Massachusetts Institute of Technology

AN INVESTIGATION OF WATER POWER DEVELOPMENT ON THE CONCORD RIVER MASS.

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TABLE OF CONTENTS

INTRODUCTION

The choice of a satisfactory water power site to-day necessitates a more systematic study of the factors involved than formerly. In olden days a site was purchased and crude wheels installed as required by increased demand, without exact knowledge of the full power of the stream. In recent years, however, when organized capital and business foresight are the governing factors in nearly all water power developments, and each horse-power obtained is becoming more valuable, it is essential to know, as nearly as possible, the actual power to be had under given conditions. The world as a whole has awakened to the fact that one of Nature's most valuable gifts, the "white coal," is wasting. Unlike coal, oil, and wood, which are preserved when not used, water power is wasted when not developed.

The people in the Pacific Coast section of the United States have realized the wonderful opportunities of power development on their swiftly flowing rivers, and consequently developments have gone on continuously. The people in the New England section have been very slow in realizing the possibilities of water power. Only during the last few years has interest been shown in this section of the country.

The development of water power has been greatly accelerated by the general restlessness and strikes in the coal fields. The uncertainty of the transportation facilities has also tended to encourage the development of power from other sources.

A time will probably come when the United States will have all of its rivers carefully studied and tabulated. This tabulation will include such items as a careful study of the basin as a whole, touching on the drainage area, source, direction, drop, falls, rapids, banks, river beds, tributaries, lakes, swamps, forests, cultivation along banks, settlements, and general typographic and geological features. This investigation will also include economic aspects for both large and small development possibilities, going into it more carefully in the latter case, because an error may result in serious financial consequences, while an error of the same magnitude in the former type may be of minor importance.

An investigation of this type will make available data which may assist in determining the location of an hydro-electric station or a manufacturing establishment, or in some cases it may lead to the establishment of community plants.

SUMMARY

Purpose of Thesis:

It is the purpose of this thesis to present the results of a preliminary investigation of the Concord River and its tributaries, the Assabet and Sudbury, for available water power.

As the time available for this work has been limited, we have not attempted to make a detailed study of the development of any particular point, but have confined ourselves to obtaining only the information leading up to a possible choice, assuming that the party interested in that location will continue the investigation.

The choice of suitable locations has led us to pick out several that are already developed. As a result of this, we have made a brief study of existing mills, mentioning, however, only the available head, the type and size of units used, and any special features that might be present.

Method of Procedure:

In a study of this type, it is necessary to know the drainage area above the point considered, the head at that point, and the availability of storage and pondage.

Maps were resorted to for this information, and to get a general idea of existing conditions, several locations have been visited and available information collected. Although knowing that the United States Geological Survey maps are slightly in error, as they are the only ones available for this purpose, we have therefore based our choices of location on the results obtained from their study, making reasonable corrections and modifications for possible existing errors.

The available heads at the locations where mills already exist have been obtained from the mill authorities, and this data augmented and checked with the maps. This, together with a preliminary study of the flow of the river, is necessary before the available power can be calculated.

A conservative value of the flow of the river has been obtained after having made several corrections, as explained in the "Flow of the Concord," in the following pages.

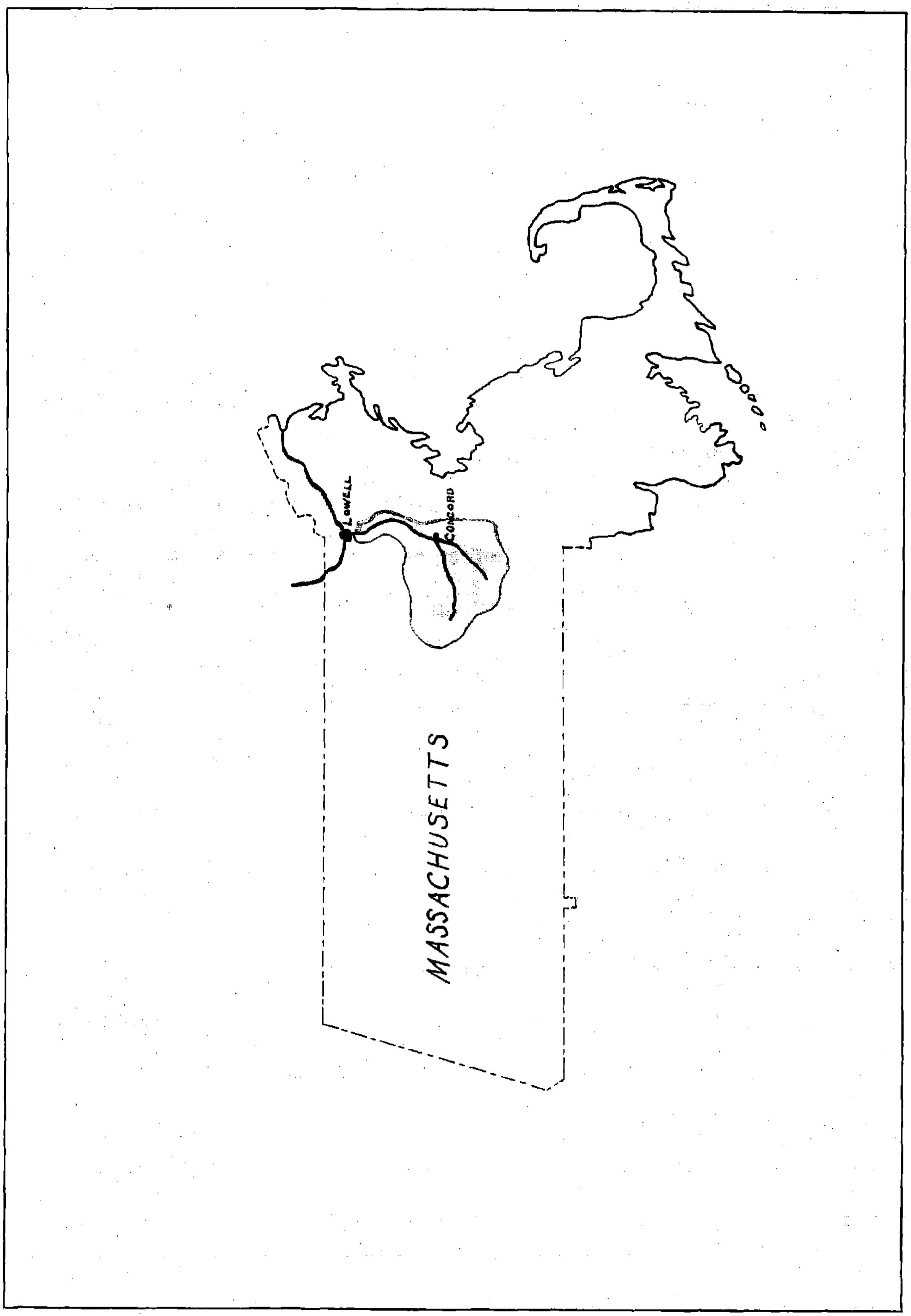
The question of storage has been studies by use of the maps, noting the areas which would be flooded by the location of reservoirs at suitable points.

Reference books have been freely used, from which valuable information has been obtained regarding storage, the choice of a location, and general factors to be considered.

Conclusions:

From our investigation of the Concord River, we have concluded that there is no suitable location for an extensive water power development. In the future, as at present, the mills situated on its banks must depend for most of their power on other sources than the river. This investigation has also shown that there is no suitable location for a storage reservoir within this drainage area. Although this was not unexpected it is, nevertheless, unfortunate, as a good reservoir would add materially to the annual power which might be obtained from the stream.

Plate 1



DRAINAGE AREA: CHARACTERISTICS

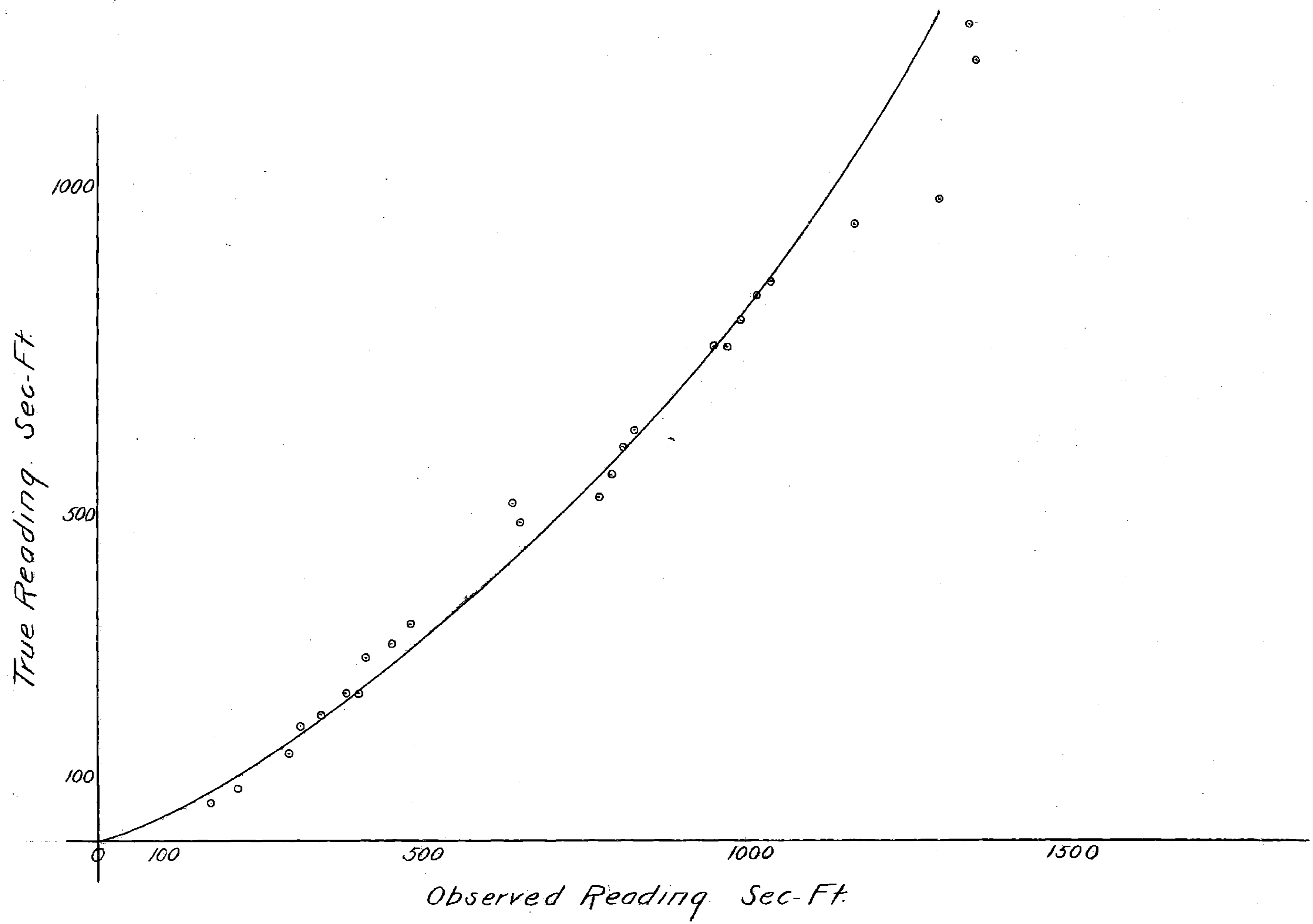
The Concord River is situated in the Middlesex County, in the eastern part of Massachusetts, and is formed in the town of Concord by the junction of the Sudbury and Assabet Rivers. The Assabet drains the larger area and is therefore considered the continuation of the main stream. It rises on the south slope of Green Hill, four miles southwest of Westboro, at an altitude of 480 feet above sea level, and flows northeastward about 30 miles to its junction with the Sudbury River. Below this junction the Concord River flows northeastward nine miles, then northward seven miles to its junction with the Merrimac River at Lowell. The Assabet has a drainage area, as obtained from the sheets of the U. S. Geological Survey, of about 176 sq. mi., or a little less than one-half of the total drainage area above Lowell, which is 376.5 sq. mi. It flows through a hilly and broken country, and has a rapid fall and high banks. The drainage area contains 3 sq. mi., or 1.7% of swamp, and 6.1 sq. mi., or 3.4%, of water area. The area is largely covered with a thick second growth of timber and bushes, especially near the source. In the lower parts of the basin a considerable part of the land is cultivated.

The Sudbury River drains a territory west and northwest of Framingham of about 164 sq. mi. The part of the area west of Framingham is hilly country but between Framingham and Concord, the river flows through meadows and swamps. The greater part of the Sudbury basin is under the control of the Metropolitan Water District Commission, of Boston, and is used by them for storage reservoirs. This will be more fully explained in the following discussion on the "Flow of the Concord River." There are 15.1 sq. mi., or 9.2% of swamp in this area, and 8.2 sq. mi., or 5.0% of water surface. As in the case of the Assabet, the upper parts of the basin are heavily wooded. There is little chance for extensive cultivation in this district.

Between Concord and South Billerica the Concord River flows through a flat stretch of country with swamps on either side. From South Billerica to North Billerica, the country is more hilly and the banks of the stream are generally high. Beyond North Billerica, however, the stream flows mostly through swamps and low meadow lands, and is exceedingly sluggish, its course circuitous, and the bed sand and mud. Near the mouth of the stream the country is also hilly and rolling, the bed is rocky, the banks are high, and the fall is large. Under normal conditions of flow, a drop of about 20 feet is obtained from the crest of the Wamesit Dam.

The geological characteristics of the Concord basin are typical of New England, that is, a firm base of solid rock, overlaid to varying depth with glacial drift.

Plate II



Flow Correction Curve
Concord River.

FLOW OF THE CONCORD RIVER

The flow of the Concord is determined by wheel ratings based on Holyoke tests, and checked by current meter measurements in place. The latter measurements are taken at the dam near the Lawrence Street Bridge in Lowell.

The discharge in second-feet, as given in the Water Supply Papers of the U. S. Geological Survey, is the mean between one forenoon and one afternoon reading, both taken while the mills between North Billerica and Lowell are in operation. At this time these mills are drawing on their pondage, which has been stored up during the hours when the units are closed down. Hence the discharge of the river at Lowell is actually somewhat larger than its flow in the natural state, because the mills are passing by, not only the natural flow, but also the water that has been held back by pondage. This excess of discharge, due to the effect of pondage, is much greater when the flow of the river is naturally small.

Starting with 1921, readings were taken four times a day in order to obtain a more representative value of the daily flow. Two of these readings were taken as before, with the mills in operation, and two were taken while the units were shut down, during which time the pondage was being built up. In the first case water which had been held back is included in the readings, and in the second case water which should flow is held back. The average of the four readings is taken as closely representing the natural flow.

In the fifteen year period under consideration, the readings of the discharge in second-feet, as obtained from the Water Supply Papers and which may be assumed to represent the flow corresponding to a 9-hour day, were corrected for that of a 24-hour day. The monthly values for the years 1921 and 1922, representing a 24-hour day, were plotted as ordinates against the corresponding 9-hour day as abscissae. From this plot the correct monthly discharges for the fifteen years were obtained. Plate II shows this plot in reduced scale.

The nearness of the Concord River drainage area, which includes the Sudbury and Assabet Rivers, to the city of Boston has caused the Metropolitan Water district to locate reservoirs for the municipal supply of Boston in this territory. For this purpose two portions of the natural drainage area of 376.5 sq. mi.

have been diverted. The first of these, the Sudbury System, having an area of 75.2 sq. mi., includes the Sudbury drainage area above Framingham. The second, the Cochituate System, has a drainage area of 18(±) sq. mi., and includes Lake Cochituate.

In the consideration of the discharge of the Concord, it must be borne in mind that the readings, as recorded at Lowell, do not represent the flow from the natural drainage area, in as far as they contain the waste water from the above mentioned systems. The waste water can be taken as representing a part of the discharge attributed to the whole drainage area.

When the City of Boston undertook to divert the water into its reservoirs in 1872, it was necessary to safeguard the mill interests at Framingham and Saxonville. Accordingly the Sudbury River Act of 1872 was passed, Chapter 177 of which provides by law that the City of Boston and its successor, the Metropolitan Water District, are required to allow 1,500,000 gallons of water per day to flow down the river below the lowest dam at Framingham, thus reducing by that amount the water available for municipal purposes from the diverted Systems. The reason that an excessive amount over the required 1,500,000 gallons per day has been wasted is that the water in the lower part of the Sudbury System is not fit to be used unless filtered, while that of the upper portion is cleaner and hence is all being used for municipal purposes. The discharge readings, as obtained from the Water Supply Papers of the U. S. Geological Survey include this excessive waste.

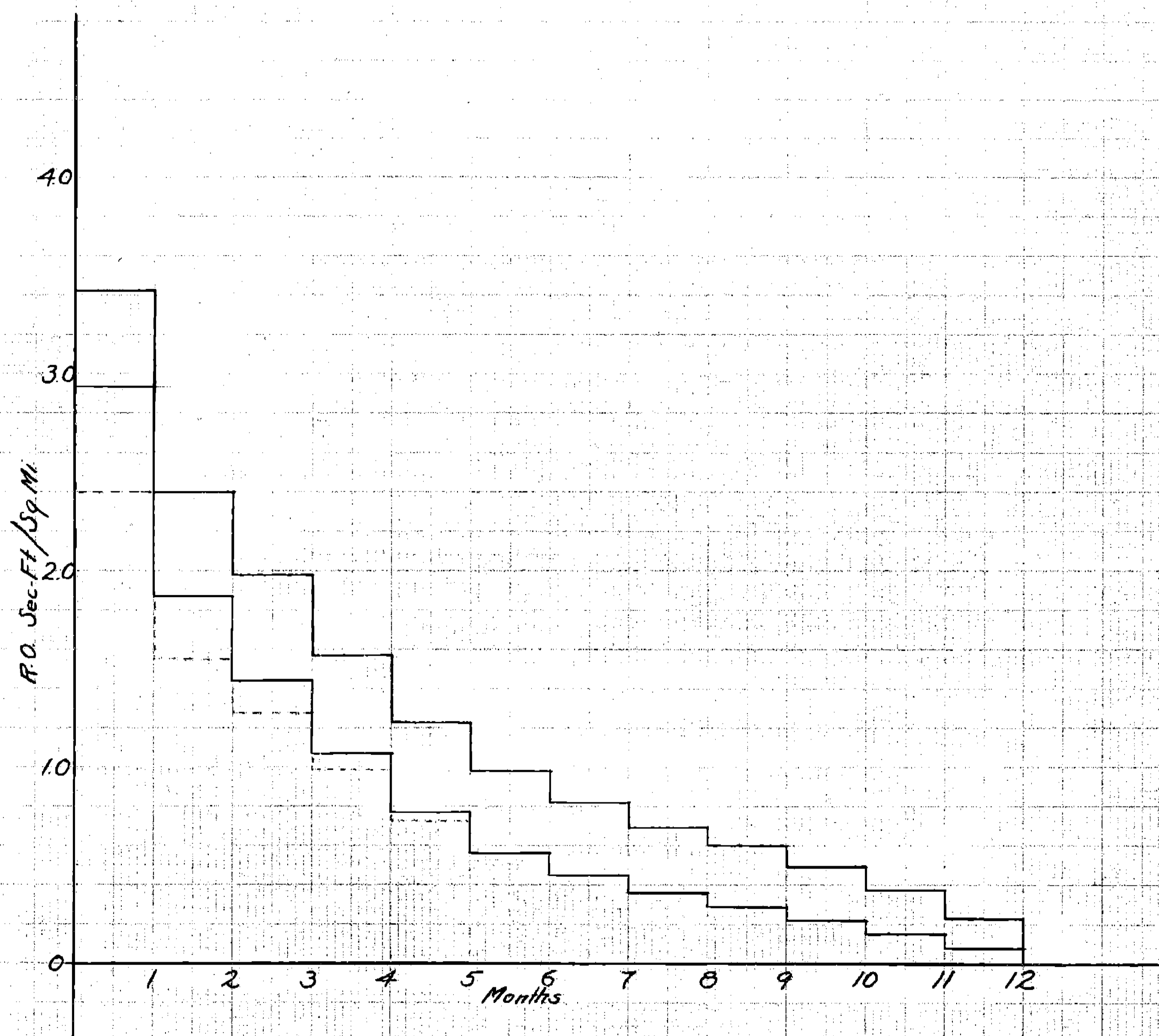
In 1922 an appropriation of $25,000 was granted to the Metropolitan Water District for the purpose of building a filtration plant in the lower district. The construction of such a plant will result in the elimination of all excessive waste, and the mills at Framingham and Saxonville will be compelled to depend on the 1,500,000 gallons per day.

The elimation of the excessive waste by filtration will also affect the flow of the Concord. A careful study of the rates of discharge during the fifteen year period shows that, although there is no connection between the yield and the amount of waste, the averages lead to the choice of 0.56 sec.-ft./sq. mi. as the discharge rate above which a loss greater than 1,500,000 gallons per day may be assumed to occur. In the average year, which is used in the power calculation, this will give a zero correction for the seven lowest months.

The same study shows that an 18% correction for the highest month is a conservative figure. The corrections for the remaining four months of the average year may be assumed in such a ratio as to give 17%, 11%, 7%, and 5% as conservative figures.

The study of the hydrograph of the Concord River at Lowell (Appendix D) shows that the maximum flow for every year occurs within the first four months of the calendar year. There is no regular cycle which occurs within the 15-year period. The month of July is regularly one of the dryest months, and each year on the average has a dry season extending over three or four months.

The Assabet River was considered in 1895 for additional water supply. The industrial developments on this river, eliminated this consideration. The effluent directed into the river from the towns also makes it unwise to consider the use of the water for city purposes. As the mills at Maynard use the entire flow available during the dry weather, the diversion of the water would necessarily be so limited as to be of not much use except in case of emergency. A recent reconsideration of the decision reached in 1895 has brought about the same conclusions.



Flow-Duration Curves
Concord River at Lowell.
24 Hour Day— 9 Hour Day.
Probable Future Condition

POWER AVAILABLE

Lowell

In the consideration of available power, it is common practice to determine the size of the wheel with capacity requisite to utilize the flow available four months of the average year. Following this practice, and having determined the drainage above Lowell to be 376.5 sq. mi. and the average available head to be 20 ft., and assuming a wheel efficiency of 85%, the wheel capacity requisite to utilize the flow of the Concord for four months of the average year would be:

$$\frac{.995 \times 376.5 \times 62.5 \times 20 \times .85}{550} = 724 \text{ H.P.}$$

Assuming 100% load factor and no waste of water, the average annual output at the wheel shaft would be:

$$\frac{6.82 \times 376.5 \times 62.5 \times 20 \times .85}{550} \times 30.4 \times 24 =$$

3,625,000 H.P.-Hrs.

Of this total, the following is primary power:

$$\frac{.08 \times 62.5 \times 12 \times 376.5 \times 20 \times .85}{550} \times 30.4 \times 24 =$$

509,500 H.P.-Hrs.

However, in actual practice a load factor of 100% is seldom, if ever, obtained, and it is impossible to prevent some waste of water. With a load factor of 50%, and assuming that 20% of the power is lost due to waste and lack of pondage, the average annual output would be:

$$\frac{4.55 \times 376.5 \times 62.5 \times 20 \times .85}{550} \times 30.4 \times 24 \times .80 =$$

1,934,000 H.P.-Hrs.

of which

$$\frac{.08 \times 62.5 \times 12 \times 376.5 \times 20 \times .85}{550} \times 30.4 \times 24 \times .80 =$$

407,600 H.P.-Hrs.

represents primary power.

In the determination of the available power at North Billerica and subsequent points to be considered, the assumptions and conditions used in the calculations for Lowell will be taken as representative.

In these calculations the power available is a function of the drainage area and the available head, the other factors remaining constant.

Hence

Wheel Capacity = 0.0961 Ah

<u>Theoretical</u>:

Average annual out-put = 481.0 Ah

Primary average annual out-put = 67.7 Ah

<u>Practical</u>:

Average annual out-put = 257.0 Ah

Primary average annual out-put = 54.2 Ah where A = drainage area above point considered, in square miles.

and h = available head in feet.

North Billerica

Drainage area = 370.1 sq. mi. Available head = 10'

Wheel capacity requisite to utilize the 4 months' flow = .0961 x 370.1 x 10 = 356 H.P.

Theoretical:

Average annual out-put = 481 x 370.1 x 10 = 1,780,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 370.1 x 10 = 250,000 H.P.-Hrs.

Practical:

Average annual out-put = 257.0 x 370.1 x 10 = 950,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 370.1 x 10 = 201,000 H.P.-Hrs.

Riverhurst

Drainage area = 362.0 sq. mi. Available head = 20 ft., estimated

Wheel capacity = .0961 x 362.0 x 20 = 696 H.P.

Theoretical:

Average annual out-put = 481 x 362 x 20 = 3,480,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 362 x 20 = 490,000 H.P.-Hrs.

Practical:

Average annual out-put = 257 x 362 x 20 = 1,860,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 362 x 20 = 392,000 H.P.-Hrs.

Westvale

Drainage area = 121.4 sq. mi. Available head = 20 ft., estimated

Wheel capacity = .0961 x 121.4 x 20 = 233 H.P.

Theoretical:

Average annual out-put = 481 x 121.4 x 20 = 1,168,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 121.4 x 20= 164,000 H.P.-Hrs.

Practical:

Average annual out-put = 257 x 121.4 x 20 = 624,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 121.4 x 20 = 132,000 H.P.-Hrs.

American Powder Co.

Drainage area = 117.0 sq. mi. Available head = 12 ft.

Wheel capacity = .0961 x 117 x 12 = 135 H.P.

Theoretical:

Average annual out-put = 481 x 117 x 12 = 675,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 117 x 12 = 95,000 H.P.-Hrs.

Practical:

Average annual out-put = 257 x 117 x 12 = 361,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 117 x 12 = 76,000 H.P.-Hrs.

Maynard

Drainage area = 115.3 sq. mi. Available head = 22 ft.

Wheel capacity = .0961 x 115.3 x 22 = 244 H.P.

Theoretical:

Average annual out-put = 481 x 115.3 x 22 = 1,220,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 115.3 x 22 = 172,000 H.P.-Hrs.

Practical:

Average annual out-put = 257 x 115.3 x 22 = 653,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 115.3 x 22 = 138,000 H.P.-Hrs.

Hudson

Drainage area = 65.8 sq.mi. Available head = 15 ft., estimated

Wheel capacity = .0961 x 65.8 x 15 = 95 H.P.

Theoretical:

Average annual out-put = 481 x 65.8 x 15 = 475,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 65.8 x 15= 67,000 H.P.-Hrs.

Practical:

Average annual out-put =257 x 65.8 x 15 = 254,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 65.8 x 15 = 53,500 H.P.-Hrs.

Northboro

Drainage area = 31.0 sq. mi. Available head = 22 ft., estimated

Wheel capacity = .0961 x 31 x 22 = 65.5 H.P.

Theoretical:

Average annual out-put = 481 x 31 x 22 = 328,000 H.P.-Hrs.

Primary average annual out-put = 67.7 x 31 x 22 = 46,000 H.P.-Hrs.

Practical:

Average annual out-put = 257 x 31 x 22 = 175,000 H.P.-Hrs.

Primary average annual out-put = 54.2 x 31 x 22 = 37,000 H.P.-Hrs.

STORAGE AND PONDAGE

It is a well-known fact that the total annual power available at any point is greatly increased if it is possible to store a part of the flow of the river during the wet season for use during the dry months, when the natural flow of the river would not be sufficient to run the wheels at rated capacity. The ideal location for a storage reservoir would be a natural lake with a narrow outlet near the source of the stream. This situation is seldom met, especially in this part of Massachusetts. In any case the development of storage requires considerable expense and the benefit to be derived from such a development should be most carefully considered before any construction is started.

After a careful study of the U. S. Geological Survey maps with reference to the Concord River drainage area, it is apparent that there are no outstanding locations for a suitable storage reservoir.

Between Lowell and North Billerica, there are no lakes which be suitable for this purpose and the land in the vicinity of the river is flat. As the river does not drop appreciably until well within the city limits, the building of a reservoir would necessitate the acquisition of so much land already developed as to make it impracticable.

Between North Billerica and Concord, the only possible location of a dam is at Riverhurst where the banks are high and the river is comparatively narrow. A dam at this place over 30 feet in height, which would bring the crest to an approximate elevation of 125, would cause the water to flood besides a considerable area of useless swamp land, several populated districts, in fact the center of Concord would be made an island. If this territory were flooded to an elevation of 125, part of the water would flow into the Shawshine system. This could be prevented only the the construction of a dam, but the cost would be prohibitive. The size of Nutting's Pond, the only body of water which need be considered, cannot be increased for the same reasons.

The Sudbury River between Concord and Saxonville flows through a wide swampy district where the construction of a dam could not be considered. No appreciable quantity of water could be stored here even though the area flooded would be large. There are no lakes in this district to be considered.

Above Saxonville the territory is controlled by the Metropolitan Water District, and although there is no law which would prevent the construction of a reservoir in this district, there is an Act which compels the Metropolitan Water District to waste only 1,500,000 gallons per day. In the future it is probable that not more than this amount will be wasted, and hence a reservoir in this district would not serve its purpose.

The only possible location for a reservoir between Concord and Maynard would necessitate the relocation of over a mile of railroad. The storage obtained would not warrant the expense. The lakes in this district are such that a use of over five or ten feet would cause overflowing.

Above Maynard, although the country is rugged, there are no lakes which might be used, and the amount of storage which could be obtained by damming some of the narrow valleys would be very small because of the nearness to the sources.

Although it is impossible to regulate the flow of the river by the construction of storage reservoirs, it is possible to do this in a smaller degree by the use of pondage. The building of a dam necessarily forms a small pond which in most cases is large enough to supply the demand for a short period of time. In dry seasons the nightly flow is held back, to be used on the following day.

PRESENT DEVELOPMENTS

The Concord, like all typical New England rivers, has for many years supplied power to mills located on its banks. The early settlers preferred to locate on a stream in many instances, starting projects which have been developed to their present status. It is certain that the present mills are located at the most advantageous points.

The Wamesit Canal is a development whereby several manufacturing companies near the Concord River in South Lowell are able to use its flow for developing a part of the power which they require. A short distance above the Lawrence St. Bridge the river suddenly changes its character from a sluggish flow through swamps to a dashing stream tumbling down a rocky slope. At this point the Wamesit Power Co. has built a dam, thus forming a pond. The water is conducted from the pond through a canal which follows around the hillsides for a distance of about half a mile. The mills which use the water from this canal are allowed a certain maximum quantity, which, however, may be reduced if the flow of the river falls below a certain amount.

The Belvidere Woolen Co. is the first user of the canal water and its maximum allotment is 27 second-feet.

The water is taken from the canal, passes through a 21 inch McCormick wheel and is discharged into the Concord, which flows directly behind the plant. The net head obtained is about ten feet.

The Bay State Mills of the American Woolen Co. have two mills side by side, which use water from the canal. Their maximum allotment is 73 second-feet and the power is developed by two wheels, a 21 inch and a 24 inch Hercules. The heads of these wheels are 12 and 15 feet respectively. The water discharges into the Concord as in the case of the Belvidere Mill.

The Sterling Mills have a maximum allotment of 48 second-feet and the power is developed with a 24 inch McCormick wheel. The head is about 15 feet, and the water is discharged into the Concord.

The Wamesit Power Co., under whose director the entire development is carried out, develops power with 2-33 inch McCormick wheels under an average head of about 20 feet, and sells the power to the U. S. Cartridge Company, located near by. The wheels are located in a small house about 20 ft.x 40 ft., and the water is delivered to the wheels in 2 - 6 1/2 ft. steel penstocks about 25 feet long, which make an angle of approximately 45° with the horizontal. The penstocks are not perpendicular to the shaft, but enter at an angle close to 65°. This is plainly a result of poor design on the part of the engineer who laid out the system, and probably causes an appreciable effect on the efficiency of the wheels. The water is discharged into a small channel which empties into the River Meadow Brook just before the latter joins the Concord. The Wamesit Power Co. has a maximum allotment of 104 second-feet, plus any surplus, their total consumption in time of high water being about 250 second-feet.

The Lowell Bleachery is the last user from the canal and they are alloted a maximum of 36 second-feet. They use this water, not for power, but in their bleaching and washing processes and discharge it into River Meadow Brook.

At North Billerica the Talbot Mills Co. has for many years taken as much power as possible from the river. The fall here is only 10 feet so that the power available is only a small part of what the mill requires for its operation. At present there are two horizontal wheels installed directly beneath the main engine room, and connecting to the main shaft. One wheel is a 21 inch McCormick and the other a 24 inch Hunt.

About half-way between Concord and Maynard is situated the black powder plant of the American Powder Co. The head available here is about 12 feet under normal conditions. Two 33 inch Hunt turbines of 104 H.P. each are installed which ordinarily give about one-half of the power required to drive the machinery. The additional power is obtained from the steam plant of the smokeless powder mill near by.

At Maynard, the American Woolem Co., has another mill. A wheel rated to give 258 H.P. under the 22 foot head available is installed here. Owing to the magnitude of the plant, however, the water power is of secondary consideration.

The above mentioned plants are the largest of those located on the Concord River. It is probable that at least a dozen more smaller plants use the river for power purposes to a greater or less degree. The location of such towns as Westvale, Hudson, and Northboro on the river undoubtedly means that what little power is available at these points is utilized. For all these cases mentioned above, it will be noted that the power obtained from the river is of secondary importance. The only way in which the power could be increased would be by constructing a higher dam or by forming a storage reservoir somewhere within the drainage area which would make the flow of the river more uniform. The first method would be impracticable in every case as it would result in the flooding of developed land. The second method is equally impracticable as has been shown in the discussion on "Storage and Pondage."

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APPENDIX A

Sec. Ft./sq. mi. 9 hr. day

Month	'01-02	'02-03	'03-04	'04-05	'05-06	'06-07	'07-08	'08-09
Nov.	0.84	0.96	0.80	0.64	0.65	0.91	2.32	0.54
Dec.	2.12	1.73	0.86	0.36	1.05	0.74	2.39	0.58
Jan.	2.53	2.06	0.62	1.45	1.45	1.83	2.90	0.66
Feb.	1.35	2.58	0.70	0.63	1.26	0.94	1.97	2.14
March	5.71	3.87	2.61	2.27	2.68	1.90	2.90	2.19
April	2.66	3.33	2.75	2.17	3.33	1.79	2.02	2.20
May	1.19	0.89	2.88	0.80	1.21	1.07	1.42	1.64
June	0.63	2.34	0.82	0.71	1.69	0.93	0.79	0.91
July	0.42	1.47	0.60	0.44	0.97	0.47	0.29	0.31
Aug.	0.53	0.68	0.61	0.40	0.85	0.20	0.53	0.21
Sept.	0.48	0.47	0.62	1.49	0.37	0.60	0.24	0.27
Oct.	0.83	0.73	0.60	0.67	0.46	1.33	0.21	0.41
Total	19.35	21.11	14.47	12.03	15.97	12.71	17.98	12.06
Mean	1.61	1.76	1.21	1.00	1.33	1.06	1.50	1.00

APPENDIX A - concluded

Sec. Ft./sq. mi. 9 hr. day

Month	'09-'10	'10-'11	'11-'12	'12-'13	'13-'14	'14-'15	'15-'16	
Nov.	0.55	0.53	0.97	0.73	0.89	0.41	0.74	
Dec.	0.71	0.51	1.27	0.87	1.16	0.57	1.19	
Jan.	1.66	0.74	1.02	1.81	1.08	2.01	1.36	
Feb.	1.93	0.79	1.20	1.08	1.80	2.28	1.49	
March	3.70	1.31	3.70	2.32	3.14	1.44	1.95	
April	1.18	1.78	3.30	3.14	2.91	0.77	3.74	
May	0.96	0.70	1.96	1.39	2.25	0.66	2.43	
June	0.91	0.54	1.07	1.00	0.62	0.28	1.99	
July	0.40	0.10	0.41	0.28	0.51	1.27	0.99	
Aug.	0.23	0.31	0.37	0.25	0.45	1.72	0.65	
Sept.	0.15	0.33	0.31	0.39	0.32	0.57	0.54	
Oct.	0.15	0.59	0.36	0.70	0.23	0.69	0.38	
Total	12.53	8.23	15.94	13.96	15.36	12.67	17.45	221.82
Mean	1.04	0.69	1.33	1.16	1.28	1.06	1.45	18.48

APPENDIX B

Area = 376.5 sq. mi. 24 hr. day

Month	'01-'02	'02-'03	'03-'04	'04-'05	'05-'06	'06-'07	'07-'08	'08-'09
Nov.	0.47	0.56	0.44	0.32	0.33	0.51	1.79	0.26
Dec.	1.06	1.23	0.48	0.14	0.63	0.39	1.86	0.28
Jan.	1.98	1.53	0.31	0.97	0.97	1.32	2.36	0.33
Feb.	0.89	2.04	0.36	0.31	0.80	0.54	1.45	1.61
March	5.69	3.36	2.07	1.74	2.14	1.39	2.36	1.66
April	2.12	2.80	2.22	1.64	2.79	1.29	1.50	1.67
May	0.74	0.51	2.34	0.44	0.76	0.64	0.94	1.14
June	0.32	1.80	0.45	0.37	1.19	0.54	0.43	0.52
July	0.18	0.99	0.29	0.19	0.56	0.20	0.11	0.12
Aug.	0.24	0.35	0.30	0.16	0.48	0.07	0.25	0.07
Sept.	0.22	0.20	0.31	1.00	0.15	0.29	0.08	0.10
Oct.	0.50	0.38	0.29	0.34	0.20	0.86	0.07	1.17
Total	14.41	15.75	9.86	7.62	11.00	8.04	13.20	7.93
Mean	1.20	1.31	0.82	0.64	0.92	0.67	1.10	0.66

APPENDIX B - concluded

Area = 376.5 sq. mi. 24 hr. day

Month	'09-'10	'10-'11	'11-'12	'12-'13	'13-'14	'14-'15	'15-'16	
Nov.	0.26	0.24	0.56	0.38	0.51	0.08	0.40	
Dec.	0.37	0.23	0.82	0.49	0.45	0.27	0.74	
Jan.	1.16	0.40	0.60	1.30	0.65	1.49	0.89	
Feb.	1.41	0.43	0.75	0.65	1.29	1.74	1.00	
March	3.17	0.84	3.18	1.78	2.61	0.96	1.43	
April	0.74	1.27	2.76	2.60	2.38	0.41	3.22	
May	0.56	0.36	1.44	0.92	1.72	0.33	1.89	
June	0.52	0.25	0.64	0.59	0.31	0.11	1.47	
July	0.16	0.03	0.17	0.10	0.23	0.81	0.58	
Aug.	0.08	0.12	0.15	0.09	0.19	1.21	0.33	
Sept.	0.05	0.13	0.12	0.16	0.12	0.27	0.25	
Oct.	0.05	0.29	0.14	0.36	0.17	0.36	0.15	
Total	8.53	4.59	11.33	9.42	10.63	8.04	12.35	152.70
Mean	0.71	0.38	0.94	0.78	0.89	0.67	1.03	12.72

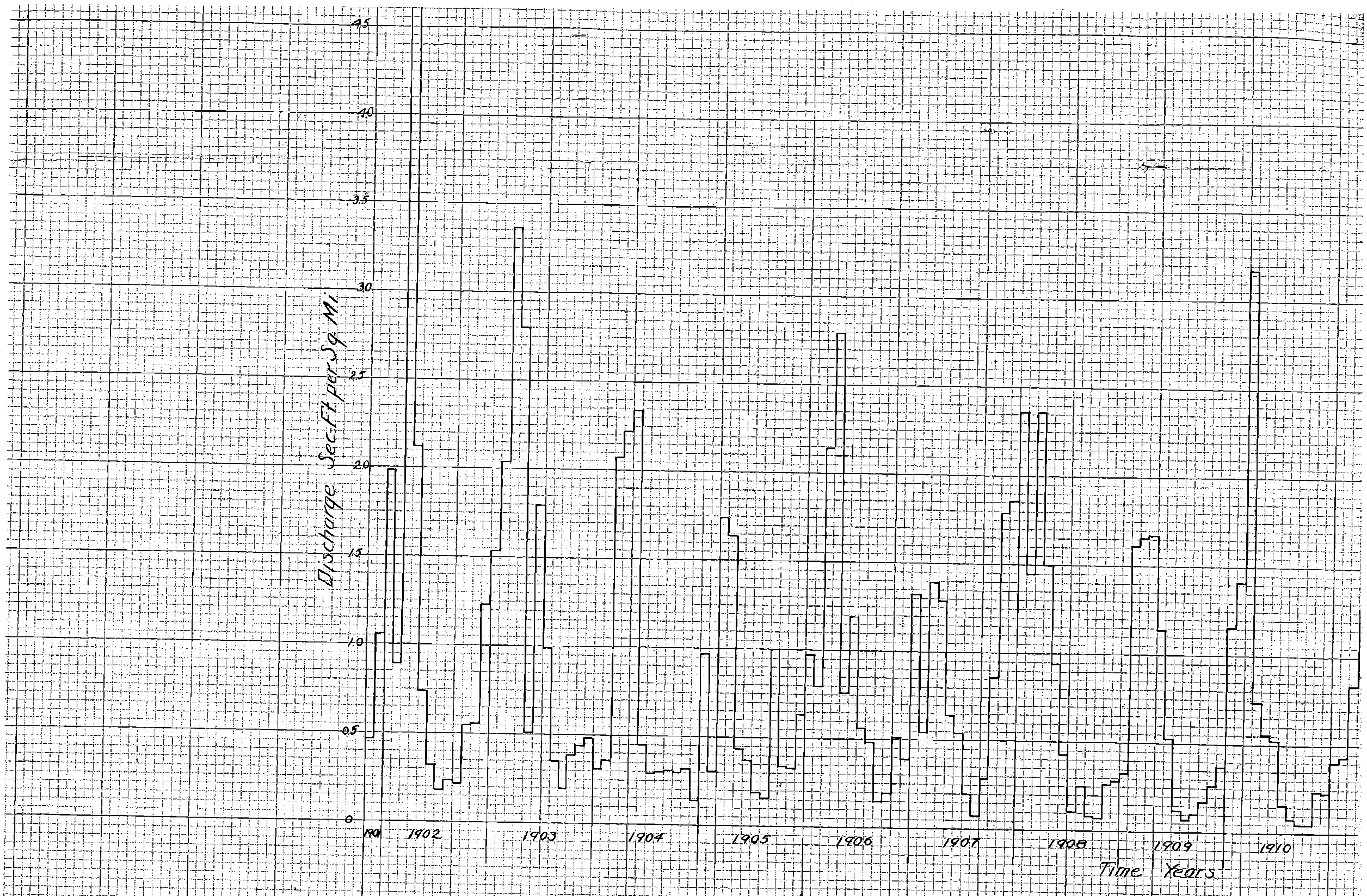
APPENDIX C

Flow Duration Table

(24-hour day)

Values arranged in order of magnitude, irrespective of year and month

	1	2	3	4	5	6	7	8	9	10	11	12
1	5.69	2.14	1.64	1.27	89	64	51	39	32	26	17	12
2	3.36	2.12	1.61	1.23	89	63	50	38	32	25	17	11
3	3.22	2.07	1.53	1.21	86	60	49	38	31	25	17	11
4	3.18	2.04	1.50	1.19	84	59	48	37	31	25	16	10
5	3.17	1.98	1.49	1.16	82	58	48	37	31	24	16	10
6	2.80	1.89	1.47	1.14	81	56	47	36	31	24	16	09
7	2.79	1.86	1.45	1.06	80	56	45	36	30	23	15	08
8	2.76	1.80	1.44	1.00	76	56	45	36	29	23	15	08
9	2.61	1.79	1.43	1.00	75	56	44	36	29	22	15	08
10	2.60	1.78	1.41	99	74	54	44	35	29	20	14	07
11	2.38	1.74	1.39	97	74	54	43	34	29	20	14	07
12	2.36	1.74	1.32	97	74	52	43	33	28	20	13	07
13	2.36	1.72	1.30	96	65	52	41	33	27	19	12	05
14	2.34	1.67	1.29	94	65	51	40	33	27	19	12	05
15	2.22	1.66	1.29	92	64	51	40	33	26	18	12	03
Total	43.84	28.00	21.56	16.01	11.58	8.42	6.78	5.34	4.42	3.33	2.21	1.21
Mean	2.93	1.87	1.44	1.07	.77	.56	.45	.36	.29	.22	.15	.08



Hydrograph
Concord River at Lowell Ma.

Hydrograph
Concord River at Lowell Mass.

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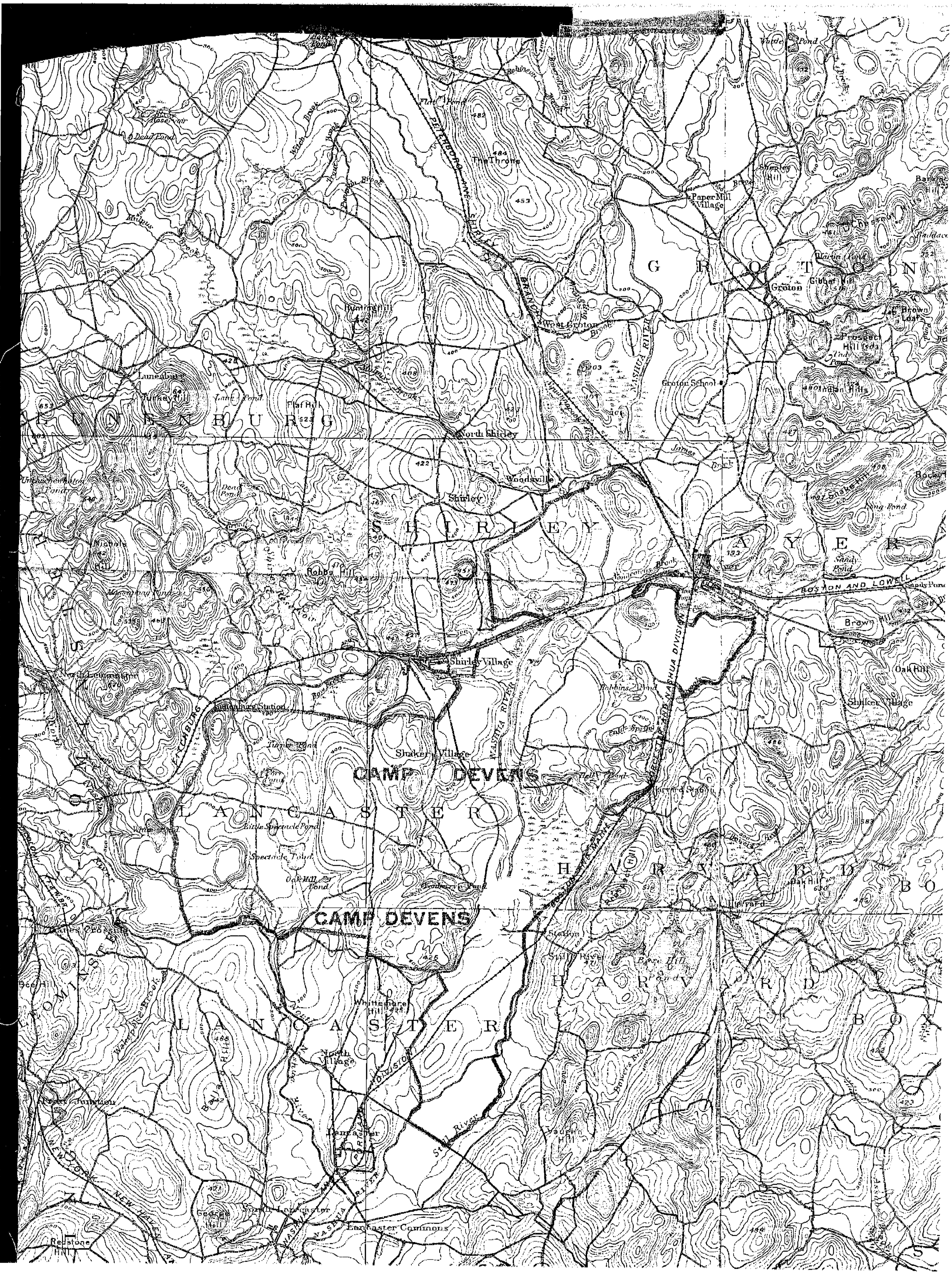

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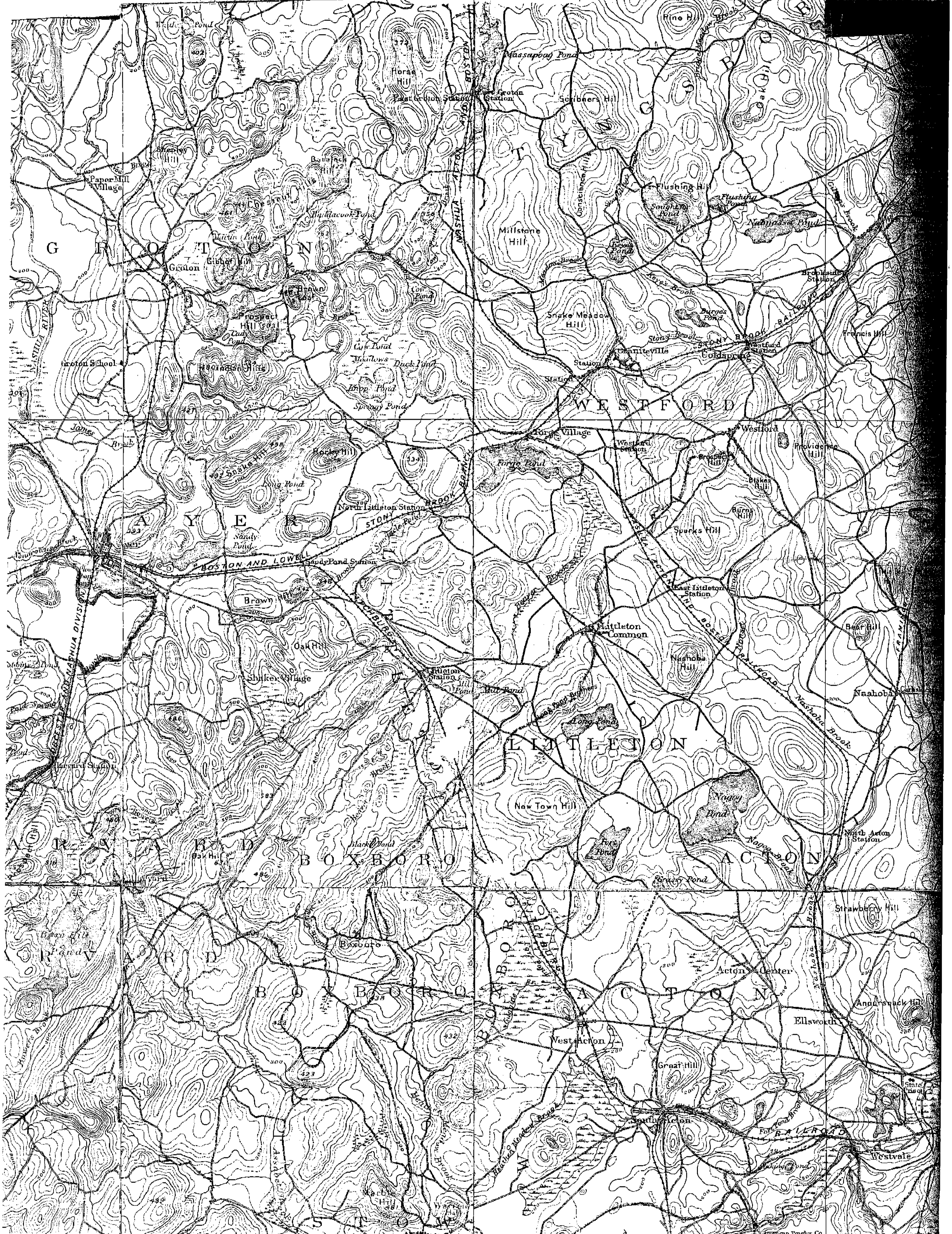
Groton
Gibbet Hill
Paper Hill Village
The Throne
West Groton
Groton School
Indian Hills
Prospect Hill
Hunting Hill
Lunenburg
Turkey Hill
Flat Hill
North Shirley
Woodsville
Shirley
S H I R L E Y
A Y E R
BOSTON AND LOWELL
Snake Hill
Long Pond
Sandy Pond
Brown Hill
Oak Hill
Shaker Village
Robbs Hill
Shirley Village
Lunenburg Station
FITCHBURG
NASHUA RIVER
NASHUA DIVISION
Robbins Pond
Shaker Village
Turner Pond
CAMP DEVENS
L A N C A S T E R
Little Spectacle Pond
Spectacle Pond
Oak Hill Pond
H A R V A R D
CAMP DEVENS
Still River
Bare Hill Pond
H A R V A R D
Whiteshore Hill
L A N C A S T E R
North Village
Lancaster
Vaughn Hill
North Lancaster
Lancaster Commons
George Hill
Redstone Hill


GROTON
AYER
WESTFORD
LITTLETON
BOXBORO
ACTON
HARVARD
Paper Mill Village
Groton
Groton School
Nashua River
Horse Hill
East Groton Station
Massapoag Pond
Scribners Hill
Pine Hill
Flushing Hill
Flushing Pond
Nabnasset Pond
Millstone Hill
Snake Meadow Hill
Keyes Brook
Burges Pond
Graniteville
Stony Brook
Coldspring
Westford Station
Brookside Station
Francis Hill
Baddacook Pond
Gibbet Hill
Prospect Hill
Cow Pond
Duck Pond
Knop Pond
Spring Pond
Forge Village
Forge Pond
Westford
Providence Hill
Sparks Hill
Snake Hill
Rocky Hill
Long Pond
North Littleton Station
Sandy Pond
Sandy Pond Station
BOSTON AND LOWELL
NASHUA ACTON AND BOSTON
East Littleton Station
Littleton Common
Nashoba Hill
Bear Hill
Nashoba
Nashoba Brook
Brown Hill
Oak Hill
Shaker Village
Littleton Station
Mill Pond
Long Pond
New Town Hill
Nagog Pond
Nagog Brook
North Acton Station
Fort Pond
Harvard Station
Strawberry Hill
Boxboro
Acton Center
West Acton
Ellsworth
Great Hill
South Acton
Fort Pond Brook
RAILROAD
Westvale
American Powder Co.


Pine Hill
Oak Hill
Flushing Hill
Flushing Pond
Nabnasset Pond
Newfield Pond
North Chelmsford
Middlesex Village
LOWELL
Lowell
Fort Hill
Wamesit
West Chelmsford
Brookside Station
Pine Hill
CHELMSFORD
TEWKSBURY
Chelmsford Center
Francis Hill
Chestnut Hill
Stony Brook
Coldspring
North Billerica
Long Pond
Robbins Hill
Rocky Hill
Westford
Westford Station
Providence Hill
Stakes Hill
Burns Hill
Sparks Hill
South Chelmsford
Beaver Brook
Farley Brook
Fox Hill
Main St. Station
BILLERICA
Billerica
Little Bear Hill
East Littleton Station
Bear Hill
Tophet Swamp
Riverhurst
Nashoba Hill
Rail Tree Hill
Nashoba
Carlisle Station
Carlisle
CARLISLE
South Billerica
Nashoba Brook
Nagog Pond
North Acton Station
Bellows Hill
Spencer Brook
Billerica Springs Station
BEDFORD
ACTON
Grassy Pond
Strawberry Hill
Acton Center
Annursnack Hill
Ellsworth
Punkatasset Hill
West Bedford
Bedford
Bedford Station
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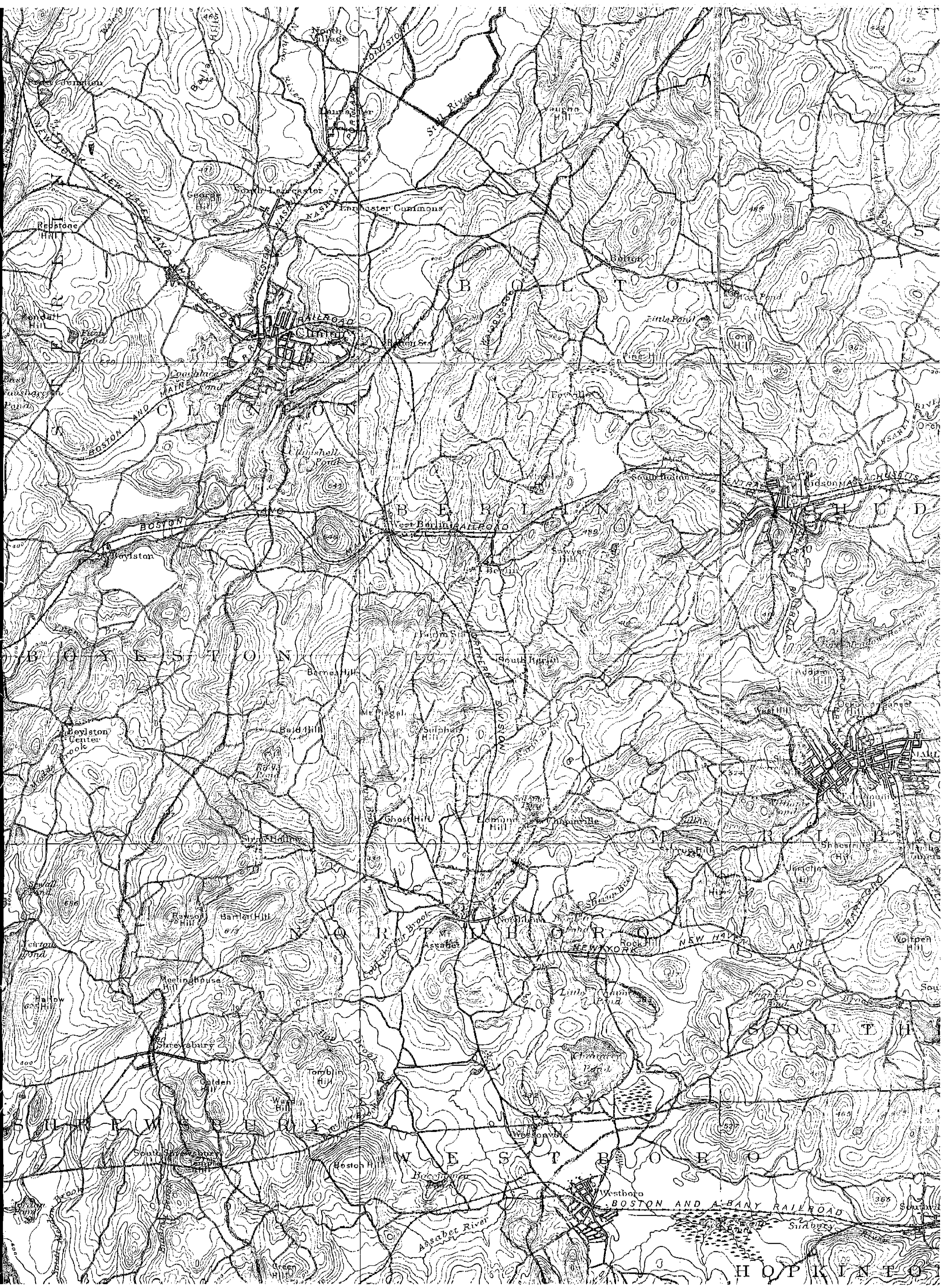
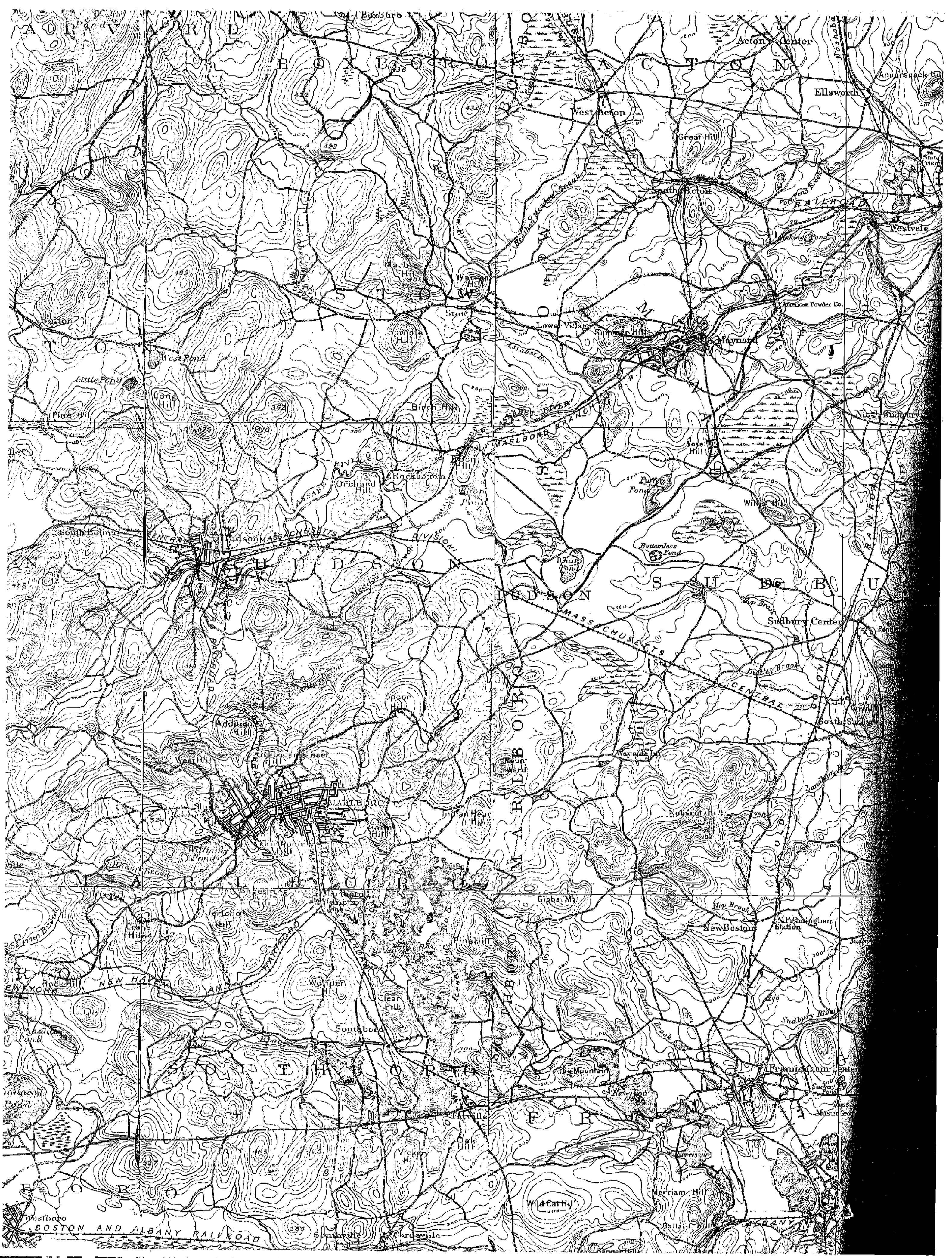
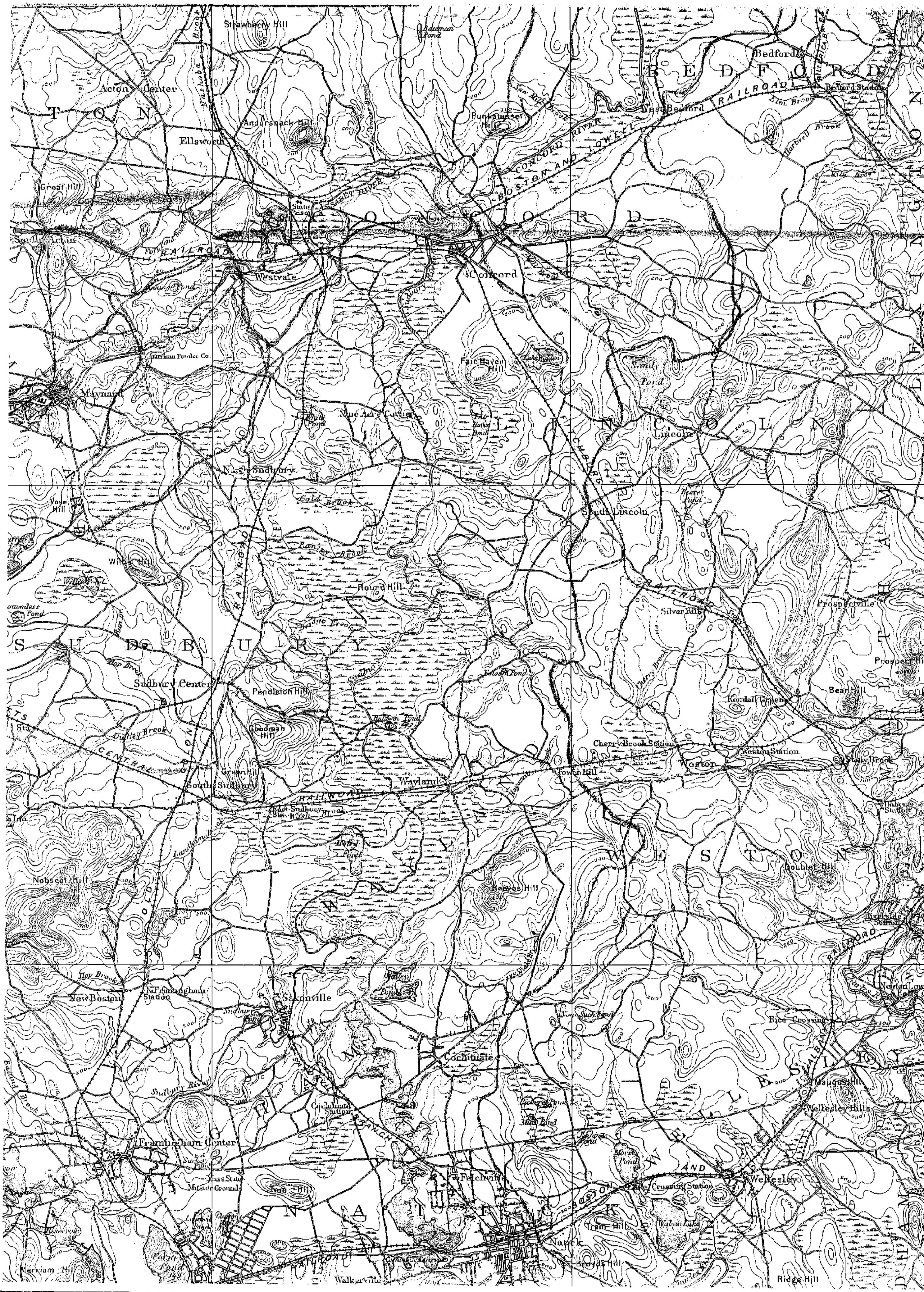
Elm Brook
Great Hill
CONCORD
South Acton
Westvale
Concord



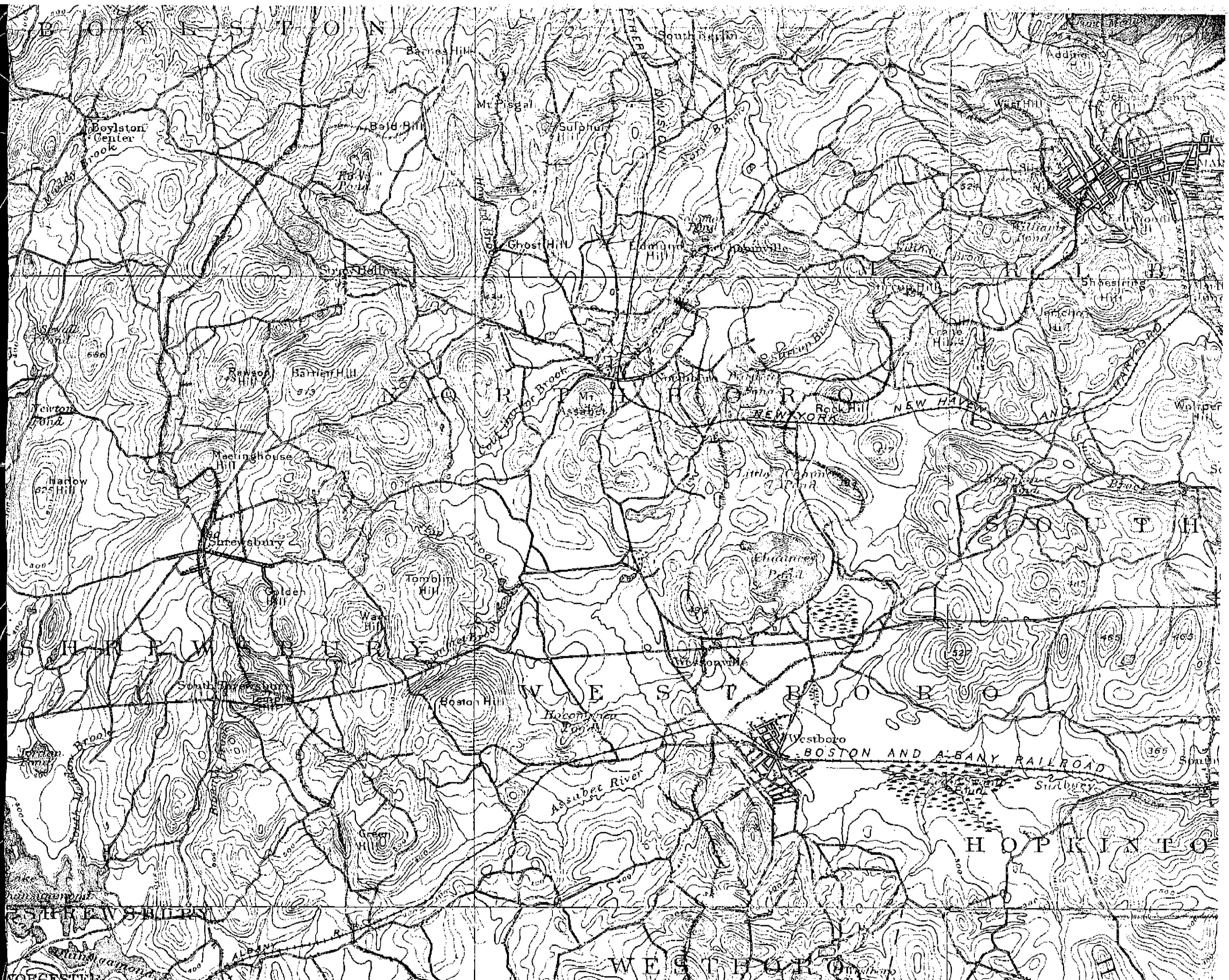
B O L T O N
C L I N T O N
B E R L I N
B O Y L S T O N
N O R T H B O R O
S H R E W S B U R Y
W E S T B O R O
North Village
South Lancaster
Lancaster Commons
George Hill
Redstone Hill
Kendall Hill
Clinton
Bolton
Little Pond
Pine Hill
Long Hill
Vaughn Hill
Still River
South Bolton
West Berlin
Berlin
Sawyer Hill
Boylston
Barnes Hill
Bald Hill
South Berlin
West Hill
Boylston Center
Ghost Hill
Rawson Hill
Sewall Pond
Northboro
Rock Hill
Meetinghouse Hill
Shrewsbury
Golden Hill
Ward Hill
Boston Hill
Westboro
Assabet River
Green Hill
Jericho Hill
BOSTON AND MAINE
BOSTON AND ALBANY RAILROAD
NEW YORK NEW HAVEN AND HARTFORD



B O X B O R O
A C T O N
Acton Center
Ellsworth
Anursnack Hill
West Acton
Great Hill
South Acton
RAILROAD
Westvale
American Powder Co.
Marble Hill
Warren Hill
S T O W
Stow
Lower Village
Maynard
Bolton
West Pond
Little Pond
Long Hill
Pine Hill
Birch Hill
Assabet River
MARLBORO BRANCH
Vose Hill
Puffer Pond
Willis Hill
Orchard Hill
Rockbottom
South Bolton
Hudson
MASSACHUSETTS
DIVISION
H U D S O N
Bottomless Pond
S U D B U
Hop Brook
Sudbury Center
MASSACHUSETTS
CENTRAL
Spoon Hill
West Hill
Wayside Inn
Mount Ward
MARLBORO
Nobscot Hill
Indian Head Hill
M A R L B O R O
Gibbs Mt.
New Boston
Framingham Station
Rock Hill
NEW YORK
NEW HAVEN
AND HARTFORD RAILROAD
Wolfpen Hill
Clear Hill
Southboro
Sudbury River
S O U T H B O R O
The Mountain
Framingham Center
Sucker Pond
Fayville
Oak Hill
Vickery Hill
Merriam Hill
Wild Cat Hill
Ballard Hill
Farm Pond
Westboro
BOSTON AND ALBANY RAILROAD
Southville
Cordaville



Strawberry Hill
Bedford
B E D F O R D
Bedford Station
West Bedford
Acton Center
Ellsworth
Concord River
Boston and Lowell Railroad
Great Hill
C O N C O R D
Railroad
Westvale
Concord
Fair Haven Hill
Sandy Pond
Maynard
L I N C O L N
Lincoln
Vose Hill
South Lincoln
Willis Hill
Round Hill
Silver Hill
Prospectville
S U D B U R Y
Prospect Hill
Sudbury Center
Pendleton Hill
Bear Hill
Kendall Green
Goodman Hill
Cherry Brook Station
Weston Station
Green Hill
South Sudbury
Wayland
Weston
Central
Railroad
W E S T O N
Nobscot Hill
Reeves Hill
Doublet Hill
Hop Brook
New Boston
Saxonville
Rice Crossing
Cochituate
Sudbury River
Maugus Hill
Wellesley Hills
Framingham Center
Wellesley
Boston
Nauck
Merriam Hill
Walkerville
Ridge Hill



BOYLSTON
Boylston Center
Barnes Hill
Mt Pisgah
Bald Hill
Sulphur Hill
South Berlin
Ghost Hill
Newton Pond
Rawson Hill
Bartlett Hill
NORTHBORO
Mt. Assabet
Rock Hill
NEW YORK
NEW HAVEN
Meetinghouse Hill
Harlow Hill
Shrewsbury
Tomblin Hill
Golden Hill
Ward Hill
Chauncey Pond
SHREWSBURY
South Shrewsbury
Boston Hill
WESTBORO
Hocomonco Pond
Westboro
BOSTON AND ALBANY RAILROAD
Assabet River
Green Hill
HOPKINTO
SHREWSBURY
WORCESTER
Millbury Junc.
North Grafton
WESTBORO
Fay Mt.
Woodville
Dorothy Hill
GRAFTON
Chestnut Hill
Grafton
Brigham Hill
MIDDLESEX CO.
WORCESTER CO.
Bear Hill
Keith Hill
George Hill
UPTON
Peppercorn Hill
Pratt Hill
Pratt Pond
North Milford
Fisherville
Farnumsville
Saundersville
Wilkinsonville
West Upton
Upton


Marlboro
Spoon Hill
Addison Hill
Wait Hill
Mount Ward
Indian Head Hill
Farm Hill
Wayside Inn
South Sudbury
Nobscot Hill
Hop Brook
Gibbs Mt
New Boston
N. Framingham Station
Sudbury River
Shoestring Hill
Pine Hill
Rock Hill
New York
New Haven and Hartford
Clear Hill
Southboro
Little Chauncy Pond
Chauncy Pond
The Mountain
Framingham Center
Sucker Pond
Mass. State Muster Grounds
Fayville
Vickery Hill
Farm Pond
Wild Cat Hill
Merriam Hill
Ballard Hill
Westboro
Boston and Albany Railroad
Southville
Cordaville
Banner Hill
Ashland
Hopkinton
Magunco Hill
Reservoir No. 6
Woodville
Whitehall Pond
Long Hill
East Holliston
Middlesex Co.
Worcester Co.
Bear Hill
Hayden Row
Holliston
Boundary Line
Peppercorn Hill
Pratt Hill
Pratt Pond
North Milford
Metcalf
Upton


Sudbury Center
Pendleton Hill
Goodman Hill
Green Hill
South Sudbury
Wayland
Cherry Brook Station
Weston
Weston Station
Kendall Green
Bear Hill
Stony Brook
W E S T O N
Doublet Hill
Nobscot Hill
Reeves Hill
New Boston
Saxonville
Cochituate
Rice Crossing
Maugus Hill
Wellesley Hills
Framingham Center
Felchville
Wellesley
N A T I C K
Natick
Merriam Hill
Ballard Hill
South Framingham
Walkerville
Broads Hill
South Natick
Ridge Hill
Peters Hill
Mooseville
S H E R B O R N
Charles River Village
Paul Hill
Pine Hill
Sherborn
Fegan Hill
Farm Pond
Long Hill
D O V E R
Snow Hill
South Sherborn
East Holliston
Cedar Hill
Nason Hill
Castle Hill
Rocky Woods
M E D F I E L D
Holliston
Medfield Junc.
Mt Nebo
Medfield
M I L L I S
Millis