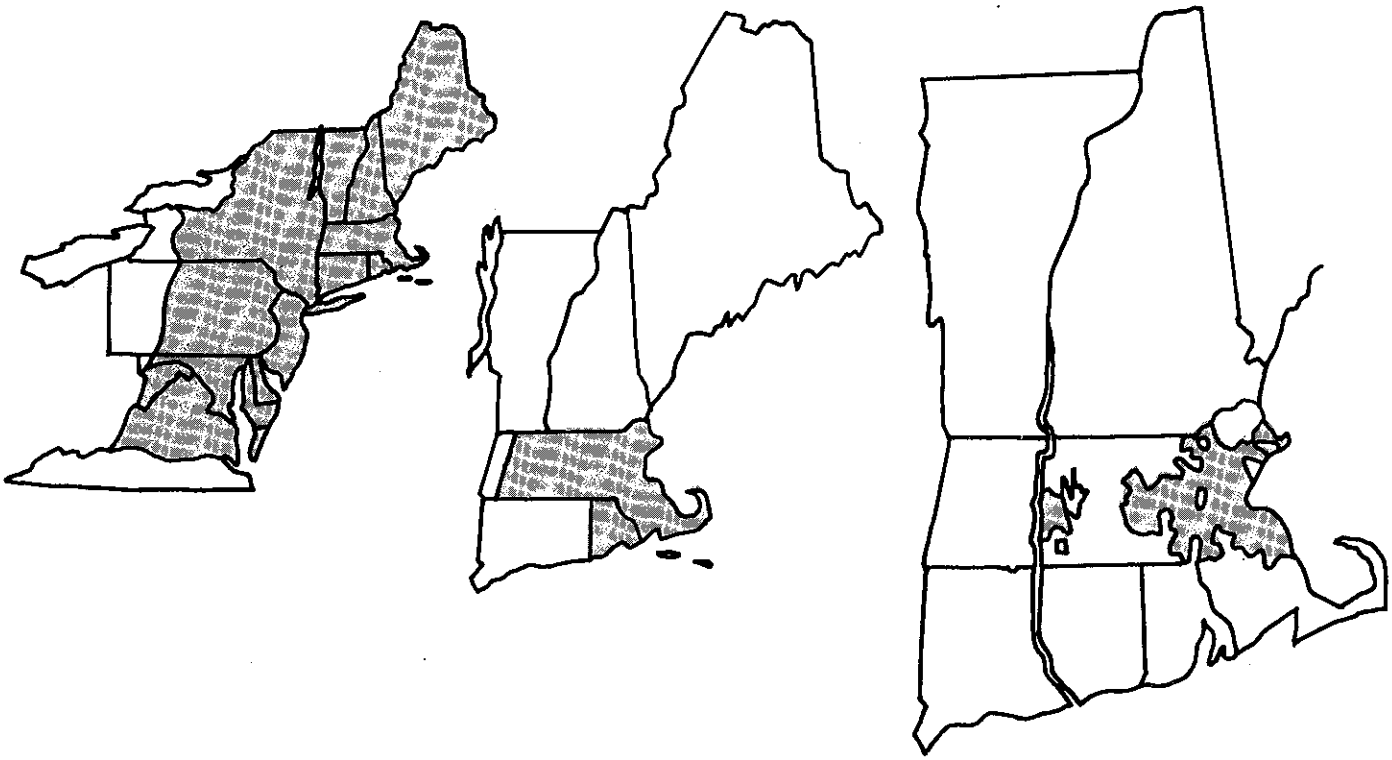
NORTHEASTERN UNITED STATES WATER SUPPLY STUDY

NORTHFIELD MOUNTAIN WATER SUPPLY PROJECT

VOLUME II, APPENDIX A-D



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NORTHFIELD MOUNTAIN WATER SUPPLY PROJECT

VOLUME INDEX

Volume	Contents
I	Main Report
II	Appendix A - Economic Development
	Appendix B - Future Population and Water Demand Studies
	Appendix C - Tunnel Geology and Cost Estimates
	Appendix D - Water Quality Studies of Connecticut and Millers River and Quabbin and Wachusett Reservoirs
III	Appendix E - Possible Effects of Various Diversions from the Connecticut River (or its estuary)
	Appendix F - Identification and Assessment of Social and Economic Impacts - Connecticut and Millers River Basin Diversions
	Appendix G - Environmental Protection Agency Report on Water Quality Studies
	Appendix H - Open Planning Program
	Appendix I - Effect of Diversion Control Flow on Project Yields and Cost of Water Delivered
	Appendix J - Letters of Comment

APPENDIX A

ECONOMIC DEVELOPMENT

The purpose of this appendix is to provide background data concerning future economic development within the study area of this report. Data presented in this appendix are based on extensions of past relationships believed to have future relevance for the measures being projected. Underlying these extensions of past relationships are the assumptions that make the projections conditional forecasts. Thus, the projections are forecasts of what might occur if the particular assumptions were to materialize.

For water resource planning purposes, the assumptions underlying the OBERS projection method yield what is essentially a base line projection. That is, no explicit account is taken of the water resources endowments of a region.

It is assumed that water will play the same role in stimulating or depressing economic growth in the future as it has in the past. Thus, the major impact which the proposed project would have is insuring the provision of good, adequate water supply.

APPENDIX A

ECONOMIC DEVELOPMENT

TABLE OF CONTENTS

Paragraph		Page
1.	General	A-1
2.	OBERS Projections	A-1
3.	Methodology	A-2
4.	Major Findings	A-3
5.	Trends in Economic and Demographic Activity	A-5
	A. General	A-5
	B. The Source Area	A-5
	C. The Service Area	A-7
6.	Past Trends in Economic Growth	A-9
	A. General	A-9
	B. Trends in Population	A-9
	C. Trends in Personal Income	A-10
	D. Per Capita Personal Income	A-10
	E. Trends in Industry Employment	A-11
7.	Future Projected Economic Growth	A-12
	A. General	A-12
	B. Population	A-12
	C. Total Personal Income	A-13
	D. Per Capita Personal Income	A-13
	E. Industry Employment	A-14

TABLES

No.	Title	Page
A-1	Total Population, Franklin County, Connecticut River Water Resource Planning Area, Massachusetts, New England and the United States	A-16
A-2	Personal Income, Franklin County, Connecticut River Water Resource Planning Area, Massachusetts, New England and the United States	A-18
A-3	Employment by Industry Divisions, Franklin County and the Lower Connecticut River Economic Area	A-20
A-4	Economic Production per Employee, Lower Connecticut River Economic Area	A-23
A-5	Total Population, Boston Metropolitan Area, Boston Water Resources Planning Area and New England	A-24
A-6	Personal Income, Boston Metropolitan Area, Boston Water Resources Planning Area, New England and the United States	A-25
A-7	Employment by Industry Division, Boston Metropolitan Area and the Boston Economic Area	A-27
A-8	Economic Production per Employee, Boston Economic Area	A-29
A-9	Employment by Major Water Using Industries, Franklin County	A-30
A-10	Employment by Major Water Using Industries, Boston Economic Area and the Lower Connecticut River Economic Area	A-31

APPENDIX A

ECONOMIC DEVELOPMENT

1. General

This Appendix examines the status of both the Franklin County and the Greater Boston area economies today, discusses the historical forces that have been influential in shaping their present-day characteristics, and indicates what they are likely to be in the next fifty years. While economic and demographic information useful to water resources planning for both regions is provided, emphasis is placed upon the source area, Franklin County, with a more general look at the Greater Boston or service area. This information includes historical and projected estimates of population, personal income, labor force, employment by industry group and output per employee. The historical years shown in this Appendix are 1929, 1940, 1950, 1959, 1960, 1962, and 1970; projections are presented for each decadal year between 1980 and 2020. The areas for which projections and historical data are presented include Franklin County, Massachusetts, the Connecticut River Water Resources Planning Area (North Atlantic Hydrologic Area 8), the Lower Connecticut River Economic Area (OBE Economic Area 01005), the Boston Metropolitan Area, the Boston Economic Area (OBE Economic Area 01004), New England and the Nation.

2. OBERS Projections

In carrying out this task, data prepared by the Office of Business Economics (OBE), Department of Commerce, and the Economic Research Service (ERS), Department of Agriculture were examined to determine their usefulness in providing meaningful bench mark projections. These projections, referred to as "OBERS Projections," are conditional forecasts of the future. They are based on extensions of past relationships believed to have future relevance for the measures being projected. Underlying these extensions of past relationships are the assumptions that make the projections conditional forecasts. Thus, the projections are forecasts of what might occur if the particular assumptions were to materialize.

Certain assumptions regarding the structure and behavior of the economy are applicable to projections generally. Examples of these are:

(1) The Federal Government will implement the policies needed to maintain relatively full employment;

(2) Government and private policies will be successful in avoiding prolonged levels of inflation; and

(3) The economy will be free of the distorting effects of a major military conflict during the 50-year projection interval.

For water resources planning purposes, the assumptions underlying the OBERS projection method yield what is essentially a "base line"[1] projection. That is, no explicit account is taken of the water resource endowments of a region. It is assumed that water will play the same role in stimulating or depressing economic growth in the future as it has in the past.

3. Methodology

The analytical approach followed in this Appendix was to compare the prospective trends for Franklin County, the source area, to those of the Boston Metropolitan Area, the service area. Because both these regions differed area-wise from their enveloping OBE economic or water resource planning areas, separate projection series for personal income and employment were developed. These projections were based on the past historical series for the areas concerned and their relationships to the historical series of the enveloping OBE and water resource planning areas.

As for the derivation of the OBERS projections, the general procedure followed was first to project national totals of each of the relevant economic measures and then to disaggregate these national totals to regional levels. Implicit in this procedure is the fact that national forces clearly dominate economic development throughout the nation. The national economy approximates a closed economy whereas the regional economics, within the United States, are open.[2] Goods and

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[1] Part I, Appendix B, Economic Base, North Atlantic Regional Water Resources Study, prepared by the Office of Business Economics, Regional Economics Division, Department of Commerce for the NAR Water Resources Study Coordinating Committee, (May 1968), pp. 39-40.

[2] The foreign trade sector of the national economy is relatively small.

people move freely between regions. This assumption involving national forces is important for viewing the future economic growth of the Franklin County and Metropolitan Boston areas which together account for an impressive share of the nation's economic activity and whose industries market their products beyond regional boundaries.

National projections of the overall economy were made in terms of bench mark aggregates such as gross national product, population, personal income and employment. From these summary measures were derived national totals of the economic series to be projected for local areas. Because of a lack of gross area product data that extend over a substantial time period, firm national - regional relationships of this measure could not be established. It is for this reason that population, personal income and employment were chosen as measures to be disaggregated to economic sub-areas for estimating the overall expansion of water resource requirements.

Furthermore, under contract to the North Atlantic Division for the Northeastern United States Water Supply Study, the Regional Planning Associates disaggregated the Water Resource Planning Area population projections to county level for dispersed, concentrated and most likely distribution patterns. The projections were then furnished to the New England Division by the North Atlantic Division for use in the Southeastern New England Water Supply Study. The most likely projections are used in this Appendix to estimate water requirements for planning purposes.

4. Major Findings

In general, the examined historical data and projections derived therefrom indicate that both the Franklin County and Boston Metropolitan Area economies will continue to expand and prosper in the period 1970 - 2020. The projected rates of expansion for the two regions, however, differ markedly. In the process of expansion, both areas will continue to export valuable services and/or manufactured goods beyond their boundaries. Changes within and among the areas' various economic sectors are, of course, inevitable and will play a dominant role in determining the regions' growth paths. Population, urbanization, employment, personal income, and the nature and composition of the industrial and business mix of the economies will all be of special relevance to the diverse water resource problems and needs of the two areas.

The major findings of this study are as follows:

(1) The Franklin County economy is projected to continue its trend of accelerating past growth and to experience moderate future growth over the projection interval. Being almost suburban to the Springfield - Chicopee - Holyoke metropolitan area, the County's future growth could be influenced by that area's future growth, for it is in the suburban rings of metropolitan areas that significant growth in New England is anticipated. This does not necessarily mean, however, that the Springfield - Chicopee - Holyoke metropolitan area will experience such future growth as to extend into Franklin County. Thus, if the County remains characteristically rural, nothing more than slow to moderate growth can be projected.

(2) Population in Franklin County is expected to increase by a factor of 1.35 between the years 1970 and 2020, although declines of 0.6 and 0.1 percent are anticipated in relation to the total populations of the Connecticut River Water Planning Area and Massachusetts respectively. At the same time, population in the Boston Metropolitan Area is expected to increase by a factor of 1.67 by the year 2020. This area, however, is expected to increase its share of the Boston Water Resource Planning Area population by 0.9 percent, but to experience a decline of 0.2 percent in relation to New England population.

(3) Total personal income in Franklin County is expected to rise by a factor of 4.95 by the end of the projection period. Since the region's population will be 1.35 times greater, per capita personal income will rise by a factor of 3.67. At the same time, total personal income in the Boston Metropolitan Area is projected to increase by a factor of 6.3. Thus, per capita personal income in the Boston Area will increase by a factor of 3.77 over the projection period.

(4) The manufacturing sectors in both Franklin County and the Boston Metropolitan Area are projected to decline relative to the non-manufacturing sectors in importance as sources of employment. Employment in Franklin County's manufacturing industries is expected to drop from 33 percent of total employment in 1970 to roughly 25 percent by the year 2020. In the Boston Metropolitan Area, manufacturing employment as a percentage of total employment is projected to decline from 29 percent to 20 percent over the projection interval. By the year 2020, there will be more employees in non-manufacturing jobs than in manufacturing positions in both areas. Expanding population and rising personal income indicate further advances for urban

services such as finance, insurance, real estate, and medicine and health in the Boston Metropolitan Area. Thus, the projections of manufacturing and non-manufacturing employment show the structural shifts which both economies are expected to experience.

5. Trends in Economic and Demographic Activity

A. General

The first part of this section describes past changes in the economic growth of both Franklin County and the Boston Metropolitan Region as compared to Massachusetts, New England and national economic growth and discusses the historical forces that have been influential in shaping their present-day characteristics. This sets the stage for the second part which analyzes the future economic growth of Franklin County and the Boston economic area and compares this to projected national growth. The purpose of this section is to provide the necessary economic and demographic information essential for assessing the future demand for water and related land resource goods and services in the study areas.

In this Appendix, economic change is measured by a set of interrelated variables; namely, population, labor force employment, personal income, and net output. These indicators express in economic terms the need for water resource development in an area. Especially important are the numbers of people projected to live in an area and any expected changes in industrial activity. Industrial output or activity at the national level is measured by gross national product. At the regional level, however, there are no official corresponding measures to the annual national output of goods and services. Therefore, employment data which is available in detail at the regional level is used to indicate changes in industrial activity and total personal income provides an overall measure of regional economic growth.

B. The Source Area

Franklin County is divided almost in half by the Connecticut River, and is drained by this River and its tributaries. West of the Connecticut the terrain is rugged, especially on the northwest, and the valleys are well defined. East of the river, the elevations are more moderate and the terrain mostly covered with rolling hills. A large section of Quabbin Reservoir, which supplies many of the municipalities of Metropolitan Boston, is located in the southeast corner of the County.

Beginning with the earliest settlements in the late 1600's, agriculture was the major industry with areas too steep for plowing used for sheep grazing. The plains yielded crops of wheat, tobacco and corn without too much difficulty, and by the late 1800's, the County had grown to be the largest potato producing area in Massachusetts.

In these early days, however, every man's home was a factory in which plows, yokes, carts, scythes and household furniture were produced. At the same time, the women carded wool, spun and wove. Articles of prime necessity, such as iron, steel, brass and pewter utensils were imported. The first cutlery in America was made in the town of Greenfield, the eastern terminus of the famed Mohawk Trail.

The abundance of water was a prime factor in the early development of hydro-electric power in the region. Later, the same abundance of water was a prime factor for the siting of a nuclear power plant of the Yankee Atomic Electric Company in the town of Rowe.

At present, Franklin County is a predominantly rural area with several industrialized areas concentrated in the central and eastern sectors. In many ways, the County has more in common with southern Vermont than with the remainder of Massachusetts. It is a slow growth region with low population density and has neither a large metropolitan area nor a major university. Its labor force, a product of the economic structure, is composed of relatively many blue collar workers and few white collar workers. In order of their importance, the five municipalities reporting the largest number of employed persons in November 1963, were Greenfield, Orange, Ewing, Montague and Deerfield.

Among the County's primarily basic or export industries, those which bring in dollars from other regions, manufacturing and agriculture stand out as being the most significant. Manufacturing, as it has throughout the early 1900's, now contributes the most to the economy of the region as measured by the number of persons employed, the next most important sector being services.

In 1963, the seven largest manufacturing groups, in order of importance as employers, were non-electrical machinery, paper and allied products, fabricated metal products, textile mill products, food and kindred products, lumber and wood products, and printing and publishing.[1] The manufacture of non-electrical machinery and fabricated metal products alone accounts for about one-half of total manufacturing employment.

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[1] Massachusetts Department of Commerce, Monograph for Franklin County (Revised August 1965).

Franklin County's industrial mix is more a consequence of historical accidents rather than a particular set of locational advantages. Most industries located in the County simply because the entrepreneur or inventor developing the industry lived in the area. The only remaining natural resource industries are food processing and lumber products manufacture which together provided 8.6 percent of manufacturing employment in 1963. Although the paper industry originally located in the County because of locational advantages, those factors no longer exist today. The remaining manufacturing industries, not dependent on natural resources, are producing products which can be described as high-valued and lightweight. This type of output is more heavily dependent on a skilled labor force, which is today the chief locational advantage of Franklin County due to its industrial tradition. Within the non-electrical machinery sector, for example, the largest firms and most of the employment are in the manufacture of taps, dies and hand tools. Within the paper sector, the second leading manufacturing industry, the product is also specialized, high value relative to bulk, and high in its technical requirements.

As for agriculture, once Franklin County's most thriving industry, it is today the most rapidly declining sector in terms of employment. The primary cause, as elsewhere in the Connecticut River Valley, is the rising value of farm land in alternative uses resulting from expanding urbanization with its high taxes and wage levels. Although the number of farms and the acreage being cultivated is declining, the output of the more efficient units remaining is increasing. In essence, at the same time urbanization is removing acres from production, it is also providing nearby markets which give farmers a transportation cost advantage.

Today, dairy farming is the leading component of the agricultural sector, followed by tobacco, corn and potatoes. Typical of the industry, the number of dairy farms has declined while output and income derived therefrom have been growing. Along with dairying, corn grown for silage has also increased in production. Other farm output on the increase are vegetables, due in large part to rising sweet corn acreage and cucumbers grown for pickling. All other agricultural products show a decline, including tobacco, once the mainstay of the industry in the valley.

C. The Service Area

One of the earliest settled areas of the United States, the central city and immediate surrounding cities and towns of the Boston Metropolitan Area, has for many years experienced a high level of urbanization.

Only in recent years, however, have the outlying towns of the area begun to feel the urban pressures which have been characteristic of the central core.

Like Franklin County, farming was a principal occupation of the early settlers in this region. Here too, an abundance of water power was a vital factor in the colonization and industrialization of the area. Saw mills, grist mills and tanneries mushroomed, powered by the waters of inland streams. Differing from the Franklin County Area, however, were the marine resources of the Boston area. Good natural harbors and rivers gave impetus to the rapid rise of shipbuilding. The abundance of herring and cod in the offshore waters provided another industrial base and item of trade. And with the most logical, and safest mode of transportation the early settlement days being by ship, this area soon became one of the most important commercial and trade centers on the east coast.

Today, the Boston Metropolitan Area is geographically and economically a part of the largest employment and population cluster in New England. This cluster is the northern terminus of "megalopolis," the Atlantic coastal strip between Washington and Boston in which live about 44 million people, approximately one-fifth of the United States population. Located in the area are the principal governmental, commercial, industrial, educational, medical, financial, insurance, and cultural institutions of New England.

The share of the total labor force employed in the manufacturing industries is higher than the national average. This manufacturing activity is quite diversified with some specialization occurring in the individual cities and towns. The area as a whole shows a degree of specialization in miscellaneous manufacturing, electrical machinery, textiles, professional services, trade and construction. The rapidly expanding electrical machinery industry has surpassed the textile industry in numbers as the leading employer in the manufacturing sector. Other manufacturing industries which are major employers include non-electrical machinery, apparel, food and kindred products, fabricated metals and printing and publishing. Also, in recent years the Boston area has experienced a remarkable growth in technologically-oriented industries which have located here in response to, or as spinoffs of, the concentration of advanced education and research facilities.

Boston, the central city, is the Massachusetts state capital, the most populous city in New England, and the center of the eighth largest SMSA in the country. While only secondarily a manufacturing center,

the city's primary function in the area is as a trade and finance center. It is a major national and international air terminal and port, and the hub for New England's rail, truck, and bus services.

6. Past Trends in Economic Growth

A. General

The prospect for future economic growth in any region is dependent on past trends and current conditions. First, past changes in the source and service area's population growth are described. As mentioned earlier, the need for water resource development in an area is primarily related to the number of people in an area. This then is followed by sections dealing with personal income and changes in employment labor force.

B. Trends in Population

Population in Franklin County increased by 19.8 percent between 1929 and 1970, rising from a level of 49,400 to 59,200 persons (see Table A-1 a). The average annual rates of growth for the selected periods shown in Table A-1 d, however, are well below the respective rates for the Connecticut River WRPA, Massachusetts, New England, and the nation, thus reflecting the region's loss of population through net outmigration. These population growth rates were also surpassed by those of the Boston Metropolitan Area for the respective periods, although the Boston rates were still below those for New England and the nation (see Table A-5 c). Population in the Boston Metropolitan Area increased by 34.3 percent between 1929 and 1970, rising from a level of roughly 2.76 million to 3.71 million persons (see Table A-5 a).

These lagging rates of population growth are also reflected in the areas' decreasing percentage shares of their enveloping water resource planning areas, Massachusetts and New England populations. From a high of 33.9 percent of total New England population in 1929, the Boston Metropolitan Area's regional share had declined to 31.3 percent by 1970 (see Table A-5 b). Likewise, Franklin County's regional share of Massachusetts population declined from 1.2 percent in 1929 to 1.0 percent in 1970 (see Table A-1 c). Franklin County's population as a percentage of the Connecticut River Water Resources Planning Area population declined from 4.2 percent in 1929 to 3.2 in 1970 (see Table A-1 b).

C. Trends in Personal Income

Reflecting population trends, personal income growth in both Franklin County and the Boston Metropolitan Areas has also been slower than its national counterpart. Expressed in 1958 constant dollars, personal income in the nation increased from about $155 billion in 1929 to about $625 billion in 1970 (see Table A-2 a). This represents an increase of 302 percent, or an average annual growth rate of 3.4 percent (see Table A-2 c). Personal income in Franklin County, however, expanded at an average annual rate of 2.7 percent during the same period, or by 201 percent in total. And in the Boston Metropolitan Area, personal income increased by 165 percent, or at an average annual rate of 2.4 percent over the 41 year period (see Table A-6 a, c).

Although the long term average annual personal income growth rate for Franklin County has been slightly higher than that of the Boston Metropolitan Area, the short-term relationship has not remained steady over the 41 year period between 1929 and 1970. From 1950 to 1970, personal income growth in the Boston area increased to an average annual rate of 3.6 percent while that in Franklin County increased to only 3.3 percent (see Tables A-2 c and A-6 c). In the eleven year period prior to 1970, however, personal income growth in Franklin County rose to an average annual rate of 4.9 percent while that in the Boston area increased to 4.0 percent.

From 1929 to 1970, the share of the Connecticut River Water Resource Planning Area's personal income received in Franklin County declined from 3.3 percent to 2.9 percent (see Table A-2 b). During this period, however, the County's share of Massachusetts increased by 0.1 percent. At the same time, the share of New England's personal income received in the Boston Metropolitan Area declined from 37.5 percent to 33.3 percent (see Table A-6 b). Thus, both the areas' lagging rates of personal income growth were reflected in their percentage shares of encompassing areas personal income.

D. Per Capita Personal Income

The critical interplay between population growth and growth in total income is reflected in the per capita levels of income which have always been higher in the Boston Metropolitan Area than in the nation but approximately the same as the nation in Franklin County (see Tables A-2 a and A-6 a). The higher levels of per capita income in the Boston Area have been attributed to higher rates of labor force participation, substantial property income, and a larger-than-national share of

employment in manufacturing (see Table A-7). The Boston Area regional trend in per capita income, however, has been to converge somewhat toward the national level and that of Franklin County.

E. Trends in Industry Employment

Over the past 30 years, overall employment has grown slower in Franklin County than in the Boston Metropolitan Area and the nation. In the period 1940 to 1970 the labor force increased by 27.5 percent in Franklin County, 49.1 percent in the Boston Area, and by 74.0 percent in the nation (see Tables A-3 and A-7).

Based on the number of employees, and as noted previously, agriculture has been relatively more important in the Franklin County economy than in the Boston Area economy (see Tables A-3b and A-7b). Manufacturing, construction, transportation, communications, and public utilities have also been more important employment-wise. In the heavily urbanized Boston Metropolitan Area, industries such as trade, finance, insurance, real estate, and government retained a larger share of total employment than they retained in the Franklin County area. The County's employment share in the general service industries, although somewhat less important during the 1940's and the 1950's than that in the Boston Area, increased by 1960 to a point where it was more important to the local economy.

The major water using manufacturing industries in both the source and service areas include food and kindred products, textile mill products, chemicals and allied products, paper and allied products and primary metals. Petroleum refining is also of some importance, though declining, in the Boston Economic Area (see Table A-10). In 1970, the major water using industries in Franklin County employed 2,256 persons (see Table A-9). This represented approximately 30 percent of manufacturing employment and 10 percent of total employment in the County for that year. Total employment in the County's major water using industries has remained relatively stable between 1956 and 1970. Hidden within these totals, however, are substantial declines in textiles and primary metals and increases in food and kindred products. The decrease in employment from 1967 to 1970 reflects the influence of national economic and social forces which dominate any regional economic activity.

In the Boston Economic Area, a total of approximately 245,000 people were employed by the major water using industries in 1970. Similar to Franklin County, this represented roughly 30 percent of manufacturing employment and 10 percent of total employment for that year.

Unlike Franklin County, however, total employment in the Boston Economic Area's major water using industries has been declining since 1950. This loss in total employment is chiefly due to the loss of over 100,000 jobs in the textile industry (see Table A-10). Although there were steady gains in chemicals, paper and primary metals, these were not enough to offset the above-mentioned losses. In all these industries, however, economic production per employee is projected to dramatically increase over the projection interval (see Tables A-4 and A-8).

7. Future Projected Economic Growth

A. General

Having reviewed past trends in both the source and service area economies, the prospect for future economic growth can be assessed. When dealing with economic and demographic projections for an area as small as Franklin County, however, their unreliability should be recognized. In essence, one single occurrence in the local economy of such a small area could completely change the expected course of events which have been based on past trends and occurrences.

B. Population

Population in Franklin County is projected to increase by roughly 20,800 persons between 1970 and 2020 (see Table A-1 a). This represents a growth of 35.1 percent, or an average annual rate varying between 0.6 and 1.0 percent for the selected periods shown in Table A-1 d. These projected annual average rates are lower than those projected for the Connecticut River Water Resource Planning Area and New England, but equal to the Massachusetts rate beginning in the year 2000 (see Table A-1 d). They are also lower than the average annual rates projected for the Boston Metropolitan Area (see Table A-5 c). Population in the Boston Area is expected to increase by 66.7 percent, rising from a level of roughly 3.71 million in 1970 to 6.18 million in the year 2020 (see Table A-5 a). The average annual rates of population growth for both the source and service areas, however, are projected to remain below those of total population growth in the United States during the 1970 - 2020 period.

Increases in the above populations are based on the estimates of labor force needs to meet the requirements of expanding economies which the local area labor forces cannot accommodate. A community is a place for earning a living and population settles or expands in a region

primarily because of employment opportunities. Hence, a greater migration into the Boston Metropolitan Area is projected based on the assumption that labor shortages will be avoided and economic activity will not be curtailed.

In the Boston Area, population growth is projected to continue to lag behind that in the nation, but to surpass the Massachusetts rate and equal the New England rate. Thus, the area's percentage share of Massachusetts population is expected to gradually increase.

In Franklin County, population growth is projected to catch up to the Massachusetts annual average rate and move closer to the New England rate during the study interval.

C. Total Personal Income

Personal income in Franklin County is projected to grow at a slower pace than that in the Boston Metropolitan Area, Massachusetts, New England and the United States (see Tables A-2 c and A-6 c). Expressed in constant 1958 dollars, it is expected to rise by a factor of roughly 4.9 in the period 1970 to 2020. At the same time, personal income in the Boston Area is projected to increase by a factor of 6.3 by the year 2020.

In addition, the proportion of the enveloping Water Resources Planning Areas' and New England's personal income received in both the study areas is projected to further decline (see Tables A-2 b and A-6 b). Franklin County's share of Massachusetts personal income, however, is expected to decline by 0.8 percent while the Boston Metropolitan Area's share of Massachusetts personal income is projected to increase from 68.7 percent to 71.2 percent over the projection interval.

D. Per Capita Personal Income

With population in Franklin County projected to increase by a factor of 1.35 and total personal income by a factor of roughly 4.95, per capita income will rise by a factor of 3.67 by the year 2020 (see Table A-2 a). In the Boston Metropolitan Area, however, per capita personal income will increase by a factor of 3.77 over the projection period (See Table A-6 a).

Although per capita income in the Boston Area is projected to remain higher than that of the nation as a whole, a regional trend to converge toward the national level is also expected to continue. From 1.12 in 1970, the index for the Boston Area per capita income relative to the

United States average is projected to decline to 1.05 by the year 2020. This projection is based on a gradual maturing of more recently developed sections of the country and the concurrent lowering of regional differences in economic opportunities.

E. Industry Employment

The changing characteristics of both the source and service areas' economies are indicated by manufacturing and non-manufacturing employment projections. While the Franklin County economy will still remain more dependent on manufacturing than the national and Boston Metropolitan Area economies, this sector is projected to decline relative to the non-manufacturing sector in importance as a source of employment (see Tables A-3b and A-7b).

Employment in Franklin County's manufacturing industries is expected to drop from 33 percent of total employment in 1970 to roughly 25 percent by the year 2020 (see Table A-3b). In the Boston Metropolitan Area, manufacturing employment as a percentage of total employment is projected to decline from 29 percent to 20 percent over the projection interval. At the same time, employment in both the areas' service industries is projected to increase its shares of total employment. Franklin County's service industries are expected to increase their share of total employment from 26 percent in 1970 to 37 percent by the year 2020. Likewise, the Boston Metropolitan Area employment in the service sector is projected to increase from roughly 26 percent to 38 percent of total employment (see Table A-7b). Thus, by the year 2020, there will be far more employees in non-manufacturing jobs than manufacturing positions in both areas.

Manufacturing or traditional industrial activity is still projected to be of greater importance to the Franklin County economy than it will be to the national economy. In the Boston Area, however, it is projected to be of less importance. As indicated in Tables A-4 and A-8, economic production per employee in both areas is expected to dramatically increase over the projection interval. This will in great part be a result of the changing mix of manufacturing industries from the labor-intensive to the capital-intensive.

With the production orientation toward the non-manufacturing sector, new concentrations of workers and occupational changes will occur. Finance, insurance, real estate, government, and business and private services stand out as the more important growth industries. As growing populations with higher per capita income spend a larger share

of their income on non-commodity items, recreational activity, medical and health services, and educational services, employment in the services will grow faster than in any other industry group.

In essence, the projections of manufacturing and non-manufacturing employment for both the source and services areas show the structural shifts which these economies are expected to experience. Both areas are projected to further move away from economies which are based on manufacturing toward economies which are based on services where employment growth in the service sectors will result from expanding population, increased general employment, and rising personal income.

TABLE A-1

Total Population, Franklin County, Connecticut River Water Resource Planning Area, Massachusetts, New England and the United States

	1929	1940	1950	1959	1960	1962	1970	1980	1990	2000	2010	2020
	Actual							Projected				
1. a. Population (in thousands)												
Franklin County	49.4	49.5	52.7	54.5	54.8	55.9	59.2	60.0	62.5	65.0	72.5	80.0
Connecticut River WRPA (North Atlantic Hydrologic Area 8)	1,178.9	1,219.2	1,383.6	1,629.4	1,640.4	1,640.4	1,869.3	1,907.6	2,113.6	2,319.6	2,679.4	3,039.3
Massachusetts	4,229.0	4,318.0	4,686.0	5,117.0	5,148.6	5,201.0	5,689.2	6,109.6	6,795.1	7,449.7	8,187.4	9,029.9
New England	8,130.0	8,449.0	9,316.0	10,437.0	10,509.4	10,726.0	11,841.7	12,870.1	14,467.0	16,054.5	17,837.3	19,844.6
United States (in millions)	122.1	132.5	151.9	177.1	179.3	185.9	205.1	234.2	269.7	306.8	348.9	397.6
1. b. Franklin County Population as a Percent of Connecticut River WRPA Population												
Percent of Connecticut River WRPA Population	4.2	4.1	3.8	3.3	3.3	3.3	3.2	3.1	3.0	2.8	2.7	2.6
1. c. Franklin County Population as a Percent of Massachusetts Population												
Percent of Mass. Population	1.2	1.1	1.1	1.1	1.1	1.1	1.0	1.0	0.9	0.9	0.9	0.9

TABLE A-1 (cont'd)

1. d. Average Annual Rates of Population Growth

Selected Periods

	1929-70	1940-70	1950-70	1960-70	1970-2020	1980-2020	2000-2020
Franklin County	0.4	0.6	0.6	0.8	0.6	0.7	1.0
Connecticut River WRPA	1.1	1.4	1.5	1.3	1.0	1.2	1.3
Massachusetts	0.7	0.9	1.0	1.0	0.9	1.0	1.0
New England	0.9	1.1	1.2	1.2	1.0	1.1	1.1
United States	1.3	1.5	1.5	1.4	1.3	1.3	1.3

TABLE A-2

Personal Income, Franklin County, Connecticut River Water Resource Planning Area, Massachusetts, New England and the United States

2. a. Total Personal Income (millions of 1958 Constant Dollars) and Per Capita Income

	Actual						Projected				
	1929	1940	1950	1959	1962	1970	1980	1990	2000	2010	2020
Franklin County	59.9	72.6	94.8	106.8	116.7	180.3	248.3	341.9	470.7	648.2	892.4
Per Capita	1,212	1,467	1,866	2,105	2,247	3,046	4,138	5,470	7,242	9,002	11,155
Relative to U. S.	0.75	1.13	1.03	0.99	1.00	1.00	1.01	1.02	1.01	0.95	0.90
Conn. River WRPA	1,835.1	2,095.8	2,882.5	3,934.5	4,353.3	6,183.3	8,368.1	11,975.6	17,280.6	26,381.4	39,244.2
Per Capita	1,557	1,719	2,083	2,415	2,596	3,308	4,387	5,666	7,450	9,846	12,912
Relative to U. S.	1.22	1.33	1.15	1.13	1.15	1.09	1.07	1.06	1.04	1.04	1.04
Massachusetts	6,971.1	7,400.0	9,232.8	11,985.2	13,262.2	18,436.9	26,171.7	37,092.5	53,697.7	77,607.6	112,078.7
Per Capita	1,648	1,714	1,970	2,342	2,550	3,241	4,284	5,459	7,208	9,479	12,412
Relative to U. S.	1.30	1.32	1.09	1.10	1.13	1.06	1.04	1.02	1.01	1.00	1.00
New England	12,759.1	13,868.1	17,986.7	24,091.8	26,849.4	38,041.2	55,275.7	79,857.5	117,766.3	173,342.1	251,992.2
Per Capita	1,569	1,641	1,931	2,308	2,503	3,212	4,295	5,520	7,335	9,718	12,695
Relative to U. S.	1.23	1.26	1.07	1.08	1.11	1.05	1.04	1.03	1.02	1.03	1.02
U. S. (billions $58)	155.2	172.2	274.1	377.9	419.6	624.6	963.0	1,442.1	2,196.7	3,303.0	4,934.1
Per Capita	1,271	1,300	1,805	2,134	2,258	3,046	4,112	5,346	7,161	9,467	12,411

2. b. Franklin County Personal Income as a Percent of Connecticut River WRPA and Massachusetts Personal Income

Percent of Connecticut River WRPA Income	3.3	3.5	3.3	2.7	2.7	2.9	3.0	2.9	2.7	2.5	2.3
Percent of Massachusetts Personal Income	0.9	1.0	1.0	0.9	0.9	1.0	0.9	0.9	0.9	0.8	0.8

TABLE A-2 (cont'd)

2. c. Average Annual Rates of Personal Income Growth
Selected Periods

	1929-70	1940-70	1950-70	1959-70	1970-2020	1980-2020	2000-2020
Franklin County	2.7	3.1	3.3	4.9	3.3	3.3	3.3
Connecticut River WRPA	3.0	3.6	3.9	4.3	3.8	3.9	4.2
Massachusetts	2.4	3.1	3.5	4.0	3.6	3.7	3.8
New England	2.7	3.4	3.8	4.3	3.9	3.9	3.9
United States	3.4	4.4	4.2	4.7	4.2	4.2	4.1

TABLE A-3

Employment by Industry Divisions, Franklin County and the Lower Connecticut River Economic Area (OBE Economic Area 01005)

3. a. Employment by Industry Divisions

Franklin County

	Actual				Projected				
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Agr., For., & Fish.	2,328	2,044	1,369	1,170	1,100	1,100	900	900	900
Mining	22	28	28	--	--	--	--	--	--
Contract Construction	803	1,221	1,226	1,422	1,500	1,600	1,700	1,900	2,100
Manufacturing	6,200	7,222	7,247	7,568	7,200	6,800	7,000	7,500	7,700
T.C.P.U.	1,426	1,677	1,459	1,422	1,300	1,200	1,000	1,000	900
Trade	2,348	3,207	3,168	3,532	3,700	3,900	4,200	4,600	5,000
F.I.R.E.	294	355	420	505	600	600	800	900	1,000
Services	3,734	3,570	4,774	5,962	7,000	7,800	8,700	10,100	11,500
Government	566	630	660	780	800	900	1,000	1,100	1,200
Military	0	12	28	--	--	--	--	--	--
Industry not Reported	270	344	470	573	600	600	700	700	800
Total Employment	17,991	20,310	20,849	22,934	23,800	24,400	26,000	28,700	31,100
Participation Rate	.363	.385	.380	.39	.40	.39	.40	.40	.39

Lower Connecticut River Economic Area

Agr., For., & Fish.	34,388	31,402	22,285	18,300	15,800	13,100	11,400	9,800	8,300
Mining	794	639	821	600	500	500	500	400	400
Contract Construction	32,523	46,496	54,418	66,400	77,600	87,700	100,200	113,100	125,500
Manufacturing	300,198	363,119	413,626	433,000	449,400	466,900	472,200	494,900	521,200
T.C.P.U.	36,933	48,498	50,653	53,200	55,800	57,900	57,700	58,000	59,000
Trade	110,640	145,083	163,609	188,200	215,700	241,500	269,700	299,400	332,500
F.I.R.E.	31,420	39,842	56,198	65,000	76,000	85,200	98,200	111,100	124,700
Services	129,627	141,959	195,221	270,700	352,600	426,500	530,400	634,300	743,500
Government	22,361	31,701	37,765	48,300	59,400	71,200	82,900	94,400	106,800
Military	1,578	11,185	21,357	17,500	16,900	16,900	16,900	16,900	16,900
Total Employment	700,462	859,924	1,015,953	1,161,300	1,319,700	1,467,400	1,640,100	1,832,500	2,038,800
Participation Rate	.39	.41	.40	.41	.42	.41	.42	.42	.41

TABLE A-3 (cont'd)

3. b. Percent Distribution of Employment by Industry Division

(United States percentages are also included for comparison)

Franklin County

	Actual			Projected					
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Agr., For., & Fish.	12.9	10.1	6.6	5.1	4.6	4.0	3.5	3.2	3.0
Mining	--	--	--	--	--	--	--	--	--
Contract Construction	4.5	6.0	5.9	6.2	6.4	6.5	6.6	6.7	6.8
Manufacturing	34.5	35.6	34.8	33.0	30.2	28.1	27.2	26.2	24.6
T.C.P.U.	7.9	8.3	7.0	6.2	5.4	4.8	4.0	3.4	3.0
Trade	13.1	15.8	15.2	15.4	15.6	16.0	16.0	15.9	15.9
F.I.R.E.	1.6	1.8	2.0	2.2	2.4	2.6	2.9	3.2	3.2
Services	20.8	17.6	22.9	26.0	29.4	31.8	33.5	35.0	37.0
Government	3.1	3.1	3.2	3.4	3.5	3.7	3.8	3.9	4.0
Military	--	--	--	--	--	--	--	--	--
Industry not Reported	1.5	1.7	2.3	2.5	2.5	2.5	2.5	2.5	2.5
Total Employment	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Lower Connecticut River Economic Area

Agr., For., & Fish.	4.9	3.7	2.2	1.6	1.2	0.9	0.7	0.5	0.4
Mining	--	--	--	--	--	--	--	--	--
Contract Construction	4.7	5.4	5.4	5.7	5.9	6.0	6.1	6.2	6.2
Manufacturing	42.9	42.2	40.7	37.3	34.1	31.8	28.8	27.0	25.6
T.C.P.U.	5.3	5.6	5.0	4.6	4.2	3.9	3.5	3.2	2.9
Trade	15.8	16.9	16.1	16.2	16.3	16.4	16.4	16.3	16.3
F.I.R.E.	4.5	4.6	5.5	5.6	5.8	5.8	6.0	6.1	6.1
Services	18.5	16.5	19.2	23.3	26.7	29.1	32.3	34.6	36.5
Government	3.2	3.7	3.7	4.2	4.5	4.9	5.1	5.2	5.2
Military	--	1.3	2.1	1.5	1.3	1.2	1.0	0.9	0.8
Total Employment	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE A-3 (cont'd)

United States

	Actual			Projected					
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Agr., For., & Fish.	19.1	12.5	6.7	4.7	3.5	2.6	2.0	1.6	1.2
Mining	2.1	1.6	1.0	0.8	0.6	0.5	0.5	0.4	0.4
Contract Construction	4.6	6.1	6.0	6.1	6.2	6.1	6.1	6.1	6.1
Manufacturing	23.7	25.8	27.5	26.5	25.2	24.1	23.1	22.2	21.6
T.C.P.U.	7.0	7.9	7.0	6.1	5.6	5.1	4.4	3.9	3.5
Trade	16.9	18.7	18.5	18.1	17.8	17.5	17.0	16.6	16.3
F.I.R.E.	3.3	3.4	4.3	4.5	4.7	4.8	4.9	5.1	5.1
Services	19.3	17.8	21.3	25.2	28.3	31.0	33.6	35.7	37.4
Government	3.3	4.4	5.0	5.6	6.2	6.6	6.9	7.1	7.3
Military	0.7	1.8	2.7	2.4	1.9	1.7	1.5	1.3	1.1
Total Employment	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE A-4

Economic Production per Employee (1958 Dollars)

Lower Connecticut River Economic Area (OBE Economic Area 005)

Industry	1960	1970	1980	1990	2000	2010	2020
Food	7,958	11,059	15,363	20,384	27,003	36,113	48,756
Textiles	5,514	8,265	11,833	16,626	23,592	33,350	47,174
Paper	8,048	10,853	13,789	17,259	21,734	27,225	34,487
Chemicals	10,760	17,815	27,823	42,676	69,652	99,419	134,884
Petroleum	7,877	20,927	42,601	82,160	155,544	280,485	503,065
Primary Metals	9,642	13,527	17,653	22,335	27,990	35,331	45,666

TABLE A-5

Total Population, Boston Metropolitan Area (Essex, Middlesex, Norfolk, Plymouth and Suffolk Counties), Boston Water Resources Planning Area (WRPA 0106) and New England

5. a. Population (in thousands)

				Actual						Projected		
	1929	1940	1950	1959	1960	1962	1970	1980	1990	2000	2010	2020
Boston Metropolitan Area	2,760.8	2,825.8	3,062.4	3,337.0	3,356.8	3,389.8	3,708.7	4,027.6	4,450.5	4,913.7	5,508.3	6,181.4
Boston Water Resources Planning Area	4,337.2	4,460.5	4,831.3	5,248.9	5,278.5	5,340.7	5,815.9	6,422.1	7,193.3	7,941.7	8,774.8	9,717.1
New England	8,130.0	8,449.0	9,316.0	10,437.0	10,509.4	10,726.0	11,841.7	12,870.1	14,467.0	16,054.5	17,837.3	19,844.6

5. b. Boston Metropolitan Area Population as a Percent of Boston Water Resources Planning Area and New England Populations

Percent of Boston WRPA Population	63.6	63.4	63.4	63.6	63.6	63.5	63.8	62.7	61.9	61.9	62.8	63.6
Percent of New England Population	33.9	33.4	32.9	32.0	31.9	31.6	31.3	31.3	30.8	30.6	30.9	31.1

5. c. Average Annual Rates of Population Growth, Selected Periods

	1929-70	1940-70	1950-70	1960-70	1970-2020	1980-2020	2000-2020
Boston Metropolitan Area	0.7	0.9	1.0	1.0	1.0	1.1	1.1
Boston WRPA	0.7	0.9	0.9	1.0	1.0	1.0	1.0
Massachusetts	0.7	0.9	1.0	1.0	0.9	1.0	1.0
New England	0.9	1.1	1.2	1.2	1.0	1.1	1.1

TABLE A-6

Personal Income, Boston Metropolitan Area (Essex, Middlesex, Norfolk, Plymouth and Suffolk Counties), Boston Water Resources Planning Area (WRPA 0106), New England and the United States

6. a. Total Personal Income (in millions of 1958 Constant Dollars) and Per Capita Income

	Actual						Projected				
	1929	1940	1950	1959	1962	1970	1980	1990	2000	2010	2020
Boston Metropolitan Area	4,790.0	5,283.5	6,287.3	8,201.3	9,065.5	12,671.2	18,309.9	26,457.5	38,229.0	55,246.4	79,841.2
Per Capita	1,735	1,869	2,053	2,461	2,678	3,417	4,630	6,037	7,912	10,179	13,033
Relative to U. S.	1.37	1.44	1.14	1.15	1.19	1.12	1.13	1.13	1.10	1.08	1.05
Boston WRPA	7,234.9	7,665.8	9,527.0	12,206.5	13,527.4	19,380.8	28,136.7	40,781.8	59,496.0	86,861.4	125,143.7
Per Capita	1,668	1,719	1,972	2,326	2,533	3,332	4,381	5,669	7,492	9,899	12,879
Relative to U. S.	1.31	1.32	1.09	1.09	1.12	1.09	1.07	1.06	1.05	1.05	1.04
New England	12,759.1	13,868.1	17,986.7	24,091.8	26,849.4	38,041.2	55,275.7	79,857.5	117,766.3	173,342.1	251,992.2
Per Capita	1,569	1,641	1,931	2,308	2,503	3,212	4,295	5,520	7,335	9,718	12,695
Relative to U. S.	1.23	1.26	1.07	1.08	1.11	1.05	1.04	1.03	1.02	1.03	1.02
U. S. (in billions)	155.2	172.2	274.1	377.9	419.6	624.6	963.0	1,442.1	2,196.7	3,303.0	4,934.1
Per Capita	1,271	1,300	1,805	2,134	2,258	3,046	4,112	5,346	7,161	9,467	12,411

6. b. Boston Metropolitan Area Income as a Percent of Boston WRPA, Massachusetts and New England Personal Income

Percent of Boston WRPA Income	66.2	68.9	66.0	67.2	67.0	65.4	65.1	64.9	64.3	63.6	63.8
Percent of Massachusetts Income	68.7	71.4	68.1	68.4	68.4	68.7	70.0	71.3	71.2	71.2	71.2
Percent of New England Income	37.5	38.1	35.0	34.0	33.8	33.3	33.1	33.1	32.5	31.9	31.7

TABLE A-6 (cont'd)

6. c. Average Annual Rates of Personal Income Growth

Selected Periods

	1929-70	1940-70	1950-70	1959-70	1970-2020	1980-2020	2000-2020
Boston Metropolitan Area	2.4	2.9	3.6	4.0	3.8	3.8	3.8
Boston WRPA	2.4	3.1	3.6	4.3	3.8	3.8	3.8
Massachusetts	2.4	3.1	3.5	4.0	3.6	3.7	3.8
New England	2.7	3.4	3.8	4.3	3.9	3.9	3.9
United States	3.4	4.4	4.2	4.7	4.2	4.2	4.1

TABLE A-7

Employment by Industry Division, Boston Metropolitan Area (Essex, Middlesex, Norfolk, Plymouth and Suffolk Counties) and the Boston Economic Area (OBE Economic Area 01004)

7. a. Employment by Industry Divisions

	Actual					Projected			
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Boston Metropolitan Area									
Agr., For., & Fish.	19,518	18,355	12,491	7,300	6,500	5,400	4,000	2,200	2,500
Mining	926	1,034	897	--	--	--	--	--	--
Contract Construction	46,993	68,118	67,099	75,960	87,600	98,800	110,900	124,600	140,700
Manufacturing	314,185	381,207	414,356	428,170	421,600	420,500	416,000	445,100	502,300
T.C.P.U.	72,994	93,631	82,659	87,650	87,600	93,400	93,100	93,500	87,900
Trade	204,161	246,159	236,436	260,180	280,500	307,300	336,800	369,400	401,900
F.I.R.E.	48,874	60,110	72,157	86,350	94,000	104,200	116,900	133,500	150,700
Services	220,968	234,634	289,174	381,430	470,200	575,000	689,400	814,500	954,400
Government	45,239	65,129	69,737	84,730	102,100	116,800	132,700	153,500	175,800
Military	3,114	13,533	25,626	23,370	22,700	21,600	21,800	22,300	20,100
Industry not Reported	17,714	13,908	68,846	48,360	48,600	53,900	59,400	66,800	75,300
Total Employment	994,686	1,195,818	1,339,478	1,483,500	1,621,400	1,796,900	1,981,000	2,225,400	2,511,600
Participation Rate	.352	.390	.399	.400	.410	.410	.410	.410	.410
Boston Economic Area (OBE Economic Area 01004)									
Agr., For., & Fish.	47,086	43,605	29,503	24,800	21,500	18,900	16,800	14,800	12,700
Mining	1,538	1,491	1,370	1,000	800	800	700	600	600
Contract Construction	80,144	114,489	118,847	141,400	160,400	178,200	199,800	221,700	245,700
Manufacturing	651,787	764,861	823,329	828,400	860,900	891,600	929,100	974,000	1,027,000
T.C.P.U.	108,435	140,336	130,290	134,300	140,200	144,700	143,400	143,400	145,100
Trade	318,968	388,895	395,048	435,500	486,900	534,000	585,300	639,400	698,700
F.I.R.E.	66,645	83,326	107,593	123,300	142,700	159,700	183,600	297,300	232,100
Services	346,841	366,301	470,281	642,200	823,500	983,300	1,211,900	1,438,400	1,673,400
Government	67,563	100,053	116,078	145,600	175,800	207,000	241,600	273,800	307,700
Military	8,122	35,701	66,416	54,400	52,400	52,400	52,400	52,400	52,400
Total Employment	1,697,129	2,039,058	2,258,755	2,530,900	2,865,200	3,170,500	3,564,600	3,965,800	4,395,500
Participation Rate	.357	.394	.398	.400	.410	.410	.410	.410	.410

TABLE A-7 (cont'd)

7. b. Percent Distribution of Employment by Industry Division

(United States percentages are included in Table 3. b. for comparison)

Boston Metropolitan Area

	Actual			Projected					
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Agr., For., & Fish.	2.0	1.5	0.9	0.5	0.4	0.3	0.2	0.1	0.1
Mining	--	--	--	--	--	--	--	--	--
Contract Construction	4.7	5.7	5.0	5.1	5.4	5.5	5.6	5.6	5.6
Manufacturing	31.6	31.9	30.9	28.9	26.0	23.4	21.0	20.0	20.0
T.C.P.U.	7.3	7.8	6.2	5.9	5.4	5.2	4.7	4.2	3.5
Trade	20.5	20.6	17.7	17.5	17.3	17.1	17.0	16.6	16.0
F.I.R.E.	4.9	5.0	5.4	5.8	5.8	5.8	5.9	6.0	6.0
Services	22.2	19.6	21.6	25.7	29.0	32.0	34.8	36.6	38.0
Government	4.6	5.5	5.2	5.8	6.3	6.5	6.7	6.9	7.0
Military	0.3	1.1	1.9	1.6	1.4	1.2	1.1	1.0	0.8
Industry not Reported	1.8	1.2	5.1	3.3	3.0	3.0	3.0	3.0	3.0
Total Employment	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Boston Economic Area

Agr., For., & Fish.	2.8	2.1	1.3	1.0	0.8	0.6	0.5	0.4	0.3
Mining	0.1	0.1	0.1	--	--	--	--	--	--
Contract Construction	4.7	5.6	5.3	5.6	5.6	5.6	5.6	5.6	5.6
Manufacturing	38.4	37.5	36.4	32.7	30.1	28.1	26.1	24.6	23.3
T.C.P.U.	6.4	6.9	5.8	5.3	4.9	4.6	4.0	3.6	3.3
Trade	18.8	19.1	17.5	17.2	17.0	16.9	16.4	16.1	15.9
F.I.R.E.	3.9	4.1	4.8	4.9	5.0	5.0	5.1	5.2	5.3
Services	20.4	18.0	20.8	25.4	28.7	31.0	34.0	36.3	38.1
Government	4.0	4.9	5.1	5.8	6.1	6.5	6.8	6.9	7.0
Military	0.5	1.7	2.9	2.1	1.8	1.7	1.5	1.3	1.2
Total Employment	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE A-8

Economic Production per Employee (1958 Dollars)

Boston Economic Area (OBE Economic Area 004)

Industry	1960	1970	1980	1990	2000	2010	2020
Food	6,952	10,053	14,357	19,378	25,997	35,107	47,750
Textiles	4,602	7,353	10,921	15,714	22,680	32,438	46,262
Paper	7,365	10,170	13,106	16,576	21,051	26,542	33,804
Chemicals	9,232	16,287	26,295	41,148	68,124	97,891	133,356
Petroleum	7,573	20,623	42,297	81,856	155,240	280,181	502,761
Primary Metals	9,322	13,207	17,333	22,015	27,670	35,011	45,346

TABLE A-9

Employment by Major Water Using Industries,
Franklin County

	1956	1958	1962	1964	1967	1970
Food, Tobacco Processing	182	200	316	302	306	207
Textiles, Apparel Leather	815	635	705	701	804	725
Chemicals	25	26	45	33	29	17
Paper	1,248	1,288	1,275	1,211	1,286	1,262
Primary Metals	70	74	101	112	112	45
Totals	2,340	2,223	2,442	2,359	2,537	2,256

TABLE A-10

Employment by Major Water Using Industries, Boston Economic Area (OBE Economic Area 01004) and the Lower Connecticut River Economic Area (OBE Economic Area 01005)

10. a. Boston Economic Area

	Actual				Projected				
	1940	1950	1960	1970	1980	1990	2000	2010	2020
Food & Kindred Products	38,778	11,659	55,740	47,300	43,700	40,000	37,400	36,400	35,500
Textile Mill Products	213,956	222,902	144,207	118,200	104,000	91,500	83,200	76,300	70,600
Chemicals	14,573	16,161	16,418	19,100	20,900	22,500	25,700	28,600	31,300
Paper		24,726	26,716	28,400	30,600	32,300	34,300	36,400	38,200
Petroleum Ref.		4,549	3,238	1,900	1,300	900	700	500	400
Primary Metals		21,422	26,766	30,000	32,500	34,600	37,200	39,700	42,000
Totals		331,419	273,085	244,900	233,000	221,800	218,500	217,900	218,000

10. b. Lower Connecticut River Economic Area

Food & Kindred Products	9,983	10,877	16,206	14,800	14,300	14,000	13,700	13,400	13,100
Textile Mill Products	55,553	59,047	37,058	33,200	28,600	24,500	21,600	19,100	16,900
Chemicals	5,845	9,311	13,698	17,900	22,100	26,800	33,900	41,300	48,900
Paper		16,168	18,495	22,000	25,600	28,500	31,900	35,500	39,000
Petroleum Ref.		619	524	--	--	--	--	--	--
Primary Metals		27,903	22,130	20,600	18,400	17,000	16,200	16,200	16,200
Totals		123,925	108,111	108,500	109,000	110,800	117,300	125,500	134,100

APPENDIX B

FUTURE POPULATION AND WATER DEMAND STUDIES

The purpose of this appendix is to show the development of the future water requirements for the potential service areas. Included is the disaggregation of projected population data to the community level, development of per capita usage curves, and estimates of future industrial water needs. Utilizing this data, together with estimates of potential safe yield of each community, a study was made to determine what cities and towns might join an expanded Quabbin - Wachusett system. Demands were then forecast for the various service areas. In the main report, these demands were used to determine the deficit and how the water made available by implementation of the project would affect this deficit.

APPENDIX B

FUTURE POPULATION AND WATER DEMAND STUDIES

TABLE OF CONTENTS

Paragraph		Page
1.	Population Studies	B-1
	A. General	B-1
	B. County Disaggregation	B-1
2.	Future Water Demands	B-2
	A. General	B-2
	B. Methodology	B-3
	C. Future Water Requirements	B-7
3.	Peak Loading Criteria	B-9
	A. General	B-9
	B. Maximum Day Considerations on the Expanded Quabbin-Wachusett System	B-9

TABLES

No.	Title	Page
B-1	Historic and Projected County Populations	B-13

PLATES

No.	Title	Following Page
B-1	Future County Population Trends	B-2
B-2	Projected Gallon per Capita Increase	B-3
B-3	Quabbin - Wachusett Water Supply System -- Existing and Future Service Area	B-7

APPENDIX B

FUTURE POPULATION AND WATER DEMAND STUDIES

1. Population Studies

A. General

As described in the previous appendix, regional population and economic projections for Water Resource Planning Areas throughout the country recently have been prepared by the Office of Business Economics, U. S. Department of Commerce for the year 1980, 2000, and 2020. These projections have been prescribed for use by the Corps of Engineers in its planning.

Under contract to the North Atlantic Division for the Northeastern United States Water Supply Study, the Regional Planning Associates disaggregated these Water Resource Planning Area population projections to county level for dispersed, concentrated and most likely distribution patterns. The most likely projections are shown graphically on Plate No. B-1. These county level projections were then furnished to the New England Division by the North Atlantic Division for use in this report and it is to these totals that all sub-county projections are controlled.

The most likely projections were used in this report to estimate water requirements for planning purposes and it is to these water needs that the alternative solutions are keyed. The dispersed and concentrated projections were used to formulate a band of future needs, to illustrate the effect which future growth following these patterns would exhibit upon the various alternative schemes.

B. County Disaggregation

During the preparation of this report, it soon became evident that a more detailed breakdown than afforded by county level was required in most areas. Thus, a further disaggregation of the furnished county figures to the community level was accomplished for those areas deemed necessary.

Recognizing the large amount of work which has been accomplished by various local planning agencies, it was decided that the county disaggregation should reflect the population trends within county as indicated by the local projections, with the furnished most likely county totals acting as controls.

In general, the method used in disaggregating the county totals to community levels consisted of aggregating community projections provided by local agencies and comparing these to the controlling county totals. The community totals were then adjusted so as to reflect the county control figure. By use of this method, the continuity of population trends in the various sectors as expressed by the local group's projections was maintained.

Since most local planning agencies population projections were estimated only through the year 1990, the direct ratio method was utilized to estimate populations for 2000. Use of this community delineation for the year 2020, however, was not used because of the many uncertainties in projections of that time length over such a small area. Thus, for this study, county totals only were used at the 2020 target date. The projections used in this study, on a county level, are given in Table B-1.

2. Future Water Demands

A. General

The approach used to estimate the future water demands on the Quabbin-Wachusett-Sudbury Reservoir system consisted of determining what cities and towns would probably be required to join this system by 1990. In addition to these municipalities, an investigation was also made of communities which have as a feasible alternative connection to the supply system.

The future water demands of these two groups and the existing MDC communities were then estimated by two different methods to provide a range of probable supply needs. The first method computed the water demands from population by determining a per capita usage for domestic, commercial, and minor industrial users while the requirement for heavy water using industry was determined from projected industrial output.

The second method estimates the future water demands based on the Water Resources Council (WRC) per capita usage increase as described in its First National Assessment on the Nation's Water Resources.

B. Methodology

1) Population Based Water Demand (NEWS)

The large coverage of the study area for this report precluded a community level analysis of future per capita demands. Thus, the approach used in this report was the development of a "study area" per capita consumption curve.

The method used to develop this curve consisted of selecting a representative grouping of 26 communities in which industrial water use was not a significant factor. These communities' consumption patterns were then studied for the period 1950-1965, this period being considered as a most likely trend upon which future usage might follow (i.e. no wars or depression). The average increase experienced during this period was calculated to be some 1.3 gallons per capita per year. Using these communities' historical trends, a curve reflecting increasing per capita future demands at a decreasing rate was then drawn.

The curve thus developed was next compared to a number of independent estimates prepared by consulting engineering firms for other water supply studies in the New England area. These studies covered most of the communities: in the Eastern Massachusetts region, in the Springfield-Chicopee-Holyoke Metropolitan area, in the Hartford, Connecticut area and the entire State of Rhode Island. The NEWS curve developed for this report was found to compare quite favorably with these independent engineering estimates.

The resulting curve, shown on Plate No. B-2, thus is felt to represent the expected per capita increase which will prevail within the study area for domestic, commercial, and minor industrial demands. In utilizing the per capita consumption curve the actual per capita usage minus water supplied to major industries was determined for the base year 1965. The increased per capita demand through 1990 as defined by the curve was then added to the base year per capita

consumption. The service population was then multiplied by its respective per capita consumption value and a total water use for this component derived.

2) Industrial Water Demands (NEWS)

Information pertaining to industrial water demands both present and future within the study area was found to be quite limited on a detailed basis. It was ascertained that although various consulting engineering firms had conducted surveys for their respective clients, no wide range canvas of the study area's industrial water needs had been performed. As a result of this data gap, most of the data and estimates presented in this section was obtained and developed by the NEWS group.

The first step in development of the industrial water need estimates was the physical location of major water using industries within the study area. The four-digit industrial groupings suggested in the Cornell University Report, "Industrial Water Use Estimates, North Atlantic Region", as major water users were adopted. The location and size of these selected industrial groups were then obtained from the 1968 Massachusetts State Industrial Directory.

Once the actual location of the plants had been established, a telephone survey was conducted of those municipalities which appeared to have significant industrial concentrations and apparent high per capita consumption levels. The yield from this survey thus enabled the study to locate and quantify the industrial use from public water supply systems within the study area.

The study team next approached the problem of preparing estimates of future industrial water requirements. Two approaches were initially suggested; namely, relating future needs to employment populations and/or to production (output) projections. After study it was felt that output projections provided a more direct correlation to future water needs than did use of employment, thus the estimates prepared in this report relate future industrial water demand to industrial output.

Economic output projections prepared for the North Atlantic Regional Study currently underway by the Corps of Engineers were adopted

for use in this study. These projections estimate output for six two-digit major water using industries; namely, Standard Industrial Classification (SIC), 20 Food and Kindred Products, 22 Textile Mill Products, 26 Paper and Allied Products, and 28 Chemicals and Allied Products, 29 Petroleum and Coal Products, and 33 Primary Metal Industries. Since SIC 29 is not recorded as a major water using industry within the study area, the remaining five groupings furnished the basis for the estimates presented in this report. These 5 SIC categories constituted some 63 percent of total fresh water use in 1967 within Massachusetts and for purposes of the report were considered to represent major water using industries. Other industries future requirements were considered minor and their needs are considered included in the curve developed for the population based water demand.

Utilizing the forementioned North Atlantic Regional Study output projections, factors were derived relating projected economic activity for 1990 as a function of the recorded 1960 output values. These factors were then combined with "hard data" on water use for product value for each of the five selected SIC groups from the 1963 Census of Manufacturers, U. S. Department of Commerce, to develop estimates of future industrial usage. The estimates thus obtained corresponds to the industrial water demand which could be expected if the 1964 water use per dollar output were to continue into the future (i. e. if no technological changes were made in production or use techniques).

A disaggregation of these SIC totals to County level was then made, based on the assumption that future industry will choose to locate in the future as they have located in 1968, utilizing the data contained in the Massachusetts Industrial Directory.

Since many apparent pressures are being exerted upon industry; such as, increasing public water costs and pollution abatement programs, a move to reducing water use by these industries by economical technology seems in order. In this report, reuse data developed by Cornell University in their study Industrial Water Use Estimates, North Atlantic Region were adopted. These technological change rates were developed by Cornell by considering the changes in water reuse which occurred during the period 1954 to 1964 as

published in the Census of Manufacturers, Water Use in Manufacturing Reports. These historically recorded use rates were then assumed to continue in the future (i.e., basically an exponential curve). The use change rates thus developed were applied to the industrial water use estimates described in the preceding paragraphs. The result of this application thus represents estimates of future industrial water requirements with the effect of the estimated technological changes.

It is recognized that use of historic trends as a basis for future technological activity is open to debate. The Cornell group itself has expressed reservations on the application of these reuse rates to small geographic areas; however, there is little other available data on this subject.

Once the water use efficiency factors had been prepared the next question which arose was that of separating public from privately supplied industrial needs. For purposes of this report, it has been assumed that future industrial demands will be drawn from public and private sources in the same proportion as indicated in the 1963 Census of Water Using Manufacturers. There is little evidence to dispute this assumption one way or the other. However, it appears reasonable to assume that a privately supplied industry would implement all available economical technology to its processes before it connected to the public system. If then this was the case, the effect of privately supplied industries joining the public system is small with a maximum departure of some 20 percent from estimated county (1) total water requirements in 2020 for the worse case. Based on these calculations it appears that the assumption to continue the present privately-publicly supplied proportion into the future is a reasonable approach.

Because of the major assumption regarding technological advantages in industrial water usage which this study was obliged to make in estimating future demands, a testing of the significance of these water demand values upon total water requirements was made. These "sensitivity tests" indicate the magnitude of change in the estimates of publicly supplied water would be insignificant if the future industrial consumption values followed trends other than that presented in this report.

3) Water Resource Council Projections

The second method of forecasting future demands utilizes the information contained in "The First National Assessment of the Nation's Water Resources" which was prepared by the Water Resources Council in 1968.

In this report, Table 3-1-2 gives the population for 1960 and projects the population for the years 1980, 2000, and 2020 for the North Atlantic Region. Table 4-1-4 lists projections of municipal water requirements for the years 1965, 1980, 2000, and 2020 for the North Atlantic Region. Using these tables, the curve shown on Plate No. B-2 was developed for the GPCD use of public water supplies through 2020. The curve shows a 10.4 GPCD increase from the 1965 consumption rate to 1990. This increase was then added to the 1965 consumption rate for each sub-county sector multiplying this derived 1990 consumption rate by its associated population yields the total estimated water demands for 1990.

C. Future Water Requirements

1) Average Daily Demands

A community by community study was made to determine what cities and towns might join the expanded Quabbin-Wachusett system. Review of engineering reports as well as personal interviews with State and regional officials were made. A number of key communities were also contacted to determine their needs, problems, and possible solutions. The communities were then placed in one of four categories; those who are presently being serviced by the MDC; those communities whose only reported feasible alternative is to join the Quabbin-Wachusett system; communities who have as one of their feasible alternatives connection to the Quabbin-Wachusett system and those who either can meet their 1990 demands from local sources or appear beyond the apparent economic boundary, which can be reasonably serviced by the Quabbin-Wachusett system. The cities and towns in each group are shown on Plate No. B-3.

In estimating the potential which the municipalities might impose on the Quabbin-Wachusett system, the safe yield of each community

was taken as the 1965 reported safe yield plus the resource potential reported upon in community and regional planning studies. The estimated demand to be met from the regional system thus would be the total community demand minus the existing and reported potential community safe yield.

Instead of computing each community's 1990 water demand individually, they were grouped together along sub-county or county lines. Using a ratio of populations, the water demands of the service communities within the given sub-county sectors were determined. The individual city or town's population used were estimated by local planning agencies but adjusted to agree with the OBE projected county population as described in the preceding section on population. The demands of each group are, thus, estimates of the 1990 water demand on the Quabbin-Wachusett system for the three groups of communities which may be served by the Quabbin-Wachusett Reservoir system. As described earlier two methods were employed in preparing the estimate. The first method used both per capita increases and industrial water use while the second method only used forecast per capita increased as prepared by the Water Resources Council.

The forecast demands estimated by using the first method (NEWS) yielded a 1990 water demand of about 410 mgd for the presently serviced communities. If the municipalities reported as having no other option were served the total demand on the system could be about 441 mgd. Communities in this category include the eastern third of Norfold County and the southwestern quarter of Middlesex County.

If those municipalities who have other options desired to and were granted entrance to the system, the estimated 1990 demand would be about 519 mgd. If all these communities were served, than the Quabbin-Wachusett system would be supplying water to all or a major portion of Middlesex, Suffolk, and Norfold Counties; the southern half of Essex County; the northern third of Plymouth County; the central portion of Worcester County and the eastern half of Hampshire County.

Utilizing the second methodology (WRC), estimates based on per capita usage increases, yields a 1990 demand of 310 mgd for the

existing system; 320 mgd including those municipalities with no reported other supply options and 360 mgd if all communities listed as possible applicants were to be serviced. Use of the two methods of forecasting provides a rather large range of possible demands on the Quabbin-Wachusett system.

The demand estimates derived by use of the Water Resources Council estimates of per capita increases appear to be lower than might be expected within the study area based on historical evidence. Utilizing the Water Resources Council estimates the forecast demand for the existing MDC system in 1990 is 310 mgd. In 1971, the actual experienced demand on the system was about 322 mgd. Based on this actual observed demand on the system, it does not appear that use of the Water Resource Council estimates portray the future supply quantities which may be needed within this report study area. Therefore, demands estimated by the first method (NEWS) using both per capita increases and industrial water demand, was used to develop the future needs for the project.

3. Peak Loading Criteria

A. General

Variations in water demands due to seasonal weather changes have always been important considerations in the design of water supply systems in the northeastern United States and particularly in New England. Historically, summer drought periods have promoted exceptionally high water demands which quite often last for several weeks. In most cases these peak demands must be met by the water supply system since storage within the distribution system itself cannot usually be economically constructed to handle these peak loads.

B. Maximum Day Considerations on the Expanded Quabbin-Wachusett System

The ratio of the maximum day demand to the average daily demand is directly related to the type and character of the development within the community or communities to be served. Communities with a large amount of commercial and industrial development and/or with high population densities have considerably lower maximum

day ratios than do suburban residential communities. This can be attributed to the use of large quantities of water by the suburban communities during summer periods for the filling of swimming pools, lawn and shrub watering and similar seasonal activities.

The MDC system, as it now exists, services 32 member communities within the greater Boston area. Twenty-five of the communities depend wholly upon the system to supply their water needs while the remaining seven communities make maximum use of their own sources and only rely upon the MDC system to supply their peak demands. The 25 wholly supplied communities range from completely residential in character to those with industrial and commercial development. During the recent drought of the 60's, the ratio of the maximum day demand to the average daily demand for the city of Boston reached a high of 1.24, while the ratio for the total 25 communities reached 1.65. This difference has been attributed to the effect of the suburban communities peak demands upon the system. If the regional system continues to expand its service area to meet the future demands of the Metropolitan Boston area, it will be adding suburban communities which are largely residential in nature. Thus, the maximum daily demand ratio can be expected to increase above the present high figure of 1.65. The amount of increase will, of course, depend on what portion of the total water demand upon the system the new members demand represents.

A total of 12 communities which may join the MDC system by the year 1990 and for which peak loading information was available were analyzed. The communities consist of:

Avon	Natick
Braintree	Randolph-Holbrook
Dedham	Stoughton
Lincoln	Weymouth
Medfield	Wellesley
	Woburn

The peak maximum day ratio for the 25 wholly served MDC members was, as previously stated, 1.65. The peak ratio for the total 32 member communities was synthetized by pro-rating the peak maximum day ratio of the 7 partially served communities based on the ratio

of their estimated 1990 average daily demand on the MDC system to the estimated 1990 average daily demand of the wholly supplied communities. This computation yielded a peak maximum day ratio for all member communities of 1.67. Using this as a base figure and the assumption that the peak maximum day demands of the individual comminities would not increase significantly by 1990, the peak maximum day ratio for the member communities and the 12 communities listed above was synthesized, as before, and resulted in a peak ratio of 1.70. Since maximum day information was available on nine other eastern Massachusetts communities who probably will not join the MDC system but who have the same characteristics as the remaining 13 communities who have no other option but to join the MDC system; these nine communities were pro-rated in the same manner as before to the existing and twelve possible MDC members resulting in a ratio of 1.71. Therefore, for purposes of this study, a maximum day ratio of 1.70 was adopted as the maximum day loading criteria.

A comparison of this figure to other available historic and projected maximum day data for large systems in the Northeastern United States was also conducted. A review of this comparison is given in the following paragraphs:

1. Metcalf and Eddy-Hazen and Sawyer in the feasibility report on Alternative Regional Water Supply Plans for Northern New Jersey-New York City - Western Connecticut Metropolitan Area for the NEWS Study suggested a maximum day to average day ratio of 1.5 for New York City and major municipalities in New Jersey and 2.0 for suburban communities.

2. Metcalf and Eddy-Hazen and Sawyer in the Comprehensive Public Water Supply Study for the city of New York and County of Winchester indicate that the peak maximum day demand from 1955 to 1965 was 1.42 and that for 12 of the 22 supply systems in Westchester County the maximum day ratio varied from 1.37 to 2.72 and the weighted average of maximum day of these communities was 1.68.

3. Hazen and Sawyer in a report to the Regional Planning Council, Baltimore, Maryland on a plan of Regional Water Supply to the year 2020 indicated that the maximum day ratio varied from

1.25 to 1.41 in Baltimore from 1961 to 1967 and estimated an increase to 1.68 by the year 2020.

4. In an article in Water and Wastes Engineering by D. M. Watt and Norman. E. Jackson (June 1970) entitled "Washington's Water Supply" the ratio of the Maximum day to the average day for the District of Columbia was estimated to be 1.82 by the year 2010.

5. A cooperative State-Federal Report on Municipal facilities communities of 25,000 population and over, United States and Possessions as of January 1, 1964 shows maximum day to average day ratios for eight major systems in the northeast varying from 1.19 to 1.64.

TABLE B-1

HISTORIC AND PROJECTED COUNTY POPULATIONS

COUNTY		1960[1]	1970[1]	1980	1990[2]	2000	2010[2]	2000
	Concentrated			590.4	666.4	742.4	854.6	966.9
Essex	Most Likely	568.8	631.0	660.7	725.2	790.0	895.0	1,000.0
	Dispersed			707.6	805.0	902.4	1,045.5	1,188.6
	Concentrated			1,185.3	1,344.2	1,503.2	1,731.0	1,958.8
Middlesex	Most Likely	1,238.1	1,388.1	1,379.2	1,564.6	1,750.0	1,883.0	2,016.0
	Dispersed			1,530.4	1,747.5	1,964.6	2,276.7	2,588.8
	Concentrated			815.4	832.4	849.3	874.6	900.0
Suffolk	Most Likely	791.3	721.2	748.7	739.4	730.0	720.0	710.0
	Dispersed			684.9	657.2	619.4	575.4	531.3
	Concentrated			885.3	999.2	1,113.2	1,281.5	1,449.8
Norfolk	Most Likely	510.2	605.4	728.7	810.2	911.7	1,205.8	1,500.0
	Dispersed			634.6	717.0	809.3	937.6	1,066.0
	Concentrated			531.4	599.8	668.2	774.2	870.3
Plymouth	Most Likely	248.4	328.9	437.2	543.5	650.0	775.0	900.0
	Dispersed			309.0	351.5	394.0	456.5	519.0

(1) Federal Census (2) Interpolated Value

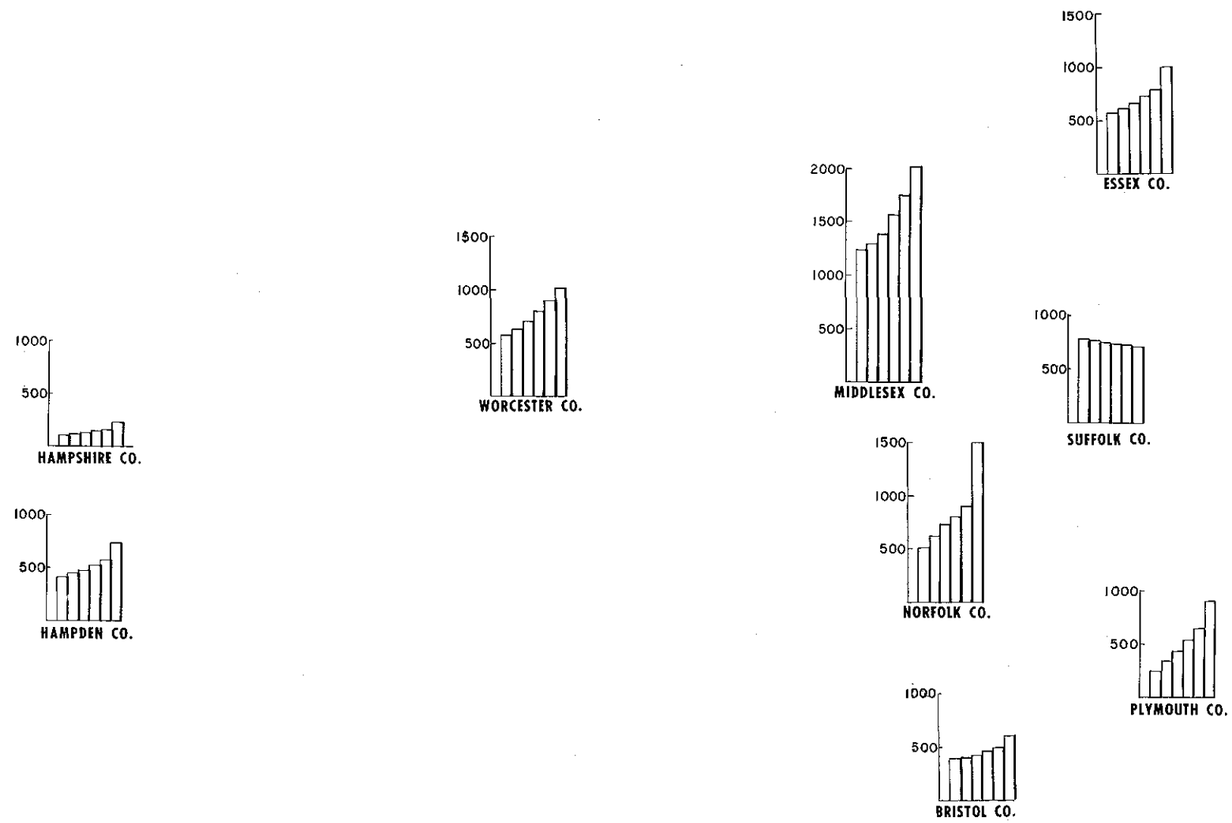
TABLE B-1 (cont'd)

HISTORIC AND PROJECTED COUNTY POPULATIONS

COUNTY		1960(1)	1970(1)	1980	1990(2)	2000	2010(2)	2000
	Concentrated			354.2	399.8	445.4	512.8	580.2
Bristol	Most Likely	398.5	441.1	417.6	543.8	490.0	545.0	600.0
	Dispersed			495.5	563.8	632.0	732.4	832.4
	Concentrated			700.0	800.0	900.0	959.2	1,018.5
Worcester	Most Likely	583.2	633.8	700.0	800.0	900.0	959.2	1,018.5
	Dispersed			700.0	800.0	900.0	959.2	1,018.5
	Concentrated			52.6	56.6	60.6	67.0	73.3
Franklin	Most Likely	54.8	58.9	60.0	62.5	65.0	72.5	80.0
	Dispersed			65.4	71.0	76.6	88.2	99.8
	Concentrated			151.3	162.8	174.3	192.6	210.9
Hampshire	Most Likely	103.2	122.6	125.0	140.0	155.0	192.5	230.0
	Dispersed			122.9	133.5	144.1	165.9	187.7
	Concentrated			493.6	545.9	598.2	690.1	782.0
Hampden	Most Likely	425.3	453.5	480.0	530.0	580.0	640.0	740.0
	Dispersed			468.4	515.1	561.8	630.4	699.1
	Concentrated			5,759.5	6,407.1	7,054.8	7,937.6	8,810.7
Totals	Most Likely	4,921.8	5,384.5	5,737.1	6,459.2	7,021.7	7,888.0	8,794.5
	Dispersed			5,718.7	6,361.6	7,004.2	7,867.8	8,731.0

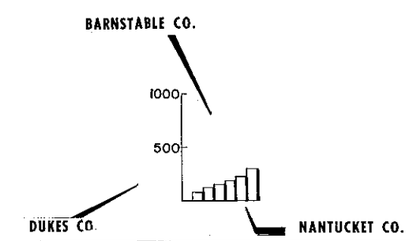
(1) Federal Census (2) Interpolated Value

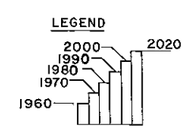
CORPS OF ENGINEERS U. S. ARMY



NOTE:

FRANKLIN COUNTY LESS THAN 100,000 PEOPLE THROUGH 2020

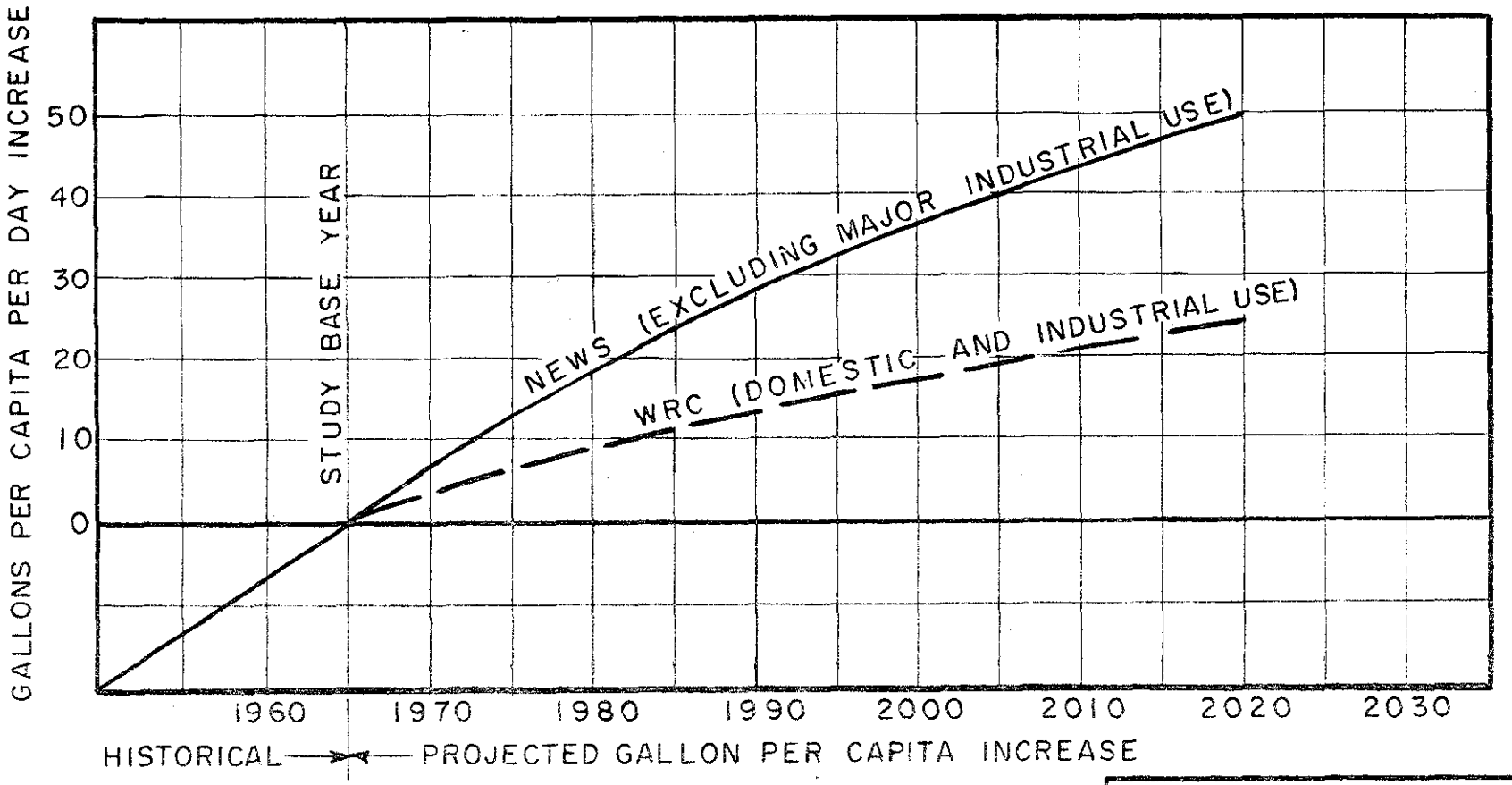




NORTHEASTERN UNITED STATES
WATER SUPPLY STUDY

FUTURE COUNTY POPULATION TRENDS

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION
CORPS OF ENGINEERS
WALTHAM, MASS.

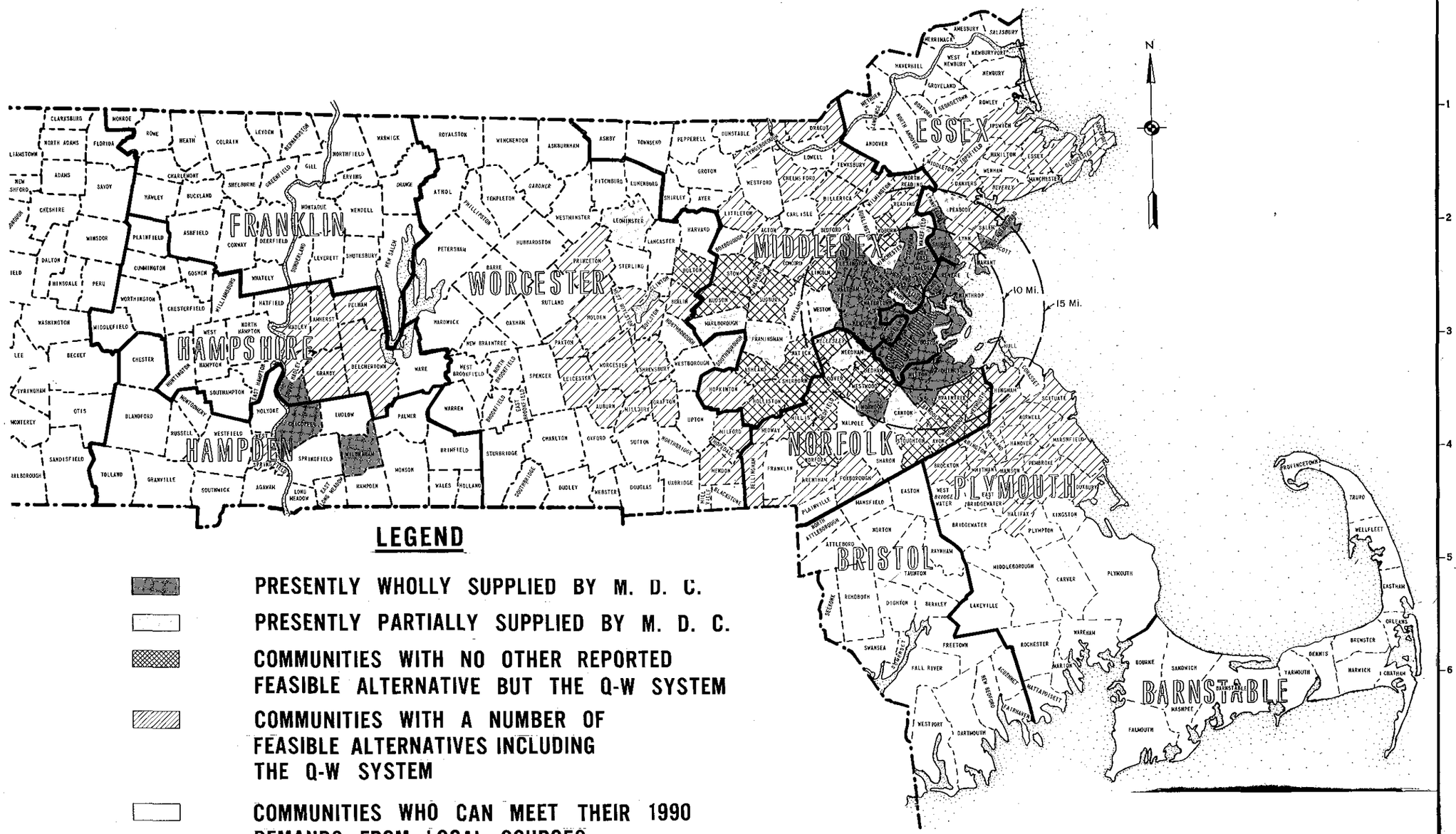


NORTHEASTERN UNITED STATES
WATER SUPPLY STUDY
MILLERS RIVER BASIN

PROJECTED GALLON PER CAPITA INCREASE

PLATE B-2

CORPS OF ENGINEERS U. S. ARMY



LEGEND

- PRESENTLY WHOLLY SUPPLIED BY M. D. C.
- PRESENTLY PARTIALLY SUPPLIED BY M. D. C.
- COMMUNITIES WITH NO OTHER REPORTED FEASIBLE ALTERNATIVE BUT THE Q-W SYSTEM
- COMMUNITIES WITH A NUMBER OF FEASIBLE ALTERNATIVES INCLUDING THE Q-W SYSTEM
- COMMUNITIES WHO CAN MEET THEIR 1990 DEMANDS FROM LOCAL SOURCES OR OTHER REGIONAL SYSTEMS
- EXISTING Q-W SERVICE AREA
- PROBABLE 1990 Q-W SERVICE AREA
- POSSIBLE 1990 Q-W SERVICE AREA

NORTHEASTERN UNITED STATES
WATER SUPPLY STUDY
QUABBIN – WACHUSETT
WATER SUPPLY SYSTEM
EXISTING AND FUTURE SERVICE AREA

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION
CORP OF ENGINEERS
WALTHAM, MASS.

PLATE B-3

APPENDIX C

TUNNEL GEOLOGY AND COST ESTIMATES

This appendix develops the rationale used to determine the major cost of the project -- the tunnel from Northfield Mountain Pumped Storage Project to Quabbin Reservoir. A computerized program was prepared which estimated tunnel construction costs. Input to the program included assumed geologic conditions with recent labor, equipment, and material rates. Geologic information was obtained from previous work in the area, together with geologic investigations performed by Northeast Utilities at the Northfield site and the Metropolitan District Commission along the proposed tunnel route.

These estimated tunnel construction costs were then added to the intake and outlet works costs and the pumped storage project costs allocated to the water supply function, resulting in the total project cost shown in the main report.

APPENDIX C

TUNNEL GEOLOGY AND COST ESTIMATES

TABLE OF CONTENTS

Paragraph		Page
1.	Introduction	C-1
2.	Available Geologic Data	C-1
3.	Proposed Scheme	C-2
4.	Cost Estimate	C-4
5.	Conclusions and Recommendations	C-5

TABLES

No.	Title	Page
C-1	Rock Formation and Engineering Properties	C-6
C-2	Rock Formation and Engineering Properties	C-7
C-3	Cost Index	C-8
C-4	Tunnel Cost and Construction Time	C-9
C-5	Computer Cost Run for Proposed Alinement	C-10

PLATES

No.	Title	Following Page
C-1	Northfield Mountain Water Supply Project	C-29

APPENDIX C

TUNNEL GEOLOGY AND COST ESTIMATES

1. Introduction

The purpose of this study is to estimate the cost of constructing a proposed tunnel from the upper reservoir of the Northfield Mountain pumped storage project to Rattlesnake Hill on the east branch of the Quabbin Reservoir. Alinement, depth, and diameter are those selected by the Metropolitan District Commission (MDC) for their proposed Water Supply System.

Estimates of construction costs were prepared utilizing a computerized tunnelling program[1] which costed both the machine tunnelling method (MOLE) and the conventional drill and blast method. All costs were based on the input of the assumed geologic conditions which controlled the design functions, with labor, equipment and material rates being costed on the basis of ENR quarterly reports including a 5 percent profit and a 25 percent overhead margin. No allowance has been made in the computer program for cost of headworks other than the discharge structure at Quabbin Reservoir. Shaft locations are those selected by the MDC and are shown on Plate No. C-1.

2. Available Geologic Data.

Geologic information pertinent to the project was obtained from a literature survey correlated with available data from the design of the Northeast Utilities pumped power project and preliminary geologic investigations conducted by MDC along the proposed route. No exploratory data was available; however, strength tests conducted on rock cores for the Northfield Mountain Project were utilized. (See Table C-1). Indicated rock structure and conditions are those

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(1) A computer program for estimating costs of hard rock tunnelling (COHART) prepared by Harza Engineering Co., 400 West Madison Street, Chicago, Illinios - May 1970 for the Office of High Speed Ground Transportation, Urban Mass Transportation Administration, Department of Transportation, Washington, D. C. 20591, (Modified by NED).

depicted on a Preliminary Geologic Structure Section along the proposed Northfield-Quabbin Tunnel dated March 7, 1972 prepared by MDC (not included). Rock formations crossed by the tunnel alinement are comprised of approximately 85 percent hard, gneissic varieties and 15 percent softer schistose types. Inflow estimates and conditions of the rock structure (RQD) were estimated from known properties of similar rock formations on other projects. The rock formations and their assumed engineering properties are shown on Tables C-1 and C-2. Critical geologic structures such as fault lines and buried valleys whose conditions and limits are unknown and assumed to be moderately severe and have been costed accordingly.

3. Proposed Scheme.

The proposed alinement shown on Plate No. C-1 represents the scheme shown on an April 1972 Plan by the MDC Construction Division entitled, "Quabbin Water Diversion Facilities - Plan of Borings", File Cont. C-390 G 3.36 P.M. All stationing is based on a NED profile used for the computer program.

Four shaft locations selected by MDC were located and are described as follows:

Shaft 1. Located at the upper reservoir of the Northfield Power Project. Coordinates N 587,465.785 and E 347,405.915 at Station 15+00. This shaft is costed as an 18-foot, 8-inch finished diameter shaft having a 12-inch minimum thickness concrete lining with an invert elevation of 300 and a top elevation of 950 m.s.l. Two excavation schemes were estimated using a conventional and mole system with the excavated material being removed through Shaft 2.

Shaft 2. Located adjacent to the easterly banks of the Millers River at approximately Station 45+00. Tunnel invert elevation is at 300 m.s.l. with a ground surface elevation of 440 m.s.l. Shaft 2 is designed as a 14-foot finished diameter with a 12 inch thick lining in accordance with MDC criteria. Shaft 2 will service the tunnel west to Shaft 1 (Station 15+00) and east to Shaft 3 (Station 200+00). Disposal of all material is considered to be within

a radius of two miles of the shaft requiring a disposal area of approximately two acres 30 feet deep.

Shaft 3. Located adjacent to Depot Road at Station 200+00, this shaft is 520 feet deep with a tunnel invert at elevation of 440 m.s.l. Shaft diameter is 14 feet, finished diameter, with a 12-inch thick lining. Shaft 3 will service the tunnel easterly to Shaft 4 (Station 385+00) and all material removed from Shaft 3 will be disposed of within two miles of the shaft in a two acre area approximately 30 feet deep.

Shaft 4. Located east of the Swift River and south of Morse Village, the shaft has a depth of 370 feet with an invert at elevation 440 m.s.l. This shaft has a 14-foot finished diameter with a 12-inch thick concrete lining. Shaft 4 will service the tunnel section between Stations 385+00 and 530+00. Disposal of material in this section is costed for a one acre area, 30 feet deep within two miles of Shaft 4.

Shaft 5. Located at Rattlesnake Hill on the East Branch of the Quabbin Reservoir the shaft is 90 feet deep with an invert elevation of 440 feet m.s.l. A horizontal cut section at elevation 530 serves as a discharge apron and varies from a 14-foot width at the tunnel shaft to a 30-foot wide discharge apron 150 feet distance at the edge of the reservoir. It is considered that excavation at Shaft 5 will be disposed of within a 1 mile radius of the shaft.

In view of the lack of specific subsurface data, Shafts 1 through 4 are considered as being driven wet and requiring full ring steel supports for the first 100-foot depth. The remaining portion of the shaft would be supported by rock bolts with a temporary wire mesh. In all cases, the required support in the first 100-foot depth is assumed to require full support equal to a tunnel in the same conditions. Below 100 feet the loading is assumed as 1/2 the stresses sustained by a tunnel in the same formation. Costing of shafts assumes that for safety reasons all supports will be installed as the excavation progresses and material costs will include preformed steel ribs with blocking and lagging in the upper 100 feet and 1-inch diameter rock bolts with wire mesh and grouting in lower section of the shaft. All costs of pumping and air conditioning in shaft construction are considered negligible.

The tunnel section, as designed by MDC, is costed as a 10-foot finished diameter tunnel with an 8-inch thick concrete lining operating at a head of approximately 475 feet with an overall length of 51,700 feet. All haulage will be done by train with a maximum slope occurring between Shaft 2 and 3 of .009 percent. Two potential fault zones and one crushed zone on the proposed alinement are costed as being done by conventional tunnelling methods with water inflows of up to 500 g.p.m. These severe assumptions require that the mole method be modified for 1000 feet at each of these areas at an additional cost of reset up to 25 percent of the initial mole setup.

4. Cost Estimate.

A computerized estimate of construction cost for mole and conventional excavation was based on the proposed design and assumed geologic conditions along the alinement shown on Plate No. C-1. Costs were based on a 5 percent profit margin and a 25 percent overhead margin with a regional cost factor of 1.2 A 1.2 factor is considered applicable for areas with a labor market having reasonable union controls and not particularly suited to underground construction or mining. Cost indices for labor, equipment, and materials are based on Engineering News Record (ENR) values for the month of April 1972 and July 1973, as shown on Table 3. All costs for ventilating and air conditioning were based on mean underground temperature of 55° F at the heading and the warmest eight hour daylight temperature at the ground surface of 75° based on records at Turners Falls, Massachusetts.

All structural design in the tunnel and shafts was based on the assumed geologic conditions and the proposed design by MDC. No costs are assumed for headworks or C.I. helical vanes at Shaft 1 or special structures or plugs in Shaft 2 for water supply operation. Noticeable increases will occur in segments 16, 17, 21, 22, 24, and 25 where the tunnel intersects assumed faults and crushed zones in the rock. Fault zones are carried as a warning on Table 6 due to the assumed crushed conditions of the rock.

Disposal costs were computed on an area basis at a circumferential distance from the most appropriate shaft. Cost of land for disposal represents a real estate estimate of the approximate values of land for the section involved. Muck disposal configuration has been

programmed to minimize construction activities within the reservoir areas. This has been done to reduce work traffic in the area of the headworks construction and to minimize contamination of the existing reservoirs.

A summary of construction costs and time for conventional and mole construction is shown on Table C-4. A separate study was made on the mole method to substitute a 3-inch shotcrete lining for the 8-inch formed concrete. Included in this study was the use of a mole excavation at Shaft No. 1. Total savings is shown on Table C-4 with approximately $206,000 of this cost being attributed to use of an automatic tunnelling machine in Shaft 1. Detailed input and cost computations for mole excavations on the proposed alinement are shown on Table C-5.

5. Conclusions and Recommendations.

a. These preliminary studies indicate that further consideration of shaft location and use of double headings could possibly reduce both construction time and cost.

b. Further geologic studies may develop alternate alinements wich could reduce the amount of construction in high cost zones.

c. Maximum importance should be placed on developing hydraulic criteria to establishing tunnel diameter. An 8-inch reduction in tunnel diameter can affect savings of up to one million dollars.

d. Further refinement of cost require geologic studies and laboratory testing to obtain a better evaluation of the rock formations and their strength parameters.

TABLE C-1

Rock Formation and Engineering Properties

Rock Formation Symbol	Formation Name	U.C. Strength (psi) Depth 0-100'	U.C. Strength (psi) Depth 100'+	R.Q.D. Depth 0-100'	R.Q.D. Depth 100'+	Inflow GPM Depth 0-100'	Inflow GPM Depth 100'+	Remarks
dh	Dry Hill Granite Gneiss	10,000	*20,000	40	90	60	30	Medium-grained pink to light gray well foliated gneiss.
pm	Popular Mountain Gneiss	10,000	20,000	40	90	60	30	Dark gray well foliated micaceous gneiss contains lenses of actinolitic quartzite and amphibolite.
fg	Four Mile Gneiss	10,000	20,000	40	90	60	30	
cmm	Crag Mountain Formation	6,000	8,000	40	90	80	60	Greenish gray, thick bedded, micaceous graywacke or quartz schist. Locally includes thin lenses of quartzite.
F	Fitch Formation	8,000	16,000	40	90	70	40	Fine grained, greenish gray, well foliated amphibolite, locally with interbeds and lenses of light green epidote.
Cf	Clough Formation	10,000	20,000	40	85	100	60	Quartzite, quartz-pebble and quartz-cobble conglomerate and minor mica schist and calc silicate rock.
D_{11} (2)	Littleton Formation (Erving Member)	6,000	10,000	40	90	80	60	Hornblende - epidote - amphibolite and interbedded quartz-plagioclase biotite granulite, mica schist and minor calc silicate rock.
K	Kempfield Anticline	8,000	16,000	40	80	60	30	Gneisses of the Kempfield Anticline fairly massive.

*Based on test data from Northfield Power Project

TABLE C-2

Rock Formation and Engineering Properties

Rock Formation Symbol	Formation Name	U.C. Strength (psi) Depth		R.Q.D. Depth		Inflow GPM Depth		Remarks
		0-100'	100'	0-100'	100	0-100'	100+	
$D_{11(1)}$	Littleton Formation (Lower Member)	6,000	8,000	40	90	80	60	Gray graphitic mica schist and minor quartzite.
O_a	Ammonoosuc Volcanics	8,000	16,000	40	80	60	30	Fine grained feldspar gneiss and amphibolite. Amphibolite with anthrophyllite with Kyanite or sillimanite are common.
O_p	Partridge Formation	4,000	8,000	40	90	100	50	Rusty - weathering sulfidic mica schist and gneiss with minor layers of amphibolite and fine grained feldspar gneiss.
G	Monson Gneiss Foliated	8,000	16,000	40	80	60	30	Gneissic microcline granite varying to a light gray to white granodiorite gneiss, mixed with amphibolite and metavolcanic rocks.
G_m	Monson Gneiss Massive	10,000	20,000	40	90	60	30	
Fault Line Noted	Fault		2,000		20	-	500	Broken, fractured and crushed zone requiring tunnel supports.
Crushed Zone Noted	Fractured Zone		4,000		40	-	500	Broken

TABLE C-3

COST INDEX

LABOR	CHICAGO - JULY 1969		BOSTON - APRIL 1972		BOSTON - JULY 1973
Common Labor					
Heavy Construction	$4.75 + 0.47		$ 6.35		$ 6.90
Skilled Labor					
Struc. Iron Workers	6.85 + 0.795		9.21		9.82
Equipment Operators					
Hoisting Engrs	5.50 + 0.50		8.98		9.78
Tractor Operators	5.60 + 0.50		8.76		9.66
Air Comp. Operators	5.10 + 0.50		7.55		8.29
Truck Drivers					
Over 4 c.y.	4.75 + 0.40		5.66		5.71
	$ 35.72		$ 46.51		$ 50.16
		Index 1.30		Index 1.42	
EQUIPMENT					
Equipment ENR (Base 1957-59 = 100)	$134.80		$150.00		$152.08
		Index 1.102		Index 1.128	
MATERIAL					
6 bbl bulk P.C.	$ 26.22		$ 29.58		$ 32.70
1 M/bm Lumber 2 x 4 fir	160.00		195.00		245.00
25 CWT Structural Steel Shapes, base mill price	163.75		202.50		212.50
	$350.00		$427.08		$490.20
		Index 1.22		Index 1.40	

TABLE C-4

TUNNEL COST and CONSTRUCTION TIME (April 1972)

Alinement	Alinement No.	Finished Tunnel Diameter	Length Ft.	Excavation Method	Cost ($1000)				Construction Time (Days)*		Disposal Areas	
					Labor	Equip	Mat'ls	Total	Max	Min	Acres 30' Deep	Shaft Nos.
UPPER RES Northfield Mt to Quabbin Res	16	10'	51,700	CONV	17,630	4,955	3,800	26,385	1,695	584	5	2, 3 & 4
	16	10'	51,700	MOLE	17,775	4,385	4,025	26,185	1,777	600	5	2, 3 & 4
	16**	10'	51,700	MOLE	19,359	4,565	4,685	28,609	1,777	600	5	2, 3 & 4
	16	10'	51,700	MOLE w/shotcrete Lining	15,189	3,547	2,956	21,692	1,559	516	4	2, 3 & 4

*Construction Time variable depends on number of shafts which are worked simultaneously

** Costs based on July 1973 price index.

TABLE C-5

COMPUTER COST RUN FOR PROPOSED ALINEMENT

```
*****************************************************************************************
*                                                                                       *
*                    NORTHFIELD MT. TO RATTLESNAKE HILL                                 *
*                          ALINEMENT NO.16 MDC                                          *
*                           MOLE EXCAVATION                                             *
*                                                                                       *
*****************************************************************************************
```

```
*******************************
* PROFIT MARGIN .......   5.00 *
* OVERHEAD MARGIN .....  25.00 *
*******************************
```

```
**** WARNING ****   RQD IN SEGMENT   16 IN REACH   4 IS IN THE RANGE OF ZERO TO 25   ******************************
**** WARNING ****   RQD IN SEGMENT   17 IN REACH   4 IS IN THE RANGE OF ZERO TO 25   ******************************
**** WARNING ****   RQD IN SEGMENT   21 IN REACH   4 IS IN THE RANGE OF ZERO TO 25   ******************************
**** WARNING ****   RQD IN SEGMENT   22 IN REACH   4 IS IN THE RANGE OF ZERO TO 25   ******************************
```

NODAL POINT	ELEVATION
1	950
2	850
3	300
4	440
5	340
6	300
7	310
8	960
9	860
10	610
11	440
12	440
13	440
14	440
15	440
16	440
17	440
18	440
19	440
20	440
21	440
22	810
23	710
24	440
25	440
26	440
27	440
28	440
29	440
30	440
31	440
32	440
33	440
34	440
35	440
36	680
37	530
38	440

TUNNEL INPUT DATA

REACH	SEG	NP BOUNDRY LEFT	NP BOUNDRY RIGHT	EXIT SHAFT	HORIZ LENGTH	TUNNEL SHAPE	TUNNEL SIZE (FT)	MUCK REMOVAL METHOD	EXCAVATION METHOD	ADVANCE RATE (FT/DAY)	**ROCK PROPERTIES** STRENGTH (PSI)	RQD	TEMP (F)	INFLOW (GPM)	**LINING** TYPE	THICK. (IN)
1	1	3	6	2	3000	CIRCLE	10.00	TRAIN	MOLE	43.0	20000	90	55	30	CONC	
2	2	6	7	2	1250	CIRCLE	10.00	TRAIN	MOLE	43.0	20000	90	55	30	CONC	
	3	7	11		4250				MOLE	43.0	20000	90	55	30	CONC	
3	4	11	12	3	450	CIRCLE	10.00	TRAIN	MOLE	43.0	20000	90	55	30	CONC	
	5	12	13		3150				MOLE	43.0	20000	90	55	30	CONC	
	6	13	14		500				MOLE	83.0	10000	90	55	60	CONC	
	7	14	15		700				MOLE	102.0	8000	90	55	60	CONC	
	8	15	16		7100				MOLE	54.0	16000	80	55	30	CONC	
	9	16	17		300				MOLE	42.0	20000	85	55	60	CONC	
	10	17	18		3350				MOLE	102.0	8000	90	55	60	CONC	
	11	18	19		250				MOLE	54.0	16000	90	55	40	CONC	
	12	19	20		300				MOLE	42.0	20000	85	55	60	CONC	
	13	20	21		1800				MOLE	102.0	8000	90	55	50	CONC	
	14	21	24		650				MOLE	51.0	16000	80	55	30	CONC	
4	15	24	25	4	400	CIRCLE	10.00	TRAIN	MOLE	51.0	16000	80	55	30	CONC	
	16	25	26		500				CONVNT	16.0	2000	20	55	500	CONC	
	17	26	27		500				CONVNT	16.0	2000	20	55	500	CONC	
	18	27	28		500				MOLE	102.0	8000	90	55	50	CONC	
	19	28	29		1650				MOLE	51.0	16000	80	55	30	CONC	
	20	29	30		4550				MOLE	51.0	16000	80	55	30	CONC	
	21	30	31		500				CONVNT	16.0	2000	20	55	500	CONC	
	22	31	32		500				CONVNT	16.0	2000	20	55	500	CONC	
	23	32	33		2700				MOLE	55.0	16000	80	55	30	CONC	
	24	33	34		500				CONVNT	55.0	4000	40	55	500	CONC	
	25	34	35		500				CONVNT	55.0	4000	40	55	500	CONC	
	26	35	38		1850				MOLE	55.0	20000	90	55	30	CONC	

********** SHAFT INPUT DATA **********

SHAFT NUM	SEG NUM	FINISHED DIAMETER (FT)	NODAL POINT BOUNDRY UPPER	NODAL POINT BOUNDRY LOWER	ROCK STRENGTH (PSI)	R.Q.D.	EXCAVATION METHOD	ADVANCE RATE	INFLOW	**LINING*** TYPE	**LINING*** THICK (IN)	DISPOSAL DISTANCE (MILES)	DISPOSAL COST ($/ACRE)	ABOVE GRND. TEMP.
1	2	18.70	1	2	10000	40	CONVNT	3.5	WET	CONC	12.00	1.00	150	80
	3		2	3	20000	90	CONVNT	9.0	DRY	CONC	12.00			
2	4	14.00	4	5	10000	40	CONVNT	3.5	WET	CONC	12.00	2.00	150	75
	5		5	6	20000	90	CONVNT	9.5	DRY	CONC	12.00			
3	6	14.00	8	9	10000	40	CONVNT	3.5	WET	CONC	12.00	2.00	150	75
	7		9	10	20000	90	CONVNT	9.1	DRY	CONC	12.00			
	8		10	11	20000	90	CONVNT	9.1	DRY	CONC	12.00			
4	9	14.00	22	23	8000	40	CONVNT	3.5	WET	CONC	12.00	2.00	150	75
	10		23	24	16000	80	CONVNT	8.7	DRY	CONC	12.00			
5	11	14.00	36	37	10000	40	CONVNT	3.5	WET	CONC	12.00	1.00	150	80
	12		37	38	20000	90	CONVNT	9.1	DRY	CONC	12.00			

********** CALCULATED TUNNEL DATA **********

REACH	SEG	STATION AT LEFT OF SEG	SLOPE LENGTH (FT)	MUCK HAUL DIST (FT)	MUCK HAUL SLOPE	**TUNNEL DIMENSIONS* FINISH (FT)	EXCAV (FT)	EXCAV WITH O.B.	ADVANCE RATE (FT/DAY)	LINING THICKNESS (IN)	EXCAV VOLUME (CY/FT)	PUMP FLOW RATE (GPM)	PUMPING HEIGHT (FT)	CONSTRUCTION TIME (DAYS) REACH	SEG	ROL-MAX (CY/HR)
1	1	0+00	3000	1500	0.000	10.00	11.33	11.33	43.0	8.00	3	74	140	0	89	20
2	2	30+00	1250	625	.008	10.00	11.33	11.33	43.0	8.00	3	48	140	463	37	20
	3	42+50	14250	8375	.009		11.33	11.33	43.0	8.00	3	281	140		426	
3	4	185-00	450	225	0.000	10.00	11.33	11.33	43.0	8.00	3	36	520	430	13	47
	5	189-50	3150	2025	0.000		11.33	11.33	43.0	8.00	3	90	520		94	
	6	221-00	500	3850	0.000		11.33	11.33	83.0	8.00	3	182	520		9	
	7	226-00	700	4450	0.000		11.33	11.33	102.0	8.00	3	218	520		11	
	8	233-00	7100	8350	0.000		11.33	11.33	54.0	8.00	3	316	520		178	
	9	304-00	300	12050	0.000		11.33	11.33	42.0	8.00	3	461	520		9	
	10	307-00	3350	13875	0.000		11.33	11.33	102.0	8.00	3	571	520		55	
	11	340-50	250	15675	0.000		11.33	11.33	54.0	8.00	3	656	520		6	
	12	343-00	300	15950	0.000		11.33	11.33	42.0	8.00	3	690	520		9	
	13	346-00	1800	17000	0.000		11.33	11.33	102.0	8.00	3	734	520		29	
	14	364-00	650	18225	0.000		11.33	11.33	51.0	8.00	3	769	520		17	
4	15	370-50	400	200	0.000	10.00	11.33	11.33	51.0	8.00	3	35	370	452	20	47
	16	374-50	500	650	0.000		11.33	13.06	16.0	8.00	4	136	370		34	
	17	379-50	500	1150	0.000		11.33	13.06	16.0	8.00	4	186	370		34	
	18	384-50	500	1650	0.000		11.33	11.33	102.0	8.00	3	174	370		8	
	19	389-50	1650	2725	0.000		11.33	11.33	51.0	8.00	3	191	370		43	
	20	406-00	4550	5825	0.000		11.33	11.33	51.0	8.00	3	284	370		119	
	21	451-50	500	8350	0.000		11.33	13.06	16.0	8.00	4	447	370		34	
	22	456-50	500	8850	0.000		11.33	13.06	16.0	8.00	4	497	370		34	
	23	461-50	2700	10450	0.000		11.33	11.33	55.0	8.00	3	493	370		67	
	24	488-50	500	12050	0.000		11.33	12.68	55.0	8.00	4	628	370		12	
	25	493-50	500	12550	0.000		11.33	12.68	55.0	8.00	4	678	370		12	
	26	498-50	1850	13725	0.000		11.33	11.33	55.0	8.00	3	661	370		45	

********** CALCULATED SHAFT DATA **********

SHAFT	SEG	STATION ALONG TUNNEL ALINE.	ELEVATION AT BOTTOM OF SEG	LENGTH (FT)	HOIST HEIGHT (FT)	*SHAFT DIMENSIONS* FINISH (FT)	EXCAV (FT)	EXCAV WITH O.B.	ADVANCE RATE (FT/DAY)	LINING THICKNESS (IN)	EXCAVATED VOLUME (CY/FT)	SIZE OF DISPOSAL AREA (ACRES)	CONSTRUCTION TIME (DAYS) SHAFT	SEGMENT	REL-MAX (CY/HR)
1	2	0-00	850	100	50	18.70	20.70	23.16	3.5	12.00	15	0	102	30	12
	3		300	550	375		20.70	21.43	9.0	12.00	13			72	
2	4	30-00	340	100	50	14.00	16.00	17.90	3.5	12.00	9	2	35	30	7
	5		300	40	120		16.00	16.57	9.5	12.00	7			5	
3	6	185-00	860	100	50	14.00	16.00	17.90	3.5	12.00	9	2	84	30	7
	7		610	250	225		16.00	16.57	9.1	12.00	7			32	
	8		440	170	435		16.00	16.57	9.1	12.00	7			22	
4	9	370-50	710	100	50	14.00	16.00	17.90	3.5	12.00	9	1	66	30	7
	10		440	270	235		16.00	16.83	8.7	12.00	8			36	
5	11	517-00	530	150	75	14.00	16.00	17.90	3.5	12.00	9	0	56	45	7
	12		440	90	195		16.00	16.57	9.1	12.00	7			11	

********** TUNNEL COSTS **********

REACH NO	SEG NO	COST IN DOLLARS PER FOOT OF TUNNEL: EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($X000)
1	1 L	92	67	0	30	76	16	2	32	30	0	6	1	352		1056
	E	15	6	0	9	10	8	2	7	10	0	0	1	68		204
	M	2	31	0	0	0	1	3	21	3	0	0	7	68		204
	T	109	104	0	39	86	25	7	60	43	0	6	9	488	3000	1464

REGIONAL COST FACTOR 1.20

COST INDEX

- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

TOTAL REACH LABOR COST..... 1056
TOTAL REACH EQUIPMENT COST..... 204
TOTAL REACH MATERIALS COST..... 204
TOTAL REACH COST..... 1464

********** TUNNEL COSTS **********

REACH NO	SEG NO		EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
2	2	L	18	66	0	26	48	16	2	30	30	0	6	0	242		302
		E	3	6	0	8	10	8	2	7	10	0	0	1	55		68
		M	0	31	0	0	0	1	3	21	3	0	0	7	66		82
		T	21	103	0	34	58	25	7	58	43	0	6	8	363	1250	452
2	3	L	18	70	0	60	48	16	2	41	31	0	6	6	298		4246
		E	3	6	0	12	10	8	2	7	10	0	0	1	59		840
		M	0	31	0	0	0	1	3	21	3	0	0	7	66		940
		T	21	107	0	72	58	25	7	69	44	0	6	14	423	14250	6026

REGIONAL COST FACTOR 1.20

COST INDEX
- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

TOTAL REACH LABOR COST..... 4548
TOTAL REACH EQUIPMENT COST..... 908
TOTAL REACH MATERIALS COST..... 1022
TOTAL REACH COST..... 6478

********** TUNNEL COSTS **********

REACH NO	SEG NO		COST IN DOLLARS PER FOOT OF TUNNEL: EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
3	4	L	16	66	0	23	49	16	2	30	30	0	8	3	243		109
		E	3	6	0	10	11	8	2	7	10	0	0	1	58		26
		M	0	31	0	0	0	1	3	21	3	0	0	7	66		29
		T	19	103	0	33	60	25	7	58	43	0	8	11	367	450	164
3	5	L	16	67	0	33	49	16	2	33	30	0	8	1	255		803
		E	3	6	0	13	11	8	2	7	10	0	0	1	61		192
		M	0	31	0	0	0	1	3	21	3	0	0	7	66		207
		T	19	104	0	46	60	25	7	61	43	0	8	9	382	3150	1202
3	6	L	16	35	0	23	28	10	2	36	30	0	4	1	185		92
		E	3	3	0	7	6	6	1	7	10	0	0	1	44		22
		M	0	18	0	0	0	1	3	21	3	0	0	7	53		26
		T	19	56	0	30	34	17	6	64	43	0	4	9	282	500	140
3	7	L	16	29	0	21	24	9	2	36	30	0	3	1	171		119
		E	3	3	0	6	5	5	1	7	10	0	0	1	41		28
		M	0	16	0	0	0	1	3	21	3	0	0	7	51		35
		T	19	48	0	27	29	15	6	64	43	0	3	9	263	700	182
3	8	L	16	56	0	48	40	14	6	41	31	0	6	4	262		1860
		E	3	5	0	13	9	7	1	8	10	0	0	1	57		404
		M	0	26	0	0	0	1	7	21	3	0	1	7	66		468
		T	19	87	0	61	49	22	14	70	44	0	7	12	385	7100	2732
3	9	L	16	73	0	76	50	16	4	46	32	0	8	8	329		98
		E	3	6	0	19	11	9	2	8	10	0	0	1	69		20
		M	0	31	0	0	0	1	5	21	3	0	1	8	70		21
		T	19	110	0	95	61	26	11	75	45	0	9	17	468	300	139
3	10	L	16	31	0	37	24	9	2	48	32	0	3	4	206		690
		E	3	3	0	8	5	5	1	8	10	0	0	1	44		147
		M	0	16	0	1	0	1	3	21	3	0	1	7	53		177
		T	19	50	0	46	29	15	6	77	45	0	4	12	303	3350	1014
3	11	L	16	58	0	72	40	14	2	50	33	0	6	9	300		75
		E	3	5	0	16	9	7	1	8	10	0	1	1	61		15
		M	0	26	0	1	0	1	3	21	3	0	1	8	64		16
		T	19	89	0	89	49	22	6	79	46	0	8	18	425	250	106
3	12	L	16	75	0	92	50	16	4	51	33	0	8	11	356		106
		E	3	6	0	21	11	9	2	8	10	0	1	1	72		21
		M	0	31	0	1	0	1	5	21	3	0	2	8	72		21
		T	19	112	0	114	61	26	11	80	46	0	11	20	500	300	148

********** TUNNEL COSTS **********

REACH NO	SEG NO	COST IN DOLLARS PER FOOT OF TUNNEL: EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
3	13 L	16	31	0	42	24	9	2	52	33	0	3	5	217		390
	E	3	3	0	9	5	5	1	9	10	0	0	1	46		82
	M	0	16	0	1	0	1	3	21	3	0	1	7	53		95
	T	19	50	0	52	29	15	6	82	46	0	4	13	316	1800	567
3	14 L	16	63	0	84	42	14	6	53	33	0	7	11	329		213
	E	3	5	0	18	9	7	1	9	10	0	1	1	64		41
	M	0	26	0	1	0	1	7	21	3	0	2	8	69		44
	T	19	94	0	103	51	22	14	83	46	0	10	20	462	650	298

REGIONAL COST FACTOR 1.20

COST INDEX
- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

TOTAL REACH LABOR COST..... 4555
TOTAL REACH EQUIPMENT COST..... 998
TOTAL REACH MATERIALS COST..... 1139
TOTAL REACH COST..... 6692

********** TUNNEL COSTS **********

REACH NO	SEG NO		COST IN DOLLARS PER FOOT OF TUNNEL: EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
4	15	L	43	56	0	20	43	14	6	30	30	0	6	0	248		99
		E	7	5	0	9	9	7	1	7	10	0	0	1	56		22
		M	1	26	0	0	0	1	7	21	3	0	0	7	66		26
		T	51	87	0	29	52	22	14	58	43	0	6	8	370	400	147
4	16	L	0	261	29	62	121	37	23	32	30	0	20	1	616		308
		E	0	83	9	30	30	19	18	8	10	39	0	1	247		123
		M	0	7	0	0	0	1	54	51	3	9	1	7	133		66
		T	0	351	38	92	151	57	95	91	43	48	21	9	996	500	497
4	17	L	0	261	29	69	121	37	23	33	30	0	20	2	625		312
		E	0	83	9	32	30	19	18	8	10	39	0	1	249		124
		M	0	7	0	0	0	1	54	51	3	9	1	7	133		66
		T	0	351	38	101	151	57	95	92	43	48	21	10	1007	500	502
4	18	L	43	28	0	15	25	9	2	32	30	0	3	0	187		93
		E	7	3	0	5	5	5	1	7	10	0	0	1	44		22
		M	1	16	0	0	0	1	3	21	3	0	0	7	52		26
		T	51	47	0	20	30	15	6	60	43	0	3	8	283	500	141
4	19	L	43	57	0	31	43	14	6	34	30	0	6	2	266		438
		E	7	5	0	11	9	7	1	7	10	0	0	1	58		95
		M	1	26	0	0	0	1	7	21	3	0	0	7	66		108
		T	51	88	0	42	52	22	14	62	43	0	6	10	390	1650	641
4	20	L	43	58	0	42	43	14	6	38	31	0	6	3	284		1292
		E	7	5	0	13	9	7	1	7	10	0	0	1	60		273
		M	1	26	0	0	0	1	7	21	3	0	0	7	66		300
		T	51	89	0	55	52	22	14	66	44	0	6	11	410	4550	1865
4	21	L	0	275	30	153	121	37	24	43	31	0	20	15	749		374
		E	0	83	9	45	30	19	18	9	10	39	1	1	264		132
		M	0	7	0	0	0	1	54	51	3	9	2	8	135		67
		T	0	365	39	198	151	57	96	103	44	48	23	24	1148	500	573
4	22	L	0	276	30	158	121	37	25	44	31	0	20	16	758		379
		E	0	83	9	46	30	19	18	9	10	39	1	1	265		132
		M	0	7	0	0	0	1	54	51	3	9	3	8	136		68
		T	0	366	39	204	151	57	97	104	44	48	24	25	1159	500	579
4	23	L	43	55	0	54	40	14	6	44	32	0	6	6	300		810
		E	7	5	0	14	9	7	1	8	10	0	0	1	62		167
		M	1	26	0	0	0	1	7	21	3	0	1	7	67		180
		T	51	86	0	68	49	22	14	73	45	0	7	14	429	2700	1157

********** TUNNEL COSTS **********

REACH NO	SEG NO	COST IN DOLLARS PER FOOT OF TUNNEL: EXC SETUP	EXC	MUCK LOAD	MUCK TRAN	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	PUMP-ING	AIR-COND	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
4	24 L	0	82	9	59	40	15	11	47	32	0	6	6	307		153
	E	0	24	3	14	9	8	6	9	10	11	0	1	95		47
	M	0	7	0	1	0	1	36	44	3	6	1	7	106		53
	T	0	113	12	74	49	24	53	100	45	17	7	14	508	500	253
4	25 L	0	82	9	61	40	15	11	48	32	0	6	7	311		155
	E	0	24	3	15	9	8	6	9	10	11	0	1	96		48
	M	0	7	0	1	0	1	36	44	3	6	1	7	106		53
	T	0	113	12	77	49	24	53	101	45	17	7	15	513	500	256
4	26 L	43	57	0	64	40	14	2	48	32	0	6	7	313		579
	E	7	5	0	15	9	7	1	8	10	0	0	1	63		116
	M	1	30	0	1	0	1	3	21	3	0	1	7	68		125
	T	51	92	0	80	49	22	6	77	45	0	7	15	444	1850	820

REGIONAL COST FACTOR 1.20

COST INDEX
- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

TOTAL REACH LABOR COST..... 4992
TOTAL REACH EQUIPMENT COST..... 1301
TOTAL REACH MATERIALS COST..... 1138
TOTAL REACH COST..... 7431

********** SHAFT COST **********

SHAFT NO	SEG NO	********** COST IN DOLLARS PER FOOT OF SHAFT ********** EXC SETUP	EXC	MUCK LOAD	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FRM	GROUT	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
1	2 L	0	1656	131	409	156	0	70	98	0	2520		252
	E	0	636	42	42	81	0	11	32	278	1122		112
	M	0	102	45	0	2	113	136	25	43	466		46
	T	0	2394	218	451	239	113	217	155	321	4108	100	410
1	3 L	0	644	51	163	68	0	64	98	0	1088		598
	E	0	247	16	16	36	0	10	32	0	357		196
	M	0	93	38	0	2	55	80	25	0	293		161
	T	0	984	105	179	106	55	154	155	0	1738	550	955

REGIONAL COST FACTOR 1.20

COST INDEX

- - LABOR	1.30
EQUIPMENT	1.10
MATERIALS	1.22

SHAFT LABOR COST.....	850
SHAFT EQUIPMENT COST.....	308
SHAFT MATERIALS COST.....	207
SHAFT COST.....	1365

********** SHAFT COST **********

SHAFT NO	SEG NO	COST IN DOLLARS PER FOOT OF SHAFT: EXC SETUP	EXC	MUCK LOAD	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FORM	GROUT	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
2	4 L	0	1376	131	409	152	0	64	80	0	2212		221
	E	0	513	42	39	78	0	10	26	232	940		94
	M	0	79	27	0	2	67	90	19	34	318		31
	T	0	1968	200	448	232	67	164	125	266	3470	100	346
2	5 L	0	507	48	151	61	0	60	80	0	907		36
	E	0	189	15	14	32	0	9	26	0	285		11
	M	0	70	23	0	2	42	57	19	0	213		8
	T	0	766	86	165	95	42	126	125	0	1405	40	55

REGIONAL COST FACTOR 1.20

COST INDEX
- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

SHAFT LABOR COST..... 257
SHAFT EQUIPMENT COST..... 105
SHAFT MATERIALS COST..... 39
SHAFT COST..... 401

********** SHAFT COST **********

SHAFT NO	SEG NO	COST IN DOLLARS PER FOOT OF SHAFT: EXC SETUP	EXC	MUCK LOAD	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FORM	GROUT	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
3	6 L	0	1376	131	409	152	0	64	80	0	2212		221
	E	0	513	42	39	78	0	10	26	232	940		94
	M	0	79	27	0	2	67	90	19	34	318		31
	T	0	1968	200	448	232	67	164	125	266	3470	100	346
3	7 L	0	529	50	159	64	0	60	80	0	942		235
	E	0	197	16	15	33	0	9	26	0	296		74
	M	0	71	23	0	2	42	57	19	0	214		53
	T	0	797	89	174	99	42	126	125	0	1452	250	362
3	8 L	0	529	50	162	64	0	61	80	0	946		160
	E	0	197	16	15	33	0	9	26	0	296		50
	M	0	71	23	0	2	42	57	19	0	214		36
	T	0	797	89	177	99	42	127	125	0	1456	170	246

REGIONAL FACTOR COST 1.20

COST INDEX
- - LABOR 1.30
EQUIPMENT 1.10
MATERIALS 1.22

SHAFT LABOR COST.....616
SHAFT EQUIPMENT COST.....218
SHAFT MATERIALS COST.....120
SHAFT COST.....954

********** SHAFT COST **********

SHAFT NO	SEG NO	COST IN DOLLARS PER FOOT OF SHAFT: EXC SETUP	EXC	MUCK LOAD	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FEM	GROUT	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
4	9 L	0	1376	131	409	152	0	64	80	0	2212		221
	E	0	513	42	39	78	0	10	26	232	940		94
	M	0	77	27	0	2	67	90	19	34	316		31
	T	0	1966	200	448	232	67	164	125	266	3468	100	346
4	10 L	0	554	53	167	67	0	61	80	0	982		265
	E	0	206	17	16	34	0	9	26	0	308		83
	M	0	67	24	0	2	47	63	19	0	222		59
	T	0	827	94	183	103	47	133	125	0	1512	270	407

REGIONAL FACTOR	COST 1.20	COST INDEX	- - LABOR	1.30	SHAFT LABOR COST..... 486
			EQUIPMENT	1.10	SHAFT EQUIPMENT COST..... 177
			MATERIALS	1.22	SHAFT MATERIALS COST..... 90
					SHAFT COST..... 753

********** SHAFT COST **********

SHAFT NO	SEG NO	COST IN DOLLARS PER FOOT OF SHAFT: EXC SETUP	EXC	MUCK LOAD	MUCK HOIST	MUCK DISP	SUP-PORTS	LIN-ING	LIN FORM	GROUT	SEG COST ($/FT)	SEGMENT LENGTH (FEET)	SEGMENT COST ($1000)
5	11 L	0	1376	131	409	150	0	64	80	0	2210		331
	E	0	513	42	39	77	0	10	26	232	939		140
	M	0	79	27	0	1	67	90	19	34	317		47
	T	0	1968	200	448	228	67	164	125	266	3466	150	518
5	12 L	0	529	50	159	62	0	60	80	0	940		84
	E	0	197	16	15	32	0	9	26	0	295		26
	M	0	71	23	0	1	42	57	19	0	213		19
	T	0	797	89	174	95	42	126	125	0	1448	90	129

REGIONAL FACTOR	COST 1.20	COST INDEX	- - LABOR	1.30	SHAFT LABOR COST..... 415
			EQUIPMENT	1.10	SHAFT EQUIPMENT COST..... 166
			MATERIALS	1.22	SHAFT MATERIALS COST..... 66
					SHAFT COST..... 647

********** TUNNEL REACH COST SUMMARY **********

REACH	EXIT SHAFT	REGIONAL COST FACTOR	**** COST INDEXES ****** LABOR	EQUIP	MATL	********** COSTS ($1000) ********** LABOR	EQUIPMENT	MATERIAL	TOTAL
1	2	1.20	1.30	1.10	1.22	1056	204	204	1464
2	2	1.20	1.30	1.10	1.22	4548	908	1022	6478
3	3	1.20	1.30	1.10	1.22	4555	998	1139	6692
4	4	1.20	1.30	1.10	1.22	4992	1301	1138	7431

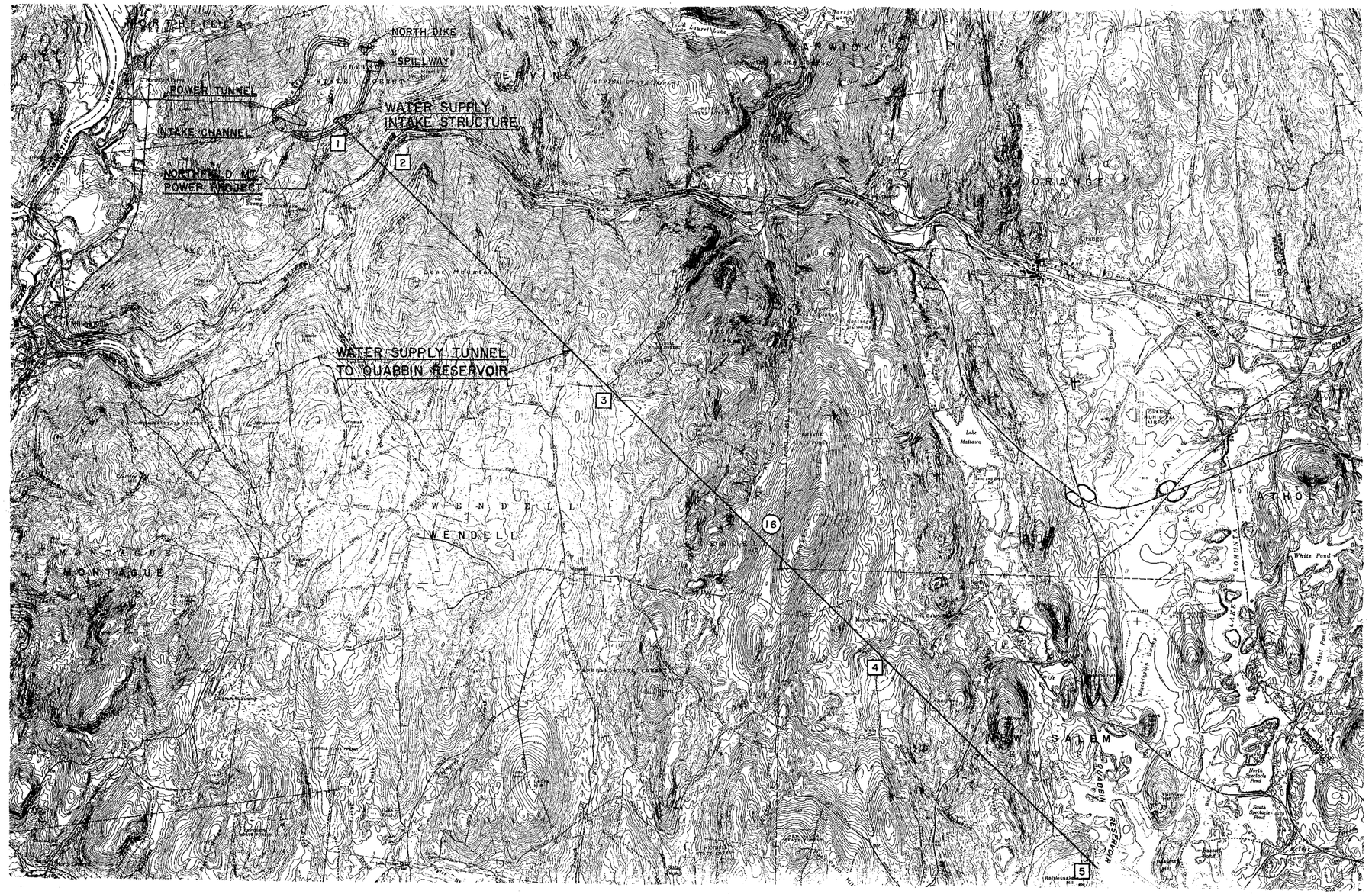
********** SHAFT COST SUMMARY **********

SHAFT	REGIONAL COST FACTOR	***** COST INDEXES ****** LABOR	EQUIP	MATL	********** COSTS ($1000) ********** LABOR	EQUIPMENT	MATERIAL	TOTAL
1	1.20	1.30	1.10	1.22	850	308	207	1365
2	1.20	1.30	1.10	1.22	257	105	39	401
3	1.20	1.30	1.10	1.22	616	218	120	954
4	1.20	1.30	1.10	1.22	486	177	90	753
5	1.20	1.30	1.10	1.22	415	166	66	647

```
*************************************************************
*              NORTHFIELD MT. TO RATTLESNAKE HILL           *
*                   ALINEMENT NO. 16 MDC                    *
*                   MOLE EXCAVATION                         *
*************************************************************
```

PROFIT MARGIN 5.00	TOTAL TUNNEL	LABOR COST.....($1000)	15151
OVERHEAD MARGIN 25.00	TOTAL TUNNEL	EQUIPMENT COST.....	3411
	TOTAL TUNNEL	MATERIAL COST.....	3503
	TOTAL TUNNEL	COST.....	22065
	TOTAL SHAFT	LABOR COST.....	2624
	TOTAL SHAFT	EQUIPMENT COST.....	974
	TOTAL SHAFT	MATERIAL COST.....	522
	TOTAL SHAFT	COST.....	4120
	TOTAL PROJECT	LABOR COST.....	17775
	TOTAL PROJECT	EQUIPMENT COST	4385
	TOTAL PROJECT	MATERIAL COST	4025
	TOTAL PROJECT	COST	26185

CORPS OF ENGINEERS U. S ARMY



LEGEND

(16) TUNNEL ALINEMENT NUMBER

[3] SHAFT NUMBER AND APPROXIMATE LOCATION

GRAPHIC SCALE

1" = 2000' 2000' 0 2000' 4000'

NORTHEASTERN UNITED STATES
WATER SUPPLY STUDY

NORTHFIELD MOUNTAIN
WATER SUPPLY PROJECT

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION
CORPS OF ENGINEERS
WALTHAM, MASS.

APPENDIX D

WATER QUALITY STUDIES OF CONNECTICUT AND MILLERS RIVERS AND QUABBIN AND WACHUSETT RESERVOIRS

This appendix was prepared by New England Research, Inc. jointly for the Commonwealth of Massachusetts Metropolitan District Commission and the New England Division, U. S. Army, Corps of Engineers. The report covers possible effects on Quabbin Reservoir from both the Northfield Mountain and Millers River Basin Water Supply Projects as well as the possible effects on the Connecticut and Millers Rivers watersheds. As such, some parts of this appendix may not apply directly to this report. However, one must be cognizant of the close relationship of the two projects and their effects.

A large amount of field and laboratory data on water quality as well as hydrodynamic studies, fisheries information and pollution abatement plans were collected, considered and evaluated. Evaluations made in this appendix were then used to analyze the various projects for acceptability as water supply sources and for their effect on the environment.

Water Quality Studies
Connecticut and Millers River Systems
and
Quabbin and Wachusett Reservoirs
Massachusetts

Northeastern United States
Water Supply Study

Sponsored by the

Commonwealth of Massachusetts
Metropolitan District Commission

and

New England Division, U. S. Army Corps of Engineers
Contract No. DACW 33-71-C-0056

Prepared By

New England Research, Inc.

With The Technical Assistance of

Alden Research Laboratories
of Worcester Polytechnic Institute
Clark University
Mason Research Institute
University of Massachusetts
Worcester Polytechnic Institute

June 1972

TABLE OF CONTENTS

LIST OF FIGURES vi

LIST OF TABLES x

SYNOPSIS OF STUDY xiii

FRONTISPIECE xvii

1. INTRODUCTION 1

2. DESCRIPTION OF PROPOSED DIVERSIONS 9

A. Connecticut River 9

B. Millers River System 11

3. SAMPLING STATIONS AND FREQUENCIES 14

4. METHODOLOGY 25

5. RESULTS OF WATER QUALITY TESTS 26

A. Biological Data 26

B. Chemical Data 73

C. Physical Data 100

D. Pesticide Data 120

E. Radioactivity 124

6. OTHER INFORMATION 125

A. Hydrodynamic Studies 125

B. Fisheries Information 134

C. Pollution Abatement Plans 137

7. GENERAL DISCUSSION OF AVAILABLE DATA 140

A. Comparison of NER and Other Data, Connecticut River . . . 140

B. Discussion of Data 149

8. IMPACTS OF PROPOSED DIVERSIONS 154

A. Impact Statements and Public Policy 154

B. Environmental Aspects 191

C. Public Health Aspects 225

D. No Diversion Alternative 230

E. Delays in Diversion 232

9. SUMMARY 234

10. RECOMMENDATIONS 241

APPENDICES 245

Appendix 1. Methods for Field and Laboratory Studies 246

Appendix 2. Summary of Pertinent Hydrological Data 262

Appendix 3. Minutes of Meeting of September 16, 1971 267

Appendix 4. Outside Contacts and Information Sources . . . 279

Appendix 5. Literature Cited 281

Appendix 6. Fourth Quarter Results 290

LIST OF FIGURES

FIGURE NO.		PAGE NO.
1	Generalized Qualitative Model of Diversion	5
2	Three Cases of Generalized Model of Diversion	6
3	Proposed Connecticut River Diversion	10
4	Proposed Tully System Diversion	12
5	Quabbin Reservoir Sampling Stations	15
6	Wachusett Reservoir Sampling Stations	16
7	Riverine Sampling Stations	17
8	Range of Fecal Coliform Bacteria for Each Station for the First Three Quarters, 1971	27
9	Logarithm of Average Number of Heterotrophic Bacteria per 100 ml	31
10	Logarithm of Average Number of Total Coliform Bacteria per 100 ml	32
11	Logarithm of Average Number of Fecal Coliform Bacteria per 100 ml	34
12	Frequency - Concentration Distribution of Total Coliform Bacteria Populations (Logarithm of Bacterial Numbers per 100 ml. First and Second Quarters, 1971)	35
13	Numbers of Fecal Coliform Bacteria in Selected Riverine Systems	36
14	Chromogenic Bacteria as Average Percent of the Total Population of Heterotrophic Bacteria	38

15	Seasonal Variations in Composition of Heterotrophic Populations (Station Q-8-S)	39
16	Percent of Samples in Which Algal Groups Present (First Quarter, 1971)	41
17	Percent of Samples in Which Algal Groups Present (Second Quarter, 1971)	42
18	Percent of Samples in Which Algal Groups Present (Third Quarter, 1971)	44
19	Monthly Variations in Numbers of Reservoir Zooplankton	47
20	Monthly Variations in Numbers of Riverine Zooplankton	48
21	Reservoir Zooplankton (Concentration of Crustaceans versus Concentration of Rotifers)	50
22	Seasonal Variations in Composition of Reservoir Zooplankton	53
23	Monthly Variations in Numbers of Reservoir Zooplankton	55
24	Riverine and Reservoir Zooplankton (Concentrations of Crustaceans versus Concentrations of Rotifers)	59
25	Number of Animals Per Square Foot at Riverine Stations	69
26	Riverine Benthic Samples (Number of Animals versus Number of Types)	70
27	Alkalinity Levels at Selected Stations, 1971	76
28	Alkalinity Levels at Selected Stations, 1971	77
29	COD (Chemical Oxygen Demand) Levels at Selected Stations, 1971	79
30	COD (Chemical Oxygen Demand) Levels at Selected Stations, 1971	80

31	Total Hardness Levels at Selected Stations, 1971	82
32	Total Hardness Levels at Selected Stations, 1971	83
33	Chloride Levels at Selected Stations, 1971	85
34	Ammonia Levels at Selected Stations, 1971	86
35	Ammonia Levels at Selected Stations, 1971	87
36	Total Phosphorus Levels at Selected Stations, 1971	89
37	Sodium Levels at Selected Stations, 1971	91
38	Potassium Levels at Selected Stations, 1971	93
39	Total Iron Levels at Selected Stations, 1971	94
40	Manganese Levels at Selected Stations, 1971	96
41	Zinc Levels at Selected Stations, 1971	97
42	Mercury Levels at Selected Stations, 1971	98
43	Color of Water at Riverine Stations	103
44	Color of Water at Quabbin "Outside" and Wachusett Reservoir Stations	104
45	Color of Water at Quabbin "Inside" Stations	106
46	Specific Conductance of Riverine Stations	107
47	Specific Conductance for Quabbin and Wachusett Reservoir Stations	108
48	Dissolved Oxygen	110
49	pH for Riverine Stations	112
50	Turbidity Measurements Made With Spectronic 20 and Hach Turbidimeter	114
51	Turbidity for Riverine Stations	116

52 Surface Water Temperature at Quabbin Reservoir (Q-2, Q-5) and Connecticut River (R-1) 117

53 Projected Quabbin Reservoir Volumes with and without Diversions 192

54 Schematic Diagram of the Possible Fates of Materials Introduced into the Waters of a Receiver System by the Waters of a Donor System 204

LIST OF TABLES

TABLE NO.		PAGE NO.
1	Modal Log Values of Bacterial Numbers per 100 ml for Major Station Groupings, 1971	29
2	Logarithm of Bacterial Numbers per 100 ml	30
3	Modal Values of Algal Populations	40
4	Riverine Zooplankton (March through September, 1971)	49
5	Reservoir Zooplankton (February through September 1971)	51
6	Reservoir Crustaceans (February through September 1971)	54
7	Relative Composition of Reservoir and Riverine Zooplankton Samples	57
8	Comparison of Various Conditions Associated With Bottom Samples of Reservoirs	61
9	General Distributions of Benthic Organisms in Quabbin and Wachusett Reservoirs	62
10	Concentrations of Chironomidae and Oligochaeta in Quabbin and Wachusett Reservoirs	64
11	Seasonal Variations of Benthic Populations in Quabbin and Wachusett Reservoirs (Average Number of Animals per grab -- 1/4 ft^2)	65
12	Seasonal Variations in Numbers of Oligochaeta and Chironomidae (Average Number of Animals per grab -- 1/4 ft^2)	66
13	Number of Types of Benthic Animals Found in River Samples (January - August, 1971)	68
14a	Summary of Physical Data	101
14b	Summary of Physical Data	102

15	Temperature Profiles at Quabbin Reservoir (Q-9) (^{o}C)	118
16	Temperature Profiles at Quabbin Reservoir (Q-2) (^{o}C)	119
17	List of Pesticides and Required Sensitivity for Detection Techniques	121
18	Summary for Detection of Trace Amounts of Pesticides and Phenols	123
19	Summary of Inflow and Outflow Conditions for the Studies of Flow Patterns	129
20	Summary of Model Flow Pattern Studies	130 and 131
21	Comparisons of Results of Water Analyses of Connecticut River - NER and MDC (April, 1971)	141
22	Comparisons of Results of Water Analyses of Connecticut River - NER and MDC (May, 1971)	142
23	Comparisons of Turbidity Values for Connecticut River Water from Various Sources for April and May, 1971	144
24	Annual Inflow to Quabbin Reservoir from Various Sources	193
25	Proportion of Quabbin Reservoir Water Originating from Various Sources at the end of a Given Year (%)	194
26	Maximum and Minimum Daily Reductions in Flow in Millers River at South Royalston during Three Representative Years Assuming Priest and Tarbell Brooks Diversions	198
27	Monthly Loss in Flow in Millers River at South Royalston Assuming Priest and Tarbell Brooks Diversions for Three Representative Years	199
28	Monthly Reductions in Flow in Millers River, at Confluence of Tully River, Assuming Tully System Diversion for an Average Year	200
29	Summary of Probable Impacts of the Proposed Diversions on Quabbin Reservoir	236

30 Probable Major Long-Term Trends in Quabbin Reservoir 237

31 Summary of Probable Impacts of the Proposed Diversions on the Connecticut River 239

32 Summary of Probable Impacts of the Proposed Diversions on the Millers River System 240

SYNOPSIS OF STUDY

This study generated and evaluated extensive data on the Quabbin and Wachusett Reservoirs and the Connecticut and Millers Rivers systems, with the objective of making predictions on the impacts of diverting portions of these riverine systems into Quabbin Reservoir. New England Research, Inc. was charged with overall responsibility for the study, and was assisted by Alden Research Laboratories of Worcester Polytechnic Institute, Clark University, Mason Research Institute, University of Massachusetts, and Worcester Polytechnic Institute.

Field and laboratory data included approximately 100 parameters, including biological, chemical, physical, and pesticides data. In addition, radiological data, hydrodynamic studies, fisheries information, and pollution abatement plans were considered and evaluated. Finally, other pertinent data available from both public and private sources, especially on the Connecticut River, were evaluated in the light of the objectives of this study.

Central to the evaluation was the development of a qualitative conceptual model of reservoir dynamics. If water of lower quality is introduced from a donor system into a receiver system, there will most likely be a loss in water quality in the receiver system. This loss of water quality is due to various materials in the water. These materials include molecules,

ions, suspended inorganic materials, organic debris, and living organisms. The fates of these materials are varied and complex, and include evaporation, transfer, transformation and deposition. These possible pathways are not mutually exclusive; for example, a DDT molecule could take all four pathways. What happens to the various materials is a function of many mechanisms. One of the central problems of ecology today is to trace the flow of materials from the various compartments of an ecosystem. While our model cannot be viewed as a quantitative model, it is nevertheless a useful qualitative model with which to begin making predictions as to changes in water quality brought about by the proposed diversions, as required by this study.

Dilution of riverine waters by ambient reservoir volume alone will probably not be sufficient to insure an acceptable water quality in Quabbin Reservoir. However, fallout of suspended materials and the "treatment plant" capacity of Quabbin Reservoir are expected to result in an acceptable water quality.

General predictions were made on the impacts of the proposed diversions on Quabbin Reservoir. Potential impacts have both public health and general environmental significance. The potential magnitude of a given impact upon Quabbin Reservoir is generally higher with the proposed Connecticut River diversion than with the proposed Millers (Tully) River system diversion. As a convenience in making evaluations of the probable impacts of the proposed diversions, the period 1972-2000 was divided into four phases. Phase I,

(1972-1976) is the period before diversion of the Connecticut River. The volume of Quabbin Reservoir will decline during this period. Phase II (1976-1980) represents the period from the beginning of the Connecticut River diversion to the time when the Tully River diversion becomes operative. The reservoir volume will increase during this period. The period 1980-1989 (Phase III) represents a period when both diversions are operative, and the reservoir volume continues to increase. During the final phase (Phase IV, 1989-2000) both diversions continue to be operative but reservoir volume declines.

The greatest potential for both ecological and public health impacts on Quabbin Reservoir is seen to exist with Phase II. Phase III will probably be associated with a general improvement in water quality. Because of declining reservoir volumes, Phases I and IV will show some deterioration of water quality in the reservoir.

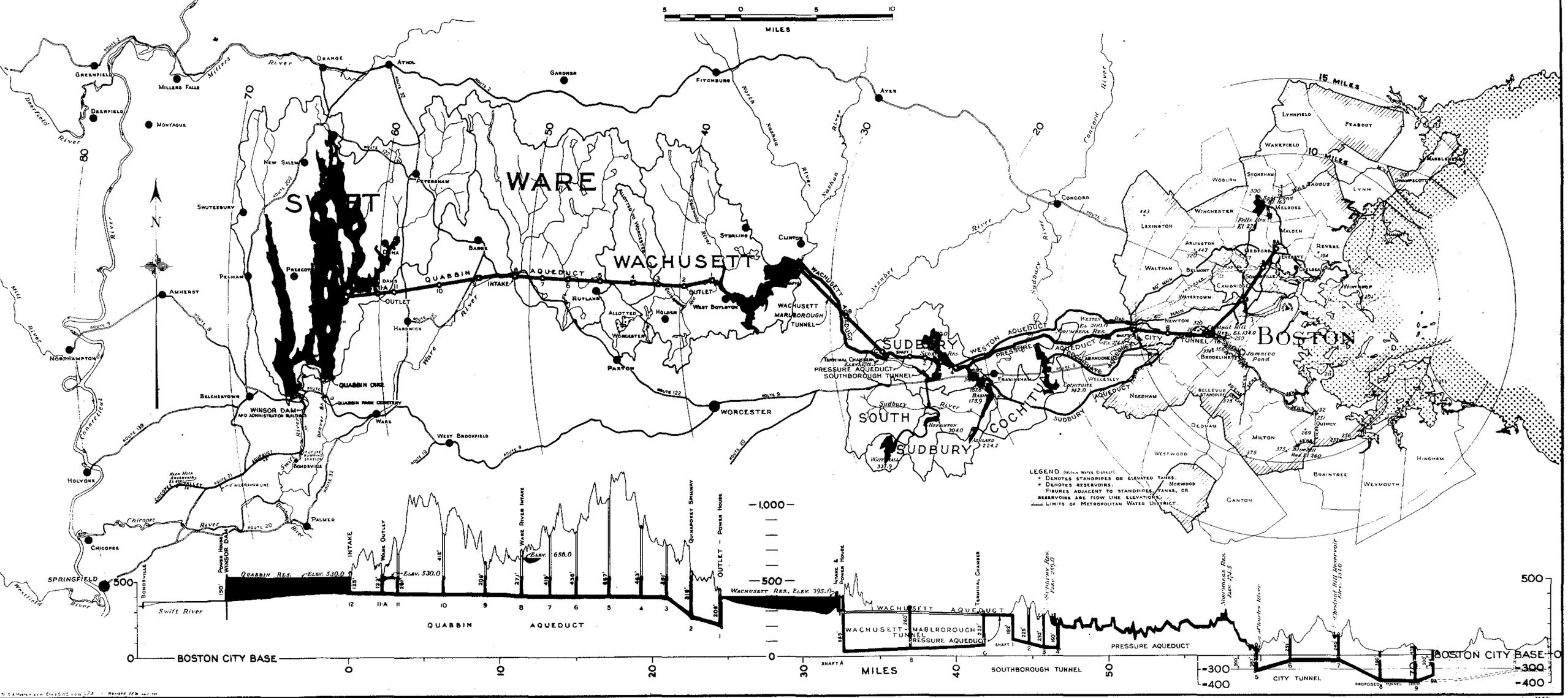
Impacts on the proposed donor systems will vary in magnitude. No significant impacts on the hydrology, water quality, or general ecology of the Connecticut River are predicted. On the other hand, some changes in hydrology, water quality and general ecology can be expected in the Millers River system. These changes will result mainly from the reduction in water flow volume and the creation of impoundments. However, some of the long term impacts will be reduced as the proposed state-federal secondary treatment cleanup of the Millers River is implemented.

A no-diversion alternative was also considered in this study. Assuming present projections on water supply and water demand, Quabbin Reservoir will have exhausted its supply by 1985. However, before that time, the general condition of the reservoir will have deteriorated to the point where it will cease to be an acceptable public water supply. Therefore, we view the no-diversion alternative as unrealistic, unless other alternatives, outside the scope of the present study can solve the projected water supply problem for Metropolitan Boston.

Related to no diversion are any delays in proposed diversions. We view Phase I (1972-1976) as a particularly sensitive period because of the continued loss of water volume in Quabbin Reservoir. This loss in water volume will increase the risks for negative impacts from the riverine diversions. Therefore, delays in diversion for only a few years will probably result in greater impacts on the reservoir.

METR. DISTR. COMMISSION — CONSTRUCTION DIVISION

WATER SUPPLY — METROPOLITAN BOSTON



1. INTRODUCTION

The objectives of the research activities which are the basis of this report are as follows:

> to acquire and interpret information and data that will permit judgments as to the probable long- and short-range effects of the proposed diversions of water from the Millers River and certain of its tributaries, and from portions of the Connecticut River into Quabbin Reservoir on (1) the quality of public water supplies to be stored in Quabbin and Wachusett Reservoirs, and (2) the ecological relationships in the donor systems and in the receiving reservoir systems.

The geographical relationships of these systems are shown in the frontispiece.

Data and information acquired and considered in the progress of this study include that which was (1) provided to New England Research, Inc. by the two sponsoring agencies: the U. S. Army Corps of Engineers and the Metropolitan District Commission, (2) collected by New England Research from other agencies, personal contacts, and published literature, and (3) generated by New England Research and its subcontractors. Data and information included in the first two categories above are referenced in Appendix 4. Data from the third category include measurements of the following parameters:

(1) <u>Physical Parameters</u>

Temperature, dissolved oxygen, color, specific conductance, odor, pH, turbidity.

(2) Biological Parameters

a. Phytoplankton (numbers and types; 11 field categories of algal types)

b. Bacteria (numbers and types; 5 groups of bacteria)

c. Planktonic and benthic animals (numbers and types; 22 groups of animals)

(3) Chemical Parameters

a. Pesticides (concentrations of 13 individual pesticides or pesticide classes)

b. Inorganic chemistries (concentrations of 38 individual chemical species)

The frequencies with which these parameters were measured and the locations of sampling stations will be found in Section 3.

In addition to data generated in the above analyses, hydrodynamic data for Quabbin Reservoir were generated by means of a scale model of Quabbin Reservoir (25' long x 11' wide) which was constructed and tested by the Alden Research Laboratories of Worcester Polytechnic Institute, Holden, Massachusetts.

The volume of raw data generated in this study is obviously large; it consists of 32,000 information bits on over 2500 pages. It cannot be presented in its totality in this report without subverting the purpose of this report; namely, to present in as clear and concise a manner as possible those judgments required by the objectives of the study. This report therefore contains compilations and reductions of raw data which are particularly useful to the discussion of scientific issues which have to be dealt with under the study objectives. Compilations and reductions of data contained in this report are based on data collected from

December 1970 through September 30, 1971. A supplementary report of data collected from October 1 through November 30, 1971 (Fourth Quarter) has also been compiled and appears in Appendix 6.

The scientific issues which are considered in this report as being essential to the study objectives derive from a qualitative model of diversion which is based upon the following working assumptions:

(1) A reservoir such as Quabbin Reservoir may be viewed as a treatment plant which operates at or close to a steady state so as to produce output water which is of a higher quality than that of the average input water which supplies the reservoir. There are dynamic seasonal changes which tend to displace the steady state, but in terms of a year or several years the reservoir can be viewed as coming back to a dynamic equilibrium.

(2) Inputs into a reservoir other than those already operative while the reservoir is in a steady state will alter the dynamics of the system and, hence, will influence any mechanisms underlying the "treatment plant" capability as discussed above.

(3) Such new inputs into a reservoir, if they contain waters of significantly lower quality than that of on-going inputs, will tend to put a heavier stress on the treatment capacity of the reservoir for some indefinite period of time.

(4) The concept of a "reserve treatment capacity" of the reservoir is central to the question of how much of an additional stress the reservoir can tolerate without a drastic change in water quality. Any assessment of short-term and long-term effects, both public health and ecological, must focus on this concept.

(5) The specific rate of change of treatment efficiency, its persistence and recovery, and the efficiency of the eventually achieved new steady state is a complex function of the ecological relationships disrupted, modified, or introduced by the additional inputs into the reservoir.

The generalized qualitative model is depicted in Figure 1. In this diagram a single diversion period is shown, with representations of the consequent loss in water quality (ΔQL) and recovery in water quality (ΔQR). An important point of this model is that the "fallout" of whatever contributes to the incremental loss of water quality (ΔQL) does not necessarily follow a logarithmic decay, as with many physical phenomena. Indeed the water quality recovery (ΔQR) is governed by a complex of factors, and in some instances there could be a further deterioration after time T_2 without an additional input.

A number of cases of this generalized model, as it can be applied to the contemplated yearly diversions into Quabbin Reservoir, are possible. Three of these cases are as follows:

Case I:	$\Delta QL =$	ΔQR for all diversion cycles
Case II:	$\Delta QL =$	ΔQR at end of first diversion cycle
	$\Delta QL >$	ΔQR for subsequent diversion cycles
Case III.	$\Delta QL >$	ΔQR for all diversion cycles

These three cases of the generalized model are depicted in Figure 2. Other cases are developed in Section 8 of this report.

The essential qualitative nature of this model cannot be overemphasized. The concept of water quality itself, for example, cannot be quantified without reference

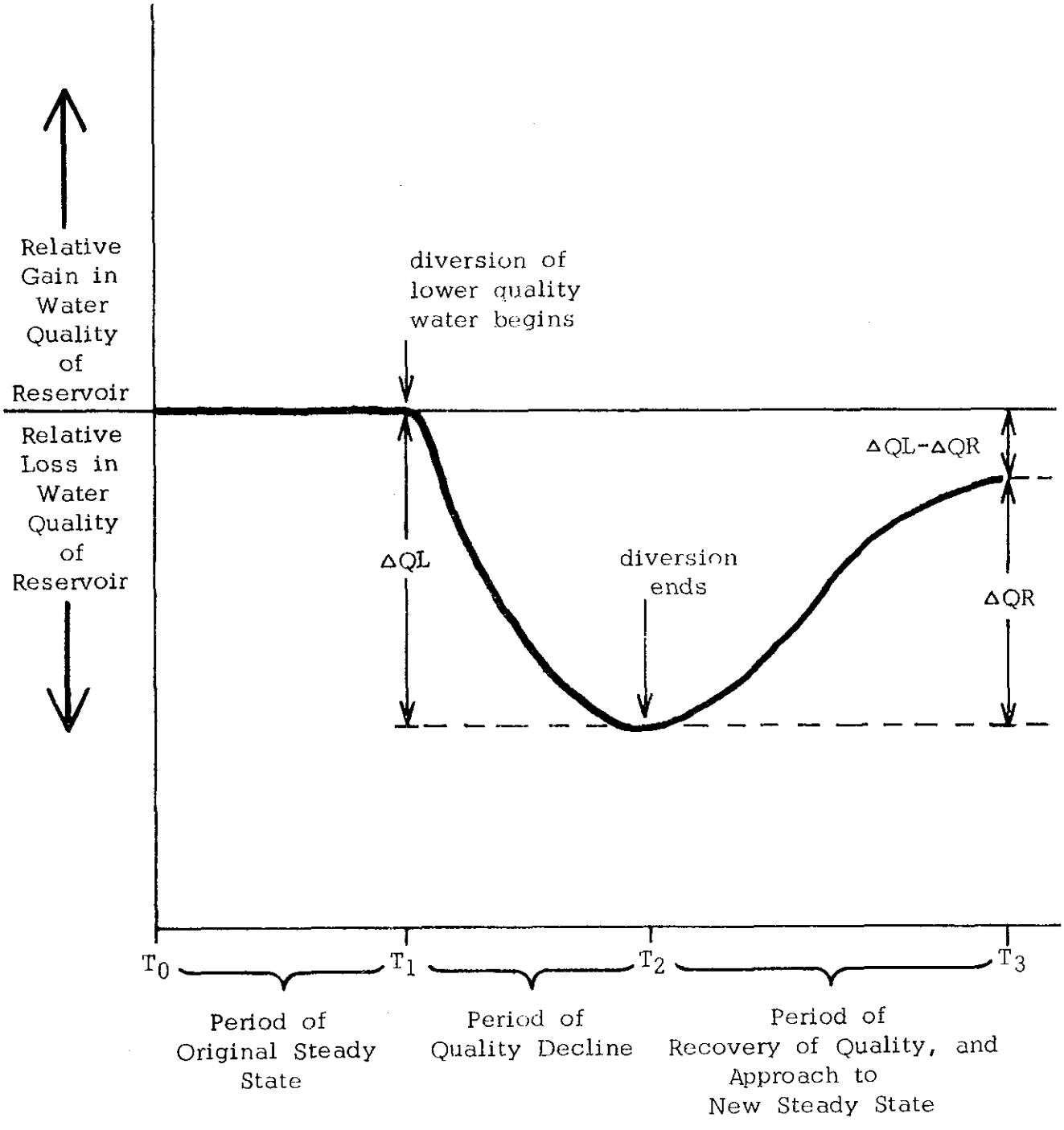
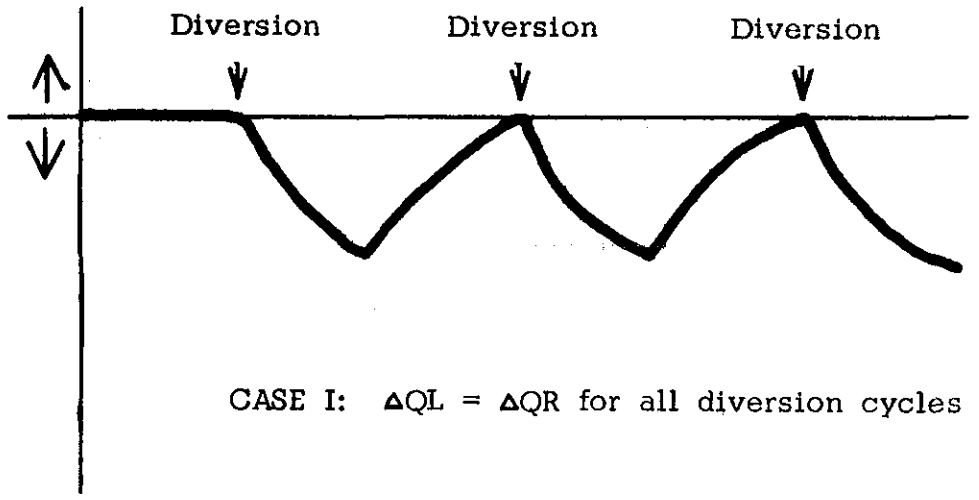
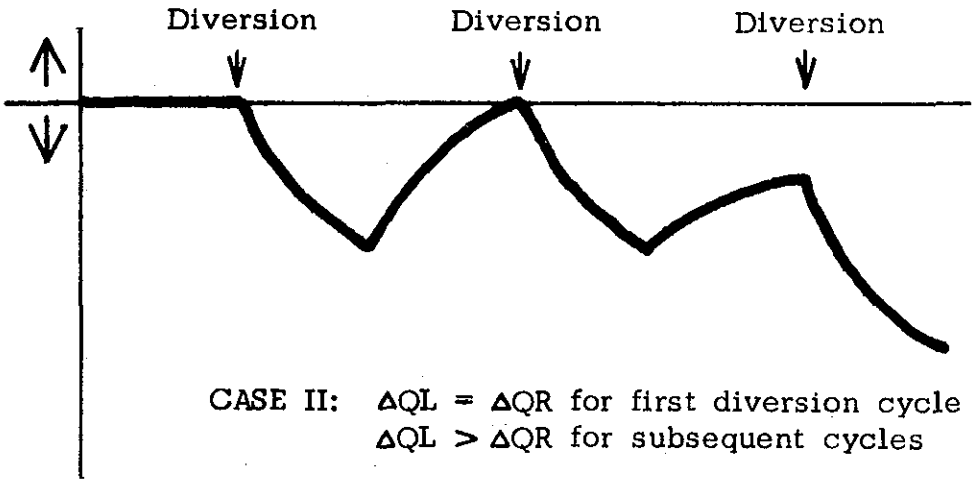


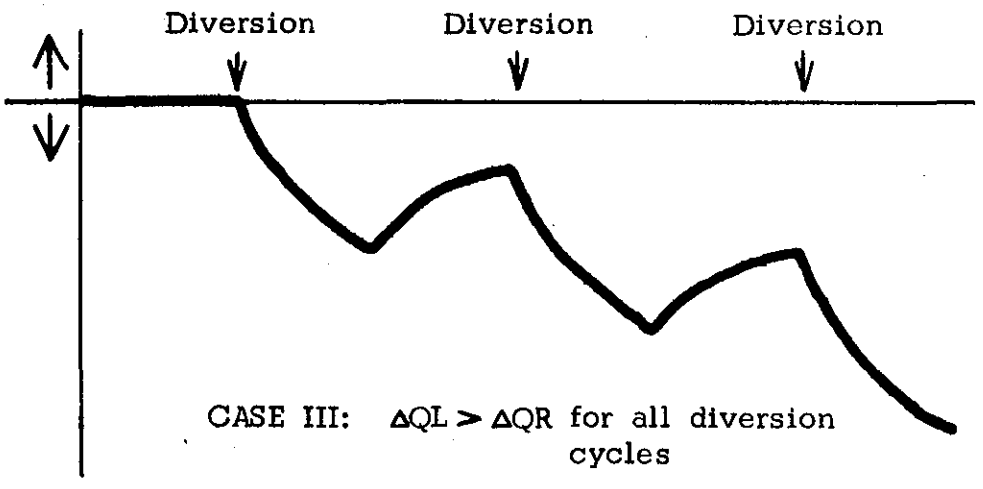
Figure 1. Generalized Qualitative Model of Diversion



Short-range impact significant. Long-range impact insignificant.



Short- and long-range impacts qualitatively different.



Short-range impact significant, and similar to long-range impact.

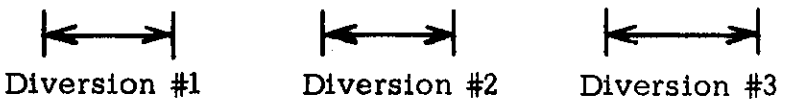


Figure 2. Three Cases of Generalized Model of Diversion

to either a specific parameter or to a specific group of parameters. Approximately 100 individual physical, biological and chemical parameters have been studied in the progress of this work. Moreover, the vast majority of complex ecological relationships characteristic of lacustrine and riverine environments are only generally understood if they are understood at all. As yet our measuring instruments most often yield numerical representations of ecological systems which are more precise than our understanding of them.

Nevertheless it is possible today, in light of work already accomplished by the National Technical Advisory Committee on Water Quality Criteria (FWPCA, 1968), as well as the growing body of research knowledge and information, to begin to apply certain contemporary priorities of public health and environmental quality significance to such a model as presented here. The President and the Congress, moreover, have decided and directed that whatever knowledge we may have shall be brought to bear on those governmental decision-making processes which may result in significant impacts on the environment (National Environmental Policy Act, 1969; Annual Reports of Council on Environmental Quality, 1970, 1971) To do or say nothing concerning the impact of human activity on the environment until all possible knowledge has been gathered and fully digested we therefore deem to be an act of extreme irresponsibility.

The public decision-making process requires that the scientific community share in this process; to demand a complete study is to subserve the public need for decisions to the demands of the scientific community for absolute truth. It is in this spirit of interplay between public needs and scientific objectivity that

we present our report.

This report is therefore an attempt to clarify the kinds of ecological and water quality problems which we judge to be probable in the diversion of waters into Quabbin Reservoir; to define the magnitudes of such problems in a manner consistent with both current scientific understanding and the spirit and requirements of the National Environmental Policy Act of 1969; and to view such problems in the context of those situations most likely to be derived from various alternative actions.

2. DESCRIPTION OF PROPOSED DIVERSIONS

A. Connecticut River

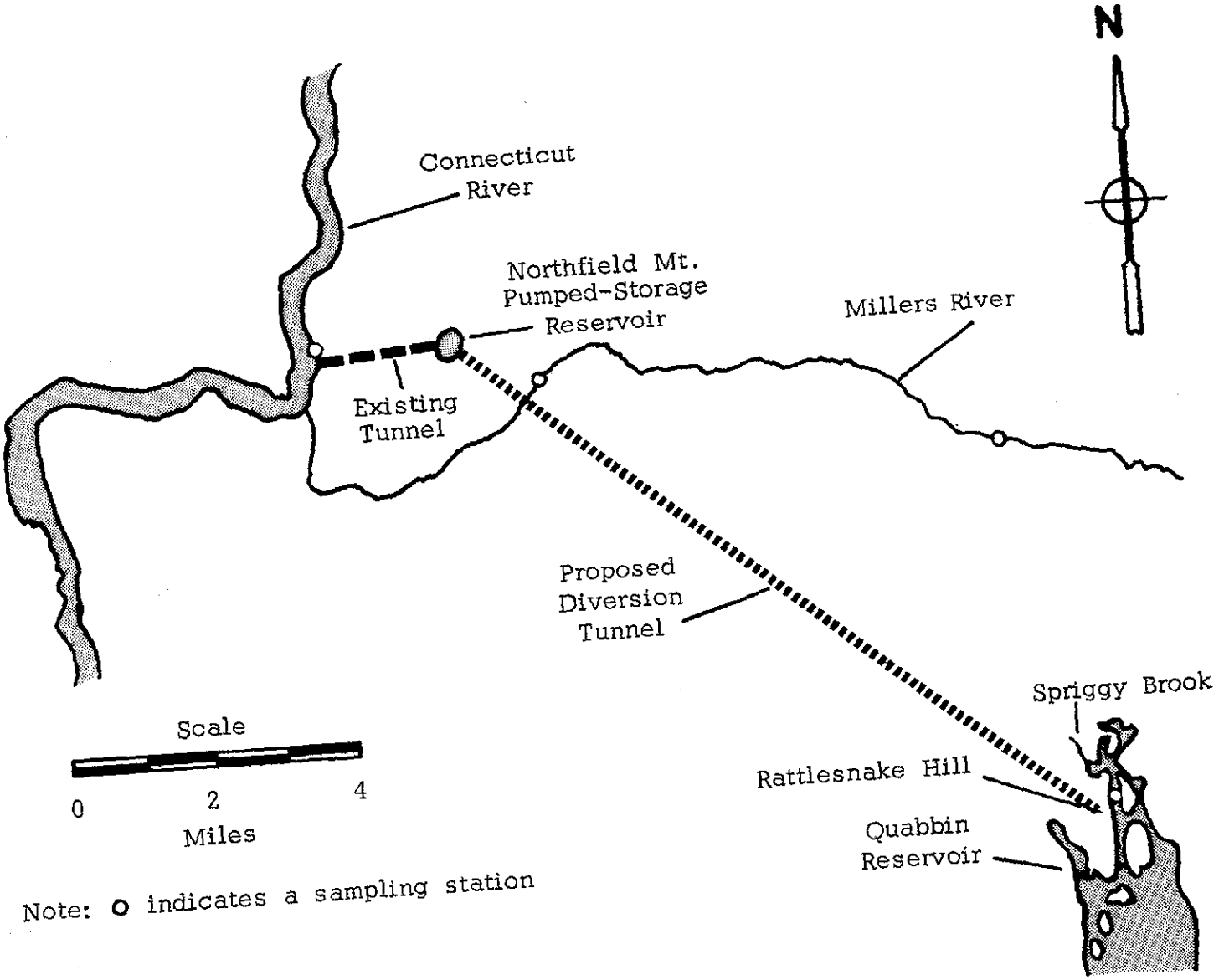
It is proposed to divert some Connecticut River water to Quabbin Reservoir during freshet flow. The diversion is conditioned by a flow in the Connecticut River of 17,000 cfs (cubic feet/second) or greater as measured at the U.S.G.S. gauging station at Montague City, Massachusetts.

The diversion (Figure 3) will be effected by pumping waters from the Connecticut River to the existing Northfield Mountain Pumped Storage Reservoir at an elevation of 1004.5 feet at full pool.[1] At Northfield Reservoir an intake tower will be built to take water from near the bottom of the dam (elevation 923 feet) through fish-screened sluice gates into an 8-foot diameter pipe under the dam. This water will then be conveyed through a proposed 10-mile underground tunnel to the vicinity of Rattlesnake Hill (elevation 838 feet). From the outlet of the tunnel, water would enter the northern end of the central arm of Quabbin Reservoir.

The rate of diversion would be 375 MGD (million gallons/day) with a capacity of up to 500 MGD. An anticipated average 70-day diversion period,

---

[1]The Connecticut Light and Power Company, The Hartford Electric Light Company, Western Massachusetts Electric Company, Drawing: Diversion Intake Works, Quabbin Water Diversion Facility, Northfield Mountain Pumped Storage Project, F.P.C. Project No. 2485.



Note: o indicates a sampling station

Figure 3. Proposed Connecticut River Diversion

at a diversion rate of 375 MGD, would result in a total volume input into Quabbin Reservoir of approximately 26 billion gallons. This volume would account for roughly 1-2% of the Connecticut River flow volume during this period, depending on higher or lower incident freshet flows respectively.

B. Millers River System

The proposed diversion of water from tributaries of the Millers River to Quabbin Reservoir would involve the construction of a series of impoundments and associated interconnecting tunnels (Figure 4).

Tarbell Brook would be dammed with a weir which would result in the inundation of 28 acres.[1] Water would be pumped through a 2-mile long pressure conduit with a 90 cfs capacity to Priest Brook. Priest Brook would be dammed, and 400 acres inundated. Water collected behind this dam would be pumped through a 5-mile long pressure conduit with a 120 cfs capacity to the upper end of Long Pond on the East Branch of Tully River, 3 miles above the present Tully Dam. Lawrence Brook is a tributary of the East Branch of Tully River. The confluence of Lawrence Brook and the East Branch of Tully River is in the flood pool of Tully Dam. The 9-mile long Tully-Quabbin tunnel is proposed to begin at an intake structure to be constructed on the outlet channel below Tully Dam (elevation 625). This tunnel would empty into the northern end of the central arm of Quabbin Reservoir. A weir impounding 13 acres of water, and a pumping station capable of injecting an additional 90 cfs of

---

[1] Data on impoundment areas and capacities added to drawing entitled: Northeastern United States Water Supply Study, Tully Dam Diversion, Millers River Basin, Massachusetts. New England Division, Corps of Engineers, U. S. Army.

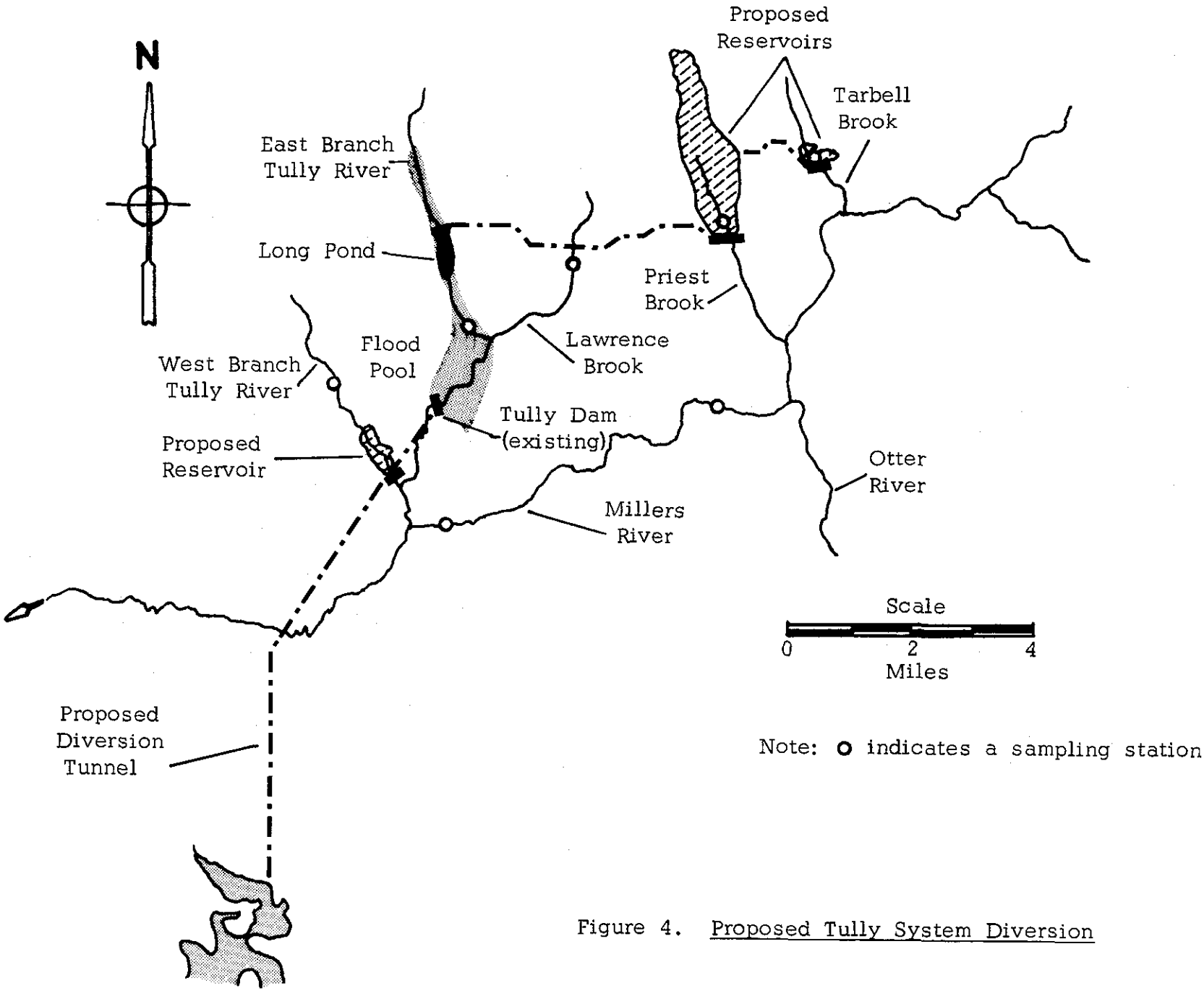


Figure 4. Proposed Tully System Diversion

water into the tunnel would be constructed at the intercept of the Tully-Quabbin tunnel with the West Branch of Tully River.

Diversion of waters from any proposed diversion stream in the Millers River system could be made whenever the control flows in the Connecticut River and at individual sites listed below are met or exceeded. This would normally occur during the spring runoff period. These values are shown below:

Control Flows[1] (cfs)

	Dec-Mar	Apr-Jun	Jul	Aug	Sep-Nov
Connecticut River	17,000	17,000	17,000	17,000	17,000
Tarbell Brook	12.8	32	51.2	25.6	19.2
Priest Brook	9.7	24.3	38.8	19.4	14.6
Tully Dam	25.2	63.0	100.8	50.4	37.8
West Branch of Tully River	9.2	23.3	37.2	18.6	14.0

The volume of water diverted into Quabbin Reservoir from the Millers River system during a typical year would be 17.5 billion gallons. This is equivalent to a daily flow of 48 MGD for 365 days.

---

[1] Tully Complex Control Flows, a data sheet from New England Division, Corps of Engineers, received November 3, 1971.

3. SAMPLING STATIONS AND FREQUENCIES

The locations of sampling stations are indicated on Figures 5, 6 and 7. Since all parameters were not required to be sampled at the same frequency, a listing follows of all sample collections made during the period December 22, 1970 through September 30, 1971. The parameter codes used in that listing are:

Code	Parameters Measured
A	Physical Chemistries
B	Pesticides and Phenols
C	Zooplankton*
D	Phytoplankton
E	Benthic Organisms*
F	Bacteria
G	Chemistries
R	Radioactivity
X	Carbon Chloroform Extract

*At reservoir sites where both a surface and a depth station are located, one composite zooplankton sample is taken by a vertical tow of the Wisconsin net. This sample is indicated by a "C" at the surface station. Collection of benthic organisms from bottom materials is indicated by an "E" at the surface station.

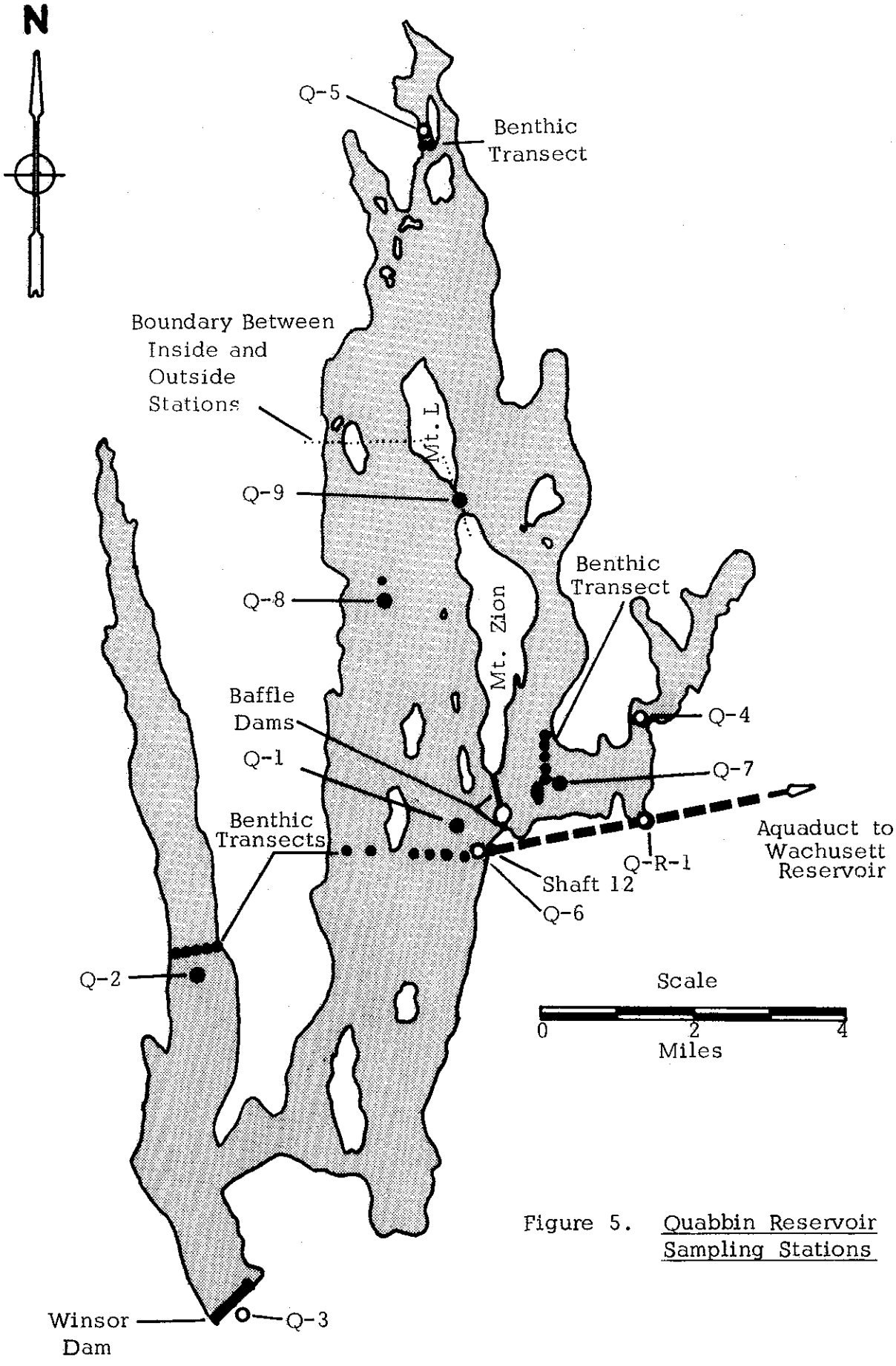


Figure 5. Quabbin Reservoir Sampling Stations

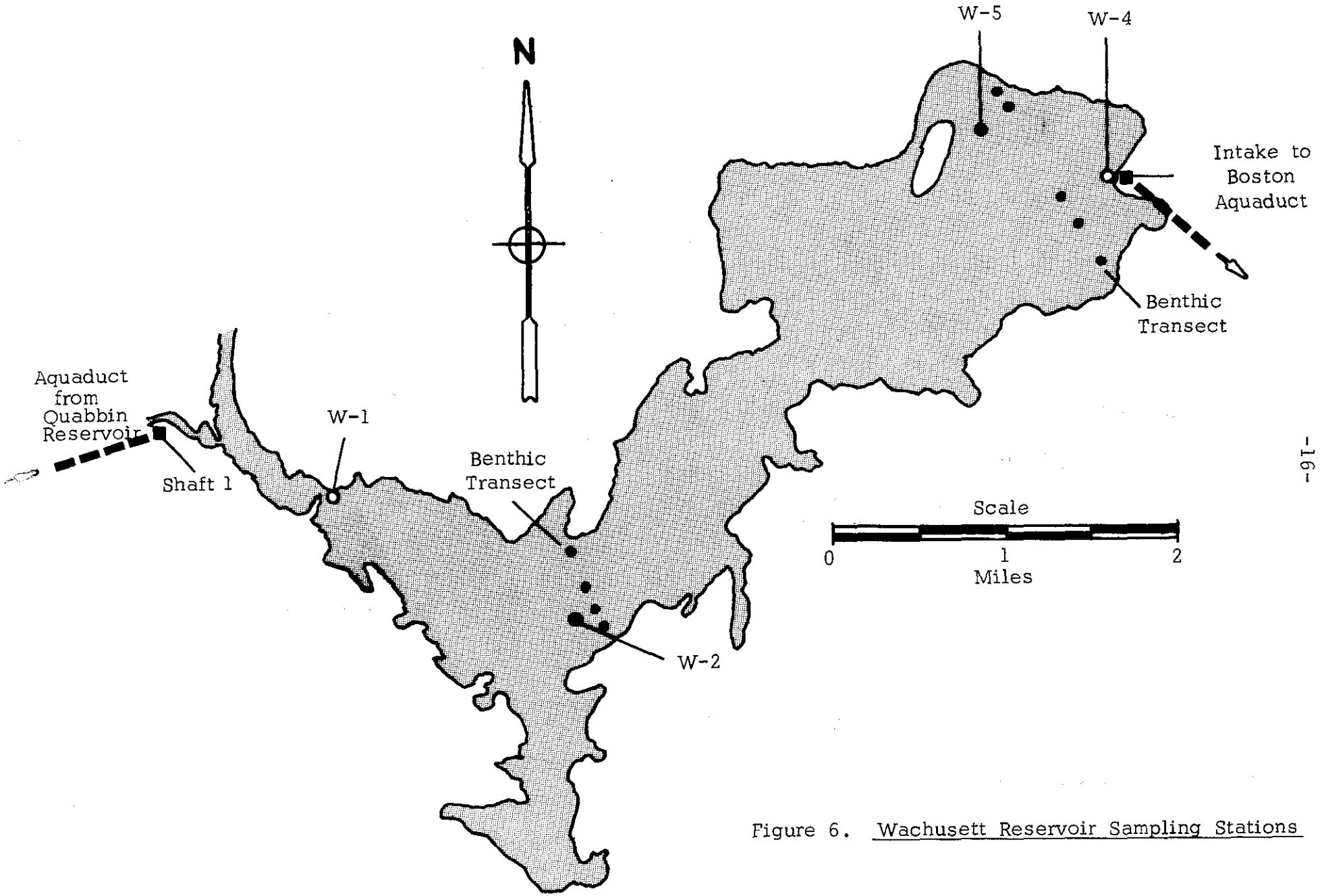
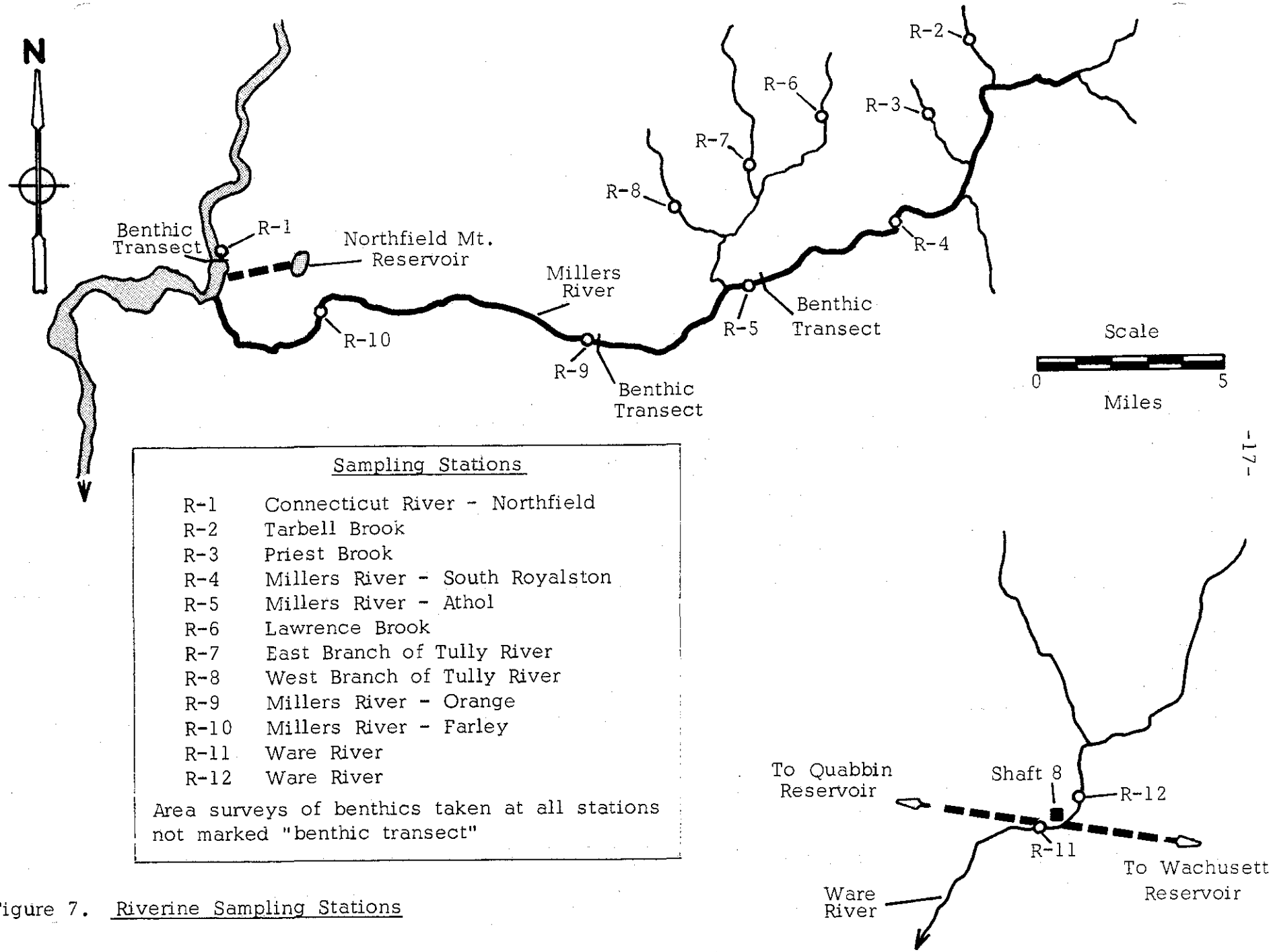


Figure 6. Wachusett Reservoir Sampling Stations



Sampling Stations

R-1	Connecticut River - Northfield
R-2	Tarbell Brook
R-3	Priest Brook
R-4	Millers River - South Royalston
R-5	Millers River - Athol
R-6	Lawrence Brook
R-7	East Branch of Tully River
R-8	West Branch of Tully River
R-9	Millers River - Orange
R-10	Millers River - Farley
R-11	Ware River
R-12	Ware River

Area surveys of benthics taken at all stations not marked "benthic transect"

Figure 7. Riverine Sampling Stations

SAMPLE COLLECTIONS - QUABBIN RESERVOIR

Depth Code: S-surface; 10 - 10 meters; tap - sink tap in powerhouse; 6.5 - 6.5 meters

STATION	22 Dec 70	07 Jan 71	20 Jan 71	25 Jan 71	01 Feb 71	02 Feb 71	03 Feb 71	22 Feb 71	24 Feb 71
Q-1-S	ADFG	-	-	-	-	-	ABDFGX	-	-
Q-1-10	-	-	-	-	-	-	ABDFGX	-	-
Q-2-S	ADFG	-	-	-	-	-	ABDFGX	-	-
Q-2-10	ADFG	-	-	-	-	-	ABDFGX	-	-
Q-3-Tap	ADFG	-	-	BX	-	-	ADFG	-	-
Q-4-S	ADFG	-	-	BX	ADFG	-	-	-	ACDEFG
Q-5-S	-	ADFG	-	BX	-	ADFG	-	CE	ADFG
Q-6-S	-	ADFG	-	BX	-	-	ADFG	-	ACDFG
Q-7-S	-	-	ADFG	-	ABDFGX	-	-	-	ACDEFG
Q-7-6.5	-	-	ADFG	-	ABDFGX	-	-	-	ADFG
Q-8-S	-	-	-	-	-	ABDFGX	-	-	-
Q-8-10	-	-	-	-	-	ABDFGX	-	-	-
Q-9-S	-	-	-	BX	-	ADFG	-	-	-
Q-9-10	-	-	-	-	-	ABDFGX*	-	-	-
Q-R-1	-	-	-	-	ABDFGX	-	-	-	-

STATION	25 Feb 71	25 Feb 71	24 Mar 71	25 Mar 71	26 Mar 71	14 Apr 71	15 Apr 71	04 May 71	05 May 71
Q-1-S	ACDEFG	-	-	ACDEFG	-	-	-	ACDGX	-
Q-1-10	ADFG	-	-	ADFG	-	-	-	ADGX	-
Q-2-S	-	ACDEFG	-	-	ADFG	-	ACDFG	-	-
Q-2-10	-	ADFG	-	-	ADFG	-	ADFG	-	-
Q-3-Tap	-	ACDFG	-	-	ADFG	-	ACDFG	-	-
Q-4-S	-	-	ADFG	-	-	ACDFG	-	-	ACDGX
Q-5-S	-	-	ADFG	-	-	ACDEFG	-	-	-
Q-6-S	-	-	-	-	ADFG	ACDFG	-	-	ACDGX
Q-7-S	-	-	-	-	ADFG	-	ACDFG	-	ACDGX
Q-7-6.5	-	-	-	-	ADFG	-	ADFG	-	ADGX
Q-8-S	ACDEFG	-	-	ACDEFG	-	-	-	ACDGX	-
Q-8-10	ADFG	-	-	ADFG**	-	-	-	ADGX	-
Q-9-S	ACDEFG	-	-	ACDEFG	-	-	-	ACDGX	-
Q-9-10	ADFG	-	-	ADFG	-	-	-	ADGX	-
Q-R-1	-	ACDFG	ADFG	-	-	ACDFG	-	-	ACDGX

* Sample taken at 3 meters depth.

** Sample taken at 8 meters depth.

SAMPLE COLLECTIONS - QUABBIN RESERVOIR

STATION	06 May 71	18 May 71	19 May 71	20 May 71	01 Jun 71 *	02 Jun 71	03 Jun 71	15 Jun 71	16 Jun 71
Q-1-S	-	ABCDEFG	-	-	ACDFG	-	-	ACDFG	-
Q-1-10	-	ABDFG	-	-	ADFG	-	-	ADFG	-
Q-2-S	ACDGX	-	-	ABCDFG	-	-	ACDFG	-	-
Q-2-10	ADGX	-	-	ABDFG	-	-	ADFG	-	-
Q-3-Tap	ACDGX	-	-	ABCDFG	-	-	ACDFG	-	-
Q-4-S	-	-	ABCDFG	-	-	ACDFG	-	-	ACDFG
Q-5-S	ACDGX	-	-	ABCDFG	-	-	ACDFG	-	-
Q-6-S	-	-	ABCDFG	-	-	ABCDFG	-	-	ACDFG
Q-7-S	-	-	ABCDEFG	-	-	ACDFG	-	-	ACDFG
Q-7-6.5	-	-	ABDFG	-	-	ADFG	-	-	ADFG
Q-8-S	-	ABCDFG	-	-	ACDFG	-	-	ACDFG	-
Q-8-10	-	ABDFG	-	-	ADFG	-	-	ADFG	-
Q-9-S	-	ABCDFG	-	-	ACDFG	-	-	ACFG	D
Q-9-10	-	ABDFG	-	-	ADFG	-	-	ADFG	-
Q-R-1	-	-	ABCDFG	-	-	-	-	-	-

STATION	17 Jun 71	29 Jun 71	30 Jun 71	01 Jul 71	12 Jul 71	19 Jul 71	20 Jul 71	21 Jul 71	22 Jul 71
Q-1-S	-	ACDFG	-	-	E	-	ACDFGR	-	-
Q-1-10	-	ADFG	-	-	-	-	ADFGR	-	-
Q-2-S	ACDFG	-	-	ACDFG	-	E	-	-	ACDFGR
Q-2-10	ADFG	-	-	ADFG	-	-	-	-	ADFGR
Q-3-Tap	ACDFG	-	-	ACDFG	-	-	-	-	ACDFGR
Q-4-S	-	-	ACDFG	-	-	-	-	ACDFGR	-
Q-5-S	ACDEFG	-	-	ACDFG	-	E	-	-	ACDFGR
Q-6-S	-	-	ACDFG	-	-	-	-	ACDFGR	-
Q-7-S	-	-	ACDFG	-	E	-	-	ACDFGR	-
Q-7-6.5	-	-	ADFG	-	-	-	-	ADFGR	-
Q-8-S	-	ACDFG	-	-	-	-	ACDFGR	-	-
Q-8-10	-	ADFG	-	-	-	-	ADFGR	-	-
Q-9-S	-	ACDFG	-	-	-	-	ACDFGR	-	-
Q-9-10	-	ADFG	-	-	-	-	ADFGR	-	-
Q-R-1	-	-	-	-	-	-	-	-	-

* 27 May Q-2, E

SAMPLE COLLECTIONS - QUABBIN RESERVOIR

STATION	17 Aug 71	18 Aug 71	19 Aug 71	14 Sep 71	15 Sep 71	16 Sep 71	20 Sep 71	27 Sep 71
Q-1-S	ABCDFGX	-	-	ACDG	-	-	E	-
Q-1-10	ABDFGX	-	-	ADG	-	-	-	-
Q-2-S	-	-	ABCDFGX	-	-	ACDFG	-	E
Q-2-10	-	-	ABDFGX	-	-	ADFG	-	-
Q-3-Tap	-	-	ABCDFGX	-	-	ACDFG	-	-
Q-4-S	-	ABCDFGX	-	-	ACDFG	-	-	-
Q-5-S	-	-	ABCDFGX	-	-	ACDFG	-	E
Q-6-S	-	ABCDFGX	-	-	ACDFG	-	-	-
Q-7-S	-	ABCDFGX	-	-	ACDFG	-	E	-
Q-7-6.5	-	ABDFGX	-	-	ADFG	-	-	-
Q-8-S	ABCDFGX	-	-	ACDG	-	-	-	-
Q-8-10	ABDFGX	-	-	ADG	-	-	-	-
Q-9-S	ABCDFGX	-	-	ACDG	-	-	-	-
Q-9-10	ABDFGX	-	-	ADG	-	-	-	-
Q-R-1	-	-	-	-	-	-	-	-

SAMPLE COLLECTIONS - WACHUSETT RESERVOIR

STATION	29 Dec 70	20 Jan 71	26 Jan 71	27 Jan 71	28 Jan 71	29 Jan 71	04 Feb 71	18 Feb 71	01 Mar 71
W-1-S	ADFG	-	BX	ADFG	E	-	-	C	ACDFG
W-2-S	ADFG	-	-	-	-	ABDFGX	F	CE	ACDFG
W-2-10	ADFG	-	-	-	-	ABDFGX	F	-	ADFG
W-4-S	ADFG	-	BX	ADFG	-	-	-	C	ACDFG
W-5-S	-	ADFG	-	ABDFGX	-	-	-	CE	ACDFG
W-5-10	-	ADFG*	-	ABDFGX	-	-	-	-	ADFG
W-3-S	ADFG	-	-	-	-	-	-	-	-
W-4-S	ADFG	-	-	-	-	-	-	-	-

STATION	29 Mar 71	16 Apr 71	29 Apr 71	13 May 71	27 May 71	10 Jun 71	24 Jun 71	06 Jul 71	15 Jul 71
W-1-S	ACDFG	ACDFG	ADG	ACDFGX	ABCDFG	ACDFG	ACDFG	-	ACDFGR
W-2-S	-	ACDFG	ADG	ACDEFGX	ABCDFG	ACDFG	ACDFG	E	ACDFGR
W-2-10	-	ADFG	ADG	ADFGX	ABDFG	ADFG	ADFG	-	ADFGR
W-4-S	ACDFG	ACDFG	ADG	ACDFGX	ABCDFG	ACDFG	ACDFG	-	ACDFGR
W-5-S	ACDEFG	ACDFG	ADG	ACDEFGX	ABCDFG	ACDFG	ACDFG	E	ACDFGR
W-5-10	ADFG	ADFG	ADG	ADFGX	ABDFG	ADFG	ADFG	-	ADFGR

STATION	12 Aug 71	07 Sep 71	09 Sep 71						
W-1-S	ABCDFGX	-	ACDFG						
W-2-S	ABCDFGX	E	ACDFG						
W-2-10	ABDFGX	-	ADFG						
W-4-S	ABCDFGX	-	ACDFG						
W-5-S	ABCDFGX	E	ACDFG						
W-5-10	ABDFGX	-	ADFG						

*Sample taken at 6.5 meters depth.

SAMPLE COLLECTIONS - RIVERINE STATIONS

STATION	30 Dec 70	06 Jan 71	19 Jan 71	26 Jan 71	28 Jan 71	29 Jan 71	01 Feb 71	04 Feb 71	10 Feb 71
R-1	ADFG	-	-	BX	-	ADFG	-	-	CE
R-2	-	ADFG	-	BX	ADFG	-	-	E	-
R-3	-	ADFG	-	BX	ADFG	-	-	E	-
R-4	-	ADFG	-	-	-	ADFG	-	-	-
R-5	-	ADFG	-	BX	-	ADFG	-	-	-
R-6	-	ADFG	-	-	ADFG	-	-	E	-
R-7	-	ADFG	-	BX	ADFG	-	-	E	-
R-8	-	ADFG	-	BX	ADFG	-	-	E	-
R-9	ADFG	-	-	-	-	ADFG	-	-	CE
R-10	ADFG	-	-	-	-	ADFG	-	-	CE
R-11	ADFG	-	E	-	-	-	ADFG	-	-
R-12	ADFG	-	E	-	-	-	ADFG	-	-

STATION	16 Feb 71	26 Feb 71	02 Mar 71	03 Mar 71	16 Mar 71	19 Mar 71	22 Mar 71	23 Mar 71	24 Mar 71
R-1	-	-	ADFG	-	-	-	ADFG	-	-
R-2	C	-	-	ADFG	CE	-	-	ADFG	-
R-3	C	-	-	ADFG	CE	-	-	ADFG	-
R-4	CE	-	ADFG	A	-	-	ADFG	-	-
R-5	E	-	ADFG	A	-	-	ADFG	-	-
R-6	C	-	-	ADFG	-	-	-	ADFG	-
R-7	C	-	-	ADFG	-	-	-	ADFG	-
R-8	C	-	-	ADFG	-	-	-	ADFG	-
R-9	-	-	ADFG	-	-	-	ADFG	-	-
R-10	-	-	ADFG	-	-	-	ADFG	-	-
R-11	-	ADFG	-	-	-	C	-	-	ADFG
R-12	-	ADFG	-	-	-	C	-	-	ADFG

SAMPLE COLLECTIONS - RIVERINE STATIONS

STATION	31 Mar 71	05 Apr 71	08 Apr 71	12 Apr 71	13 Apr 71	14 Apr 71	21 Apr 71	22 Apr 71	27 Apr 71
R-1	-	-	C	ACDFG	-	-	-	X	-
R-2	-	-	-	-	ACDFG	-	X	-	ADG
R-3	-	-	-	-	ACDFG	-	X	-	ADG
R-4	C	E	-	ACDFG	-	-	X	-	ADG
R-5	-	CE	-	ACDFG	-	-	X	-	-
R-6	CE	-	-	-	ACDFG	-	X	-	ADG
R-7	CE	-	-	-	ACDFG	-	X	-	ADG
R-8	C	-	-	-	ACDFG	-	X	-	ADG
R-9	-	C	-	ACDEFG	-	-	-	X	-
R-10	-	CE	-	ACDFG	-	-	-	X	-
R-11	-	-	-	-	-	ACDFG	-	X	-
R-12	-	-	-	-	-	ACDFG	-	X	-

STATION	28 Apr 71	11 May 71	12 May 71	25 May 71	26 May 71	08 Jun 71	09 Jun 71	22 Jun 71	23 Jun 71
R-1	ADG	-	ACDFG	-	ABCDFG	-	ACDFG	-	ACDFG
R-2	-	ACDG	-	ABCDFG	-	ACDFG	-	ACDFG	-
R-3	-	ACDG	-	ABCDFG	-	ACDFG	-	ACDFG	-
R-4	-	ACDG	-	ACDFG	-	ACDFG	-	ACDFG	-
R-5	ADG	-	ACDFG	-	ABCDFG	-	ACDFG	-	ACDFG
R-6	-	ACDG	-	ACDFG	-	ACDFG	-	ACDFG	-
R-7	-	ACDG	-	ABCDFG	-	ACDFG	-	ACDFG	-
R-8	-	ACDG	-	ABCDFG	-	ACDFG	-	ACDFG	-
R-9	ADG	-	ACDFG	-	ACDFG	-	ACDFG	-	ACDFG
R-10	ADG	-	ACDFG	-	ACDFG	-	ACDFG	-	ACDFG
R-11	ADG	-	ACDFG	-	ACDFG	-	ACDFG	-	ACDFG
R-12	ADG	-	ACDFG	-	ACDFG	-	ACDFG	-	ACDFG

SAMPLE COLLECTIONS - RIVERINE STATIONS

STATION	08 Jul 71	13 Jul 71	14 Jul 71	15 Jul 71	26 Jul 71	02 Aug 71	04 Aug 71	10 Aug 71	11 Aug 71
R-1	E	-	ACDFG	R	-	-	-	-	ABCDFGX
R-2	-	ACDFG	-	R	E	-	-	ABCDFGX	-
R-3	-	ACDFG	-	R	E	-	-	ABCDFGX	-
R-4	-	ACDFG	-	R	-	-	E	ACDFGX	-
R-5	-	-	ACDFG	R	-	-	E	-	ABCDFGX
R-6	-	ACDFG	-	R	-	E	-	ACDFGX	-
R-7	-	ACDFG	-	R	-	E	-	ABCDFGX	-
R-8	-	ACDFG	-	R	-	-	-	ABCDEFGX	-
R-9	-	-	ACDFG	R	-	-	E	-	ACDFGX
R-10	-	-	ACDFG	R	-	-	-	-	ACDFGX
R-11	-	-	ACDFG	R	-	-	-	-	ACDFGX
R-12	-	-	ACDFG	R	-	-	-	-	ACDFGX

STATION	16 Aug 71*	30 Aug 71	07 Sep 71	08 Sep 71					
R-1	-	-	-	ACDFG					
R-2	-	-	ACDFG	-					
R-3	-	-	ACDFG	-					
R-4	E	-	ACDFG						
R-5	-	-	-	ACDFG					
R-6	-	-	ACDFG						
R-7	-	-	ACDFG						
R-8	-	-	ACDFG	-					
R-9	-	-	-	ACDFG					
R-10	E	-	-	ACDFG					
R-11	-	E	-	ACDFG					
R-12	-	E	-	ACDFG					

* 23 Aug R-1, E

4. METHODOLOGY

Analytical methods for the various parameters were in keeping with the methods recommended in the United States Public Health Service, Drinking Water Standards (USPHS, 1962).

Many of the parameters are not covered in Drinking Water Standards (DWS) nor in Standard Methods for the Examination of Water and Wastewater (Standard Methods; APHA, 1971) recommended for analytical methods in DWS. In other instances only tentative procedures are suggested (e.g. chlorinated hydrocarbon pesticides). Finally, some of the sampling and analytical methods recommended in Standard Methods for macroinvertebrates had little relevance to some of the bottom substrates we encountered in some riverine stations.

Procedures followed in this study, then, were in keeping with Standard Methods and DWS. Changes were adopted to fit particular circumstances, usually after consultation with the MDC and the Corps of Engineers. Attempts were made to use the best methods available in the state-of-the-art, consistent with reasonable costs. Details in methodology are discussed in appropriate sections in the rest of this report and more extensively in Appendix 1.

5. RESULTS OF WATER QUALITY TESTS

A. Biological Data

(1) Bacteria

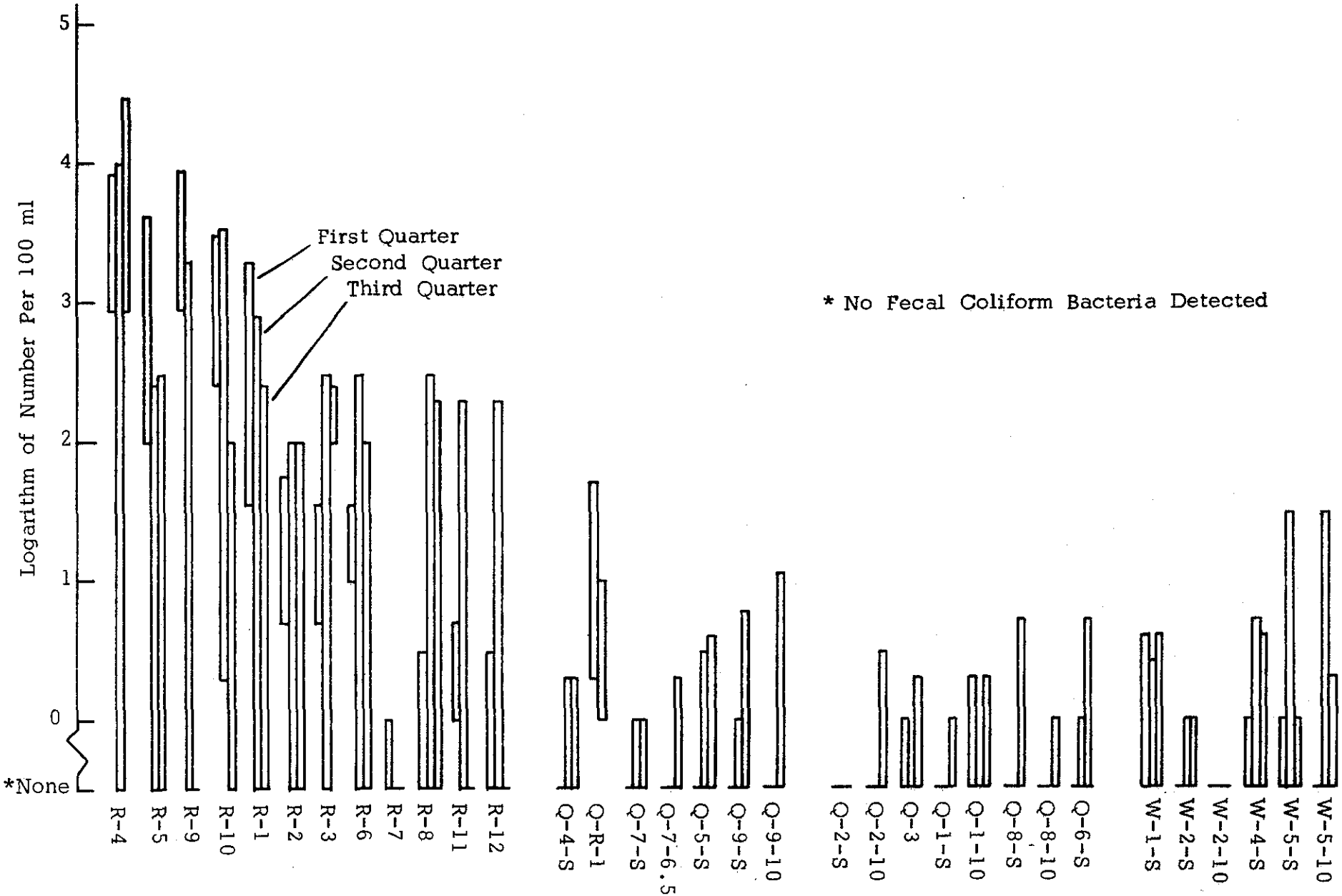
Bacterial data collected from Quabbin Reservoir are subdivided, in this report, into two groups: data collected from "inside" stations (Q-4, Q-5, Q-7, Q-9, Q-R-1), and data collected from "outside" stations (Q-1, Q-2, Q-3, Q-6, Q-8) (Figure 5). Bacterial populations observed in waters collected from "outside" stations were often one-half the bacterial populations observed in waters collected from "inside" stations. Bacterial concentrations observed in Wachusett Reservoir waters (Figure 6) were generally intermediate to those observed in Quabbin "inside" and "outside" waters.

The range of bacterial numbers observed at any one time in the various riverine waters was extremely variable, as can be seen in Figure 8; and subdivisions of riverine data, based upon ranges of numbers of bacteria typically detected in individual riverine systems (Figure 7) are as follows:

(a) data collected from the Millers and Connecticut River stations (R-1, R-4, R-5, R-9, R-10)

(b) data collected from the Millers River tributaries (R-2, R-3, R-6, R-7, R-8) and the Ware River (R-11, R-12).

Figure 8. Range of Fecal Coliform Bacteria for Each Station for the First Three Quarters, 1971



Bacterial concentrations in the Millers River tributaries and Ware River were generally comparable with concentrations observed in reservoir waters, while those in the Millers and Connecticut Rivers were significantly higher (Table 1).

The Connecticut River and Millers River system showed few changes in numbers of hetrotrophic bacteria over the first two quarters of the year and a general decrease in the third quarter, with the exception of the Millers River at South Royalston (R-4) (Figure 9). Most of the tributary rivers, however, showed a significant rise in average numbers of heterotrophic bacteria from the first to the second quarter, and a comparable drop in numbers in the third quarter. Most Quabbin "inside" and "outside" stations demonstrated a general increase in heterotrophic bacteria populations throughout the three quarters, the major increase in the "outside" stations occurring between the first and second quarters. A general increase in heterotrophic populations was observed in Wachusett Reservoir between the first and second quarters. No overall pattern of increase or decrease, however, was noted in Wachusett Reservoir between the second and third quarters.

Abrupt increases in numbers of total coliform bacteria were noted in almost all systems in the second quarter. Abrupt decreases in these numbers occurred between the second and third quarters (Table 2 and Figure 10).

There was little significant change in numbers of fecal coliform

Table 1. Modal Log Values of Bacterial Numbers per 100 ml for Major Station Groupings, 1971

	Total Heterotrophic Bacteria			Total Coliform Bacteria			Fecal Coliform Bacteria		
Modal Log Value	First Quarter	Second Quarter	Third Quarter	First Quarter	Second Quarter	Third Quarter	First Quarter	Second Quarter	Third Quarter
6.5	MC	MC							
6.0									
5.5			MC						
5.0									
4.5	T	Qi T	Qi T						
4.0									
3.5	Qi	Qo W	Qo W	MC	MC T	MC	MC		
3.0									
2.5	Qo W					T		MC	MC*
2.0									
1.5				T					
1.0									
<1.0				Qi Qo W	Qi Qo W	Qi Qo W	Qi Qo T	Qi Qo W T	Qi Qo W T MC*

*Bimodal distribution

Legend

Qi: Quabbin "inside"
Qo: Quabbin "outside"
W: Wachusett
MC: Millers and Connecticut Rivers
T: Millers Tributaries and Ware River

Table 2. Logarithm of Bacterial Numbers Per 100 ml.

		Heterotrophic Bacteria			Total Coliform Bacteria			Fecal Coliform Bacteria		
Quarter		1	2	3	1	2	3	1	2	3
Quabbin "Outside"	No. of Readings	27	36	18	29	36	20	29	36	20
	Average	3.4	4.0	4.4	<0	0.2	0.3	<0	<0	<0
	Mode	2.5	3.5	3.5	<1	<1	<1	<1	<1	<1
	Range	1.5 4.7	2.7 4.8	3.2 5.4	* 1.0	* 1.3	* 1.0	* 0.3	* 0.0	* 0.7
Quabbin "Inside"	No. of Readings	24	30	16	24	30	16	24	28	16
	Average	4.4	4.3	5.0	0.8	1.2	0.3	0.4	<0	0.2
	Mode	3.5	4.5	4.5	<1	<1	<1	<1	<1	<1
	Range	1.9 5.4	3.0 5.0	3.9 5.9	* 1.9	* 2.0	* 1.0	* 1.7	* 1.0	* 1.0
Wachusett	No. of Readings	19	29	18	21	30	18	21	30	18
	Average	4.1	4.2	3.9	0.1	1.3	0.9	<0	0.6	<0
	Mode	2.5	3.5	3.5	<1	<1	<1	<1	<1	<1
	Range	2.4 5.2	2.8 5.0	3.3 4.4	* 1.0	* 2.4	* 1.7	* 0.6	* 1.5	* 0.6
Millers Tributaries and Ware River	No. of Readings	28	30	21	28	30	21	28	30	21
	Average	4.7	5.2	4.8	3.1	2.9	2.2	0.9	1.7	1.7
	Mode	4.5	4.5	4.5	1.5	3.5	2.5	0.5	<1	<1
	Range	4.0 5.6	4.3 5.9	4.3 5.2	* 2.0	* 3.6	* 2.6	* 1.7	* 2.5	* 2.4

* No Bacteria Detected (hence no log entry for lower limit)

Figure 9. Logarithm of Average Number of Heterotrophic Bacteria per 100 ml

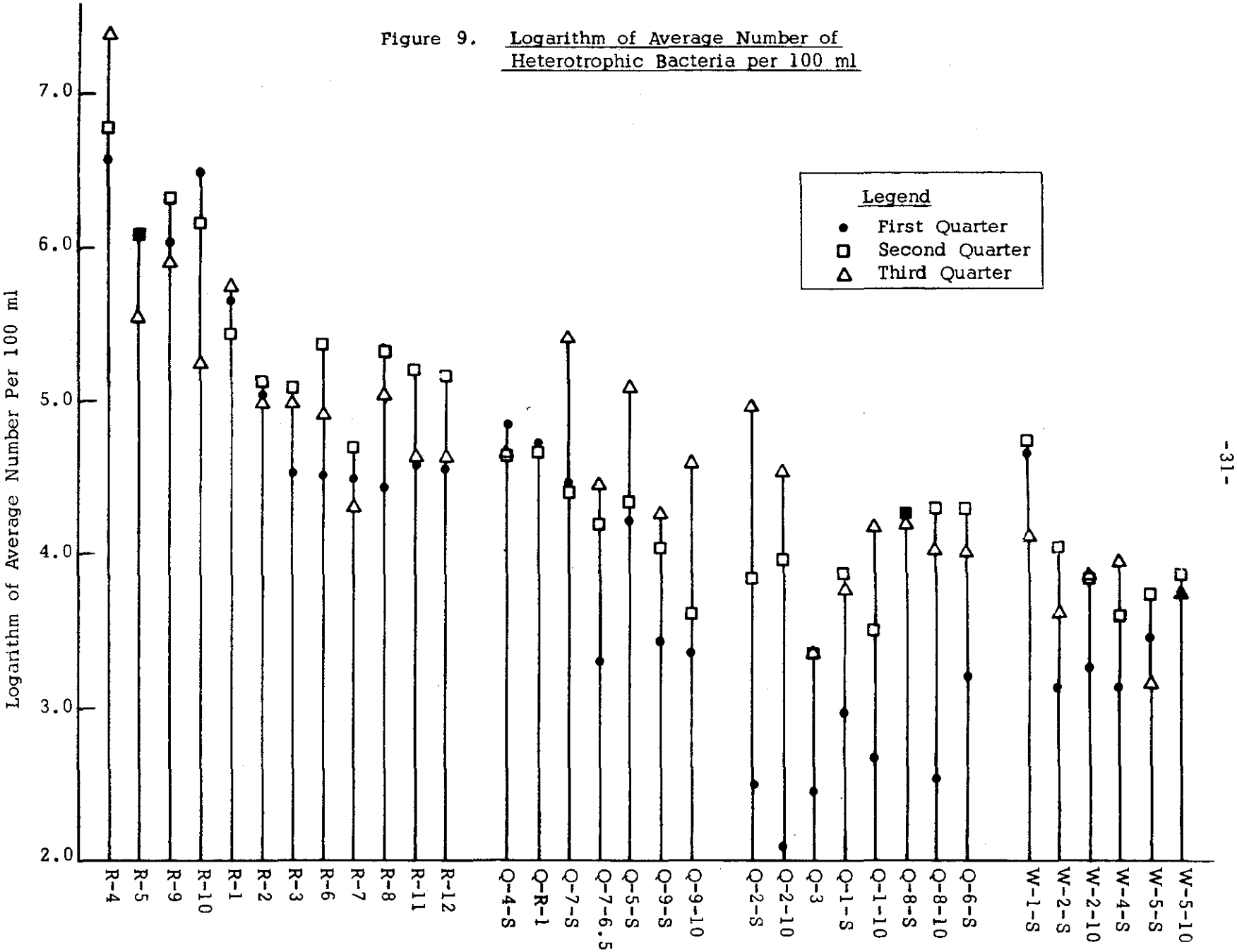
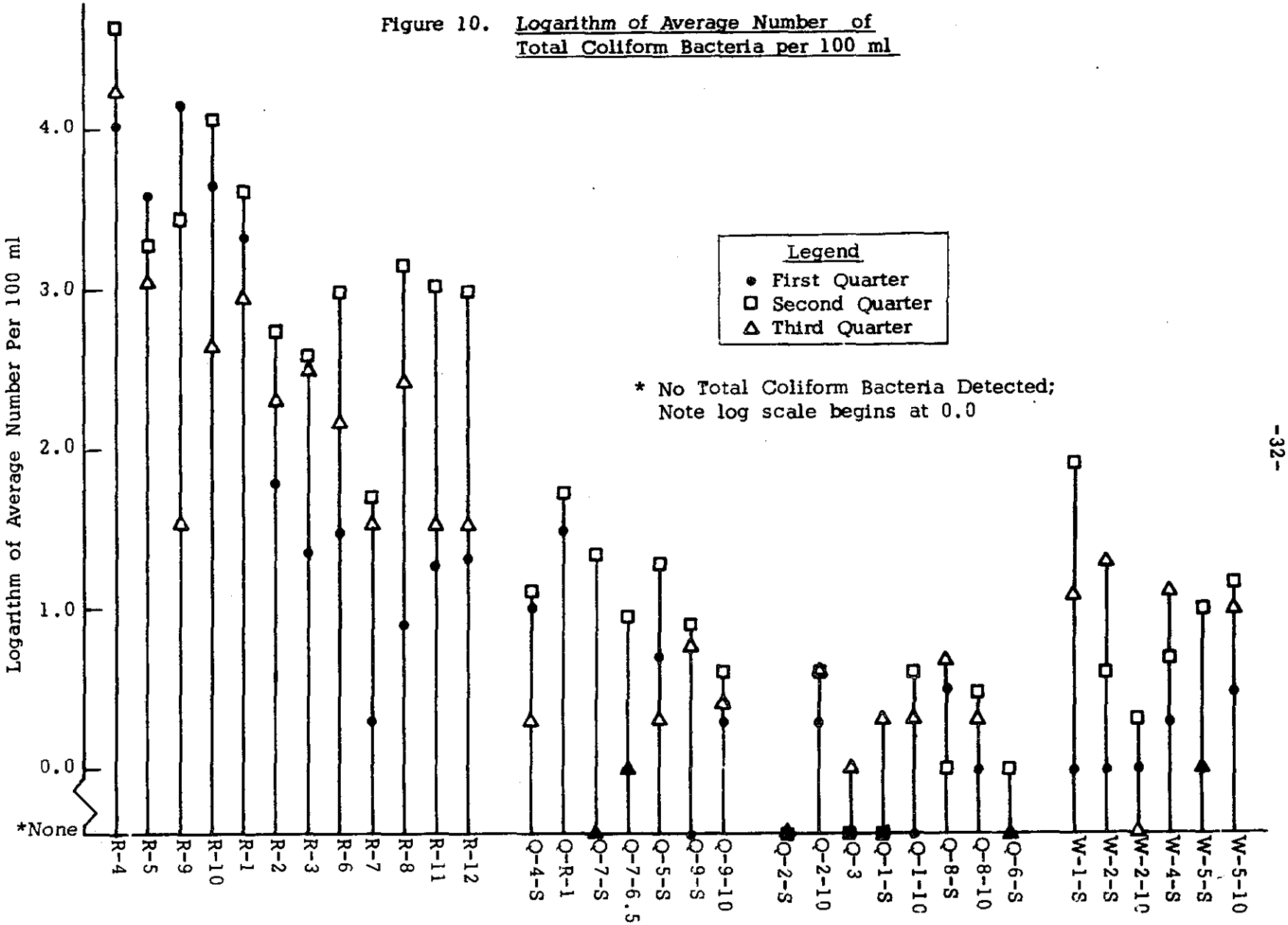


Figure 10. Logarithm of Average Number of Total Coliform Bacteria per 100 ml



bacteria in the reservoirs throughout the three quarters. About half of the tributary rivers (Millers River and the Ware River) showed an increase in fecal coliform numbers in the second quarter. In some instances this population increase persisted through the third quarter. The Millers and Connecticut Rivers showed a general decrease in fecal coliform numbers in both the second and the third quarters, with the exception of the Millers River at South Royalston (R-4) (Figure 11).

Patterns of overall similarity between the individual systems examined over two quarters can be depicted by means of the total coliform data plotted in Figure 12. In general, bacterial populations of the Millers and Connecticut Rivers were comparable, and were distinguished from the bacterial populations observed in other systems by their being up to several orders of magnitude greater than those observed in other systems. The tributaries to the Millers River typically showed bacterial populations intermediate between the reservoirs and the Ware River.

The highest numbers of bacteria were usually found in the South Royalston area of the Millers River (R-4). The bacterial populations tended to decrease between South Royalston and Athol (R-5), and then either remained constant or increased downstream to Orange (R-9) and Farley (R-10) (Figure 13).

Chromogenic (pigment-producing) bacteria were less than 20% of the total heterotrophic populations of all the riverine and most of the reservoir

Figure 11. Logarithm of Average Number of Fecal Coliform Bacteria per 100 ml

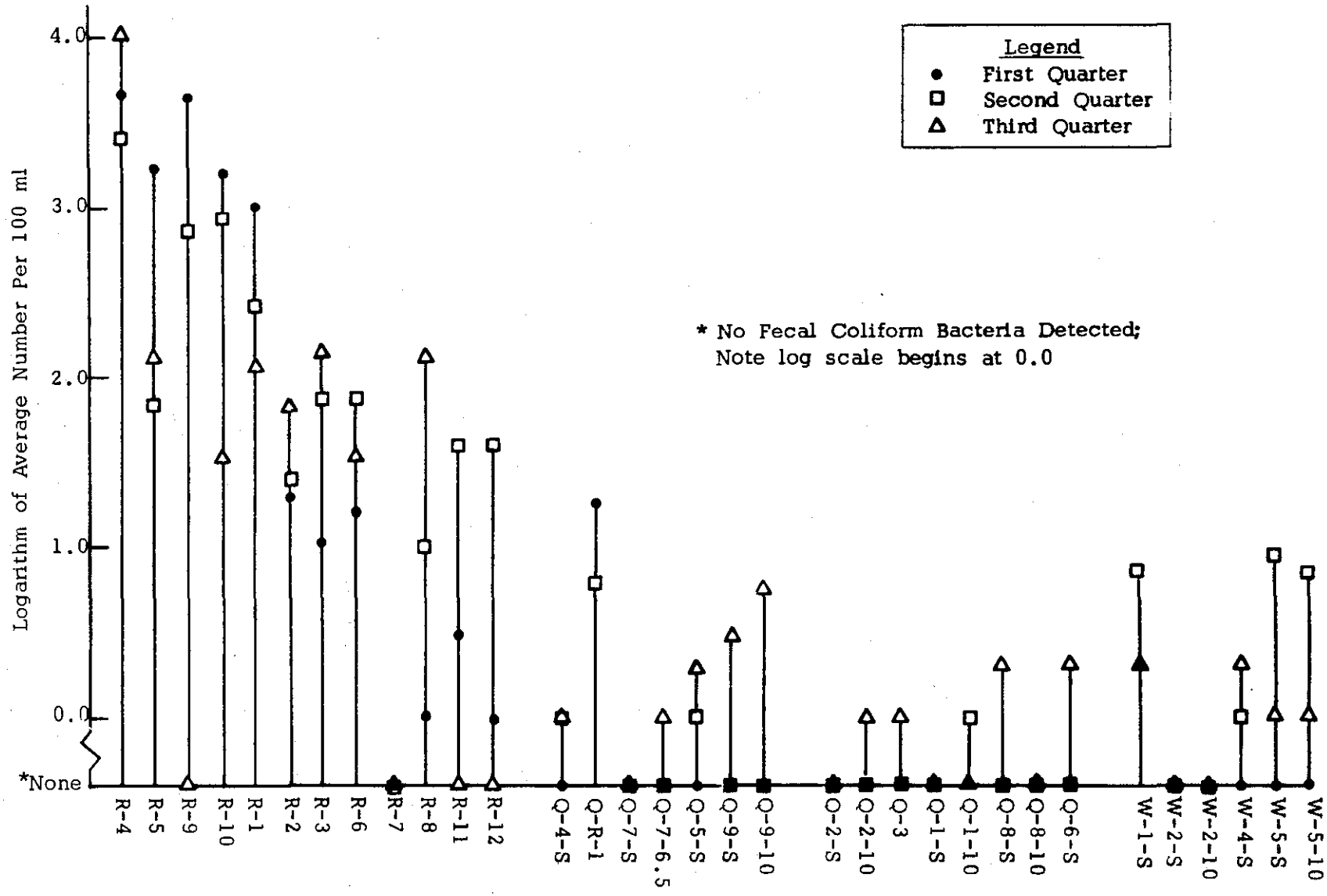


Figure 12. Frequency-Concentration Distribution of Total Coliform Bacteria Populations
(Logarithm of Bacterial Numbers per 100 ml.
First and Second Quarters, 1971)

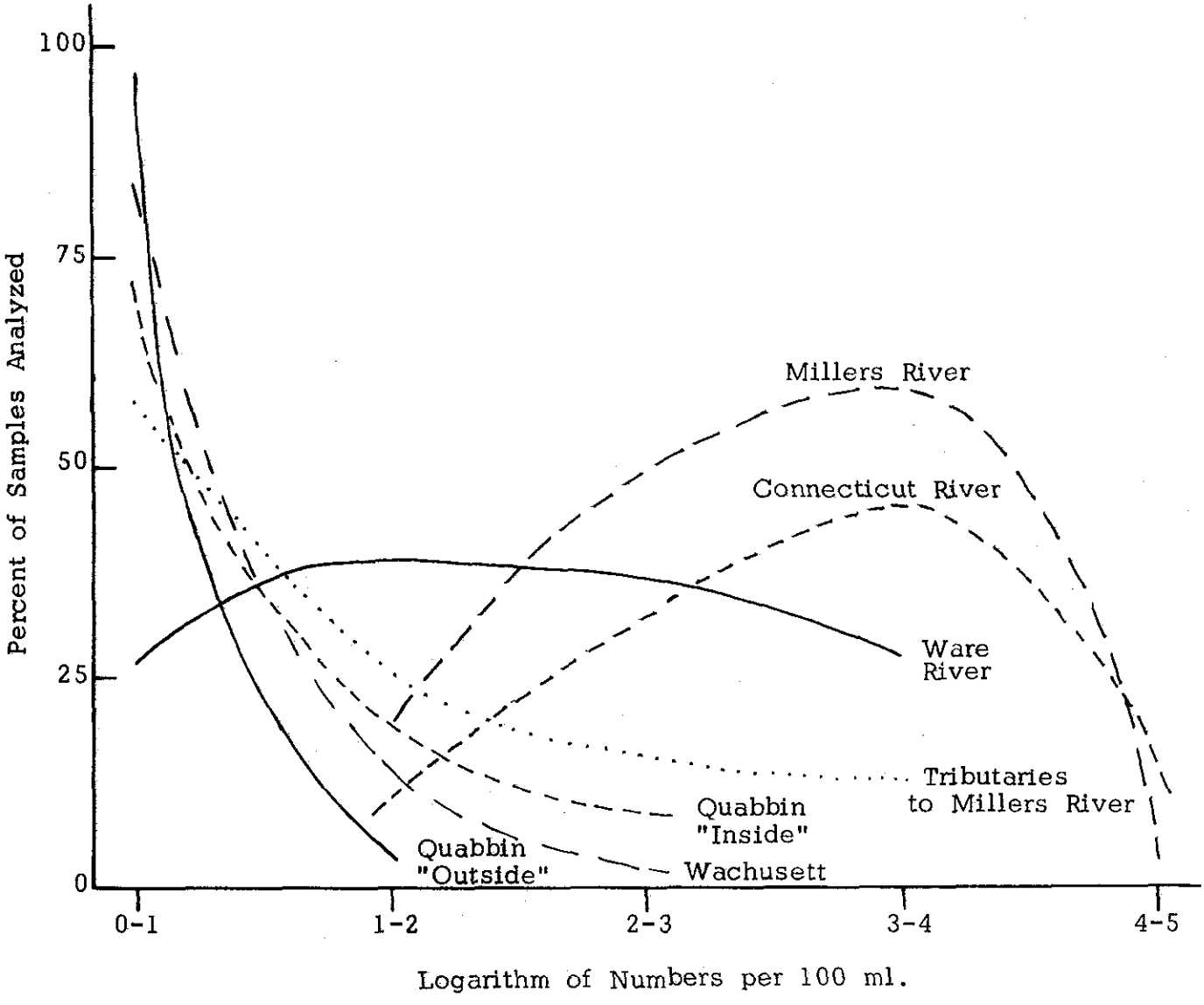
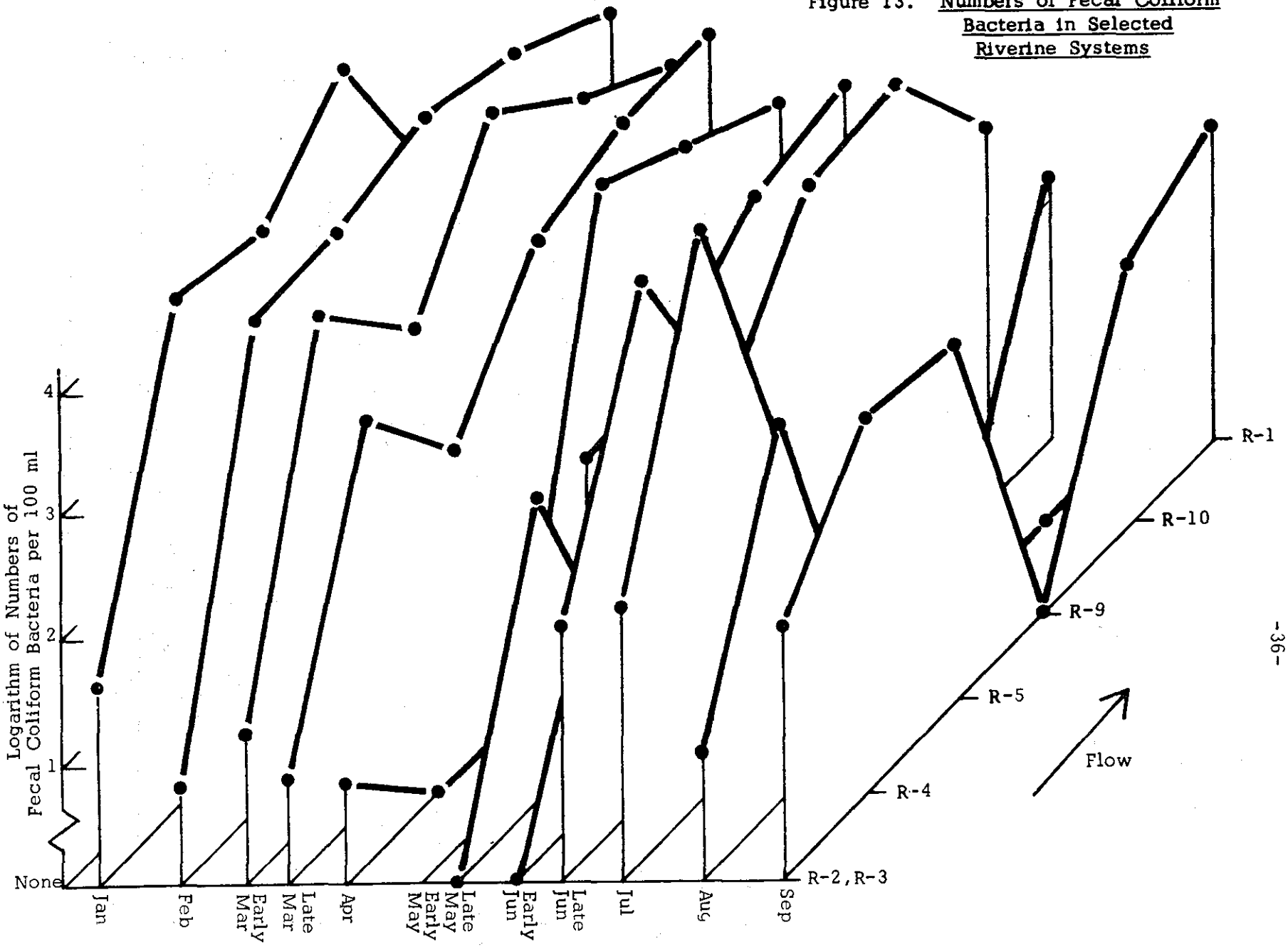


Figure 13. Numbers of Fecal Coliform Bacteria in Selected Riverine Systems



stations during the first quarter (Figure 14). Although individual stations within each system did not show identical patterns of chromogenic populations, the reservoir systems tended to have significantly higher proportions of chromogenic to total heterotrophic bacteria than the riverine systems. Two explanations should be considered. First, chromogenic heterotrophs are considered by some investigators to be true aquatic bacteria adapted to lacustrine environments which have a low nutrient concentration. Second, the riverine systems have higher coliform bacteria (Non-chromogenic) populations than the reservoirs; these higher counts tend to reduce the chromogen: total heterotroph ratios. Chromogen populations increased dramatically in the reservoirs in the second quarter, reaching up to and over 50% of the heterotrophic bacterial populations in June-July. A typical example of this increase in chromogenic populations is depicted in Figure 15.

(2) Phytoplankton

Reservoir and riverine systems generally showed different frequencies and concentrations of specific algal groups (Table 3). These differences were greatest during the first quarter when reservoir waters showed relatively higher frequencies of occurrence of coccoid green algae, desmids, other green algae, pennate diatoms, centric diatoms, dinoflagellates, and golden-brown flagellates. Riverine waters showed only pennate diatoms frequently occurring during the first quarter (Figure 16). During the second quarter, the riverine and reservoir systems had more similar phytoplanktonic populations. However, while reservoir systems showed little change in the frequency of occurrence of algal groups between the first

Figure 14. Chromogenic Bacteria as Average Percent of the Total Population of Heterotrophic Bacteria

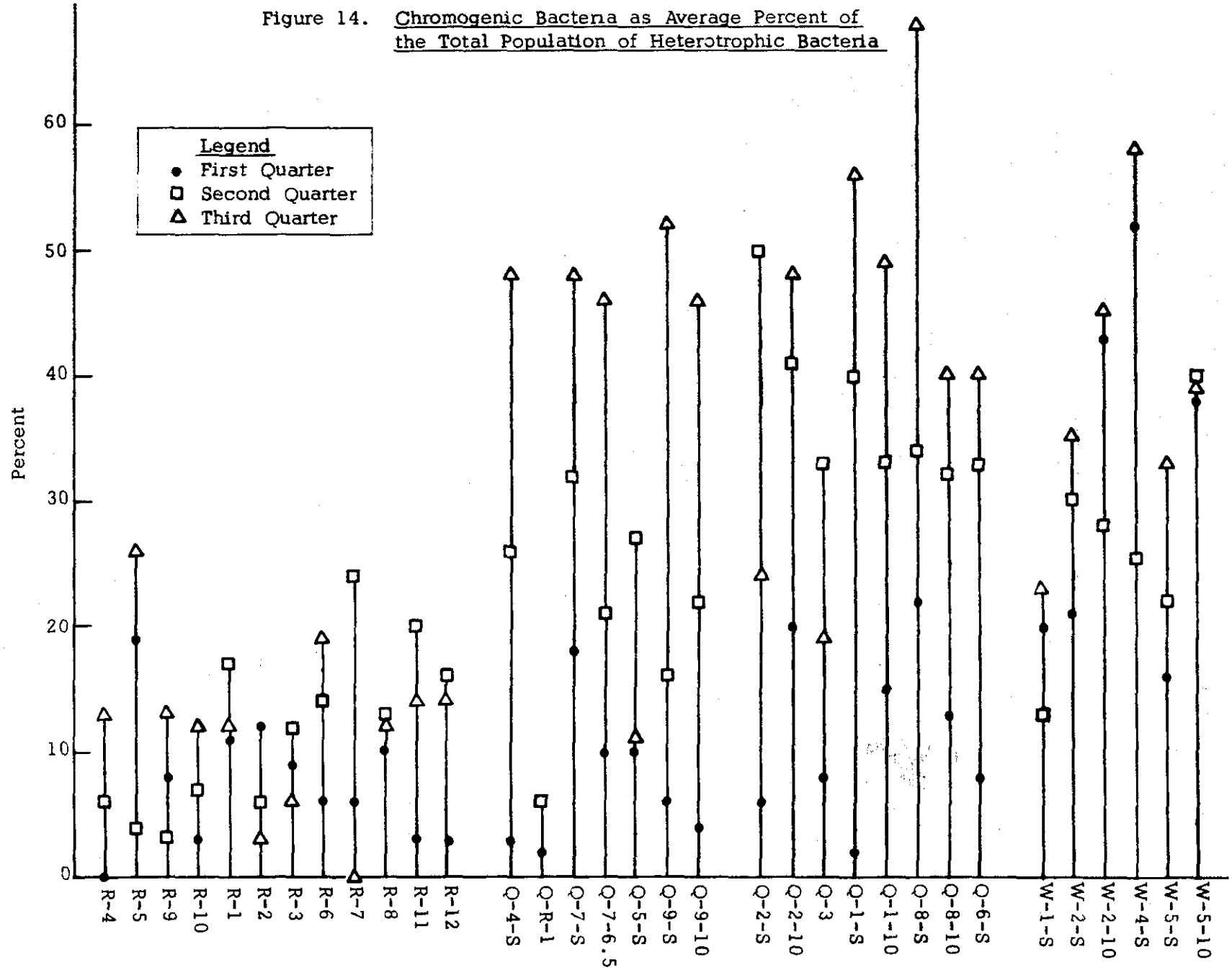


Figure 15. Seasonal Variations in Composition of Heterotrophic Populations (Station Q-8-S)

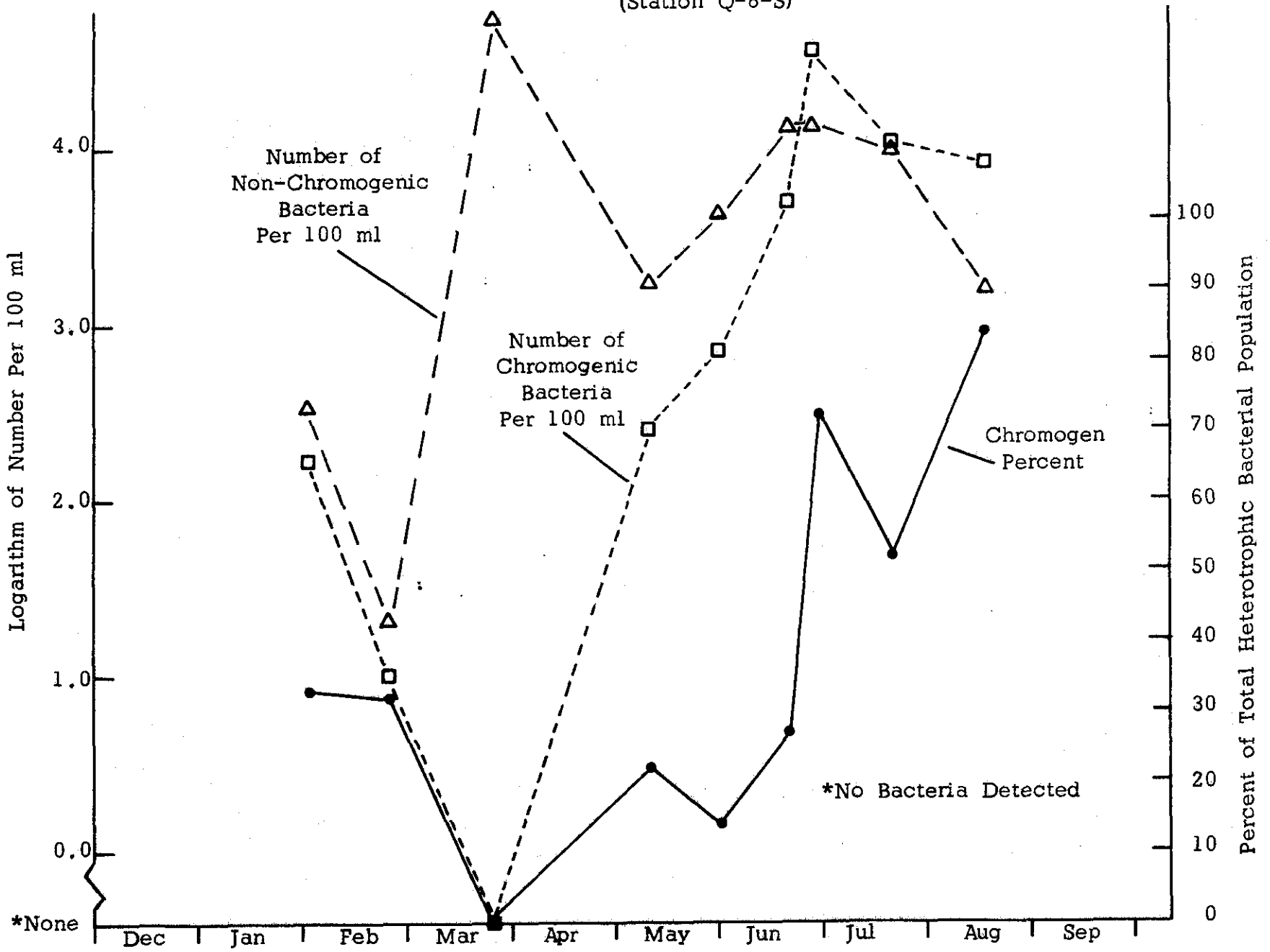


Table 3. Modal Values of Algal Populations

Algal Groups	FG			FilG			CG			Des			Other			FilBG			CBG			PenD			CenD			Dino			GBF		
Quarter	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Range of Number/liter																																	
> 5000			4 5					5*	2 3 5						5						1 2 3	2 3	4 5	1			1 2 3						
1000-5000									1	1	1	1 2 3			1 2 3							4 5	1 2 3	2 3 4 5		3*			3*				3
500-1000										3																							
100-500											3														1* 3	3*							
<100	All systems not indicated in above columns																																

* A bimodal distribution was observed in this system.
The second modal value is <100, unless shown.

Location Codes

1 = Quabbin "Outside"
2 = Quabbin "Inside"
3 = Wachusett Reservoir
4 = Millers River Tributaries
5 = Millers and Connecticut Rivers

Code for Algal Groups

FG = Flagellated Greens
FilG = Filamentous Greens
CG = Coccoid Greens
Des = Desmids
Other = Other Greens
FilBG = Filamentous Blue-greens
CBG = Coccoid Blue-greens
PenD = Pennate Diatoms
CenD = Centric Diatoms
Dino = Dinoflagellates
GBF = Golden Brown Flagellates

Figure 16. Percent of Samples in Which Algal Groups Present (First Quarter, 1971)

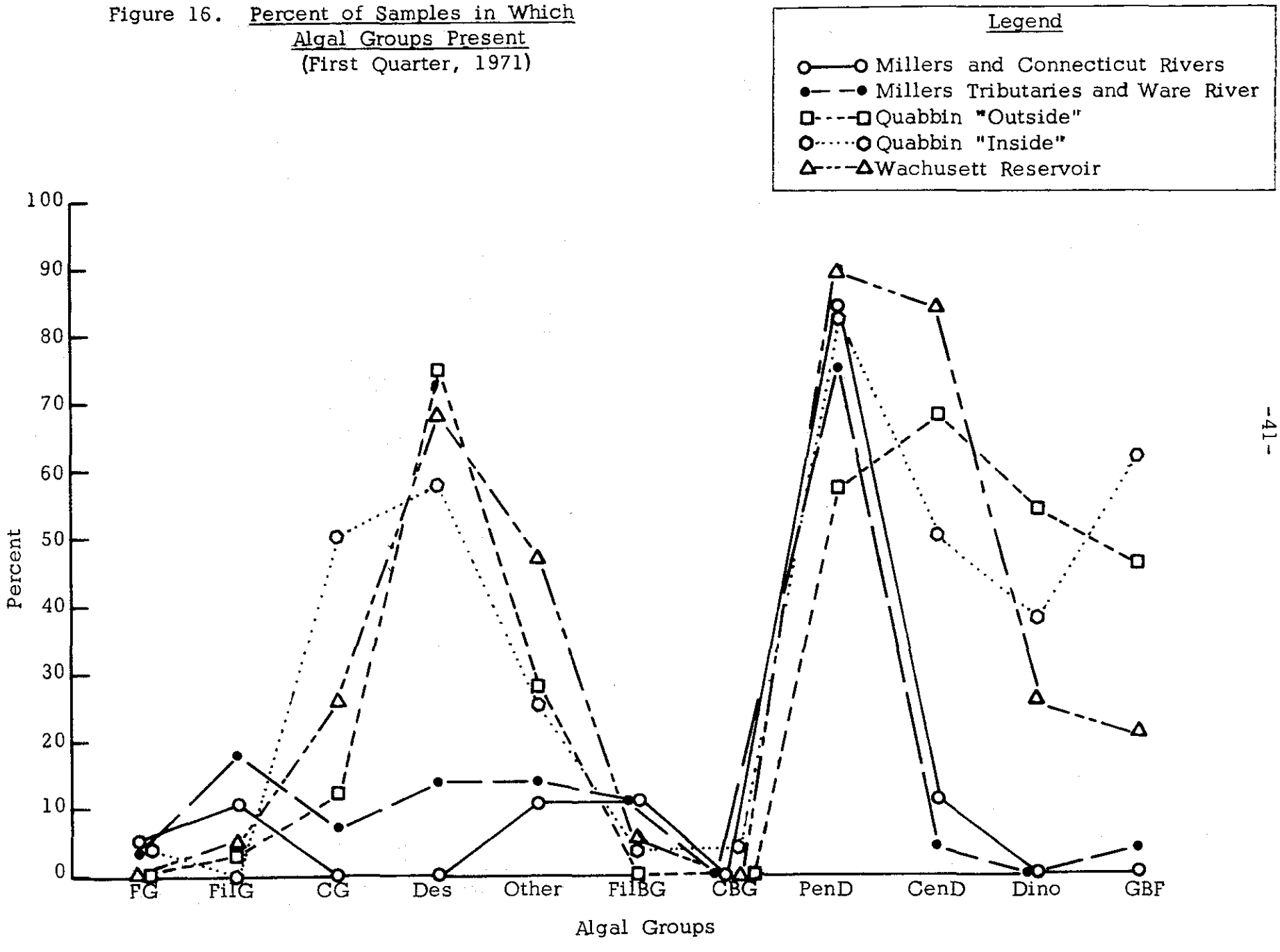
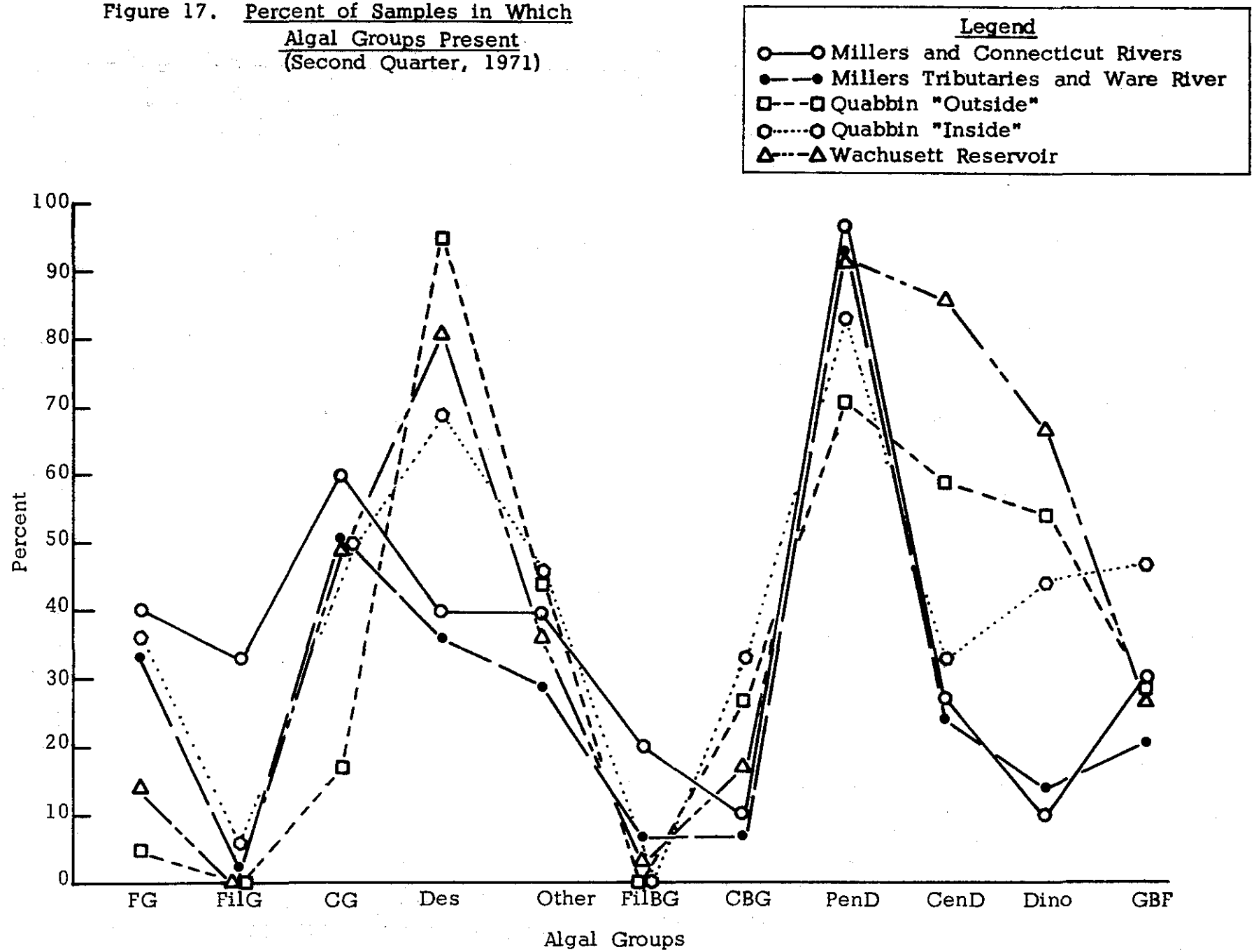


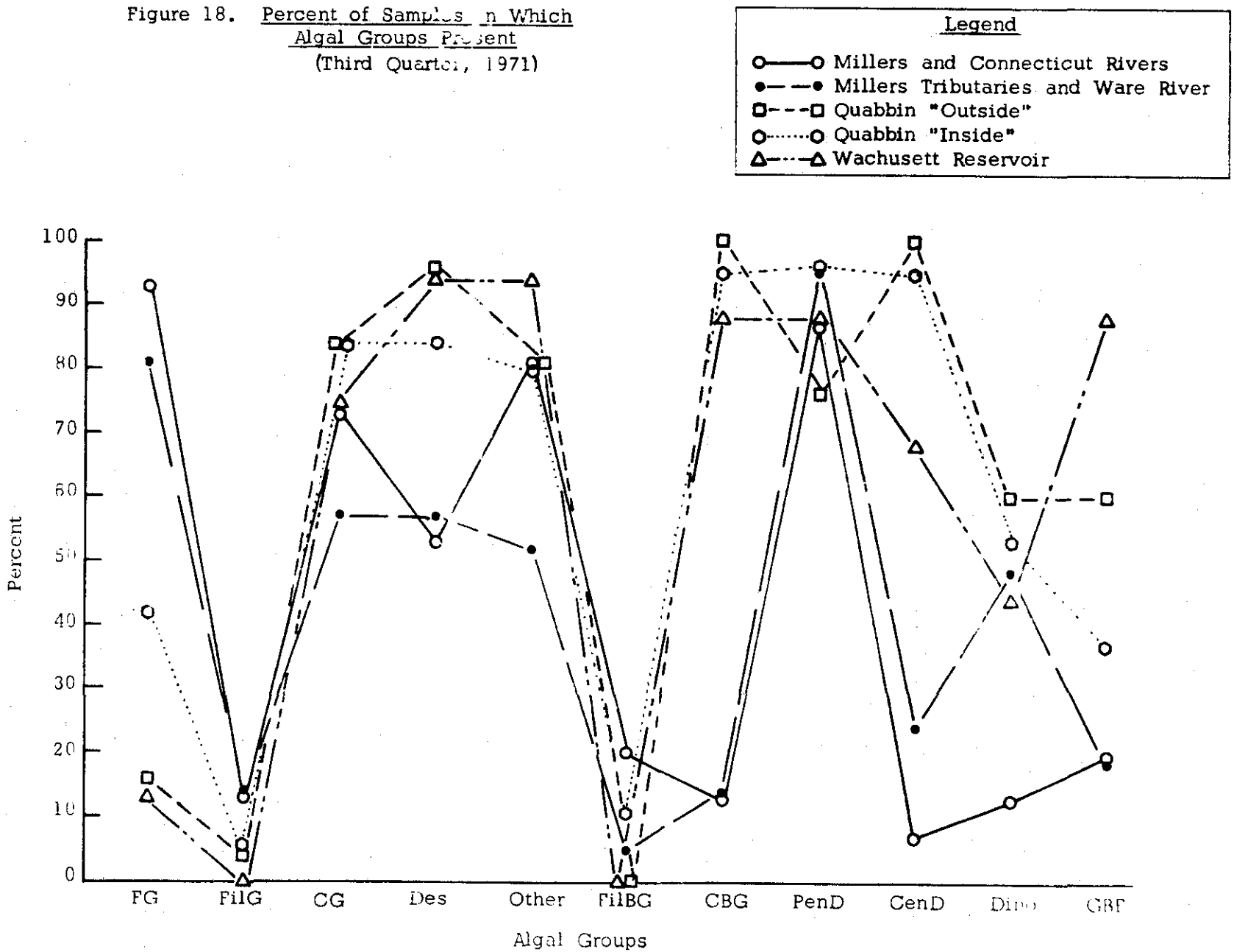
Figure 17. Percent of Samples in Which Algal Groups Present (Second Quarter, 1971)



and second quarters, riverine systems showed an increased occurrence of coccoid green algae, desmids, and other green algae (Figure 17). The Millers and Connecticut River system, in particular showed the development of a moderate abundance of flagellated and filamentous green algae. Most systems showed an increased frequency of occurrence of most groups of algae during the third quarter (Figure 18). The only major drops in frequency of occurrence during the third quarter were in centric diatoms in Wachusett Reservoir and the Millers and Connecticut River systems, and in dinoflagellates in Wachusett Reservoir.

Modal values of algal numbers for each quarter for the various algal groups are compared in Table 3. Filamentous green and filamentous blue-green algae rarely occurred in any system. Flagellated green, other green and coccoid blue-green algae showed few numbers during the first and second quarters, but higher values were common for some systems during the third quarter. Most riverine and reservoir systems showed high third-quarter values for other green algae. Only reservoir systems had high third-quarter values for coccoid blue-green populations. Pennate diatoms commonly occurred in high numbers in most all systems during all three quarters. Centric diatoms were commonly absent in riverine systems, but commonly occurred at low levels, and even increased, over the three quarters in reservoir systems. Dinoflagellates and golden-brown flagellates rarely occurred in riverine systems. Dinoflagellates and golden-brown flagellates occurred in reservoir waters, but at low levels. Coccoid green algae showed an increased frequency of occurrence of high numbers from first to third

Figure 18. Percent of Samples in Which Algal Groups Present
(Third Quarter, 1971)



quarters in most systems. Desmids occurred more often in reservoir than in riverine systems. In general the modal values for the populations of all algal groups except flagellated green algae were the same or higher in the reservoir systems than in the riverine systems.

Numbers of desmids, centric diatoms, and coccoid blue-green algae show major differences between the reservoir and riverine systems. Populations of each of these algal groups were typically higher in reservoir than in riverine waters. This was particularly true of coccoid blue-green populations in the third quarter.

(3) Zooplankton

Although a variety of kinds of animals were observed in water samples collected for zooplanktonic analysis, the zooplankton of both the reservoirs and rivers belong to two major groups, the Class Crustacea (Phylum Arthropoda) and the Phylum Rotifera. Organisms which are not classified in either of these two groups, but which were observed in water samples specifically collected for zooplanktonic analysis are designated in this report as either Protozoa* or benthic organisms.

Benthic animals are often observed in riverine surface waters collected for zooplanktonic analysis. Of all the rivers examined, the Millers River showed the largest numbers of benthic organisms and Protozoa.

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*Protozoans technically may be either benthic or planktonic. However, the methodology employed in the enumeration of crustaceans and rotifers does not yield an adequate representation of actual protozoan populations, and this group is therefore handled in this report as a separate group.

In general, water samples from Wachusett and Quabbin Reservoirs contained comparable concentrations of crustaceans and rotifers (Figure 19). Water samples from most of the riverine systems also contained similar concentrations of crustaceans and rotifers. Exceptions were (1) Connecticut River, in which rotifers tended to predominate over crustaceans, and (2) the East Branch of the Tully River (R-7), and the Millers River at Orange (R-9) in which crustaceans predominated over rotifers (Figure 20 and Table 4).

A plot (Figure 21) of the average concentration of rotifers versus crustaceans (Table 5) shows the concentrations of these organisms in the reservoirs to be directly correlated, and reveals three kinds of quantitative differences among the reservoir stations. First, all the Wachusett stations are at the lower end of the plot. Second, there is an apparent trend among the Quabbin stations of high to low zooplankton concentrations as one moves from stations near the inputs to the reservoir to stations located near outputs from the reservoir (the only exception is Q-4 at Pottapaug Pond). Third, all 6 depth stations (see note on Figure 21) occupy the middle portion of the plot.

This third observation, however, in contrast to the other two, may be an artifact of the sampling patterns and procedures employed and may therefore be of only methodological significance. For example, the depth stations are ones in which the plankton concentration was averaged over the top 10 meters. The plankton concentrations at Q-5, which is a relatively

Figure 19. Monthly Variations in Numbers of Reservoir Zooplankton

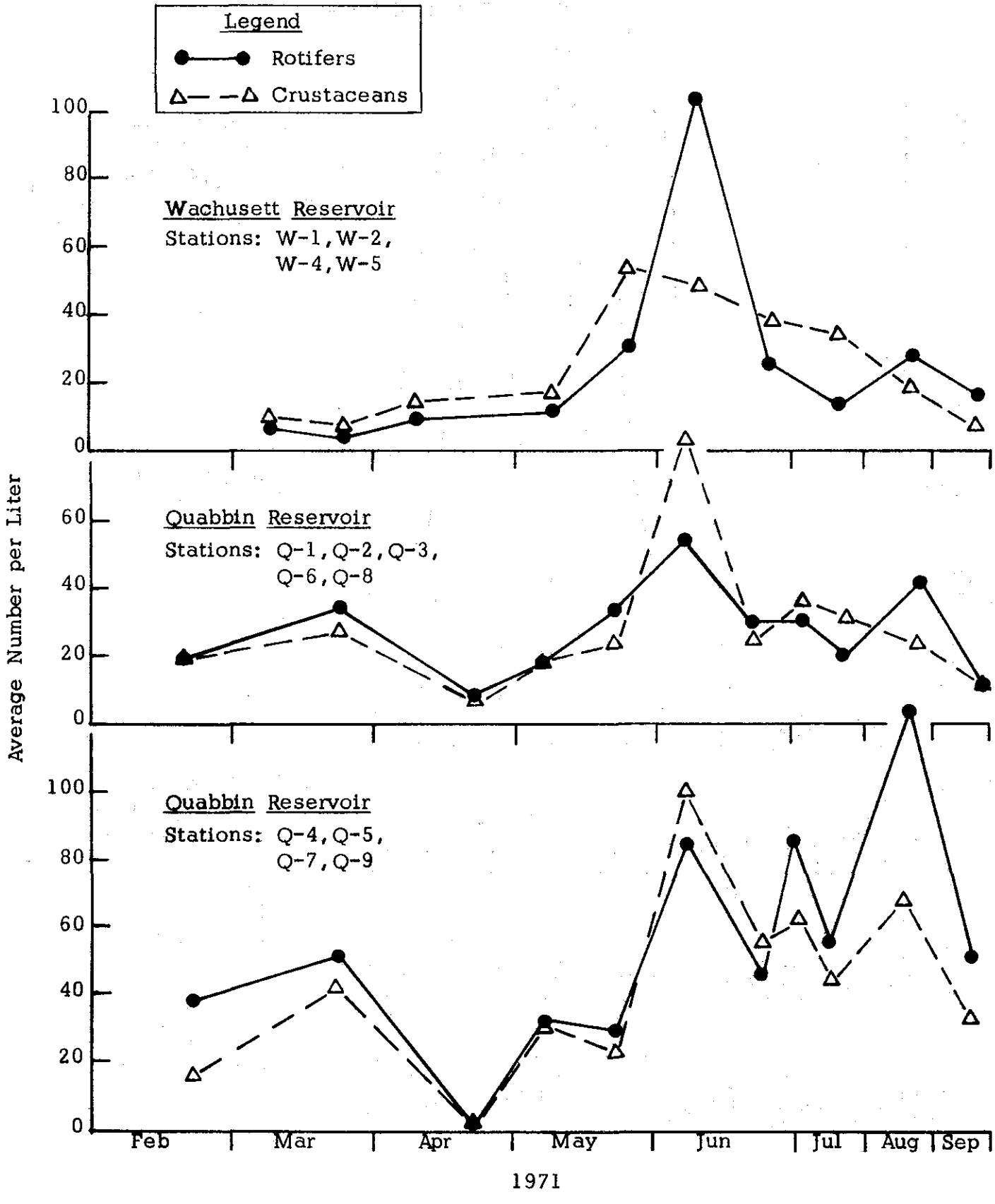


Figure 20. Monthly Variations in Numbers of Riverine Zooplankton

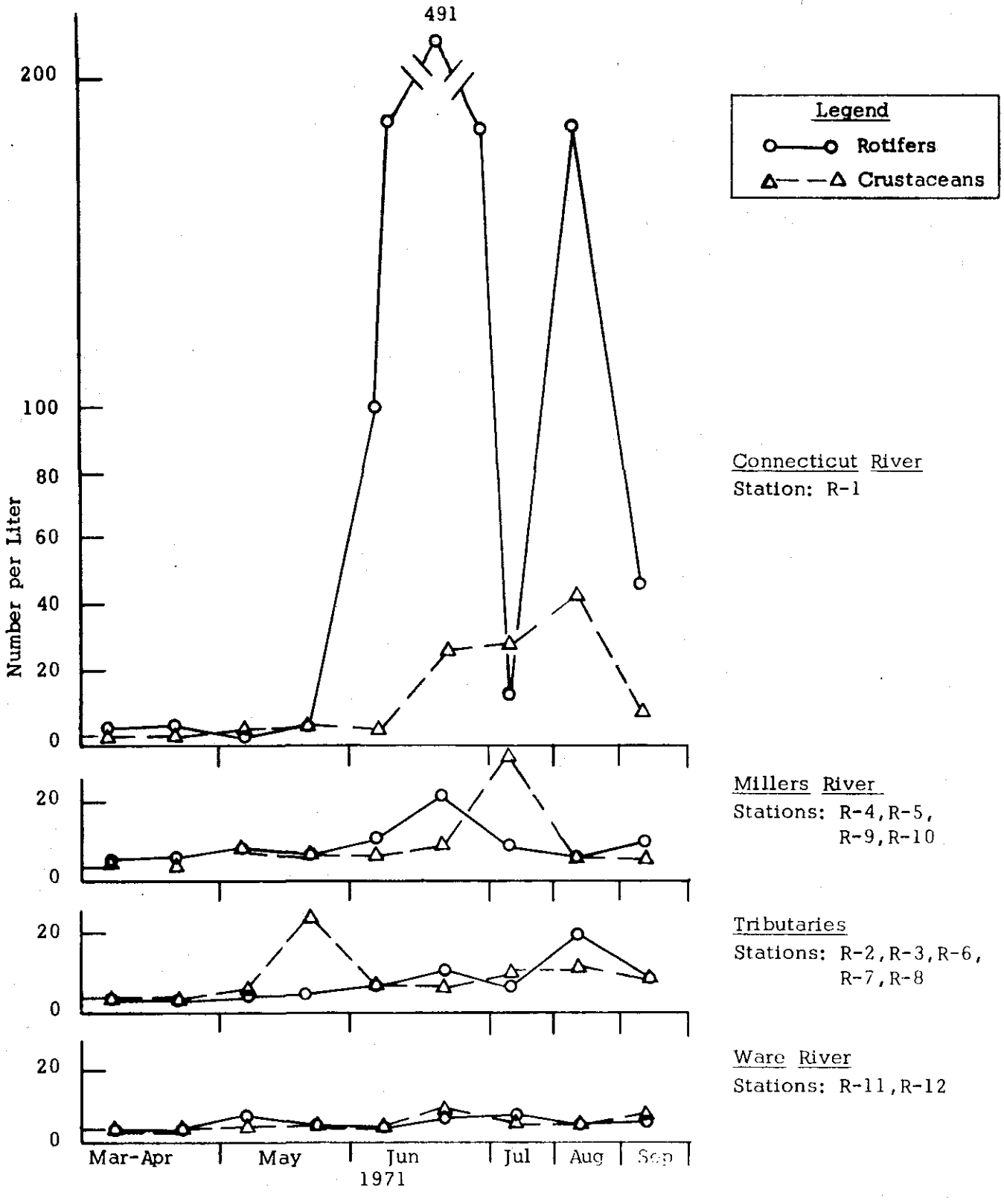


Table 4. Riverine Zooplankton
(March through September, 1971)

	Station	No. of Samples	Average No. Crustaceans per Liter	Maximum No. of Crustaceans per Liter	Average No. Rotifers per Liter	Maximum No. of Rotifers per Liter
Ware River	R-11	9	0.3	1	1	6
	R-12	9	2	10	2	7
Connecticut River	R-1	9	12	41	93	491
Millers River	R-4	7	1	4	6	26
	R-5	9	2	6	5	27
	R-9	9	17	119	10	30
	R-10	9	3	10	4	15
Tributaries	R-2	9	1	3	2	13
	R-3	9	0.4	1	2	16
	R-6	9	0.6	5	0.6	3
	R-7	9	23	116	15	89
	R-8	9	4	18	1	8

Figure 21. Reservoir Zooplankton

(concentration of crustaceans versus concentration of rotifers)

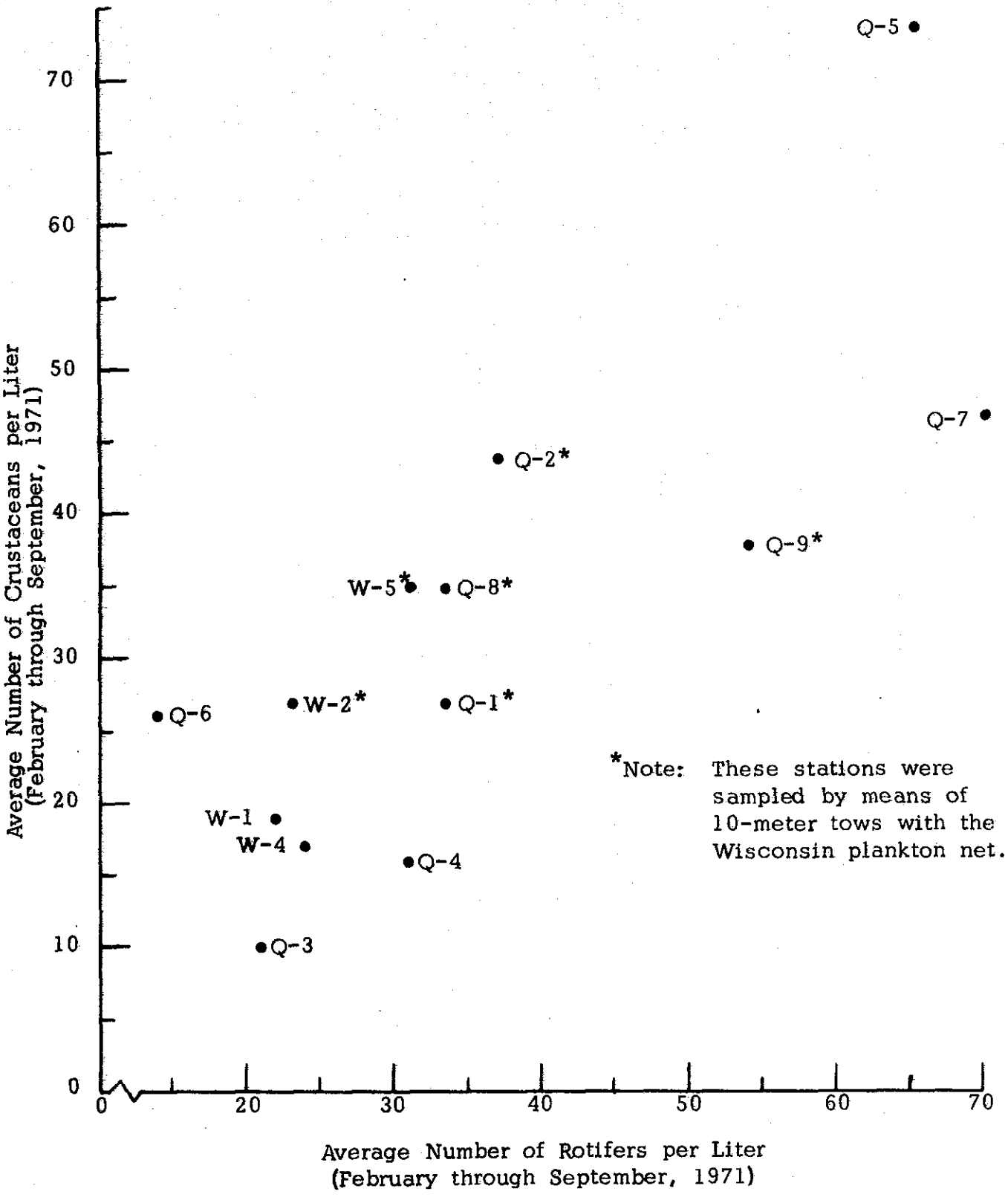


Table 5. Reservoir Zooplankton
(February through September, 1971)

	Station	No. of Samples	Average No. Crustaceans per Liter	Range of Nos. of Crustaceans per Liter	Average No. Rotifers per Liter	Range of Nos. of Rotifers per Liter
Wachusett Reservoir	W-1	10	19	1-92	22	1-142
	W-2	9	27	3-64	23	3-47
	W-5	10	35	6-137	31	4-80
	W-4	10	17	1-36	24	2-146
Quabbin Reservoir "inside" stations	Q-4	10	16	1-45	31	1-183
	Q-7	10	47	7-143	70	1-126
	Q-9	10	38	12-61	54	10-192
	Q-5	10	74	1-259	65	1-281
Quabbin Reservoir "outside" stations	Q-2	10	44	14-129	37	10-83
	Q-8	10	35	16-71	33	8-58
	Q-1	10	27	10-64	33	15-84
	Q-6	10	26	1-160	14	0-49
	Q-3	10	10	1-21	21	1-48

shallow station, were averaged over the top 1 meter. Because of similar considerations of depth, the plankton concentrations at Q-7 were averaged over the top 5-6 meters. Also, the 5 stations at the low end of the scatter diagram represent running outlets (Q-3, W-4) or surface samples taken from shore (Q-4, Q-6, W-1). Two of the latter have shallow bottoms (Q-4, Q-6) and two have moderate currents (Q-4, W-1). The outlet stations in Quabbin and Wachusett Reservoirs are different in two respects. The Chicopee outlet (Q-3) at Winsor Dam draws deep water from below the thermocline while the outlet at Wachusett (W-4) draws water close to the surface. The sampling technique employed at these stations also differed. Water was drawn by tap at Q-3, but hauled up by bucket from the surface of the intake at W-4. In addition, zooplankton fragments in the samples from Q-3 gave evidence of destruction of some plankters from turbulence in the plumbing system.

The composition of the zooplankton was the same throughout the reservoirs, but some differences in the relative abundance of zooplanktonic types were observed from station to station and over time (Figure 22 and Table 6). All stations show a dramatic expansion of the Order Cladocera in early June, but cladocerans formed a much larger proportion of the crustacean zooplankton in Wachusett than in Quabbin (57% and 37% respectively for June through September; see Figures 22 and 23).

Some notion of the relative abundance of the various genera of zooplankton can be gained by comparing their frequency of occurrence in the

Figure 22. Seasonal Variations in Composition of Reservoir Zooplankton

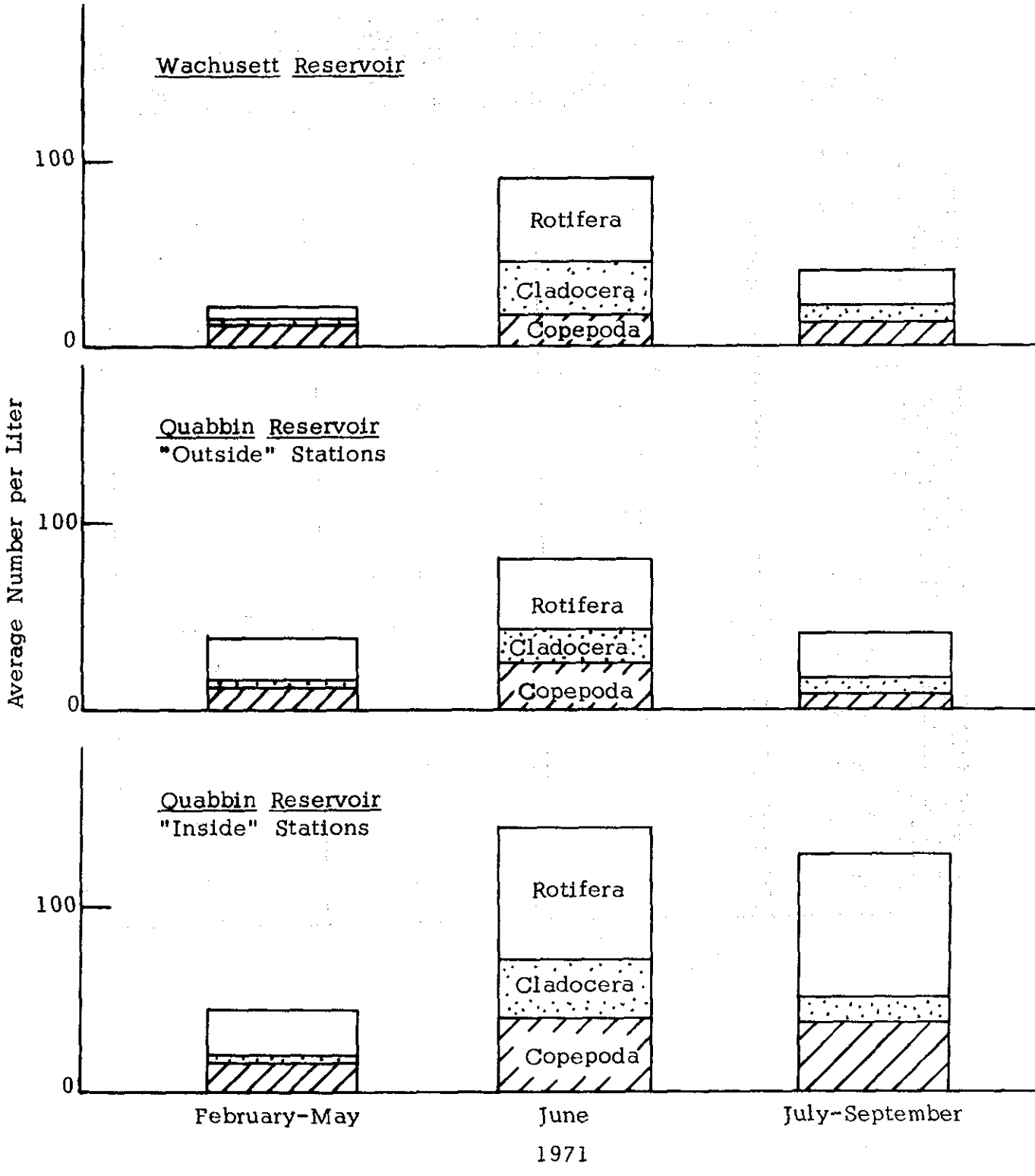
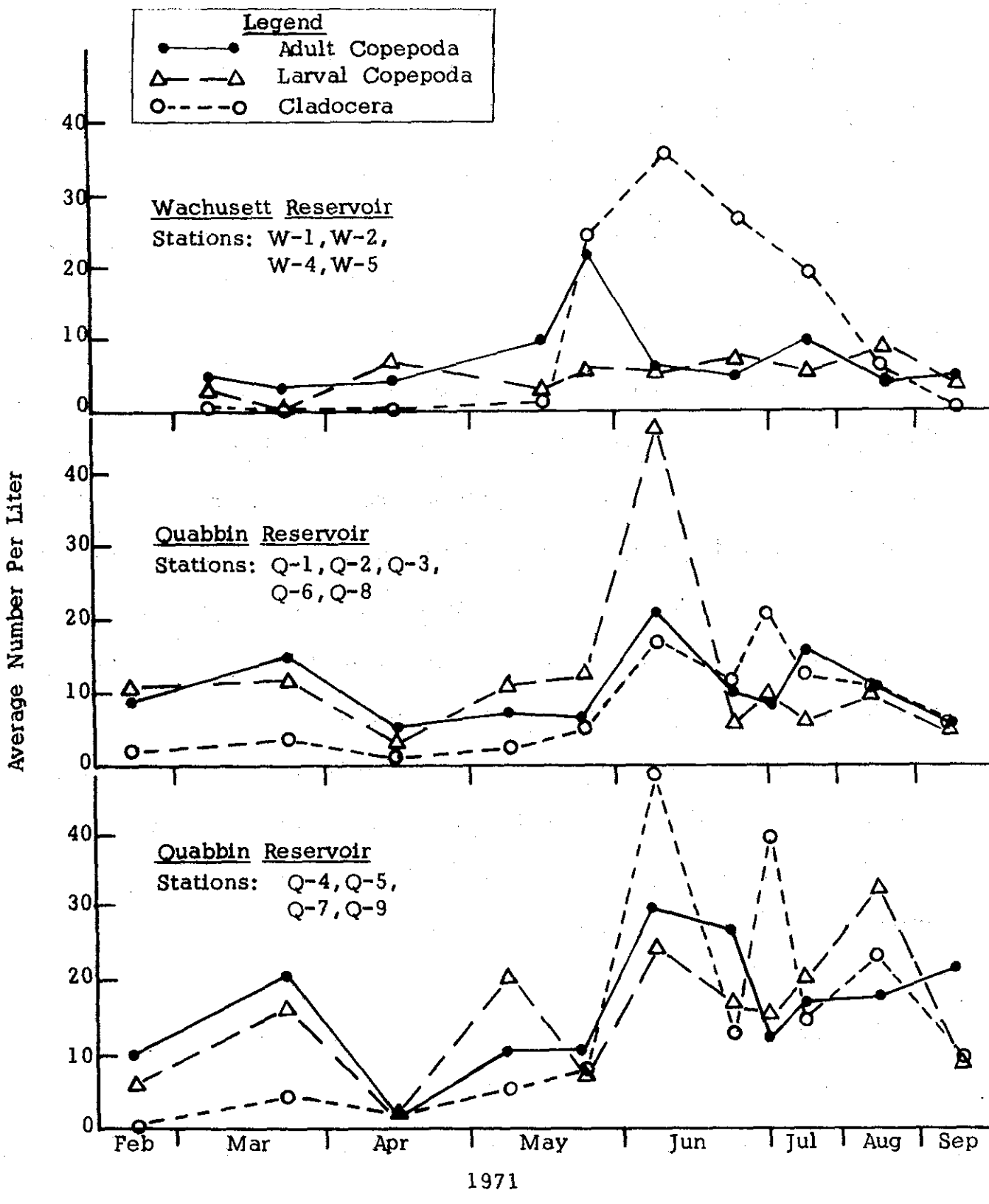


Table 6. Reservoir Crustaceans
(February through September, 1971)

	Station	Average Number Per Liter		
		Cladocera	Adult Copepoda	Larval Copepoda
Wachusett Reservoir	W-1	13	4	3
	W-2	15	6	5
	W-5	17	14	5
	W-4	5	5	7
Quabbin Reservoir "inside" stations	Q-4	4	4	8
	Q-7	26	11	11
	Q-9	11	15	13
	Q-5	20	28	25
Quabbin Reservoir "outside" stations	Q-2	17	14	13
	Q-8	12	15	9
	Q-1	8	9	9
	Q-6	2	4	20
	Q-3	2	4	5

Figure 23. Monthly Variations in Numbers of Reservoir Zooplankton



samples (Table 7). The only genus which can be readily used to differentiate groups of reservoir stations from each other was the colonial rotifer Conochilus. Conochilus was present in 69% of the Quabbin "inside" station samples, and 58% and 53% of the Quabbin "outside" and Wachusett stations,respectively. Conochilus was not only present but was also noted as the predominant rotifer in 43% of the Quabbin "inside" station samples, but in only 17% of the samples from all other reservoir stations. Conochilus did not make its appearance in the reservoirs until May, and its predominance within the rotifer population was associated with all but one of the subsequent rotifer peaks shown in Figure 19. In Wachusett Reservoir Conochilus was predominant in 7 of the 8 samples taken in the June and August peak periods, and was not predominant in any of the 16 samples taken during non-peak periods. In Quabbin Reservoir Conochilus was predominant in 12 of the 22 samples taken in the peak periods, and in only 7 of the 30 samples taken during non-peak periods.

Rotifers and crustaceans which were commonly found in the reservoirs were also found in the rivers (Table 7), but there was a greater variety of rotifers in the rivers than in the reservoirs. Many riverine rotifers lacked the skeletons characteristic of reservoir rotifers, and were observed to be actively climbing on debris.

The frequencies of occurrence of riverine zooplankton were less than those of reservoir zooplankton, and the average concentration of zooplankton at most of the riverine stations was about one order of magnitude less

Table 7. Relative Composition of Reservoir and Riverine Zooplankton Samples

Note from the numbers of samples in the reservoirs (column 3) that subcategorie of Rotifera, Copepoda and Cladocera were not identified for all samples.

Type of Organism	% of Reservoir Samples in which present	Total Reservoir Samples	% of Riverine Samples in which present	Total Riverine Samples
ROTIFERA	99	129	67	106
Keratella	84	116	33	106
Kellicottia	80	116	8	106
Polyarthra	75	116	13	106
Conochilus	59	116	14	106
Gastropus	26	116	12	106
Lepadella	5	116	2	106
Monostyla	4	116	5	106
Asplanchna	3	116	0	106
Filinia	3	116	1	106
Unidentified	52	116	46	106
CRUSTACEA	100	129	63	106
Copepoda	100	129	52	106
Calanoid	82	109	5	106
Cyclopoid	83	109	19	106
Harpacticoid	2	109	0	106
Larvae	98	129	42	106
Ostracoda	0	129	5	106
Cladocera	87	129	34	106
Bosmina	73	113	25	106
Holopedium	67	113	4	106
Daphnia	60	113	7	106
Polyphemus	7	113	3	106
Leptodora	5	113	0	106
Scapholeberis	0	113	5	106
Chydoridae	4	113	5	106
PROTOZOA	9	129	32	106
BENTHICS	19	129	51	106
Turbellaria	7	129	7	106
Chironomidae	4	129	33	106
Acari	3	129	9	106
Oligochaeta	3	129	11	106
Nematoda	2	129	17	106
Miscellany	5	129	7	106

than that of reservoir stations (Tables 4, 5 and Figure 24). Exceptions were those concentrations observed at R-1 (Connecticut River), R-7 (East Branch of Tully River), and R-9 (Millers River at Orange).

Zooplankton populations did not develop in rivers until late May or June (Figure 20). Rotifer concentrations peaked in most rivers in late June, with the exception of Tarbell Brook (R-2) and possibly the Ware River (R-11, R-12) where concentrations remained too low to show a discernible pattern. The high June peak in rotifer concentration in the Connecticut River (Figure 20) was associated with 8 genera. No one type was predominant. However, in August only two rotifers were present in the Connecticut River, Polyarthra and Keratella.

In general, the riverine stations examined fall into 3 basic groups with respect to overall plankton concentrations:

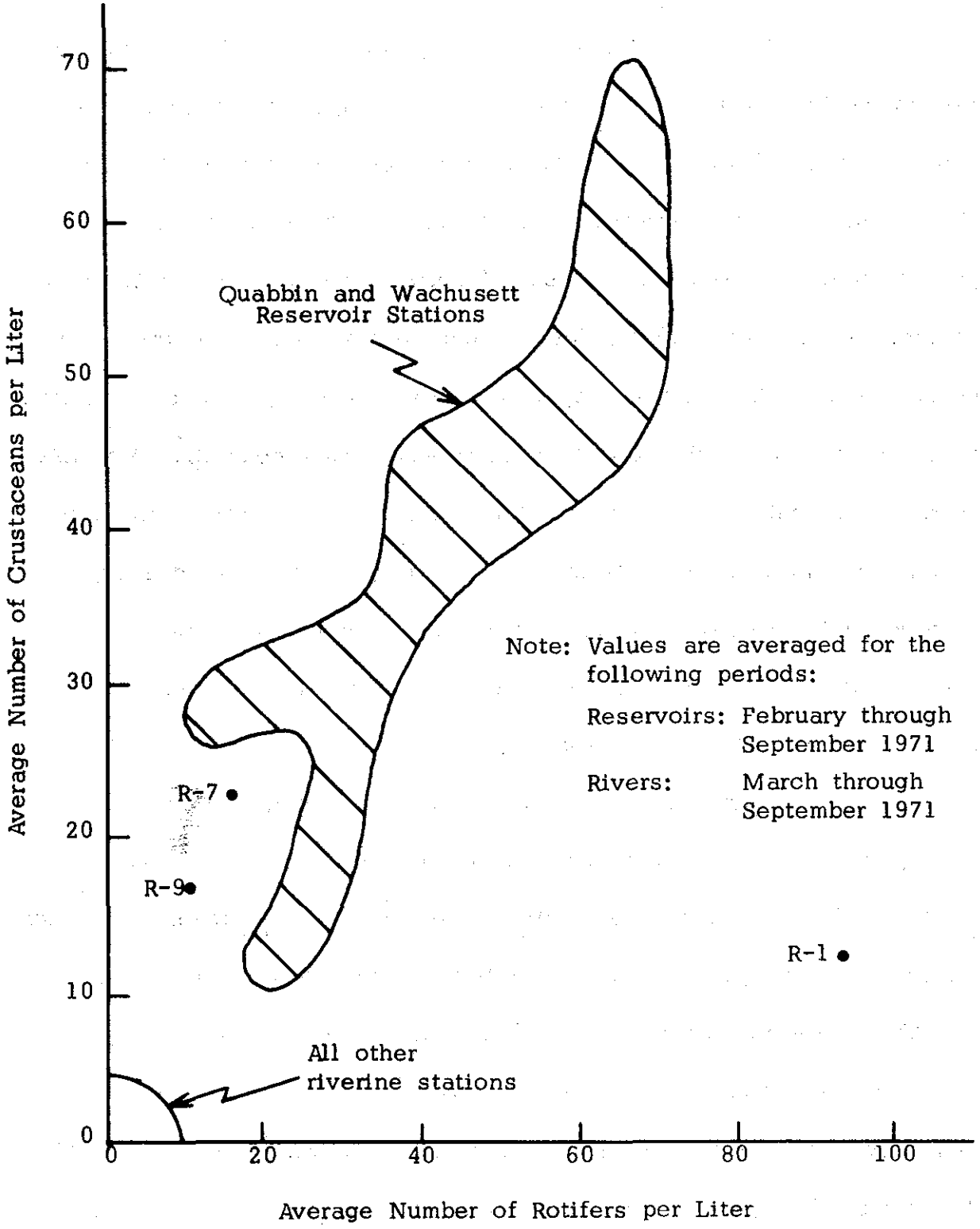
(a) high concentrations of plankton, with rotifers predominating (Connecticut River)

(b) intermediate concentrations of plankton, with crustaceans predominating (East Branch of Tully River and Millers River at Orange)

(c) low concentrations of plankton with equal concentrations of rotifers and crustaceans (all other stations)

Within the third group, the Millers River stations are distinguished from all other stations (Ware River and tributaries to the Millers River) by relatively higher numbers of planktonic animals as well as benthic animals observed in surface waters.

Figure 24. Riverine and Reservoir Zooplankton (concentrations of crustaceans versus concentrations of rotifers)



(4) Benthic Organisms

At the beginning of the project, benthic samples were collected monthly at each station. Beginning in May, benthic organisms were collected along transects in the reservoirs, and by multiple samples in the rivers on a quarterly schedule. Basic differences between the transects made in reservoirs are summarized in Table 8. These differences in depth, plant communities, and nature of bottom muds are associated with differences in the kinds of populations and distributions of benthic organisms observed in these aquatic systems. Two major types of distributions were detected (Table 9). One type included animals generally distributed in muds throughout the reservoirs. These animals were present in higher concentrations in Wachusett Reservoir. A second type included animals largely restricted to littoral areas, or associated with the presence of aquatic plants. These animals were present in higher concentrations along the Q-5 transect in Quabbin Reservoir.

Localized concentrations of individual groups of benthic organisms, however, were not observed to be directly correlated with their general type of distribution. The Pelecypoda, for example, were present in higher concentrations along the Q-5 transect than at any other transect, even though they were generally distributed throughout the reservoir.

The highest average concentration of Chironomidae (from February through September inclusive) was observed in the northeast area of Wachusett Reservoir (W-5), and the lowest in the area of Shaft 12 in Quabbin

Table 8. Comparison of Various Conditions Associated With Bottom Samples of Reservoirs

Station in Immediate Area of Transect	Average Depth of Sampling Points on Transect	Plants Present	Nature of Bottom Mud
W-2	19 meters	No	Very fine mud composed of well decomposed organic material
W-5	19 meters	No	
Q-1	18 meters	Yes (in 6 of 20 samples)	Generally large amounts of only partly decomposed organic material (leaves, twigs, bark, etc.). Least amount of such debris consistently noted in area of station Q-2
Q-2	16 meters	Yes (in 2 of 16 samples)	
Q-5	3 meters	Yes (in all 17 samples)	
Q-7	11 meters	No	
Q-8*	11 meters	No	
Q-9*	13 meters		

*Note: These stations were sampled individually in the first quarter, and were not included as points on a transect in subsequent sampling periods.

Table 9. General Distributions of Benthic Organisms in Quabbin and Wachusett Reservoirs

Type of Distribution	Animals Present	Percent of Samples in Which Found	Average No. per Grab Sample *
I. Animals generally distributed among all stations	Chironomidae	98	17.1
	Oligochaeta	77	5.8
	Pelecypoda	42	1.7
	Isopoda	30	0.9
	Acari	35	0.8
	Turbellaria	23	0.8
II. Animals associated with weeds and/or littoral areas of reservoirs	Amphipoda	27	2.3
	Gastropoda	15	1.1
	Heleidae	16	0.4
	Cladocera & Copepoda	9	0.3
	Odonata, Ephemeroptera, and Trichoptera Larvae	16	0.2

* 1/4 ft^2

Reservoir (Q-1) (Table 10). The highest average concentration of Oligochaeta was also observed along the W-5 transect, and the lowest in the western arm of Quabbin Reservoir (Q-2).

There were seasonal differences in the average concentration of organisms (Table 11). Minimum values occurred at different seasons for different animals.

Chironomids were most often found in highest concentrations during the earliest sampling period, before the emergence of the adult flies. After an overall decrease in concentrations in May and June, chironomid concentrations again began to increase in late summer. However, individual transects demonstrated variation to this general pattern (Table 12). Transects in the area of W-2, W-5, and Q-1 all showed a sharp rise in chironomid populations between July and September, whereas transects in the area of Q-2, Q-5, and Q-7 showed decreases. These changes in concentrations at individual transects were associated with changes in genera of chironomids. For example, September increases in chironomid concentrations at the W-2 and W-5 transects reflected increases in numbers of Calopsectra.

Peculiarities of individual transects were also noted in seasonal variations of Oligochaeta concentrations (Table 12). Oligochaetes showed drops in concentrations between July and September except at the Q-5 transect which showed a significant increase. The smallest seasonal variation in numbers of oligochaetes was observed at the Q-2 transect, and

Table 10. Concentrations of Chironomidae and Oligochaeta in Quabbin and Wachusett Reservoirs

Transect Location	Chironomidae			Oligochaeta		
	No. of Samples Processed	Total No. of Organisms Observed	Average No. per Sample*	No. of Samples Processed	Total No. of Organisms Observed	Average No. per Sample*
W-2	14	266	19	14	65	5
W-5	17	380	22	17	167	10
Q-1	20	258	13	20	169	9
Q-2	16	255	16	16	38	2
Q-5	17	267	16	17	70	4
Q-7	16	216	14	16	88	5

* 1/4 ft^2

Table 11. Seasonal Variations of Benthic Populations in Quabbin and Wachusett Reservoirs
(Average number of animals per grab--1/4 ft^2)

Animals	February, March, April 14 Samples	May, June 30 Samples	July 30 Samples	September 30 Samples
Chironomidae	36	12	14	16
Oligochaeta	7	8	6	3
Pelycepoda	1	<1	3	2
Isopoda	3	<1	<1	<1
Turbellaria	<1	2	<1	<1
Amphipoda	4	1	2	4

Table 12. Seasonal Variations in Numbers of Oligochaeta and Chironomidae
(Average number of animals per grab - 1/4 ft^2)

	Transect Locations						
	W-2	W-5	Q-1	Q-2	Q-5	Q-7	Q-8 Q-9
Chironomidae							
February, March, April	31	56	13	42	52	20	35
May, June	9	11	14	17	19	8	-
July	9	14	10	21	10	18	-
September	34	28	18	5	4	13	-
Oligochaeta							
February, March, April	3	24	6	4	6	0	3
May, June	8	8	19	2	5	8	-
July	6	14	7	2	<1	8	-
September	1	3	3	2	6	1	-

the largest, at W-5.

The river systems show differences in both the kinds and numbers of animals present. Three of the Millers River stations had the fewest kinds of animals present but the highest numbers of animals per square foot, frequently over a thousand per square foot (Table 13 and Figure 25). This lack of correlation between numbers and diversity in the Millers River is illustrated in Figure 26 for samples from two types of river bottoms. All but one of the muddy bottom samples came from stations R-4 (South Royalston), R-5 (Athol) and R-9 (Orange), whereas most of the samples from sandy or gravel bottoms came from R-10 (Farley). At R-10 there was more overlap in diversity with samples from the tributaries of the Millers River, but for both types of bottoms there was not only more diversity in the tributaries, but also, by contrast with the Millers River, a tendency for high numbers of animals to be associated with the presence of many different types of animals.

Using mud samples taken with the Ekman grab as the basis for comparison, average numbers of animals per square foot at R-4, R-5, and R-9 were 101, 945, and 309 respectively. These may be compared with average values of 105 for the Ware River stations and 124 for the reservoir muds. The Oligochaeta were the predominant animals at R-4, R-5, and R-9. Midge fly larvae were predominant in the Ware River and the reservoir muds.

Table 13 shows several patterns which distinguish the Ware River and

Table 13. Number of Types of Benthic Animals Found in River Samples (January - August, 1971)

	Millers River Tributaries					Ware River		Millers River				Conn. River
Station	1	3	6	7	8	11	12	4	5	9	10	1
Animals												
Porifera	1	1	1	1		1						
Turbellaria	1	2		1		1			1			3
Oligochaeta	5	2	3	5	1	1	3	2	2	2	5	4
Hirudinea	1	1	2	4					3		6	2
Amphipoda		1	1	1	1	1	1					
Isopoda									1		1	1
Diptera	13	11	10	9	14	11	7	7	7	4	11	7
Other Insect Orders	30	42	44	34	16	31	15	3	5	1	16	2
Acari	4	7	2	5	4	9	2	1			1	2
Mollusca	1	3	2	1		2			1		3	5
Miscellaneous		3	4	2	1		3			1	1	1
Total	56	73	69	63	37	57	31	13	20	8	44	27

Figure 25. Number of Animals Per Square Foot at Riverine Stations

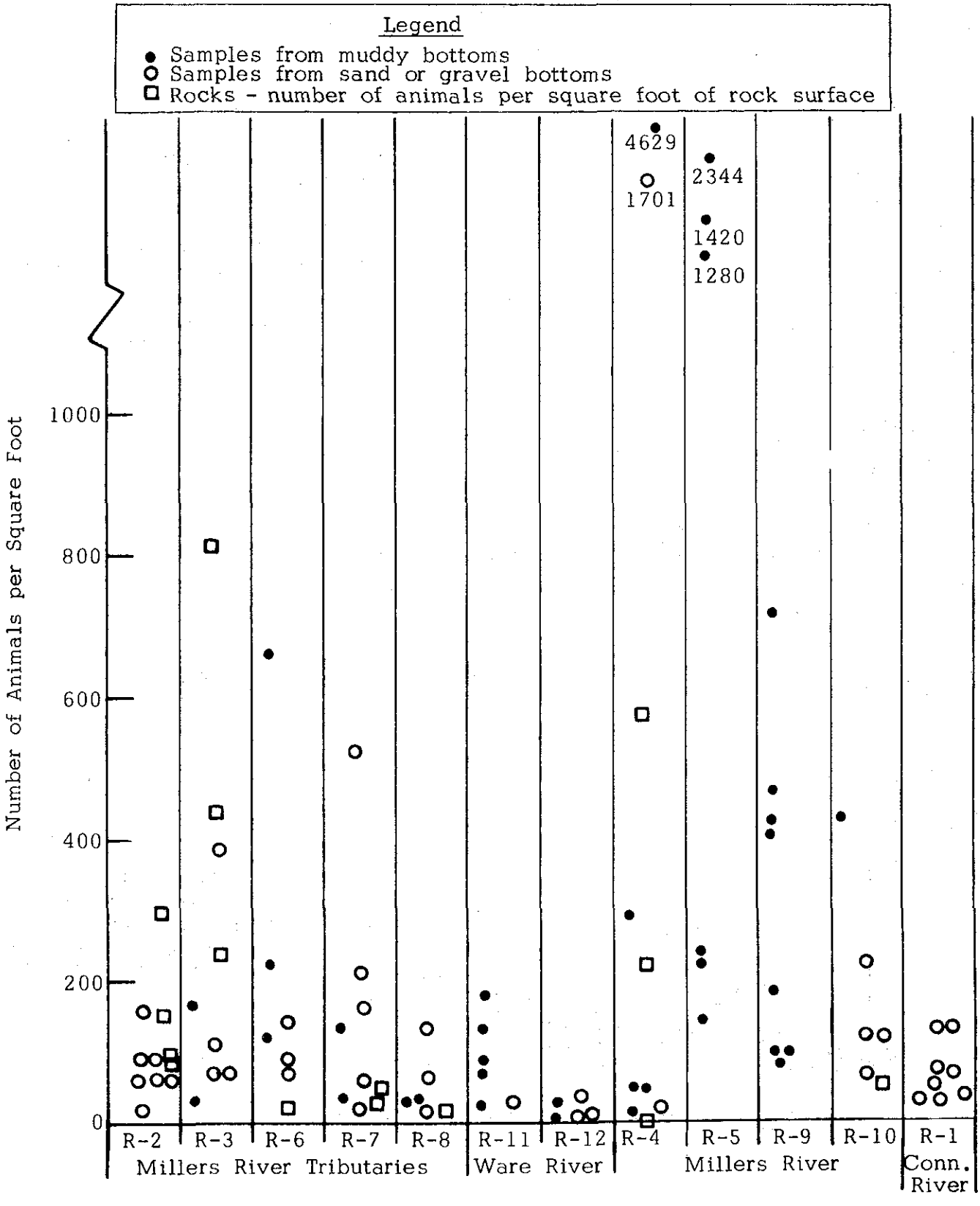
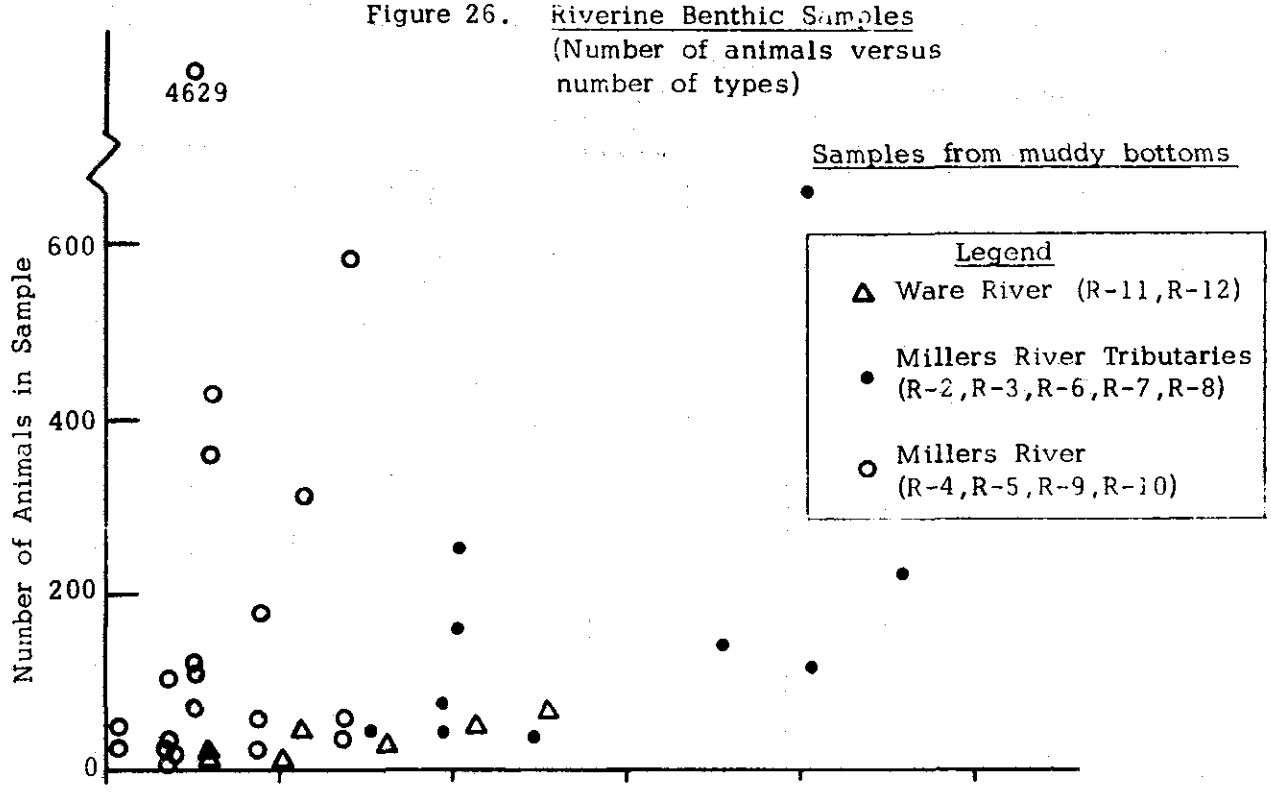
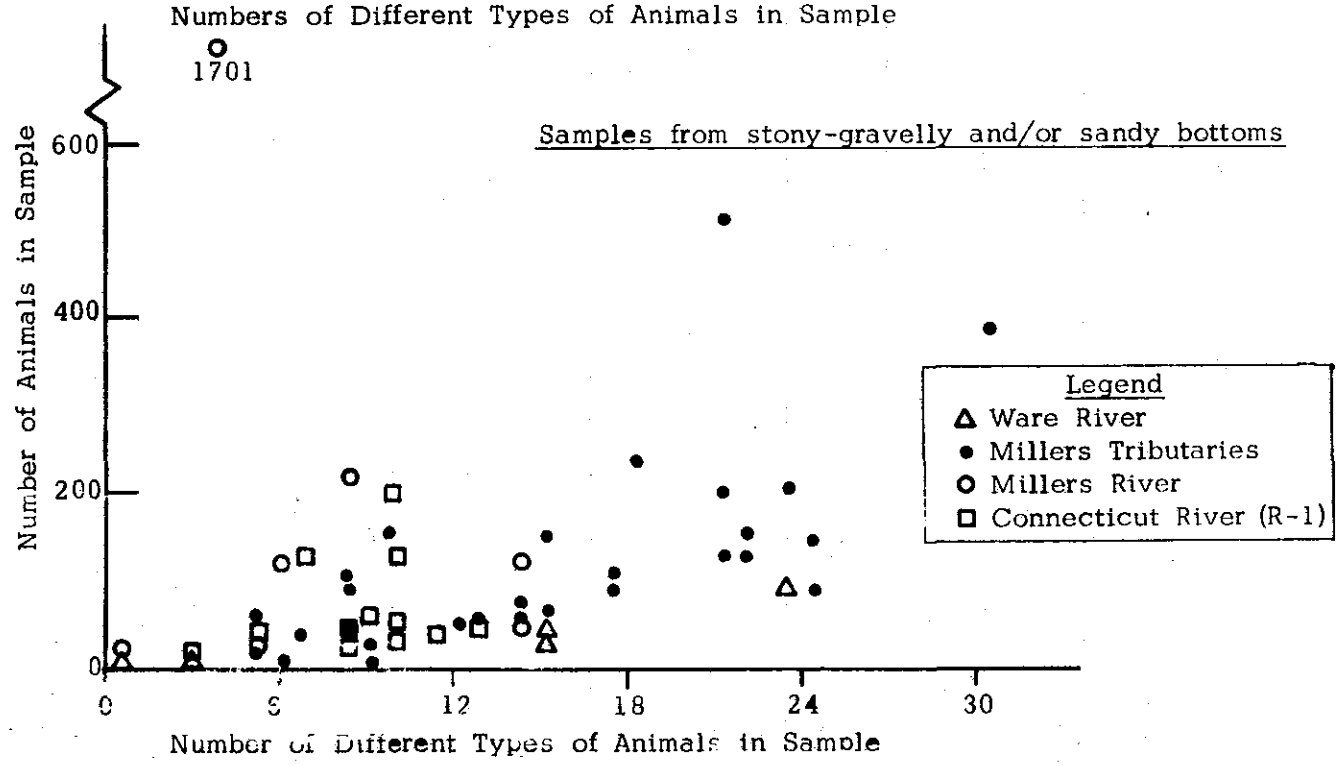


Figure 26. Riverine Benthic Samples
(Number of animals versus number of types)





northern tributary stations from the Millers River and Connecticut River stations. Sponges (Porifera) and Amphipoda (Class Crustacea) were present in the former only while Isopoda (Class Crustacea) were present in the latter only. While the northern tributaries and Ware River showed a greater diversity of animals belonging to the Order Diptera (midge flies, crane flies, etc.), the difference between these two groups of river stations is most striking for insects belonging to other Orders, such as the Trichoptera (caddis flies), Odonata (dragonflies) and Ephemeroptera (mayflies). These other insect Orders account for a much larger proportion of the total diversity present in the northern tributaries and Ware River than in the other river stations.

Distinct differences between the Connecticut River and the Millers River were detected. Worms were never the predominant organism in samples from the Connecticut River. Also, burrowing mayfly larvae, which were present in Connecticut River samples, were not found in Millers River samples. The Connecticut River bottom also had large clams (Margaritifera), several inches long, which were not found at any of the other river stations.

Among the northern tributaries, R-8 (West Branch of Tully River) showed the lowest diversity of benthic organisms. Concentrations at this station were comparably low. In addition to these general differences, specific differences in the distribution of certain genera among the tributaries were observed. For example, Rhyacophila (caddis fly) was found only at station

R-2. Two genera of burrowing mayfly larvae, Hexagenia and Ephemera were found at R-8, but Hexagenia was the only burrowing mayfly larva found at other river stations.

B. Chemical Data

Most chemical parameters exhibited a broad annual pattern which was generally predictable. For example, in the rivers, a decrease in some parameters was observed during high flows in the spring, and an increase with decreasing flows later in the year. This type of pattern was not so obvious in the reservoirs. Substances readily associated with photosynthetic activity in both riverine and reservoir systems also varied in an expected manner. Annual pattern of individual parameters will be discussed in more specific detail in the following sections. Refer to Appendix 1 for methods.

A number of parameters were either never or very infrequently detected and, thus, will not be discussed. These include: detergents (MBAS), aluminum (Al), arsenic (As), barium (Ba), boron (B), cadmium (Cd), hexavalent chromium (Cr), cobalt (Co), copper (Cu), lead (Pb), selenium (Se), silicon (Si), silver (Ag), uranyl ion (UO_2^{2+}), cyanide (CN^-), and fluoride (F^-). Of these, it is interesting to note that most of the few incidences of Cd, Co, and Cu occurred in the Millers River tributaries and, thus, were probably derived from natural rather than human sources.

Sulfate sulfur (SO_4-S) was present in all samples, but exhibited no annual patterns. There was little significant variation between riverine and reservoir stations; riverine samples ranged from 2.0 to 8.0 μg/ml while reservoir samples ranged from 1.5 to 5.0 μg/ml of SO_4-S. No further discussion will be given this parameter.

For the discussion of chemical parameters, six individual sampling stations have been selected as being representative of all others (Figures 5, 6 and 7).

They are as follows:

(1) Connecticut River (R-1)

This station is reasonably unique among the rivers and stands alone.

(2) Millers River near Athol (R-5)

This station is characteristic of all the Millers River stations (R-4, R-9 and R-10).

(3) Lawrence Brook (R-6)

This station is quite representative of the other tributaries to the Millers River, i.e. R-2, R-3, R-7, and R-8. Of these, only R-8 (West Branch of Tully) is somewhat different; the difference is one of magnitude and not kind, in that R-8 tends to have values on most parameters lower than the other streams.

(4) Quabbin Reservoir (Q-1)

This station is representative of the "outside" reservoir stations which also include Q-2, Q-3, Q-6, and Q-8. Q-1 was sampled at the surface and at a depth of 10 meters; the values indicated in the following graphs are averages of the two depths.

(5) Quabbin Reservoir (Q-4)

This station is representative of the "inside" reservoir stations which also include Q-5, Q-7, and Q-9.

(6) Wachusett Reservoir (W-2)

This station was selected to be representative of the reservoir as a whole primarily because of its central location. While differences were found between various parts of the reservoir, one station was chosen for simplicity of presentation; differences between sites were not outstanding.

The parameters which are to be discussed for these six representative locations are alkalinity, chemical oxygen demand, total hardness, chloride, ammonia nitrogen, total phosphorus, sodium, potassium, iron, manganese, zinc, mercury, and carbon chloroform extract (CCE).

Our contract did not require us to measure aluminum, cobalt, silicon, sodium and potassium; analyses were conducted by the subcontractor because of interests in these parameters. Secondly, many of the parameters were measured at frequencies greater than those specified in the contract. Finally, several parameters of total and dissolved nitrogen and phosphorus were measured. However, discussions are based on total phosphorus and ammonia nitrogen.

Alkalinity

The data for alkalinity are shown in Figures 27 and 28. It is immediately apparent that alkalinity is very low in Quabbin and Wachusett Reservoirs and the tributary streams (R-6). Wachusett Reservoir (W-2) is most similar to Quabbin (Q-4), while Lawrence Brook (R-6) is almost identical to Quabbin (Q-1 It would be unwise to attach any significance to the variations of alkalinity with time in these particular systems since such low alkalinities are undoubtedly accompanied by a low buffer capacity; thus, relatively small changes in conditions could result in pH changes of a magnitude sufficient to alter the alkalinity as shown.

The highest alkalinities were obtained in the Connecticut River (R-1), being about an order of magnitude higher than those in the reservoirs or tribut

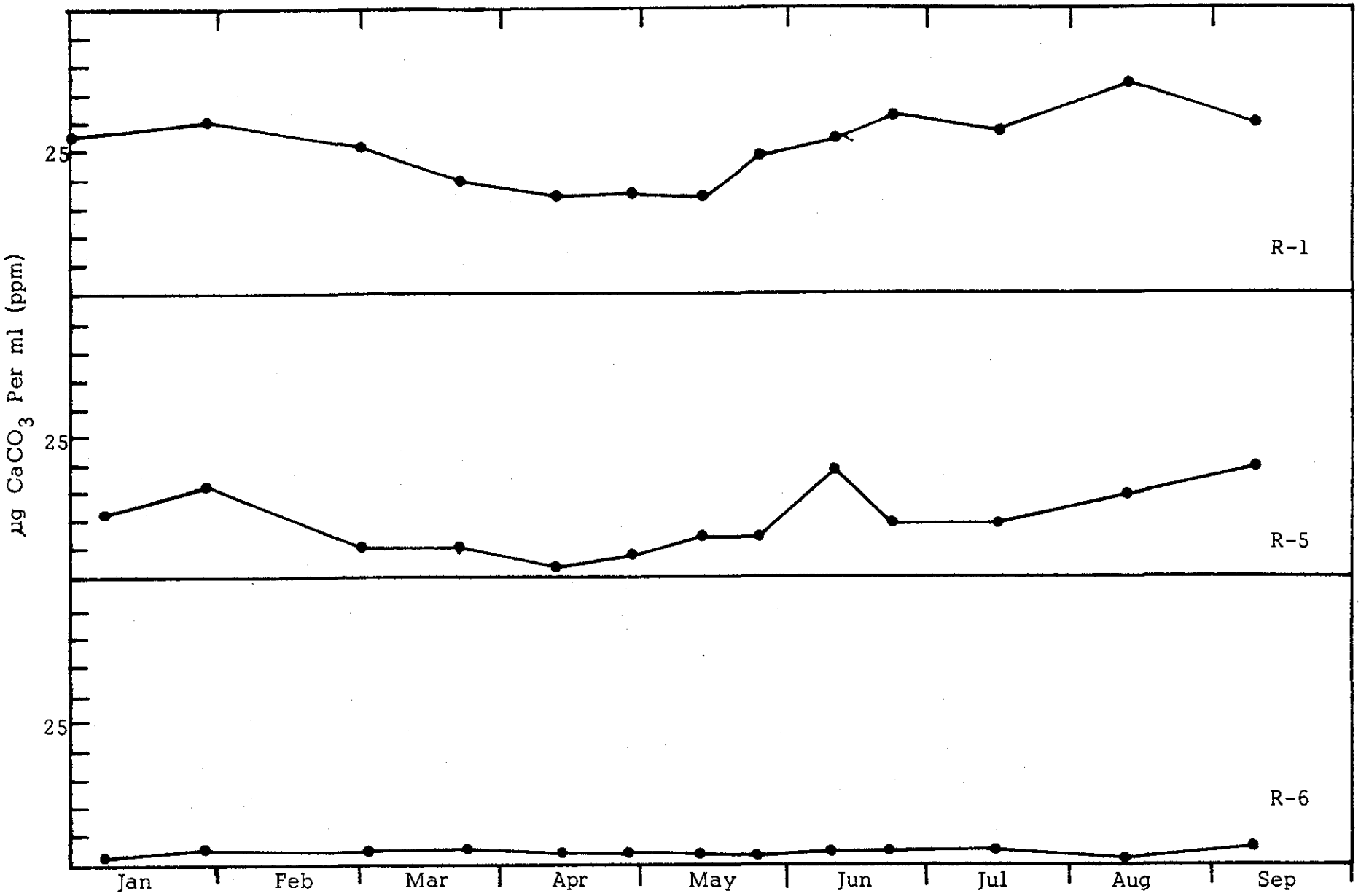


Figure 27. Alkalinity Levels at Selected Stations, 1971

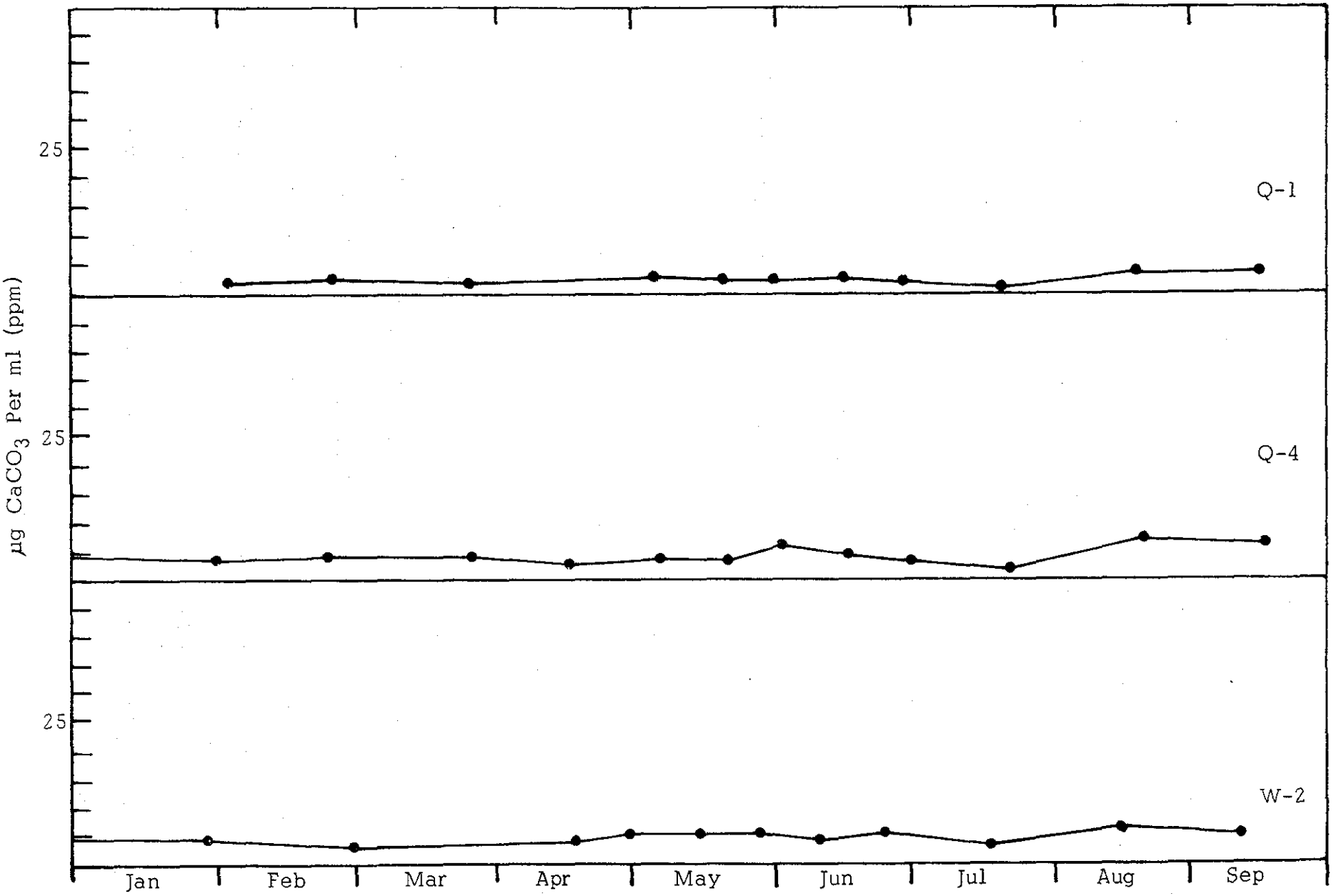


Figure 28. Alkalinity Levels at Selected Stations, 1971

streams. A definite annual pattern is seen also at R-1, with a minimum occurring at the end of April. The Millers River station (R-5) is qualitatively similar to R-1, but is lower in value and erratic.

The annual variation in the Connecticut River is probably related to dilution and concentration effects at high and low flows, respectively, since the pattern correlates well with the total hardness (vide infra). This correlation with hardness is not readily possible in the Millers River.

Alkalinity, as measured, could be a composite of bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), and strong base (OH^-). Strong base alkalinity would only result from man's activities; this was never found. In fact, only bicarbonate alkalinity was found in all cases.

Chemical Oxygen Demand (COD)

The COD data are shown in Figures 29 and 30. The Q-1, Q-4, and W-2 patterns are similar to those found for alkalinity at these stations, with subtle differences; namely, Q-1 and W-2 are very similar, and Q-4 is somewhat higher. It is interesting to note that R-6, which compared with Q-1 in alkalinity, showed a higher (order of magnitude) COD, and an annual pattern that suggests a flow correlation. The Millers River at R-5 showed a COD pattern almost identical to that at R-6. This is interesting since R-6 has no known interaction with man and his activities; thus, the COD is most likely of a natural origin. High COD values in the tributary streams are common, except at R-8, and were associated with high color; several spot checks were made for tannins and lignins and these were found to be present in large amounts.

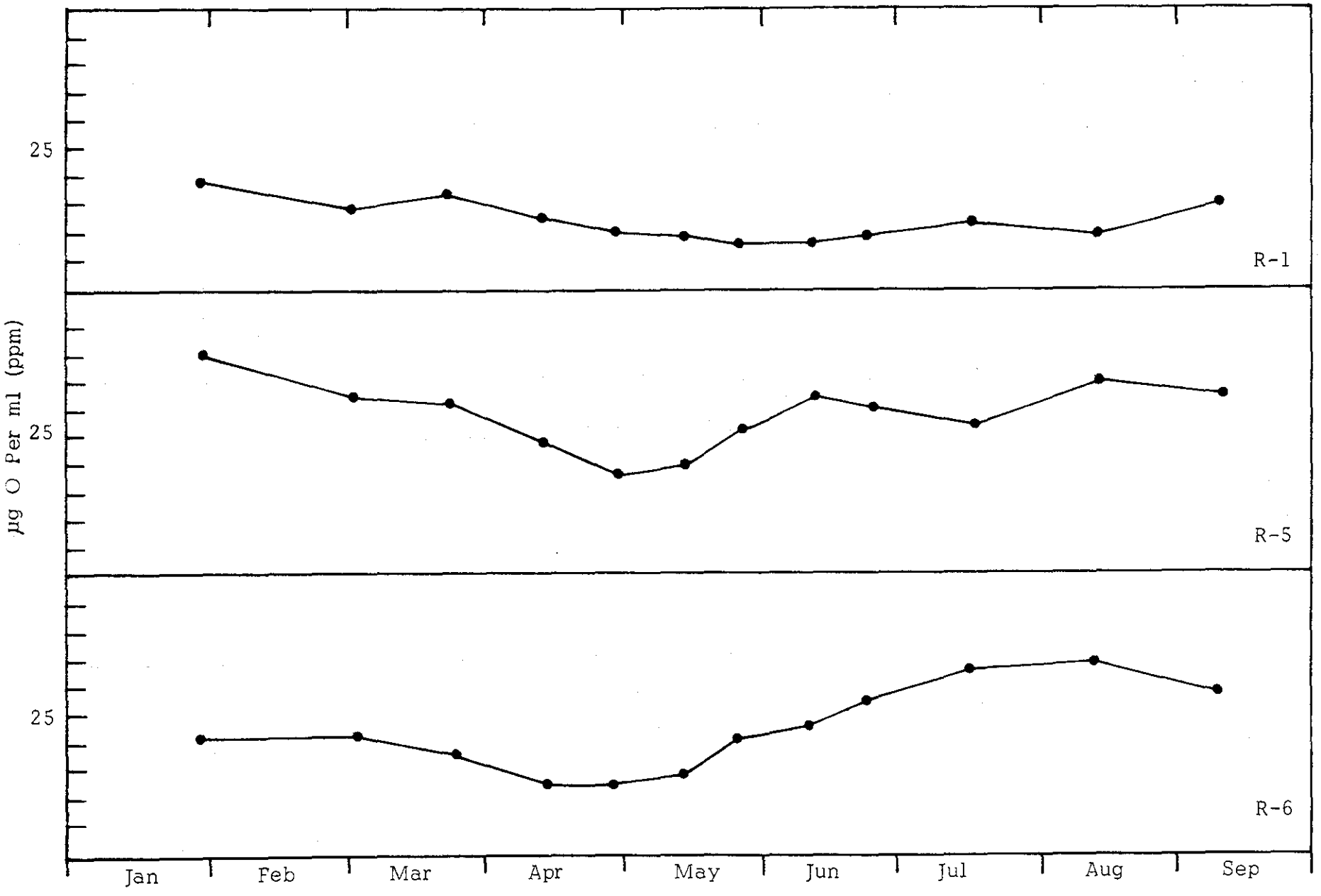


Figure 29. COD (Chemical Oxygen Demand) Levels at Selected Stations, 1971

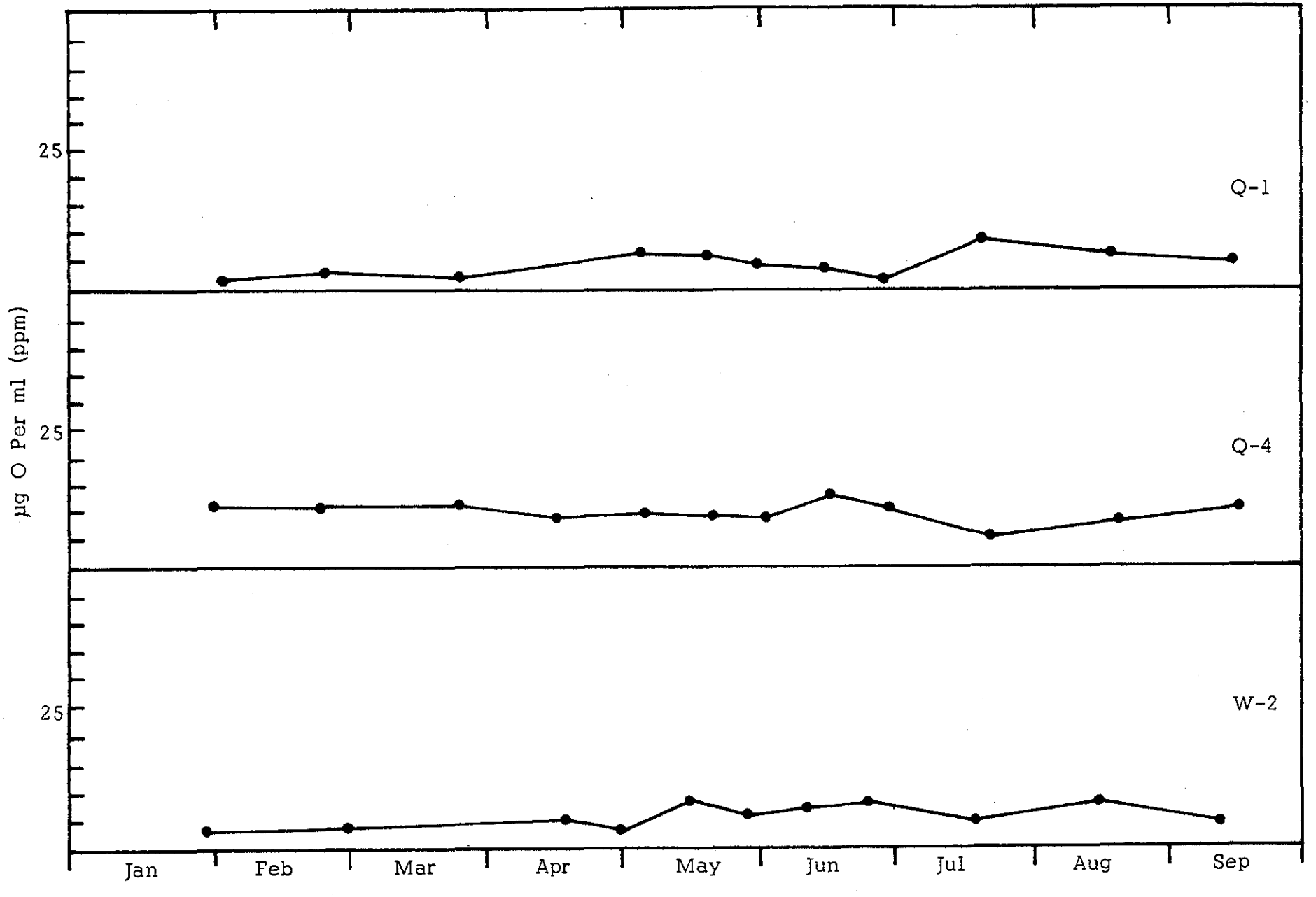


Figure 30. COD (Chemical Oxygen Demand) Levels at Selected Stations, 1971

Thus, it appears that this COD (at R-6) is due to organic substances and to ammonia (vide infra) from natural sources. The source of COD in the Millers River (R-5) is not as apparent because the Millers River does reflect the impact of man. The Connecticut River maintained a COD not appreciably different from that found in Quabbin (Q-4).

Total Hardness

In a strict sense, total hardness would be a measure of all metal ions of charge 2+ and higher and, perhaps, lithium and thallous (Tl^+) ions as well; that is, those metals which form insoluble soaps. Because of the relative abundance and predominance of calcium and magnesium in natural waters, total hardness is usually determined to measure these ions only. In this study, hardness was not measured by the more conventional titrimetric techniques because of the imprecision usually introduced by poor indicator response and interferences; rather, total calcium and magnesium were determined separately by the more sensitive and precise atomic absorption spectroscopy, and hardness calculated from these.

The data are shown in Figures 31 and 32. The lowest hardness levels were experienced in Quabbin (Q-1) and the tributary streams (R-6), both areas showing approximately the same values. Quabbin values (Q-4) were similar to Quabbin values (Q-1) but somewhat higher. Wachusett Reservoir (W-2) was higher than Quabbin or the tributary streams; in fact, Wachusett hardness was not substantially different from the Millers River values (R-5), except in annual pattern. The Connecticut River (R-1) exhibited the highest hardness levels, the

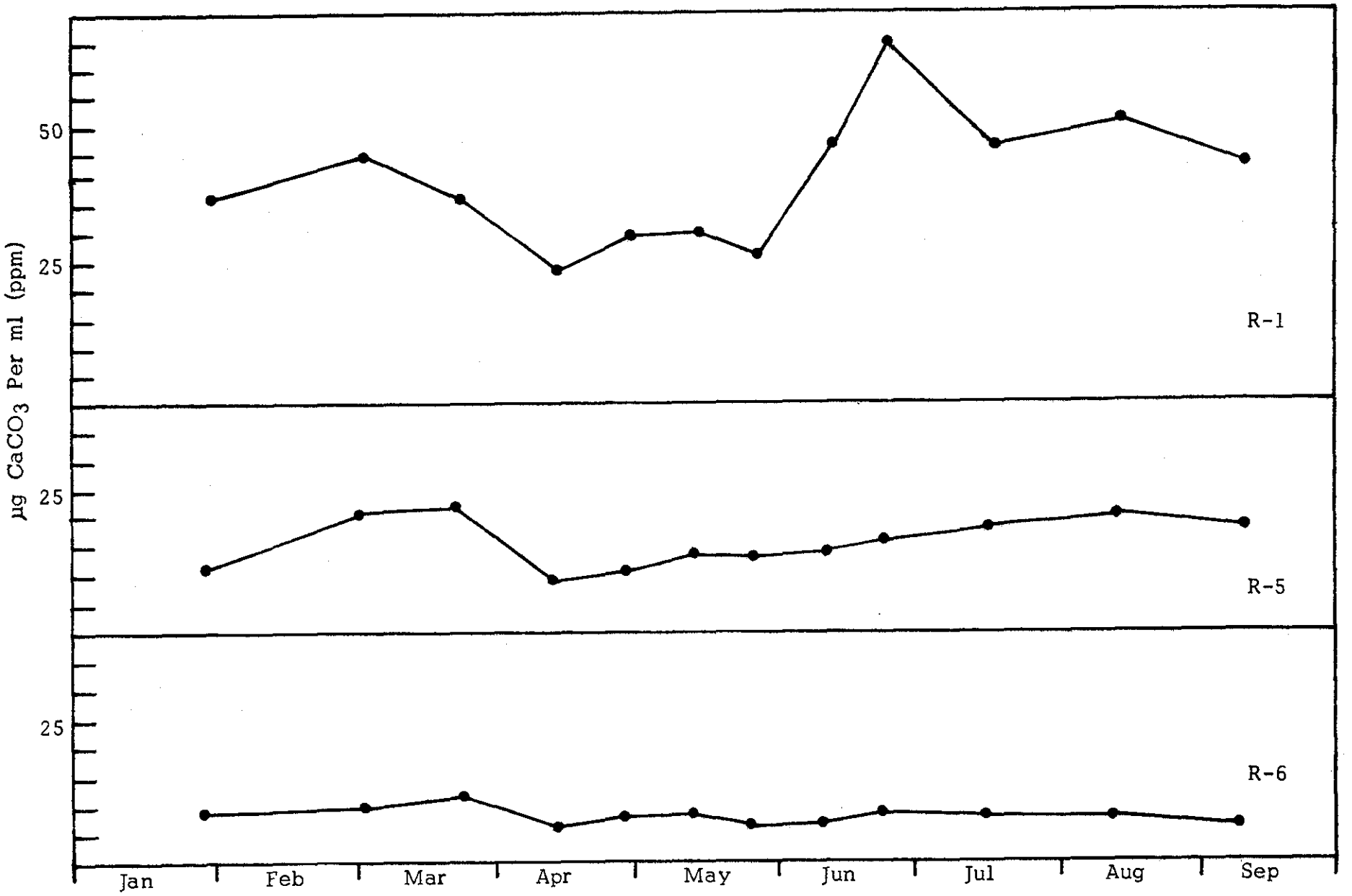


Figure 31. Total Hardness Levels at Selected Stations, 1971

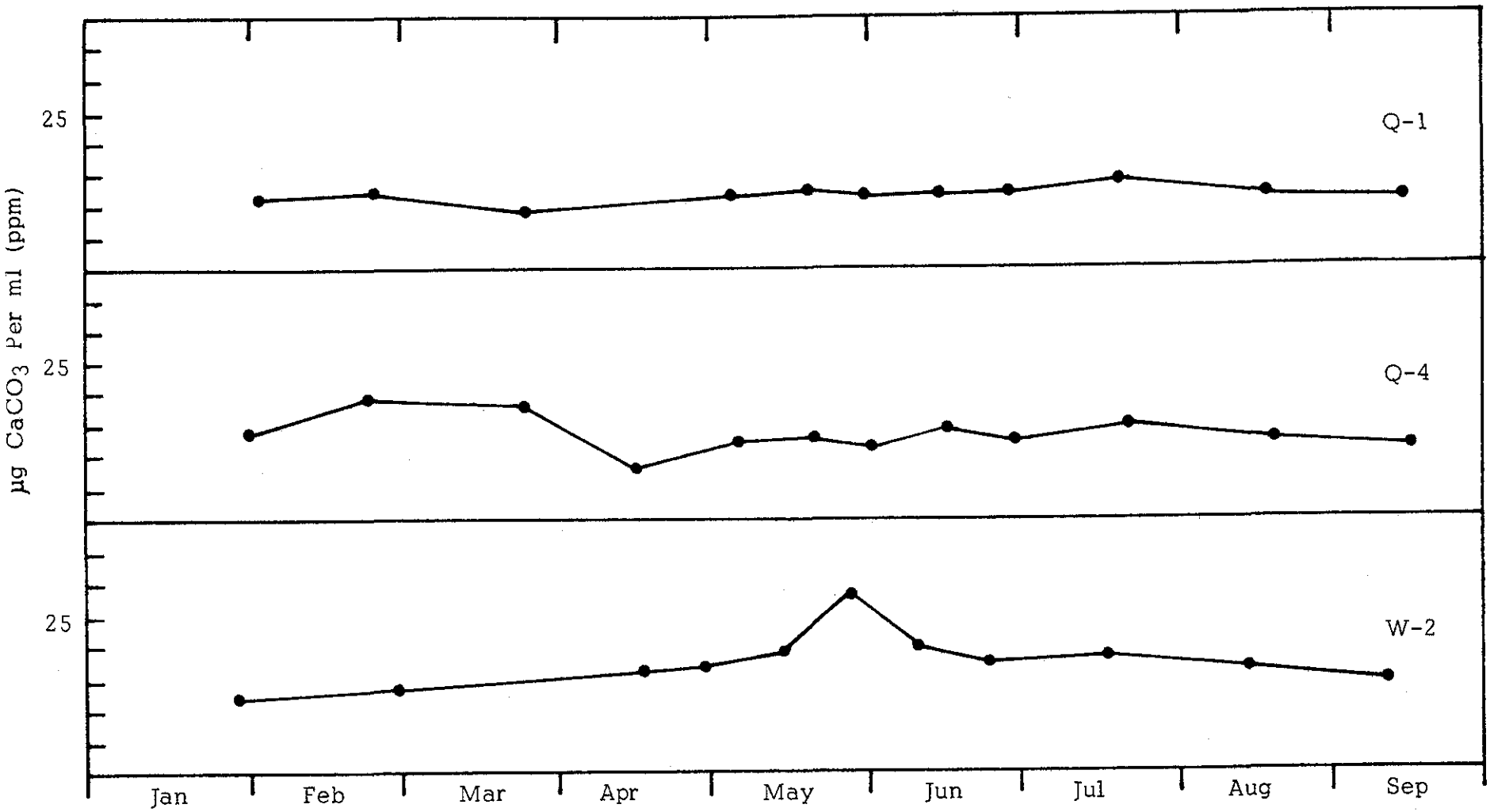


Figure 32. Total Hardness Levels at Selected Stations, 1971

pattern of which, as pointed out earlier, correlates quite well with alkalinity. This suggests that the majority of the Connecticut River hardness is due to natural causes.

Chloride

All chloride values found in this study are below 25 ppm, as seen in Figure 33. Chloride in Quabbin Reservoir and Wachusett Reservoir were low and exhibited no particular seasonal variation; the tributary streams behaved like the reservoirs. Connecticut River values were not significantly higher than the reservoirs, but did exhibit a seasonal variation, decreasing through April and reaching a minimum in early May, probably because of dilution. The Millers River behaved like the Connecticut River except that the level was higher.

Ammonia Nitrogen

Typical ammonia nitrogen data from this study are shown in Figures 34 and 35. Quabbin and Wachusett Reservoirs were generally below 0.5 ppm, with occasional increases above 0.5 ppm. During the winter months, levels were quite low (not below 0.01 ppm, however), with increased levels and erratic behavior during the late spring and the summer. While it is not possible to be more specific, there seems to be a relationship between ammonia levels and periods of biological activity, certainly with regard to general level. There is a tenuous balance between the dissolved nitrogen forms, ammonia, nitrite, and nitrate in solution; relatively small changes in pH and redox potential can shift the equilibrium one way or the other to a considerable extent. Increased surface

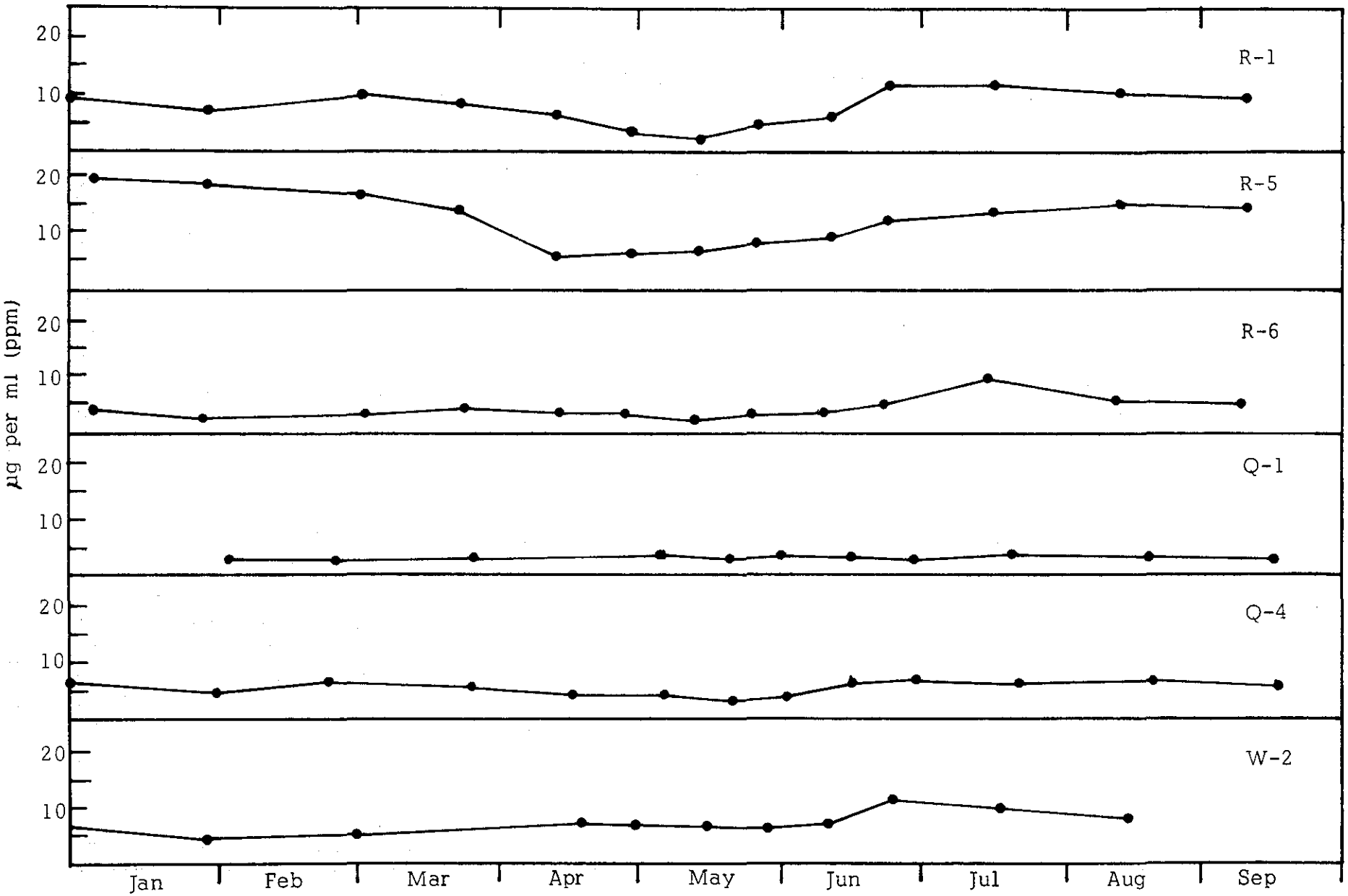


Figure 33. Chloride Levels at Selected Stations, 1971

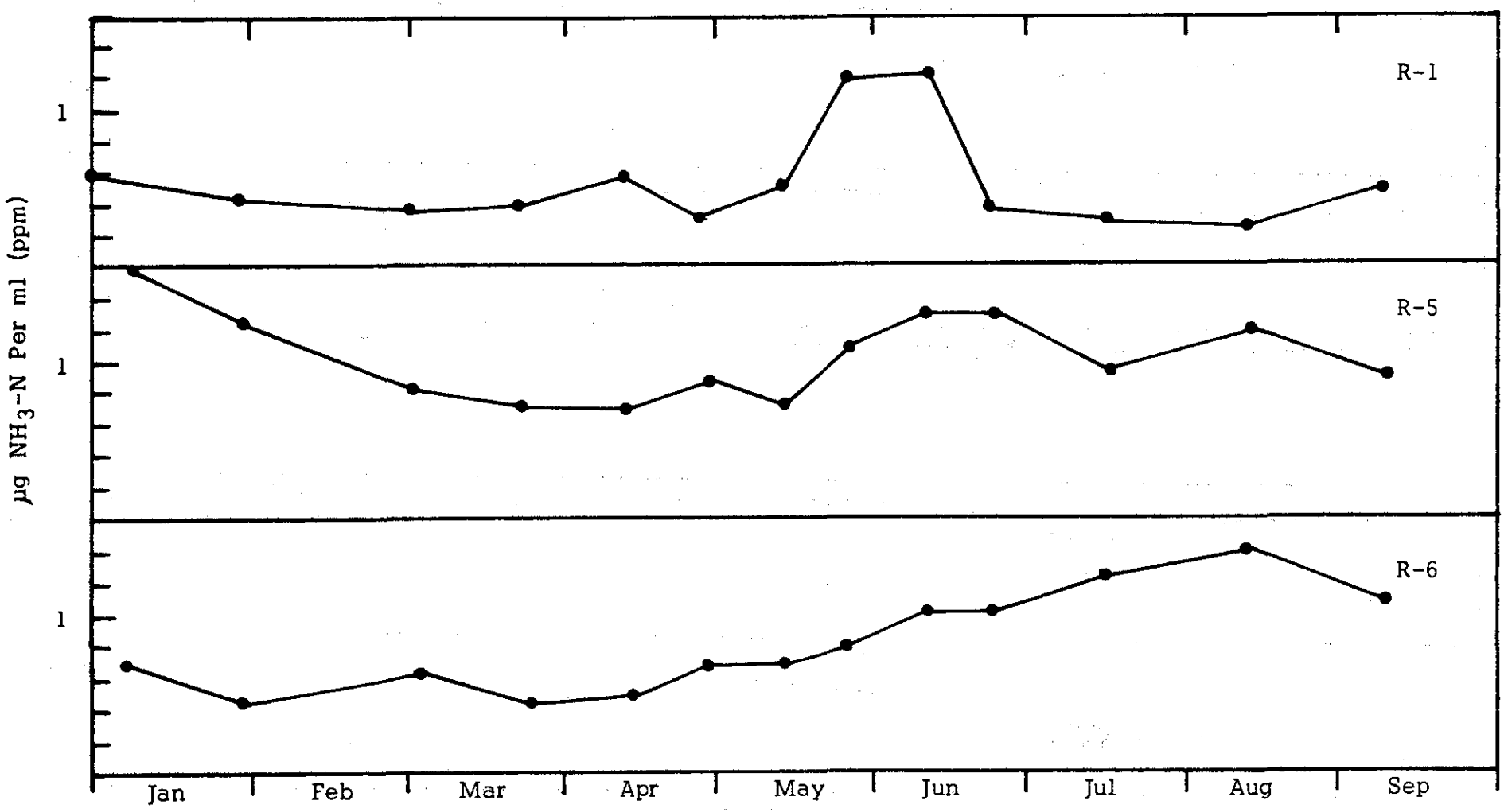


Figure 34. Ammonia Levels at Selected Stations, 1971

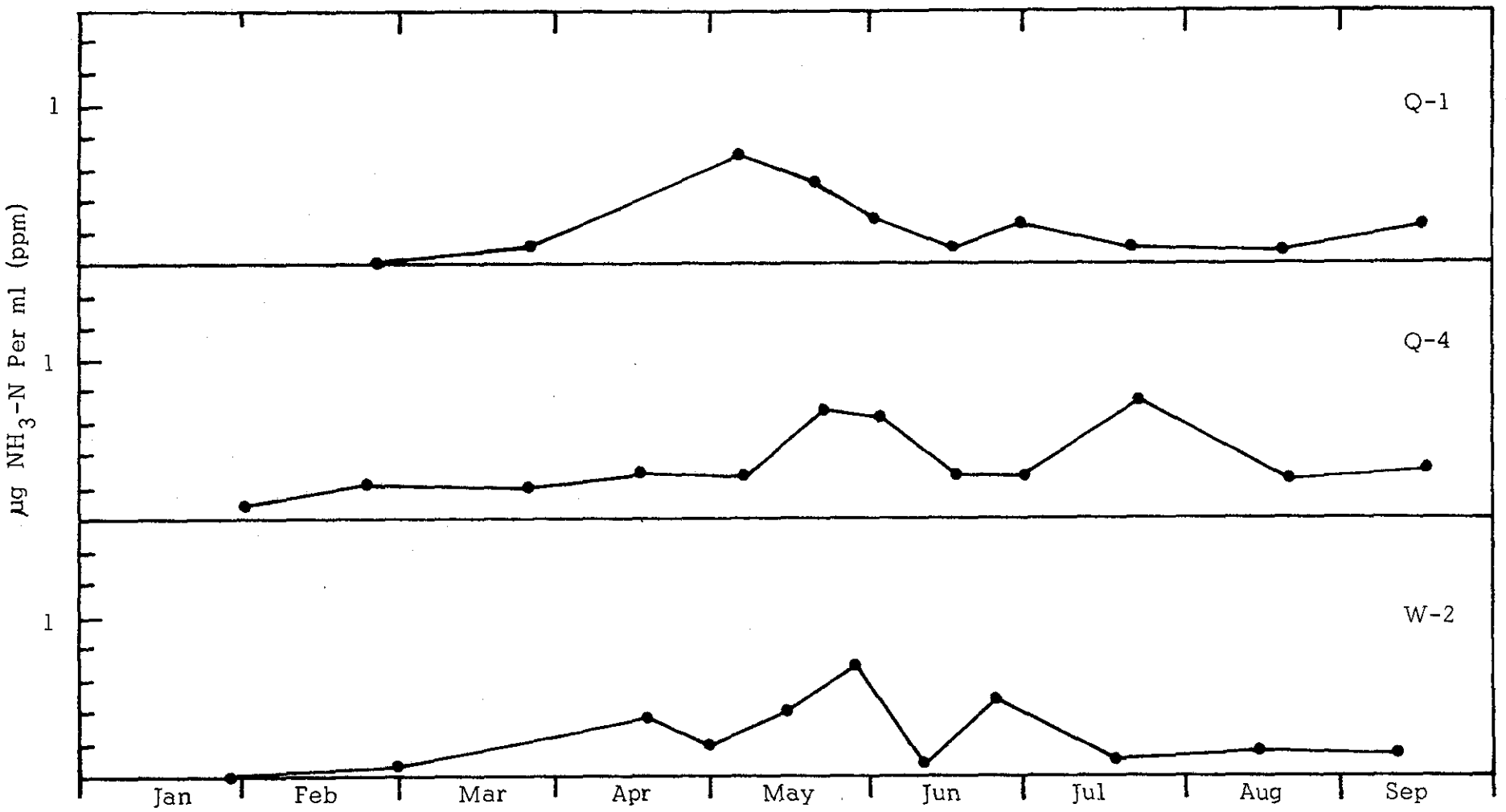


Figure 35. Ammonia Levels at Selected Stations, 1971

area (algae, bacteria, etc.) and variable biological activity can combine to shift the relative balance between these species, so that it is not surprising that ammonia levels were variable.

The Connecticut River pattern was similar to that found in Quabbin (Q-4) with slightly higher levels; the Millers River was always high in ammonia, even during the winter months. The tributary streams exhibited rather high ammonia levels in the late summer (the same period in which high colors were observed), presumably from natural causes.

Nitrate and nitrite nitrogen have not been shown graphically since the general patterns for these species are similar to that for ammonia. In general, nitrite levels were relatively higher when ammonia was high, which indicates conditions conducive to the formation of reduced species. In no case did any water tested have nitrate plus nitrite levels in excess of 10 ppm total, the level above which a danger of methemoglobinemia may occur.

Total Phosphorus

Total phosphorus rather than particular species, was selected for discussion because, from an algal point of view, it represents the total reservoir of nutrient, for short and long-term supply. Total phosphorus includes orthophosphate, polyphosphates, and organic phosphorus. The data are shown in Figure 36.

Except for the Millers River (R-5), phosphorus levels were reasonably low, but definitely finite. The analysis procedure used was reliable down to 0.01 ppm P. While there is no general agreement as to what level of phosphorus is limiting for algal growth, it seems clear that, if other growth factors

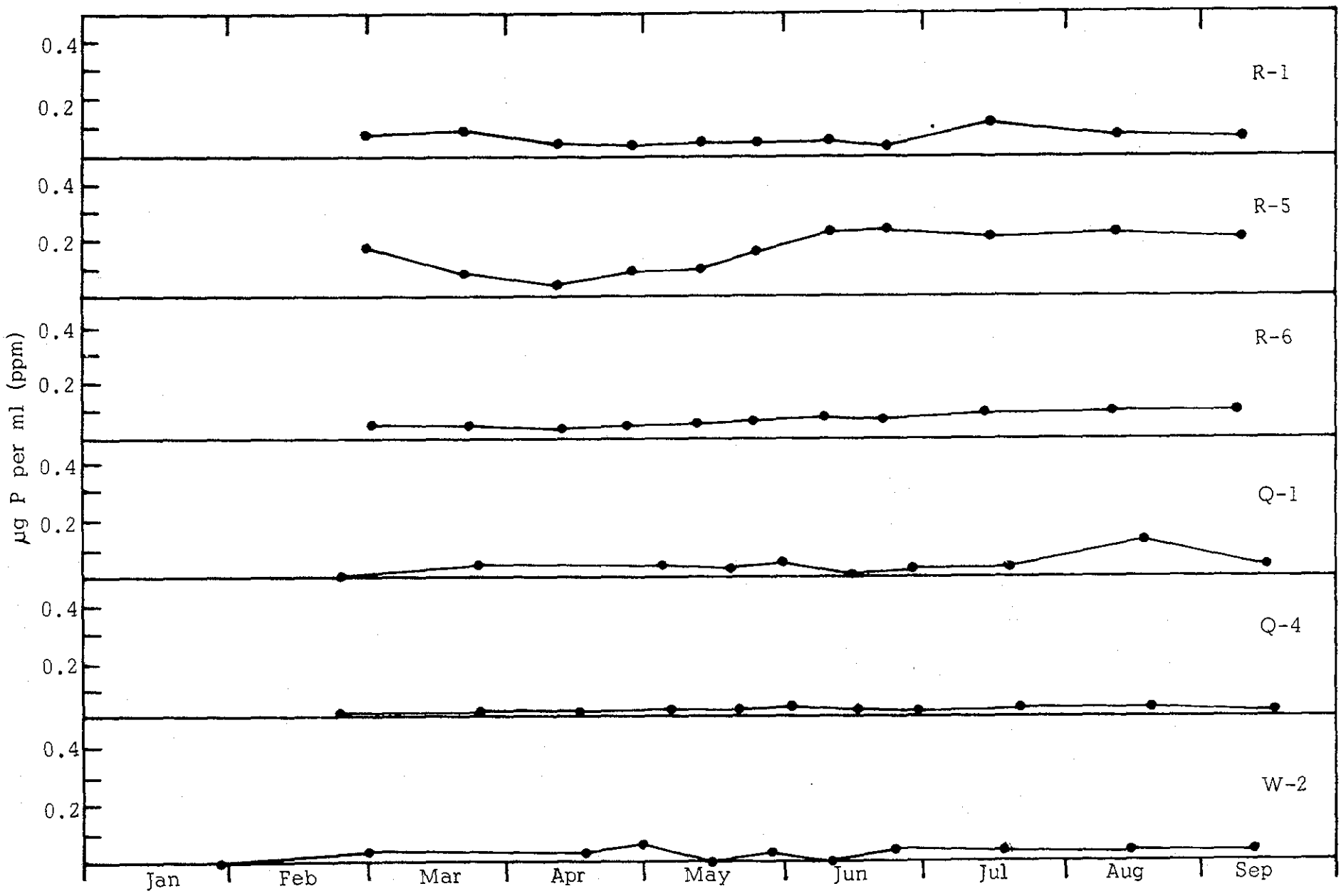


Figure 36. Total Phosphorus Levels at Selected Stations, 1971

are favorable, phosphorus levels in excess of 0.01 ppm will support algal growth and even blooms. Thus, all waters sampled in this study could support algal populations in excess of those found, based on the phosphorus level. That frequent blooms and high algal levels are not often observed suggests that some other growth factor, or factors, are limiting; in the waters observed in this study, the general lack of available carbon (as evidenced by the low alkalinities) probably aids in limiting algal growth.

The phosphorus levels in "outside" waters of Quabbin are higher than those found in "inside" waters of Quabbin. The Millers River had the highest phosphorus levels of all waters, values as high as 0.2 ppm being common.

Sodium

While sodium was not called for in the project contract, it was measured because of its requirement in living systems. It has proved to be an instructive parameter. None of the sodium levels observed were high enough to impart any taste to the water.

The influence of man and his activities is clearly seen from a study of Figure 37. Both the Connecticut (R-1) and Millers (R-5) Rivers show marked increases in sodium during the early spring, no doubt due to the introduction of road salt. These levels drop when the freshet flow occurs, due to dilution. The level recovers from this dilution and tends to rise, then level off, during the summer. The Millers River remained moderately high and erratic, probably indicating that man's activities may have a more obvious impact on this river.

Wachusett Reservoir (W-2) showed a similar effect, except that the

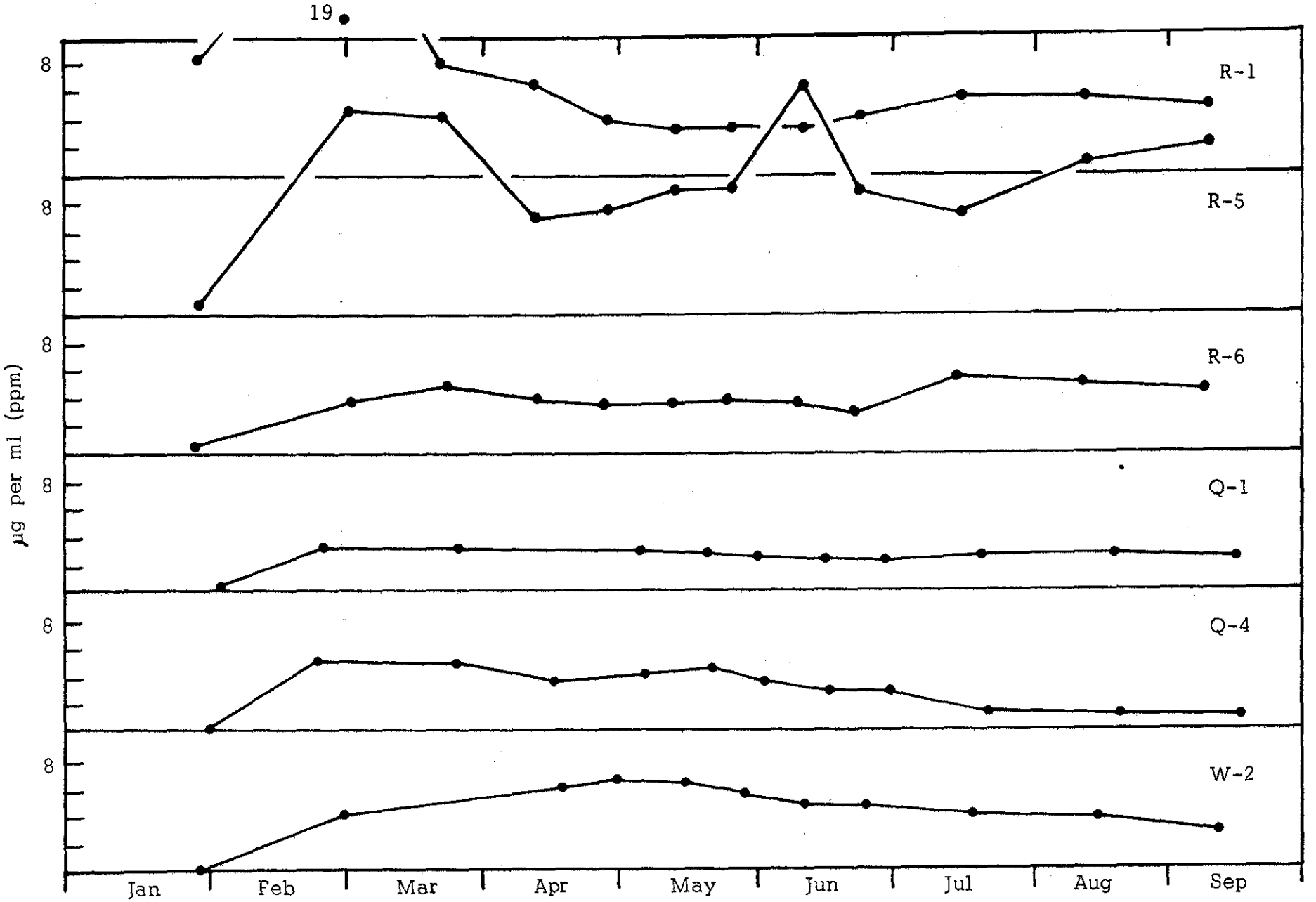


Figure 37. Sodium Levels at Selected Stations, 1971

maximum did not occur until April-May, and it was more gradually approached. In Quabbin and the tributary streams, sodium seems to be low in the winter and higher in the spring through fall months, but no marked changes were observed.

Potassium

Potassium levels, shown in Figure 38, were measured because of the need for potassium by living systems. They are included here primarily to illustrate that, generally, potassium did not vary in the same way as did sodium, especially in the Connecticut River. This supports the contention that much of the sodium observed was not due to natural causes, but was a result of human activity.

Total Iron

Some concern has been expressed about the possible introduction of iron (and manganese, etc.) into Quabbin and Wachusett Reservoirs upon the introduction of Connecticut River waters into Quabbin. Figure 39 illustrates the potential direct sources of iron. Virtually all iron found was present as the oxidized iron (III).

Quabbin "outside" waters and Wachusett Reservoir were almost free of detectable iron; Quabbin "inside" waters frequently showed moderate levels approaching the 0.3 ppm (filterable) level.

The Connecticut River exhibited fairly high iron levels until the end of April after which the level was virtually nil. In contrast, both the Millers River and the tributary streams consistently exhibited high iron, the level of

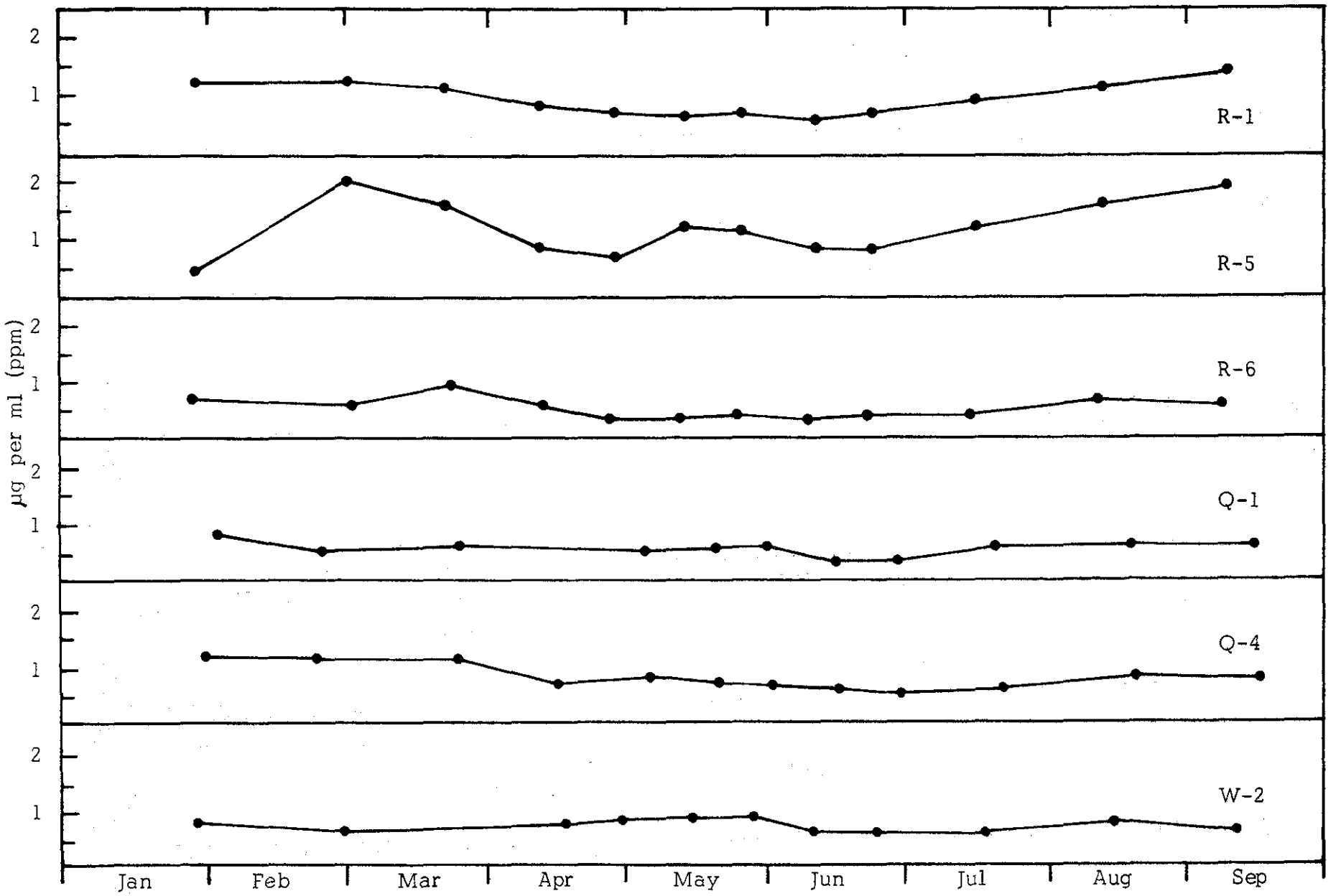


Figure 38. Potassium Levels at Selected Stations, 1971

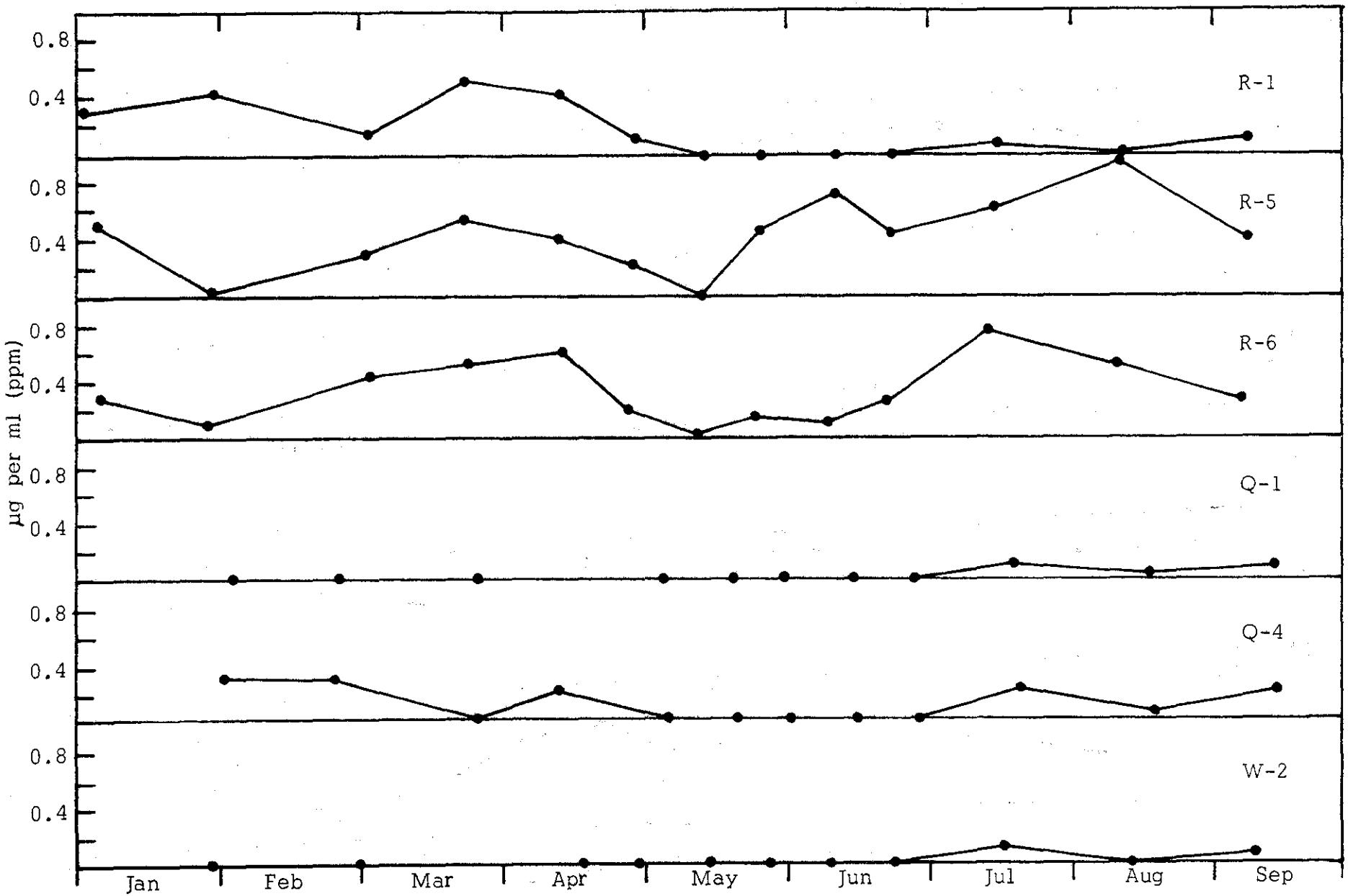


Figure 39. Total Iron Levels at Selected Stations, 1971

which varied markedly.

Manganese

Figure 40 shows that levels in excess of 0.05 ppm were found in the spring. Subsequent to this, all levels decreased to nil during the early summer. All stations showed the same general annual pattern.

Zinc

From Figure 41 it can be seen that, except for one surge at Q-4, the zinc levels of all stations were very similar in annual pattern, with all stations exhibiting irregular patterns.

Mercury

Low levels of mercury have been found at all of the sampling sites. Several spikes of mercury in excess of 5 ppb (U.S.P.H.S. standard) have been found at some locations, especially in the Millers River, Quabbin and Wachusett Reservoirs. Of these, the most significant findings have been those relative to Wachusett Reservoir where periodically high values were found earlier in the year. These values decreased and remained at low levels in the third quarter. As has been pointed out in earlier reports, it is not possible, due to the sampling regimen, to define the source of this mercury. Mercury levels at selected locations are shown in Figure 42.

Carbon Chloroform Extract

CCE values for all waters examined were in the range of 0.1 - 0.2 ppm in the first quarter, and thereafter remained in the range of 0.01 - 0.04 ppm. It is impossible to attach any significance to these values until a second year

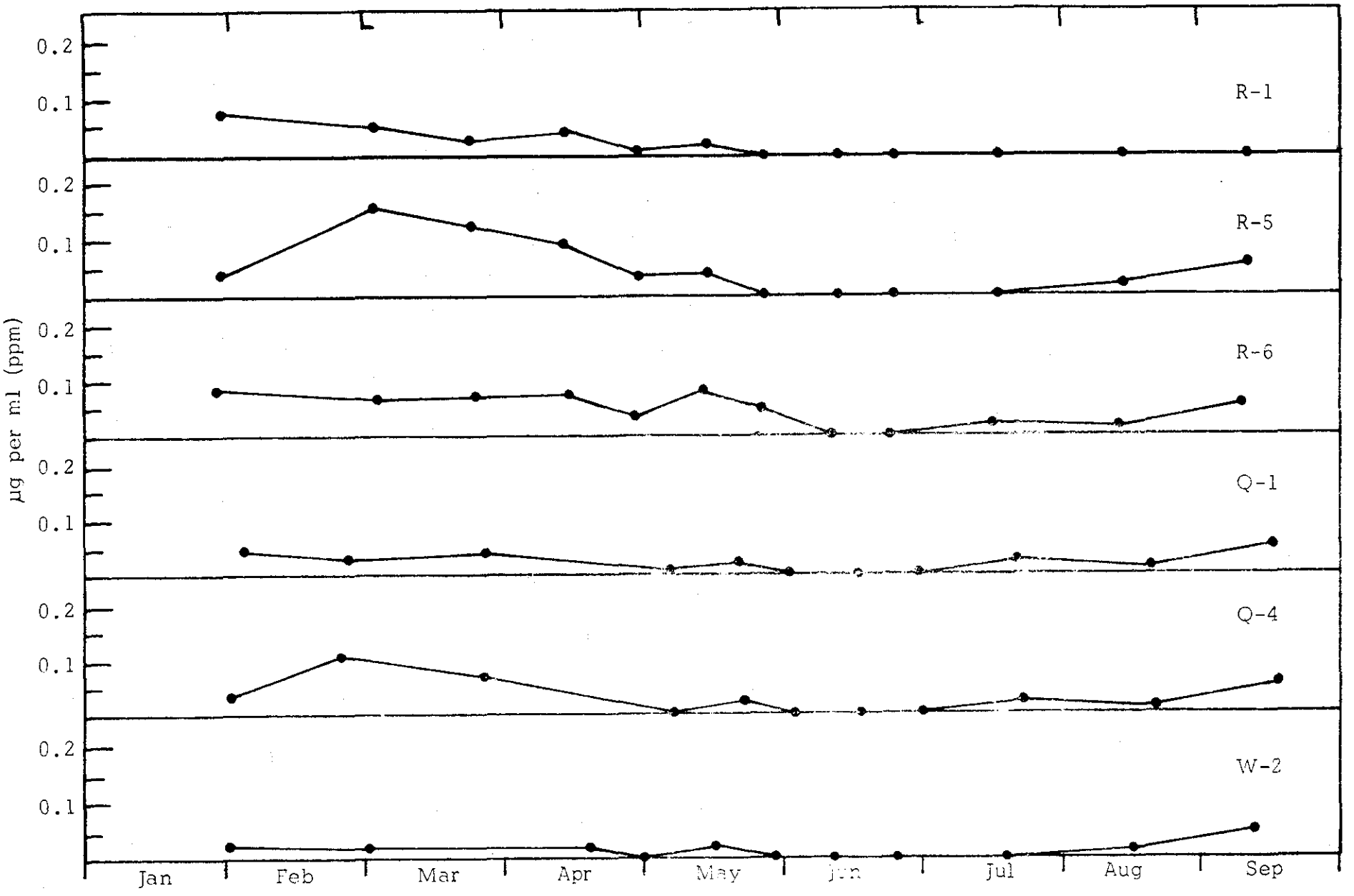


Figure 40. Manganese Levels at Selected Stations, 1971

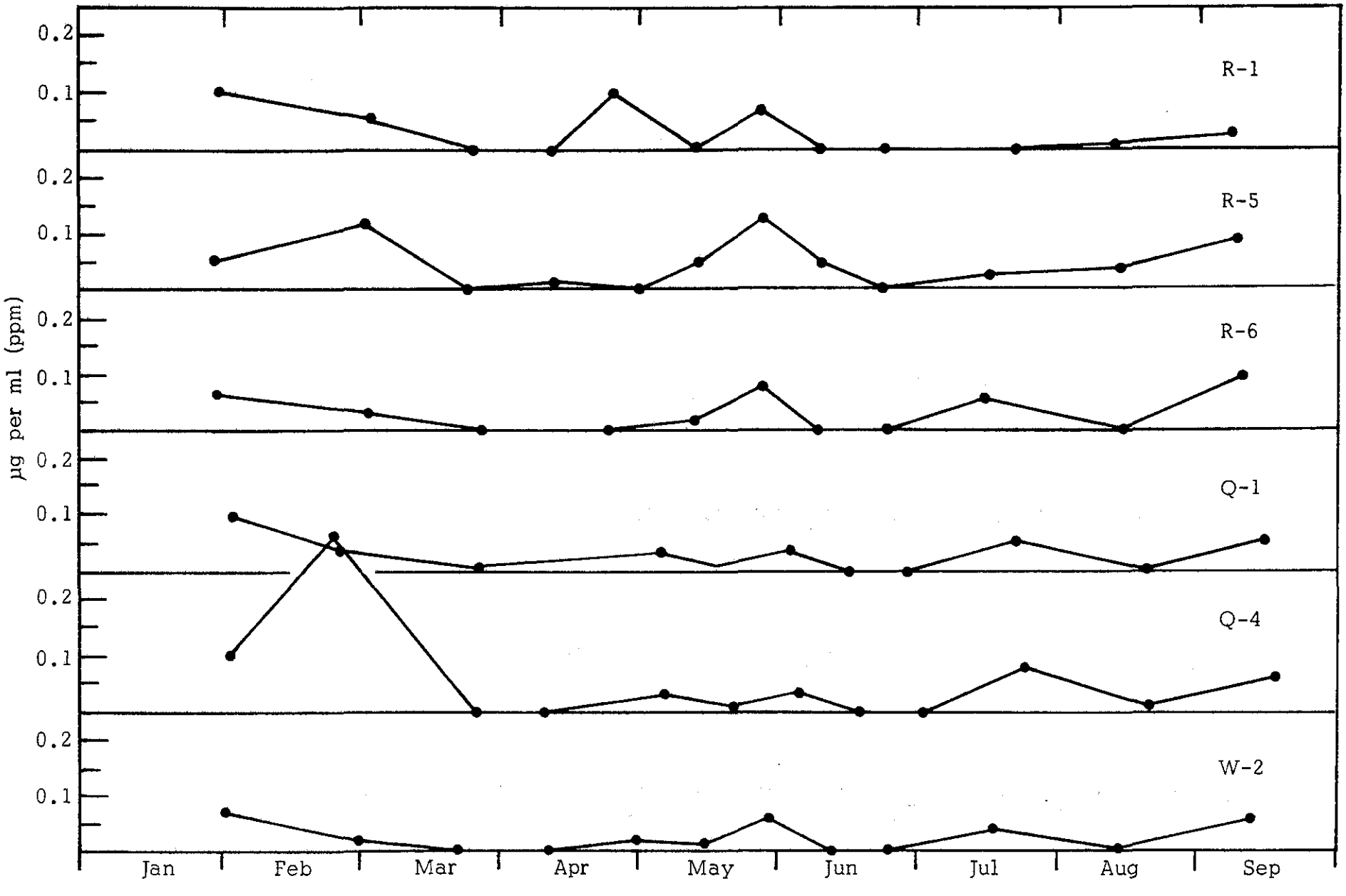


Figure 41. Zinc Levels at Selected Stations, 1971

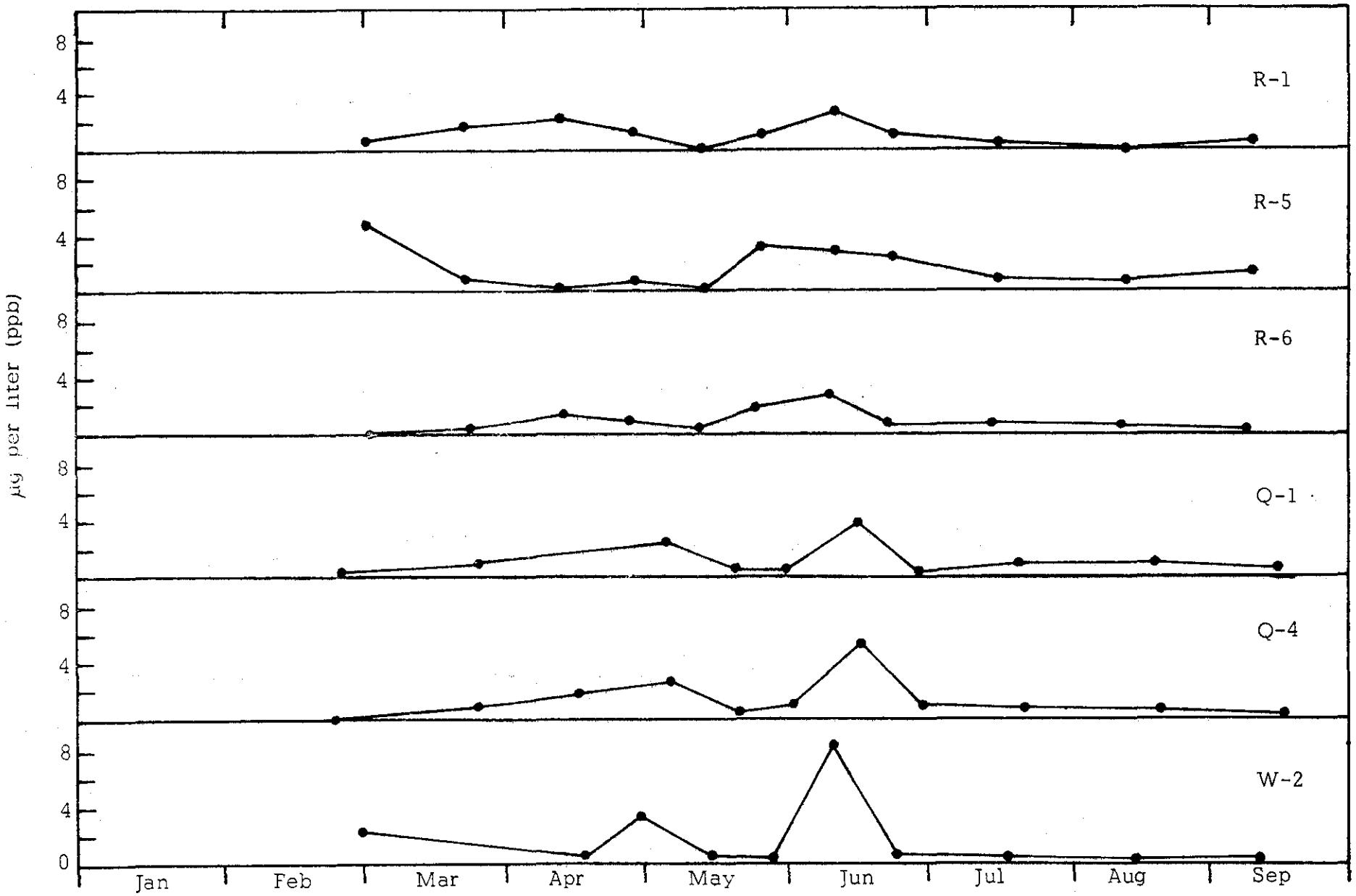


Figure 42. Mercury Levels at Selected Locations, 1971

study can confirm the relatively high first quarter values. Except for this apparent difference between the earliest and all other values, no other patterns to the CCE data were observed.

C. Physical Data

(1) Color

Quarterly averages of color (Table 14) for the various systems examined yield a pattern from highest to lowest color for each quarter, as follows:

(a) tributaries to Millers River

(b) Millers River

(c) Ware River

(d) Connecticut River

(e) Quabbin Reservoir ("inside" stations)

(f) Wachusett Reservoir

(g) Quabbin Reservoir ("outside" stations)

Color generally decreased or remained constant in riverine systems during the first quarter, and increased in the middle of the second quarter (Figure 43). Most riverine stations showed decreases in color during the third quarter. Of all riverine waters, Connecticut River waters were the most constant with respect to color, with quarterly averages ranging from 20 to 25 color units.

Color increased only slightly at most Wachusett Reservoir stations, but increased dramatically between the first and second quarter in the area of the Route 12 crossing (W-1) (Figure 44). The only significant increase in color in Quabbin "outside" stations was noted at station Q-6 (Shaft 12) and was perhaps the result of water from the Ware River

Table 14-A. Summary of Physical Data

		Color Pt.-Co. Units			Specific Conductance Micromhos/cm			Dissolved Oxygen mg/l			pH			Turbidity Hach J.T.U.			Turbidity Spec. 20 J.T.U.	
Quarter		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2
Quabbin "Outside"	No. of Readings	28	41	27	28	41	27	13	41	27	28	41	27	7	44	27	28	20
	Range	1.0 6.0	2 10	5 5	33 59	40 44	42 46	11.0 14.6	9.0 12.6	6.4 10.8	5.8 6.4	6.0 6.7	0.3 7.1	0.3 0.8	0.3 0.8	0.6 1.0	4 4	4 8
	Average	3	4	5	44	42	43	13.8	11.2	8.6	6.2	6.4	6.6	0.5	0.5	0.8	4	4
Quabbin "Inside"	No. of Readings	25	37	19	25	36	19	10	35	19	25	36	19	7	36	19	25	19
	Range	3 35	5 65	5 25	37 73	41 55	44 53	10.3 13.9	7.6 12.1	6.0 8.5	4.6 6.4	5.4 6.7	6.3 7.0	0.7 1.0	0.5 1.0	0.7 2.0	4 26	4 30
	Average	15	20	12	54	48	48	12.5	10.2	7.9	6.1	6.2	6.7	0.9	0.8	1.0	10	16
Wachusett	No. of Readings	23	36	18	25	36	18	17	36	18	25	36	18	4	36	18	25	24
	Range	1 17	3 40	5 10	36 108	60 98	47 79	12.4 13.8	9.3 12.8	6.8 9.4	4.8 6.5	6.2 7.0	6.4 7.3	0.4 0.9	0.3 1.0	0.5 0.8	4 16	4 22
	Average	4	11	7	58	72	67	13.1	11.0	8.4	6.0	6.6	6.8	0.6	0.5	0.6	4	8
Tributaries of Millers River	No. of Readings	20	30	15	20	30	15	14	30	15	20	30	15	5	30	15	20	20
	Range	12 80	15 165	20 150	37 60	31 48	32 66	9.3 13.2	6.2 11.9	5.6 8.4	5.1 6.1	4.8 6.4	5.6 6.9	0.4 1.0	0.4 2.0	1 2	4 56	8 54
	Average	39	55	98	47	40	48	11.6	9.5	6.9	5.5	5.5	6.2	0.6	0.8	1.6	30	29

Table 14-B. Summary of Physical Data

		Color Pt.-Co. Units			Specific Conductance Micromhos/cm			Dissolved Oxygen mg/l			pH			Turbidity Hach J.T.U.			Turbidity Spec. 20 J.T.U.	
Quarter		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2
Ware River	No. of Readings	8	12	6	8	12	6	5	12	6	8	12	6	2	12	6	8	8
	Range	25 30	30 80	45 70	57 71	44 59	45 62	12.2 14.2	6.7 11.4	7.0 8.7	5.3 5.9	5.4 6.3	6.3 7.3	0.8 0.8	0.6 2.0	2 3	20 22	22 36
	Average	28	51	55	65	49	55	13.1	9.3	7.8	5.7	6.0	6.9	0.8	1.2	2.8	21	28
Connecticut River	No. of Readings	4	6	3	4	6	3	2	6	3	4	6	3	1	6	3	4	4
	Range	18 22	20 25	22 25	112 123	71 123	116 150	12.0 12.1	9.4 13.4	8.3 9.3	5.7 6.7	6.8 7.1	6.7 7.7	2.0 2.0	2.0 6.0	3.0 3.0	20 22	16 26
	Average	20	22	25	118	94	135	12.0	11.2	8.8	6.4	7.0	7.2	2.0	2.8	3.0	21	20
Millers River	No. of Readings	14	24	12	16	24	12	8	24	12	16	24	12	4	24	12	16	16
	Range	25 42	20 90	45 90	49 170	62 119	101 146	9.0 13.5	1.4 12.0	0.7 9.4	5.6 6.9	5.4 7.1	6.4 7.6	8 15	2.0 70	6 40	39 128	30 80
	Average	34	54	72	115	80	121	11.8	8.6	5.5	6.3	6.4	6.9	11	16	16	62	46

Figure 43. Color of Water at Riverine Stations

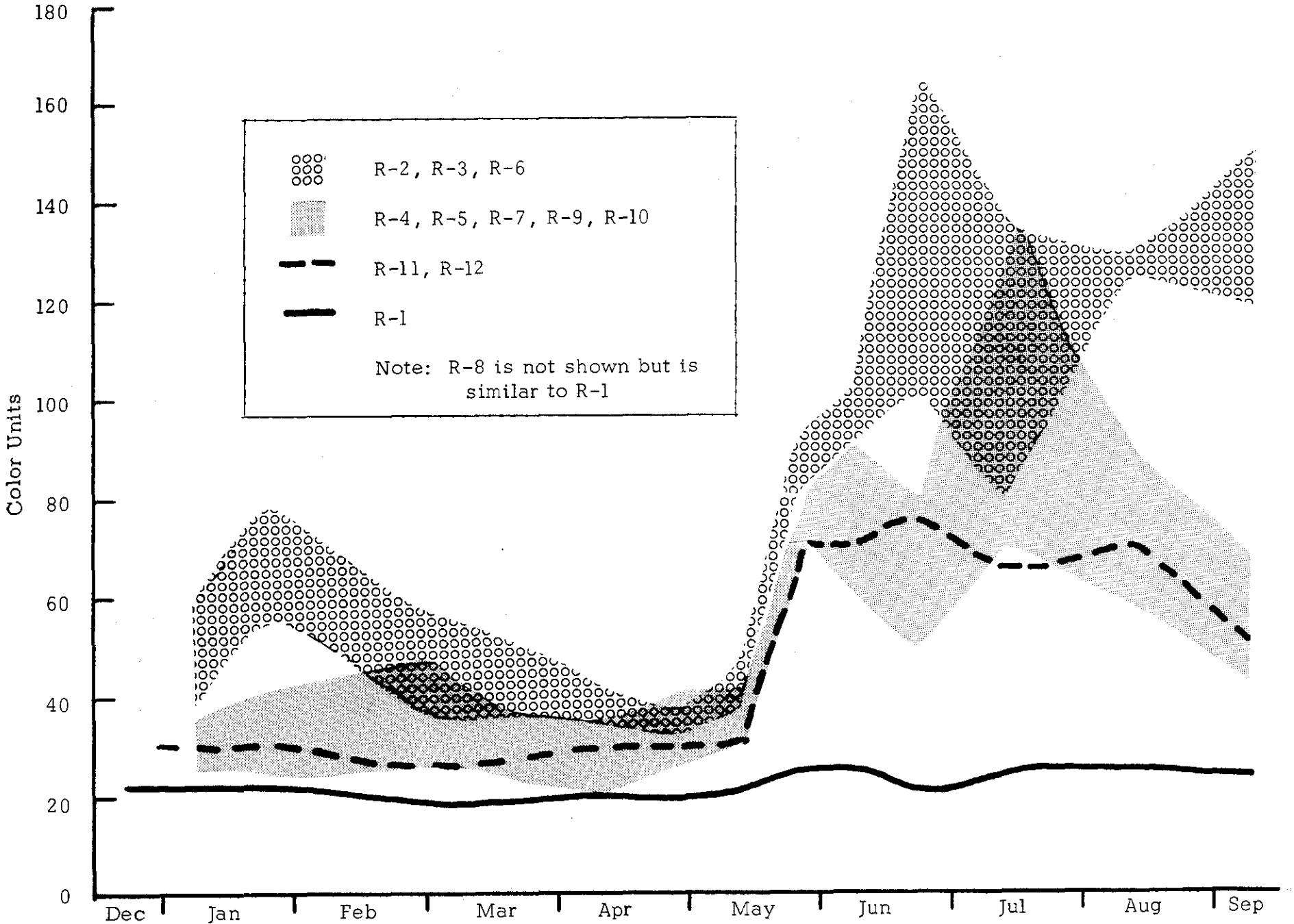
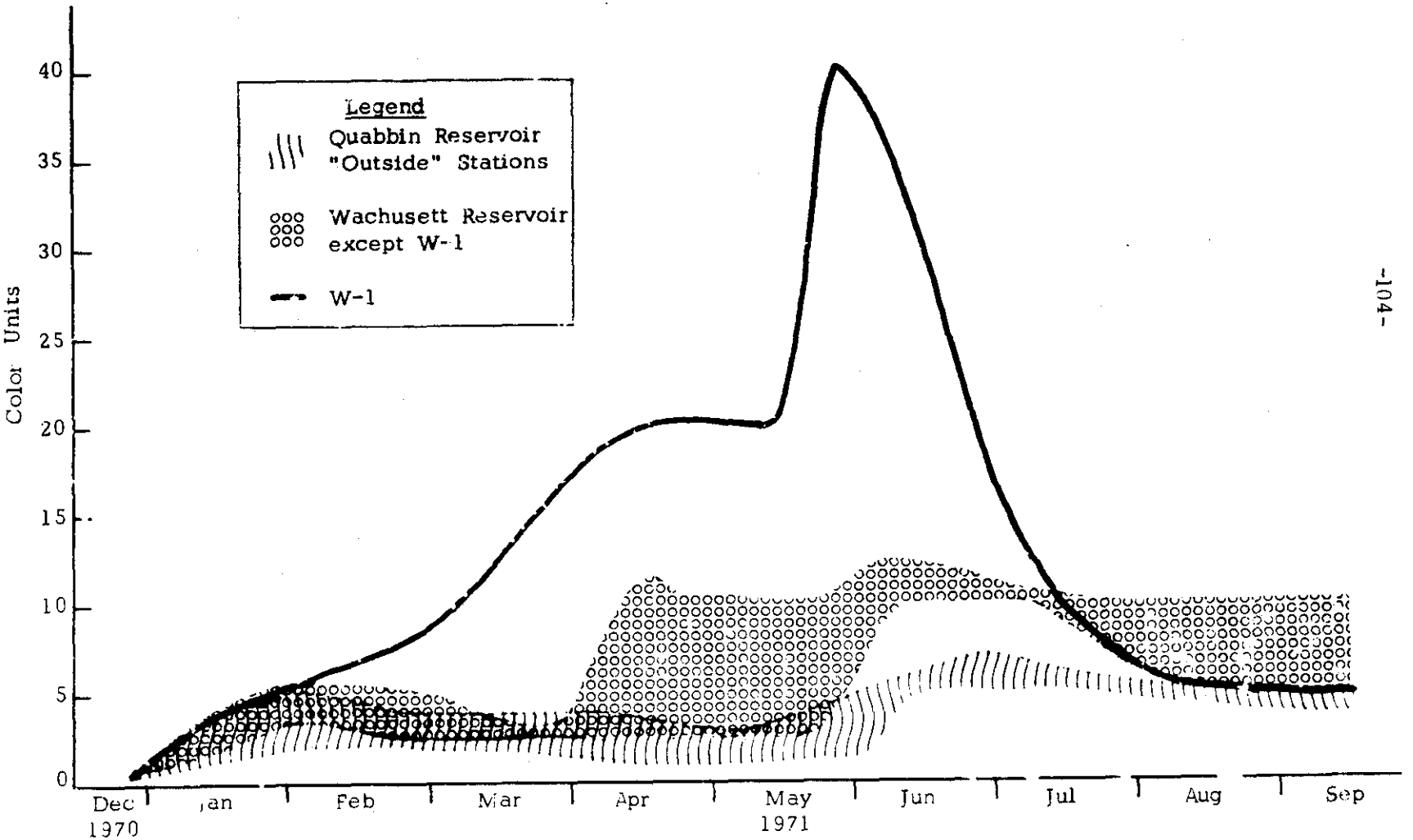


Figure 44. Color of Water at Quabbin "Outside" and Wachusett Reservoir Stations



diversion leaking into the sampling area through closed gates on the shaft. General increases in color were observed in Quabbin "inside" stations between the first and second quarters (Figure 45). Color generally decreased at these stations in the third quarter. Among these "inside" stations, Q-9 was significantly lower in color, and appeared intermediate between values obtained for the other "inside" stations and the "outside" stations. This result corresponds with the station's physical position (Figure 5) relative to other stations on the reservoir.

(2) Specific Conductance

Values of specific conductance fluctuated over wide ranges in each of the systems examined. These fluctuations were particularly large in the first quarter (Table 14 and Figures 46, 47), and became progressively smaller in the second and third quarters. In general, the systems examined can be arranged according to decreasing values of specific conductance (Table 14) as follows:

(a) the Connecticut and Millers Rivers

(b) Wachusett Reservoir

(c) tributaries to the Millers River, and the Ware River

(d) Quabbin "inside" waters

(e) Quabbin "outside" waters

Values of specific conductance in the Millers and Connecticut Rivers as well as many from Quabbin Reservoir, showed significant drops in April and early May. Only slight changes in values were noted in the tributary

Figure 45. Color of Water at Quabbin "Inside" Stations

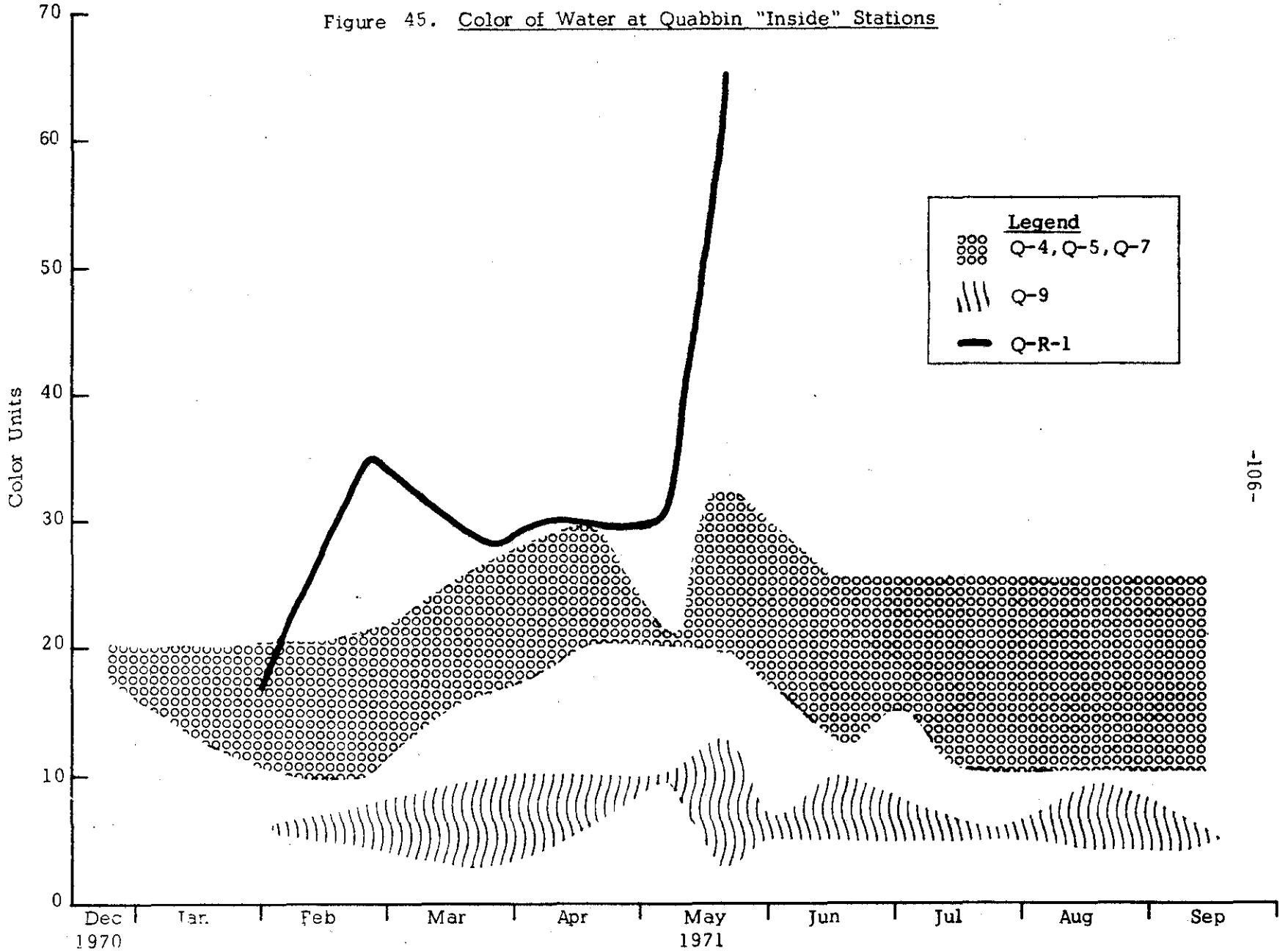


Figure 46. Specific Conductance of Riverine Stations

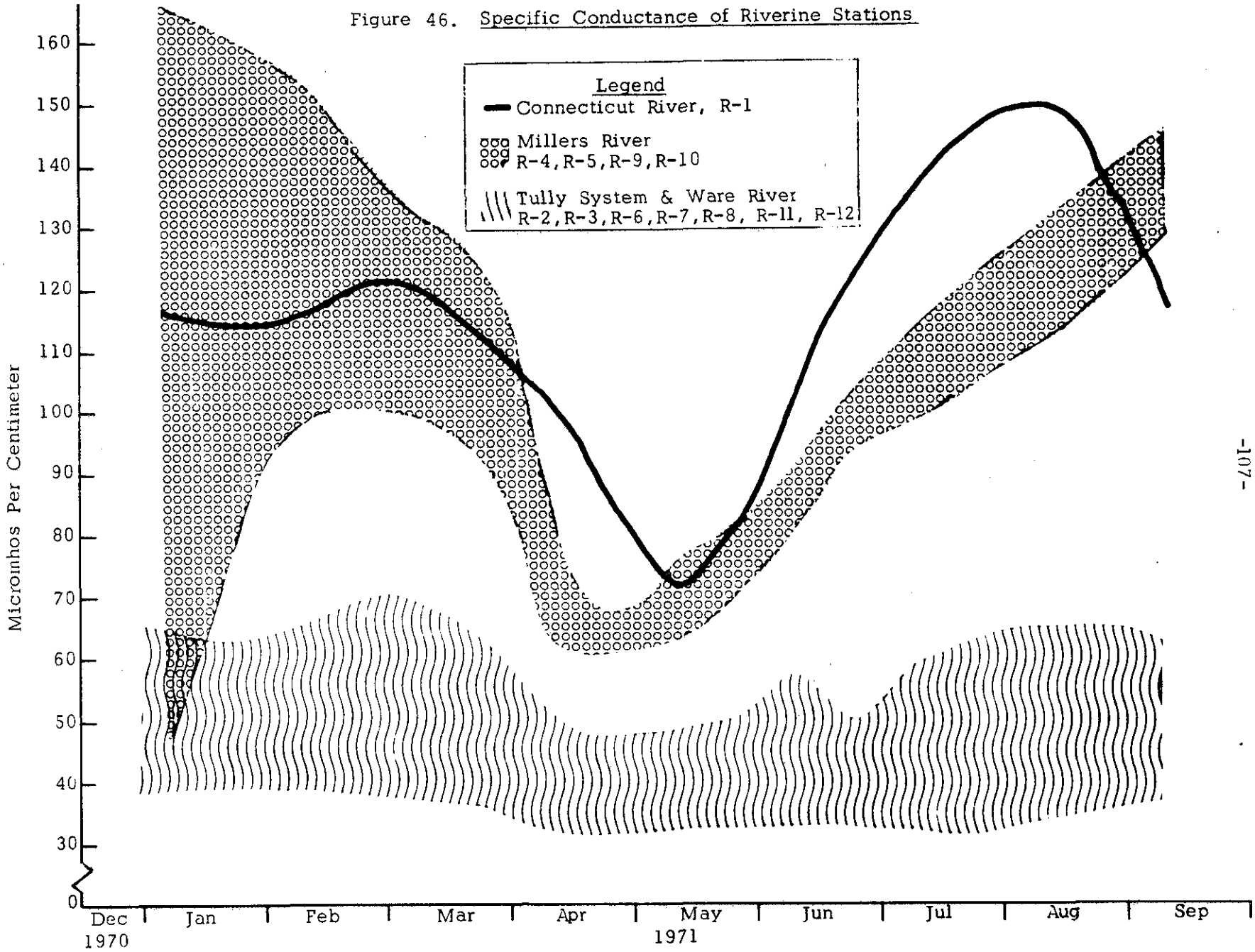
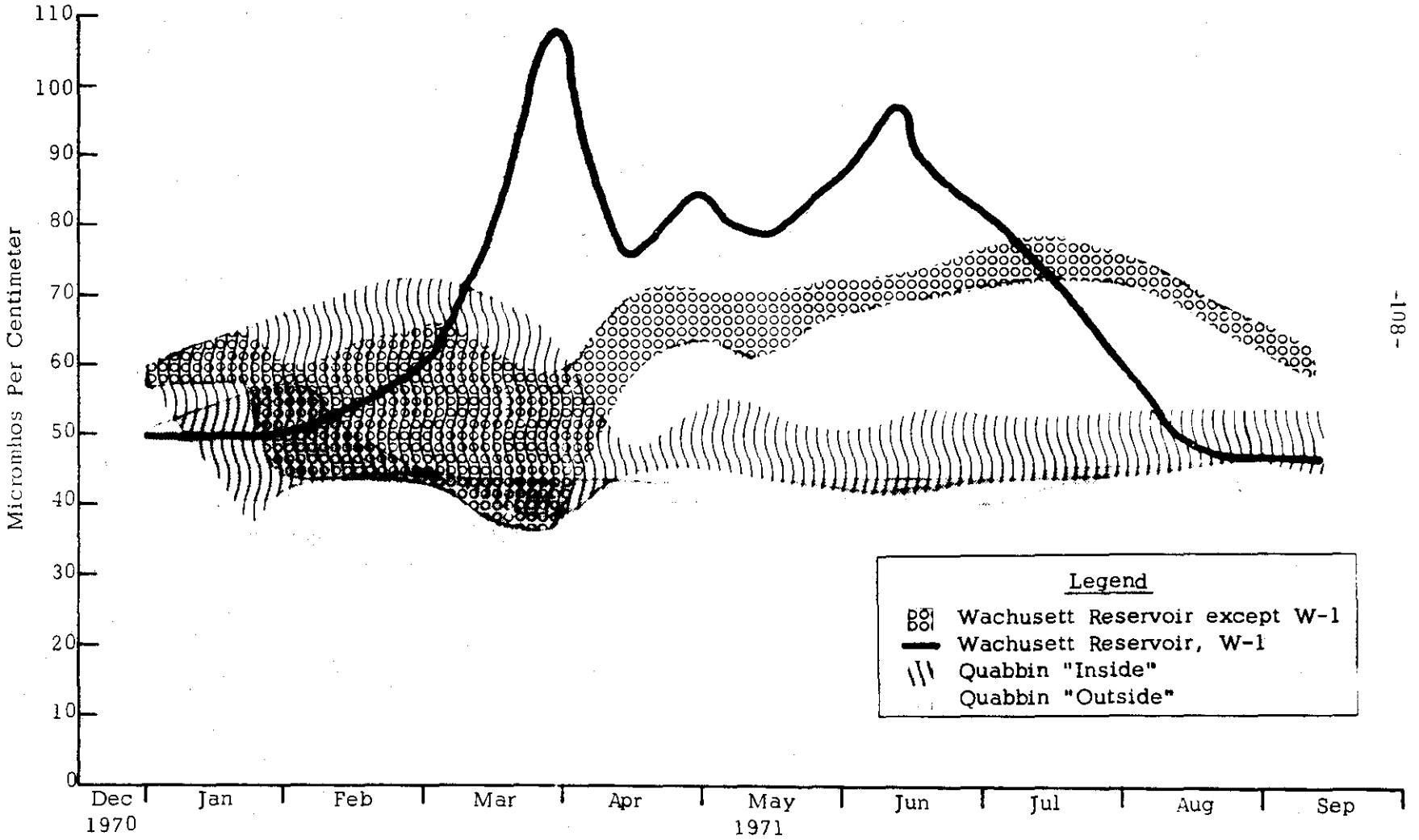


Figure 47. Specific Conductance for Quabbin and Wachusett Reservoir Stations



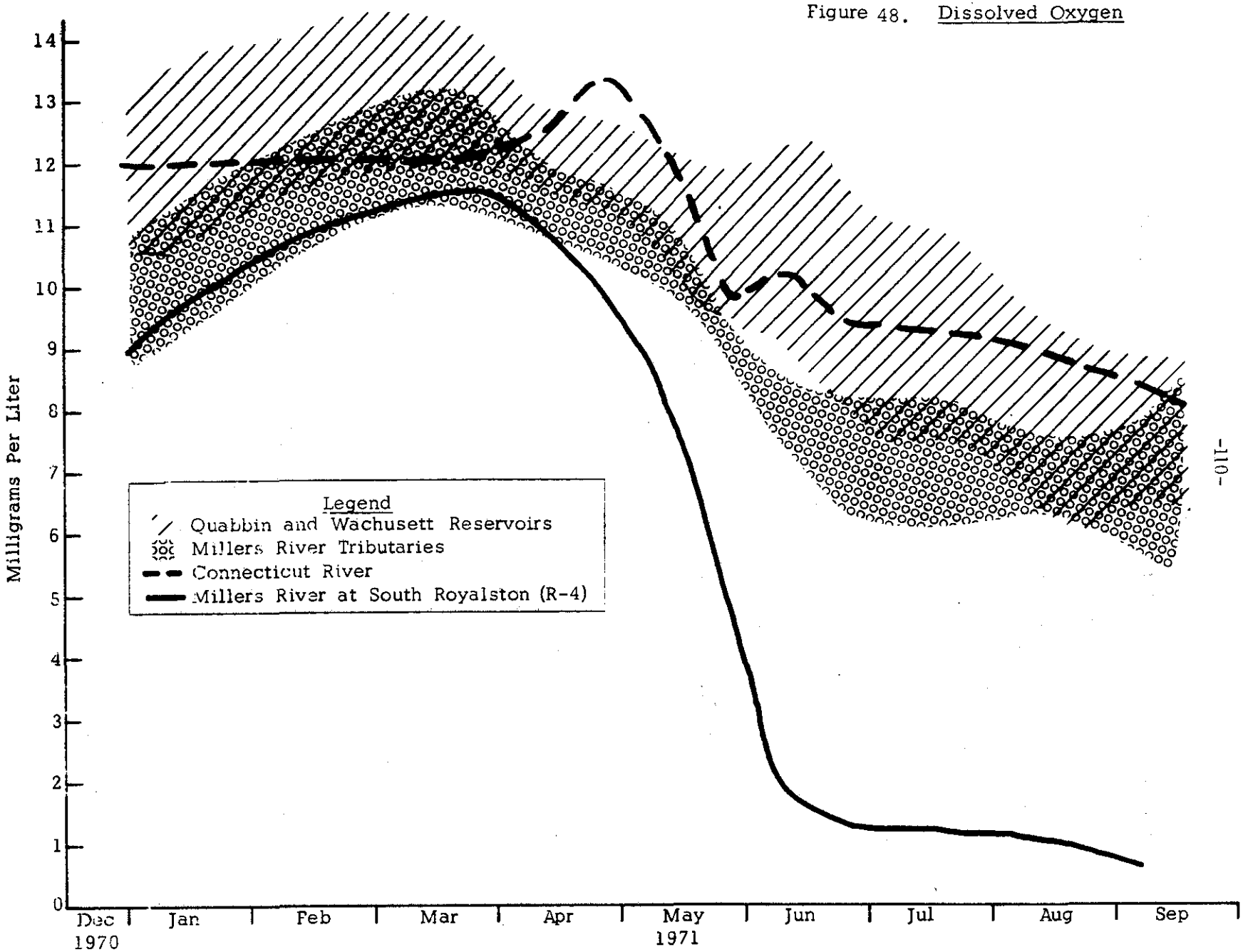
rivers throughout the three quarters. The lowest values obtained from the Millers and Connecticut Rivers (April-May) were about 60-70 µmhos/cm. The range of values obtained from Wachusett Reservoir in April and May was 45-85 µmhos/cm.

(3) Dissolved Oxygen

Quarterly averages of dissolved oxygen values in each of the systems examined (Table 14) indicate a basic similarity between all systems with the exception of the Millers River which showed the lowest dissolved oxygen concentrations in the third quarter. The lowest values within the Millers River were always obtained from samples collected in the South Royalston area (R-4).

As depicted in Figure 48, there was a general increase in dissolved oxygen in most systems between January and March, and a decrease in oxygen concentrations (which corresponded generally with temperature increases) from March through September. Dramatic decreases in oxygen concentrations which cannot be directly correlated to temperature change alone occurred in the Connecticut River and in the Millers River in April and May. The greatest range of dissolved oxygen values was consistently noted in the reservoirs, and while the reservoir values were often observed to overlap values found in tributary waters, the tributaries to the Millers River showed generally lower values of dissolved oxygen throughout most of the three quarters.

Figure 48. Dissolved Oxygen



(4) pH

Quarterly averages of pH (Table 14) for station groupings employed in earlier sections of this report cannot be used to distinguish these groupings from each other. They do show, however, obvious increases in pH between the first and third quarters for each grouping.

An examination of changes in pH at each individual riverine station, moreover, reveals the following three persistent patterns of pH values (Figure 47):

(a) pH values ranging between 5.7 and 7.7, with a persistent increase in values from first through second quarter (Connecticut River)

(b) pH values ranging between 5.3 and 7.7, with a significant drop in values in mid-April (Millers River, Ware River, and West Branch of Tully River)

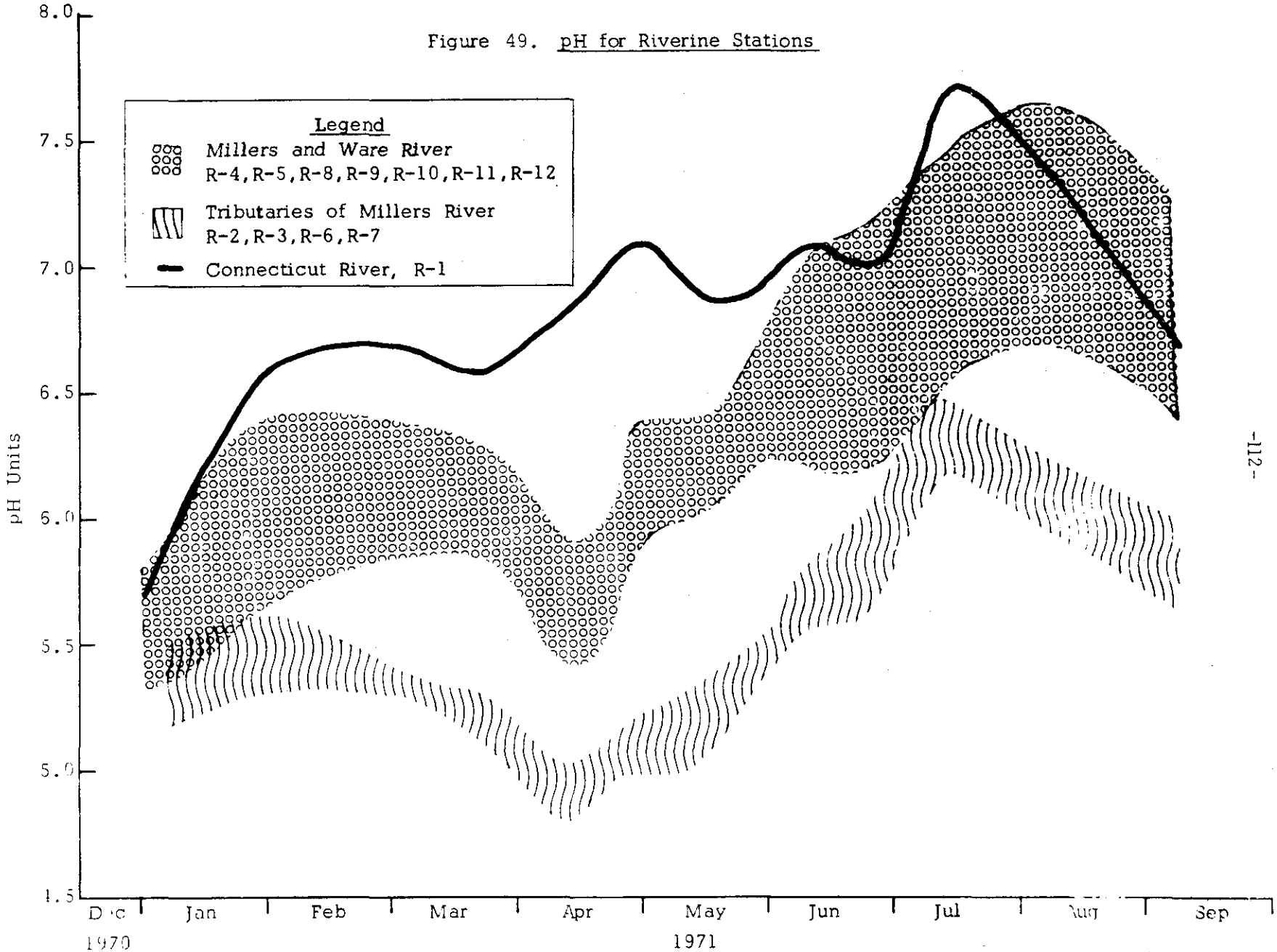
(c) pH values ranging between 4.8 and 6.6, with a significant drop in values in mid-April (Tarbel, Priest, and Lawrence Brooks, and East Branch of Tully River)

All pH values for reservoir waters fall within the second pattern with the following exceptions:

(a) Wachusett and Quabbin "outside" stations did not show an April decline in pH, and values were more alkaline than the Millers, Ware and West Branch of Tully Rivers by about 0.5 log units.

(b) In February, station Q-5 in Quabbin (Rattlesnake Hill area), and station W-5 in Wachusett (Clinton intake area) showed pH values of 4.6 and 4.8 respectively.

Figure 49. pH for Riverine Stations



(5) Turbidity

Originally turbidity measurements were made on a spectrophotometer (Spectronic 20), calibrated to a formazin standard. Later, this method was compared with the Hach turbidimeter, which is a true nephelometer, and is also calibrated with formazin (see Appendix 1). The Hach turbidimeter readings were consistently lower than the photometric readings, and direct correlations between turbidimetric and photometric values could not be made (Figure 50). The Hach turbidimeter readings were compared with those of the MDC Laboratory at Quabbin Reservoir, and found to be in good agreement. After the second quarter, duplicate readings on the Spectronic 20 were abandoned. However, both sets of data are entered in Table 14.

Quarterly averages of turbidity for the systems examined (as measured by the Hach method) indicated an overall pattern of decreasing turbidity (Table 14) as follows:

(a) Millers River

(b) Connecticut River

(c) Ware River

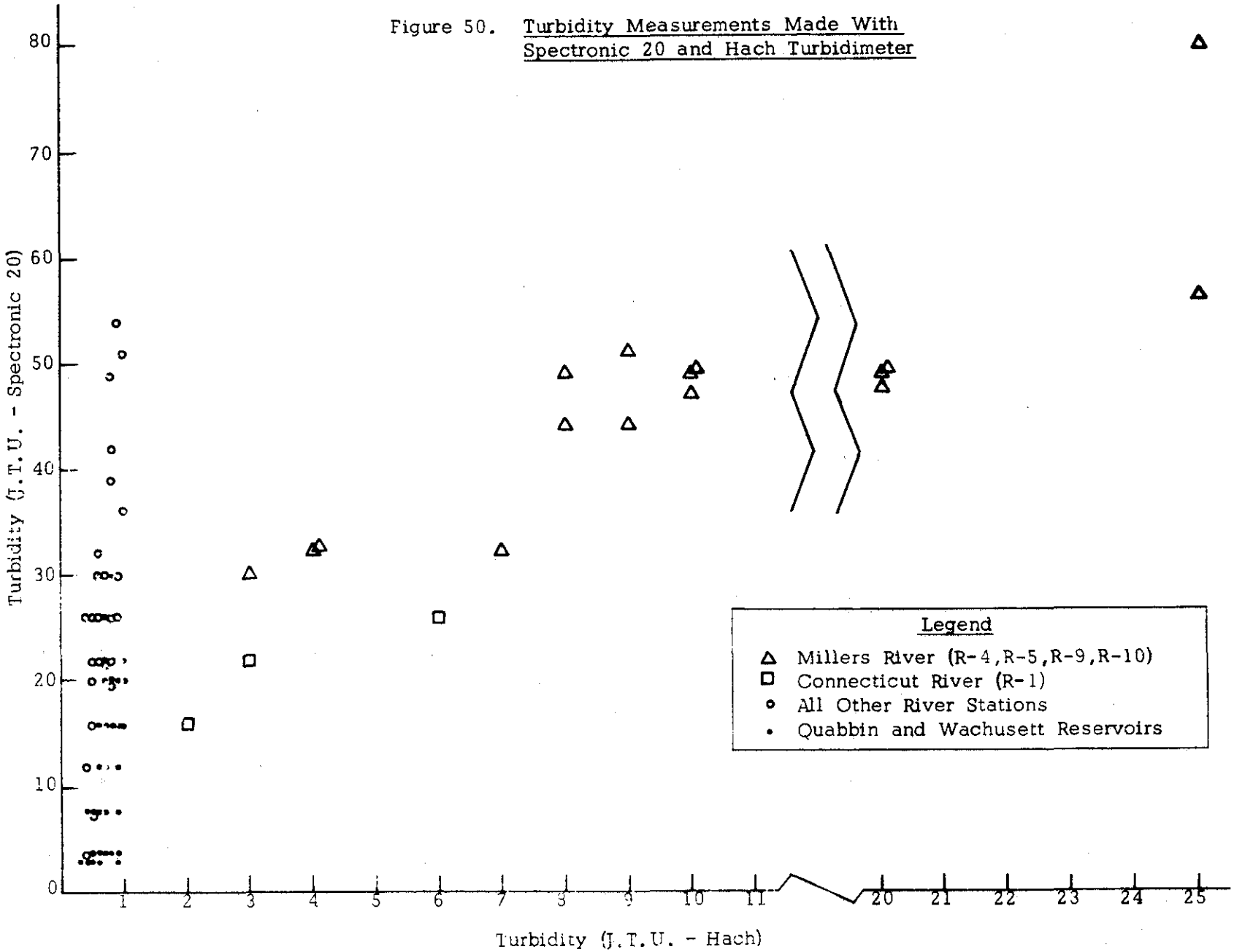
(d) Millers River tributaries

(e) Quabbin Reservoir ("inside" waters)

(f) Wachusett Reservoir

(g) Quabbin Reservoir ("outside" waters)

Figure 50. Turbidity Measurements Made With Spectronic 20 and Hach Turbidimeter



Major differences in turbidity in these systems are depicted in Figure 51. The reservoirs consistently averaged 1.0 JTU or less.

(6) Temperature

Daily fluctuations of temperature in all riverine systems are most likely far greater than differences noted between individual systems in the same time period. Temperature differences which were noted between individual riverine systems ranged from about 1°C in late February to 10°C in early June. The highest riverine temperature in early June was recorded in the Millers River at South Royalston (27°C), and the lowest in the western branch of the Tully River (17°C). The temperature recorded in the Connecticut River at this time was 20°C.

Surface temperatures of riverine waters were generally comparable with surface temperatures of reservoir waters for all quarters. Quabbin "inside" stations were generally warmer than Quabbin "outside" stations. A comparison of temperatures recorded at selected Quabbin stations and the Connecticut River from January through June is made in Figure 52.

The depth of the thermocline in Quabbin Reservoir varied from about 5 to 11 meters over the summer season. Temperature profiles from various areas of the reservoir were generally comparable (Tables 15 and 16).

Figure 51. Turbidity for Riverine Stations

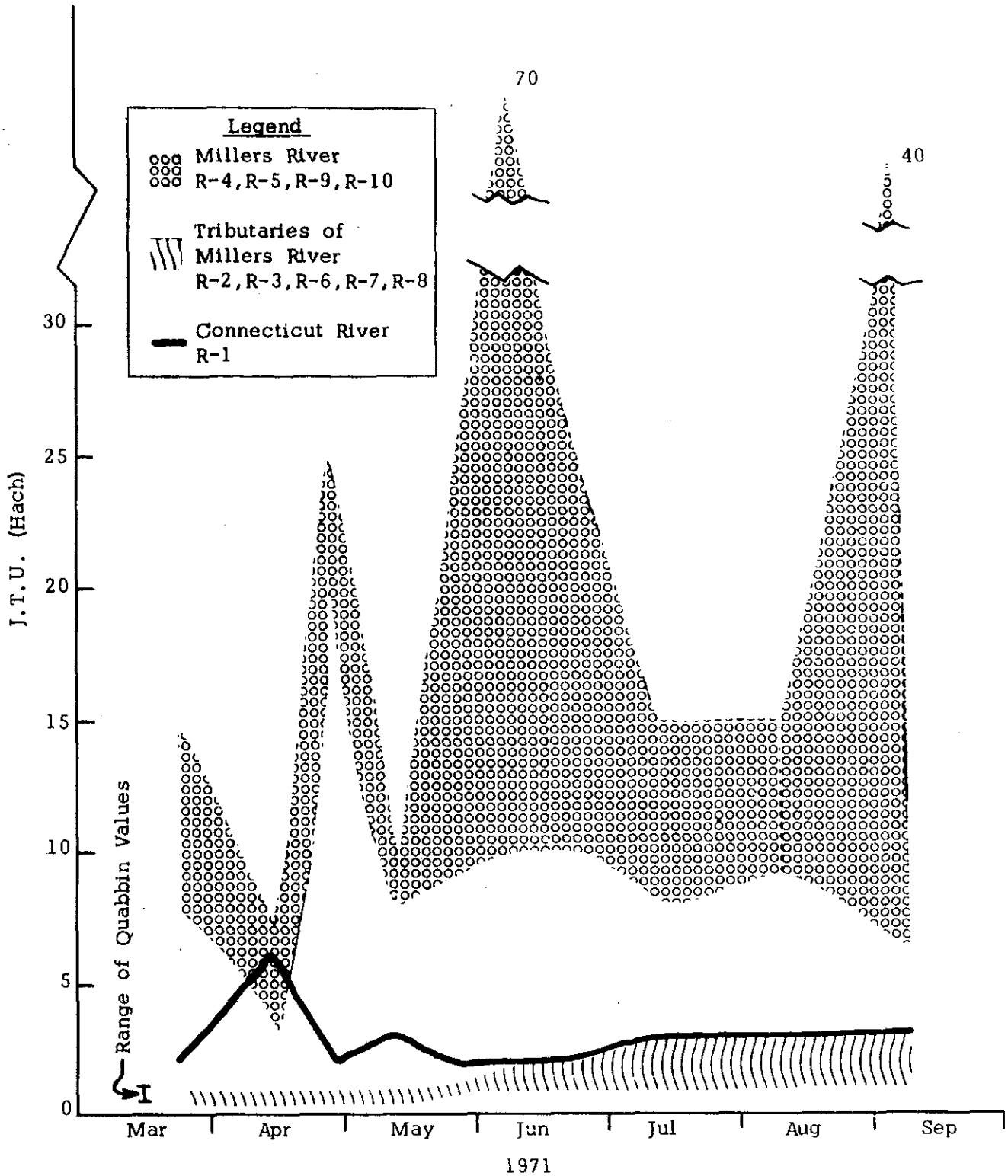


Figure 52. Surface Water Temperature at Quabbin Reservoir (Q-2, Q-5) and Connecticut River (R-1)

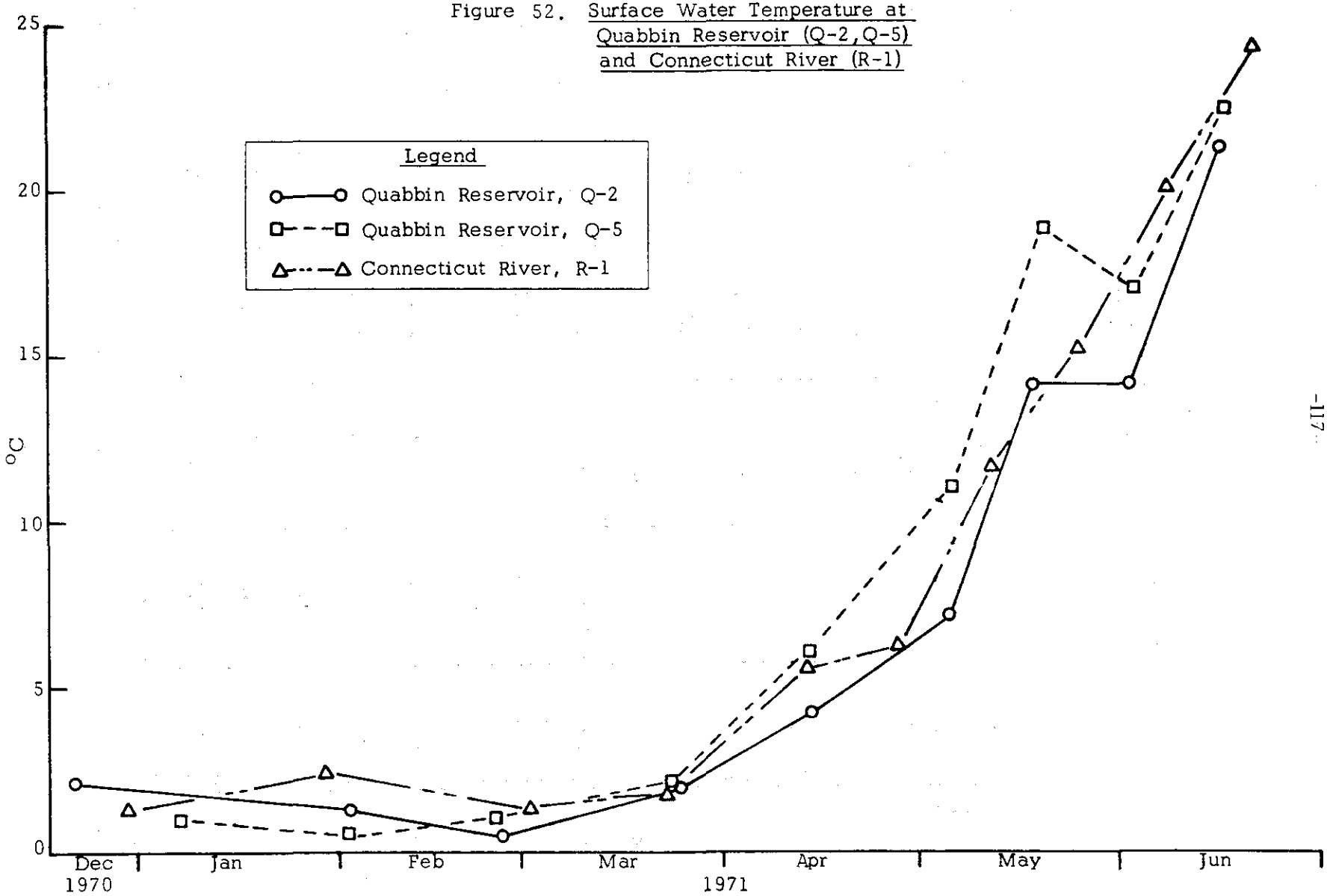


Table 15. Temperature Profiles at Quabbin Reservoir (Q-9) (°C)

Depth (meters)	1 Jun	15 Jun	29 Jun	20 Jul	17 Aug	14 Sep
0	X	20	23	24	X	24
1	15	20	23	23.9	25	24
2	17	19.8	22.9	23.9	24.9	24
3	16.5	19.6	22.9	23.7	24.9	24
4	16	19.4	22.9	23.5	24.9	24
5	13.5	19.0	22.9	23.3	24.8	24
6	13	18.2	22.5	23.3	24.7	24
7	12.5	17.8	22.0	23.1	24.5	24
8	12	15.2	20.2	23.1	24.0	24
9	12	14.2	19.1	23.0	22.2	24
10	12	14.0	17.1	22.1	18.9	24
11	X	13.2	X	18.5	17.0	21
12	X	13.0	14.3	16.2	15.5	18
13	X	12.5	X	X	X	17
14	X	X	14.1	X	X	16

Table 16. Temperature Profiles at Quabbin Reservoir (Q-2) (°C)

Depth (meters)	22 Dec	15 Apr	3 Jun	1 Jul	22 Jul	19 Aug	16 Sep
0	2	4.2	X	24.2	X	24.6	26.0
1	5	4.2	X	23.9	24.0	24.4	25.0
2	5	4.2	X	23.9	23.8	24.4	23.7
3	5	4.1	15	23.5	23.5	24.3	23.3
4	5	4.1	X	23.3	23.2	24.2	23.3
5	5	4.1	X	23.1	23.1	24.1	23.3
6	5	4.1	14.8	23.0	23.1	23.9	23.1
7	5	4.1	X	21.5	23.0	23.7	23.0
8	5	4.1	14.5	19.0	22.9	23.5	X
9	5	4.1	X	17.5	22.9	23.3	X
10	5	4.1	X	16.0	19.0	23.1	X
11	5	4.1	X	15.5	16.0	18.5	X
12	5	4.1	X	13.8	X	X	X
13	5	4.1	X	X	X	X	X
14	5	4.1	X	X	X	X	X
15	5	4.1	X	X	X	X	X

D. Pesticide Data

Twenty-seven reservoir and riverine stations were sampled and tested for pesticides. The breakdown on the stations is as follows:

Quabbin Reservoir	15
Wachusett Reservoir	6
Rivers (Stations 1,2,3,5,7,8)	6

The stations were sampled during the winter (Jan.-Feb.), the spring (May) and the summer (August). One station (Q-R-1) was not sampled in August because of no flow from the Ware River Diversion. Fourth quarter samples were collected in November; the results are presented in the subsequent supplementary report, (Appendix 6, Fourth Quarter Data).

Table 17 lists the pesticides and the detection sensitivities required for the project. In no instance did the water samples contain insecticides or herbicides above the required detection sensitivities. For example, whenever a trace amount of any chlorinated hydrocarbon pesticide was detected, the levels were reported as less than 10^{-4} ppm. Trace amounts of the chlorinated insecticides and the organic phosphates/carbamates were seen in both the winter and summer samples. Nothing was detected in the second quarter (May) samples. Absolute identification was not required for trace amounts. No attempt was made to positively identify PCBs in any of the waters. They may have been present, but the levels were so low that no positive identification of any peaks possibly attributable to these compounds was carried out. Table 18 summarizes the presence of trace amounts of various groups of compounds. No herbicides were detected.

Table 17. List of Pesticides and Required Sensitivity for Detection Techniques

Compound	Sensitivity in ppm
Aldrin	±0.0001
Chlordane	±0.0001
DDT	±0.0001
Dieldrin	±0.0001
Endrin	±0.0001
Heptachlor	±0.001
Heptachlor epoxide	±0.001
Lindane	±0.0001
Methoxychlor	±0.0001
Organic Phosphates and Carbamates	±0.01
Toxaphene	±0.0001
2,4-D	±0.01
2,4,5-T	±0.01
2,4,5-TP	±0.01
Phenols	--

As seen in Table 17 the project required the detection of phenolic compounds. Because of confusion on sensitivity requirements, no analyses were possible on the winter samples. Subsequent water samples were analyzed as described in the methods section of this report. No traces of phenols were detected in the May samples. Trace amounts (0.01 to <0.01 ppm) of phenolic substances were detected in 4 river samples collected in August. Specific locations are shown in Table 18.

In conclusion, the results show only trace amounts of pesticides where present, no amounts exceeded the sensitivity requirements, the spring (May) samples were free of pesticides, and traces of phenolic compounds were seen in the summer river waters.

Table 18. Summary for Detection of Trace Amounts of Pesticides and Phenols

Stations omitted from the Table showed no traces of any compounds.

Station	First Quarter	Third Quarter
Q-2-S	OP/C	
Q-2-10		A
Q-3-Tap		OP/C
Q-7-S	OP/C	
Q-8-S	OP/C	
Q-9-S	A,L	
Q-9-10	OP/C	
Q-R-1	OP/C	
W-2-S	OP/C	
W-5-S	A	
W-5-10	A,L	
R-1	L	
R-2		Ph
R-3	A,D,L	Ph
R-5	A,H,HE,L	L, OP/C
R-7	A,D,H	Ph
R-8	A	Ph

Compound Codes: OP/C = Organic Phosphates/Carbamates, A = Aldrin, D = Dieldrin, H = Heptachlor, HE = Heptachlor Epoxide, L = Lindane, Ph = Phenols

E. Radioactivity.

Originally it was agreed that the sponsoring agencies were to provide NER with the appropriate data on radioactivity for all systems under study. Later it was decided that NER would collect the water and deliver it to the Lawrence Experiment Station for analyses at their Radiological Health Lab. Over the period July 15-22 a total of 32 samples were collected. They were distributed as follows: rivers - 12; Quabbin Reservoir - 14; Wachusett Reservoir - 6. Station Q-R-1 at Quabbin was omitted because it was dry; the Ware River was not being diverted.

The results of analyses showed all samples to have gross beta activity below 10 $\mu\mu$c/liter. Of the river stations, R-2, R-4, R-6 and R-7 showed the highest values (6 and 7 $\mu\mu$c/liter). No gross alpha activity was detected in any water samples. Because of the low beta activity and undetectable alpha activity, no tests were performed for ^{226}Ra and ^{90}Sr. The policy of the Lawrence Experiment Station is not to test for ^{226}Ra if the gross alpha activity is under 1 $\mu\mu$c/liter, nor for ^{90}Sr if the gross beta activity is less than 10 $\mu\mu$c/liter.

Additional water samples were collected in November. The results of those analyses are reported in the subsequent supplement, (Appendix 6).

6. OTHER INFORMATION

A. Hydrodynamic Studies

This section is a summary of the hydrodynamic studies of the Quabbin Reservoir carried out under subcontract by the Alden Research Laboratories (Hecker and Yale, 1971).

Because of the three-dimensional geometry of the reservoir and the complex, periodic nature of the diversions, analytic techniques could not be applied with confidence until some understanding of the basic reservoir hydrodynamics was available. To this end, a small-scale hydraulic model of Quabbin Reservoir was constructed and tested. The horizontal scale was 1:4000, while the vertical conversion ratio was 1:200. Appropriate Froude model similitude and scaling criteria were employed. Flow patterns in a model of this type are due mainly to inertia and gravity forces. Isothermal conditions (i.e. no stratification) were assumed, and no attempt was made to account for surface shearing forces due to winds. Finally, the density of the inflow water was the same as that of the reservoir water. Dye tracers were used to study flow patterns. Photographs were taken at periodic intervals, and the running time in hours was converted to the equivalent time in days. Thus basic reservoir dynamics including retention times and circulation patterns over a period of days could be studied on the model.

The study is presented in three sections. The first is an attempt to study the flows between the west branch and the main reservoir. The second section includes calculations of dilutions and retention times. Finally the third section

is a discussion of the flow patterns.

(1) Flow Between West Branch and Main Reservoir

Stage-volume curves for both the west branch and the entire reservoir were prepared. For known inflows or withdrawals over a given period, the change in volume and thus the change in surface elevation of the entire reservoir can be determined. Assuming a horizontal water surface, volume changes in the west branch can be determined. Therefore, for the same time period, the average flow into or from the west branch can be calculated.

Two cases producing inflows to the west branch from the main reservoir, and one case producing outflow from the west branch into the main reservoir were considered. Using the cross-sectional area of the narrows connecting the west branch and the main reservoir, the calculations indicate that the velocities associated with the net flows into or from the west branch would be negligible and not measurable with standard current meter techniques. While the stage-volume curves of the MDC differed,[1] the results show that an exchange of water between the west branch and the main reservoir should be expected irrespective of those differences. This conclusion was verified by the flow pattern studies described below.

(2) Dilutions and Retention Times

Several cases involving various operating conditions were considered

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[1]The model was constructed with templates prepared from U. S. Coast and Geodetic and Borden Surveys taken in 1885 and 1887. The M.D.C. conducted field surveys in the 1930's.

for calculating dilution ratios. Assumptions included an initial reservoir level of 508 feet and diversion and Swift River inflows of 70 days. The results are shown below:

Case	Inflows	Inflow Duration (days)	Dilutions
I	Ware River Diversion & Swift River branches	70	5.2
II	Connecticut River Diversion and Swift River branches	70	2.1
III	Connecticut and Ware River Diversions and Swift River branches	70	1.5

The dilutions represent the amount that the input volume would be diluted by the volume of the reservoir in the main and east branches north of Shaft 12. If the reservoir volumes of the east and main branches to Winsor Dam are considered, the dilution ratio for Case III is 3.5. Slightly higher values would be obtained from the MDC stage-volume data.

Retention times were computed using the model topographical and stage-volume data. Calculations were based on velocities of total inflows at various reservoir cross-sections, and on the inflows displacing all reservoir volume north of Shaft 12. The conditions shown in Table 19 for Test 3 were used for the calculations. Assuming all ambient reservoir volume northeast of the baffle dams and the "gap" between Mt. Zion and

Mt. L (Figure 5) were displaced by the inflow, it would take approximately 35 days for the Connecticut, Ware and Swift River flows to reach the gap. An additional 50 days would be required to displace the reservoir volume from the gap to Shaft 12, or a total "travel time" of 85 days. Slightly shorter travel times resulted from calculations based on cross-sectional flow velocities southward from the gap. Travel times would presumably be slightly longer when based on the somewhat greater volumes of the MDC stage-volume data.

(3) Flow Patterns

Three different test series to study flow patterns were run on the model. The test conditions for the three test series are shown in Table 19. Appropriate dyes were used for the various inflows. The advance of the dye "fronts" was used to gain insight into the dynamics of the flow patterns. The results of these tests are summarized in Table 20. Note that the reservoir level for Tests I and II was 530', whereas it was 508' for Test III. Of interest is the lack of a direct flow path toward Shaft 12. To confirm this, concentrated dye was introduced at four locations in the intake vicinity after 260 days of elapsed time in Test II. The results show random fluid motion in the southeastern portion of the middle branch, and indicate that the withdrawn flow is a mixture of water from that area.

(4) Tully Diversion Studies

Following these studies, the Army Corps of Engineers requested that

Table 19. Summary of Inflow and Outflow Conditions for the Studies of Flow Patterns

			Months 1	2	3	4	5	6	7	8	9	10	11	12
TEST I														
Reservoir El. 530 ft.														
INFLOWS:	Ware River	250 cfs	→	→	→	→	→	→	→	→	→	→	→	→
OUTFLOWS:	Winsor Dam	50 cfs	→	→	→	→	→	→	→	→	→	→	→	→
TEST II														
Reservoir El. 530 ft.														
INFLOWS:	Ware River	250 cfs	→	→										
	Connecticut River	600 cfs	→	→										
OUTFLOWS:	Winsor Dam	50 cfs	→	→	→	→	→	→	→	→	→	→	→	→
	Shaft 12	450 cfs			→	→	→	→	→	→	→	→	→	→
TEST III														
Reservoir El. 508 ft.														
INFLOWS:	East Br. Swift River	100 cfs	→	→	→									
	Middle Br. Swift River	30 cfs	→	→	→									
	West Br. Swift River	50 cfs	→	→	→									
	Ware River	250 cfs	→	→	→									
	Connecticut River	600 cfs	→	→	→									
OUTFLOWS:	Winsor Dam	50 cfs	→	→	→	→	→	→	→	→	→	→	→	→
	Shaft 12	450 cfs			→	→	→	→	→	→	→	→	→	→
TEST IV														
Reservoir El. 508 ft.														
INFLOWS:	East Br. Swift River	100 cfs	→	→	→									
	Middle Br. Swift River	30 cfs	→	→	→									
	West Br. Swift River	50 cfs	→	→	→									
	Ware River	250 cfs	→	→	→									
	Connecticut River	600 cfs	→	→	→									
	Tully River	350 cfs	→	→	→									
OUTFLOWS:	Winsor Dam	50 cfs	→	→	→	→	→	→	→	→	→	→	→	→
	Shaft 12	450 cfs			→	→	→	→	→	→	→	→	→	→

Table 20. Summary of Model Flow Pattern Studies

Test Series	Position of Dye Front	Days Required to Reach Position	Comments
I	Southeast corner of Mt. Zion	35	
	Slight additional advance	50	
	Narrow section east of Mt. Zion	110	
	Gap north of Mt. Zion	230	Some diffusion into middle branch.
II	Conn. River water in northern portion of middle branch	50	
	Ware River water south-east side of Mt. Zion	60	
	Conn. River water through gap north of Mt. Zion	additional time beyond 50	Water follows original Swift River bed.
	Conn. River water south-ward along Swift River bed. Ware River water at narrow section east of Mt. Zion.	100	40 days after diversions stopped and withdrawal from Shaft 12 begun.
	Conn. River water mixed with southern portion of west branch.	200	Diffusion of both waters with water of main reservoir.

Table 20. Continued

Test Series	Position of Dye Front	Days Required to Reach Position	Comments
III	Conn. River and Ware River waters join at gap.	30	Begin to flow into middle branch.
	Beyond cut into middle branch.	55	
	Additional southward movement in middle branch.	70	Extensive mixing with middle branch. After withdrawal from Shaft 12 begun no evidence of established flow to Shaft 12.
		70 + 7 months	Extensive mixing of diverted waters with middle branch and southern part of west branch.
IV	All 3 Diversions mixed and at gap.	25	
	Dye well advanced into upper portion of middle branch.	65	Mixing continues
		70	Complete mixing in northern portion of middle branch. (Diversions stopped at 70 days; Shaft 12 flow started)
	Mixed flows at position opposite Shaft 12.	85	No direct flow path to Shaft 12.
	West Branch	275	Extensive mixing.

additional studies be conducted to include the proposed diversion flow from the Tully River System.

The test conditions for the model studies including the Tully System are shown in Table 19 under Test IV. The results are summarized in Table 20. In general, the results are similar to those with Test III, including the flow dynamics, travel time, and lack of direct flow to Shaft 12.

Calculations of flow times with the Tully Diversion results in a figure of 60 days, as opposed to 85 days for the model studies. This figure is less than the 85 days calculated for Test III, and is based upon the additional inflow from the Tully Diversion. The difference in travel time resulting from calculations as opposed to model tests is believed to be due to the difficulty in defining the exact position of the diffused dye front on the model. Calculations are believed to be more consistent and more indicative of trends than the model tests. Nevertheless all values, whether from computations or test runs fall within a relatively narrow range. Consequently, a retention time of 60 to 90 days for Connecticut River water is a reasonable range to consider for this study.

Finally, dilution ratios for the case of all three diversions were computed based on inflow volume relative to volume in the appropriate portion of the model reservoir. Swift River inflows from the east and middle branches during the 70 days of diversion were included to obtain a total ambient volume. The total diversion volume was then divided into the

ambient volume north of Shaft 12 to obtain a dilution ratio of 1:1. If the reservoir volume in the entire east and middle branches to Winsor Dam is considered, the dilution ratio is 2.5:1. See page 127 for dilution ratios of Cases I, II and III.

Dilution ratios and retention times would be slightly greater if the greater volume of the MDC stage-volume data were used. Thus a dynamic range of ratios is possible depending upon reservoir volume. We wish to stress that travel times as reported in this study are only approximate values. Also, dilutions are based on assumptions of complete mixing. Stratification and wind phenomena under field conditions may result in less dilution and reduction in retention times for waters of riverine origin. This must be borne in mind when one reads Sections 7 - 10 of this report.

It is important to note that no basic differences in hydrodynamics were noted for the differences in elevation used in the tests. Flow of diversion input waters followed the same course in the reservoir, essentially along the original riverbed. We assume the model will show similar flow patterns for even lower elevations (e.g. 490 feet). However, the lower volumes will result in lesser dilution capacity for riverine waters.

B. Fisheries Information

Most of the information of this section came from Mr. Colton H. Bridges and his research staff of the Massachusetts Division of Fisheries and Game. The information came from both written reports and personal communications.

Sports fisheries in Quabbin Reservoir has its main attraction in a good salmonid (Salmonidae) fisheries program. Lake trout became well established in Quabbin Reservoir in the 1950s (Mullan, 1958). Smelt were also introduced, thus providing a forage for the lakers that reached piscivorous size. The smelt population grew so rapidly that the MDC experienced problems in its water supply and distribution system. Eventually control measures were instituted and the smelt population was reduced. This also had an impact on the lake trout and consequently the lake trout population was also reduced. In recent years attempts to restock lake trout and smelt have been carried out. These now appear to be successful, and there is concern within the Massachusetts Division of Fisheries and Game to maintain a proper ecological balance and viable fisheries program in the reservoir.

A checklist of species in Quabbin supplied by the Division of Fisheries and Game indicates 26 species. These include both warm water and cold water species. It is important to stress, however, that if the salmonid population decreases, the number of angler trips also declines. This is true even if the warm water population of fishes increases. Therefore, the maintenance of the water quality required to support the salmonids is considered vital by the Division of Fisheries and Game. Creel census figures for the 1950s and

1960s indicate that other species, including bass, pickerel, perch, bullheads, and walleye pike are also taken from Quabbin (Quabbin Reservoir Investigations, Project No. F-6-R-12, Job. No. 1)

Several other points are important to the current project. A Connecticut River Anadromous Fish Restoration Program is currently underway. The states of Vermont, New Hampshire, Massachusetts and Connecticut are cooperating with federal agencies to restore runs of anadromous fish in the river. This will require the development of fish ascending facilities. When these are completed, many species including lampreys will get above the Turners Falls Dam. A second point of interest is that experience with the Muddy Run (Pennsylvania) pumped storage facility shows that fish from the river were found in the upper reservoir. Finally, experiences with Quabbin have shown that smelt introduced into Quabbin also got into Wachusett Reservoir.

Turning briefly to the rivers, the mainstem Millers cannot now sustain a good fishery. The Tully System has species which are similar to those found in Quabbin. These are stocked each year. The Connecticut River has several undesirable species as far as possible introduction to Quabbin in concerned. These include carp, eels, and lampreys.

Field operations during the present study did not include an investigation of fisheries. However, our benthic and zooplankton samples were examined for fish eggs and fish larvae. One fish embryo was seen in a Quabbin zooplankton sample, and at one river station (R-7) developing larvae were present in a benthic sample. This lack of fish eggs or larvae is not attributable to

the mesh size of the plankton nets, but rather is related to sample locations and volume of water concentrated. In the reservoirs our stations are located in deep water whereas most spawning occurs in shallower waters. Fish eggs in streams are generally buried or attached, and are too infrequent to be found in the volumes of water concentrated for plankton samples. The same is true with regard to the frequency of larvae. Special techniques which take into consideration actual nesting spots would have to be considered in order to increase the probability of detecting eggs and larvae in samples.

3. Pollution Abatement Plans

In response to a request for a time schedule for the abatement of pollution on the Millers River, Mr. Slagle (Chief of Implementation and Enforcement, Massachusetts Division of Water Pollution Control) stated that by the end of 1972 all planned treatment plants on the Millers River should be operational. He also stated that water quality goals specified for the various Millers River basin waters by the Division of Water Pollution Control will have been met by the same date. According to the Millers River Basin Classification Plan (Massachusetts Division of Water Pollution Control, River Basins Classifications, 1967), all Millers River and its tributary waters examined in the progress of this study are expected to be up to Class "B" standards when the abatement program is complete.* This same master plan also calls for the eventual upgrading to Class "B" of waters of the Connecticut River from the New Hampshire, Vermont, Massachusetts state line to the dam at Holyoke, Massachusetts. No timetable is specified in that report.

Class "B" waters are defined in Water Quality Standards (Massachusetts Division of Water Pollution Control, 1967) as waters "suitable for bathing and recreational purposes including water contact sports; acceptable for public water supply with appropriate treatment; suitable for agricultural, and certain industrial cooling process uses; excellent fish and wildlife habitat; excellent aesthetic value". The water quality criteria upon which this classification is based are as follows:

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*Recent information indicates that it is unlikely that the proposed timetable for completion of the abatement program will be met. (Personal Communication, April 5, 1972, Mr. Everett Maynard, U S. Army Corps of Engineers).

Item	Water Quality Criteria
(1) Dissolved oxygen	Not less than 75% of saturation during at least 16 hours of any 24-hour period and not less than 5 mg/l at any time.
(2) Sludge deposits-solid refuse-floating solids-oils-grease-scum	None allowable
(3) Color and turbidity	None in such concentrations that would impair any usages specifically assigned to this class.
(4) Coliform bacteria per 100 ml	Not to exceed an average value of 1000 during any monthly sampling period nor 2400 in more than 20% of samples examined during such period.
(5) Taste and odor	None in such concentrations that would impair any usages specifically assigned to this class and none that would cause taste and odor in edible fish.
(6) pH	6.5 - 8.0
(7) Allowable temperature increase	None except where the increase will not exceed the recommended limit on the most sensitive receiving water use and in no case exceed 83° F. in warm water fisheries, and 68° F. in cold water fisheries, or in any case raise the normal temperature of the receiving water more than 4° F.
(8) Chemical constituents	None in concentrations or combinations which would be harmful or offensive to human, or harmful to animal or aquatic life or any water use specifically assigned to this class.
(9) Radioactivity	None in concentrations or combinations which would be harmful to human, animal, or aquatic life for the appropriate

Item	Water Quality Criteria
	water use. None in such concentrations which would result in radio-nuclide concentrations in aquatic life which exceed the recommended limits for consumption by humans.
(10) Total phosphate	Not to exceed an average of 0.05 mg/l as P during any monthly sampling period.
(11) Ammonia	Not to exceed an average of 0.5 mg/l as N during any monthly sampling period.
(12) Phenols	Shall not exceed 0.001 mg/l at any time.

7. GENERAL DISCUSSION OF AVAILABLE DATA

A. Comparison of NER and Other Data, Connecticut River

In the progress of this study NER has reviewed a number of sources of water quality data which were available from public and private agencies (see Appendix 5). Any comparison of these data, however, must be qualified by the particular differences in time and place of collection of water samples which vary from study to study. Tables 1 and 2, for example, show values for parameters analyzed by NER and the MDC[1] using water samples collected from the Connecticut River during freshet flow. Water samples analyzed by the MDC were collected about 6 miles upstream from where samples were collected for analysis by NER, and were usually taken on different days and at different times of the day. The discrepancies noted in these data cannot therefore easily be attributed to any particular cause, and most likely reflect a complex set of factors. Similarly, no specific agreement of values can be used as definite proof of validity of these numbers.

Comparisons of all these data, however, are extremely useful in the definition of general water quality trends and patterns. They are necessary for setting individual data in perspective. Indeed, such comparisons can very well serve to define future research needs. For example, included in the report of water quality analyses which is abstracted into Tables 1 and 2 was the report of a

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1. Data provided by Leslie Campbell of the Quabbin Laboratory, MDC, November 4, 1971.

Table 21. Comparisons of Results of Water Analyses of Connecticut River - NER and MDC (April, 1971)

	NER Apr 12	MDC Apr 14	MDC Apr 15	MDC Apr 21	MDC Apr 22	NER Apr 28	MDC Apr 28
Dissolved Oxygen	12.5	12.8	13.7	12.8	12.6	13.4	13.0
Turbidity	6	16	15	12	18	2	6
Color	20	35	28	28	28	20	25
Hardness	22.8	30	32	30	X	28.9	28
pH	6.8	7.2	7.4	7.2	7.2	7.1	7.1
Iron	0.4	1.1	1.0	0.7	X	0.1	0.1
Manganese	0.04	X	0.00	0.00	X	0.00	X
Orthophosphorus	0.01	X	0.10	X	0.15	0.00	X
Nitrate Nitrogen	0.24	0.38	X	0.06	X	1.9	0.20
Nitrite Nitrogen	0.006	0.005	X	X	0.002	0.003	X
NH_3 Nitrogen	0.58	X	0.12	X	0.17	0.32	X
Specific Conductance	101	X	106	102	95	81	102
Fecal Coliforms per 100 ml.	300	300	410	520	600	X	450
Total Coliforms per 100 ml.	500	340	2900	2200	3000	X	5000

Table 22. Comparisons of Results of Water Analyses of Connecticut River - NER and MDC (May, 1971)

	NER May 12	MDC May 12	MDC May 13	MDC May 18	MDC May 19	NER May 26	MDC May 26
Dissolved Oxygen	12.1	X	11.6	10.5	X	9.7	9.4
Turbidity	3	5.5	X	5.0	6.0	2	4.2
Color	20	26	26	25	23	25	25
Hardness	29.7	X	32	X	34	25.6	32
pH	6.9	7.2	7.1	7.1	7.1	6.9	7.2
Iron	0.00	0.03	X	X	0.05	0.00	0.25
Manganese	0.01	0.00	X	0.00	X	0.00	X
Orthophosphorus	0.01	0.02	X	X	0.07	0.01	X
Nitrate Nitrogen	0.14	0.38	X	X	0.30	0.18	X
Nitrite Nitrogen	0.00	X	0.10	X	X	0.002	X
NH_3 Nitrogen	0.50	X	0.58	X	0.50	1.18	X
Specific Conductance	71	77	77	93	X	84	X
Fecal Coliforms per 100 ml.	750	1600	1000	1300	4000	0	3000
Total Coliforms per 100 ml.	12000	5500	6400	8000	15000	44	4400

small-scale laboratory study conducted by the MDC. This study indicated that over a 50% drop in turbidity in 24 hours was observed in undisturbed Connecticut River waters. Differences in turbidity readings indicated in Tables 21 and 22 may therefore be partly or wholly explained by a settling out of some turbidities between the two sampling sites used for the collection of these data. Thus differences in turbidity data underscore the importance of conducting future settling studies in these waters, especially in the upper pool of the Northfield Mountain project.

In an effort then to define general water quality trends and patterns more completely, to place individual data in a more general perspective, and finally to inquire into possible reasons for discrepancies in accumulated data, comparisons of selected physical, biological and chemical data are presented below. These comparisons deal specifically with values from Connecticut River waters during freshet flow, even though all values which have been available for the Connecticut River and other systems studied, have been examined.

(1) Turbidity

Table 23 compares turbidity values (J.T.U.) obtained by NER, the Massachusetts Department of Public Health, the MDC and Webster-Martin, Inc. (see Appendix 5 for specific references). The Webster-Martin (W-M) values are 24-hour averages of readings taken above Vernon Dam.

It is evident that differences in instruments and station locations may account for major discrepancies in these data. When these differences are taken into account, there is a remarkable similarity between the analyses conducted by the various agencies. However, it would be a mistake

Table 23. Comparison of Turbidity Values for Connecticut River Water from Various Sources for April and May 1971

Organization	Station	Method	April 1971	May 1971
NER	R-1	Spec. 20	26, 16	22, 16
NER	R-1	Hach	6, 2	3, 2
DPH	Rt. 10 Bridge	N.A.	4.4, 6.8, 3.4	4.2, 8.6, 0.8, 1.6
MDC (Quabbin Lab)	Rt. 10 Bridge	Hach	16, 15, 12, 18, 6.0, 5.5	22, 18, 5.5, 5.0, 6.0, 4.2, 3.8
MDC (Construction Division)	Rt. 10 Bridge	Hach	0.0, 6.0, 2.0	
Webster-Martin	No. 7	Honeywell W-20	5-10*	6-20*

*Daily averages over part of month; monitor inoperative for remainder of month.

to assert that this general pattern of turbidity which was observed in 1971 is representative of patterns observed in other years. Turbidities approaching and even exceeding 100 J.T.U. have been periodically observed in Connecticut River waters (D.P.H. data, 1970; Webster-Martin, 1971). On the basis of all data considered to date, which have varied from hourly to monthly readings, it is most reasonable to presume that during freshet flow the turbidity in Connecticut River waters in the vicinity of the Northfield pumped storage intake is a variable multiple of the maximum turbidities observed in Quabbin Reservoir during the same period. The possibility that waters shall be diverted which have turbidities approaching or exceeding 100 J.T.U. does exist; however, the probability of this occurrence appears low on the basis of the most current data. A frequency analysis of given turbidity ranges would support this conclusion.

(2) Iron

Total iron values obtained from the Webster-Martin Study indicate a yearly range in 1970 of 0.1 to 3.4 ppm in Connecticut River waters about 15 miles north of the pumped storage intake. Data obtained from the Department of Public Health from samples collected about 8 miles downstream from where the Webster-Martin values were obtained indicate a range of values in April and May of 1970 of 0.19 to 0.42 ppm. In 1971, the April and May values obtained by the D.P.H. from these same stations ranged from 0.24 to 0.9 ppm. The MDC also collected samples from the same

location as the D.P.H. in 1971 and obtained values in April and May which ranged from 0.03 to 1.1 ppm. NER values obtained in the same period, but from samples collected several miles downstream from the MDC and D.P.H. sites ranged from 0.00 to 0.4 ppm.

(3) Chemical Oxygen Demand

COD values from the Connecticut River below Northfield were retrieved from the STORET System (retrieval date 71/03/09) for the years 1962 to 1968. April values throughout this period ranged from 12-66 ppm, with an average of 24.7 ppm. May values throughout this period ranged from 13-59 ppm, with an average of 22.2 ppm. NER values for COD in waters collected in April and May of 1971 from the pumped storage intake area varied very little from about 15 ppm.

(4) Nitrate Nitrogen

Values of nitrate nitrogen reported by Webster-Martin for the period June 1969 to May 1970 ranged from 0.08 to 0.39 ppm, with a mean value of 0.14 ppm. Approximately the same range of values was reported by the MDC for April and May, 1971. Values reported by the D.P.H. for April and May 1971 from samples collected from the same general area as the MDC samples were somewhat higher, ranging from 0.37 to 0.56 ppm. The lowest reading recorded by NER in the period April-May 1971 was 0.14 ppm

and the highest was 1.9 ppm. The average value of data obtained by NER in this period was 0.64 ppm.

(5) Ammoniacal Nitrogen

Values reported by the MDC for April and May 1971 ranged from 0.11 to 0.58 ppm. The D.P.H. reported values, for samples collected in the same time period and area as the MDC samples, which ranged from 0.012 to 0.110 ppm. NER values for April and May 1971 ranged from 0.32 to 1.18 ppm, the average value being 0.65 ppm.

(6) Orthophosphorus

Values of orthophosphorus reported by Webster-Martin for the period June 1969 to May 1970 ranged from 0.00 to 0.15 ppm, with a median value of 0.04 ppm. The MDC reported values for April and May 1971 which ranged from 0.02 to 0.15 ppm, NER values for April and May 1971 ranged from 0.00 to 0.01 ppm.

(7) Total Coliform Bacteria

The D.P.H. reported that April-May (1971) concentrations of total coliform bacteria in waters about 6 miles upstream from the pumped storage intake ranged from 2.8 to 3.9 log units/100 ml, with an average concentration of 3.3 log units/100 ml. MDC values obtained from the

same area and in the same time period ranged from 2.5 to 4.2 log units/ 100 ml, with an average concentration of 3.7 log units/100 ml. NER values for April and May, but obtained from samples collected in the immediate area of the pumped storage intake, ranged from 1.6 to 4.1 log units/100 ml, with an average of 3.6 log units/100 ml.

(8) Radioactivity

The Lawrence Experiment Station has been testing Connecticut River water as part of the cooperative efforts of the Tri-State Commission for some time and has detected neither ^{226}Ra nor ^{90}Sr in the water. Also surface waters, including reservoirs, from all over Massachusetts have been tested in the spring and fall, and no presence of ^{226}Ra or ^{90}Sr has been detected. On the other hand, some of the STORET data (retrieval date 69/06/27) for the 1960s show Connecticut River water with total beta activity in excess of 10 $\mu\mu c$/liter. This is not true for the more recent data.

(9) Summary Statement

The above comparisons of water quality data obtained from Connecticut River waters indicate that both small, probably unimportant, and large, probably important, differences between accumulated data do exist. The magnitude of such differences can be useful in setting individual data into perspective; however, they cannot be resolved until a coordinated monitoring program is implemented, and the present differences in time and place of water sampling are eliminated.

B. Discussion of Data

Data collected by NER from December 1970 through September 1971, as well as that generated by other public and private agencies and reviewed by NER, reinforce the idea that the various groupings of stations emphasized in this and earlier progress reports (May, August 1971) reflect a range of "productivity potential" which may be pictured, from the lowest to the highest, as follows:

Relatively Lowest Productivity Potential → Relatively Highest Productivity Potential

Quabbin (outside)
Wachusett
Quabbin (inside)
Northern Tributaries
Ware River
Connecticut River
Millers River

As in our earlier reports, productivity is understood to mean biological productivity as reflecting a eutrophication process. Because riverine systems cannot be directly compared with lacustrine systems due to the more pronounced hydrological impact on biological processes in rivers than in reservoirs, the term "potential" implies a comparison of reservoir and riverine waters under similar quiesent conditions.

The heterotrophic bacteria are essential to nutrient recycling in lakes, and therefore to the productivity of other aquatic biota. Their presence in concentrations of up to 2 orders of magnitude higher in the Millers and Connecticut Rivers than in the other systems studied can be used as evidence of

a higher concentration of bacterial nutrients in these rivers than in the other systems. Such bacterial nutrients in turn reflect not only man-made inputs into these rivers, but also the non-living organic matter found in the same waters.

While the kinds of phytoplankton observed in all systems were similar, Millers and Connecticut River waters generally showed the most abrupt seasonal changes. This was particularly true with respect to the summer increase in green algae which included many forms usually considered indicative of "nutrient rich" waters. Species of green algae observed in the reservoir, on the other hand, are usually considered indicative of "nutrient poor" waters.

Concentrations of rotifers and crustaceans were generally lower in rivers as compared with reservoirs. This may reflect a constant flushing away of riverine organisms, thus resulting in a smaller standing crop than in the case of reservoirs. The relatively higher proportion of rotifers in the Connecticut River over the reservoirs is characteristic of the riverine environment. This was also seen at Orange and the East Branch of the Tully where the relative impoundment-like situations reflected fewer rotifers in relation to crustacea. Both rotifers and crustaceans are microphagous, tending to feed on particulate matter. Many differences in species and numbers are no doubt related to numbers and sizes of particles available for feeding. Such correlations cannot be made at this time.

Perhaps the most marked differences in benthic organisms were seen along the Millers River. The relatively large numbers of total organisms, especially

worms and the fewer numbers of species are characteristic of polluted water. Of interest is the recovery of more diversity of species downstream at Station R-10 (Farley); this paralleled the general improvement in water quality. In general, greater numbers of species are expected at rivers because of more potential diversity in habitats. The relatively smaller number for the Connecticut River may reflect the limited number of habitats that were sampled. The reservoirs had a bottom fauna that were typical both in numbers and kinds of organisms for the lacustrine environment. Seasonal variations in benthic organisms for all stations are influenced by both emergent fly populations and possible seasonal migrations (e.g. isopoda in reservoirs). These are complex patterns and not understood at present.

Essential to biological productivity, of course, is carbon. One measure of available carbon is the alkalinity of water. The highest alkalinities were observed in the Connecticut River; the Millers River showed the second highest alkalinities. Reservoirs showed the lowest alkalinities.

Chemical oxygen demand is a non-specific measure of the organic and inorganic load in waters which can be oxidized. Again, the pattern of productivity described above was observed in terms of this parameter.

Phosphorus and nitrogen are also essential to bio-productivity in water, and occur in a variety of forms. While concentrations of these elements were not dramatically higher in riverine than in reservoir systems, definite, higher concentrations were observed in the rivers. This was also true for sodium and potassium, two elements which are also required by living things.

The general classification of the waters studied from "low" to "high" potential productivity, is also useful in defining the range of potential public health hazards associated with these waters as a direct result of fecal contamination. However, a number of specific public health parameters do not follow this same pattern. The presence of mercury at all sampling sites, for example, suggests that it might be reasonable to assume that mercury is a component of all waters in this region. The Massachusetts Division of Fisheries and Game report mercury levels in fish taken from Quabbin Reservoir which are comparable with levels found in fish in the Connecticut River (1971).

Similarly, because no ^{226}Ra or ^{90}Sr has been detected in a recent state survey of surface waters, radioactivity does not now appear to be a basis for comparing these different systems with respect to a public health hazard.

The public health officials, however, must be concerned with those factors that can interfere with the treatment of waters even if the factors are not direct threats to human health. Turbidity and color, for example, can interfere with the effective chlorination of waters. These and other factors to be considered in the possible treatment of waters will be discussed in the following impact sections.

In general, the waters of the two potential donor systems are of poorer quality than those of the two receiver systems. More specifically, some constituents of the Connecticut River (e.g. ammonia nitrogen) at certain times, exceeded the recommended standards of the U. S. Public Health Service

(USPHS, 1962) or the permissible criteria of FWPCA (1968) for drinking water. The rationale for even considering such waters as potential sources of drinking water rests with both the treatment plant capacity of a reservoir (see Section I) and the total judgements on public health hazards. This issue is discussed in detail in later sections.

8. IMPACTS OF PROPOSED DIVERSIONS

A. Impact Statements and Public Policy

Every piece of legislation undergoes a process of maturation whereby its aims, intent, and procedures become more precisely defined. Public Law 91-190, otherwise known as the National Environmental Policy Act of 1969 (NEP Act), is no exception. Executive, legislative, judicial, and public review of this major legislation continues at an ever quickening pace. The results have often been dramatic. Most recently, the U.S. Court of Appeals for the District of Columbia (102 Monitor, September 1971) held that the U.S. Atomic Energy Commission must undertake a major revision of its rules governing consideration of environmental issues required under the NEP Act. Three months earlier the Council on Environmental Quality (102 Monitor, May 1971) issued revised guidelines to federal agencies on how to handle environmental impact statements in light of additional legislation as well as initial judicial decisions in cases involving Section 102 (2) (C) of the NEP Act. These revised guidelines include a directive to federal agencies "to maximize public information about environmentally significant programs so that the public's views can be considered", (Council on Environmental Quality, 1971).

Out of these and numerous other instances of review of the NEP Act have emerged certain clarifications which are essential to the environmental study here under consideration. Two clarifications are particularly important:

(1) Protection of the environment is not the exclusive goal of the NEP Act. The NEP Act is to ensure that environmental costs and benefits assume

a proper place along with other considerations in the decision-making process.

(2) Research on the environmental impact of projects is not to be used to justify decisions already made, but rather, the decisions are themselves to be influenced by research.

The fact that these clarifications have had to be made is ample proof of another fact; that the purposes of Public Law 91-190, as stated within the legislation itself, have been largely misinterpreted.

There are four stated purposes in Public Law 91-190. They are:

(1) to declare a national policy which will encourage productive and enjoyable harmony between man and his environment,

(2) to promote efforts which will prevent or eliminate damage to the environment and biosphere, and stimulate the health and welfare of man,

(3) to enrich the understanding of the ecological systems and natural resources important to the Nation,

(4) to establish a Council on Environmental Quality.

What recent national experience with the NEP Act has forcefully established, then, is that the NEP Act is to be used to achieve not simply a harmony between man and his environment, but a harmony based upon man's understanding of his environment.

It is certainly not presumed by the NEP Act that we do understand ecological systems, and that we therefore have the requisite knowledge to justify decisions affecting the environment. The presumption is to the contrary.

President Nixon himself, in his Message to the Congress which accompanied the First Annual Report of the Council on Environmental Quality (August 1970) recognized the deficiencies of present knowledge: "Existing systems for measuring and monitoring environmental quality are still inadequate. There also is a great deal yet to be learned about the significance of these facts for the human condition." In short, no impact study is an adequate impact study, under the NEP Act guidelines, which addresses itself to any question other than "what will happen, in light of the scientific understanding and facts that we now have, should a certain activity be undertaken".

The task of any impact study is therefore doubly difficult. It is not enough to present scientific facts. The scientific context and meaning of those facts must also be presented, and presented in such a way as to satisfy the sometimes conflicting requirements of both the scientific and non-scientific communities.

The number of disciplines involved and the amount of raw data (approximately 2,500 pages of raw data) generated by the present study, together with the limitations of time and space, certainly preclude any exhaustive development of all the scientific qualifications involved in any understanding of the significance or meaning of each parameter or groups of parameters. However, certain of these parameters are of such contemporary concern and/or scientific complexity that particular attention must be given to an explanation of the present "state of the art" of ecological knowledge in which they play their part. Topics selected for this more extensive treatment are: (1) viruses, (2) pesticides, (3) mercury, (4) radioactivity, and (5) bacteria.

(1) Viruses

In the last decade considerable advances have been made in the study of viruses in the water resource. Yet it is still common to note the preface, "Uncertainties still exist concerning the virus hazard. . ." in current research efforts. As the accelerating need for water continues, the environmental engineer is still plagued by several basic problems in evaluating the hazard of viral transmission in water resources.

This section will review briefly the current status of the public health hazards associated with viruses in the water resource.

What viruses capable of infecting man may be spread through water?

First, some of the basic properties of viruses must be understood. Viruses are a molecular complex consisting of a nucleic acid core and a protein coat surrounding the core. The viruses are usually spherical, having diameters ranging from 10 to 100 millimicrons. Viruses are generally resistant to a low pH of 3.0 and lipid solvents such as ether. In a water environment, viruses probably exist as aggregates of varying numbers and may be embedded within organic debris or may adhere to various particles. Most important is the fact that viruses must have a living host or cell in which to multiply. Consequently, viruses infectious to man would probably not multiply in the water environment.

About 100 different viruses may be isolated from human feces. These may be grouped into the enteric viruses, including the polioviruses,

Coxsackieviruses, and echoviruses; the virus(es) of infectious hepatitis IH; the adenoviruses; and the rheoviruses. As yet, the viral agent(s) of IH has not been isolated.

In addition to the above, the viruses of non-human animal origin must also be considered as a potential source of infection to man, since it is possible for them to find their way into water supply systems.

According to Mosely (1965) of the Public Health Service National Communicable Disease Center:

> Any virus excreted in the feces and capable of producing infection when ingested should theoretically be transmissible in drinking water. Waterborne transmission has accordingly been suspected for enteric virus thought to be transferred from person-to-person by the fecal-oral route. We now know, however, that some viruses transmitted by the respiratory route are also excreted in the stool in quantities detectable by tissue culture techniques. The agent of rubella is a recently demonstrated example (Green, et al., 1965). Past experience has indicated that the circumstances under which contaminated water may be used for drinking are almost as numerous as the ways in which drinking water may become contaminated. It is conceivable, therefore, that at some time almost any virus can be transmitted through water.

It must also be assumed that diseases listed as "viral gastroenteritis" can be transmitted via the water route, even though attempts to isolate the causative agents have failed. Typical of many reports is one according to Jacobson (1970) in which a small village near Buffalo, N.Y. suffered a wide-spread outbreak of gastroenteritis. The water source for the affected area came from Lake Erie and was processed by a water treatment plant

utilizing rapid sand filtration and sedimentation. "Specimens from multiple sources in the water supply and stools from ill subjects were all negative in bacteriologic, virologic and chemical analysis" according to the report, yet the "characteristics and distribution of this illness, as well as its relationship to the water treatment plant and its distribution lines, clearly pointed out the waterborne nature of this outbreak".

The capability of the infectious hepatitis virus(es) to infect man through drinking water is well documented. Therefore, it may be concluded that IH, and the enteric viruses and possibly the causative agents of viral gastroenteritis may all be transmitted by drinking water.

Compared to more direct means of contracting viral disease, the water route is generally agreed to present a far lower hazard in terms of reported cases. Yet according to Berg (1967), the amount of virus that can infect man is often equal to or smaller than the amount of virus that can infect susceptible cell culture systems. Thus any amount of virus detectable in water is likely to be sufficient to infect susceptible individuals.

In this country, where adequate disinfection practices are in general usage, the documented waterborne outbreaks of infectious hepatitis are very small in number, yet epidemiological studies are often hindered since many sub-clinical cases can go unreported. It is pertinent to note here that the great outbreak in New Delhi in 1955-1956 resulted from a water supply which met acceptable coliform standards.

How are water supplies monitored for viruses?

The literature shows clearly that routine monitoring of water for virus is difficult and costly, and for the near future, at least, is an impossible task for the average water laboratory. Analysis requires the concentration of often large quantities of water (100 liters or more at times) and subsequent extraction or elution of the viruses onto tissue cultures at appropriate dilutions. Examination of the cultures for evidence of cell abnormalities shows the presence of virus and the specific titer may be thereby determined.

In the past, most monitoring involved the "swatch test", in which a gauze pad was left suspended in a water source for a period of time and the viruses would be later eluted from it for analysis. Although the presence or absence of virus in the water can be ascertained by this method, it does not give any quantitative information and its sensitivity is open to question.

More recent work has been done with a variety of materials by which the water sample may be concentrated. Polyelectrolytes, coagulants, cellulose-acetate (Millipore) filters, etc. are some of those now being evaluated. It is to be hoped that these more promising techniques will add greatly to our understanding of the concentrations of viruses in the natural environment.

The use of coliform numbers as an indication of virus in water would be ideal. Yet the New Delhi outbreak of infectious hepatitis clearly

shows this to be an invalid practice. The relative numbers of coliform bacteria to viruses may vary greatly in polluted water. Clarke, et al. (1964) calculated the average virus density in domestic sewage to be about 500 virus units per 100 ml, and in polluted surface water not more than one virus unit per 100 ml. Coliform densities in domestic sewage average 46 x 10^6 per 100 ml, and in polluted surface waters they average between 10^4 to 10^5 per 100 ml. Thus, these authors agreed upon a coliform-virus ratio in sewage to be approximately 92,000:1 and in polluted surface waters, about 50,000:1. Apparently then, because the coliform numbers are much higher than viruses, the coliform numbers would be a better indication of the presence of viruses in non-polluted waters than actual virus analysis (should similar ratios hold for non-polluted waters).

However, several factors rule out the effectiveness of the coliform numbers as an indication of the presence of virus. First, new techniques of virus detection may well show higher numbers to be present in water than has been heretofore believed, thereby developing a situation similar to that of the much discussed mercury pollution. Then too, the relative survival rates of bacteria to viruses may vary greatly from virus to virus and even in different qualities of water. Add to this the New Delhi incident and one may reject completely the use of coliform numbers as quantitative or qualitative indicators for the presence of viruses in water. Although a positive coliform index must indicate the possibility of viruses to be present in water, a negative coliform index may not indicate the absence

of viruses (Committee on Environmental Quality Management, 1969). In this respect, a better assurance of the absence of viruses in water may be given by low turbidities and good chlorination as will be discussed later. Otherwise, positive tests for the presence of viruses in water must ultimately depend upon actual testing for viruses directly.

What is the effectiveness of sewage treatment processes in the elimination of viruses?

Research in this area is generally inadequate in presenting absolute values for virus removal by each process. Chiefly, this is due to the inadequacy of different laboratories in using similar or comparable techniques and standards for virus analysis and evaluation. Then too, since most research in this field involves the addition of one or a few laboratory-prepared viruses to a treatment influent and then analysis of the effluent for the virus, objections may be taken as to the validity of the assumptions made in these tests. It may be more realistic (although very costly and considerably time-consuming) to test the treatment process for the elimination of those viruses occurring naturally in the wastewater.

The efficiencies of virus removal for the various treatment techniques are listed below:

(a) Primary treatment - This process removes very little of the viruses present in sewage. According to Berg (1971), only 0-3% of poliovirus type I added to the raw sewage, was removed after a three-hour settling period, although greater than 50% solids had been removed.

Greater retention times can remove more of the virus, however, but removals of better than 70% are impractical and not consistent.

(b) Activated Sludge - A variety of reports show inconsistent removals of virus up to 90% (Sproul, et al., 1967). Yet it must be noted that the viruses are not killed by this process and others which involve actually separating them from the wastewater. The ultimate disposal of the viruses must also be considered.

(c) Trickling Filtration - Although some removals may occur with this process (reported up to 40%), it is very inconsistent (Sproul, et al.).

(d) Oxidation Ponds - Removals up to 90% may occur with this process (Sproul, et al.). However, several factors such as short-circuiting may decrease virus removal. In addition, since the actual relative survival times of the many viruses are not known under differing environmental conditions or even standard conditions, this process deserves more research for a definite statement.

(e) Adsorbents - A variety of materials such as activated carbon, bentonite, polyelectrolytes, clay particles, ion exchange resins, etc. may adsorb viruses to their surfaces, thereby removing them from water. The virus-adsorbent bindings show varying degrees of strength and some allow a final elution of the viruses from the adsorbent. These processes may vary in their effectiveness with the concentration of many different solutes and with differing turbidities. Generally, their maximum effectiveness is only reached after parallel treatment operations.

(f) Filters - A filter must obviously have a pore size of less than 10 mμ in order to eliminate viruses from water. Such filters are very costly and can operate usually only under highly controlled conditions.

(g) Coagulants - Viruses may be precipitated by the use of additives such as $Al(OH)_3$, phosphates, and lime, and removals may attain 90% or better (Liu, 1971). Yet again, this process reaches maximum efficiency only with controlled conditions and with other, parallel treatment.

(h) Disinfectants - Free chlorine, hypochlorite, bromine and ozone may all be used to destroy waterborne viruses. The relative rates of inactivation of the different viruses by free chlorine is currently being examined by Liu (1970) and others. In general, for 99.99% devitalization by 0.5 mg/l of free chlorine, survival times vary greatly from several minutes to 36.5 minutes for poliovirus type 2. The Committee on Environmental Quality Management (1969) believes that a high level of protection is afforded by chlorination of secondary treatment effluent to a level producing an amperometric chlorine residual of +5 mg/l after 30 minutes of contact.

(i) Other Processes - Chemical reactions, ultraviolet light, temperature, and other natural and employed processes within the water environment may all affect the survival of viruses. Water samples containing viruses may be stored for several weeks to months and retain their infectious properties. It is in this basic area that work must be continued to fully understand the ecology of waterborne viruses.

It may be concluded that although data are still incomplete, virus elimination up to 99.99% removal may be attained by using the best treatment processes available, followed by good free residual chlorination. It is to be noted that even the best of the conventional treatment practices may produce an effluent which may still contain infectious viruses. The discussion of Shuval (1967) of the possible significance of low concentrations of viruses is pertinent:

> The findings of Dr. Lund, confirmed by the research in South Africa, that sewage treatment plants reduced the viral content of sewage by 1, or possibly 2, logs added to the estimate of Dr. Coin that one infectious dose of virus was present in 250 liters of Paris drinking water, provoke speculation. If the viral concentration in a sewage is 10 $TCID_{50}$/ml, and this amount is reduced by as much as 2 logs in a sewage treatment plant, another 3 logs by dilution in a river, and 2 or 3 more logs in a water treatment plant, a total of 7 or 8 log reductions in viral concentration results. This leaves a water containing perhaps 1 $TCID_{50}$ (tissue culture infectious dose) of virus per 1000 liters. I suggest that this is not an unimportant amount. It is true that one person does not drink 1000 or even 250 liters of water per day, but one in 250, or one in 1000 or even one in 10,000 persons ingests 1 $TCID_{50}$ of virus daily, and 1 $TCID_{50}$ is an infectious dose for man, as Dr. Plotkin suggested, even after the viral concentration has been reduced 99.9999%, we have a level of ingestion of virus that could be responsible for a proportion of the endemic viral diseases in communities consuming highly treated waters.

<u>What is the fate of viruses in natural water systems?</u>

Although many studies have been conducted on the determination of viruses in sewage and water under a variety of chemical and hydraulic conditions, very few attempts have been made to study the effect of

drainage systems, lakes and streams, infiltration systems and the like, upon the reduction of viruses.

1. Streams and Lakes - McLean, Brown and Laak (1966) conducted a number of experiments which showed the following:

   (a) "Movement of water in creeks induces rapid dilution and thereby disperses virus infectivity, but virus concentration in stagnant lake water remains relatively unchanged for considerable periods."

   (b) Although streams may rapidly disperse the virus content, "continuous addition of virus over a prolonged period, for example, infectious hepatitis virus in unchlorinated sewage effluent, into a slowly moving river increased the hazard of infection to such an extent that six of nineteen subjects at Bathurst, Australia (Wallace, 1958) contracted infectious hepatitis after drinking river water contaminated by sewage. Similarly, slowing of water movement to stagnation point in the upper Illinois River near Chicago, permitted the accumulation of enteroviruses both upstream and downstream from sewer outfall (Lamb, et al., 1964)."

2. Overland Flow - According to Liu (1971), "this system does not include any obvious step which can safeguard a high order of viral elimination". The system is difficult to assess since many processes and variables are involved, such as aging, adsorption onto clay particles, and a variety of other environmental conditions. Although some types of clay may adsorb viruses, others may not. It is

known that sand or soil columns may freely permit the passage of poliovirus type 3, (McLean, et al., 1966).

3. Infiltration Basins and Spray Irrigation - Again the types of soil involved may offer varying degrees of viral adsorption capabilities. Liu suggests that intermittant rates of filtration may be beneficial to the retention of virus, but again, the system does not provide any assured removal of virus.

It must be assumed that the recreational use of any of these systems could potentially involve hazards. However, the Santee, California project is a well-known example of what can be done in the way of removing viruses to provide recreational resources using treated water (Culp, 1971).

Summary

It is essential to understand that while there is much confusion among scientists about the public health hazards to be associated with surface waters, practical experience with public water supplies suggests that much of the concern expressed over the dangers of viral agents in water supplies is academic. For example, the Massachusetts Department of Public Health has carefully monitored the public health effects of the consumption of water taken from the Merrimack River by the cities of Lawrence and Lowell. No detriment to public health has ever been noted as a result of this consumption, even though we must assume, on scientific grounds discussed above,

that viral agents are present in the Merrimack River. It is, therefore, a mistake to presume that scientific concerns are always real concerns. It would also be a mistake to disregard completely such concerns.

(2) Pesticides

(a) Basic Considerations

There are many classes of pesticides, including those intended to kill or control plants, invertebrate animals, and vertebrate animals. The types that concern us most are herbicides and insecticides. These chemicals are used in large quantities, they are spread over large areas, and hence they may come eventually in direct contact with surface waters. The Federal Insecticide, Fungicide, and Rodenticide Act provides for their registration and use.

Herbicides are used to control plant, weed and algal growths in both the terrestrial and aquatic environments. A variety of both organic and inorganic herbicides are used. Herbicides used in the aquatic environment include such organic chemicals as 2,4-D. Others may enter surface waters through run-off. Persistence in the environment may be as long as several months. One convenient classification of insecticides is based on persistence in the environment. Some organochlorine insecticides, of which DDT is perhaps the best known, persist for a long time (years). Others, like the organophosphorus compounds are chemically more labile and undergo rapid breakdown in the environment.

Of major concern, then, are such considerations as persistence, general concentrations in the environment, and toxicity. An understanding of these points is necessary before estimates of any public health hazards or environmental impacts can be made.

So important is the question of harmful effects of pesticides, that a special report on the Ecological Effects of Pesticides on Non-Target Species was prepared through the President's Office of Science and Technology (Pimentel, 1971). Another recent publication entitled Report of the Secretary's Commission on Pesticides and their Relationship to Environmental Health (so-called Mrak Report, 1969) is an exhaustive inquiry into this whole area, and the reader cannot escape the general message. Pesticides are potentially dangerous chemicals.

There is no question that some pesticides are globally distributed by the atmosphere. Both DDT and dieldrin are found in dust and rain water. The atmosphere is probably the principal source of contamination for many areas. Average concentrations of pesticides in rain water (0.1 to 0.4 ppb) is equivalent to and often higher higher than those found in river waters. Reviews of the evidence on atmospheric contamination include Frost (1969) and Wurster (1971). Therefore, the presence of pesticides in surface waters need not reflect their use in the immediate vicinity.

In addition, pesticides may be found in the tissues of both plants and animals. Persistent insecticides have very long half-lives in the

environment; it takes a very long time for 50% of the chemical to disappear. Compounds such as DDT also have long half-lives in the human body. Thus, a compound which disappears slowly from the environment or the body is subject to accumulation when the input exceeds the losses.

Another important consideration with persistent pesticides is the tendency for the compounds to be concentrated by successive steps in the food chain (National Academy of Sciences, 1970). Progressive stages of the food chain (plankton, herbivores, primary carnivores, etc.) concentrate the pesticide chemicals. Several log units greater concentration in tissues above ambient concentrations in water are achieved. Hard pesticides are extremely insoluble in water, and tend to disappear from water due to evaporation into the atmosphere, precipitation to the bottom sediments, or uptake by animals and plants. A good demonstration of these characteristics can be seen in an experiment in Ohio, where a marsh was sprayed with radioactive DDT (Peterle, 1969). The highest levels in surface waters were found one hour after application, and dropped below detectable levels in two weeks. Concentrations in the mud remained constant for over a year, and rooted plants showed a slight rise in concentrations of DDT two years later. Maximum concentration in one type of alga occurred one week after application; the algal concentration of DDT was 3000 times the

initial concentration in the water. Thus, whereas concentrations of hard pesticides in surface waters rarely exceed 1 ppb, levels in living tissues may be routinely in the range of 1-10 ppm.

As a general rule herbicides and insecticides are relatively non-toxic to mammals with respect to acute effects. Oftentimes lethal doses are several hundred mg/kg body weight (Pimentel, 1971). Conversely, fishes and other aquatic organisms are more sensitive, with lethal concentrations often in the range of 1 ppb in water. Therefore, pesticides may often present potential hazards to the ecological balance of a given ecosystem, without presenting a public health hazard to man.

(b) Potential Hazards to Man

In discussing human toxicology, it is essential to distinguish between the organophosphates and the chlorinated insecticides, and between acute and chronic effects.

Very poor information on the toxicity of hard pesticides like DDT to humans exists. More is known about acute effects than chronic effects. Accidental ingestions of DDT in gram amounts are not fatal (O'Brien, 1967). This implies that a human could ingest 1,000,000 liters (250,000 gallons) of water containing 1 ppb of DDT without running the risk of acute toxic effects. The toxicity data of most hard pesticides on mammals would indicate that the potential hazards

to man from ingestion of water supplies is virtually non-existent. Similar conclusions can be drawn from the toxicity data on such herbicides as 2,4-D and 2,4,5-T.

The organophosphorus insecticides, however, present another picture. Closely related to the so-called "nerve gases", these compounds are very toxic to both mammals and lower forms. Trace amounts can be toxic, and cases of accidental poisoning in humans are well known. However, because of ester linkages, these compounds undergo relatively rapid breakdown. Hence, persistence and potential accumulation are not potential problems. Possible exceptions are parathion, which degrades more slowly, and some intermediate degradation products which have greater longevity than their parent pesticides, and whose toxicity is relatively unknown (Chesters and Konrad, 1971).

The chronic effects of pesticides are relatively unknown. Long-term exposure to various pesticides is a major concern of the Mrak Report (1969). There are difficulties in extrapolating from studies with adult human males to females, children and fetuses (Wurster, 1971). Pesticides, in common with many chemicals, can influence metabolism (Kraybill, 1969). Such problems, however, are not unique to public water supply issues. They encompass a wide spectrum of public issues, and at this point in our knowledge we must be aware of the possibility of such chronic effects in man. Human exposure to hard pesticides comes primarily from foods, rather than drinking water.

(c) Ecological Effects

The ecological effects of pesticides are now widely appreciated, even though the full impacts of some trace amounts are not known. The literature is full of warnings on the hazards to some species, especially from the more persistent pesticides (American Chemical Society, 1966; O'Brien, 1967; Wilber, 1969; Pimentel, 1971). It is difficult to generalize because of species differences, toxicity differences among chemicals, and the potential influences of other factors. However, some animals are affected by very small concentrations. Experiments at Lake George showed that 100% mortality of lake salmon fry occurred when DDT was present in the eggs at concentrations of 5 ppm (Mrak Report, 1969). In addition, there is evidence that the biological magnification of DDT and dieldrin residues in food chains is causing reproductive failure in predatory birds (Shea, 1969). Toxic effects are not limited to animal species, since DDT in concentrations of 1-10 ppb can also reduce photosynthesis in algae (Wurster, 1968). Many ecosystems may be at or near the level at which pesticide residues are damaging to the more sensitive species.

In conclusion, then, trace amounts of pesticides present mainly potential environmental effects, rather than public health hazards associated with water supplies. Because of the behavior of pesticides in the environment, potential contamination of the environment will be reflected not only in water concentrations, but also in sediments and

particularly in animals near the end of the food chain. Therefore, for purposes of this report, pesticide levels in both water and fish tissues will be discussed in a subsequent section.

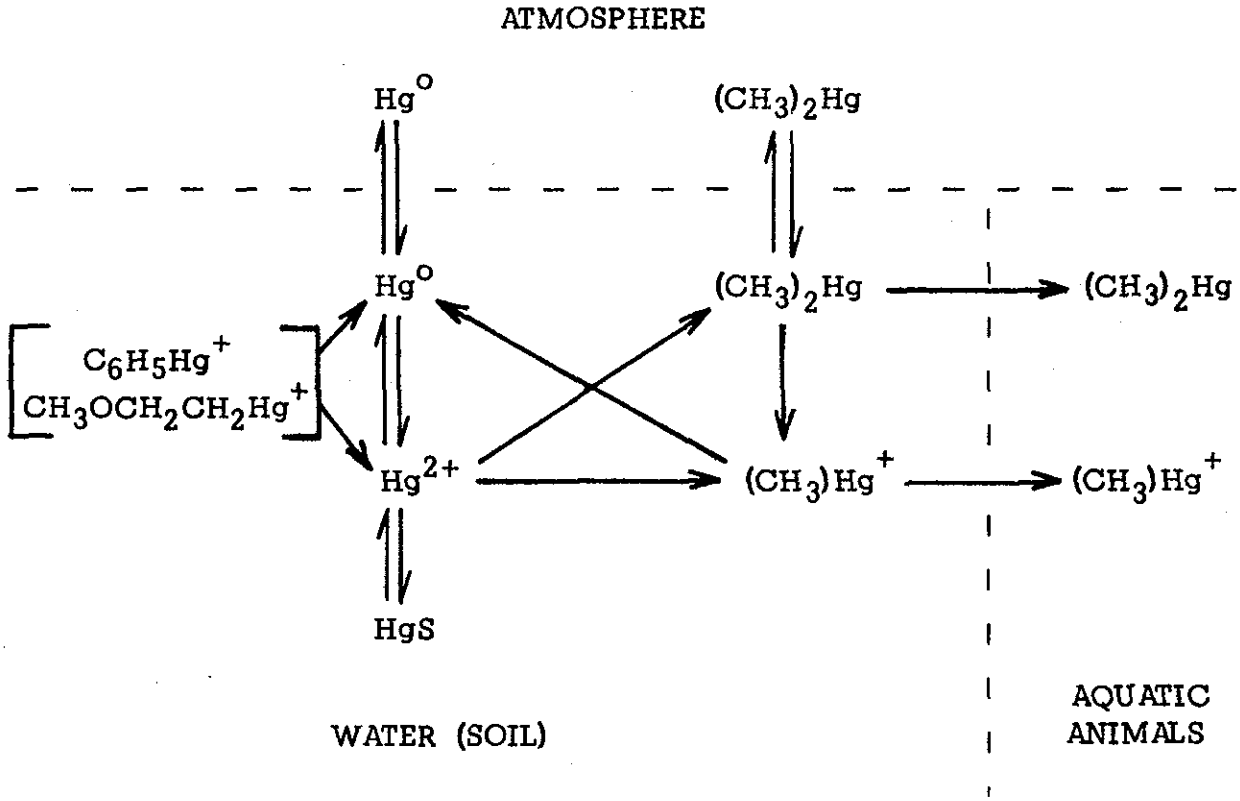
(3) Mercury in the Environment

Recent reviews (Wallace et al., 1971; Oikos Suppl. 9, 1967; Miller and Berg, 1969; Stahl et al., 1969) have outlined the major aspects of the mercury-environment-man interactions. It is now clear that the industrial uses of mercury, primarily its use as a cathode in the chlorine-sodium hydroxide industry and the distribution of organomercury compounds as antifungal agents, have increased the mercury in the environment to a level that has produced many local hazardous situations, with deaths and poisonings, human as well as other animals, reported in several countries. As recently as 1969 (August), mercury poisoning of a farm family in Alamagordo, New Mexico, brought on by eating pork that had been fed grain treated with an organomercury fungicide, resulted in neurological disorders (Curley et al., 1971). The recent banning of the commercial sale of swordfish in the United States was a preventative measure stemming from the finding that an appreciable fraction of recent catches contain more than the recommended maximum permissible concentration for human foods.

Our present state of knowledge of the dynamics of the geo-biochemistry of mercury is fragmented. That is, we cannot predict with any reasonable level of assurance of being correct, what the fate will be of the mercury

already introduced into the environment. The rate with which mercury passes from the natural and man-made terrestrial sources to long-term stabilization in sinks is unknown. The influence that the natural production of dimethylmercury (and other organomercury species) in anaerobic environments has on the pathways from sources to sinks is not clear.

Mercury may exist in nature as the metal Hg^{o}, as inorganic mercurous Hg_2^{2+} (generally unstable, but can be present in small amounts in several possible equilibria) and mercuric salts Hg^{2+}, and as organometallic compounds. Metallic mercury and several organomercury compounds have appreciable vapor pressures so that the atmosphere may carry significant quantities of the substances. Wallace et al. (1971) have given what they call 'transformation pathways', shown schematically in the diagram below.



They state:

> More information is certainly needed on the interconvertibility of each of these steps; nevertheless, the overall equilibria in nature tends (sic) to proceed toward the right, since the methylmercury and dimethylmercury compounds are not tightly bound to substrates, are water soluble or volatile, and are rapidly taken up by living organisms in which they are relatively stable.

The theme appears to be a recurrent one; our ability to measure a potentially toxic material is greater than our understanding of the significance of a particular level. This is complicated by the dynamics of the various transformation pathways in the environment, as shown above for mercury. Our interpretations of the public health and environmental aspects of certain levels of mercury, therefore, must be tentative. In the meanwhile, we must rely on whatever standards we now have.

(4) Radioactivity

(a) Radioactivity in Natural Waters

Because of the universal presence of the tritium (^3H) atom as a structural component of some water molecules, and the fact that trace amounts of practically all elements are found in natural waters, natural waters must show radioactivity. The amount of radioactivity of course, is the critical point. Radioactivity in water is customarily reported in $\mu\mu c$/liter, and is usually specified as alpha or beta activity. Often the exact isotopes are not identified, and it is more important to know the quantity of alpha and beta activities being emitted (Wilber, 1969). Gross alpha and beta activities reported in $\mu\mu c$/liter therefore is the standard analysis of radioactivity in natural waters.

A number of elements contribute radioactivity to natural waters, including uranium isotopes (Hem, 1970). ^{226}Ra is a disintegration product of ^{238}U. Because of a relatively long half-life, ^{226}Ra is the dominant form in natural water and contributes most of the alpha activity. Beta activity may be produced by strontium isotopes, as well as radioactive iodine, cesium, phosphorus and cobalt. By convention, when significant levels of gross beta activity are detected, specific analyses for radioactivity from ^{90}Sr are carried out. In summary, then, natural waters contain both alpha and beta forms of radioactivity. When gross levels exceed a certain amount, specific

analyses for ^{226}Ra and ^{90}Sr are carried out.

(b) Current Standards

The FWPCA Water Quality Criteria (1968) and the USPHS Drinking Water Standards (1962) list specific recommendations for radioactivity levels in water. Drinking water standards set a maximum gross beta activity at 1000 μμc/liter, alpha activity from ^{226}Ra at 3 μμc/liter, and beta activity from ^{90}Sr at 10 μμc/liter. Desirable criteria are listed as <100 μμc/liter, <1 μμc/liter, and <2 μμc/liter, respectively. Water quality criteria for freshwater organisms are also specified. Radionuclides should not be present at concentrations greater than those specified by the USPHS Drinking Water Standards.

(c) Potential Hazards to Man

There is no question about the public concern over radioactivity. Radioactivity is invisible, it is technically difficult to understand, and it has dramatic overtones resulting from the continual publicity of atomic energy. Lack of agreement among scientists as to safety measures contributes to the sense of apprehension among the public, and results in a general lack of confidence in scientific judgments. A case in point may be seen in some of the proceedings of a conference on Nuclear Power and the Environment held in Vermont (Atomic Energy Commission, 1969).

At this same conference the question of safety from radiation was discussed, and it was pointed out that a man living near the edge of a reactor would receive an additional dose of 5 mrem (milli-roentgen-equivalent-man) per year. This is one percent of the current maximum permissible exposure of 500 mrem/year. Normal exposure of the population ranges from 80 to 200 mrem/year. We agree that this case represents a reasonable risk, as the maximum permissible exposure is the point where there is no evidence of any radiation damage to humans.

Turning our attention to water, concentrations of radioactive materials must be translated in terms of exposure resulting from either ingestion or contact. One of the problems is the correlation of radiation dose equivalence with the concentration of tritium in water (Moghissi, 1970). At any rate, the operation of a major nuclear facility on the Savannah River is estimated to add a tritium concentration of 4 $\mu\mu$c/liter to the water which is used as drinking water in Beaufort, S. C. This corresponds to 0.8 mrem/year, or 0.5% of the average annual dose. It is also less than 0.2% of the maximum permissible concentration.

The pathways through which radioactive materials may reach man are very numerous (Straub, 1970). The concept that man is surrounded by a sea of dilute radioactivity, and that his own body is radioactive (Atomic Energy Commission, 1969) are important to

bear in mind. However, these facts do not argue against a concern for radioactivity. They merely reinforce the need for objectivity and a willingness to understand the risks involved in any project involving atomic energy. We still cannot fully predict the public health implications. We can only state them in probabilistic terms.

(d) Environmental Implications

The fate of radionuclides in a stream is determined largely by the normal chemical, physical and biological processes taking place within the stream (Straub, 1970). Radioactive chemicals enter into metabolic cycles and food webs just as the chemicals without radionuclides. Accumulation of radioactive materials is of great concern to biologists, because of the accumulation through the food chain of valuable species (Warren, 1971). Studies have shown that the accumulation of radioactive materials in fish tissues may affect the the life span and growth rates of fish. The accumulation in aquatic organisms may be by three ways: (1) ingestion, (2) absorption, and (3) adsorption to surfaces (Mackenthun, 1969). The uptake may be fairly rapid, as seen with the maximum uptake of radiophosphorus by algae in 18 days. In general, the radioactivity decreases as one progresses in the food chain. However, the amounts of some radionuclides in tissues can still be considerably over that of the surrounding water.

At the same conference in Vermont mentioned above, a question (p. 117) as to absolute certainty that radioactivity will not harm microorganisms in the environment was raised. Of course absolute certainty cannot exist, but the answers stressed the lack of evidence over many years for changes attributable to the accumulation of radioisotopes. In the same series of statements, the need for continual monitoring was also stressed. One important point is worth stressing in this connection. The available evidence strongly shows that the concentrations of radionuclides in fish and shellfish that would limit their use as food are substantially below the concentrations that would injure the organisms from radiation (FWPCA, 1968). Therefore, there is no need to establish separate criteria in water beyond those needed to limit the intake by humans. Thus public health factors appear to outweigh environmental effects for radionuclides in the aquatic environment.

(5) Bacteria

The bacteria present at any time in natural waters are usually considered in three categories (Collins, 1960): (1) those washed in from outside sources, of which a large proportion will ultimately perish, but some will find conditions suitable for growth; (2) "indigenous" types capable of existence in a dilute nutrient solution as represented by lake water, and able to use for growth low concentrations of available organic matter; and (3) those dependent on a solid surface for their proliferation and therefore found in connection with soil particles, mud detritus and plankton. Category (3) may be inclusive of category (2).

Methods of water bacteriology have been described in a series of methods manuals and monographs on general and aquatic microbiology (Fred and Waksman, 1928; Zobell, 1946; Rasumov, 1947; Frobisher, 1962; Vollenweider, 1969; A.P.H.A., 1971).

It is not intended here to give a full account of all bacteriological methods used in aquatic bacteriology. Our goals here are twofold: (1) to give the reader an insight into how the methods of this study compare to the "state-of-the-art", and (2) to enumerate some of the considerations which must be evaluated in interpretation of bacteriological data.

Methodology

The study of aquatic bacteria has taken two main courses. One has been the study of heterotrophic bacteria, and their enumeration and relation to mineral cycling. The other has been the use of certain bacterial groups,

e.g. coliform, as indicators of sanitary conditions. While the methods of analysis for coliform enumeration and identification are fairly standardized, the methods applied to studies of total bacterial populations are many and varied.

(A) Culturing Techniques

A number of early aquatic microbial studies using culturing techniques for enumeration of bacteria have been reported (Fred, Wilson and Davenport, 1924; Snow and Fred, 1926; Graham and Young, 1934; Henrici, 1938). These studies were mostly enumerative in nature with only limited consideration given for the methods used. It was later recognized that neither one single medium nor any one set of cultural conditions would support the growth of all "naturally occurring" heterotrophic bacteria (Zobell, 1941; Carlucci and Pramer, 1957). Subsequent investigations have compared various counting methods, both viable and direct counts.

1. Plating Methods

Carlucci and Pramer (1957) compared pour and spread plating techniques with media of varying composition for marine bacteria. They found the number of bacterial colonies that developed on pour plates was greater by 30 to 40% than the number that developed on surface innoculated plates. They reported, however, that colony counts were made more easily with a surface innoculum due to larger, more uniform and better distributed colonies.

Buck and Cleverdon (1960) had contrasting results to Carlucci and Pramer (1957). Their spread plates always revealed higher counts. The ratio of counts, spread/pour, ranged from 1.1 to 9.5. The reproducibility was equal for both methods.

Zobell and Conn (1940) have shown that some marine bacteria are thermosensitive and are killed at the congealing temperature of agar. Conversely, Jannasch and Jones (1959) found no direct evidence that the heat of the agar adversely affects the microorganisms developing on agar plates.

A number of studies (Carlucci and Pramer, 1957; Floodgate, 1964; Jones, 1970) have found that the composition of viable count media exerts an effect on the count estimate. A recent publication (Jones, 1970) compared media recommended by the American Public Health Association (1965) with the casein-peptone-starch (CPS) medium of Collins and Willoughly (1962). Their results were reported for 4 to 6 samples from 5 freshwater systems with 5 or more replicas for each. They found tryptone-glucose-yeast extract (TGE) and Plate Count Agar gave higher counts on 85% of the samples at 48 hr. incubation (20° C), but only 20% of the increases were statistically significant. At prolonged incubation (14 days, 20° C) higher counts were obtained on CPS with 96% of the samples, of which 74% were statistically significant. At lower temperatures (10° C, 23 days) the counts on

CPS were higher with 84% of the samples and all were significant. They concluded that under the specified growth conditions CPS is more suitable for counts of freshwater bacteria than the recommended media of the American Public Health Association (1965).

2. Membrane Filters

A number of investigations have used membrane filters for culturing and enumeration of bacteria. These include bacterial counts from sediment (Anthony, 1970), microcolony counts (Jannasch, 1958; Jannasch and Jones, 1959) and plate counts (Bennett, 1969) for planktonic bacteria. Membrane filters have an advantage in allowing an investigator to concentrate a sample. This is especially beneficial in areas of low bacterial populations. Where 0.1 ml and 1.0 ml of innoculum are usually used for spread and pour plate, respectively, bacteria from up to 100 ml or more of water can be filtered on a membrane filter.

Windle Taylor and Burman (1964) published an article on membrane filter application and techniques. They compared 3 types of membrane filter (each manufactured in a different country) for different properties. Among their findings were the following:

(a) Spreading of colonies rarely occurs on the American filters with nutrient broth as a medium. Profuse spreading at 37° C,

but rare spreading at 22° C was characteristic of the British and German filters.

(b) Colony spreading is closely related to moisture control. Excess moisture encourages spreading, but too little moisture causes poor colony growth.

(c) The use of absorbant pads instead of agar as a method of media application is recommended for economical reasons. They concluded that with membrane filters results can be obtained in a shorter time (for some tests) than standard techniques. They also effect marked savings in the amount of culture media and glassware used, as well as savings of time and labor in the laboratory.

There was little mentioned about a comparison of results between membrane filter and other techniques.

(B) Direct Counting Methods

Direct microscopic counting of bacterial populations is generally recognized as a most important technique in determining microbial growth rates and assessing population numbers (Collins, 1963; Jannasch and Jones, 1959; Jannasch, 1965).

1. Artificial Substrates

The use of artificial substrates in microbial ecology has simplified direct counting procedures. The substrate most commonly used in both aquatic and soil microbiology has been the glass

slide (Cholodny, 1930; Sladecekova, 1962). Glass slides, though, have led to difficulties in use because they cannot be removed and replaced without disturbing the environment and it is difficult to observe a living organism. Hence, isolation and subsequent cultural study is almost impossible.

Other studies (Collins and Kipling, 1957; Perfilyev and Gabe, 1969) have used capillary tube techniques. This method has some advantages over glass slides. These can be found in a book by Perfilyev and Gabe, 1969.

2. Membrane Filters

The use of membrane filters for direct counts involves the filtering of a known volume of water through the filter. The membrane filter is then dried and stained for microscopic examination. Richards and Krabek (1954) have employed a phase microscope for counting microorganisms on the filter.

Membrane filters were first suggested for the enrichment of bacterial plankton by Cholodny (1929). Subsequent investigations showed that the use of culturing techniques for the enumeration of bacterial populations accounted for only a fraction of the true population.

Butkevich (1938) and Salimovskaga-Rodina (1938) showed that direct counts gave 200 to 5000 times higher counts than plating methods. Kusnetsov (1958) using viable staining methods estimated

that 10% of the bacteria counted by direct methods were non-viable. A study by Jannasch (1958) suggested the type of natural water sampled influences the degree of discrepancy between plate counts and direct counts. He showed the differences between plate and direct counts to be four times greater in "highly contaminated areas" than in "rather clean sections" of a river. Jannasch suggests the discrepancies are due to the tendency of planktonic bacteria to clump on the surface of suspended solids in natural waters.

Zobell and Anderson (1936), Stark, Stadler and McCoy (1938) and others have shown the attachment of bacteria to suspended solid surfaces follows previous adsorption of soluble organic matter. Henkelekian and Heller (1940) showed that the growth of bacteria in the presence of suspended solid surfaces depends on the concentration of soluble nutrients present.

Attempting to overcome the problem of clumping, Jones and Jannasch (1959) used surface active agents to remove the bacteria from particles, but Buck and Cleverdon (1960) were unable to repeat their success. Jones and Jannasch (1959) were unable to remove bacteria from clumps by mechanical shaking.

Jannasch and Jones (1959) used 5 different cultural and 2 direct microscopic methods for estimating the abundance of bacteria in sea water. Direct counts showed the presence of from

13 to 9700 times as many bacteria as cultural methods. Their results also showed a marked decrease in bacterial numbers just below the thermocline using cultural methods but not the direct microscopic methods. An explanation may be found in the work of Kriss (1953) who found that at depths descending from the thermocline, the bacterial numbers are regulated by the concentration of organic matter. Jannasch and Jones also suggest the possibility of inactive cells at that depth.

While there are apparent advantages to direct counting methods, some disadvantages must be considered. Stumm-Zollinger (1968) found direct counting undesirable due to the inability to differentiate between particulate matter and bacteria. Direct counts cannot differentiate autotrophic from heterotrophic organisms, nor can any physiological or metabolic properties of the bacteria be studied. Thus, direct counts can contribute to the overall understanding of microbial populations, but the limitations toward investigating metabolic and physiological characteristics of the population must be recognized.

Summary and Conclusions

1. Neither spread plates nor pour plate techniques have been shown to be superior.
2. Whether or not the heat of agar in pour plates affects bacterial counts is undetermined.

3. The composition of cultural media affects the total viable count.
4. Cultural conditions (temperature and length of incubation) affects total viable counts.
5. Membrane filters have advantages of economy and better suitability for waters of low bacterial populations.
6. Moisture control is very important in membrane filter techniques.
7. The information obtained from the use of artificial substrates for population enumeration is limited.
8. The use of membrane filters for direct counts has shown bacterial populations to be up to 9700 times higher than those detected with culturing methods.
9. Discrepancies in counts are probably due to the clumping characteristics of bacteria in natural waters.
10. The limitations of direct counts are: (a) they cannot differentiate autotrophic from heterotrophic organisms; (b) bacteria cannot be isolated for further metabolic studies; and (c) it is often difficult to differentiate particulate matter from bacteria.
11. No one single method has been shown to be completely satisfactory in studying microbial populations.

B. Environmental Aspects

(1) Impact on Hydrology

This section attempts to outline what will happen to the hydrology of the donor and receiver systems from the year 1972 to about 2000.

Without any additional inputs over those already operative, and assuming Wachusett Reservoir will be kept at a reasonable operational level (elevation 380 - 385 feet), Quabbin Reservoir under average inflow conditions and projected demand, will be dry by 1985 (Figure 53). The present volume of Quabbin represents about 50% of maximum capacity. Assuming that a Connecticut River diversion is implemented in 1976, and a Tully diversion by 1980, Quabbin Reservoir will increase in volume for about 20 years and then return to its present volume by 1998. These figures are based on current estimates of projected demands (450 mgd in 1992) and the assumed inputs to the system (see Table 24).[1] Assuming these implementation dates for the two diversions, and the figures as outlined, four distinct time periods during which the volume of water impounded at Quabbin Reservoir will undergo major changes are as follows:

1972 - 1976 (Phase I)	No Connecticut River or Tully System diversion. Quabbin water consists of about 11% Ware River water. Volume steadily declines.
1976 - 1980 (Phase II)	Connecticut River diversion implemented. Volume steadily increases. Ware River diversion represents decreasing proportion while Connecticut River represents an increasing proportion of total volume (Table 25).

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[1] Figures supplied by Construction Division, MDC and U. S. Army Corps of Engineers.

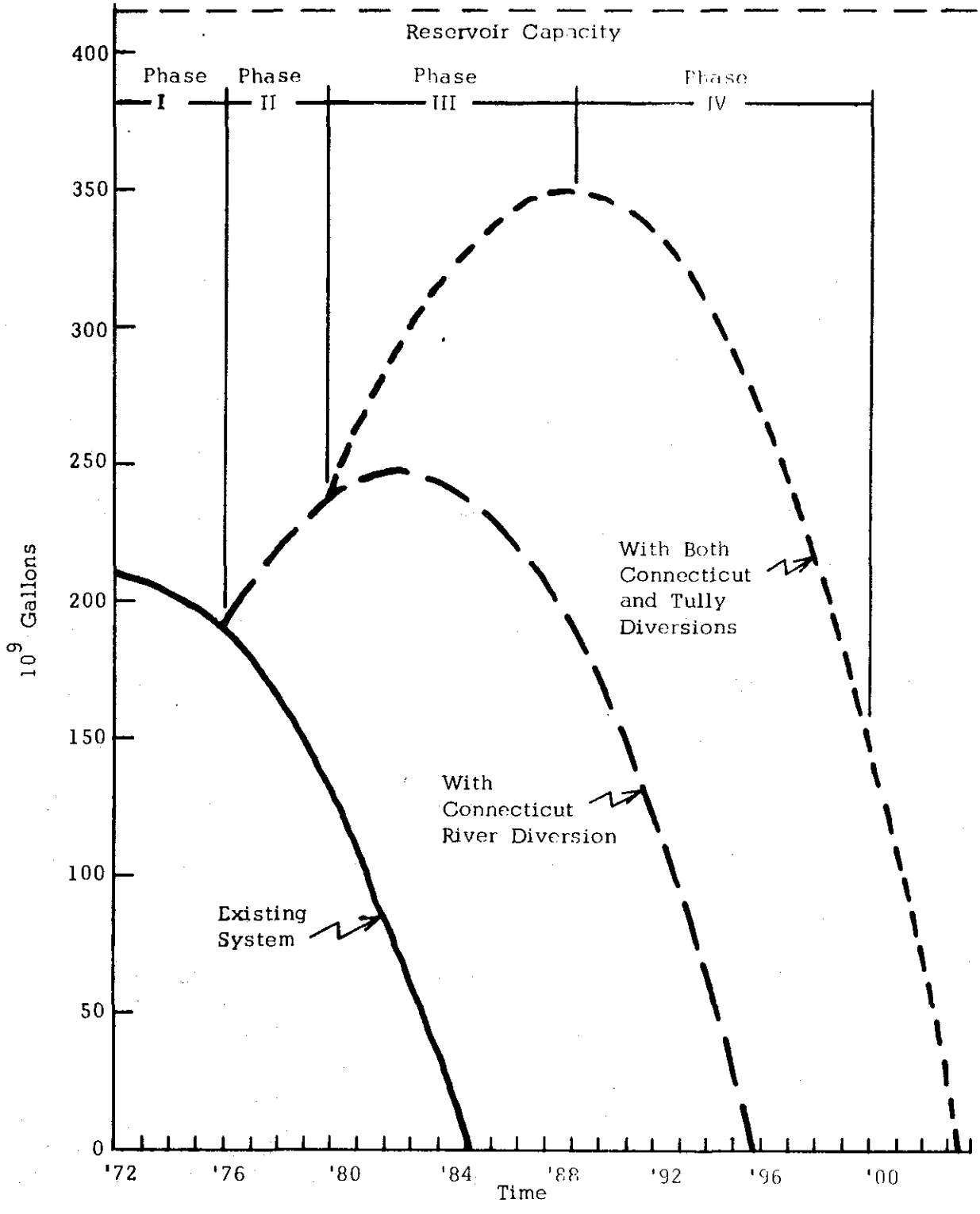


Figure 53. Projected Quabbin Reservoir Volumes With and Without Diversions

Table 24. Annual Inflow to Quabbin Reservoir From Various Sources

	Quabbin Watershed	Ware Diversion	Connecticut River Diversion	Tully System Diversion	Total
Average Inflows per Year (10^9 gal)	85	11	26.3	17.5	139.8
1972 Relative Input (%)	89	11	-	-	100
1976 Relative Input (%)	70	9	21	-	100
1980 Relative Input (%)	61	8	19	12	100

Table 25. Proportion of Quabbin Reservoir Water Originating from Various Sources at the End of a Given Year (%)

	Quabbin Watershed	Ware Diversion	Connecticut River Diversion	Tully System Diversion
1972	88.5	11.5		
1976	81.0	10.5	8.5	
1978	74.1	9.6	16.3	
1980	68.2	8.8	18.4	4.6
1982	64.0	8.3	18.7	9.0
1984	62.3	8.1	18.7	10.9
1986	61.6	8.0	18.7	11.7
1988	61.2	8.0	18.7	12.1
1990	61.0	8.0	18.7	12.3
2000	60.8	7.9	18.8	12.5

This Table is based on the following assumptions:

1. Average annual runoff from Quabbin watershed each year

2. Average annual diversion volumes each year

3. Reservoir outflow is comprised of water from each source in the same proportion as water in storage from that source is to the entire contents

1980-1989 (Phase III)	Connecticut River and Tully System diversions operative. Volume of Quabbin reaches peak of about 87% of its maximum capacity (Figure 53).
1989-2000 (Phase IV)	Quabbin Reservoir volume steadily declines (Figure 53). Relative proportions of waters originating from various sources becomes stabilized (Table 25).

During the year 1971 the level of Wachusett Reservoir dropped significantly. This was caused by lack of diversion of Quabbin Reservoir water into Wachusett Reservoir for a period of time because of maintenance operations. We assume in this report that the volume of Wachusett Reservoir will be kept at a reasonable working level, because drastic reduction of its volume might impair water quality. Therefore we visualize no impact of the proposed diversions on the hydrology of Wachusett Reservoir.

The impact on the hydrology of the donor systems will be to reduce the peak flows of the rivers during high runoff periods in the spring and sometimes in the autumn. This effect is similar to that produced by a flood control dam. A corollary effect of reducing peak flows, is to reduce the amount of flooded area in the river flood plain downstream and consequently the amount of water recharge of the flood plain aquifers.

During each spring diversion period, about 1-2% of the Connecticut River flow volume will end up in Quabbin Reservoir through the Northfield diversion. An additional 1% will come to Quabbin through the Tully diversions, when they are completed. For the spring of 1971, the theoretical figures

would have been 1.5% had the Northfield diversion been implemented, plus an additional 0.9% by way of the Tully system. These amounts represent 1% of the total annual flow of the Connecticut River at Montague City. No appreciable impact on the hydrology of the Connecticut River and its watershed downstream from the Northfield diversion site is expected. Berger (1971) has estimated that the Northfield diversion to Quabbin would create a stage reduction of 0.2 foot at Montague City. It is thus certain that flooded area and recharge of flood plain aquifers will be reduced and the magnitude of these reductions will be small. Obtaining precise estimates of recharge loss would entail additional study of the flood-plain hydrology.

The Tully and Millers River systems will be affected proportionately more than the Connecticut River, with maximum effects on flows in the river reaches immediately below the diversion sites and at the confluence with the main-stem of the Millers River. Tarbell Brook and Priest Brook diversions will reduce peak flows at South Royalston during diversion days. On a monthly basis, up to 17% of the flow will be diverted. On a daily basis, up to 48% of the normal flow at South Royalston may be lost by diversion during the diversion period. As indicated in Table 26, most months will have some days with no diversion loss at all (minimum reduction = 0) because the control flow requirements cannot be met. During wet years, proportionately more water will be diverted and during dry years, diversion

will be minimal (Table 27).

Further downstream, at the confluence of the Tully and Millers Rivers, diversion effects on flow will be most pronounced. Up to 31% of the monthly flow may be diverted during an average year, and on especially high runoff periods, 50% of the daily flow may be expected (Table 28). The impact of these flow reductions on water quality will be discussed in a subsequent section. Further downstream, the reductions in flow will be proportionately less, as additional tributaries add to the flow.

The impact on recharge of groundwater in the main Millers River valley is expected to be minimal because the steep topography of the valley sides adjacent to the river limits the extent of any aquifers that can be recharged from the river. Thus, although the diversions may significantly lower peak flows during the diversion period, the amount of aquifer recharge loss would be small.

Table 26. Maximum and Minimum Daily Reductions in Flow in Millers River at South Royalston during Three Representative Years Assuming Priest and Tarbell Brooks Diversions.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	PERCENT											
Wet Year (1951)												
Max. %	21	23	38	43	12	0	0	0	0	20	34	23
Min. %	0	0	0	9	0	0	0	0	0	0	0	0
Average Year (1943)												
Max. %	0	17	24	22	22	9	0	0	0	1	8	0
Min. %	0	0	0	0	10	0	0	0	0	0	0	0
Dry Year (1965)												
Max. %	0	0	17	26	7	0	0	0	0	0	0	0
Min. %	0	0	0	0	0	0	0	0	0	0	0	0

Table 27. Monthly Loss in Flow in Millers River at South Royalston Assuming Priest and Tarbell Brooks Diversions for Three Representative Years.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	PERCENT											
Wet Year (1951)												
	2	7	15	17	2	0	0	0	0	2	16	6
Average Year (1943)												
	0	5	16	15	17	1	0	0	0	1	9	0
Dry Year (1965)												
	0	0	1	14	0	0	0	0	0	0	0	0

Table 28. Monthly Reductions in Flow in Millers River, at Confluence of Tully River, Assuming Tully System Diversion for an Average Year.

Month	Average % Reduction in Flow	Maximum Daily % Reduction
Jan	0	0
Feb	9	29
Mar	29	45
Apr	26	39
May	31	42
Jun	2	16
Jul	0	0
Aug	0	0
Sep	0	0
Oct	2	15
Nov	15	50
Dec	0	0

Impoundments to be formed by the construction and operation of the diversions will vary greatly in area and duration of water storage. Tarbell Brook weir will impound during the summer a 28-acre pool with a maximum depth of 9 feet, at the spillway, and much of the area with depths less than 5 feet. Fluctuations in pool elevation will be up to 2 feet above spillway elevation during high flows. Priest Brook dam will be operated as a temporary reservoir, filling only when the combined diversion water from Tarbell and Priest Brooks exceed the 120 cfs pumping capacity at Priest dam. When filled to spillway crest elevation, the pool will cover 400 acres with a maximum depth of 25 feet. Using data from an average year, for example, 1943, the pool would be empty until mid-March, increase to 240 acres by March 31 and then become empty again by mid-April. After being empty for 4 days, it would fill again and fluctuate between 90 and 260 acres during the month of May. After diversion stops on June 2, the pool would empty in 6 days. The pool would remain empty throughout the summer and may fill partially in November for a few days. A wildlife conservation pool will be maintained in the middle of the cleared reservoir area, when the water supply pool is emptied.

Tully Dam will be operated in a manner similar to the operation of Priest Dam, with rapid fluctuations in reservoir area and volume. After June 15, the current plan is to maintain a summer recreational pool of 620

acres (maximum depth of 48 feet) through Labor Day. There would be no diversion during this period because of water-contact sports use of the pool. After Labor Day, the pool would be emptied to its winter level of a nominal nine-foot depth to keep the gates from freezing. Long Pond would also be flooded during high water storage and then return to pond status when the reservoir empties. West Branch Tully River dam would be similar to Tarbell Brook installation. A 13-acre pool would be created and maintained by the overflow weir at the pumping station. Only nominal fluctuations in water depth would occur there.

In summary, the operation of the Priest and Tully dams would cause widely fluctuating pools during March, April and May and sometimes in late autumn. Priest Reservoir would be dry during the summer and Tully Reservoir would have a 620-acre pool during this time. Tarbell Brook and West Branch Tully River would have small pools which would be drained each autumn.

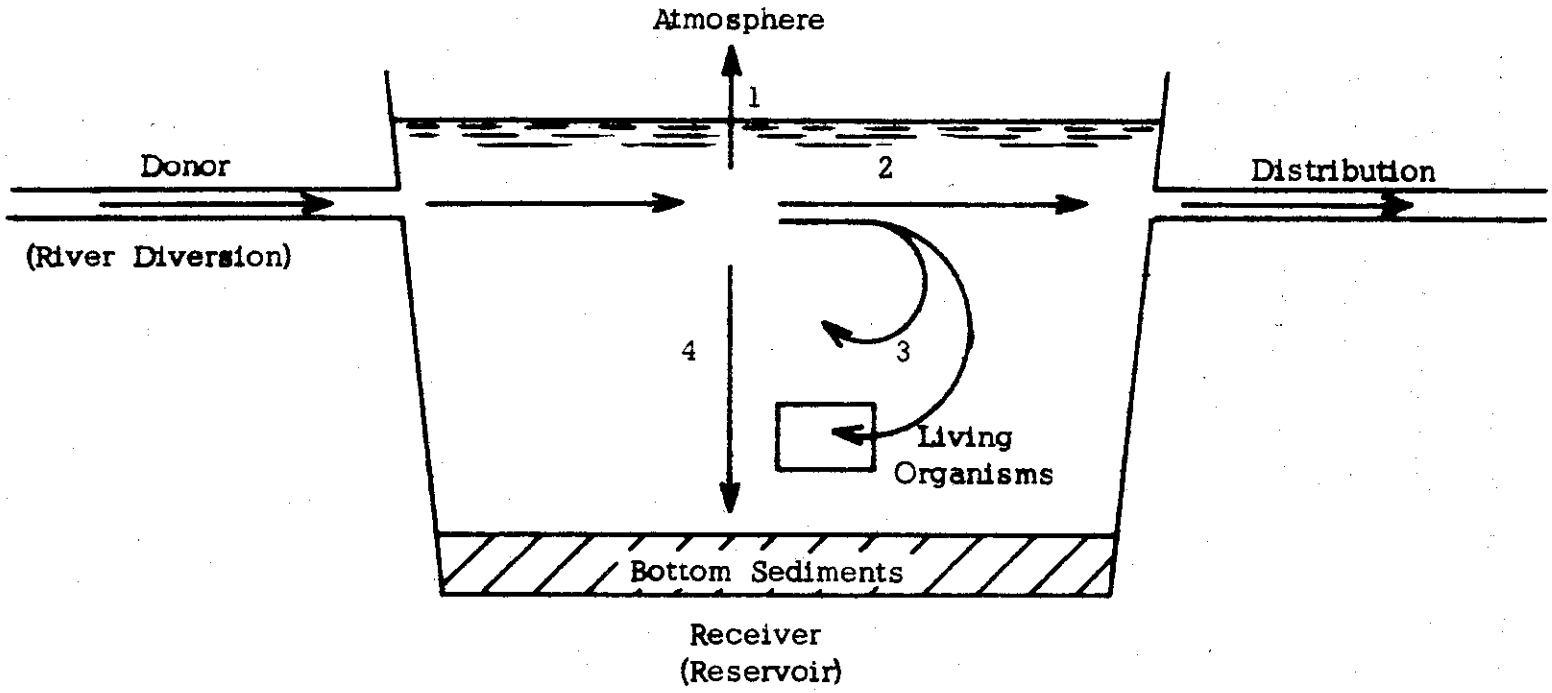
The creation of the impoundments which are a part of the Tully Diversion system may tend to increase groundwater recharge in the Tully area. Although most of the land surface in this region is covered by glacial till deposits, there are glacio-fluvial deposits of sand and gravel adjacent to the several stream channels involved. These deposits are readily receptive to the intake of water and the annual draining of the large pools will help to maintain an unsealed bottom over much of the pool area. The

magnitude of recharge water volume will depend on the extent of the deposits and head of water on them in addition to their permeability. The amount of low flow augmentation resulting from the recharge of these coarse deposits will depend on the proportion of recharge water that penetrates deeply into the underlying faulted gneiss and granite bedrock. There should be some flow augmentation from the surficial deposits during the early part of the summer season.

(2) Impact on Water Quality

Before we undertake a discussion on ecological and public health aspects of the proposed diversions, it would be helpful to analyze the chemical dynamics that underlie the water quality changes in a reservoir as presented in the model in the Introduction (Figure 1).

As water of lower quality is introduced from a donor system into a receiver system, there will most likely be a loss in water quality in the receiver system. This loss of water quality (Figure 1) is due to various materials in the water. These materials include molecules, ions, suspended inorganic materials, organic debris, and living organisms. The fate of these materials is shown in Figure 54. These pathways are not mutually exclusive; for example, a DDT molecule could take all four pathways. What happens to the various materials is a function of many mechanisms. One of the central problems of ecology today is to trace the flow of materials from the various compartments of an ecosystem.



1. Evaporation to atmosphere.
2. Transfer (no change).
3. Transformation, either with or without the involvement of living organisms.
4. Deposition to bottom sediment.

Figure 54. Schematic Diagram of the Possible Fates of Materials Introduced into the Waters of a Receiver System by the Waters of a Donor System.

While our model cannot be viewed as a quantitative model, it is nevertheless a useful qualitative model with which to begin making predictions as to changes in water quality brought about by the proposed diversions, as required by this study.

Several major points must be borne in mind as we expand our discussion on water quality. First, there are dozens of physical, chemical, and biological parameters to consider. Second, we have four hydrologic phases for the entire project to consider, extending from the year 1972 to 2000. Finally, the relative proportions of Ware River, Connecticut River, Tully River and Quabbin watershed waters will vary over this period of years. In this section, the discussion will focus on changes in water quality as a result of the proposed diversions. Attempts will be made to restrict the discussion to the more important issues; no attempt is made to discuss all parameters. Subsequent sections will deal with broader ecological issues and public health aspects, and will include most of the biological parameters.

Diversion of Connecticut River water into Quabbin Reservoir in 1976 will initially increase the turbidity of the reservoir water. The final turbidity will depend upon mainly (1) fallout of some material in Connecticut River water to the sediment after diversion, (2) the relative dilution of Connecticut River water by ambient Quabbin volume, (3) transformations of materials, (4) the influence of ionic strength changes, and (5) the

influence of pH changes. Based on only preliminary data (see Section 7A, paragraph 2), the fallout of material could be significant after a residence time of 60-90 days. The dilution, however, can never exceed a factor of about 5 to 10 depending upon what volumes and how much mixing one considers. Also, water originating in the Connecticut River will be between 18 and 19% of the volume of the entire reservoir during the period 1980 to about 2000 (Table 25). Transformations may change the molecules or colloidal aggregates but will not necessarily cause an elimination. Finally, Connecticut River water will undergo a drop in specific conductance after it enters Quabbin; this will tend to stabilize the colloidal suspensions. If we assume that the Connecticut River will have an average turbidity of less than 25 during freshet flow (Table 23), and that extremely high values are possible but infrequent occurrences, all factors considered above will tend to bring the final turbidity down to a lower value. While we cannot predict what this value will be, it will probably vary between 0.5 (present turbidity) and about 2. Thus, it may not meet future U. S. Public Health Service Standards for drinking water. The turbidity will probably not rise as much during the first two diversion cycles (years 1976 - 1978) because of the smaller relative proportion of total water originating in the Connecticut River (see Table 25). After the Tully diversion begins in 1980, the turbidity will be stabilized at the then

current value, since the turbidity of the Tully system is less, and the percentage of Connecticut River water in the reservoir volume will remain approximately constant (Table 25).

Ions that form insoluble complexes (Mn, Fe, Ca) tend to precipitate out into the sediment if suitable anions are available. Such anions decrease in concentration as the pH becomes more acid, and thus these ions will tend not to precipitate out as the Connecticut River waters mix with Quabbin waters. On the other hand, these ions originating from Tully River waters will tend to precipitate out as the more alkaline conditions of the Quabbin Reservoir are encountered. Thus there is a tendency to balance. However, we cannot predict what the trend will be over a two-decade period, because the exact proportions cannot be predicted and the long-range stability for pH values in all systems is unknown.

There are at least two major concerns on the possible deterioration of water quality that have ecological significance. One concerns oxygen depletion, and the other is the introduction of additional nutrients which can lead to eutrophication.

A comparison of NER data with other available data suggests that COD values for the Connecticut River are about two times as high as for the Quabbin "inside" stations, and are somewhat greater than twice the values for the Quabbin "outside" stations. Reference to STORET data for the past decade shows occasional COD values for the Connecticut River above

50 mg/l. Both the Connecticut River and Quabbin Reservoir waters maintain high O_2 levels, and during the freshet-flow periods are probably close to saturation. The concern here is an assessment of the potential depletion of O_2 from Quabbin waters as a result of the proposed diversion.

COD represents a potential O_2 consumption that is measured using a strong chemical oxidizing agent. Such potential oxidation may never be achieved under field conditions, where biological processes mediate the chemical reactions. Actual oxygen consumption is a function, in part, of the kind of materials that are included in the COD measurement. Organic materials may represent a major portion of the COD when COD's are high and usually exert an oxygen demand through biological processes. Although these organics are all oxidized in measuring COD, some, such as simple sugars, are easily oxidized through biological processes, while others, such as cellulose (a sugar polymer) are relatively resistant to biological oxidation. Depending on the ease with which the material can be oxidized under natural conditions, the full COD may or may not be exerted upon the water.

If most of the COD is in particulate form (which is probably true for the Connecticut River) much of the material with a potential demand for oxygen could settle out either in the Northfield Pumped Storage Reservoir or in upper Quabbin Reservoir after diversion. Although settling reduces the COD of the water column, the potential oxygen demand is conserved

in the mud. Moreover, the organic component of the sediment may be acted upon by the lacustrine microbial populations at the mud-water interface, and transformed into more easily oxidized compounds. Some materials in the diverted waters may interfere with biological activity in the mud-water interface and either inhibit or enhance the transformation processes. Seasonal turnover and wind effects can stir up these bottom deposits into the water column. These effects are intensified if the reservoir levels decrease. The resuspension of transformed organic muds can serve to deplete available oxygen quickly because COD that had accumulated over many years through the settling process is suddenly present in the water column. If the stirring of the bottom mud never occurs, then COD that is settled out may be buried in the anerobic sector of the mud and may never exert its O_2 demand on the water.

Included in COD values are the oxygen demands of inorganic materials such as iron and manganese. These inorganic species can have high O_2 demands if they are in a chemically reduced state. However, in the Connecticut River, laboratory analysis shows that the iron is mainly FeIII and that the manganese may also be already oxidized.

All the above factors make it difficult to predict the impact of diverting Connecticut River waters with a higher COD into Quabbin Reservoir. Localized oxygen-depletion effects have been observed in the eastern arm of the reservoir. It is probable that similar effects will be observed after

diversion in the northern part of the reservoir as well. The impact on the hypolimnion in the deeper part of the reservoir cannot be predicted at this time. Diversion of waters from the Tully system will probably cause relatively less impact, since the COD values are lower. However, this depends on the specific molecules which comprise the COD and comparisons based on COD values alone must be tentative. Oxygen depletion will depend on a complex of biological and chemical processes in these aquatic systems. In conclusion, then, it's very possible that the proposed diversions may result in some localized oxygen depletions in the reservoir. The extent and magnitudes of such depletions cannot be predicted.

The changes in water quality resulting from nutrients introduced from the diversions must also be assessed. Most experts agree that C, N, P and trace materials are important nutrients for algal growth. However, significant levels of C, N, and P already exist in Quabbin, especially in the general area of the proposed diversion discharge (Q-5). Connecticut and Tully Rivers have higher values for N and P in general than Quabbin, but not by large factors. Nutrients are discussed further in subsequent sections. Their importance as far as water quality is concerned lies in the potential for eutrophication.

The presence of phenolic compounds during the third quarter warrants some discussion. Phenols were reported in four riverine stations in the

northern tributaries of the Millers River in concentrations in the order of 1-10 ppb. This is considered an undesirable level for drinking water (FWPCA, 1968). However, several factors must be considered here. First, no odors were detected and secondly, in a spot check the presence of lignins and tannins was found in these waters (see Section 5 B). When the detection method is not sensitive enough, as in this case, it is possible to get a positive indication from any phenolic substances. Also, these test results were for the third quarter after an extensive growth of vegetation, and when color in the water was also high. It is very probable, then, that the phenols reported may not have been simple phenolic materials, but the presence of phenolic groups on more complex molecules.

Referring back to our model (Figure 54), a number of mechanisms can be expected to operate after the diversions of river waters. Much of the larger material will settle out, probably within hours and days. Many transformations can be expected, based on both inorganic and biological reactions. Detergents would be degraded, although no significant MBAS levels were found. As the carbonates from the Connecticut River reach the more acid reservoir waters, equilibria will shift and some CO_2 will go off to the atmosphere. Those from the Tully would be retained. However, they are relatively low. Organic materials including the CCE will probably be oxidized. Some NH_3 may also be oxidized, but most of it

would be transformed by the biota. Color would decrease. This loss of color could be at least tenfold, based on evidence from the existing Ware River diversion. Finally, many highly insoluble organic materials, including hydrocarbon pesticides and organomercury compounds would tend to evaporate, as they reach the relatively large surface area of the reservoir.

The general trend will be towards an improvement in quality as the diverted water is retained in the reservoir. Whether the retention time of 60 to 90 days before the Connecticut River and Tully system waters reach the general position near Shaft 12 is sufficient to cause recovery ($\Delta QR = \Delta QL$) is unknown. However, the much longer retention times to reach the Winsor Dam area (See Section 6A) could also allow for some recovery. We can predict, however, that dilution with ambient reservoir volume will not restore the water quality alone. Some "fallout" of materials due to sedimentation, transformation and evaporation must occur to restore quality. The "treatment plant" capacity of the reservoir can probably handle some restoration of water quality. The magnitude of this capacity is now unknown. Because of its capacity to handle waters from the Ware River diversion with efficiency for 30 years of diversion, we may assume it has some reserve capacity. However, assuming that a loss of water quality occurs with some diversions of Connecticut River water (Case II or III, Figure 2), further deterioration will

be checked as Phase III begins.

Before ending this section, several general statements appear useful to tie together our thinking. During Phase I the water quality will deteriorate as the volume in Quabbin Reservoir decreases. This loss of quality could progress to a dangerous point if the volume of hypolimnion waters is drastically reduced. Any losses in quality due to Connecticut River diversion must be judged in the light of water quality loss without diversion. Secondly, the volumes of water represented by Connecticut River origin will be relatively low during the first few diversions. This allows ample time to study the actual impact of diversion during a period of lower potential to cause a negative impact on water quality. Thirdly, the Tully system diversion in increasing total volume (Phase III) should improve the "treatment plant" capacity of the reservoir and thus an improvement in quality may take place. Also, it must be remembered that as the pollution abatement plans are implemented in the 1970's, the quality of riverine waters will improve. Finally, without even further sources of water inflow, Quabbin Reservoir is destined to deteriorate rapidly by the end of the century, because low water levels will interfere with natural treatment processes.

Turning now to the donor systems, diversion of water from any stream or river, which is receiving inputs of nutrients or pollutants downstream from the diversion site, will have the effect of increasing the concentration

of the nutrient or pollutant above what it would have been without the diversion. Berger (1971) has pointed out that the reach of the Connecticut River between Northfield, Massachusetts and Thompsonville, Connecticut receives a disproportionate load of nitrogen and phosphorus. The effect of the proposed diversions would be to increase the concentration of these additional nutrients by 3% at most. Considering, for example, that flood flows now have a 50% lower concentration of both nutrients than do low flows at Thompsonville, the projected increases would not be significant. Indeed, they would be less than normal annual fluctuations in the water.

On similar grounds, other water quality parameters would not change to any significant degree. One might argue that slight reduction in flow volume will reduce the total mechanical erosion of the banks and thus reduce the solid load and turbidity downstream. We view these changes of a few percent, however, to be insignificant, and to leave neither positive nor negative impacts on water quality below the proposed diversion site on the Connecticut River. We add, however, the possibility that retention of Connecticut River water in the upper reservoir of the Northfield pumped storage facility may cause some changes in water quality. However, the impact of these changes in water quality will probably be minor, after the water is returned to the Connecticut River.

Because of the complex of impoundments and the larger relative volumes proposed to be diverted, the impacts on the Millers River

system are potentially greater. Diversion from Priest and Tarbell Brooks would decrease the water quality on the Millers River under present conditions during days of diversion, especially at South Royalston. Diversions from other locations of the Tully System would increase even further any losses in water quality along the mainstem of the Millers River.

During the spring runoff period, paper pulp in suspension was noted at South Royalston and at decreasing concentrations at all other Millers River stations. Apparently, the turbulence associated with high flows can scour some deposits of pulp and carry them downstream, thereby partially cleansing the bottom habitats. Reduction in peak flows would tend to reduce the effectiveness of this cleansing action. However, apparently the existing uncontrolled flows are not adequate to clean the river. It is necessary to stop the input of pulp before this suspended load can be reduced. After the proposed state-federal secondary treatment cleanup of the Millers River, the diversion during spring runoff periods would have only minimal impacts on water quality downstream to the Connecticut River. Thus the short term impact of the proposed diversion will be to decrease water quality downstream, but because of the proposed cleanup, long term impacts should be minimal.

Impoundments present other problems. Shallow ponds, such as those proposed for the tributary streams, tend to reduce the quality of

water impounded in them. Water temperatures are increased, algal populations tend to bloom, and dissolved oxygen depletions occur as the algae blooms decline. The short-term outlook for water quality in the impoundments, is a decline in quality. The long-term (20 year) projection is definitely toward lower water quality from the impoundment areas.

In general, the longer the retention time, the greater the probability of ecological changes towards the lentic condition. Although specific changes in the ecology of a single impoundment are difficult to predict, it is reasonable to assume that the ecological changes in the impoundments at Tarbell Brook and the West Branch of the Tully River will progress more closely towards a relatively stable lentic condition than will those at Priest Brook, for example. Thus we visualize a whole range of ecological changes in the impoundments.

(3) Impacts on Ecology

There can be little doubt that increased levels of nutrient chemicals will be detected in Quabbin Reservoir after the implementation of the Connecticut River diversion and before the implementation of the Tully system diversion. However, not all nutrients can be expected to show such an increase in this time period. Phosphorus increases are possible, but not probable. Increases in available carbon, on the other hand,

are quite probable, if only due to the relatively high alkalinity of the Connecticut River. Also, the fact that fecal contamination of the Connecticut River does occur increases the likelihood that complex organic molecules will be introduced into Quabbin and possibly into Wachusett where they will become part of the nutrient pool. The future abatement of pollution in the Connecticut River will contribute significantly to the lowering of any such nutrient addition to the reservoir through diversion.

It is important to note that current nitrogen, phosphorus, and carbon levels in Quabbin are sufficient to support larger phytoplanktonic populations than presently exist. Increased levels of these nutrients do not necessarily mean, then, that higher concentrations of algae in Quabbin can be expected as a direct result of the diversion. It is quite possible, however, since nitrogen, phosphorus and carbon appear not now to be limiting, that the Connecticut River diversion may increase the levels in Quabbin Reservoir of some now unknown limiting growth factor, such as a vitamin. The importance of this possibility cannot be overemphasized. Additional studies on limiting growth factors in both Quabbin Reservoir and Connecticut River waters are required (see Section 10, Recommendation No. 2).

Finally, we cannot overlook physical factors such as water temperature as possible limiting factors in algal growth. For example, not all algae have the same optimum growth temperature. Therefore, any

differences in temperature between donor and receiver systems could influence numbers and types of algae in the final water mass. A relatively cooler water mass from the Connecticut River might suppress the growth of some species of blue-green algae. This could however, also augment the growth of other species. Not enough is known about the growth requirements of the algae in question to permit meaningful predictions. Any increases in nutrient levels in Quabbin waters due to the Connecticut River diversion will most likely tend to be lessened by the diversion of the Tully system.

There is no reason to believe that undesirable algal species will be introduced into Quabbin Reservoir by either diversion. Any changes in the current algal populations in Quabbin will most likely be the result of the response of present populations in Quabbin to changing levels and kinds of nutrients brought about by the diversions.

The proposed diversion of Connecticut River waters into Quabbin Reservoir stands a good possibility of having an ecological impact upon the fisheries of Quabbin. Furthermore, in view of the position of the Massachusetts Division of Fisheries and Game, the impact would be a negative impact. We must assume that undesirable species will be introduced into Quabbin Reservoir if Connecticut River waters are diverted into Quabbin.

Experience with the present Ware River diversion into Quabbin Reservoir does not provide any insight into this problem. Fish species in

the Ware River and Swift River watershed and hence Quabbin are about the same. There is no evidence of carp or eels in the Ware River (personal communications, Massachusetts Division of Fisheries and Game). Thus we cannot refine our estimates on the impacts on fisheries from experience with the Ware River diversion. The consequences of introducing undesirable species could be felt in several ways. First, the present ecological balance between species will be lost. Secondly, if the salmonid population is decimated by undesirable species competition, and a warm water fish population predominates there is good likelihood that the number of angler trips by sports fishermen to Quabbin Reservoir will decline. This in turn will reduce the harvest and further influence ecological balance. The issue, then, is not a reduction of the standing crop of total fishes in Quabbin Reservoir, but the disruption of the present success in the management of a salmonid fisheries program.

Since the species representation in Quabbin Reservoir is similar to that of the Tully System, the proposed diversion of the waters of the Tully into Quabbin will not have any significant effect on the fisheries in Quabbin Reservoir.

When presented with a request for recommendations for fish exclusion measures, the Division of Fisheries and Game presented the following alternatives.

a) A fine mesh traveling screen,

b) An electrical barrier utilizing a low-gradient voltage pulsating DC current, backed up by a fine mesh traveling screen,

c) Chemical treatment through chlorination at a high rate to kill eggs, larvae and juvenile fish, and facilities to dissipate chlorine prior to diverted water entering the reservoir.

These alternatives must be designed to function with the proposed flow rates. No detailed specifications for the alternatives are presented. Before a decision is made, the Division feels that further studies to determine the rate of chlorination necessary to kill eggs, larvae and juvenile fish are necessary. However, the reactions of chlorine with organic material dissolved and/or suspended in the diverted waters will also produce chloramines which may adversely affect benthic populations in Quabbin Reservoir which are part of the fisheries food chain. This impact cannot now be precisely defined. Continuous monitoring of fish populations over long periods of time will be required for any further elucidation of the likelihood and magnitude of this problem.

Increased concentrations of organic molecules in Quabbin as a result of both the Connecticut River and Tully system diversions may affect the dissolved oxygen content of Quabbin waters due to the oxygen demand of these molecules as discussed earlier. The magnitude of any overall decrease in oxygen in the hypolimnion and the epilimnion of the Quabbin

Reservoir, however, cannot be predicted. Localized depletions of oxygen in Quabbin Reservoir have been periodically noted over the past half dozen years as a result of the present Ware River diversion. These depletions have been observed only in the southern part of the eastern arm of Quabbin, and have been short lived. The proposed diversions may be expected to produce similar, localized phenomena. The salmonid fisheries in Quabbin are not expected to be affected by any lowering of dissolved oxygen in the upper portion of the middle arm and in the eastern arm of the reservoir. Salmonid fishes are typically found in the main body of Quabbin Reservoir.

Because of the number of factors governing the disposition of pesticides in surface waters (see Section 8A), it is not surprising that only small traces of pesticides were detected in this project. Similar findings are seen in the STORET retrieval data on the Connecticut River (STORET Retrieval Date 69/06/27). Analyses for aldrin, BHC, DDT, dieldrin, endrin and other pesticides during the 1960's show little or no residues in the water. Finally, the findings of Lichtenberg et al, (1970) in a 5-year summary of pesticides in surface waters of the United States report only trace amounts (< 0.1 ppb) of pesticides in the Connecticut River.

A prediction with some certainty can be made about the ecological effects of pesticides in the proposed diversions. The Massachusetts Division of Fisheries and Game has supplied us with data that indicate significant levels of DDT, endrin, dieldrin and PCBs in the tissues of

lake trout taken from Quabbin Reservoir. These pesticides in lake trout reflect the expected concentrations by the food chain if traces of pesticides are already available in the reservoir ecosystem. Nor were the residues of DDT in fish from the Connecticut River (Lyman et al., 1968) any higher than those reported for the fish in Quabbin Reservoir. While more extensive monitoring of the waters, muds, and biota of both the Connecticut River and Quabbin Reservoir for pesticides would increase the certainty of our prediction, we feel that it is highly improbable that the proposed diversion will have any important environmental effects. Similar reasoning can be applied to the proposed Tully System diversion.

Somewhat different from the above impacts is the much more general question of ecological balance. This question cannot be answered in any but very general terms. That any change in an ongoing ecological system is effected and becomes persistent is good indication that a shift in ecological balance has been achieved. The probabilities of some of the more important, possible changes in Quabbin due to the proposed diversions have been discussed above. However, what all the effects of any shift in ecological balance may actually be cannot now be predicted. For example, an increase in Quabbin of "trash fish" populations may result from slight shifts in competition patterns which in turn may result from the introduction of species into Quabbin by the

Connecticut River diversion. The salmonid population could remain essentially unaffected. However, the number of angling trips to Quabbin may very well decline. The harvest of fish would then be lowered and could conceivably be lowered to such an extent that a second shift in the ecological balance would be realized. This second shift, or any subsequest shift, might in turn directly affect the salmonid population. This is a good example of how sociological and biological events can interact to produce a series of complex phenomena which cannot be predicted in any but the most general form.

Similarly the impacts of the proposed diversions into Quabbin or Wachusett Reservoirs are impossible to discuss in any but very general terms until such a time as the specific impacts discussed above can be more fully defined by future studies. On the basis of current data, we believe that the possibility of a degeneration in turbidity in Wachusett deserves some mention due to the importance of turbidity in any contemplated future treatment of Wachusett waters prior to their final distribution to consumers. This will be discussed in Section 8 C.

We predict no significant impacts on the general ecology of the mainstem Connecticut River as a result of the proposed diversions. Losses in flow volume and shifts in water quality will be so minor that it is difficult to envision any significant changes in bacterial, algal and benthic

populations. Similarly, no major changes in the existing fish populations, or in the future anadromous fish program are expected.

On the other hand, specific impacts on the ecology of the Millers River system are probable. The impoundment of waters from the northern tributaries will cause changes in the algal and heterotrophic bacterial populations. While the probability that these changes will occur is good, the details cannot be predicted. Eutrophication and algal blooms will increase over the years, and thus offer a long term (over 20 years) impact. Changes in benthic populations in the mainstem Millers River will be slight, except for a possible increase in the benthic fauna characteristic of poor quality water at Station No. 4 (South Royalston). This, however, will be a short term impact, and will reverse itself after the Millers River is cleaned up under the proposed state-federal abatement plans. The impoundments will result in gradual changes in both benthic fauna and fish populations, as they change from lotic to lentic environments. These changes will be influenced by drawdown and other dynamic changes in the hydrology. Tributaries will experience minor changes in general ecology. Consistent with previous statements, changes in the ecology in impoundments are more probable in Tarbell Brook and the West Branch of the Tully.

Finally, little detailed information on the construction phase of the proposed diversions has been available for study. Therefore, the impact

of this phase on donor and receiver systems has not been discussed in this report. However, both the MDC and the Corps of Engineers are well aware of the importance of this phase to any understanding of the overall environmental impact of the proposed diversions.

C. Public Health Aspects

Coliform bacteria are indicators of possible human fecal contamination and therefore of the possible presence of human pathogens, including bacteria and viruses. Coliform bacteria are not themselves, however, pathogenic. It is reasonable to assume that concentrations of coliforms will increase in Quabbin Reservoir as a direct result of the Connecticut River diversion. Therefore the possibility of finding agents of human infection in the area of Shaft 12 in Quabbin will also be increased by the diversion. The measure of real risks to public health associated with this possibility is, however, a function of a number of other variables. These variables include the general health of populations contributing to the fecal pollution of the Connecticut River, treatment of water before its entry into Quabbin, residence time of this water in Quabbin, dilution of diverted waters by Quabbin waters; and finally, treatment prior to final distribution.

While the MDC is currently planning, according to a Massachusetts Department of Public Health directive, to chlorinate diverted waters prior to their entry into Quabbin, we feel that the varying turbidities of these waters, and the resultant inefficiencies of chlorination, ensure the possibility that pathogens imbedded within suspended debris will find their way into Quabbin. Chlorination of diverted waters prior to entry into Quabbin will probably be less important a means of controlling the introduction of these pathogens than will the implementation of present

pollution abatement plans for the Connecticut River.

Even with the implementation of present abatement plans an important question is how long diverted waters can be expected to remain in Quabbin. In general, the natural purification processes of a lake will reduce the coliform concentrations in proportion to the length of time these bacteria are in residence in the lake. The die-off rates of coliform bacteria are generally considered to be similar to die-off rates of pathogens. While recent research indicates that there is not necessarily a direct correlation between the die-off rates of coliform bacteria and pathogens, it is generally assumed that residence times of several weeks provide reasonable disinfection (Fair, Geyer, and Okun, 1968).

Our model studies thus far indicate that diverted waters will have reached the general area of Shaft 12 within 2-3 months of the time they are introduced into Quabbin. Portions of these waters will be mixed with waters derived from the southerly portions of the main body of the reservoir as they are taken into Shaft 12; other portions will continue in a southward flow to mix eventually with the waters in the western arm. While it can be expected that significant die-offs of pathogens will occur within a 2-3 month residence in Quabbin, and that maximum dilutions of diverted waters will probably be realized within one diversion cycle, the possibility that some pathogens may find their way into the Quabbin aqueduct has to be assumed. The possibility that some pathogens will find their way into the Chicopee outlet at Winsor Dam also has to be assumed; however, because preliminary laboratory model studies indicate it will take about 7 months for diverted waters to reach Winsor Dam, and because of the greater dilution of these waters

which would then have taken place, the probability of detecting pathogens at the Chicopee aqueduct would be lower than that of detecting them at the Quabbin - Wachusett aqueduct.

Because model studies to date have not taken into account the effect of winds on residence times of diverted waters, and because pertinent information of the die-away phenomenon is by no means complete, it is not now possible to predict the actual number of pathogenic organisms which may possibly find their way into the Quabbin-Wachusett and Chicopee aqueducts as a result of the Connecticut River diversion. Average times in days for a 99.9% reduction of enteric organisms, reported by Fair, Geyer, and Okun (1968) range from 10 (for Coxsackie A9 virus in Little Miami River) to 130 for Echo 7 virus in sewage). These rates are published with the provision, however, that they are useful only for similar conditions of test.

Because coliform concentrations within the Tully System are comparable with the minimal concentrations already observed in Quabbin, and because current model studies indicate that the residence time for Connecticut River diversions in Quabbin will not be reduced appreciably by the Tully System diversion, the impact of the Tully System diversion will be to reduce further any public health hazard associated with the Connecticut River diversion.

It is important to note that any pathogens which do find their way into the Quabbin-Wachusett aqueduct will be subjected to dilution by Wachusett waters as well as to the self-purification processes of that reservoir. Given the dilutions and residence times of diverted waters in both reservoirs, we conclude that while the introduction of pathogens into Wachusett Reservoir is possible, it is improbable

that they will be detected in Wachusett. Finally, any enteric organisms which may be present in Wachusett as a direct result of the contemplated diversion may be easily destroyed by existing or contemplated chlorination within the distribution system.

The presence of mercury at all sampling sites suggests that it is reasonable to assume that mercury is a component of the waters of this region. While the levels are generally low and thus pose no immediate hazards, the possibility of significant concentrations in the food chain must be assumed. Indeed, data from the Massachusetts Division of Fisheries and Game indicate levels of mercury in fish taken from Quabbin Reservoir to be in the range of 10^2 - 10^3 ppb, in this regard being similar to levels found in fish in the Connecticut River. Several peak values for mercury in excess of 5 ppb have been found in some locations, including the Millers River and Quabbin and Wachusett Reservoirs. Most of these values occurred earlier in the year, and recent data indicate lower values. The reasons for these values are unknown, nor can the present study, due to the sampling situation, define any possible sources. This would require a separate study in itself. Our conclusions on the impacts of the proposed diversions, however, must be based on comparative data for the proposed donor and receiver systems. On the basis of the data, we must conclude that no public health hazards due to higher levels of mercury can be expected from the proposed diversions. Indeed, the data suggest that lower levels in water exist in the proposed donor systems.

Because of the number of factors governing the disposition of pesticides in surface waters (see Section 8 A), it is not surprising that only small traces of pesticides were detected in this project. Similar findings are seen in the STORET

Retrieval Date 69/06/27). Analyses for aldrin, BHC, DDT, dieldrin, endrin and other pesticides during the 1960s show little or no residues in the water. Finally, the findings of Lichtenberg et al. (1970) in a 5-year summary of pesticides in surface waters of the United States report only trace amounts (< 0.1 ppb) of pesticides in the Connecticut River.

Pesticide information was reviewed in earlier sections. The findings confirm the position that the Connecticut River waters would not present a public health hazard if diverted into Quabbin Reservoir. In the first place the amounts of pesticides are too low, and secondly the evidence indicates trace amounts to be present in Quabbin Reservoir already. Therefore, the proposed diversion would not introduce pesticides into a reservoir that was already free from such compounds before the diversion.

Our data on radioactivity, and recent information from the Lawrence Experiment Station of the Massachusetts Department of Public Health (Donlon, personal communication) leads us to conclude that no public health hazards will result from the diversions of Connecticut River waters or Tully System waters into Quabbin Reservoir. The Lawrence Experiment Station has been testing Connecticut River water as part of the cooperative efforts of the Tri-State Commission for some time, and has detected neither ^{226}Ra nor ^{90}Sr in the water. Also surface waters, including reservoirs, from all over Massachusetts have been treated in the spring and fall, and no presence of ^{226}Ra or ^{90}Sr has been detected. On the other hand, some of the STORET Data (Retrieval Date 69/02/27)

for 1960s show Connecticut River water with total beta activity in excess of 10 μμc/liter. This is not true for the more recent data. These discrepancies are common for Connecticut River data, and point out the need for continual monitoring. Such continual monitoring is also desirable in view of the future operation of a nuclear power plant at Vernon, Vermont. We affirm our conclusion, however, that in view of existing guidelines, we see no immediate or long-range public health hazards from radioactivity in the donor systems.

The risks to human health which are inherent in the consumption of any surface waters cannot, of course, be completely eradicated. However, given man's past experience with public water supplies and his present technology, we conclude that those risks which can be associated with the proposed diversion are reasonably comparable with those generally taken in the consumption of Massachusetts surface waters.

Based on available evidence, there is no reason to anticipate any public health hazards to the donor systems resulting from the proposed diversions. A positive impact on the Millers River system is possible, the main reason coming from the probable decrease in any pathogens as a result of the impoundments. Impoundment of water results in a decrease in pathogens, due to die-off. However, while coliform bacteria are present in these waters, we have no direct evidence of any pathogenic organisms.

D. No-Diversion Alternative

Within the intent of the National Environmental Policy Act of 1969, we

should also consider the alternative of no diversion. Mention has already been made of the probable deterioration in water quality in Quabbin Reservoir during Phase I. Extending our time reference beyond 1976, we predict a further deterioration in the condition of Quabbin Reservoir if the projections as shown in Figure 53 are operative. Central to these projections are average inflow conditions and the realization of the projected increases in water supply demand.

An analysis of the dilemma can be approached in terms of classical limnological concepts. Under full pool conditions, Quabbin Reservoir would resemble a temperate lake of the second order (Welch, 1952). Moreover, the condition would be quite characteristic of an oligotrophic lake. In such a lake nutrients are low, electrolytes are low, dissolved oxygen levels are high, algal blooms are rare, and cold-water fishes (salmon, trout) are found in abundance. As the reservoir loses volume, it will approach the conditions of a temperate lake of the third order, the chief characteristic of which is a loss of thermocline and the development of essentially isothermous conditions. Such a lake will move faster toward a eutrophic condition than will a second order lake. Eutrophic lakes are relatively shallow, nutrients are abundant, dissolved oxygen may be absent in deeper layers, blooms are common, and the fish populations are predominantly warm-water fishes (Welch, 1952).

However, the situation at Quabbin Reservoir is complex in that some sections are very deep (over 100 feet), whereas some areas of the northern section are very shallow. Moreover, the reservoir is a dynamic and not a static pool, with

substantial, annual inflow-outflow volumes. Therefore, it is very difficult to state at what elevation (or volume) the reservoir will reach a "critical point". Water quality conditions, algal growth patterns, and fishes in the northern sections suggest that progression toward eutrophication is already taking place there. Water quality in the main body is still of a high quality. As the projected volumes decrease over the years, the relative masses of high versus low quality water will shift toward an overall loss in water quality. Losses in volume will decrease the treatment capacity and possibly the retention times of new inflow waters. Losses in hypolimnion volume will certainly diminish the standing crop of salmonid fishes. Finally, at some point in time before total water depletion (1985), Quabbin Reservoir will not be acceptable as a public water supply. Our conclusion, therefore, is to regard the no-diversion alternative as unrealistic unless other alternatives, outside the scope of the present project, offer better solutions to the projected Boston metropolitan water supply problem.

E. Delays in Diversion

Related to the no-diversion alternative is the concept of delays in diverting the proposed riverine sources. Again, we cannot set a critical time limit, after which diversion of riverine waters might pose a higher risk to the maintenance of a good water supply. Several seasons with good inflow into Quabbin Reservoir, such as with the current situation in the spring of 1972, would displace the curve "existing system" of Figure 53 to the right. Another drought period would shift it to the left. Assuming again, as we did earlier, that the supply and demand

remains as projected, about half of the current volume of Quabbin Reservoir will remain by the end of this decade. As a first approximation, we are guessing that the relative decrease in water quality, the marked decrease in diluting volume, the reductions in retention time and the reductions in treatment capacity will increase the risks of diversion if diversion is delayed by four years to 1980. If on the other hand the water quality of Quabbin Reservoir decreases faster than we believe during this period of delayed diversion and if the Connecticut River waters improve faster than projected through abatement procedures, we could indeed be faced with a reversed situation, in which the riverine waters are of a higher quality than those of the then-existing reservoir. Irrespective of the exact year, at some point in time, riverine waters will actually be of a higher quality than the reservoir. Under these conditions, it is impossible to predict the final water quality after diversion and retention of Connecticut River water in the then-existing reservoir. We can predict, however, that the maintenance of a good water supply will be greatly impaired following significant delays in the proposed diversions.

9. SUMMARY

This study was a cooperative effort of several organizations to generate and evaluate extensive data on the Quabbin and Wachusett Reservoirs and the Connecticut and Millers Rivers systems, with the objective of making predictions on the impacts of diverting portions of these riverine systems into Quabbin Reservoir.

Field and laboratory data included approximately 100 parameters, including chemical, physical, biological, and pesticides data. In addition, radiological data, hydrodynamic studies, fisheries information, and pollution abatement plans were considered and evaluated. Finally, other pertinent data available from both public and private sources, especially on the Connecticut River, were evaluated in the light of the objectives of this study.

Central to the evaluation was the development of a qualitative model of reservoir dynamics. Such events as evaporation, sedimentation, transformations, and direct transfer of materials from potential donor to receiver and finally to the distribution system were discussed. Any predictions on water quality as a result of diversions were qualified by our present knowledge of the underlying dynamics.

Dilution of riverine waters by ambient reservoir volume alone will probably not be sufficient to insure an acceptable water quality in Quabbin Reservoir. Fallout of suspended materials and the "treatment plant" capacity of Quabbin Reservoir are expected to result in an acceptable water quality.

A general summary of the impacts of the proposed diversions on Quabbin

Reservoir is shown in Table 29. The potential magnitude of a given impact upon Quabbin Reservoir is generally higher with the proposed Connecticut River diversion than with the proposed Tully River system diversion. Predictions on the temporal aspects of any impacts cannot be made at this time.

As a convenience in making evaluations of the probable impacts of the proposed diversions, the period 1972-2000 was divided into four phases. Phase I (1972-1976) is the period before diversion of the Connecticut River. The volume of Quabbin Reservoir will decline during this period. Phase II (1976-1980) represents the period for the beginning of the Connecticut River diversion; the Tully River diversion is not yet operative. The reservoir volume will increase during this period. The period 1980-1989 (Phase III) represents a period when both diversions are operative, and the reservoir volume continues to increase. During the final phase (Phase IV, 1989-2000) both diversions continue to be operative but reservoir volume declines. Probable, major long-term trends in Quabbin Reservoir for this overall period are summarized in Table 30.

The greatest potential for both ecological and public health impacts on Quabbin Reservoir is seen to exist with Phase II. Because of declining reservoir volumes, Phases I and IV will show some deterioration of the reservoir.

Impacts of the proposed diversions on the two donor systems will differ. We expect no significant changes in the hydrology, water quality or general ecology of the mainstem Connecticut River. Temporary storage of Connecticut River water in the upper reservoir of the Northfield pumped storage facility may

Table 29. Summary of Probable Impacts of the Proposed Diversions on Quabbin Reservoir

Note: This summary does not predict the duration of the impact.

Description of Impact	Relative Probability Impact Will Occur			
	No significant change over existing conditions	Possible but Probability Low	Probable	Probability High
Increase in Nutrient Chemicals		T	C	
Increase in Eutrophication		T	C	
Modification of Present Equilibration			C T	
Introduction of Undesirable Species		T		C
Increase in Coliform Bacteria		T	C	
Increase in Human Pathogens		C T		
Interference with Water Treatment at Quabbin		T	C	
Increase in Levels of Toxic Materials	T	C		
Increase in Levels of Radioactivity	C T			
Increase in Levels of Pesticides	C T			
Increase in extent and magnitude of oxygen depletion		T	C	

C = Connecticut River Diversion T = Tully System Diversion

Table 30. Probable Major Long-Term Trends in Quabbin Reservoir

Phase	Trend
I (1972-1976)	Progressive deterioration of northern part of middle branch, and the eastern branch.
II (1976-1980)	Shift in ecological balance, especially middle branch. Water quality changes probable. Volume increase may actually retard some deterioration from Phase I. Potential public health hazard greater than Phase I.
III (1980-1989)	Probable improvement in water quality. Further reduction in deterioration in northern part of middle branch begun in Phase I. Potential public health hazard reduced over Phase II.
IV (1989-2000)	Progressive deterioration of entire reservoir.

cause some changes in water quality. However, the impacts of these changes after diversion to the receiver or return to the donor will probably be minor. In the Millers River system we envision probable changes in the hydrology, in general water quality and in the ecology. These changes will be a consequence of the diversion of relatively large volumes of higher quality water and the impoundment of waters. Because of the proposed cleaning up of the Millers River, changes in water quality in the mainstem Millers River will not be a long term impact. Changes associated with the impoundments will have both long term and short term impacts. There will be no significant public health impacts on the donor systems. Tables 31 and 32 summarize the probable impacts of the proposed diversions on the donor systems.

Realistic appraisal of a no-diversion alternative is also important for this project. Under average inflow conditions and projected demand, Quabbin Reservoir will be dry by 1985. At some time before this year, water quality will decrease, eutrophication will increase, and fish populations will change. Also at some point before total water depletion in 1985, the reservoir will not be an acceptable public water supply. As a related problem, the losses in volume and water quality of Quabbin water will increase the risks of diversion if a diversion is delayed by only a few years. We conclude that the no-diversion alternative is unrealistic unless other alternatives, outside the scope of the present project, offer better solutions to the projected Boston metropolitan water supply problem.

Table 31. Summary of Probable Impacts of the Proposed Diversions on the Connecticut River

	Relative Probability Impact will Occur			
Description of Impact	No significant change over existing conditions	Possible but Probability Low	Probable	Probability High
Significant Changes in Hydrology	X			
Loss of Groundwater Recharge	X			
Changes in Bacterial Populations	X			
Changes in Benthic Organisms	X			
Changes in Fish Populations	X			
Significant changes in Water Quality	X			

TABLE 32. Summary of Probable Impacts of the Proposed Diversions on the Millers River System

	Relative Probability Impact Will Occur			
Description of Impact	No significant change over existing conditions	Possible but probability low	Probable	Probability High
Significant changes in Hydrology			M	I T
Changes in Ground-water Recharge		M (Decrease) T (Decrease)	I (Increase)	
Decrease in Pathogens (if present)		M T	I	
Changes in Heterotrophic Bacteria[1]		M T		I
Changes in Algal Populations[1]		M T		I (Increase in number and change in type)
Changes in Benthic Organisms[1]	T	M (short term)	I[2]	
Changes in Native Fish Populations[1]	M T		I[2]	
Decrease in Water Quality		T	I (short M term)	I (Long term[2])

I = Impoundments on tributaries
T = Tributaries below diversion point
M = Mainstem of Millers River

[1] Specific quantitative changes impossible to predict, except where noted

[2] Refers primarily to Tarbell Brook and West Branch of Tully River

10. RECOMMENDATIONS

In a recent letter to the editor of Science, Alvin M. Weinberg (1971) of Oak Ridge National Laboratory, states that scientists "must admit that some questions, including the most important ones raised by concern for the environment, are really trans-scientific, not scientific". Disagreements among scientists concerned with environmental impacts of human actions are usually over these trans-scientific, not scientific, questions, and are therefore not resolvable by science. The basis of such disagreements is usually the question of the validity of the extrapolation of data collected in one set of circumstances to other and different situations.

We believe that the diversion of freshet flows as a means of supplementing dwindling public water supplies is destined to increase in importance in this country, and that disagreements among scientists as to just what the impacts of these diversions will be also will increase. Furthermore, such disagreements will increase in direct proportion to the degree that the issue of freshet flow diversions remains in the trans-scientific domain. Should the frequency of these disagreements continue to increase, the value of science and scientists to those responsible for making decisions of public import will necessarily diminish. This would be inconsistent with the intent of the National Environmental Policy Act of 1969 and other major legislation concerned with environmental quality.

Perhaps the most direct way of insuring that the question of the environmental impact of diversion will become more firmly based on scientific facts as opposed to trans-scientific rhetoric is to work toward the construction of quantitative models

which can take the place of such qualitative models as contained within this report.

The following recommendations are, therefore, predicated by the view that the current studies were only a first attempt to come to grips with the question of impact of the proposed diversions on Quabbin and Wachusett Reservoirs. They are, in short, recommendations for future research which we think is necessary for the realization of a more complete scientific understanding of data already collected, and to improve the model.

(1) Initiate diurnal studies at Quabbin Reservoir. Parameters measured should provide rates of turnover of important algal nutrients, and provide additional information on ecological relationships which may govern those rates.

(2) Initiate algal potential growth studies using water samples taken from both donor and receiver systems. These studies should yield further information on limiting algal nutrients in these waters and on maximum concentrations of algal species which might be expected under given nutrient conditions.

(3) Initiate studies of the nutritional significance of heterotrophic bacteria in both donor and receiver systems. These studies should provide further information on the rates of nutrient turnover in Quabbin Reservoir, before and after diversion, which may be primarily influenced by the capacity of these organisms to degrade organic material.

(4) Initiate studies on the diagenesis of the eastern arm of Quabbin, including analyses of the remains of organisms deposited in the sediment, in an attempt to define "fallout" rates and other changes in water quality in Quabbin which may be associated with the present diversion of Ware River waters.

(5) Initiate chemical analyses of mud samples from Quabbin in order to measure the nutrient potential of the reservoir and to gain some insight into chemical and biological processes occurring at the mud-water interface.

(6) Continue studies on current physical model of Quabbin which will include the conditions of winds and thermal stratification.

(7) Continue a general monitoring program on both the receiver and donor systems so that the development of quantitative models will be continually up-to-date. This is especially true for waters of the Connecticut River and the northern part of Quabbin Reservoir, and the Northfield Mountain Impoundment.

(8) Conduct settling studies on waters collected from both donor and receiver systems in an attempt to define the rate of "fallout" of suspended materials in Quabbin Reservoir after diversion and under different circumstances of diversion.

(9) Computerize all data generated and considered in this report so that cross correlations of these data and other national data may be more precisely examined.

(10) Consider any other studies which might increase an understanding of all dynamic processes in the reservoir, and which are aimed specifically at increasing the predictive capability of the model.

These and other recommendations for future research have been discussed with both the MDC and Corps of Engineers, and are under active consideration. Priorities for each of these recommendations will be decided in conference with these agencies.

APPENDICES

APPENDIX I

METHODS FOR FIELD AND LABORATORY STUDIES

A. Field Methods

(1) Collection of Surface Waters

Surface waters refers to water obtained from about the first one-half meter in depth. For most surface "grab samples", no special device was used. The appropriate container was held underwater by hand at the desired depth. Glass Winkler bottles were used to collect samples for dissolved oxygen analyses. Glass jugs with teflon-lined caps were used to collect water for pesticide analyses. Polyethylene bottles and jugs of various sizes were used for the collection of waters for other analyses. The usual care to avoid bubbling of air was exercised in the collection of water for dissolved oxygen tests. Manganese sulfate and alkali-iodide-azide reagents were added to the dissolved oxygen bottles in the field.

(2) Depth Sampling Techniques

Depth sampling techniques were necessary for collecting water at depths greater than one-half meter, or for sampling from bridges, embankments or in other instances where the hand was not immersed into the water. A Van Dorn sampler was used to obtain water samples for all analytical tests except for pesticides or bacteriological samples. A prototype harness and weight assembly was built to house the jugs for collecting deeper waters for pesticide analyses.

(3) Collection of Waters for Bacteriological Tests

Unlike the collection for other analyses, collection of water for bacteriological analyses was carried out with sterile, evacuated bottles using a J-Z sampler. Use of the J-Z sampler equipped with a messenger will permit the sampling of both surface and deeper waters.

(4) Collection of Zooplankton

Zooplankton were collected with a Wisconsin plankton net equipped with a number 20 mesh net. The removable bucket of the plankton net was equipped with number 25 mesh. At all deep stations the net was lowered about 10 meters and then pulled straight up at approximately 1 meter per second. The 12-cm diameter and 10-meter high water column resulted in a plankton haul of about 113 liters of water. For surface waters of reservoirs and rivers, a plastic bucket filled to a measured 12-liter mark was used. Five buckets were poured into the Wisconsin net for a total volume of 60 liters. After the water was passed through the net, the bucket was removed and the contents carefully rinsed into a glass jar. Except for the infrequent cases when formalin was added in the field, all plankton samples were returned to the lab alive. If the samples were not counted within the next day and a half, they were preserved in formalin. Final concentration for all preserved specimens was 5% formalin.

Various difficulties were encountered. During winter operations, freezing of the net produced obvious problems. At some Millers River stations

waters polluted with pulp and debris would clog the mesh of the plankton net bucket. Finally, because no meter device is used, the actual volume of water passing through the net during vertical hauls is unknown and probably less than the theoretical volume.

(5) Collection of Benthic Organisms

Whenever possible the Ekman Bottom Sampler or a Peterson Dredge was used to collect bottom samples. The heavy Peterson Dredge was usually operated from a boat crane, but the Ekman Sampler was operated either from shore or a boat, depending upon the station. Many of the locations, especially the riverine stations, had rocky bottoms so that the Ekman Sampler or Peterson Dredge could not be used. In those instances, a Surber Sampler, or most often, a shovel and D-net were used to collect benthics. Care was exercised to obtain quantitative and representative samples. Finally, when none of these measures was possible, large rocks were collected and placed in buckets of water, to be later scraped and analyzed for benthic organisms. Our experience agrees with Hynes (1971) who reviews the evidence and states that all methods of collecting stream benthics are biased in favor of some animals and less for others, and that there is no single satisfactory method.

(6) General Procedures

All water samples were usually placed in large, plastic, insulated containers with ice to keep them cool while in transit to the laboratory

for analysis. During the winter months the samples were packed in snow to prevent them from freezing.

In the winter, holes were cut through the ice surface with a combination of auger, saw, and chipper. The size of the hole depended upon what parameters the water was being sampled for, and which instruments had to be lowered through the hole in the ice.

Each container (plastic bottle, glass jar, bucket) had a number which was entered on an appropriate field control sheet. Field control sheets contained all pertinent information, including station codes, date and container numbers. Each analyst, whether in-house or at a subcontractor, received a receipt form with the sample code numbers and date only at the time of sample delivery.

B. Laboratory Methods

(1) Physical Chemical Tests of Water

After the water was delivered to the laboratory, the following parameters were measured, usually in the sequence listed:

Odor. No quantitative procedure was used. Freshly collected water was used. Freshly collected water was allowed to come to room temperature, and any odor present was judged qualitatively as suggested in Standard Methods (APHA, 1965).

Dissolved Oxygen. The standard Winkler method of titration was used. All reagents were checked at appropriate intervals, and when not in use were stored in a refrigerator.

pH. A Beckman pH meter previously standardized with a standard buffer solution was used for making pH measurements. Samples were placed in 100-ml beakers and allowed to stand at room temperature. A magnetic stirrer was used to stir the sample, and the pH was recorded after the reading had stabilized.

Turbidity. Originally a B & L Spectronic 20 spectrophotometer was used. A table based on a formazin standard was used to obtain the turbidity in Jackson Units (Hach Chemical Company, 1969). Later, a Hach Turbidimeter (Model 860A) which is a true nephelometer was used and the turbidity readings were generally lower. This instrument has its own calibrating rod using formazin as a turbidity standard, and it can be read directly in Jackson Units.

Specific Conductance. Specific conductance was obtained with a Conductivity Bridge Meter (RC-16B2). Unfiltered water was read directly for conductance and the temperature was recorded. Values were then converted and expressed in µmhos/cm @ 25°C.

Color. Unfiltered water was placed in Nessler tubes and compared with matched Nessler tubes filled with chloroplatinate color standards (Standard Methods, APHA, 1971). If the water was too turbid, the water sample was centrifuged before testing against the color standards.

(2) Other Chemical Tests for Water

The parameters described in this section were carried out by standard colorimetric methods or atomic absorption spectroscopy using a Perkin-

Elmer 403 atomic absorption spectrometer. All analyses involving titration were done in Class A burets. All water used in the analyses was purified by passing tapwater through an activated carbon filter, two mixed-bed deionizing columns in series and finally, a 0.22 μ particle filter. The water thus obtained consistently had a resistance of 10 megohms or more.

Alkalinity. A 100-ml sample was titrated with 0.0200 NH_2SO_4 using Brom Cresol Green - Methyl Red indicator; the endpoint was taken at the gray intermediate color of the indicator. Results were reported as μg $CaCO_3$/ml (ppm).

Carbon Chloroform Extract. The method used was a modification of that given in Standard Methods; the changes were in size of equipment and volume of sample tested. A sample (usually 4 liters) was passed through activated charcoal, washed, and the charcoal extracted with chloroform. The chloroform was evaporated in weighed dishes and the residue weighed to the nearest 0.1 mg. The results were reported in μg residue/ml (ppm).

Chemical Oxygen Demand. COD was determined using the method given in the FWPCA Methods (1969). Organic and oxidizable inorganic substances were oxidized by potassium dichromate in 50% H_2SO_4. The excess dichromate was titrated with standard ferrous sulfate using ferroin indicator. The results were reported as μg O/ml (ppm).

Hardness. Because of the inherent difficulties associated with the complexometric titrations of hardness, this parameter was obtained by combining the Ca and Mg levels determined by atomic absorption spectroscopy.

The Ca and Mg were converted to $CaCO_3$ and reported as such, i.e., Hardness (μg $CaCO_3$/ml, ppm) = (ppm Ca x 2.5) + (ppm Mg x 4.1).

MBAS. Methylene Blue Active Substances, i.e., detergents, were determined by extraction of the anionic detergents into toluene with buffered methyl green (methyl green is more reliable than methylene blue). The intensity of the blue color developed in the presence of detergents was read spectrophotometrically. The results were reported as μg Alkyl Benzene Sulfonate/ml (ppm).

Metals and Other Elements. The metals listed below were all determined by atomic absorption spectroscopy using an automated Perkin-Elmer 403 spectrometer. The instrument settings and conditions used were those suggested by Perkin-Elmer in their instrument handbook; in some cases, minor modifications were used which increased the sensitivity and/or precision. All sample runs were preceded by standard samples which spanned the range of values found in the samples.

Aluminum	Lead
Arsenic	Manganese
Barium	Potassium
Boron	Selenium
Cadmium	Silicon
Cobalt	Silver
Copper	Sodium
Total Iron	Uranyl ion
	Zinc

Hexavalent Chromium. Hexavalent chromium, or chromate, was determined using the pink-colored dye formed when chromate reacts with 1,5-diphenylcarbohydrazide. The intensities were determined spectrophotomet-

rically. The results were reported as μg Cr(VI)/ml (ppm). Total Cr was also determined by atomic absorption.

Ferrous Iron. Iron (II) was determined as the o-phenanthroline complex colorimetrically. Reported as μg Fe/ml (ppm).

Ferric Iron. Obtained by subtracting ferrous iron from total iron.

Mercury. A 100-ml sample was treated with potassium permanganate to remove organic material, hydroxylamine to remove the excess potassium permanganate, and stannous chloride to reduce mercury to the element; mercury vapor was swept out of the solution with a stream of nitrogen and the mercury absorption measured using a Coleman mercury analyzer. The results were reported as μg Hg/ml (ppm).

Chloride. A 100-ml sample was titrated with 0.0141 N $Hg(NO_3)_2$ using diphenylcarbazone as the indicator. The endpoint was taken as the first permanent faint purple color. The results were reported as μg Cl/ml (ppm).

Cyanide. Cyanide (free) was determined colorimetrically using the pyridine-pyrazalone method given in Standard Methods. Results were reported as μg CN/ml (ppm).

Fluoride. Determined colorimetrically using the SPADNS method cited in Standard Methods. Initially the results were checked using a fluoride specific electrode. The results were reported as μg F/ml (ppm).

Sulfate. Sulfate sulfur was determined turbidimetrically as $BaSO_4$ upon the addition of barium chloride and a gelatin stabilizer. Turbid samples were filtered before analysis, and colored samples were measured against

pure water for correction. Results were reported as μg S/ml (ppm).

Ammonia Nitrogen. Ammonia was determined by direct Nesslerization; at first, tests were made to determine that the hardness levels encountered did not interfere with the direct analysis. Initially, samples were run on filtered and unfiltered water (0.45 μ filter). Since no difference was found between the two, it was assumed that all ammonia nitrogen was in solution and the filtration was discontinued. The results were reported as μg N/ml (ppm).

Nitrate Nitrogen. Nitrate was determined colorimetrically as the pink dye formed upon reduction of nitrate to nitrite which, in acid solution, couples via a diazotization process with 1-naphthylamine-sulfanilic acid. Both nitrate and nitrite in the sample are measured; nitrate is obtained by subtracting nitrite. The results were reported as μg N/ml (ppm). The filtered-unfiltered results were the same as those found for ammonia.

Nitrite Nitrogen. Performed as described for nitrate with the omission of the reduction step. Results were reported as μg N/ml (ppm).

Organic Nitrogen. Organic nitrogen was obtained by performing a total Kjeldahl nitrogen analysis; in this procedure, organic nitrogen is converted to ammonia, and determined as outlined above. The resulting value is the sum of ammonia due to free (dissolved) ammonia nitrogen and organic nitrogen. The values cited are those obtained by subtracting the value of ammonia nitrogen from the total. The method used was that given in the FWPCA methods (1969). Results were reported as μg N/ml

(ppm).

Total Phosphorus. The sample was digested (boiled) with H_2SO_4 and $HgSO_4$ to convert all phosphorus to orthophosphate. The orthophosphate thus formed was determined colorimetrically by the method given in the FWPCA manual (1969). The results were reported as µg P/ml (ppm).

Orthophosphate. Determined using the method cited above on an undigested sample. Results reported as µg P/ml (ppm).

Polyphosphate. Determined by digestion as described above with the omission of the $HgSO_4$. This converts all polyphosphates to orthophosphate; the polyphosphate level is obtained by subtracting the orthophosphate value from the value obtained here. Results were reported as µg P/ml (ppm).

Organic Phosphorus. Organic phosphorus was obtained by subtracting orthophosphate and polyphosphate from the total phosphorus. Results were reported as µg P/ml (ppm). Phosphorus analyses were performed on filtered and unfiltered samples to give a measure of the dissolved and particulate levels.

(3) Pesticide and Phenol Analyses

(a) Sample Handling

Coded samples were collected in one-gallon amber glass jugs with plastic screw caps. The sample bottles were thoroughly precleaned using the following sequence: detergent wash, rinse, chromic acid wash, rinse with tap water, distilled water, redistilled acetone

and pesticide quality hexane. The caps were lined with Saran or Teflon. Each sample consisted of 2 gallons. Upon receipt they were placed in a walk-in cold room at $4^{o}C$ in the dark.

(b) Sample Analyses

In order to test for all the required parameters, each water sample was subjected to five different analytical procedures. The following classes of compounds were determined by these methods:

Total phenols
Chlorinated hydrocarbon insecticides
Organic phosphate insecticides
Carbamates (Carbaryl)
Herbicides

A one-liter portion was withdrawn from each water sample for determination of total phenols by the 4-aminoantipyrine colorimetric method as described in Standard Methods (APHA, 1965). One sample from each day's collection was steam distilled prior to analysis in order to achieve greater sensitivity. The others were extracted and analyzed directly by a simplified aminoantipyrine method. In this way all samples collected on a given day could be analyzed during the same day as specified for phenolic compounds in water.

Solvent extracts of the water samples were prepared for the analysis of pesticides. A 2-liter aliquot of sample water was extracted with two 60-ml portions of 15% ethyl ether in hexane followed by a third extraction with 60 ml of hexane alone after addition of 70 ml of sodium sulfate-saturated water to the sample. The combined

extracts were dried over anhydrous sodium sulfate and concentrated to a final volume of 1 to 2 ml. These procedures for sample preparation were similar to those found in the EPA Manual (1971). This concentrated extract was used for the determination of chlorinated hydrocarbons by gas liquid chromatography (GLC) with electron capture (EC) detection, soluble organic phosphates by GLC with alkali flame ionization detection (AFID), and carbaryl by photofluorometry. For the herbicidal acids (2,4-D, 2,4,5-T, and 2,4,5-TP) a fresh one-liter aliquot of water sample was extracted with ethyl ether.

The gas chromatographic parameters used were as follows:

Instrument - Varian Aerograph Model 1400, equipped with interchangeable tritium-source electron capture detector and alkali flame ionization detector.

Column - Coiled glass (6 ft. x 2 mm ID) packed with 1.5% OV-17/1. 95% QF-1 on Supelcoport 100/120 mesh.

Carrier gas- Prepurified N_2, 40 ml/min, 45 psi

Temperature- Inlet, 225°; column, 200°; detector, 220°

Although the standard references and many other references were consulted for guidelines in optimizing gas chromatographic conditions for the pesticides of interest in this study, the information reported by Thompson, et al. (1969) and Leoni and Puccetti (1969) were the most useful. Under these conditions, with the EC detector, it was possible to separate and detect all of the required organochlorine insecticides (aldrin, chlordane, DDT, dieldrin, endrin, heptachlor, hepta-

chlorepoxide, lindane, methoxychlor, and toxaphene). Organophosphates would also be detected with the EC detector if they were present in the same sample concentrates but the specificity would be limited. To check for the presence of phosphorus-containing compounds each sample was rechromatographed after replacement of the EC detector with the AFID which is specifically sensitive to phosphorus. Appropriate standards were used as controls for the analytical procedures.

A procedure was not available for total pesticidal carbamates. The most widely used substance in this class is probably carbaryl (Sevin); thus a fluorimetric method that would measure carbaryl and its product of hydrolysis (1-naphthol) was used (Argauer et al., 1970). Appropriate aliquots from the same sample concentrates that were used for gas chromatography (above) were extracted with 0.25 N sodium hydroxide and the fluorescence compared with standards in an Aminco-Bowman Spectrophotofluorimeter set at excitation and emission wavelengths of 335 nm and 465 nm, respectively.

Finally, the herbicides were determined by EC-GLC after esterification with chloro-ethanol as described by Woodham et al. (1971). This involved extraction of an acidified water sample with diethyl ether, reextraction of the ether solution with 0.5 N sodium hydroxide, reextraction of the acidified aqueous phase again with ether, and finally reaction of the ether extract residue with borontrichloride-

chloro-ethanol reagent to form the chloroethyl ester derivatives of the phenoxy acids.

(4) Analyses of Algae (Phytoplankton)

All samples were usually processed within 12 hours after collection. Occasionally, samples were preserved by adding formalin (final conc. 5%). Samples were shaken to evenly distribute the phytoplankton, and subsequently each sample was processed by the continuous centrifuge technique (Standard Methods, APHA, 1965). Concentrated samples were examined in a Sedgwick-Rafter counting cell with the aid of a calibrated microscope. Both total and differential counts were done, and all values were converted to numbers of organisms contained in one liter of the original sample.

(5) Bacteriological Tests

All samples were processed within 12 hours after collection. Analyses were carried out by means of the membrane filter technique (Standard Methods, APHA, 1971) using Millipore filters with a pore size of 0.45 μ. Three aliquots of appropriate volumes from each water sample were processed in duplicate for each of the three media used. After filtration, filters were placed in petri dishes on sterile pads saturated with the appropriate medium. Standard media, incubation temperatures, and counting procedures were used for the analyses of fecal coliform and total coliform bacteria (Standard Methods, APHA, 1971). Total heterotrophic bacteria were incubated at 20°C on pads saturated with Difco m-Plate Count Broth. Daily

counts of heterotrophic bacteria were made for nine days. After 9 days plates were refrigerated at 8° C for one day, and a final count was made. In addition to total counts, differential counts of chromogenic and non-chromogenic heterotrophic bacteria were made for each of the 10 days. The highest total count in this 10-day period was used to calculate the number of heterotrophic bacteria in 100 ml of the original water sample. The highest chromogenic count in this period was used to calculate the percent of the total heterotrophic bacteria in the original sample that was pigmented.

(6) Analysis of Zooplankton

The jars containing zooplankton were turned upside down twice for mixing. A medicine dropper was used to remove a portion of sample to a Sedgwick-Rafter counting cell. The cell was placed on a piece of paper ruled into 10 sections, and it was viewed with an overhead light with 50x magnification under a stereoscope. Total and differential counts were made, and after appropriate calculations, values were eventually converted to number of organisms per liter of water. The keys in Ward and Whipple, Freshwater Biology 2nd edition (Edmondson, 1959) were used for identification.

(7) Analysis of Benthic Organisms

(a) Initial Sampling in the Field

When time and weather permitted, some benthic samples were

processed in the field. For stony and rocky samples, the organisms were scraped off and the stones were discarded. For gravel or sandy samples, the samples were rinsed with water, the sand stirred by hand and the supernatant poured through a U.S. Standard No. 30 copper sieve to concentrate the organisms. Usually the samples were split in half, each half being rinsed about 10 times. The organisms were washed off the sieve by backpouring into a plastic bucket.

(b) Processing in the Laboratory

Initial processing was carried out as described above if not already done in the field. Most of the mud collected by the Ekman Sampler could be washed through the No. 30 mesh by rocking and submerging in a pail of water. After sieving, the remainder was backwashed into white enamel or plastic pans in a shallow layer of water. Debris was sorted out and organisms were lifted out with tweezers and placed in small petri dishes. They were then identified into major groups and counted with the aid of a stereoscope. Where possible, the organisms were expressed in number per unit area of substrate. The keys in Edmondson (1959) were used for identification.

APPENDIX 2

SUMMARY OF PERTINENT HYDROLOGICAL DATA*

1. Quabbin Reservoir

Area, June 1971	19,200 acres
Volume, January 1971	226×10^9 gallons
June 1971	253×10^9 gallons
December 1971	212×10^9 gallons
Projected Annual Input, 1971	
a) Swift River, East Branch	15.7×10^9 gallons
Swift River, Middle Branch	3.9×10^9 gallons
Swift River, West Branch	8.15×10^9 gallons
b) Ware River Diversion	10.68×10^9 gallons
c) Other Inputs**	49.12×10^9 gallons
TOTAL	87.55×10^9 gallons
Projected Annual Losses, 1971	
a) Diversion to Wachusett	76×10^9 gallons
b) Chicopee Outlet	5.14×10^9 gallons
c) Surface Losses	11.5×10^9 gallons
d) Other Losses***	10.95×10^9 gallons
TOTAL	103.59×10^9 gallons

*These data were supplied by the Metropolitan District Commission and the U. S. Army Corps of Engineers and were verified by them to be adequate assumptions for this report.

**Direct precipitation on reservoir surface and inflow from watersheds other than the Three Swift River Branches.

***Includes deep seepage and loss to bank storage.

2. Wachusett Reservoir

Area, June 1971	3,570 acres
Volume, January 1971	52.6×10^9 gallons
June 1971	49.7×10^9 gallons
December 1971	46.3×10^9 gallons
Projected Annual Input, 1971	
a) Diversion from Quabbin	76.0×10^9 gallons
b) Other Inputs*	48.0×10^9 gallons
Specific dates of operation of diversion from Quabbin	Jan 1-5; Jan 11-Feb 5; Feb 10-17; Feb 22-27; June 22-30
Projected Annual Losses, 1971	
a) Water Supply to Boston	104.2×10^9 gallons
b) Other Losses**	5.41×10^9 gallons

3. Average Daily Flow Rates, Quabbin Inputs for Period Mar-June 1971

a) Ware River Diversion	118.91 MGD
b) Swift River, East Branch	91.70 MGD
Swift River, Middle Branch	22.74 MGD
Swift River, West Branch	48.69 MGD
c) Other Inputs*	164.63 MGD
TOTAL	446.67 MGD

*Direct precipitation and inflow from surrounding watershed lands.

**Evaporation and deep seepage.

4. Connecticut River (at Montague City)

Average Daily Flow Rates, 1971

January	4,975 MGD
February	5,802 MGD
March	7,782 MGD
April	25,242 MGD
May	24,253 MGD
June	4,057 MGD

Specific dates proposed diversion would have been possible during Jan - June 1971:

Theoretical (T): March 18, 20, 21; May 27, 28

Most Probable (MP): April 3 - May 25

Average daily flow rate during this period	T: 25,147 MGD MP: 26,408 MGD
Percentage of Connecticut River flow volume ending up in Quabbin during this period	T: 1.491 % MP: 1.420 %
Total Volume added to Quabbin during this period	T: 21.75×10^9 gallons MP: 19.88×10^9 gallons

5. Ware River

Average Daily Flow Rates, 1971

January	39.13 MGD
February	58.16 MGD
March	129.30 MGD
April	286.86 MGD

May	141.48 MGD
June	49.45 MGD

Specific dates of Ware River diversion during this period:

Feb 18; Feb 28 - Mar 10; Mar 16 - May 28

Average daily flow rates during this period	192.85 MGD
Percentage of Ware River volume ending up in Quabbin during this period	55.92%
Total Volume added to Quabbin during this period	9.447×10^9 gallons

6. Millers River System

Average Daily Flow Rates, 1971 in MGD

Station	January	February	March	April	May	June
2	13.15	17.01	28.75	96.60	43.38	7.12
3	8.98	12.56	25.75	77.64	33.47	5.53
4		242.47	240.61	640.61	339.21	92.16
5		259.20	257.21	684.81	362.62	98.52
6 & 7	22.09	29.71	64.75	145.48	75.83	13.77
8	8.84	11.88	25.90	58.19	30.33	5.47
9	267.45	415.46	474.89	994.07	500.84	134.15
10	323.79	502.98	574.93	1203.48	606.35	162.19

The following figures apply to the final proposed diversion aqueduct from the Tully System to Quabbin:

Specific dates proposed diversion would have been possible during Jan-June 1971:

March 18, 20, 21; April 3 - May 23
(Total 54 days)

Average daily flow rate during this period	334 MGD
Percentage of Tully System flow volume ending up in Quabbin during this period	67.1 %
Total volume added to Quabbin during this proposed diversion period	12.097×10^9 gallons

APPENDIX 3

MINUTES OF MEETING OF SEPTEMBER 16, 1971

Background Information

Mr. Everett L. Maynard of the Division of Water Hygiene, Environmental Protection Agency (EPA), now on assignment to the Corps of Engineers, made a trip on May 19-21, 1971 to Cincinnati, Ohio to discuss the proposed diversion of the Connecticut River into Quabbin Reservoir with Dr. James Symons of the EPA. A Trip Report was received by NER on July 7, 1971. The implications of the report were considered important enough for a separate meeting. Therefore, NER drew up a series of questions and forwarded them to the MDC and the Corps of Engineers. Subsequently, a meeting was held on September 16, 1971 to discuss these questions.

Appendix 3 includes the agenda for that meeting, entitled "Suggested Sequence for Discussion", a copy of the minutes of the meeting, held on September 16, 1971, and finally a verbatim copy of the Trip Report of Dr. Symons.

Suggested Sequence for Discussion

1. Point of discharge of Connecticut River water into Quabbin

2. Hazards of discharging Connecticut River water into western arm of Quabbin

3. Tully River complex and Millers River diversion into Quabbin

4. Problems associated with diversion of Connecticut River waters into Quabbin

5. Nitrate and phosphate

6. Significance of stratification in Quabbin

7. Treatment of Connecticut River water

8. Treatment of Connecticut River water and bypass of Quabbin to Wachusett

Minutes of Meeting
September 16, 1971

Place of Meeting: Army Corps of Engineers, New England Division
Waltham, Massachusetts

Purpose of Meeting: To discuss contents of the trip report of Everett Maynard's visit with Dr. James Symons to discuss the proposed diversion of a portion of the Connecticut River into Quabbin Reservoir.

Persons in Attendance:

James Symons	Environmental Protection Agency Division of Water Hygiene
Everett Maynard	Environmental Protection Agency Division of Water Hygiene
Floyd Taylor	Environmental Protection Agency Division of Water Hygiene
George Camougis	New England Research, Inc.
Paul Erickson	New England Research, Inc.
Warren Zepp	New England Research, Inc.
O. T. Zajicek	University of Massachusetts
Joseph Ignazio	Army Corps of Engineers New England Division
Lawrence Bergen	Army Corps of Engineers New England Division
Paul Pronovost	Army Corps of Engineers New England Division
Martin Cosgrove	Metropolitan District Commission Construction Division

Thomas Baron	Metropolitan District Commission Construction Division
Leonard Fenocketti	Metropolitan District Commission Construction Division
Harold Willey	Metropolitan District Commission Construction Division
John Copithorne	Metropolitan District Commission Water Division
William Tompson	Metropolitan District Commission Water Division
Edward Tyler	Metropolitan District Commission Water Division

In his introductory remarks, Dr. Camougis suggested an agenda for the meeting which was accepted by all present. The following items refer to the items of that agenda:

Item 1. Point of discharge of Connecticut River water into Quabbin

Dr. Symons felt that it was best to be conservative and to be prepared for the worst possible case with regard to the Connecticut River diversion. The "Y" proposal offers the most flexibility. He said that there was always reason, if only on the basis of experience with other systems, to be concerned about short-circuiting in water supplies. Dr. Symons felt that the model studies should therefore be continued with simulations of wind and thermal stratification.

The MDC stated that provisions would be made in the proposed aquaduct to allow for the future addition of a diversion into the western arm if needed. The MDC agreed that more model studies were desirable.

Present standards for turbidity and impending new standards were mentioned. Turbidity requirements will be raised from 5 J.T.U. to 1 J.T.U. for potable water. Since this requirement must be met at the tap, and since there may be deterioration of water quality during delivery, reservoirs must produce water that is better than 1 J.T.U. Shaft No. 12 produces about 0.5 J.T.U. at present, but there was some speculation that the diversion of Connecticut River water could raise the turbidity in Quabbin Reservoir beyond permissible limits. There was a further discussion and concern over turbidity measurements. It was agreed that apparent discrepancies in measurements of turbidity constitute a complex methodological problem and should be examined.

Item 2. Hazards of discharging Connecticut River water into western arm of Quabbin

If Connecticut River water were discharged only into the western arm of Quabbin Reservoir, Dr. Symons felt that there would be few problems since a large dilution factor was involved. If water quality deteriorated at the Chicopee outlet, Dr. Symons felt that the outlet could be moved up to Shaft No. 12, which would allow for greater dilution.

The MDC did not agree with Dr. Symons that the Chicopee outlet could be easily moved. There were questions about the cost, but the MDC felt that the most prohibitive factor would probably be head problems associated with a longer pipeline.

The MDC also pointed out that the Chicipee outlet would run continuously during the Connecticut River discharge and they were concerned that the Chicopee

outlet would get direct draw of Connecticut River water if the diversion were in the western arm. The MDC also explained that Shaft No. 12 physically could not operate while the Ware River was being diverted, and that the proposed diversion dates for the Connecticut River are almost identical to those for the Ware River. Therefore, Shaft No. 12 would not be operating during discharge, thus minimizing any possible direct draw of diverted waters into Wachusett Reservoir.

The dilution figures for Quabbin Reservoir were explained. The western arm diversion would give a large dilution factor with respect to Shaft No. 12 since about 2/3 of the water volume in the reservoir is below an east-west line drawn through Shaft No. 12. A diversion into the middle arm would be diluted by only 1/3 of the reservoir under ideal conditions. If the Chicopee outlet is considered, the western arm diversion gives poor dilution at the Chicopee outlet since only 1/4 of the reservoir is available for dilution.

Dr. Symons at this point indicated that he preferred a split diversion to utilize the maximum possible amount of the hypolimnion volume to minimize depletion of the dissolved oxygen due to increased organic loads.

Dr. Zajicek did not foresee a problem with organic loading and depletion of dissolved oxygen since COD values for Connecticut River water, during freshet flow and Quabbin Reservoir water were similar. Values cited were:

10-15 ppm in the Connecticut River during freshet flow
5-10 ppm in northern Quabbin
about 5 ppm at Shaft No. 12

At this point, Mr. Maynard pointed out that Connecticut River COD values can be much higher than those given by Dr. Zajicek, and that those higher numbers posed

a real problem from diversion. It was recognized that the Connecticut River is extremely variable and the present data may not reflect the potential problem of diversion.

Dr. Symons asked for clarification of the degree of pollution in the Connecticut River. He had formed the impression that it was much worse than Quabbin Reservoir, but if data indicated that the Connecticut River was not that bad, Dr. Symons said that he was perhaps being an alarmist when he answered the various questions reported in the original trip report.

Item 3. Tully River complex and Millers River diversion into Quabbin

Dr. Symons felt that he was probably not accurate when he answered the question about the Tully and Millers systems. There were some communication problems and confusion about the relative descriptions of the Tully River complex and the Millers River. It was agreed that the Millers River was of poor quality. There was little further discussion on the Millers and Tully River systems.

Item 4. Problems associated with diversion of Connecticut River waters into Quabbin

All groups involved expressed concern over the possibility of short-circuiting, and although the diversion schedule and hydrodynamic studies may attenuate this concern, they cannot eliminate it.

Dr. Symons felt that the model studies did not eliminate the possiblity of short-circuiting if only because stratified waters were not considered, and stratified waters can have strange flow patterns. If short-circuiting were put in perspective, Dr. Symons felt that one or two unacceptable values during a year

would not bring legal action, so a diversion system would not have to be designed to accommodate the worst storm in a 100-year period. Furthermore, if a water treatment plant were placed below the Wachusett Reservoir, standards now applied to Quabbin waters could probably be relaxed. The people who spend the money would have to decide the size risk the consumers would take.

The MDC felt that short-circuiting of wind-driven water is minimized at all but the highest reservoir levels by glacial deposits in the northwestern area of the middle branch. A permanent baffle dam system was suggested as a possibility by Dr. Symons to maintain this pattern of flow at high reservoir levels.

Mr. Maynard expressed a concern over keeping diverted waters in the eastern reservoir where potential eutrophication problems could cause this area to become a "creeping cancer". Maynard preferred to dilute and mix the diverted waters within the entire reservoir.

Should diverted waters require treatment, Dr. Symons would prefer to treat them within an artificial area rather than in the reservoir itself, since more control is possible in an artificial area.

The MDC discussed a proposal for a prereservoir to monitor water quality. Poor quality water could be dumped into a tributary of the Millers River and be returned to the Connecticut River. Dr. Symons would prefer the prereservoir to damming the upper Quabbin Reservoir to form a separate basin.

Item 5. Nitrate and phosphate

The potential nutrient problem worried Dr. Symons and he recommended mixing

and algal growth potential studies in the laboratory to determine limiting nutrients and growth potentials.

Item 6. Significance of stratification in Quabbin

Stratification was considered reasonably covered during previous discussion.

Item 7. Treatment of Connecticut River water

Dr. Symons clarified the term "complete treatment" by explaining that it would be the treatment necessary to upgrade Connecticut River water to meet Public Health standards for potable water. If properly mixed with Quabbin Reservoir water, Connecticut River water may be acceptable with no treatment.

If Connecticut River water were treated before entrance into Quabbin Reservoir, possibly only coagulation and settling to remove turbidity would be necessary. Turbidity removal must be done prior to disinfection with chlorine. Nutrient removal, if necessary, could be performed at this stage. Dr. Symons did not think disinfection of Connecticut River waters before entry into Quabbin Reservoir was worthwhile unless the reservoir were to be used for bathing purposes. Disinfection could be done elsewhere. However, the introduction of undesirable biological species (e.g. fish) raises another issue.

Dr. Symons felt that viruses would be no problem if the water were disinfected after turbidity was removed. If the water is clear (<1 J.T.U.) after leaving Wachusett Reservoir, all viruses will be destroyed by a contact time of 30 minutes with a free chlorine residual of 0.3 to 0.5 ppm. A well-operated filter plant at Wachusett Reservoir should deliver water at about 0.5 J.T.U.

Item 8. Treatment of Connecticut River water and bypass of Quabbin to Wachusett

A bypass to Wachusett Reservoir was considered impractical due to the large capital investment for a system that would be idle most of the time.

At this point the MDC asked for an estimate of the time that untreated Connecticut River water could be diverted into Quabbin Reservoir with little or no damage. All parties agreed that a diversion of 3-5 years could probably be realized before serious damage to Quabbin might be expected to occur, but that additional monitoring of the reservoir must be done during diversion. With 3-5 years flexibility the MDC felt it would be better to treat any water quality problems after some actual experience with diversion than try to design treatment plants in the dark. The MDC also felt that an actual diversion would put pressure on the groups that were polluting the Connecticut River to stop, and that the quality of Connecticut River water entering Quabbin Reservoir could therefore probably be raised.

5555 Ridge Avenue, Cincinnati, Ohio 45268

October 8, 1971

Trip Report - Boston, Massachusetts

Dr. Pringle
Through: Mr. Robeck

Travel Order #
T2789481

Dates of Trip
Sept. 15-16, 1971

Purpose of Trip: To discuss the proposal to divert Connecticut River water into Quabbin Reservoir.

Persons Contacted: The meeting consisted of 7 persons from the Metropolitan District Commission of Boston, Massachusetts, 3 persons from the U. S. Army Corps of Engineers, 3 persons from New England Research, Inc., 1 person from the University of Massachusetts, Mr. Floyd Taylor of Region I, EPA, and the writer.

Observations, Evaluation and Conclusions: The meeting revolved mainly about a discussion of a trip report prepared by Mr. Everett Maynard, of the U. S. Army Corps of Engineers, a copy of which is attached. The personnel from New Englang Research, Inc. had reviewed Mr. Maynard's trip report and prepared a formal list of questions and comments, a copy is attached. A copy of the agenda is also attached.

Most of the discussion revolved around essential points: 1) would diversion of the Connecticut River water into Quabbin Reservoir influence the ecology of the reservoir itself, and 2) would the above mentioned diversion influence the quality of Boston's drinking wtter. The Metropolitan District Commission (MDC) reported that no diversion would take place for at least four years because of legislative delays, and time for construction of the diversion pipe line. During this time, additional hydraulic model studies are proposed by New England Research, Inc. to determine more completely the flow patterns to be expected in Quabbin Reservoir during the time of diversion. The MDC also stated that in their design of the diversion pipe line, they would build in the capability of a tee to permit diversion of some of the water into the west arm of Quabbin Reservoir, if this should ever be needed in the future. We all agreed that any ecological damage to the reservoir would develop slowly, and that if the water quality in the reservoir were closely monitored after diversion began, changes could be made in the diversion scheme if any deteriorating quality were detected. I continued to insist that maximum dilution was essential to maintaining water quality, and I found the MDC's suggestion of building a low dam between two islands in the central arm of the reservoir to further

prevent short-circuiting at higher water levels encouraging.

I also continued to press for some sort of filtration for Boston's water supply. Mr. Taylor and I discussed the proposed new turbidity standard of 1 T.U., and the Division's general policy that all surface waters should receive some turbidity control. I said that although the present water quality of Boston met the Drinking Water Standards, that a relatively small, high-rate, direct filtration plant would serve as a vital additional protection for the consumers in the MDC service area. While the MDC seemed inclined to link any deterioration of the water quality in Quabbin Reservoir, because of diversion, to the necessity for filtration of their water, I ask that the question of filtration be considered independently of any change in water quality in Quabbin Reservoir.

Recommendations and Conclusions: The meeting was a very useful exchange of ideas for all the parties involved with the project. I think that the course of action selected by the MDC is wise, but I do hope that they will continue to investigate the actual cost involved of filtration of their water supply.

James M. Symons
Chief, Control Technology
Water Hygiene Division

JMSymons:ml

cc: Floyd Taylor

APPENDIX 4

OUTSIDE CONTACTS AND INFORMATION SOURCES

Considerable information and technical data were supplied to us by the MDC and the Corps of Engineers as this project progressed through the various stages. In addition, we have made contacts with several organizations, from which we have received both verbal and written information. We are grateful for their assistance and cooperation. The list of contacts appears below.

Central Massachusetts Regional Planning Commission
Worcester, Massachusetts 01609

Division of Fisheries and Game
Commonwealth of Massachusetts
Westboro, Massachusetts 01581

Division of Water Pollution Control
Water Resources Commission
Commonwealth of Massachusetts
Boston, Massachusetts 02202

Franklin County Department of Planning
Greenfield, Massachusetts 01301

Lawrence Experiment Station
Massachusetts Department of Public Health
Lawrence, Massachusetts

National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151

Northeast Utilities Service Company
Hartford, Connecticut 06101

U. S. Geological Survey
Department of the Interior
J.F.K. Federal Building
Boston, Massachusetts 02203

Vermont Yankee Nuclear Power Corporation
Rutland, Vermont 05701

Water Resources Research Center
University of Massachusetts
Amherst, Massachusetts 01002

Webster-Martin, Inc.
South Burlington, Vermont

APPENDIX 5

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APPENDIX 6

FOURTH QUARTER RESULTS

A. Preface

The data from October and November, 1971 were examined in the light of the discussion of data for the period from December 1970 through September 1971. Data were studied to determine if they contradicted or otherwise altered the conclusions that were drawn from the earlier data.

B. Biological Data

(1) Bacteria

Bacterial data collected during the fourth quarter were consistent with the data collected during the first three quarters. In general, numbers of heterotrophic bacteria in the reservoir systems increased from the first quarter to a peak in the second or third quarter, and decreased during the fourth quarter. This trend was observed at most reservoir stations; and is commonly observed in lacustrine environments. Numbers of heterotrophic bacteria at individual riverine stations usually remained the same or slightly increased from third to fourth quarters.

No general trends were noted in riverine, or lacustrine systems with respect to total coliform or fecal coliform bacteria. Riverine stations and Quabbin "inside"stations usually showed no change or slight increases in total coliform bacteria from third to fourth quarters. Other reservoir stations showed small changes in populations and followed no discernable pattern.

No pattern of changes in fecal coliform numbers was detected at any stations except those from the Quabbin "outside" system where stations showed fecal coliform numbers decreasing from the third to the fourth quarters.

(2) Phytoplankton

The frequency of occurrence of most algal types dropped from the third quarter to the fourth quarter for all systems studied. Pennate diatoms, however, did not change from the third quarter. This group occurred frequently during each quarter and was usually found in high concentrations (about 10^3 cells/liter) in all systems. Golden-brown flagellates occurred more frequently and usually in higher concentrations (about 10^3 cells/liter) during the fourth quarter in all systems except the Millers and Connecticut River systems.

(3) Zooplankton

During the fourth quarter, the numbers of crustaceans and rotifers remained at low values or decreased from summer or fall peaks at most stations. However, Quabbin Reservoir stations and the Millers and Connecticut River systems showed small peaks in numbers of rotifers during October with a decline in numbers during November. The average, relative composition of zooplankton populations in the reservoir systems varied little from third to fourth quarter, although the absolute numbers of each type did change in the manner noted above.

(4) Benthic Organisms

Fourth quarter benthic samples were collected in the reservoirs during late September and were discussed fully in Section 5. Riverine benthic samples were collected later and were not discussed. Fourth quarter riverine benthic data, however, followed the same general patterns presented in Section 5 and the discussion can be considered complete.

C. Chemical Data

In general the results shown in the fourth quarter data for chemical parameters support the discussions in Section 5 based upon the data for the first three quarters.

All parameters that were not discussed in Section 5 because they were rarely or never detected, were not detected during the fourth quarter. Sulfate sulfur was detected, but little significant variation in values in time and at various sampling stations was seen. All parameters that were discussed in Section 5 showed fourth quarter values that supported the conclusions already presented in the report.

D. Physical Data

(1) Color

If systems are arranged in order from highest to lowest average color based on fourth quarter data alone, the resulting pattern is the same as

that given in Section 5.

The group of river stations, R2, R3 and R6 showed a slight downward trend in color values during the fourth quarter, while other river stations showed an upward trend. The Quabbin "outside" and Wachusett systems and station Q9 from Quabbin "inside" showed little change in color in the fourth quarter, while all other Quabbin "inside" stations showed a slight increase in color.

(2) Specific Conductance

The pattern obtained by arranging systems in order of decreasing specific conductance is the same for the fourth quarter as that reported in Section 5 for earlier quarters.

There was a slight increase in specific conductance in the Connecticut River, a slight drop in the Tully and Ware system and a larger drop in specific conductance values for the Millers River for the fourth quarter.

(3) Dissolved Oxygen

All systems showed an increase in dissolved oxygen (from about 8 mg/l to 10 mg/l) during the fourth quarter, but these increases were small except in the Millers River where there was a ten-fold increase in dissolved oxygen values at South Royalston (R9), from low summer values of 1 mg/l up to 10 mg/l. The Millers River system as a whole went from a third quarter average of 5.5 mg/l to a fourth quarter average of 8.7 mg/l.

(4) pH

The Millers River and Ware River stations decreased slightly in pH during the fourth quarter while the Connecticut River increased slightly. The tributaries to the Millers River (R2, R3, R6, R7) increased in pH early in the fourth quarter then dropped back to levels that were observed late in the third quarter. The pH of the reservoirs decreased slightly.

(5) Turbidity

The fourth quarter pattern obtained by arranging systems in order of decreasing turbidity is identical to that in Section 5.

There was a large fourth quarter increase in turbidity at the Millers River stations (from 16 units to 32 units), while the Connecticut River increased slightly (from 3 to 4 units). Other systems showed only small fourth quarter changes in turbidity.

(6) Temperature

The temperature at all stations dropped in the fourth quarter. The reservoirs and the Connecticut River cooled slowly, dropping from 17-19°C in October to 9-11°C in November. The smaller rivers however, declined more rapidly, dropping from 12-18°C in October to 2-6°C in November. Some shallow reservoir stations (Q4, Q5) cooled almost as rapidly as the rivers.

E. Pesticide Data

All samples except two had no detectable pesticides or phenolic compounds during the fourth quarter. In November a presumptive value of 0.0002 ppm O, P -DDD was detected at Q3 and less than 0.01 ppm phenolic compounds was detected at Q2 at a depth of ten meters.

F. Radioactivity

There was no detectable gross alpha activity in any sample during the fourth quarter. All samples had gross beta activities below 10 μμC per liter during the fourth quarter except for a sample from Q8 at a depth of 10 meters. This particular sample had a gross beta activity of 18 μμC per liter. Since this was the only sample throughout the year which had high beta activity, it is difficult to draw any conclusions about the significance of this value.

G. Summary

The data collected during the fourth quarter are consistent with the conclusions drawn in the main report. The data follow trends that might be expected from seasonal variations in lacustrine and riverine environments. Variations that might be expected between relatively clean and relatively polluted riverine environments were noted when systems such as the Tully System and the Millers River were compared.

Fourth quarter data constitute a continuation of the patterns discussed in Section 5 of this report. No trends were noted during the fourth quarter

that contradicted the conclusions drawn from the patterns observed in data from the first three quarters. The additional data did not contain new patterns that would add to the conclusions already drawn.