. Exp. Biol. 41, 499–511.

Miller, D.C., 1984. Mechanical post-capture particle selection by suspension and deposit-feeding *Corophium*. J. Exp. Mar. Biol. Ecol. 82, 59–72.

Moore, D.C., Rodger, G.K., 1991. Recovery of a sewage sludge dumping ground. 2. Macrobenthic community. Mar. Ecol. Prog. Ser. 75, 301–308.

Moore, K., 1993. Contaminant loadings to the Fraser river estuary. Technical Report Series WQWM-93-04. Fraser River Estuary Management Program, New Westminster, 92 pp.

Nishimura, D.J.H., Piercey, G.E., Levings, C.D., Yin, K., McGreer, E.R., 1996. Changes in fish communities and water chemistry after cessation of municipal sewage discharge near the Iona Island foreshore, Fraser river estuary, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 2096, 17 p.

Otte, G., 1975. A laboratory key for the identification of *Corophium* species (Amphipoda, Corophidae) of British Columbia. Fisheries and Marine Services of Canada Technical Report No. 519. 78 pp.

Otte, G., 1979. Untersuchungen uber die Auswirkung kommunaler Abwasser auf das benthische Okosystem mariner Watten (Investigations on the effects of domestic sewage on the benthic ecosystem of marine intertidal flats). Helgoländer. Meeresunters. 32, 73–148.

Otte, G., Levings, C.D., 1975. Distribution of macroinvertebrate communities on a mudflat influenced by sewage – Fraser river estuary, British Columbia. Fisheries and Marine Services of Canada Technical Report No. 476. 159 pp.

Pearson, T.H., Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. Oceanogr. Mar. Biol. Ann. Rev. 16, 229–311.

Peer, D.L., Linkletter, L.E., Hicklin, P.W., 1986. Life history and reproductive biology of *Corophium volutator* (Crustacea :Amphipoda) and the influence of shorebird predation on population structure in Chignecto Bay, Bay of Fundy, Canada. Neth. J. Sea Res. 20, 359–373.

Pomeroy, W.M., Levings, C.D., 1980. Association and feeding relationships between *Eogammarus confervicolus* (Amphipoda, Gammaridae) and benthic algae on Sturgeon and Roberts banks, Fraser river estuary. Can. J. Fish. Aquat. Sci. 37, 1–10.

Read, P., 1987. The intertidal benthos and sediments of particulate shores in the Firth of Forth, Scotland, with particular reference to waste water discharges. Proc. R. Soc. Edinburgh, Sect. B 93, 401–413.

Rebele, L., 1994. Observations of the macrobenthos of a tidal flat community at: Sturgeon bank, British Columbia. B.Sc. thesis, University of British Columbia, Vancouver, 78 pp.

Ross, L.R., 1998. Primary Productivity on Sturgeon bank. M.Sc. thesis, University of British Columbia, Vancouver, 168 pp.

Segerstråle, S.G., 1960. Fluctuations in the abundance of benthic animals in the Baltic area. Commentat. Biol. Soc. Sci. Fenn. 23, 1–19.

Stanhope, M.J., 1983. The effects of estuarine log debris on the population characteristics and parameters of the benthic salmon food organisms in the Squamish estuary, British Columbia. Unpublished report submitted to MacMillan Bloedel Ltd, Woodland Services Division, Vancouver, 54 pp.

Tabata, S., Giovando, L.F., Devlin, D., 1971. Current velocities in the vicinity of the Greater Vancouver Sewerage and Drainage District's Iona Island Outfall – 1968. Fish. Res. Bd. Can. Tech. Rep. 263, 278 pp.

Thomas, C.A., Bendell-Young, L.I., 1998. Linking the geochemistry of an intertidal region to metal bioavailability in the deposit feeder *M. balthica*. Mar. Ecol. Prog. Ser. 173, 197–213.

Ueda, N., Tsutsumi, H., Yamada, M., Takuchi, R., Kido, K., 1994. Recovery of the marine bottom environment of a Japanese bay. Mar. Pollut. Bull. 28, 676–682.

Underwood, A.J., Chapman, M.G., 1997. Subtidal assemblages on rocky reefs at a cliff-face sewage outfall (North Head, Sydney, Australia): What happened when the outfall was turned off? Mar. Pollut. Bull. 33, 293–302.

Waldichuk, M., 1984. Sewage pollution in British Columbia in perspective. *Presented in* The Workshop on Municipal Marine Discharges – 1984. Canadian Environmental Protection Service, Pacific Region, Vancouver, 365 pp.

Yin, K., Harrison, P.J., 2000. Influences of flood and ebb tides on nutrient fluxes and chlorophyll on an intertidal flat. Mar. Ecol. Prog. Ser. 196, 75–85.