OKS Document Delivery
Journal Title: Limnology and oceanography
Volume: 12
Issue: 1
Month/Year: 1967
Pages: 27-
Article Author: King,
Article Title: Comparative energetics of a polluted stream

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COMPARATIVE ENERGETICS OF A POLLUTED STREAM[1]

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ABSTRACT

An attempt was made to relate changes in production to variation in stream ecology within a 48.3 km section of a polluted warm-water stream. Energy budgets were constructed for the entire river and for five different ecological zones. The greatest variations were associated with industrial and domestic pollution and the inflow of inorganic sediment from an area of highway construction. Net yield of various aquatic invertebrates was determined from changes in population size between sampling periods. Average net yields for the summer of 1961 were 17 cal m^{-2} day^{-1} for the herbivorous aquatic insects, and 13 cal m^{-2} day^{-1} for the tubificid worms. Photosynthetic efficiency was estimated to be 0.045% of the solar energy available at the surface of the stream.

INTRODUCTION

Relationships between aquatic productivity and environmental conditions have been investigated only recently. Teal (1957), Odum (1957), and Nelson and Scott (1962) studied community biodynamics in limited parts of streams, but there have been no studies of these relationships in large sections of natural streams. This study differs from those mentioned in that an extensive ecological investigation was conducted to correlate changes in primary and secondary production with variation in stream ecology within a 48.3 km portion of a polluted warm-water stream.

During this investigation, the study stream received industrial wastes, domestic wastes, and large amounts of inorganic sediment. These substances caused the greatest variations in stream ecology, so special attention was given to their influences on community relationships.

THE STUDY AREA

The Red Cedar River, a tributary of the Grand River, is a warm-water stream in the south-central portion of the lower peninsula of Michigan. The study section consists of 48.3 km of the main river, extending upstream from the Michigan State University campus, and drains 91,945 ha of rolling farm and suburban land. The width of the river varies from 7.6 to 24.4 m, the average gradient is 0.45 m/km, and the discharge varies seasonally between the all-time low of 0.08 m^3/sec and the record high of 155 m^3/sec. The river arises in an area made up primarily of marsh and wet lands, and much of the upper portion of the river has been dredged to drain the marshes. The area adjacent to the river is predominately woodland, and most of the watershed is used for dairy and small grain farming.

The study section is divided ~~naturally~~ into five zones. The first (zone I) begins on the Michigan State University campus and extends 5.6 km upstream. It is entirely within an urban area and during the study period received domestic pollutants from storm drains and septic tank overflows. Zone II extends 13.7 km upstream from the upper end of zone I. Woodlands adjoin the river in most of this zone in which there is no known source of domestic or industrial pollution. Zone III includes the polluted and recovery areas of the stream below the Williamston sewage treatment plant and is 4.0 km long. Zone IV includes the section of the river under the influence of a dam at Williamston and is 6.4 km long. Its upper portion is bordered by woodlands while the lower 1.6 km is in the city of Williamston. Zone V is 19.3 km long and includes the rest of the study section. It is

[1] This research is part of a thesis for the degree of Ph.D. presented to the Graduate Faculty of Michigan State University by DLK and was supported by a National Institutes of Health Grant (WP-00011-06).

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bordered by woodlands and pastures and receives metal plating wastes and raw sewage at Fowlerville.

METHODS

The *Aufwuchs* communities of the Red Cedar River were collected on artificial substrata at randomly selected sites throughout summer of 1961, and the productions of the autotrophic and heterotrophic portions were determined by the method given by King and Ball (1966).

Aquatic macrophytes were sampled during early September 1962 at randomly selected sites in each of the five zones of the river. Each location was 30.5 m long, and 10 individual samples of 0.09 m^2 were collected within the 30.5-m stratum at randomly selected points. Each 0.09-m^2 sample contained all of the macrophytes, including the roots, attached within the inscribed area.

After collection, the macrophytes were washed to remove silt and sand, drained for a constant time, and weighed on a dietetic balance. These wet weight measurements were converted to dry weight using the conversion factor derived by Vannote (1963).

The macrophytes begin their growth about 15 May and die and become detached early in September. The production rate for each zone was estimated by dividing the average standing crop for a given zone by the number of days in the growth period.

The macroinvertebrate populations were sampled at four different randomly selected locations in each of the five zones during summer of 1961. Two samples, of 10 dredge hauls each, were taken from each randomly selected point, with an interval of 28 days between the two samples. The bottom material was screened with a 30-mesh sieve to remove silt and the finer sand. The organisms were separated alive from the bottom material by flotation, using a concentrated sugar solution, the same day they were collected. Final sorting was done by hand and all organisms were preserved in a 70% ethanol solution containing 5% glycerine. All organisms were separated into ordinal groups and the aquatic insects were separated into family groups. Before weighing, they were removed from the preservative, soaked in tap water for 30 min, placed in small 30-mesh screens, and spun in a centrifuge for 30 sec at 1,800 rpm to remove the excess moisture. Wet weight was then determined on an analytical balance accurate to ±0.001 g. The weight obtained by this procedure closely approximates live weight. Conversion factors were obtained to convert live weight to dry weight.

The caloric values of representatives of various trophic levels from the Red Cedar River were determined with a series of 1300 plain type Parr oxygen bomb calorimeters according to the methods given by the Parr Instrument Company (1960). All samples used for these determinations were dried at 55C, powdered, and formed into pellets.

SAMPLING ADEQUACY

Collection of *Aufwuchs* communities on Plexiglas substrata is an accurate method of measuring the accumulation of organic material. The 95% confidence limits for the rate of accrual of organic matter on the substrata regardless of whether they were placed in a vertical or a horizontal position and regardless of the time of the summer or the area of the river, were ±41.04 mg organic weight m^{-2} day^{-1}, or ±13.48% of the mean of 305.2 mg organic weight m^{-2} day^{-1}.

Although an increase in standing crop of aquatic insects was observed over the 28-day sampling periods, the variability of the benthic environment limited the level of significance to the 0.20 level. While this is greater than the 0.05 level generally used to judge such data, for this variable habitat a difference significant at the 0.20 level probably represents good precision.

CALORIMETRY

The caloric values of representatives of various trophic levels from the Red Cedar River are given in Table 1. With the ex

TABLE 1. *Caloric values of various organisms collected from the Red Cedar River and measures of variability. Units are cal/g dry weight*

Organism	Mean	No. of samples	SD	Confidence limits ±95%
Tubificid	5,261	4	12.42	20
Crayfish	2,901	5	30.10	84
*Aufwuchs**	830	5	22.40	28
Hydropsychidae	4,313	5	331.82	412
Ephemeridae	4,613	2	186.00	1,666
Mixed insects (carnivores)	5,028	2	10.25	92
Unionid clams	4,490	1		

* Uncorrected for sedimentation. *See* text.

ception of the *Aufwuchs,* all values based on dry weight were used directly in converting production estimates from dry weight to the appropriate caloric values. The mean caloric value for the Hydropsychidae and Ephemeridae was used for the herbivorous aquatic insects and the value determined for mixed carnivorous aquatic insects was used for the carnivores. Food habits of these organisms were determined from published material, and a list of the herbivorous and carnivorous insects collected from the Red Cedar River is given in Table 2.

The large quantities of inorganic material settling onto the artificial substrata necessitated a correction of the *Aufwuchs* caloric conversion factor. Therefore, the *Aufwuchs* production estimates were expressed as cal/g ash-free dry weight.

Englemann (1961) found that the mean caloric value of the puff ball was 3,856 cal/g ash-free dry weight and this value was used as the caloric value of the heterotrophic *Aufwuchs.* As 24.5% of the *Aufwuchs* in the Red Cedar River is composed of heterotrophic organisms (King 1964), a gram of dry organic weight of *Aufwuchs* contains (0.245 × 3,856) or 945 cal produced by the heterotrophs. The remaining 3,476 of the 4,421 cal/g dry organic weight of total *Aufwuchs* are produced by the autotrophs, which account for 75.5% of the sample. The caloric value for the autotrophic *Aufwuchs,* then, is 4,604 cal/g dry organic weight.

TABLE 2. *Herbivorous and carnivorous aquatic insects encountered in Red Cedar River*

Herbivores	Carnivores
Poduridae	Perlidae
Heptageniidae	Corydalidae
Baetidae	Sialidae
Ephemeridae	Sisyridae
Hydropsychidae	Gomphidae
Psychomyiidae	Cordulegasteridae
Phryganeidae	Libellulidae
Brachycentridae	Coenagrionidae
Limnophilidae	Agrionidae
Hydroptilidae	Gyrinidae
Leptoceridae	Corixidae
Pyralidae	Belastomatidae
Elmidae	Saldidae
Hydrophilidae	Mesoveliidae
Psephenidae	Heleidae
Haliplidae	Tabanidae
Dryopidae	Empididae
Tipulidae	
Culicidae	
Simuliidae	
Tendipedidae	
Ephydridae	

ENERGY BUDGETS

Energy budgets calculated from the data available from the Red Cedar River illustrate the effects of several types of human activity upon natural stream communities. However, estimates of production for the various biotic levels in the study stream were obtained by different techniques and a slightly different interpretation must be used for each level.

Herbivorous organisms were rare on the Plexiglas substrata, so the production estimates of autotrophic *Aufwuchs* are believed to approximate net production; that is, the amount of energy they make available to the other trophic levels in the community.

The estimates of macrophyte production were made from collections of these plants taken from the river during the summer of 1962. Vannote (1963) found that the macrophytes were expanding in the river and that their production in 1961 was only 30% of that for summer of 1962. Therefore, the macrophyte production estimates made during summer of 1962 were corrected by Vannote's factor to correspond with the 1961 estimates of other community levels.

Macrophyte production estimates probably approach net production in that there is little evidence that stream organisms feed directly on the live plants. Vannote noted that crayfish consume small amounts of *Vallisneria* and that lesser amounts may be consumed by fish. However, the macrophytes are utilized by the decomposers after they die and become detached.

Production estimates of the heterotrophic *Aufwuchs* may approach net production, but the degree of predation, mortality, and drift is unknown. The heterotrophic *Aufwuchs* of the Red Cedar River appear to be approximately the same as the decomposer bacteria described by Odum (1957). He estimated that these decomposer bacteria, living on the surface of the mud, had a tissue growth efficiency (production/assimilation) of 9% and that value was used in the construction of the energy budgets for the Red Cedar River.

Estimates of invertebrate production are estimates of net yield rather than net production in that they did not include predation, mortality, emergence, or downstream drift. Odum found a tissue growth efficiency of 23% for the herbivorous aquatic insects, and Teal (1957) estimated the tissue growth efficiency of carnivorous aquatic invertebrates to be 59%. Teal also noted that the tissue growth efficiency of *Limnodrilus*, a tubificid worm, was 26%. These values were used in the construction of the various energy budgets for the Red Cedar River.

Tissue growth efficiencies are calculated by dividing by total assimilation, so they cannot be used to correct net production estimates to true net production. Total assimilation represents all of the energy utilized by the organism being considered, including all of the energy taken in except that ingested but not digested. Total assimilation is therefore what is often referred to as gross production (Clarke 1946), and the accuracy of the corrected estimate of assimilation depends largely on the accuracy of the original production estimate and the tissue growth efficiency. The difference between total energy assimilated by an organism and the net energy stored by it is the amount of energy used metabolically to maintain the organism. It is for these reasons that the production estimates given here are not directly comparable with those of Nelson and Scott (1962).

During summer of 1961, some areas of the river sustained net gains in the standing crop of invertebrates while in other areas there was a net loss. As these estimates were made by the harvest method, it should be stressed that they refer to average net changes in standing crop; that is, the changes in standing crop exclusive of predation, mortality, emergence, and downstream drift, so they are averages of the net yield for the river or the various river zones during summer of 1961. This appears to be a more reasonable approach than that of correcting this value to true net production by the use of several hypothetical correction factors. It was not possible to estimate production of invertebrates other than aquatic insects and tubificid worms, and thus, their energy requirements are not considered in these calculations.

The organisms composing the hetero trophic *Aufwuchs* undoubtedly have a rapi turnover and, if Odum's tissue growth ef ficiency of 9% can be applied to the Re Cedar River, require an overwhelmin majority of the energy necessary to sustai the entire biotic community. The Re Cedar is a heterotrophic stream and a the minimum, 65% of the energy require ment of the entire biotic community is de rived from allochthonous sources (Table 3 These estimates do not include the energ necessary to sustain the substantial fis populations in the stream. The energ budget for each of the five zones of th river during summer of 1961 is given i Table 3. Zones I and IV appear to requir no allochthonous energy. Heterotrophi *Aufwuchs* production is believed to hav been considerably underestimated in zor I during summer of 1961, primarily becaus of an algal production that approache bloom proportions during one samplin period. This atypical production ove shadowed that of all other periods and i

TABLE 4. *Energy budgets for the entire study section of the Red Cedar River before and during the periods of heavy siltation in summer of 1961. Units are cal m^{-2} day^{-1}*

Trophic level	Before siltation	During siltation
Energy fixed		
Autotrophic *Aufwuchs*	1,140	368
Macrophytes	127	127
Total primary producers	1,267	495
Heterotrophic *Aufwuchs*	360	170
Insects:		
Herbivores (net yield)	43	–9
Carnivores (net yield)	13	6
Tubificid worms	65	–39
Energy required		
Heterotrophic *Aufwuchs*	4,000	1,889
Total insects	283	4
Tubificid worms	200	–115*
Total energy required	4,483	1,893

* Negative values are not included in the total energy required.

g. This would be equal to 2.09 g of dry organic material added to each square meter of zone III each day. If this material had a caloric value of 4,705 cal/g, the 2.09 g m^{-2} day^{-1} would supply all of the estimated required allochthonous energy of 9,833 cal m^{-2} day^{-1}. This seems to be reasonable for this material because this waste receives only primary treatment.

The 402 cal m^{-2} day^{-1} of allochthonous energy required by the biotic community of zone II could be supplied by transport of organic matter from zone III or by autumnal leaf fall from the trees that border the stream in this area.

During summer of 1961, factors other than domestic and industrial pollution limited biotic production in the Red Cedar River. The greatest limitation of *Aufwuchs* production was the sediment entering the river from the construction site of an interstate highway (I-96). Although this road does not cross the main river except at the extreme upper end of the study section, intense rains during late August and early September carried large amounts of sediment to the river from the bared areas of the tributary watersheds. On 4 September 1961, the turbidity of the main river was 387 turbidity units compared to the 20 to 30 units common for that time of the year.

These sediments drastically reduced production of the biotic community of the Red Cedar River (Table 4). During the siltation, there was an apparent reduction of 68% in autotrophic *Aufwuchs* production, but the effects of this inorganic sediment were not confined to the primary producers. There was also a reduction of 58% in the amount of energy required by the heterotrophic members of the community. Thus inorganic sediments originating from the area of highway construction caused large reductions at all levels of the community and the reduction in the amount of energy required approached the reduction in the amount of energy fixed.

ECOLOGICAL EFFICIENCIES

During summer of 1961, the average ne efficiency of the primary producers ove the entire study section of the Red Ceda River was 0.022%, based on total solar ir solation as measured by a pyrheliometer i an open field. Photosynthetic efficienc based on 50% of the total solar energy wa 0.045% and was 0.298% when based on ligl available at the substrate level.

Based on total solar insolation, Silve Springs had a net photosynthetic efficienc of 0.52% (Odum 1957), and the rock ou crop investigated by Nelson and Sco (1962) maintained a net photosynthet efficiency of 0.28%. These efficiencies wei calculated on an annual basis, whereas tl estimate of 0.022% for the Red Cedar Riv is for the summer period, when maximu photosynthetic efficiency occurs. The ma rophytes begin growth during the midd of May and die and become detached l late August or early September, and tl only primary producers present in the riv during the other seasons are the periphyt algae.

Odum confined his measurements natural springs where environmental co ditions approached those of a controll laboratory system, and Nelson and Sc studied a single rock outcrop atypical the remainder of a Georgia river. This stu differs from those in that an attempt was made to measure the relationships of various trophic levels within the entire 48.3-km section of the stream.

While the Red Cedar River is not typical of all streams, the mean photosynthetic efficiency of 0.022% is probably closer to that of entire stream systems than are the above values from areas noted for their high productivity. There are parts of the Red Cedar River where the photosynthetic efficiency is higher than the mean value, but there are also extensive areas of sand flats where primary production is low. Vannote (1963) found a photosynthetic efficiency of 0.46% of total incident solar radiation for a 3.5-km section of the Red Cedar River where the aquatic macrophytes were much denser than in other areas of the stream, but this efficiency and the area where it occurred are not typical of the study area.

ALLOCHTHONOUS ENERGY

The level of primary production found in most streams is inadequate to support the observed standing crops of heterotrophic organisms, so most stream communities depend on allochthonous material for a large part of their required energy. The community of the Red Cedar River receives at least 65% of its required energy from allochthonous sources, and this estimate does not include the energy required by the fish population. The extent to which the community relies on extrinsic energy varies with the type of land bordering the stream, but the type and amount of inflowing organic material also determine the nature of the biotic community present. In the study zones of the Red Cedar River, the dependence of the stream biota on allochthonous energy varied from nil in a reservoir zone to 91% in an area below the outfall of a sewage treatment plant.

This dependency of stream biota on extrinsic organic material was also noted by Teal (1957) and Nelson and Scott (1962). Teal estimated that 76% of the energy at the primary producer level in Root Spring was of allochthonous origin, while Nelson and Scott estimated that 66% of the energy required to sustain the biota of the rock outcrop in a Georgia river came from outside of the river. Thus, it appears that the level of productivity of a stream is largely determined by the amount and kind of organic material entering from the watershed.

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