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AN EVALUATION OF THE EFFECTS OF GEOTHERMAL ENERGY DEVELOPMENT ON AQUATIC BIOTA IN THE GEYSERS AREA OF CALIFORNIA

by

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ABSTRACT

The Geysers of Sonoma County, California, currently the largest geothermal energy field in the world, is expected to expand its electrical generating capacity considerably in the coming years. However, these future developments may result in watershed modification and potentially deleterious effects on aquatic biota due to the topography of the area. Analysis of the response of benthic populations and communities to past and ongoing geothermal energy development and operational practices was undertaken by means of an extensive six site sampling program on Big Sulfur Creek and a concentrated colonization study above, in, and below a heavily impacted tributary (Little Geysers Creek).

Differences in species diversity were noted among the six Big Sulfur Creek sites that were selected relative to the presence or absence of natural fumaroles or hot springs and the absence or stage of geothermal energy development. Distribution and colonization patterns of a population of sericostomatid caddisfly, *Gumaga nigricula*, and especially its dominance in high silt areas, suggest that both siltation and fumarole activity may select for certain populations.

Introduction

The procurement of energy resources is a vital part of this nation's social and economic wellbeing. However, energy development has often contributed to watershed alteration and national trends toward water quality deterioration (Hynes 1966, Pikul and Rabin 1974, Risser 1974, Dorfman 1976). Scarce fossil fuel resources and increasing power demands have stimulated a large-scale program to develop "alternative" energy resources. Since some of these developments have largely unknown impacts to aquatic resources, a thorough investigation of their potential hazards is necessary (Pikul and Rabin 1974). The scarce water resources in California and other western United States are essential for both community and economic development, and also are highly valued for their recreational and aesthetic aspects. It is essential then that particular care be taken in their protection.

One such alternative energy source with great development potential in California and other western states is the generation of electricity with geothermal energy. Beal _et_ _al_. (1974) report that projections for geothermal power use range from as low as 0.005% to as high as 22% of the nation's energy supply by the year 2000. The world's largest Geothermal Energy facility is operated by Pacific Gas and Electric Company at the Geysers, in Northern California. This development has proven to be both productive and highly economical. The Geysers power plants currently produce about 500 megawatts (roughly the electricity requirements of a city the size of San Francisco) at a cost lower than many other forms of electrical energy production. Ultimate electricity production at the Geysers is anticipated to be at least 2,000 megawatts.

This report represents a summarized version of the results of a two-year study involving faculty and students of the University of California, Berkeley, with the assistance and cooperation of personnel from the California Department of Fish and Game, United States Fish and Wildlife Service, and Pacific Gas and Electric Company. The purpose of this study has been to identify the effects of geothermal energy development and operation on the aquatic biota of The Geysers area. Additional research in The Geysers area is underway (described below) that expands on the results presented here. A full manuscript, originally planned for immediate publication as a University of California Water Resources Center Contribution, has been prepared. However, because this study was carried out during the severe California drought, and it is possible that the drought conditions may have accentuated geothermal effects on aquatic biota, we are delaying publication of a WRC report until these further studies are completed. Manuscripts (published or in press) that deal with research carried out in conjunction with this overall project are enclosed. We anticipate that a full report of the research summarized here, including information from on-going projects at the Geysers, will be produced within the next year.

The Concept of Biomonitoring in Evaluating the Effects of Geothermal Energy Development and Operation on Aquatic Biota in the Geysers Area of Northern California

Stream water quality monitoring by means of aquatic organisms has been successfully applied worldwide (Hynes 1966, Weber 1973, Cairns and Dickson 1973, Resh and Unzicker 1975). Biological data can greatly supplement physical and chemical measurements that provide only instantaneous information on water conditions which can vary greatly depending on factors such as stream flow and associated dilution factors, times of discharge of effluents, and rates of precipitation. However the inclusion of information about the composition of the aquatic biota reflects the cumulative effects of all substances entering a body of water including the interaction of contaminants that together might act differently and in many cases more severely than they might individually.

Macroinvertebrates are particularly favorable for biomonitoring purposes because they: 1) occupy a middle trophic level and can be expected to respond to changes in primary producers and their numbers indicate amounts of food resources available to fish; 2) are relatively sessile and are less capable than fish of rapidly dispersing great distances to avoid environmental disturbances (thus their community composition may directly reflect the conditions of their habitat over time); 3) typically include a great diversity of species each with respective environmental tolerances and thus reflect a tremendous range of aquatic conditions; 4) have rapid reproductive capacity and are often the first group of aquatic organisms to show a biological response to an environmental change (Gaufin and Tarzwell 1952, Aston 1973, Goodnight 1973, Olive and Dambach 1973, Weber 1973, Wiederholm 1973, and Gaufin 1973).

The Basis for Geothermal Energy Development

The extraction of geothermal energy at The Geysers involves the drilling of wells to depths of approximately 3000 m in order to tap reservoirs of subsurface steam. This superheated high pressure steam is transported distances up to several hundred meters to on-site power plants via surface pipelines. At the time of this study the geothermal energy operations at the Geysers consisted of 6 power plants involving 11 generating units and 150 steam wells with an additional four power plants under construction. Most of this development, as well as numerous roads in various stages of construction, is located within the steep and highly erodable watershed of Big Sulfur Creek. The clearing and devegetation practices associated with construction activities as well as occasional spills of geothermal condensate have resulted in unavoidable alteration of the watershed environment and potential hazard to the aquatic community of Big Sulfur Creek.

Natural and Manmade Factors Influencing Aquatic Biota of Big Sulfur Creek

The physical, chemical, and geologic characteristics of The Geysers provide a complex of unique conditions which must be considered in detail in developing an experimental design that can adequately assess the factors influencing aquatic life in this area. These include natural and manmade factors.

Natural Factors

Hot and mineral springs and fumaroles present along the course of Big Sulfur Creek (the locale of this study) introduce heated water and a number of chemical compounds into the stream (ammonia, sulfates, sulfides), heavy metals (mercury, arsenic, cadmium, lead), as well as trace elements such as boron and radon (Allen and Day 1927, Griffin and Sharp 1974, LeGore 1975, Price and Griffin 1975, Price 1977). Depending on their concentrations most of these materials can be toxic to numerous types of aquatic organisms (Roback 1974, Cushman *et al*. 1977). Habitats immediately surrounding hot mineral springs support a unique algal and bacterial flora and invertebrate fauna. Macroinvertebrate species composition of hot springs have been studied by numerous investigators, notably Brues (1924, 1927, 1928), Stark *et al*. (1976), and Winterbourn (1968). In a study of hot springs fauna in Virginia, Robinson and Turner (1975) reported many genera in common with the fauna of thermal waters located in other parts of the U.S. (Brues 1924, 1928 and Stockner 1971) as well as some found in New Zealand hot springs (Winterbourn and Brown 1967). The environmental conditions immediately surrounding the natural hot springs along Big Sulfur Creek suggest that natural selective pressures may induce possible faunal differences relative to those hot spring influences. Thus, an investigation of these natural factors was necessary in this study in order to proceed with assessment of geothermal development effects on the aquatic community.

Steam-condensates from geothermal operations

Most chemicals, heavy metals, and trace elements found in hot springs at the Geysers are also present in sizable amounts in the geothermal steam reservoir (Cushman *et al*. 1977, U.S. Dept. of Interior 1971). McNitt (1963) hypothesized that ground water and the steam reservoir are in intimate contact and thus ground water of the area would be expected to consist of water from rainfall percolation and condensed steam from the reservoir Ramey (1968) presents an alternative hypothesis that the steam reservoir is essentially a closed system with little physical communication between the reservoir and ground water. However, this idea contrasts with the observed fact that hydrogen sulfide and ammonia are present in the steam emanating from both fumaroles and the hot springs. Ground surfaces around fumaroles are encrusted with minerals carried to the surface in vapor form. White (1967) found mercury precipitated in natural steam vent areas at the Geysers. Sulfur precipitating from condensed geothermal steam at the Geysers (Unit Number 2) was found to contain 5,000 ppb Hg (White, Hinkle and Barnes 1970). The twenty percent of the original steam that is not lost to evaporation has high salinities and contains amounts of boron, ammonia, hydrogen sulfide and other potentially toxic substances normally associated with hot springs.

Currently all steam condensate fluids at the Geysers are reinjected into the underground steam reservoir. However, this was not the case in the early stages of development when condensate was released directly into Big Sulfur

Creek. This practice was discontinued in 1969 (Price 1977). There have been a number of instances when steam well blowouts and spillage of geothermal fluids resulted in contamination of Big Sulfur Creek and at least one reported kill of steelhead trout (White 1974, 1975).

Boron as boric acid present in the discharge of geothermal condensate was identified as a possible toxin in that particular case by Axtmann and Peck (1976). However, other substances could have been responsible (Price, personal communication). In addition, two steam well blowouts occurred in unstable substrate areas when well casings were sheared off by landslides (Ermak and Phelps 1978) and caused radical devegetation in their surrounding area. Toxic substances present in geothermal steam and condensates can also enter the local watershed and stream by several means including: a) steam from pressure release valves and uncapped wells; b) drift from cooling towers; c) drift from cooling tower blowdown; and d) steam condensation from steam lines. Details of toxic substances present in geothermal steam and condensates to aquatic organisms are found in Axtmann (1975), and Axtmann and Peck (1976). Some of these elements have potential for bioaccumulation within the aquatic food chain to levels in fish which are hazardous to man (Cushman _et_ _al_. 1977).

Although reinjection and other engineering practices such as sufficiently large and stable sump basins now utilized in drilling and transmission of fluids at the Geysers have greatly reduced the possibility of catastrophic spills, factors such as gross human error could make them possible. Geothermal well drilling activities also present several potential impacts to the stream community. Drilling muds contain clay, detergents and sodium hydroxide, which could be detrimental to aquatic life and water supplies if allowed to enter aqua systems by seepage or overflow of drill sumps. Fresh water aquifers occurring above a geothermal reservoir could be contaminated through an improperly sealed well. Limited information exists on the effects of geothermal power development on aquatic invertebrates. At the Wairakei Power Plant in New Zealand geothermal condensate has been routinely discharged into the Waikato River since the early 1960's. Hill (n.d.) reported that Lake Aratialia, located immediately downstream from the power plant, had a zooplankton diversity of less than half that of Lake Ohakuri, which is further down-river. Reinjection systems have been proposed for this development site.

Sedimentation from Natural Sources

As noted earlier, most of the drainage of Big Sulfur Creek consists of steep, highly erodable terrain (Brown and Jackson 1974). Neilson (1975) estimates that approximately 70-75% of the area has slopes greater than 30% and much of this is unstable and prone to landslides. Ermak and Phelps (1978) have stated: "The causes of the unusually rapid erosion and landslides lies in the character of the rocks under the slopes; much of it is physically incompetent because of severe fracturing and chemical weathering." West of the Geysers are major active faults of the San Andreas system, which can be sites of significant earthquakes. Any such earthquakes may reactivate landslides and induce movement of active landslides.

Sedimentation and Metals from Other Types of Development

Similarities in the geologic origins and characters exist between mercury ores and hot springs (Dickson and Tunnel 1968, White *et al.* 1970, Weisberg and Zobel 1973). Sediment particles may adsorb or release heavy metals (Alabaster 1972, Golterman 1973) and these heavy metals, adsorbed on sediment, may be ingested, absorbed, and concentrated by aquatic organisms (Oschwald 1972).

Developments such as the mining operations at Mercuryville (in the same watershed but downstream from study area) and at Socrates mine (also same watershed but upstream from study sites) undoubtedly introduced significant amounts of sediment and mercury (as smelter tailings) into Big Sulfur Creek's drainage during past operations. . Since the amounts introduced are unknown, it is difficult to estimate the contribution of this activity to current background levels of sediments and metals. However water analysis of several sites along Big Sulfur by LeGore (1975) indicates that mercury concentrations generally ranged from .30 μg/liter to 116 μg/liter. Results varied widely at given sites for separate dates however. According to their analysis the bulk of the mercury originates upstream from the original geothermal development area (our sites 1 -3). Less than 5% of the mercury content of Big Sulfur Creek within this area appears to be contributed by the various hot springs and fumaroles in this area. Values exceeding the EPA limit of .05 μg/l occur fairly consistently through the original development area. It should be noted however, that the validity of these mercury estimations determined by Parametrix has been questioned (Price, personal communication).

Sedimentation as Related to Geothermal Energy Development

Soil characteristics and steep terrain of the Big Sulfur Creek watershed make it particularly vulnerable to erosion resulting from clearing and devegetation operations associated with geothermal development (Legore 1975, Neilson 1975). Although the area is also naturally prone to landslides, there have been several cases where landslides appear to have been induced by development activities (Steele and Emig, draft ms.).

Clearing and compaction of soil increases runoff and erosion rates (Megahan and Kidd 1972). High runoff rates may cause abrupt fluctuations in stream flow; such fluctuations may limit the size and stability of macroinvertebrate communities (Hynes 1973).

Studies conducted by PG&E over the period 1968 to 1975 indicate trends whereby color, turbidity, and settlable solids in Big Sulfur Creek have increased over this period. This is largely attributed to erosion from expanding geothermal development (Price and Griffin 1975, Price 1977). On the average, construction of each power plant requires clearing, slope cutting and filling of an area of 5-7 acres, and each drill site involves similar operations on a minimum of 2.5 acres (Steele and Emig, draft ms.).

Earth moving and clearing operations are also required for trailers, shops, and office sites as well as geothermal steam pipes and electrical transmission pipes. The total cleared area is approximately 20% of the watershed (USFWS 1978). Full development projections for the entire area estimate 1300 acres will be cleared of vegetation (U.S. Dept. of Interior 1971).

Spills from steam condensate holding ponds and settling basins have also eroded soil into steam channels and added to the silt load (CDF&G records). On June 10, 1977 an accidental spill of 300,000 gallons of condensate from cooling towers on the north canyon wall of Big Sulfur Creek carried a large volume of sediment into the stream.

A study undertaken by California Department of Fish and Game in 1976 and 1977 (Steele and Emig, draft ms.) found that size composition of fine sediments (< 0.8 mm) in the upper seven miles of Big Sulfur Creek was higher (significant difference at 5% level) than in Little Sulfur Creek, a stream in an adjacent watershed not yet subjected to geothermal development. A similar study by Parametrix (1976) indicated that fine sediment in Big Sulfur Creek in the geothermal development area is no greater than in other nearby streams but that the amount of sand in Big Sulfur Creek is significantly greater. Parametrix attributes this to the numerous tributaries in the area and is not related to development activities. Dr. Richard Moore (personal communication), who sampled benthic invertebrates in Big Sulfur Creek in 1968, re-examined the stream again this year and indicated that corresponding periods reflect precipitation trends. Volume of flow during normally heavy rain months (November through March) remained below 1000 GPM (0.06 m^3/sec) during all sampling dates of 1976-1977 and peaked at 800 GPM (0.05 m^3/sec) in February 1977. In contrast, minimal flow during 1977-1978 rain months was recorded as 3000 GPM (0.19 m^3/sec) during November 1977 and ranged from 10,000 GPM (0.63 m^3/sec) to 50,000 GPM (3.15 m^3/sec) between the months December 1977 to March 1978. Associated with these marked volume differences (and probably differential groundwater recharging) were low volumes of flow during the summer season of 1977 (minimum volume as 200 GPM or 0.013 m^3/sec in August) and relatively greater volume during the summer of 1978 (minimum volume as 390 GPM or 0.025 m^3/sec in July).

Vegetation

Riparian vegetation along Big Sulfur Creek is dominated by the trees *Alnus rhombifolia* (white alder), *Umbellaria californica* (California bay or laurel), *Arbutus menziesii* (madrone), and several *Quercus* (oak) species. Shrubs include *Rubus vitifolius* (blackberry), *Rhus diversiloba* (poison oak), *Salix* (willow) sp. and *Vitis* (wild grape) spp. Other dominant riparian vegetation, often approaching waters' edge, includes *Equisetum* (horsetail) sp. and the sedge *Carex* sp. Plants less commonly encountered include the fern *Woodwardia fibriata* and buckwheat, *Polygonum* sp.

STUDY RESULTS

Macroinvertebrate Survey of Big Sulfur Creek

Over 100 taxa and 51,000 specimens were collected during five sampling dates for Sites 1-3 (7/14, 8/13, 8/28, 9/22, 10/28/77, month/date/yr) and six sampling dates for Sites 4-6 (those above plus 6/22/77). Four species of caddisflies (Trichoptera) and midge larvae (Family Chironomidae) together comprised over 73.8% of all individuals collected. The two most abundant species, Gumaga nigricula (McLaughlan) (Trichoptera: Sericostomatidae) and Helicopsyche borealis (Hagen) (Trichoptera: Helicopsychidae) comprised 22% and 16%, respectively, of all macroinvertebrate individuals collected.

Species Composition and Abundance in Response to Site-Specific Parameters

Fewer taxa and greater numbers of individuals were found at Site 1 than 2 or 3 (Table 3). Distinct faunal differences are present in each site. Individuals of H. borealis, G. nigricula and Chironomidae larvae comprised 78% of all individuals collected at Site 1, 66% of those at Site 2 but only 28% of those at Site 3. Two species, Psephenus (Coleoptera: Psephenidae) and Optioservus (Coleoptera: Elmidae), rare at Sites 1 and 2 (< 1% of total individuals collected), each increase to > 5% of total individuals at Site 3.

In terms of their abundance at Site 1, relative to Sites 2-3, Leucotrichia (Trichoptera: Hydroptilidae, 60 individuals at Site 1 cf. 78 individuals at Sites 1-3), Ambrysus (Hemiptera: Naucoridae, 87/124), H. borealis (3734/6072), G. nigricula (3006/5438) and Simulium (Diptera: Simuliidae 48/55) and acari (46/53) predominated at Site 1. In contrast, several taxa were restricted to Site 3: Centroptilum (Ephemeroptera: Baetidae), Rhyacophila (Trichoptera: Rhyacophilidae), Lepidostoma (Trichoptera: Lepidostomatidae) and Psychoglypha (Trichoptera: Limnephilidae) whereas others predominated at Site 3: Psephenus (448/487), Optioservus (344/433), Ordobrevia (Coleoptera: Elmidae 210/224), Tricorythodes (Ephemeroptera: Baetidae 218/241), Sialis (Megaloptera: Sialidae 55/73), Marilia (Trichoptera: Odontoceridae 109/128), Claassenia (Plecoptera: Perlidae 21/25), Antocha (Diptera: Tipulidae 11/13) and Euparyphus (Diptera: Stratiomyiidae 85/112). Several taxa abundant at Sites 2 and 3 are absent (or nearly absent) from Site 1, e.g.

Zaitzevia (Coleoptera: Elmidae 2/178), *Baetis* (Ephemeroptera: Baetidae 23/277), *Paragyractis* (Lepidoptera: Pyralidae 6/79), and *Wormaldia* (Trichoptera: Philopotamidae 0/240), *Marilia* (0/128), and *Tinodes* (Trichoptera: Psychomyiidae 4/146).

Sites 4-6. Fewer taxa were collected at Site 4 than at Sites 5-6, although sample densities were similar (Table 1). A similar pattern for *G. nigricula*, *H. borealis*, and Chironomidae dominance was observed in Sites 4-6: 48%, 42%, and 31%, respectively, as reported above for Sites 1-3, however the magnitude of this dominance is reduced by lower *H. borealis* densities.

Abundance relative to all species at a site, the following taxa: *Paragyractis* (< 1%, < 1%, 5%, sites 4-6 respectively), *Cheumatopsyche* (< 1%, 5%, 19%), *Marilia* (< 1%, 6%, 6%), *Psephenus* (< 1%, 1%, 14%), and *Optioservus* (< 1%, 2%, 5%) increase from Sites 4-6. In contrast Hydropsyche (13%, 3%, 2%) and *Oligochaeta* (6%, 1%, < 1%) decrease. Nematodes are limited to Site 4, whereas Oligochaeta (282/307), Chironomidae (1690/2617), and *Hydropsyche* (721/963) are dominant there relative to Sites 5-6. In contrast *Cheumatopsyche* (23/1305), *Marilia* (17/635), *Tinodes* (21/236), *Psephenus* (19/1362), *Optioservus* (15/407), *Ordobrevia* (20/202), *Helichus* (Coleoptera: Dryopidae 3/53), and *Baetis* (52/354) are greatly reduced at Site 4 and *Physa* (Gastropoda) is greatly reduced at Site 6 (14/910).

Community Organization

Diversity indices. Species diversity estimates calculated as Sequential Comparison Indices using the method of Cairns *et al*. (1968) indicate differences in community structure at the different sites along Big Sulfur Creek. Samples taken in riffles had significantly lower diversity estimates in the heated areas (Sites 1, 2, and 4) than in Sites 3, 5, and 6 (Mann-Whitney nonparametric test, $p = 0.05$). However, comparison of diversity values for samples from Big Sulfur Creek pools showed no significant difference for sites 1-6.

SCI diversity estimates calculated using the theoretical formula (found in Table and analyzed by the Kruskal-Wallis test) indicated significant differences between Sites 1-3 (p = 0.03) and between Sites 4-6 (p = 0.007) (see Table 4). Similarly, Wilcoxon rank sum tests indicated significant differences between species diversity estimates at Sites 1 and 3 (p = 0.01) and 2 and 3 (p = 0.05). In addition, comparisons of Sites 4 and 5 by this method indicate a high, but less than statistically significant, relationship (p = 0.07).

Similarity indices. Similarity indices generated from between-site comparisons for respective dates are presented in Table 5. For each set of appropriate comparisons, i.e.

1 vs 2 4 vs 5
1 vs 3 and 4 vs 6
2 vs 3 5 vs 6

indices were ranked within dates. High ranks in the similarity measurements correspond with high faunal similarity between compared sites, whereas high ranks in the distance measurements (Bray and Curtis, Canberra Metric, Euclidean Distance) correspond with low similarity since these are measurements of dissimilarity. Ranks were then summed over all dates for each between-site comparison type and using the Friedman nonparametric statistical test for non-independent samples, significant differences were found for the Jaccard Index for between-site comparisons of Sites 4, 5, and 6. Although significant differences were not shown in other similarity and distance comparisons, the significant value (p = 0.093) for the Euclidean distance comparisons for sites 1, 2, and 3 approaches the standard α significance value of .05 which would indicate a significant difference in this distance measurement.

Sums of the ranks for distance measurements exhibit patterns consistent with those found in the diversity analysis. Diversity values indicate similar levels in Sites 1 and 2 and distance measurements showed highest similarity (or least distance) between these two sites. Likewise, Sites 5 and 6 had similar SCI diversity values and also had the highest similarity according to the distance measurements. However, similarity indices showed less consistent patterns. Jaccard Index values indicated higher similarity between Sites 1 and 2 than combinations with Site 3, but also between Sites 4 and 5. The Community Coefficient of Similarity was in disagreement with both the diversity and distance analyses in indicating high similarity between Sites 4 and 5 and lower similarity (although far from a significant difference) between Sites 1 and 2.

Macroinvertebrate Colonization Study of Big Sulfur Creek at Little Geysers Tributary

Substrate implants. Numbers of taxa and individuals for substrate implants in each of the three study sites at the Little Geysers Creek study area are presented in Table 6. A total of sixty different taxa were collected in the three sites of this study area. The dominance of the below tributary fauna by Chironomidae (36% of all individuals collected) and *G. nigricula* (47%) is similar to the observed patterns of these populations at other downstream silted and heated study sites on Big Sulfur Creek. *H. borealis* and *Cheumatopsyche*, the other dominant taxa, were totally absent from this site and *Hydropsyche* was a minor faunal component (< 1%).

Two taxa were limited in their distribution to above the tributary: isopods and the mayfly *Stenonema* (Ephemeroptera: Heptageniidae), and four were only found below the tributary: *Hydropsyche*, planarians, *Eubrianax* (Coleoptera: Psephenidae), and *Athrichopogon* (Diptera: Ceratoponidae). The damselfly *Argia* (Odonata: Coenagrionidae) was only found in the tributary. Small Plecoptera nymphs were found in all three sites, but mainly above (184/296) in contrast to G. nigricula (4848/4964) and Oligochaeta (520/569), which was mainly found below and Palpomyia (Diptera: Ceratopogonidae), which was mainly found within the tributary (255/347).

Of the thirteen taxa common to both above and below tributary habitats only immature Plecoptera nymphs and Palpomyia populations were more abundant above the tributary. Populations of several groups [e.g., Baetis (220/77), G. nigricula (4848/112), Lepidostoma (212/37), Optioservus (148/8), Oligochaetes (520/44), Chironomidae (3640/5227)] were much more abundant below than above the tributary. Chironomidae abundance was far greater within the tributary (14,759) than below (3,640) or above the tributary (248).

Colonization Traps

A total of 53,424 organisms were obtained by the 16 traps and 4 control trays at the two sites above and below Little Geysers Creek. If all of the traps (excluding the control trays) are grouped together at each site, then the following observations can be made: 1) The "below tributary" traps collected about 3.6 times as many organisms as the ones above the tributary (Table 7), and by excluding the chironomids, it can be seen that the below traps collected some 2.3 times as many individuals; 2) Chironomidae make up about the same proportion of the fauna at both sites, and are the dominant group at about 80% of the total at each; 3) The number of taxa collected at each site was approximately the same -- 48 below the tributary, 44 above it. If the chironomids are excluded and the occurrence of some of the more numerous taxa within such grouped traps are examined, it is apparent that Gumaga, the most abundant non-chironomid, is a considerably larger component of the "below" community, whereas Lepidostoma, Hemerodrominae (Diptera-Empididae), and Hydroptila appear in greater proportions at the "above" site.

The drift traps collected approximately the same numbers of total organisms, and non-chironomids at both sites, but the other three types showed considerable increases at the "below" site -- especially the aerial traps which collected some 20 times as many organisms, largely chironomids, as the "above" ones did.

When the numbers of organisms, including chironomids, collected in the traps is compared to the numbers in the control trays, the ratios are 2.7/1 "below" and 4.3/1 "above." These values are considerably different than those Williams and Hynes (1976) obtained in their study, which was conducted with a recolonization period of one month, rather than the 9 weeks used here. Notable observations on specific taxa include: 1) *Gumaga nigricula*, the most abundant non-chironomid, recolonizes mostly by aerial and upstream modes in the above tributary site, but primarily by the upstream mode only in the below tributary site. However, the use of the hyporheic mode by this trichopteran is restricted largely to the "below" site; 2) *Baetis* recolonizes the above tributary site primarily by the hyporheic route, but below the tributary the aerial route is most important. The importance of the aerial route "below" is also evident in examining the Hemerodrominae (Empididae) and Chironomidae, these two taxa making significant use of the upstream route in the above tributary site; 3) *Lepidostoma* appears to recolonize in similar ways at both sites.

Greater algal growth and primary productivity has frequently been noted in thermal streams (Stockner 1968, Winterbourn 1969). As in our study, Armitage (1958) noted a marked increase in standing crop in heated stretches of the Firehole River. Thus greater standing crop in heated areas may be a function of greater availability of primary foodsources.

Kaesler *et al*. (1974) have noted that often as much information about a biota's response to a particular activity can be obtained by studying a selected group of organisms as by considering all organisms collected. For this reason future benthic analysis in the Geysers may be greatly expedited by concentrating on key indicator species. In terms of determining which organisms may best serve as key indicator species, we have adopted the following criteria: species must have 1) widespread distribution throughout the Geysers area; 2) a quantifiable response to a specific parameter of interest; and 3) "taxonomic soundness," the quality of being able to be distinguished from other taxa.

The Chironomidae, an extremely broad group in terms of the environmental requirements of individual species, are often abundant in silted (Erman *et al*. 1977, Bjorn *et al*. 1977) as well as heated waters (Howell and Gentry 1974, Benda and Proffitt 1974) including natural hot springs (Robinson and Turner 1975, Stark 1976). Chironomidae comprised a significant portion of the total fauna at all sites, but they were most abundant in the warm, heavily silted Site 4, and in the within-tributary site of the colonization study (again, the warmest and most heavily silted site). However, the lack of detailed taxonomic work with this group necessarily precludes more definitive interpretations of these patterns. Criterion number three (above) prevents this group (for the present) from being highlighted as key indicator organisms.

Gumaga nigricula also appears to have a high tolerance to silt and thermal inputs. Its greatest abundance is in silted and moderately warm areas (Site 1, 2, 5, and the "below" tributary site). A difference in thermal tolerance between *G. nigricula* and Chironomidae may occur in the range of temperature differences observed between Sites 1 and 2 (average temperature 25.6° and 24.6°C, respectively) and Site 4 (average temperature 27.8°C). The Chironomidae appear to exhibit increasing abundance with temperature increases, whereas *G. nigricula* is not as abundant in Site 4 and is nearly absent from the within tributary (the warmest) site. Benthic samples collected in 1968 (between our Sites 1 and 2) prior to much of the geothermal development in the Geysers had far fewer *G. nigricula* individuals than our study indicates. *G. nigricula* was very abundant below the tributary in the hyporheic colonization traps which suggests that this species has the capacity to colonize silted areas not only through substrate surface entry but also through the hyporheic zone. This organism exhibits a high potential as an indicator species in that it fulfills all of the above three criteria.

Helicopsyche also exhibits both silt and thermal tolerance, being abundant at Sites 1 and 2. Although this species is often described as an inhabitant of clear, swift, stony streams, Cummins and Lauff (1969) reported its selective movement onto silted as opposed to coarse substrate particles. Wiggins (1977) has commented on this species' broad thermal tolerances. Like *G. nigricula*, *H. borealis* also exhibits high potential as an indicator species.

Patterns exhibited by other macroinvertebrate species at the Geysers also qualify them for consideration as potential indicator species. For example, *Paragyractis truckeealis* had far greater abundance at Site 6 than the lower stations. *Tinodes* and *Optioservus* also exhibit silt sensitivity. Chutter (1969) observed that elmid beetles were reduced in numbers by siltation, corresponding with our observations on *Optioservus*. However, other elmid species in the Geysers, *Ordobrevia* and *Zaitzevia* did not show distinct distributions in terms of silt differences along the sites.

Certain other species appear to be particularly sensitive to thermal inputs. *Marilia flexuosa* in particular has very low abundance in Sites 1, 2, and 4 but is considerably more numerous in the colder Sites 3, 5, and 6. *Psephenus falli* is also far rarer in the heated sites. A previous observation by Leech and Chandler (1956) that *Psephenus* "requires well aerated water and protection from erosion and silting" also agrees with our results.

Measurements of community diversity and similarity provided a means of estimating how macroinvertebrate populations varied relative to the sample site characteristics and the parameters of interest. Similar ranges of diversity values were obtained in the riffle samples for Sites 1 and 2 (see Table 4). Likewise, distance measurements indicated closer correspondence between these two sites than comparisons involving either site with Site 3. This supported the first hypothesis (H_1: No difference in community composition between a site located in the long term development area and exposed to natural geothermal heat and chemical inputs and a long term development site with thermal input only). From this, we have concluded that the chemical inputs of Geysers Canyon Tributary do not have a significant effect on benthic community composition.

The significantly higher diversity of Site 3 as compared with sites 1 and 2 indicates that while natural geothermal chemical inputs do not significantly affect the macroinvertebrate community, temperature regime does appear to influence community structure. The thermal effects appeared to be similar to those reported by Coutant (1962), Howell and Gentry (1974), and Benda and Proffit (1974) where species diversity was reduced in areas of increased water temperature. These results support rejection of the second hypothesis (H_2: No difference between a long term development site with natural geothermal heat input and a long term development site without heat input).

Similar diversity values for Site 5 and 6 along with a marked decrease in diversity at Site 4 (the area below the hot springs) would support rejection of the third hypothesis (H_3: No difference between a current development site with natural geothermal heat and chemical inputs and a current development site witout these inputs). However a limitation in the formation of this hypothesis was the unavailability of adequate chemical data for these sites. If chemical characteristics of Sites 4 and 5 were similar to those of Sites 1 and 2, respectively, then it would appear likely that water temperature was again the causal factor in observed community differences. This hypothesis requires more detailed testing before a definitive conclusion can be reached.

Distance measurements and diversity values indicated high faunal correspondence between Sites 5 and 6. This information indicates acceptance of the fourth hypothesis (H_4: No difference between a site exposed to current development and a reference site with background levels of silt and other characteristics) and suggests that physical changes such as increased sedimentation which may have occurred in Site 5 due to development, did not significantly alter macroinvertebrate community composition at that site.

Considerable differences were found between the numbers and types of organisms colonizing the traps and baskets below the Little Geysers Tributary and those located above the tributary. This information supports by inference rejection of the fifth hypothesis (H_5: No difference between a site with thermal, chemical and heavy silt inputs and site with background levels of those parameters). Faunal differences particularly as they related to types of traps clearly reflects the differences between the two sites.

The sixth hypothesis (H_6: No difference in macroinvertebrate colonization patterns in that sites differ considerably in amount of silt, thermal, and chemical inputs) was also readily rejected. More importantly, the great faunal differences (particularly the dominance of Chironomidae in the tributary) clearly demonstrated that upper tolerance limits to silt, natural geothermal chemicals, and increased temperature, were exceeded in Little Geysers Tributary for many macroinvertebrate taxa found in Big Sulfur Creek.

It has been shown by Winterbourn and Brown (1967) and Robinson and Turner (1975) that the fauna of streams in the intermediate "warm water" below a hot spring inflow are not greatly different from the fauna of the surrounding area.

It appears, however, in this study that those species which are most tolerant to warm water conditions increase in abundance (sometimes to a point of dominance) below hot springs and community diversity as a whole consequently decreases. Similar results to ours were found by Vincent (1967) in a study of the Gibbon River in Yellowstone National Park where riffles below a hot spring input had less diverse fauna and were dominated by Trichoptera. It would be expected that the macroinvertebrate fauna of Big Sulfur Creek would include many species which are tolerant and well adapted to inputs of national geothermal heat and chemicals as well as to considerable levels of siltation in this watershed of naturally high erosion. More in-depth studies of habits and distribution of specific taxa are necessary to more precisely discern the tolerance and sensitivity limits of species shown to vary with these parameters.

FUTURE RESEARCH NEEDS

A key consideration in evaluating each of the above hypotheses, especially those involving siltation effects, is that in this, as in almost all benthic studies, sampling was restricted to the upper 15 cm of substrate. It is more likely, however, that many or possibly most of the main effects of siltation occur some distance into the hyporheic zone, an area in which some investigators have suggested (e.g. Hynes 1970 and later papers) the majority of the fauna may reside. Management programs for stream habitats have often assumed that heavy rains (as present in the Geysers on a seasonal basis) will generally flush the stream bed free of these sediments. However, Einstein (1968) has observed that the water velocities required to dislodge and resuspend particles settled into the stream substrate are far greater than the velocities needed to originally carry these same particles. Although thorough examination of silt particle movement within the hyporheic has not yet been executed, it is likely that a sizable portion of the sediment deep within the substrate (approximately 30 cm below surface) may be redistributed during periods of high discharge, but not removed in significant amounts from the hyporheic. Sediments trapped in the hyporheic at the Geyser streams may be of particular significance as a reservoir of heavy metals adsorbed to sediment particles. Nehring (1976) reported that certain macroinvertebrates concentrate heavy metals in direct proportion to their concentration in the organism's environment. It was found in a study by Finlayson (1977) that mercury concentrations varied between 110 and 220 ppb in invertebrates (wet wt.) and 2500-12000 ppb in sediments (dry wt.) collected at the stream bottom surface between Aug. 29, 1974 and June 25, 1975 on Big Sulfur Creek near the Geysers. Leitner (1978) has stated that determination of the ultimate fate of potentially toxic materials released during geothermal activities is a high research priority at the Geysers.

Another critical area of research at the Geysers involves evaluation of geothermal activities on stream energetics. Considerable attention has been devoted to the study of energy flow between trophic levels in stream ecosystems, in particular, the importance of accumulated detritus deposits as energy sources. The influence of different levels and aspects of geothermal development (as discussed in the hypotheses above) on trophic associations is largely unknown.

The third area of future research needs is a detailed evaluation of streams in the Geysers in terms of the influence of the severe two-year drought that was concurrent with this study. Hypotheses tested above were based on data obtained when geothermal effluents and effects were at their most concentrated levels. By analyzing the recovery rates of the benthic community from these severe drought conditions, data from a broader spectrum of environmental conditions would establish a broader baseline in testing the above hypotheses.

In terms of applying these results to other geothermal development, a comparison of Big Canyon Creek watershed, a potentially rich geothermal area where only experimental wells have thus far been drilled, with those of the Big Sulfur Creek watershed, a veteran of geothermal development and the site of the previous study, is necessary. The two watersheds have drastically different water chemistry components, with Big Canyon Creek having a liquid dominated reservoir with high concentrations of sodium, magnesium, chlorides, and bicarbonates, and alkaline conditions, while Big Sulfur Creek has high concentrations of ammonia (NH_3) and sulfates (SO_4^{-2}), and acidic conditions (McColl _et al_. 1977). The analysis of constituents of geothermal waters has been used in evaluating environmental degradation by effluents from geothermal power plants (Axtmann 1975). Similarly, the analysis of biotic components of these same systems has excellent potential for evaluating changes in environmental quality.

Finally, the utilities and government agencies currently operating in the Geysers, especially in areas where the development of geothermal facilities is planned but not yet underway, have been requested by the local governments to include the analysis of benthic organisms in their monitoring systems. The difficulty in complying with this request is due to a lack of information on the fauna present throughout the Geysers and suitable methods for sampling the biota. This could be remedied by further studies on the macroinvertebrate fauna throughout the Geysers and the development of appropriate sampling methods.

Each of the above future research needs is currently under examination at the Geysers, largely funded through the project: "The influence of Geothermal Origin and Drought Conditions on Aquatic Biota of the Known Geothermal Resource Area of California" (W-548 B-200-CAL). Future reports on this research will expand and further clarify the summary of this two-year project presented here.

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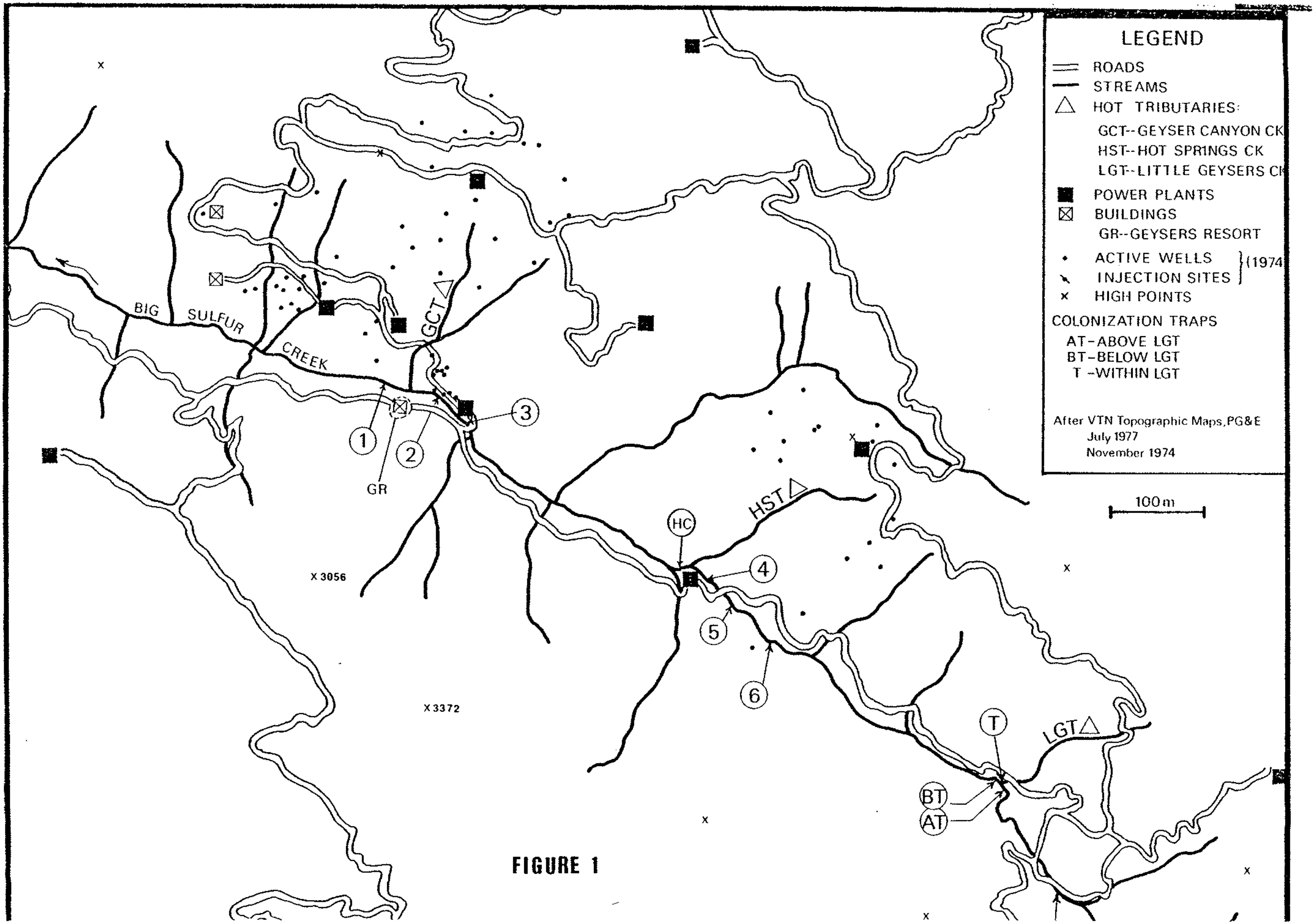

LEGEND
ROADS
STREAMS
HOT TRIBUTARIES:
GCT--GEYSER CANYON CK
HST--HOT SPRINGS CK
LGT--LITTLE GEYSERS CK
POWER PLANTS
BUILDINGS
GR--GEYSERS RESORT
ACTIVE WELLS
INJECTION SITES
(1974)
HIGH POINTS
COLONIZATION TRAPS
AT-ABOVE LGT
BT-BELOW LGT
T -WITHIN LGT
After VTN Topographic Maps, PG&E
July 1977
November 1974
100 m
BIG SULFUR CREEK
GCT
HST
LGT
GR
HC
1
2
3
4
5
6
T
BT
AT
X 3056
X 3372

FIGURE 1

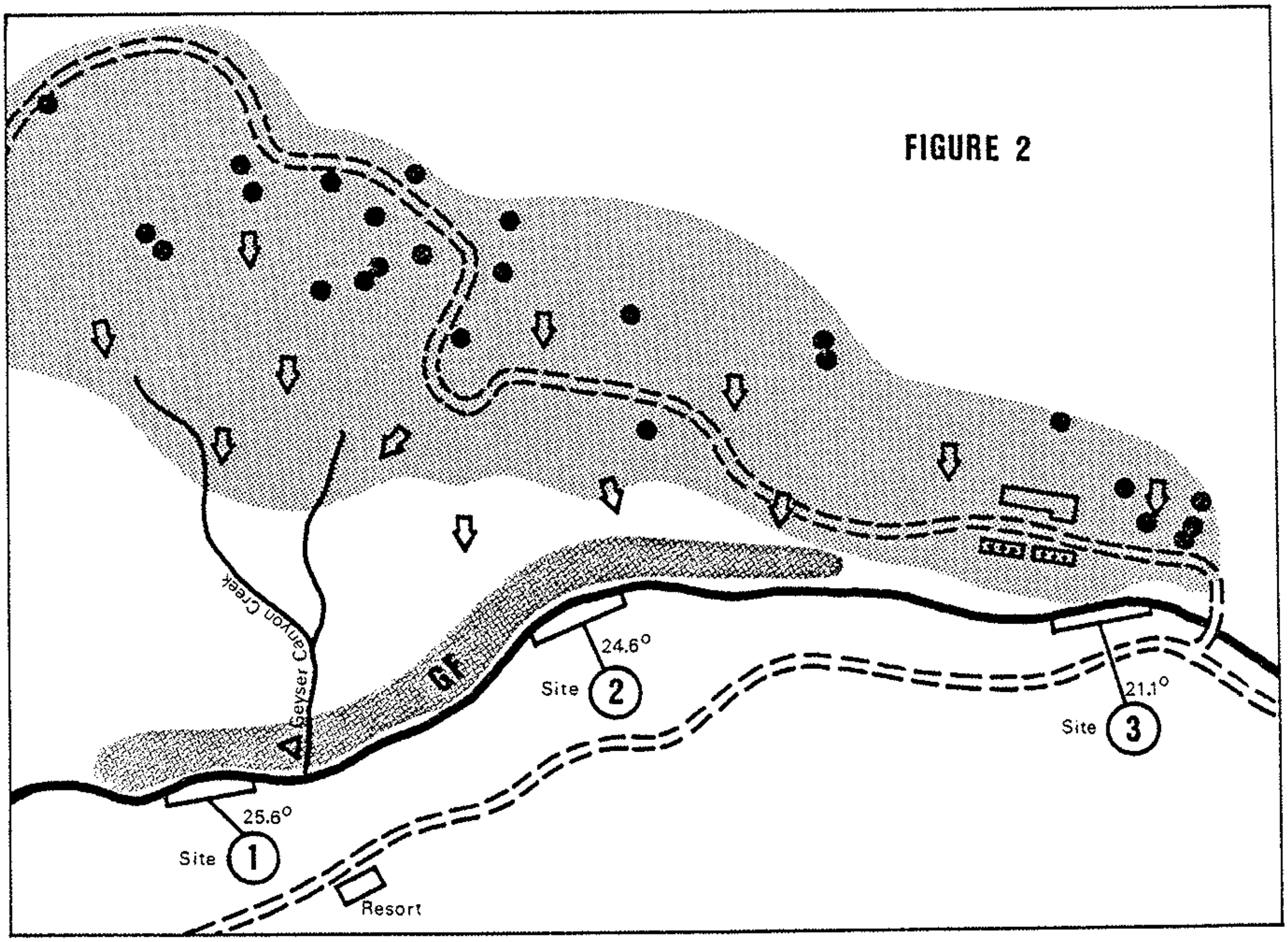


FIGURE 2

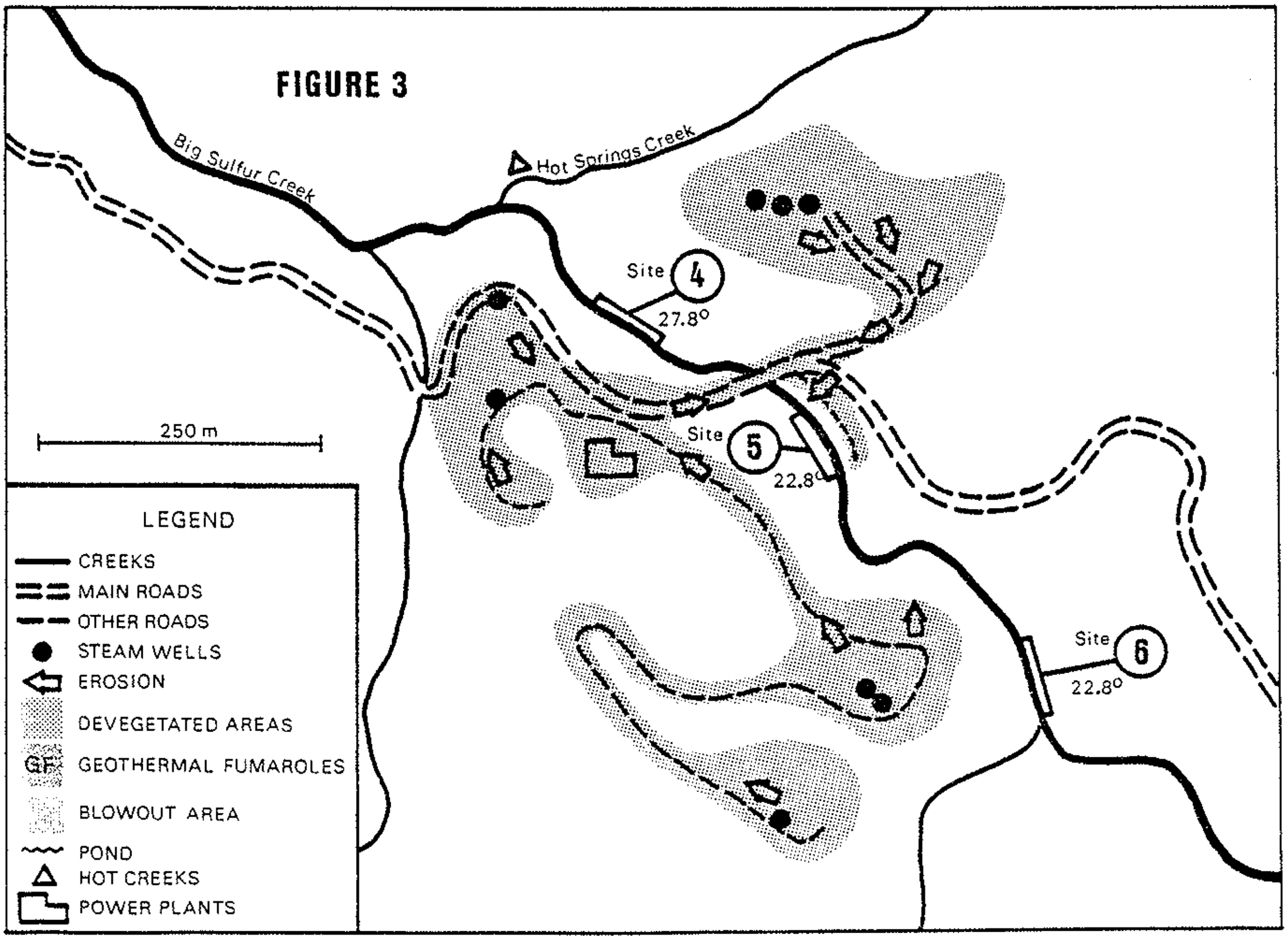


FIGURE 3

FIGURE 4

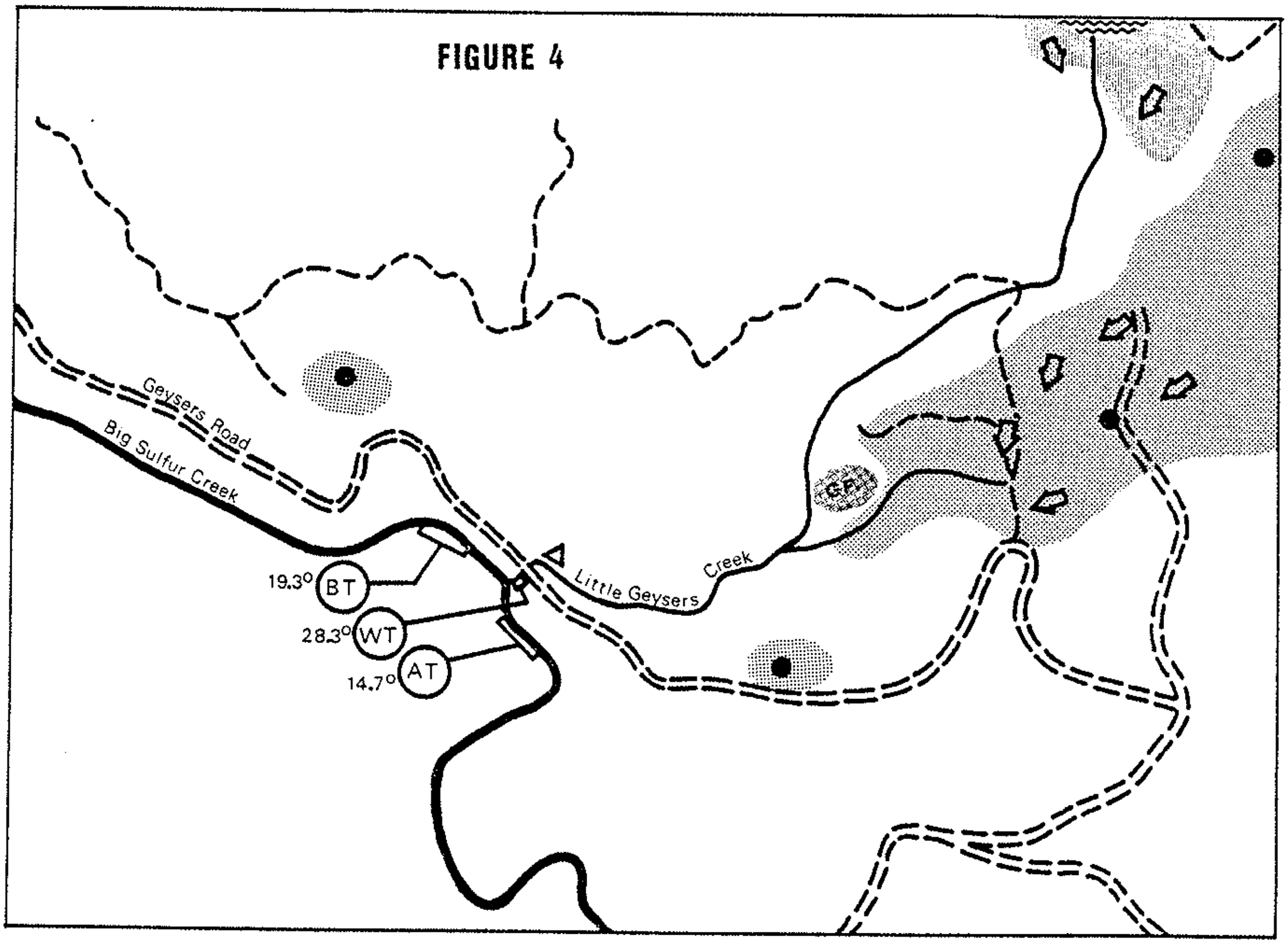
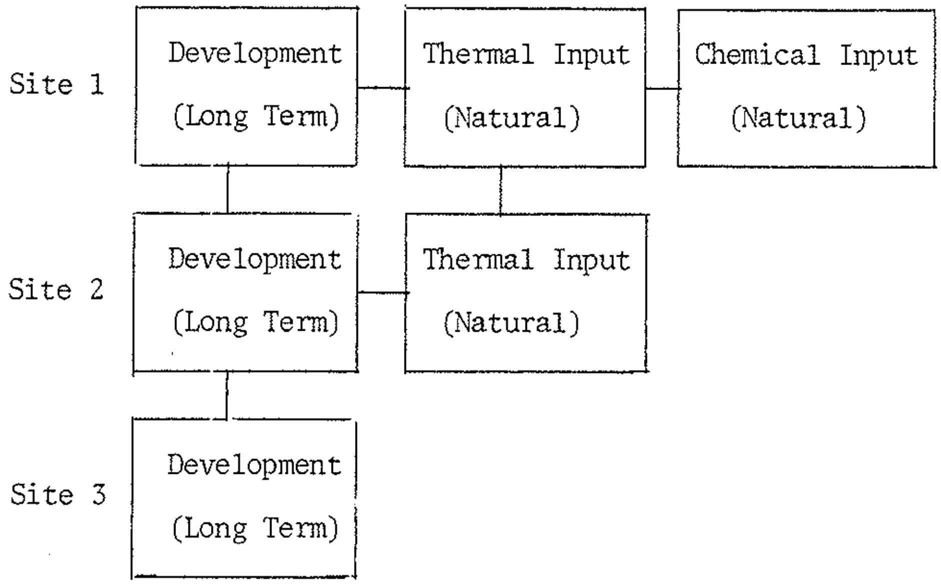

Geysers Road
Big Sulfur Creek
Little Geysers Creek
GP
19.3° BT
28.3° WT
14.7° AT

Figure 5. Schematic Description of Sites

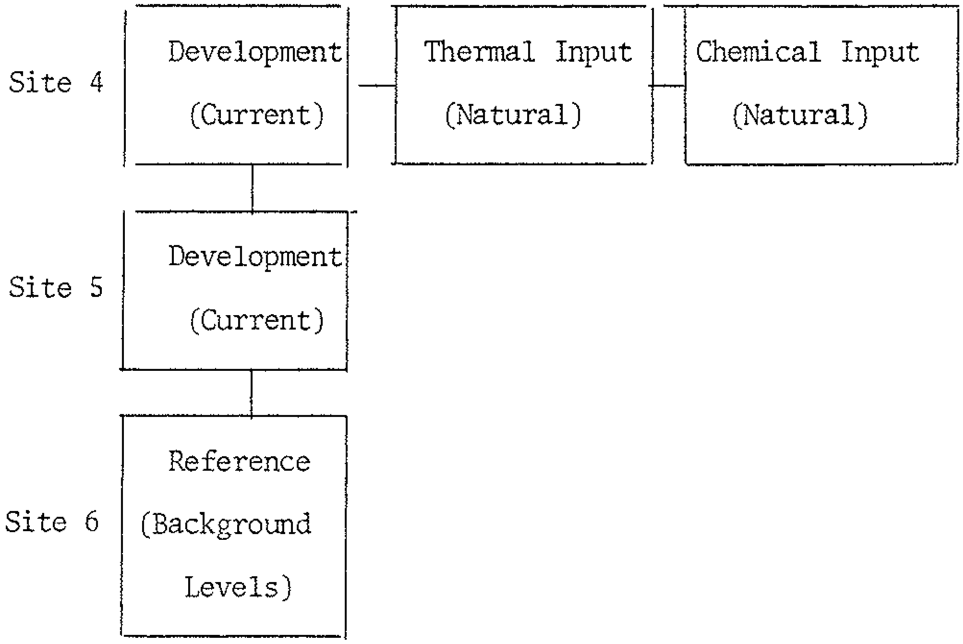


	Avg. Temp. (°C)	Mean No. of Taxa	No./ft.^{2}
Site 1	25.6°	14.4	1,085
Site 2	24.6°	20.0	644
Site 3	21.1°	29.0	634

Development (Long Term): Within watershed directly below operating wells and power plants

- high sedimentation areas (source not proven)
- past geothermal spills, intentional condensate releases, cooling tower drift, and possible unknowns

Site selection isolates development effects from natural thermal and chemcal inputs.



	Avg. Temp. (°C)	Mean No. of Taxa	No./ft.^{2}
Site 4	27.8°	22.2	442
Site 5	22.8°	26.3	452
Site 6	22.8°	25.3	448

Development (Current): No major spill of geothermal fluids or drilling muds

- Clear source of sedimentation

Site selection isolates current development related sedimentation effects from natural thermal and chemical inputs and allows comparison with background levels of all substances.

Table 1

Chemical Data - Pacific Gas and Electric. Collected 1977.

	Ammonia [mg/1 as N]		Boron [mg/1]		pH		Sulfate [mg.1]		Total Alkalinity [mg/1. as $CaCO_3$]		Specific Conductar. [uMhos/cm]	
	Site 1	Site 3	Site 1	Site 3	Site 1	Site 3	Site 1	Site 3	Site 1	Site 3	Site 1	Site 3
January	0	0	2.4	.9	7.3	7.4	97	52	-	-	427	344
February	5.6	0	.4	.4	7.4	7.4	158	27	39	125	439	245
March	0	0	2.2	.9	7.7	7.7	81	34	139	175	434	334
April	0	0	1.8	.7	8.3	8.4	70	41	136	159	396	330
May	0	0	1.5	.7	8.0	8.8	57	27	139	154	335	250
June	0	0	4.2	1.1	8.0	8.1	144	51	154	233	499	373
July	0	0	7.4	.8	8.2	8.3	207	53	145	262	638	424
August	0	0	9.5	1.1	7.8	8.3	239	60	141	305	639	495
September	0	0	1.1	.5	7.9	7.9	41	20	99	112	240	213
October	0	0	2.0	1.2	8.4	8.1	72	48	134	222	335	431

Table 1, cont.

	Color		Turbidity [JTU]		Flow (gal./min.)	Settleable Solids [mg./1.]		Flow	Total Susp. Matter [mg./1. at 105°C]	
	Site 1	Site 3	Site 1	Site 3		Site 1	Site 3		Site 1	Site 3
January	14	19	5	< 5	500	4.0	0.1	500	4.4	4.0
February	20	18	30	25	800	13.6	11.6	800	50.4	32.4
March	25	28	5	5	350	.4	.4	350	7.2	4.0
April	12	9	10	10	350	6.4	3.2	350	12.0	12.4
May	31	22	5	< 5	1000-1500	10.4	4.4	1000-1500	15.2	7.2
June	30	28	10	5	1000	4.4	5.2	1000	8.4	6.8
July	4	3	10	10	500	4.4	5.6	500	11.2	9.2
August	3	3	15	10	200	< 0.1	7.2	200	4.8	11.2
September	27	22	25	40	2000	27.6	52.4	2000	33.8	77.2
October	19	4	5	5	600-1000	8.8	9.6	600-1000	16.0	19.2

Table 2
Chemical Data - Pacific Gas and Electric Collecting Dates 6-29-77 and 8-19-77

	Above Trib		Below Trib
Ammonia	Higher both dates	(1.2, 2.4)	(.77, 1.2)
unionized	" " "	(*.15, *.05)	(*.06, *.03)
Arsenic	Higher 2nd date only	(.03, .015)	(*.05, .008)
Boron	Lower above trib	(.3, 2.9)	(4.9, 6.6)
Hardness	Approximately the same	(170)	(180)
Mercury	" " "	(1)	(1)
pH	Higher above	(8.0, 7.6)	(7.8, 7.4)
Specific conduct.	Varies	(500, 570)	(535, 520)
Temp. °C	Lower above	(___, 23.0)	(34.5, 33.0)
TDS	" "	(290)	(370)
TSS	" "	(9.2)	(14)
Turbidity (JTU)	" "	(9.6)	(12.0)
Sulfate	Higher above	(40)	(32)
Within Trib			
	Furthest upstream	[LG1]	[LG2]
Ammonia		(.40)	(2.2, 1.7)
unionized		(*.03)	(2.2, 1.7)
Arsenic		(.04)	(.035, .0007)
Boron		(.2)	(4.5, .0007)
Hardness		140	120
Mercury		1	1
pH		8.2	(7.2, 6.8)
Temp. °C		21	60
TDS		230	310
TSS		12	9.6
Turbidity		2.4	7.4
Sulfate		14	49

Footnotes, Table 2

*Exceeds criterion.

Values, except conductivity and turbidity in mg/l. Dates 6-29-77 and 8-19-77.

Table 3

$$\text{SCI value} = \frac{N^2 + N - \Sigma n_k{}^2}{N^2}$$

where
N = total number of individuals in sample
n_k = number of individuals in each of k species

Table 4

Numbers of taxa and density of macroinvertebrates Sites 1-6

Multiple-date Quadrant (Surber) Survey

	Total No. of Taxa	$\bar{x}$ No. Taxa	$\bar{x}$ No./ft^2 sample
Site 1	33	14.4	1,085
2	43	20.0	644
3	43	29.0	634
4	37	22.2	442
5	53	26.2	452
6	50	25.3	448

Table 5

Sequential Comparison Indices (Theoretical formula-generated) for riffle samples, Big Sulfur Creek sites (ranks in parentheses).

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
7-14-77	.7303(12)	.6479(9)	.7730(14)	.5108(3)	.8377(15)	.8860(20)
8-13-77	.5458(7)	.4852(6)	.8944(20)	.6206(5)	.6683(6)	.7861(9)
8-28-77	.3857(3)	.2919(1)	.8293(16)	.8367(16)	.3884(1)	.7482(8)
9-22-77	.4406(5)	.3396(2)	.8237(15)	.7461(7)	.7907(11)	.8291(14)
10-21-77	.7399(13)	.8406(17)	.8722(18)	.7983(10)	.8398(17)	.8120(13)
5-12-77	.4068(4)	.5210(34)	.7258(11)		.8902(21)	
5-30-77	.5755(8)		.9036(21)	.5867(4)	.8102(12)	
6-21-77	.7217(10)		.8773(19)	.4934(2)	.8436(18)	.8599(19)
Avg.	.5683(62)		.8374(130)	.6548(47)	.7586(101)	.8202(63)

Table 6

Similarity and Distance Measurements Sites 1-6

Sampling Dates		Jaccard	Rank	Community Similarity	Rank	Bray Curtis	Rank	Euclidean Distance	Rank	Canberra Metric	Rank
July 14, 1977	1vs2	.4348	(2)	.7018	(3)	.2982	(1)	787.0515	(1)	.2900	(1)
	1vs3	.4074	(1)	.4901	(1)	.5099	(3)	992.5205	(3)	.3305	(3)
	2vs3	.5000	(3)	.5540	(2)	.4460	(2)	814.839	(2)	.3295	(2)
August 13	1vs2	.3529	(3)	.2813	(2)	.7187	(2)	1887.287	(2)	.2423	(2)
	1vs3	.3448	(2)	.3068	(1)	.6932	(1)	1923.374	(3)	.4036	(3)
	2vs3	.2903	(1)	.2465	(3)	.7535	(3)	499.956	(1)	.4686	(3)
August 28	1vs2	.1579	(3)	.5240	(1)	.4760	(1)	815.209	(2)	.3011	(1)
	1vs3	.1600	(2)	.2767	(3)	.7233	(3)	191.206	(3)	.3774	(2)
	2vs3	.3667	(1)	.3685	(2)	.6315	(2)	484.1797	(1)	.4267	(3)
September 22	1vs2	.4615	(1)	.4584	(1)	.5416	(1)	442.487	(1)	.1634	(1)
	1vs3	.2400	(3)	.0545	(3)	.9455	(3)	637.925	(3)	.4077	(3)
	2vs3	.3043	(2)	.0671	(2)	.9329	(2)	625.670	(2)	.3545	(2)
October 21	1vs2	.3462	(3)	.2333	(2)	.7667	(2)	414.661	(3)	.3891	(3)
	1vs3	.3846	(2)	.1998	(3)	.8002	(3)	262.578	(2)	.3817	(2)
	2vs3	.7308	(1)	.5880	(1)	.4120	(1)	262.341	(1)	.2128	(1)
July 14	4vs5	.4375	(2)	.1669	(3)	.8331	(3)	602.601	(3)	.4727	(3)
	4vs6	.4333	(3)	.2695	(2)	.7305	(2)	543.814	(2)	.4066	(2)
	5vs6	.7097	(1)	.5669	(1)	.4301	(1)	277.428	(1)	.2960	(1)
August 13	4vs5	.4286	(3)	.5308	(1)	.4692	(1)	461.181	(2)	.3568	(2)
	4vs6	.5238	(1)	.1527	(2)	.8473	(2)	439.145	(1)	.2744	(1)
	5vs6	.4615	(2)	.0967	(3)	.9033	(3)	834.067	(3)	.3638	(3)
August 28	4vs5	.4800	(3)	.1657	(3)	.8343	(3)	818.169	(3)	.3143	(2)
	4vs6	.5000	(2)	.2631	(2)	.7369	(2)	187.753	(1)	.3209	(3)
	5vs6	.5909	(1)	.3558	(1)	.6442	(1)	688.332	(2)	.2584	(1)
September 22	4vs5	.3913	(3)	.1990	(2)	.8010	(2)	66.791	(1)	.3066	(1)
	4vs6	.4800	(1)	.2369	(1)	.7631	(1)	277.166	(2)	.3387	(3)
	5vs6	.4091	(2)	.1298	(3)	.8702	(3)	278.593	(3)	.3346	(2)
October 21	4vs5	.4615	(3)	.2308	(3)	.7692	(3)	146.281	(3)	.3527	(3)
	4vs6	.5000	(2)	.4708	(2)	.5292	(2)	116.598	(1)	.3262	(2)
	5vs6	.7917	(1)	.7118	(1)	.2882	(1)	123.373	(2)	.1446	(1)
June 21	4vs5	.3103	(3)	.0844	(2)	.9156	(2)	483.236	(1)	.4384	(2)

Table 7

Colonization Study-Little Geysers Tributary

Numbers of Taxa and Individuals

	Number of Taxa	Number of Individuls
Substrate Implants - Five per site		
Above Tributary	38	1,322
Below Tributary	42	10,221
Within Tributary	15	15,230
Colonization Traps - Two of each trap per site		
Below Tributary Site:		
Upstream	23	7,660
Drift	26	5,687
Hyporheic	23	3,181
Aerial	18	12,880
Trap total	40	29,405
Control	31	10,766
Above Tributary Site:		
Upstream	21	2,914
Drift	33	5,960
Hyporheic	14	1,245
Aerial	16	639
Trap total	41	10,758
Control	20	2,492

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Preliminary observations on spatial distribution patterns of stream caddisfly populations

V.H. RESH

Abstract

Spatial heterogeneity may influence sampling variability of stream caddisfly populations. The mean number of *Cheumatopsyche pettiti* (BANKS) larvae/Surber square foot sample in a riffle of uniform depth and substrate size (Rock Creek, Carroll County, Indiana, USA) was calculated for sample sizes ranging from 2 to 52 with 30 replicates for each sample size. With a sample size of 2, means ranged from 1.5 to 14.5 larvae/square foot, a departure from the population mean of 6.2. Hyporheic distributions, resource orientation, and population age structure may influence the negative binomial distribution pattern of *C. pettiti.* Larvae of *Dicosmoecus gilvipes* (HAGEN) in the McCloud River, Shasta County, California, USA, exhibited non-aggregated distribution patterns in areas of uniform substrate size and aggregated patterns in areas of mixed substrate size. A reduction in sampling variability may reflect the differences in microenvironmental variation between uniform and mixed substrate areas. Spatial distribution patterns may change temporally, *e.g.* the value of *k* for a population of *Ceraclea ancylus* (VORHIES) in Brashears Creek, Spencer County, Kentucky, USA ranged from 0.12 to 0.23 during larval development but increased to 0.39 during pupation. Both taxonomic and biometric considerations are necessary in designing ecological studies.

Populations of caddisflies and other aquatic insects exhibit distinct patterns in both time and space. Temporal patterns may reflect the phenology of individual species, mortality rates, or population recruitment. Spatial patterns may be influenced by abiotic (e.g. substrate, current) and biotic factors (e.g. territoriality, location of food sources). Furthermore, these patterns may also be interrelated, e.g. when pre-pupation movements result in a change in spatial arrangement. The purpose of this report is to provide information on spatial distribution patterns of stream caddisfly populations and to relate these patterns to problems of sampling variability.

The spatial pattern of a multiple cohort population of the hydropsychid caddisfly *Cheumatopsyche pettiti* (BANKS) was analyzed in a riffle of uniform depth (10-12 cm) and substrate particle sizes (ϕ-5, ϕ-6), located in Rock Creek, Carroll County, Indiana, USA. Fifty-two Surber square foot samples were collected from 26 randomly chosen locations in the riffle. The frequency distribution of the number of larvae for each of the 52 samples and the calculation of statistics k, U, and T (ELLIOTT, 1971) indicate a non-random distribution that best agrees with the

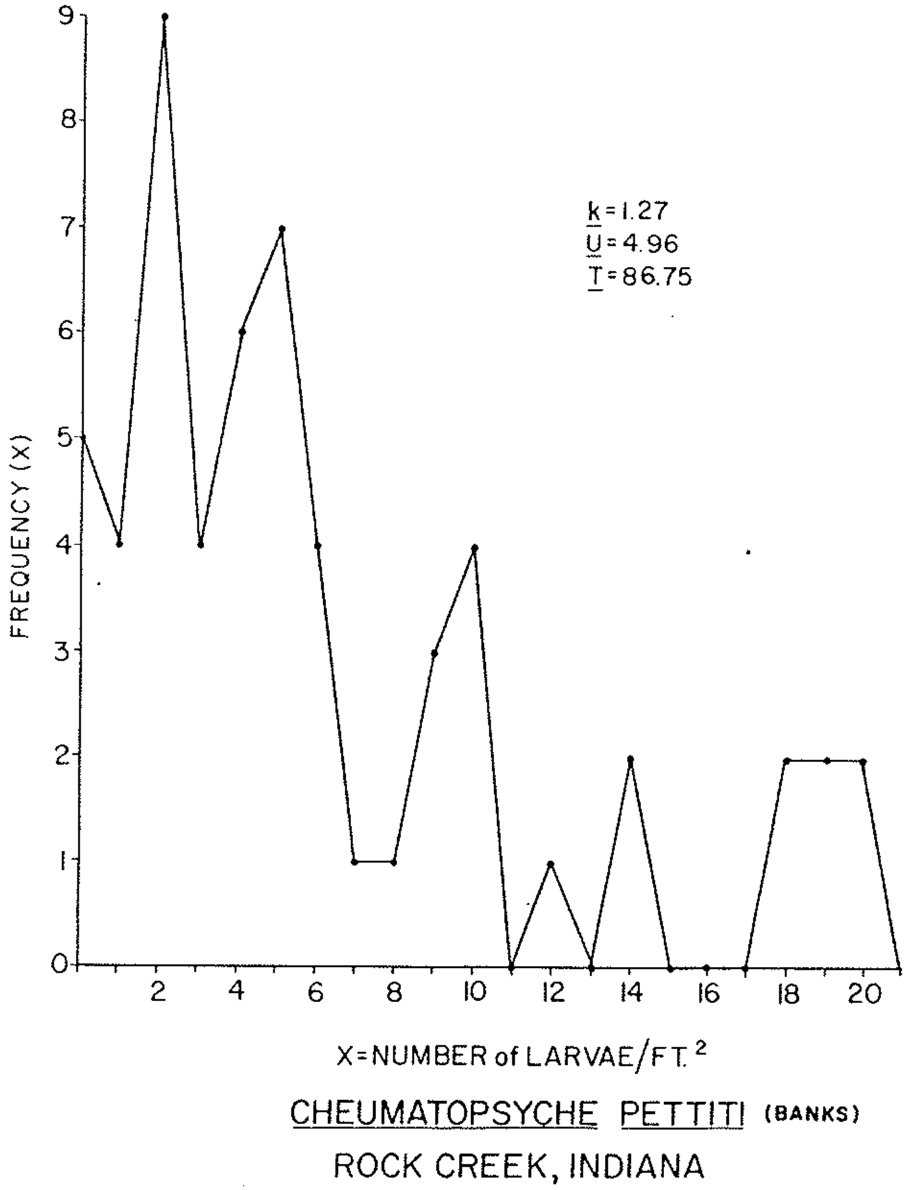

Fig. 1. Frequency distribution of *C. pettiti* larvae/Surber sample (ft^2) in Rock Creek, Carroll Co., Indiana, USA. Formulae for clumping statistics k, U, and T are in ELLIOTT (1971).

spatial pattern predicted for a negative binomial distribution (Fig. 1). Analysis of the predominant caddisfly species from the 100 Surber samples collected by NEEDHAM & USINGER (1956, Table 3) indicates similar non-random distribution patterns: *Sericostoma* (k = 6.31), *Glossosoma* (k = 0.42), *Hydropsyche* (k = 0.65), *Brachycentrus* (k = 0.67), *Lepidostoma* (k = 0.62), and *Rhyacophila* (k = 1.19).

Spatial heterogeneity of benthic populations may greatly influence sampling variability. In order to illustrate this interaction, a data matrix was constructed using the number of *C. pettiti* larvae in each of the 52 quantitative samples (Fig. 1) and a hypothetical sampling regime was developed in which a mean population estimate was calculated for sample sizes ranging from 2 to 52 and arranged in increments of 2. Numbers were replaced in the matrix and could be drawn and included in the calculations more than once for a given value of n. The procedure was repeated 30 times for each sample size, resulting in mean estimates calculated for 780 analyses.

The results of these manipulations indicate that with a small sample size the variability of mean estimates is very large (Fig. 2). For example, means range from 1.5 to 14.5 larvae of *C. pettiti*/sample with a sample size of 2, a significant departure from the sample mean of 6.2. There are several factors that could be involved in producing the spatial patterns of *C. pettiti* (Fig. 1) and the resulting sampling variability (Fig. 2), including: 1) inconsistent underestimations of population size because of hyporheic distributions; 2) microhabitat preference of the net-spinning larvae; and 3) instar specific patterns which may produce clumped distributions when all larvae of *C. pettiti* are considered together as a single population.

A reduction in sampling variability may result from more narrowly defining the sampling site to areas with similar physical characteristics (ALLEN, 1959). LAMBERTI & RESH (unpublished data) examined the spatial distribution patterns of a univoltine single cohort population of the limnephilid caddisfly *Dicosmoecus gilvipes* (HAGEN) in the McCloud River, Shasta County, California, USA. In areas of uniform substrate size, *D. gilvipes* had a non-aggregated distribution, whereas in areas of mixed substrate sizes, aggregated, negative binomial patterns occurred. The reduction in microenvironmental variation within these uniform substrate ribbons may influence these distribution patterns. The corresponding reduction in sampling variability indicates the potential value of these considerations in the development of future sampling regimes.

The spatial pattern of *C. pettiti* presented above (Fig. 1) represents a measurement of instantaneous population distribution. However, these patterns may change over time. A univoltine single cohort population of the leptocerid caddisfly *Ceraclea ancylus* (VORHIES) in Brashears Creek, Kentucky, USA, exhibited a different spatial pattern (which can be identified by a change in k) when examined during pupation in May than had been observed during the previous larval period (Fig. 3, see RESH, 1975, for sampling methods). Problems of sampling variability that are present in examining instantaneous population distributions become compounded in an analysis of population dynamics over time. This is especially true in calcula-

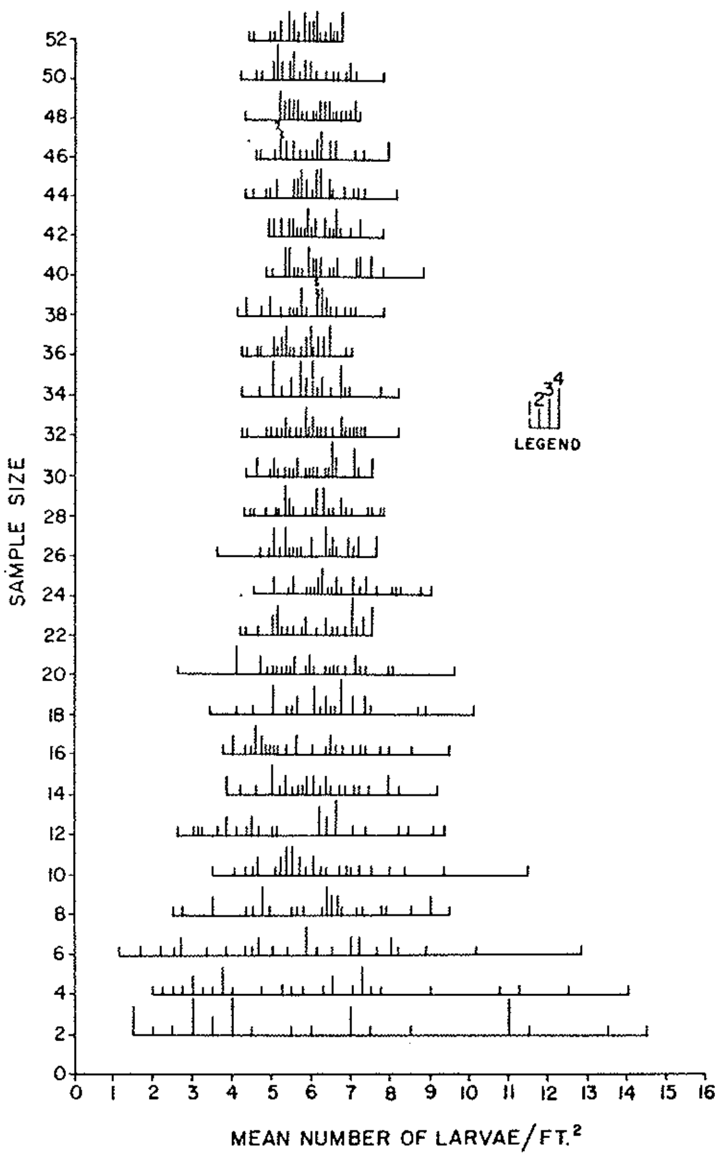

Fig. 2. Sample size influence on mean number of *C. pettiti* larvae/Surber sample (ft^2) in Rock Creek, Carroll Co., Indiana, USA. For each sample size the horizontal line refers to the range of means calculated, with the vertical lines referring to the number of times an individual mean (to the nearest tenth) was calculated.

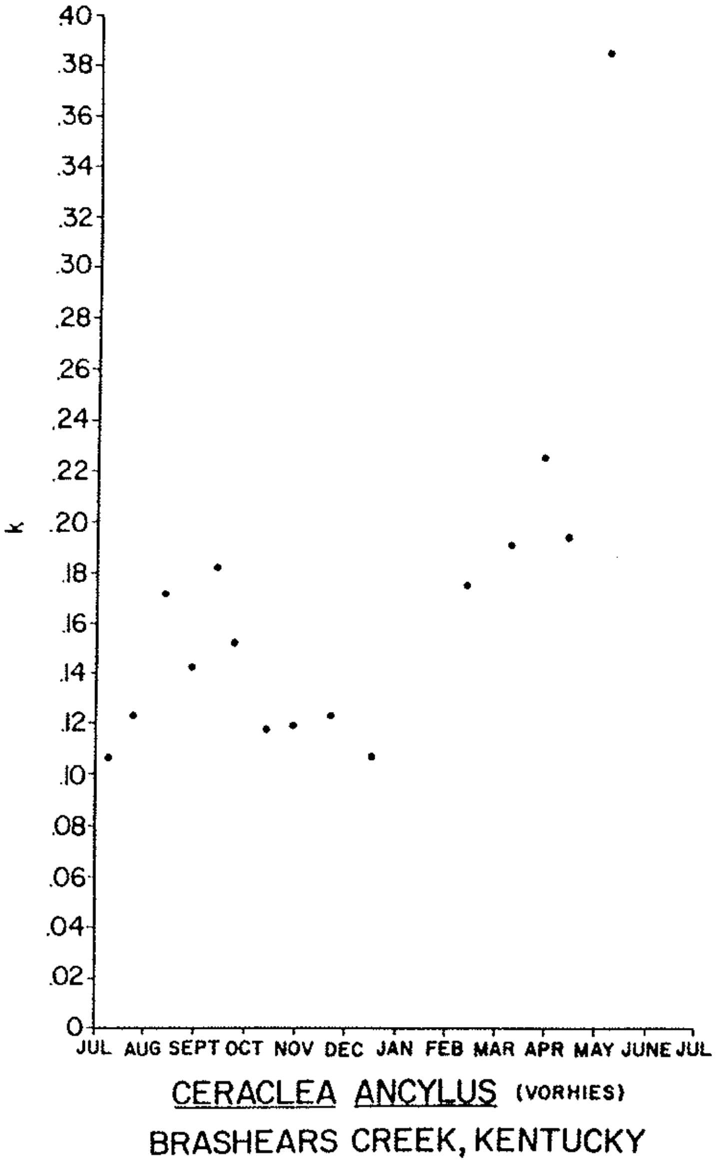

Fig. 3. Changes in *k*, 1971-1972, for *C. ancylus* in Brashears Creek, Spencer Co., Kentucky, USA.

tions of secondary production of aquatic insects since both population and standing stock dynamics must be accurately measured over the duration of the life cycle.

Many of the papers presented in these proceedings have dealt with taxonomic problems of Trichoptera. Taxonomy must be considered as an integral part of any ecological study. However, the biometric components of such a study must be taken into account. Without either part of this matched pair, taxonomy and biometrics, the quantitative interpretation of the ecological interactions of caddisflies and other aquatic insects are subject to a wide range of error. With these points in mind, quantitative sampling regimes must be devised that consider in detail the spatial patterns of the population under examination.

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Discussion

MACKAY: Small streams are often highly heterogeneous in substrate. How can we obtain the large number of samples necessary for precise estimates of production etc., without damaging the stream?
RESH: Quantitative sampling designs should also consider the dimensions of the sampling unit. In small streams, I have been using a 15 cm^2 sampling device. The critical factor to be taken into account is the relationship between the dimension of the sampling device and the size of the clumps of the population under examination.

ECOLOGICAL AND STATISTICAL FEATURES OF SAMPLING INSECT POPULATIONS IN FOREST AND AQUATIC ENVIRONMENTS

by

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ECOLOGICAL AND STATISTICAL FEATURES OF SAMPLING INSECT POPULATIONS IN FOREST AND AQUATIC ENVIRONMENTS

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SUMMARY: Forest and aquatic insects are important to man in both adverse and beneficial contexts, and sound quantitative methods are necessary to obtain reliable data for specific applications. They share some ecological and statistical features which point to the development of sampling techniques and methods of analysis useful to each. Relevant work is further advanced in sampling forest insect populations, and many of the approaches developed thus far have application to aquatic insects. Some basic features, requisites, and constraints of sampling forest and aquatic insect populations are described, with specific examples of the problems encountered and suggestions for their resolution.

KEY WORDS: Forest insects, aquatic insects, sampling distributions, stratification, aggregation, population dynamics, biomonitoring

Biomonitoring, Species Diversity Indices, and Taxonomy

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SAMPLING VARIABILITY AND LIFE HISTORY FEATURES: BASIC CONSIDERATIONS IN THE DESIGN OF AQUATIC INSECT STUDIES

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ABSTRACT

Sampling variability in benthic studies may result from sampling device operation, physical features of the environment, laboratory sorting procedures, and biological features of study populations. Selected factors and procedures that influence variability, samplers affected, and proposed remedies, are presented. Benthic macroinvertebrate research has often indicated that study objectives might be better met by incorporating life history information into sampling designs. Consequences of not considering autecological components in sampling designs are illustrated by analysis of larval counts of *Cheumatopsyche pettiti* (Banks), a multiple cohort caddisfly with an aggregated population. The range of mean numbers of *C. pettiti* was great with low sample numbers. Aggregation is more reliably measured at low sample numbers with the Index of Dispersion and the Mean Crowding Index than with the dispersion parameter k, the calculation of which from the maximum-likelihood equation, is integrally-related to sample size. Non-random patterns of *C. pettiti* observed from samples collected in an Indiana, USA, stream riffle, may result from a failure to consider hyporheic distributions, spatial influences (*e.g*. sampling both favored and non-favored microhabitats), instar-specific differences, and behavioral features. Variability in secondary production estimates of an aggregated population of *Ceraclea ancylus* (Vorhies) from a Kentucky, USA, stream indicated similar relationships to sample size.

The size of the mean, the degree of aggregation, and the desired precision of the mean estimate will influence the number of samples required to estimate densities of benthic populations. Sample size requirements calculated from data reported in previous studies were high at accepted levels of precision. Habitat stratification may reduce the numbers of samples required. *Dicosmoecus gilvipes* (Hagen) exhibited non-aggregated patterns and required fewer samples to estimate density in uniform substrate areas of a California, USA, river pool than did aggregated populations in both mixed substrate areas and the entire pool. _C. ancylus_ required fewer samples for density estimates in stratified (by habitat or substrate type) than unstratified habitats, the fewest samples being necessary when the individual stone was the sampling unit. Judicious choice of study populations may permit larger numbers of samples to be collected and processed with reduced cost, as an alternative to stratification. For example, larvae of _C. ancylus_ and _D. gilvipes_ could be separated in the field; density underestimation due to a hyporheic population component was eliminated because of surface dwelling behavior or by choice of study sites; and compounded spatial distributions due to co-occurring instar-specific patterns were absent because the populations have a single cohort.

Data presented indicate that larger numbers of samples may be necessary than are generally taken in benthic studies. Further research is needed to assess variability in secondary production estimates and community diversity analyses. Improved methods for substrate surface area estimation and increased use of experimental approaches and sequential sampling techniques should be considered in future benthic sampling designs.

KEY WORDS: sampling, benthos, aquatic, macroinvertebrate, Trichoptera, insect, experimental design, autecology, life history, variability.