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EFFECTS OF WATER TRANSFER ON AQUATIC INSECTS IN A STREAM IN HONG KONG

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ABSTRACT

Hong Kong streams serve as indirect catchments for storage reservoirs to which they are connected by a network of undergound tunnels. Water transfer to reservoirs reduces stream flow downstream of the extraction point, and surface flows may disappear in affected reaches during the dry season. The ecological effects of periodic dewatering on aquatic insects were investigated in Tai Po Kau Forest Stream, Hong Kong, where water extraction at a weir gives rise to intermittent flow immediately downstream of a well studied perennial stream section. Benthic samples were taken from the intermittent reach on 48 occasions over a two year period encompassing two dry seasons. Trends in total population densities were unclear, with considerable fluctuations over the study period. In contrast, species richness declined markedly after surface flow disappeared, reaching the lowest values at the end of both dry seasons. A rapid increase accompanied flow resumption on the onset of the summer monsoon, and maximum wet season values were up to five times greater than species richness during the dry season. Dry season declines in Ephemeroptera and Trichoptera were accompanied by a dramatic increase in Coleoptera (Elmidae and especially Helodidae). The situation was reversed during the wet season when Trichoptera (especially *Cheumatopsyche* and *Chimarra*) and Ephemeroptera (Leptophlebiidae, Baetidae and Heptageniidae) were numerous. Community structure in the intermittent reach recovered quickly from the dewatering disturbance, due largely to recolonization by drifting animals. At the scale investigated, the community was resilient to disturbance because a source of mobile colonists was available upstream. However, if dewatering affects reaches far downstream, the presence of suitable colonists in upstream reaches cannot be guaranteed, and recovery from disturbance will be delayed. Lowland streams in Hong Kong are often polluted and host to exotic species; in such circumstances the effects of water transfers are exacerbated and recolonization is hindered.

KEY WORDS Aquatic insects Hong Kong Stream Benthos Recolonization Drift Disturbance Water transfer

INTRODUCTION

River regulation, defined in the broadest sense to include the construction of dams and weirs as well as canalization and water transfers, has a long history in Hong Kong. The first stream-fed reservoir was constructed in 1863, and streams remain the main source of water for Hong Kong's reservoirs. Increased efficiency of water capture and storage is achieved through linkage of impounding reservoirs and catchments by a series of underground pipelines and associated pumping stations. Transfer of water to reservoirs from indirect catchment streams must have a considerable impact on the ecology of reaches downstream of the water capture. There have been no studies of these effects in Hong Kong, and data from elsewhere in the seasonal tropics are scarce when compared with research on regulated rivers in the temperate zone (e.g. Ward and Stanford, 1979; Lillehammer and Saltveit, 1984; and references cited therein). Reduced flow volumes in reaches downstream of water transfer sites are especially marked during the winter dry season in Hong Kong. In many instances these reaches either dry up, or the flow disappears into the stream bed colluvium. This study looked at changes in the benthic insect fauna of an intermittent reach of Tai Po Kau Forest Stream, New Territories, Hong Kong, situated downstream of a weir from which water was extracted. Although the stream flows throughout the year in upstream reaches, it is intermittent below the weir where flow ceases during the dry season.

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STUDY AREA

The site was a short (30 m), intermittently flowing reach of Tai Po Kau Forest stream (TPKFS; latitude 22°25N′, longitude 114°11′E) situated below a weir at the lower end of a perennial riffle. A detailed description of the site and the sediments and water chemistry of that riffle is given elsewhere (Dudgeon, 1982a; 1982b). In essence, the stream waters were well oxygenated, slightly acidic, soft and nutrient poor. Bottom sediments were coarse and poorly sorted, but showed across-stream gradients and were finer close to the banks. Sediment characteristics varied with current velocity: spates during the wet season scoured the stream bed washing out fine particles with the result that all sediment patches came to resemble each other closely.

Immediately below the intermittent reach, the TPKFS was blocked completely by a 12 m high concrete dam where all flow was diverted into an underground water-catchment tunnel connected to the Hong Kong reservoir and water supply system (Figure 1). Water was also extracted from the TPKFS above the weir but, during the summer wet season, water spilled over the weir and flowed down the intermittent reach to the dam and catchment tunnel. Approximately 84% of Hong Kong's average annual rainfall (2225 mm) takes place between April and September and, as stream discharge declined during the drier months, the continued extraction of water at the weir reduced the volume of water flowing downstream. As a result, surface flows in

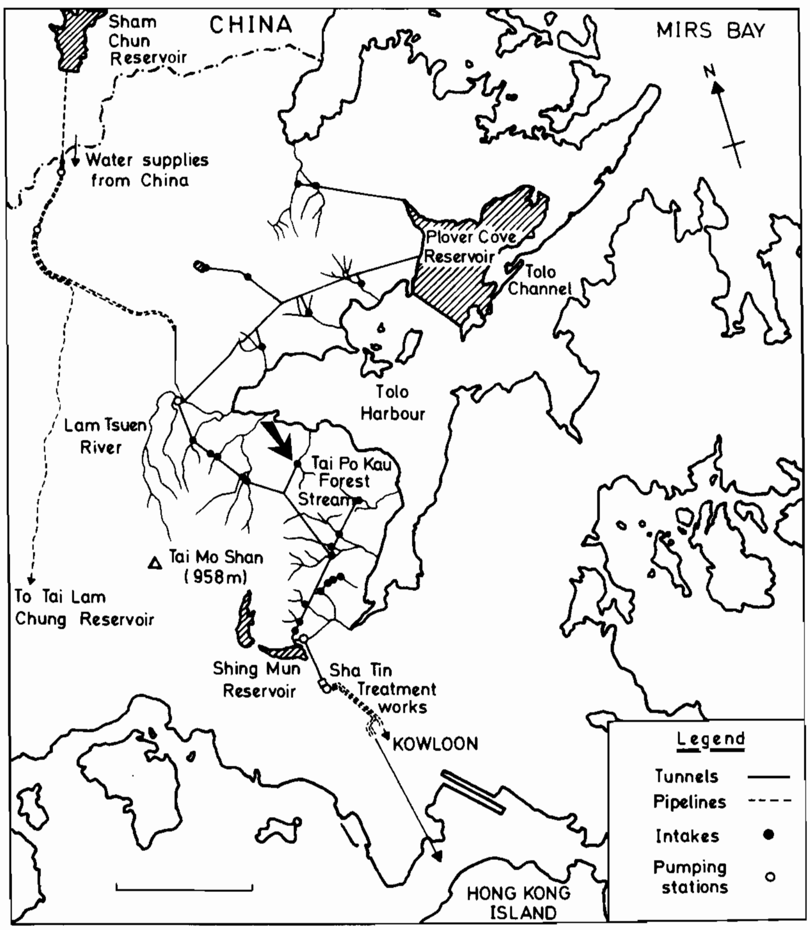

Figure 1. Part of the network of tunnels carrying water from the East River in China, and from a number of indirect catchments, to Hong Kong reservoirs. The site of water extraction from Tai Po Kau Forest stream is marked by an arrow. The scale line represents 5 km

the intermittent reach diminished and then ceased completely (as in December 1977 and January 1979). At this time the upper 1–3 cm of the stream bed dried out completely, but buried sediments remained moist. Surface flows resumed with the onset of the summer monsoon in May.

The TPKFS has been the subject of detailed ecological studies focusing on the dynamics of benthic fauna (reviewed by Dudgeon, 1992). The present exploratory investigation was undertaken as an adjunct to these studies and involved sampling over two years. The TPKFS is not gauged and, when work began, there was no information on the stream and the seasonal pattern of water flow in the study reach was not known. In view of the small size of the study reach, the need to avoid repeated sampling of the same patch of stream bed, and the logistical constraints imposed by research work proceeding in parallel in the perennial riffle upstream, sampling on any one date was limited. However, sampling was maintained over a two year period to determine whether seasonal patterns were repeated between years, thereby enhancing the generality of conclusions drawn from this work.

MATERIALS AND METHODS

Benthic collections were made from what appeared to be a homogeneous area in the central part of the intermittent reach. Samples were taken on each of 48 visits to the site made at approximately two week intervals between May 1977 and May 1979. As the stream was not gauged, it was not possible to measure discharge directly, but flow characteristics (e.g. bankfull, spate, lack of surface flow) were noted on each visit.

The benthos sampler consisted of a clear Perspex box fitted with a foam rubber skirt around the base which, when pressed against the stream bed, produced a water-tight seal enclosing an area of 1000 cm^2. The top of the apparatus protruded above the water surface. Once a sample unit had been isolated by the box, all sediments and associated material in the enclosed area, down to the level of parent rock (generally < 25 cm), were scooped out; animals and fine material in the water column were recovered with a 200 μm mesh net. A single sample was taken on each visit, and the same sampling procedure was used whether or not surface water flow was present.

In the laboratory, detrital and faunal components of the sample were separated from the inorganic fraction by flotation in brine. Insects were separated from detritus on a toluene–70% ethanol interface (see Dudgeon, 1989), rinsed and preserved in ethanol. Animals were sorted and counted at 15× magnification under a stereomicroscope. Aquatic insect taxonomy in south-east Asia has received little attention, and thus not all individuals could be sorted to named species. Where several undescribed species were congeneric, they were designated letters or numbers following procedures used in earlier publications (Dudgeon, 1988a). Chironomidae (Diptera) larvae have been excluded because of difficulties in distinguishing higher taxa within the family and the fact that small larvae of these animals would have been under-sampled by the mesh size of nets used (Storey and Pinder, 1985).

RESULTS

A total of 14 356 insects (excluding chironomids), comprising 114 species, was recorded from the study reach (Table I). None of the species collected were restricted to the intermittent reach, and all were found elsewhere in the TPKFS. Total population densities varied dramatically over the study period (Figure 2), with marked peaks separated by troughs immediately before cessation of surface flow and during the dry period. Smaller fluctuations in density during the summer wet season may have been related to the incidence of spates caused by heavy rains associated with typhoons, but the lack of sample replication does not allow further investigation of this matter. The pattern of changes in benthos species richness over the two years was clearer (Figure 2): conspicuous declines followed the disappearance of surface flows, and species richness was lowest at the end of both dry seasons (April 1978 and 1979; see also May 1977). Maximum wet season species richness in summer 1977 and 1978 was five times greater than the total of 10 species recorded in April 1978 just before the summer monsoon, and more than twice that noted in March and April 1979.

There were striking contrasts in the seasonal trends of abundance of Ephemeroptera, Trichoptera and Coleoptera (representing 34·3, 19·3 and 39·3% of the total standing stock, respectively). Total mayfly

Table I. Tai Po Kau Forest stream intermittent reach: mean population densities ($\pm$ 1 SE) of benthic insects in samples taken on 48 occasions between May 1977 and May 1979

Ephemeroptera	102·6 ± 12·9	Nemouridae	
Baetidae	34·0 ± 6·9	*Amphinemura* sp.	0·7 ± 0·2
Indobaetis sp.	6·6 ± 1·3	Leuctridae (1 sp.)	0·5 ± 0·2
Baetis nr *pseudofrequentus*	10·8 ± 2·0		
Baetis T3	6·4 ± 3·9		
Baetis T5	<0·1	Trichoptera	57·8 ± 8·0
Chopralla sp.	1·3 ± 0·4	Rhyacophilidae	
Baetiella sp.	3·0 ± 0·7	*Rhyacophila* T1	0·9 ± 0·3
Pseudocloeon (2 spp.)	5·7 ± 2·0	Glossosomatidae	
Platybaetis sp.	<0·1	*Agapetus* T1	1·9 ± 0·4
Oligoneuriidae		Philopotamidae	
Isonychia kiangsinensis	1·4 ± 0·4	*Chimarra* sp.	15·7 ± 3·5
Ephemeridae		Stenopsychidae	
Ephemera spilosa	0·7 ± 0·2	*Stenopsyche angustata*	10·0 ± 0·4
Ephemerellidae	4·8 ± 1·0	Psychomyiidae (1 sp.)	0·2 ± 0·1
Ephemerellina T1	1·6 ± 0·4	Xiphocentronidae	
Serratella T2	3·0 ± 0·7	*Melanotrichia serica*	0·2 ± 0·1
Teloganodes sp.	<0·1	Polycentropodidae	
Caenidae (2 spp.)	2·7 ± 0·9	cf. *Polycentropus* sp.	<0·1
Leptophlebiidae	40·6 ± 6·0	Pseudoneureclipsidae	
Choroterpes spp.	23·4 ± 5·2	*Pseudoneureclipsis* sp.	1·6 ± 0·4
Isca purpurea	15·8 ± 2·8	Ecnomidae	
Habrophlebiodes gilliesi	1·4 ± 0·4	*Ecnomus* sp.	0·2 ± 0·1
Thraulus cf. *bishopi*	<0·1	Hydropsychidae	31·1 ± 6·1
Heptageniidae	20·0 ± 3·6	*Polymorphanisus astictus*	<0·1
Paegniodes cupulatus	3·6 ± 0·8	*Macrosternum fastosum*	2·8 ± 0·6
Epeorus (*Iron*) T1	1·0 ± 0·3	*Cheumatopsyche spinosa*	24·2 ± 5·4
Epeorus (*Epeorus*) T2	2·0 ± 0·4	*Cheumatopsyche ventricosa*	4·5 ± 1·0
cf. *Cinygmina* (2 spp.)	13·5 ± 3·0	*Herbertorossia quadrata*	<0·1
		Hydropsyche (4 spp.)	<0·1
		Calamoceratidae	
Odonata	9·3 ± 1·5	*Anisocentropus maculatus*	1·3 ± 0·4
Ephaeidae		Leptoceridae (1 sp.)	<0·1
Euphaea decorata	6·4 ± 1·3	Lepidostomatidae	
Platystictidae		*Goerodes* sp.	0·6 ± 0·3
Protosticta taipokauensis	<0·1	Odontoceridae	
Calopterygidae		*Psilotreta kwantungensis*	0·2 ± 0·1
Mnias mneme	<0·1		
Libellaginidae			
Rhinocypha perforata	<0·1	Megaloptera (Corydalidae)	
Libellulidae		*Neochauliodes boweringi*	0·5 ± 0·1
Zygonyx iris	0·2 ± 0·1		
Gomphidae			
Onychogomphus sinicus	1·8 ± 0·3	Coleoptera	117·4 ± 20·8
Heliogomphus scorpio	0·6 ± 0·1	Dytiscidae (4 spp.)	3·5 ± 0·8
		(including *Neptosternus hydaticoides* and *Hydrovatus subvittulus*)	
Hemiptera: Heteroptera	2·41 ± 0·6	Hydrophilidae (7 spp.)	4·6 ± 0·8
Corixidae		Helodidae	
Micronecta sp.	<0.1	*Helodes* sp.	61·4 ± 15·3
Helotrephidae		Ptylodactilidae (2 spp.)	1·8 ± 0·2
Distotrephes stysi	<0·1	Psephenidae (4 spp.)	3·1 ± 0·6
Helotrephes semiglobosus	0·9 ± 0·3	Gyrinidae	
Naucoridae		*Orechtochilus* sp.	2·8 ± 0·8
Aphelocheirus dudgeoni	1·4 ± 0·4	Dryopidae (2 spp.)	0·1 ± 0·1
		Elmidae: Elminae (11 spp.)	39·3 ± 6·1
Plecoptera	13·6 ± 2·4	Elmidae: Larinae (1 sp.)	0·4 ± 0·2
Perlidae indet. (6 spp.)	12·3 ± 2·2	Hydraenidae (2 spp.)	0·7 ± 0·3

Table I. *Cont.*

Non-chironomid diptera	5·3 ± 1·2	Dixidae (1 sp.)	<0.1
Simuliidae (1 sp.)	0·8 ± 0·3	Nymphomyiidae (1 sp.)	0·6 ± 0·3
Tipulidae (4 spp.)	2·4 ± 0·9		
Ephydridae (1 sp.)	<0.1	Total insects: 299·1 ± 31·2	
Empididae (1 sp.)	0·3 ± 0·2		
Ceratopogonidae (3 spp.)	1·0 ± 0·3	Total species: 114	

densities fluctuated considerably, but were generally low (< 50 individuals m^{-2}) in February, March and April, and higher during the wet season (Figure 3). However, Baetidae densities (especially *Pseudocloeon* spp. and *Baetis* T3) peaked in early summer (May, June and July, with some variation among years), whereas Heptageniidae and Leptophlebiidae attained the greatest densities in December 1978 (and January 1979 for leptophlebiids) when stream flow ceased and animals were crowded into the few favourable patches remaining. Leptophlebiids were least affected by the cessation of surface flow, and some larvae (especially *Choroterpes* spp.) persisted in February, March and April during both dry seasons when baetids and heptageniids had been largely eliminated.

Seasonal trends in the abundance of Trichoptera were again well defined (Figure 4), with summer peaks separated by catastrophic declines in abundance during the dry season. All three of the most numerous taxa [*Stenopsyche angustata* (Stenopsychidae), *Chimarra* sp. (Philopotamidae) and *Cheumatopsyche* spp. (Hydropsychidae)] showed the same general pattern. These filter feeders were affected more severely than Ephemeroptera, and no *S. angustata* or *Chimarra* sp. were found from January until May during both dry seasons (Figure 4). In contrast with other major groups, aquatic Coleoptera (mainly Helodidae and Elmidae) were most numerous in the dry season although there were sometimes great differences in the population counts from successive samples (Figure 4). The trend towards dry season increases was especially apparent for larvae of *Helodes* sp., which was the most numerous species in the study reach (Table I). *Helodes* sp. was

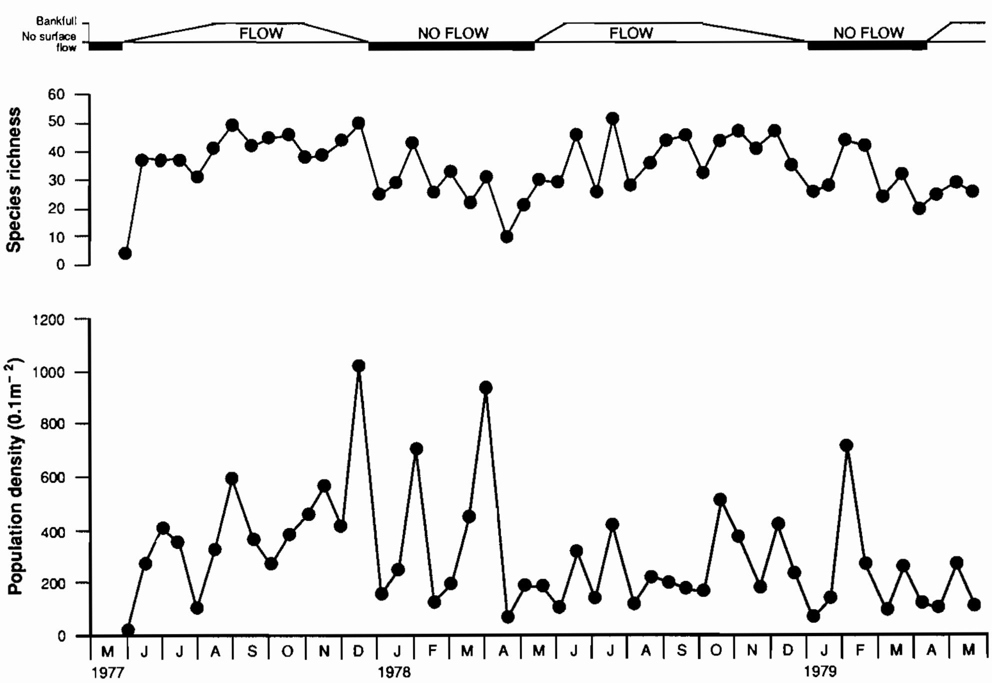

Figure 2. Changes in total population density and species richness of benthic insects in an intermittent reach of Tai Po Kau Forest stream, 1977–9. Periods of dewatering (no surface flow) and bankfull stream flow are also shown

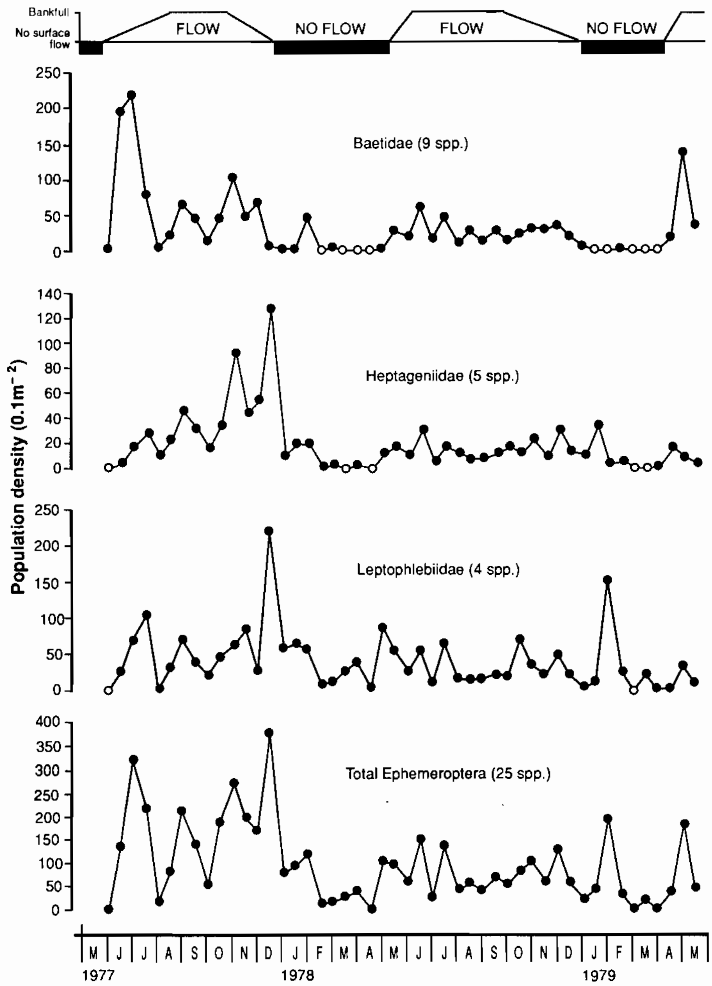

Figure 3. Changes in population density of total Ephemeroptera, Leptophlebiidae, Heptageniidae and Baetidae in an intermittent reach of Tai Po Kau Forest stream, 1979. Periods of dewatering (no surface flow) and bankful stream flow are also shown

more abundant in 1978 than in 1979, which accounted for the smaller dry season increase in density during 1979 (Figure 4).

Spearman's correlation analysis of stream discharge (estimated from stream width at the time of sampling) against total macroinvertebrate density, species richness, and densities of Ephemeroptera, Trichoptera and Coleoptera on each date, yielded a negative relationship for Coleoptera [$r_s = -0{\cdot}33$; degrees of freedom (df) $= 46$; $p = 0{\cdot}022$] and positive relationships for species richness ($r_s = 0{\cdot}341$; df $= 46$; $p = 0{\cdot}018$) and Trichoptera ($r_s = 0{\cdot}434$; df $= 46$; $p = 0{\cdot}002$).

DISCUSSION

The effects of water transfer leading to intermittent flow in the TPKFS were clear. A marked decline in species richness accompanied the disappearance of surface flows, whereas densities of most Ephemeroptera and Trichoptera declined. Conversely, Coleoptera (especially *Helodes* sp.) increased in abundance during the dry seson. Correlation analysis showed that total species richness and trichopteran population densities increased at times of greater stream flow; conversely, Coleoptera were more numerous at times of low flow. Pronounced fluctuations in population density accompanied these general trends and reflected, in part,

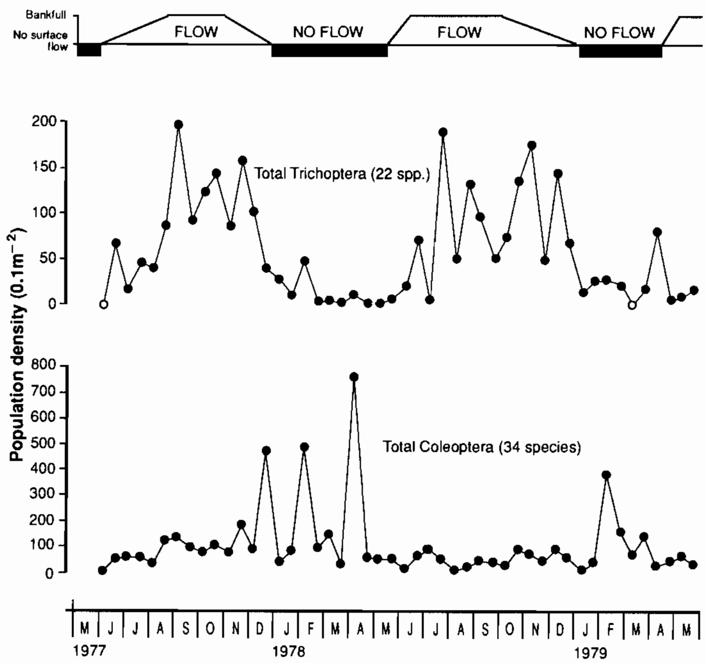

Figure 4. Changes in population density of Trichoptera and Coleoptera in an intermittent reach of Tai Po Kau Forest stream, 1977–79. Periods of dewatering (no surface flow) and bankfull stream flow are also shown

variability arising from the limited sampling effort expended on each sampling date. Wet season spates and patch-specific differences in water retention during the dry season would have increased this variability, as would benthic insect movement patterns which lead to the concentration of animals in patches within drying riffles (Delucchi, 1989). However, the consistency of seasonal trends in abundance between years indicates that the changes observed are genuine and not artifacts of the sampling strategy. In addition, the view that these seasonal fluctuations reflect genuine changes in benthic standing stocks gains support from comparison with the (fairly small) standard errors for mean population density estimates in the study reach (see Table I).

How does benthic composition and species richness in the intermittent reach compare with perennial streams in Hong Kong? Data obtained from four Hong Kong streams in summer 1983 (Dudgeon, 1988a) show that perennial riffles support between 70 and 94 species (excluding chironomids), which is less than the 114 species recorded from the intermittent reach. A perennial section of the TPKFS immediately upstream of the intermittent reach yielded 94 species, which, given the limited temporal span of the 1983 study, suggests that the intermittent section was not species-poor (see also Delucchi, 1988).

The five most abundant taxa in the perennial section of the TPKFS were *Cheumatopsyche* spp. (mean density 29·4 individuals 0·1 m^{-2}), *Chimarra* sp. (25·8), *Serratella* T2 (13·2), *Simulium* sp. (12·7) and *Choroterpes* spp. (11·9) (Dudgeon, 1988a); in the intermittent reach they were *Helodes* sp. (61·4), *Cheumatopsyche* spp. (28·7), *Chimarra* sp. (15·7), *Choroterpes* spp. (23·4) and *Isca purpurea* (15·8) (see Table I). Notwithstanding the time elapsed between the 1977–9 and 1983 studies, community composition of the intermittent reach was similar to that of the perennial section upstream in that three taxa were common to both lists. However, the relative importance of *Helodes* in the intermittent reach is striking, and both *Serratella* and *Simulium* were scarce in this section. The relative importance of *Helodes* reflects this beetle's abundance among the damp stones and gravels of the stream bed during the dry season, whereas the reduced prominence of *Simulium* (and perhaps *Serratella*) is due to a requirement for a fast current which was not met for part of the year in the intermittent reach. Note that helodids are well adapted to inhabiting damp substrates, and may be abundant in ground water (Klausnitzer and Pospisil, 1991). Hydropsychid larvae can survive in damp gravel for up to 30 days after dewatering (Imhof and Harrison, 1981), although they did not persist in significant numbers during the four month dry season at the Hong Kong study site.

Recolonization of the intermittent reach was rapid following flow resumption in summer, when a diverse community dominated by Trichoptera and Ephemeroptera was restored. Samples taken in the dry reach penetrated down to bedrock, showing that the hyporheic zone could not have provided a source of colonizers in the TPKFS (*cf.* Williams, 1984). Instead, drift from upstream was probably a major mechanism of recolonization, and 102 taxa have been recorded from TPKFS drift (Dudgeon 1990). Apart from *Chimarra*, Trichoptera were poorly represented in the drift. The abundance of *Cheumatopsyche* in the study reach probably reflects recruitment from oviposition which (in hydropsychids) peaks during summer (Dudgeon, 1988b, and unpublished observations), but recolonization by crawling may also be significant (*cf.* Doeg *et al.*, 1989). Early recolonization of the study reach by baetids (especially in 1977 and 1979; Figure 3) reflects their importance in TPKFS drift where they comprised 40% of individuals caught.

The seasonal changes in benthic communities due to dewatering in the TPKFS, and subsequent recolonization mechanisms, are broadly similar to those occurring in streams elsewhere (e.g. Hynes, 1970; Sagar, 1983; Weisberg *et al.*, 1990): drift is the major mechanism of recolonization (e.g. Waters, 1964; Williams and Hynes, 1976) where (as is inevitably the case for water transfers) the intermittent reach is downstream of a source of colonizers. Crawling as a means of recolonization or avoiding drying patches is relatively unimportant in some streams (Delucchi, 1989), but not in all such habitats (Doeg *et al.*, 1989). Where the stream dries completely (e.g. Harrison, 1966; Hynes, 1975; Williams, 1977; Morrison, 1990), however, recolonization depends on the arrival of ovipositing adults (especially in the tropics: Harrison, 1966; Hynes, 1975) or on individuals which spent the drought as dormant forms buried in the substrate.

The results presented here suggest that, at the scale investigated, stream communities are resilient (see also Morrison, 1990), and drifting animals allow rapid community recovery from disturbances caused by interruptions in flow due to water transfer. This resilience at the reach scale concords with Frid and Townsend (1989) and Townsend (1990, and references cited therein) who consider that the effects of disturbances in streams are short-lived because denuded patches are colonized rapidly by mobile (drifting) community members. For this reason there is little difference in community structure between perennial and intermittent stream reaches in the TPKFS, or elsewhere (Delucchi, 1988).

The wider implications of water transfer for Hong Kong streams are two-fold. Firstly, reduced dry season flows below extraction points effectively increase pollution loads (from agricultural run-off and livestock rearing) in the lower course of streams. Secondly, Hong Kong has a rugged, hilly terrain and coastal plains are limited; stream courses are therefore short and steep with restricted lowland (potamon) reaches. Extraction of water from hillstreams causes downstream reductions in flow, and thus mortality of the potamon biota. Although recolonization of the denuded area can begin when flow is restored, re-establishment of the original potamon community will depend on the presence of all such species in upstream reaches. Clearly, this presence cannot be guaranteed, and colonists derived from the stony upper course will not necessarily restore the original community structure of the potamon. Under these circumstances, lowland streams in Hong Kong are vulnerable to invasion by exotic species, and support large populations of exotic fishes (especially Poeciliidae), gastropods (Planorbidae and Ampullariidae) and macrophytes (Dudgeon, 1992).

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