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A Hydroclimatic Study of the Narragansett Bay Drainage Basin: The Effects of Climate and Urban Land Use on Runoff

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A HYDROCLIMATIC STUDY OF THE NARRAGANSETT BAY DRAINAGE BASIN: THE EFFECTS OF CLIMATE AND URBAN LAND USE ON RUNOFF

BY

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ABSTRACT

This study analyzes the relationship between the climate of the Narragansett Bay Drainage Basin and the increasing urban land use into a relative increase in runoff in the Basin streams. Data for thirty-five years were collected to discern the trends in runoff within the Basin.

It was hypothesized that runoff is increasing in relation to an increase in urban acreage. Runoff data were analyzed in two forms. The Thornthwaite water budget was used to estimate runoff. For this, Basin temperature and precipitation records were necessary inputs. The estimated runoff was plotted against observed runoff by double-mass analysis. Deviations from the actual runoff are indicative of changes in runoff which relate to changes in land use. When the estimate becomes less than the actual the trend would be for an increase in impervious surface. Precipitation was plotted against runoff as a further indication of increasing runoff in certain drainage areas. Comparisons were made between basins with an analysis of the relative change in urban acreage and the relative change in runoff over the thirty-five year period.

There were three major findings concerning the effects

of the climate and runoff in the Drainage Basin. A period of above average precipitation (the 1950's) finds a higher amount of runoff occurring. Conversely, a period of dry years (the mid-1960's) there is a large decrease in the amount of runoff within the study area. Runoff is increasing within areas of the Basin relative to the amount of precipitation. Those basins that are urbanizing at a higher rate than neighboring ones are showing a relative increase in runoff. In some areas there is one inch of runoff added for every two percent difference in urban acreage over the study period. In other cases a runoff rate of one inch of added runoff for every one percent difference in urban acreage was found. The increased runoff could be due to increased and intensified urban land use. Lastly, impervious surfaces did not increase runoff during all periods. A general trend was found where the higher the urban acreage within a basin, the more pronounced were the effects of the period of below normal precipitation of the mid-sixties on runoff. Less urbanized basins had a much better recovery rate after the dry sixties. There is a need for more studies of this type in large drainage basins, with the effects of all forms of land use on runoff being investigated.

ACKNOWLEDGMENTS

Many people have been very helpful at all stages of the preparation of this thesis. My major professor, Dr. James M. Havens, contributed ideas and criticism throughout the progress of the paper giving it unity and substance. Useful and practical suggestions were contributed by my other committee members, Dr. Henry J. Warman and Dr. John J. Fisher.

I would also like to thank the numerous people and agencies that led me to various data sources that were available to successfully undertake and complete this type of study. This group includes Mr. Hans Bergey of the Providence Water Supply Board, who assisted in the location of the Scituate Reservoir precipitation data. The assistance by Dr. Russell B. Capelle Jr. in the formative stages was immeasurable.

The undergraduate and graduate students, past and present, of the Geography Department assisted the completion of the thesis by their interest, encouragement, and answers to procedural questions. Lastly, I would like to thank my parents for six years of college.

CHAPTER 1

INTRODUCTION

As man increases in numbers in an area he changes the surface of the land to suit his purposes. He builds homes and apartment complexes to house himself from the elements. He concentrates business offices and factories in small areas, usually near expanding transportation networks that facilitate the movement of goods and services. He recently has discovered the convenience of large shopping malls and these often are built on previously undeveloped land. In this process man alters the natural features of the surface of the earth. Impervious surfaces that drain water through special channels replace the natural drainage provided by the soil and its vegetation. In addition, these man-made surfaces tend to modify the overlying atmosphere, producing, for example, higher temperatures.

This alteration of the natural landscape is a continuing process in southern New England. For Narragansett Bay the consequences could be of major importance. The population in the drainage basin of the Bay has been increasing since 1940. Along with this the amount of land being developed and the extent of impervious surfaces have increased. Because water from precipitation has less chance to percolate into the soil or to evaporate and transpirate as vapor into the atmosphere, it tends to run off directly into rivers and streams, thereby increasing the amount of water that flows into the Bay.

It is possible to determine the amount of runoff that is flowing into the Bay by analyzing the water records from river gauging stations. But just as important are the climatological factors that influence the runoff. By calculating the runoff from a model that takes into account temperature and precipitation it is possible to determine the years of increases and decreases in the actual runoff. In this manner a standard is set in which to observe the auged runoff that flows into the Narragansett Bay.

Formulation of the Research Problem

As will be seen below, urbanization tends to increase the amount of runoff flowing into a river system. This paper identifies the amount of added runoff that portions of the Narragansett Basin have produced. With the use of precipitation records, temperatures for the various stations, C. W. Thornthwaite's water budget equations, and gauging station records, it is possible to determine trends in runoff into the Bay.

Review of Relevant Literature

Most urban drainage studies have been of the following two types: (1) small watershed studies and (2) small urban flow studies in relation to sewage systems. In the first category, Ward[1] describes the objectives and methods of conducting a watershed study. He includes an extensive bibliography that concerns a variety of small watershed studies that have been performed in the past. A volume by Moore and Morgan[2] contains several papers concerning land-use changes in small watersheds. Divided into two sections, one deals with rural watersheds, and the other with small urban runoff areas.

In the second major category, most of the works deal with the impervious urban surface and its associated sewer system. An urban area lacks the degree of infiltration and evapotranspiration present in a rural area and therefore runoff characteristics within this area are different than those found in a rural area. In an urban area water tends to run off into streams at a faster rate and in greater amounts due to the impervious surface. Cities must, of course, consider these factors when designing their drainage systems. One such study by Tholin and Keifer[3] began to

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[1] R. C. Ward, Small Watershed Experiments (Hull, England: University of Hull, 1971), p. 132.

[2] W. L. Moore and C. W. Morgan, eds., Effects of Watershed Changes on Streamflow (Austin, Texas: University of Texas Press, 1969).

[3] A. L. Tholin and C. J. Keifer, "The Hydrology of Urban Runoff," Transactions of the American Civil Engineers, 125 (1960), 1353.

identify the effects of buildings and roofs, the percent of impervious surface, and slope of the land in relation to the intensity of individual storms. As a result of this type of study the University of Cincinnati designed a computer simulation of urban runoff. When applied to Chicago's sewer system it was able to estimate both the time of occurrence of surface runoff and its amount.[4] Other studies[5] have taken into account such factors as infiltration rates, intensity as well as amount of rainfall, length of travel in the watershed, and channel storage in an effort to estimate as accurately as possible the characteristics of urban runoff.

There have been some large scale studies that analyze the tendency in the annual runoff. Hoyt et al.[6] conducted one of the first of these important studies. He, and his associates, looked at the relation of a basin to its runoff,

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[4] C. Papadakis and H. C. Preul, "University of Cincinnati Urban Runoff Model," Journal of the Hydraulics Division, 98 (October, 1972), 1799.

[5] D. P. Heeps and R. G. Mein, "Independent Comparison of Three Urban Runoff Models," Journal of the Hydraulics Division, 100 (July, 1974), 1007; J. P. Riley and V. V. Dhruva Marayana, "Modeling the Runoff Characteristics of an Urban Watershed by Means of an Analog Computer," in Effects of Watershed Changes on Streamflow, ed. W. Moore and C. Morgan (Austin: University of Texas Press, 1969), p. 186.

[6] W. G. Hoyt et al., "Studies of Relations of Rainfall and Runoff in the United States," U. S. Geological Survey Water Supply Paper 772, (1936), 109.

and in particular the relationship between runoff and precipitation for various stations across the United States. For the Merrimack River near Lawrence, Mass., from 1880 to 1934 it was found that there was a tendency toward smaller amounts of runoff relative to the amount of precipitation during the later half of the period. They speculated that the change could be due to an increasing amount of transpiration and evapotranspiration or a land use change that negated the potential increase in runoff due to human activities.[7]

As the knowledge of man's influence on the environment has grown, investigators have included additional factors in their analyses of changes. Generalized studies that included the variety of ways man has altered former rural areas indicate that urbanization has significantly changed the magnitude and frequency of floods in the urban area.[8] Nationwide, studies have been undertaken to detect any changes in runoff in the past few decades. Busby[9] looked at various discharge records over long periods in New

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[7] *Ibid.*, p. 110.

[8] J. C. Schaake, Jr., "Water and the City," in *Urbanization and Environment*, ed. T. R. Detwyler and M. G. Marcus (Belmont, Calif.: Duxbury, 1972), p. 99.

[9] M. Busby, "Yearly Variations in Runoff for the Conterminous U. S., 1931-1960," *U. S. Geological Survey Water Supply Paper 1669-S* (1963), 49.

England and reported no general increase in runoff. Southern New England, however, shows a variable yearly runoff in Busby's study, with slightly lower than normal runoff during the 1940's and slightly higher than normal runoff in the 1950's.[10] Hidore[11] found that some streams in southern New England exhibited a long term increase in run-off, but during the climatological normal period of 1931-1960 very little change in runoff occurred in our area of concern.

The climatological and surface characteristics of a drainage area are important in that they determine the amount of water that is to be added to local rivers and streams. One study in Finland discovered that for a cold humid region the meteorological factors are more important in the amount of runoff than the characteristics of the basin.[12] In another study, Brater[13] looked at runoff near the city of Detroit and concluded that infiltration was the key factor in a flood investigation, as increases in the

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[10] Ibid., pp. 15-34.

[11] J. J. Hidore, "Annual, Seasonal and Monthly Changes in Runoff in the U. S.," Water Resources Bulletin, (June, 1971), 559.

[12] S. E. Mustonen, "Effects of Climatologic and Basin Characteristics on Annual Runoff," Water Resources Research, 3 (First Quarter, 1967), 129.

[13] E. F. Brater, "Steps Toward a Better Understanding of Urban Runoff Processes," Water Resources Research, 4 (April, 1968), 346.

amount of impervious surfaces decreases the ability of the water to infiltrate.

Waananen has been investigating the hydrology and increases in storm runoff in an urban area.[14] Later he looked at aspects of urban runoff and found that urbanization produced the following: an increase in the annual discharge, a decrease in the base flows (the amount of water provided by the groundwater supply to the stream), an additional input consisting of waste water, a decrease in recharge, and an increase in the amount of precipitation in urban areas.[15]

A study analyzing land use and runoff has been conducted in the Chesapeake Bay area. Using the Thornthwaite water budget Hartmann[16] calculated an increase in the yearly runoff over an area that had been urbanized. The percent of area in four types of land use was calculated with the Thornthwaite water budget calculated using the water holding capacity of that surface. By looking at two periods it was shown that urbanization has increased the surface runoff by

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[14] A. O. Waananen, "Hydrologic Effects of Urban Growth--Some Characteristics of Urban Runoff," U. S. Geological Survey Professional Paper 424-C (1961), 354.

[15] A. O. Waananen, "Urban Effects on Water Yield," in Effects of Watershed Changes on Streamflow, ed. W. Moore and C. Morgan (Austin: University of Texas Press, 1969), p. 181.

[16] B. J. Hartmann, "The Effect of Urbanization on Annual Water Yield," in The Influence of the Climatic Water Balance on Conditions in the Estuarine Environment, J. R. Mather, F. J. Swaye, and B. J. Hartmann (Elmer, N. J.: Laboratory of Climatology, 1972), p. 65.

0.1 inches per year.[17]

Changes in the surface of the land can cause several changes in streamflow.[18] Studies are currently being conducted in several countries in respect to increases in runoff, water quality, and water management.[19] The effect of urbanization on runoff is being closely studied in the United States. The American Society of Civil Engineers has set up a Task Force to investigate the need for further research.[20] One result has been the publication of an annotated bibliography of significant research both completed and in progress.[21] The need today is for additional investigations into the effect of urbanization on surface runoff as the country continues to expand, now and in the foreseeable future.[22]

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[17] Ibid., p. 65.

[18] N. H. Crawford, "Analysis of Watershed Changes," in Effects of Watershed Changes on Streamflow, ed. W. More and C. Morgan (Austin: University of Texas Press, 1969), p. 30.

[19] M. B. McPherson, Hydrological Effects of Urbanization, (Paris: Unesco Press, 1974), p. 22.

[20] Task Force, "Effect of Urban Development on Flood Discharges--Current Knowledge and Future Needs," Journal of the Hydraulics Division, 95 (January, 1969), 292.

[21] Ibid., p. 293.

[22] M. B. McPherson, "The Nature of Changes in Urban Watersheds and Their Importance in the Decades Ahead," in Effects of Watershed Changes on Streamflow, ed. W. Moore and C. Morgan (Austin: University of Texas Press, 1969), p. 162.

Methodology

Study Area and Data Sources

The area to be investigated is the drainage basin of Narragansett Bay. This area includes most of Rhode Island and a section of Massachusetts. Characteristics and features of the basin will be described in more detail in Chapter 2.

Monthly precipitation and temperature records were gathered from stations either within or adjacent to the drainage basin for January 1940 to December 1974, a period of 35 years. Runoff data were obtained for this period for the several basin rivers that are gauged. The sources of these data, along with their application will be described in Chapter 5.

If there are definite increases in runoff then the added water is due possibly to the change in population within the particular basin. The most appropriate method of study would be by investigating the change of acreage within the area from the beginning of the study to its conclusion. These types of studies were very rare in the early forties. In fact, upon investigation it was found that the first land use survey of the state of Rhode Island of any major importance was conducted as recently as 1962. Information for Massachusetts, however, is available for both an earlier and a later period. In 1951 the entire state was surveyed by towns to determine the acreage amounts within the communities. MacConnell and his associates updated this information in 1971 in such a way that the acreage statistics are comparable.[23] The major difficulty with using this information is that river basins generally do not follow the community boundaries. As a result use of this valuable information will be limited to an estimate of the amount of acreage that has been urbanized.

In those cases where urban acreage statistics are not available the use of population density statistics may be indicative of land use changes. Brater, in his Detroit study, found that a hydrologically significant impermeable area was related to the population density of the area.[24] By comparing similar population density areas with areas of higher urban acreage he was able to determine that the

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[23] W. P. MacConnell, Remote Sensing 20 Years of Change in Plymouth County Massachusetts, 1951-1971 (Amherst, Mass.: Cooperative Extension Service, University of Massachusetts, 1973); W. P. MacConnell and A. Mueller, Remote Sensing 20 Years of Change in Bristol County Massachusetts, 1951-1971 (Amherst, Mass.: Cooperative Extension Service, University of Massachusetts, 1973); W. P. MacConnell and W. Niedzwiedz, Remote Sensing 20 Years of Change in Worcester County Massachusetts, 1951-1971 (Amherst, Mass.: Massachusetts Agricultural Experiment Station, 1974); W. P. MacConnell, H. R. Pywell and P. E. Young, Remote Sensing 20 Years of Change in Suffolk and Norfolk Counties, Massachusetts, 1951-1971 (Amherst, Mass.: Massachusetts Agricultural Experiment Station, 1974); Comparable statistics were gathered for Rhode Island based upon information in 1970 and published in the following source: W. P. MacConnell, Remote Sensing Land Use and Vegetative Cover in Rhode Island (Kingston, R. I.: Cooperative Extension Service, University of Rhode Island, 1974).

[24] Brater, p. 346.

amount of impervious surface increased at about the same fashion as the population densities.[25] Although population density is not the most preferred measurement, in some cases it suffices as an indicator of urbanization within the drainage basin.

Hypothesis

An increase in population in the drainage basin of Narragansett Bay should lead to an increase in the areal extent of impervious surfaces. Therefore, there should be a corresponding increase in the amount of runoff into streams flowing into the Bay. It is hypothesized that runoff has been increasing through the past thirty-five years in relation to the amount of precipitation with one factor being urbanization.

It is expected that use of the Thornthwaite water budget model, applied for average soil conditions in the basin, will indicate deviations from expected river flow. Large deviations in one section of the basin compared to another may be attributed to increasing urbanization.

Methodological Techniques

The main technique will be to use the Thornthwaite water budget system, on a monthly basis, to determine runoff. This process will be explained further in Chapter 4.

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[25] Ibid., p. 345.

The emphasis will be on the use of monthly data for precipitation, temperature, and runoff. Areas of detailed analysis will be those basins that have adequate discharge figures and include areas of increasing urbanization. The findings at these stations will be the major indicators of any runoff tendencies during the period of analysis.

The major method of study is double-mass analysis. Data are plotted on a cumulative basis for two related factors, such as precipitation and actual runoff or calculated runoff and actual runoff. There are three factors that must be met to use this method accurately.[26] First, the two factors must be highly correlated. Second, the data should be homogeneous. In other words, there should be no breaks in the records or station changes during the period of analysis. And third, the factors should be directly proportional to one another. It is felt that precipitation and runoff, while correlated to a high degree, do not correspond to a set ratio. The higher the amount of precipitation the higher is the relative amount of runoff. The less precipitation there is the smaller the percent that runs off. Kohler[27] has suggested a correction should be

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[26] H. W. Anderson, "Detecting Hydrologic Effects of Changes in Watershed Conditions by Double-Mass Analysis," Transactions of the Geophysical Union, 36 (February, 1955), 119.

[27] M. A. Kohler, "On the Use of Double-Mass Analysis for Testing the Consistency of Meteorological Records and for Making Required Adjustments," Bulletin of the American

made with these two factors, dealing with homogeneity and amount of precipitation, but it will not be used here. It will be assumed that the calculated runoff should be an accurate indicator of actual runoff and any double-mass analysis in this format can be related to the precipitation and actual runoff of that region.

When these factors are considered, double-mass analysis becomes an indicator of changes affecting the two factors. Precipitation can be considered to be constant for a region while the amount of runoff will be variable due to the surface factors that influence it. The effect also will be shown with the Thornthwaite estimate of runoff, which considers only the climatological effects, not the surface features or changes. Any changes in the slope of fitted linear equations during these years should be indicative of changes in one of the two factors being plotted, either precipitation and actual runoff or calculated and actual runoff.

If the location of a station remains constant throughout the period then slope changes would most likely be indicative of changes in the runoff regime. Anderson found that the double-mass technique was appropriate for the "detection of hydrologic effects of changes in watershed

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Meteorological Society, 30 (May, 1949), 189.

condition."[28] Therefore, it is possible to use double-mass analysis as a tool in investigating the runoff of a drainage basin.

Graph 1 is an example of the method used to plot the data. Yearly points are plotted on a cumulative basis for the analysis of the two factors. The cumulative data are plotted for all stations and the various changes, or breaks, in the slopes estimated by eye. The data were then entered into the Statpack program of the University of Rhode Island Academic Computer Center. One function of this program is to provide regression analysis. Particular attention was given to the slopes of the best fit lines which became the focal point of analysis. In Graph 1 three sample regression equations are included, containing two break periods. It is the M or slope factor of the equation that is the indicator of changes in the double-mass graph. Any changes in the slopes through the years for a particular station, or in comparison to another station, would be indicative of a change in the runoff. By plotting the various lines of "best fit" the amount of change of runoff can be determined.

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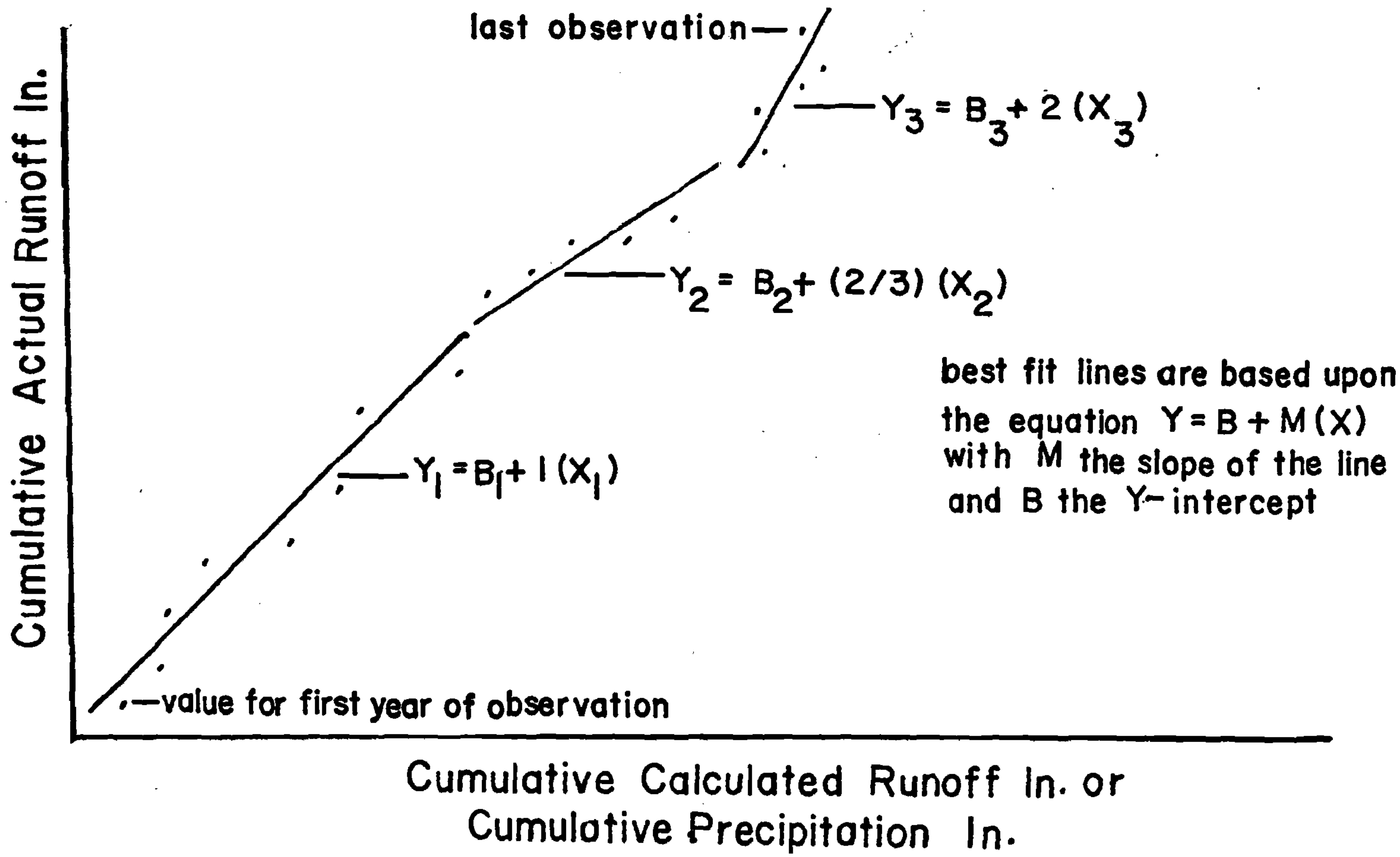
[28] Anderson, p. 125.

GRAPH I
Example of Double Mass Analysis



CHAPTER 2

THE NARRAGANSETT BAY DRAINAGE BASIN

A major landscape feature of southeastern New England is Narragansett Bay. The Bay with its access to the open sea has served many purposes. During the summer it is a major recreation area with its many beaches and facilities for boating. Fishermen find its setting practical for the commercial aspects of their trade. The U. S. Navy has used the location for naval and naval air stations which recently have been abandoned due to Armed Forces cutbacks. These former government facilities may be used in connection with the drilling of oil off the New England coast and nuclear power stations.

The Physical Setting

Rivers that flow into Narragansett Bay go through several communities in the states of Rhode Island and Massachusetts. The drainage basin consists of 862 square miles (2233 square kilometers) of Rhode Island and 1052 square miles (2725 square kilometers) of Massachusetts.

The total basin includes 94 communities in the two states.[29]

Map 1 delineates the drainage basin and locates the major cities within the basin. This area contributes the water that flows into the Bay. The geological structure and surface characteristics of the Basin, as well as its climatological factors, are important in determining the amount of runoff that actually occurs.

Regional Geology

There are four basic geological features within the drainage basin.[30] The first consists of old metamorphic rocks of the Blackstone basin. Extending from Woonsocket to Worcester this area is composed of quartzite, schists, and marble along with granitic rock in the Northbridge area. These metamorphic rocks are particularly resistant to

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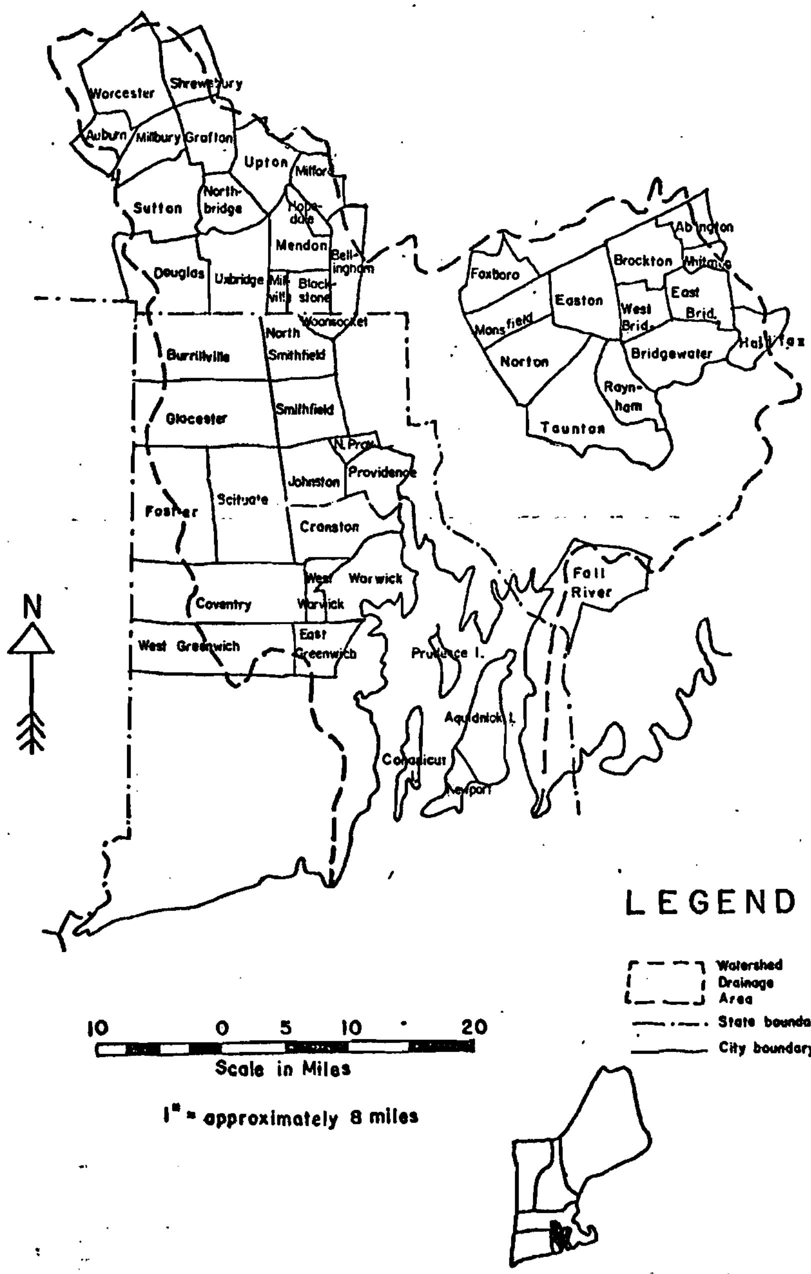
[29]The drainage area of the Bay was determined from maps of the following publications: L. M. Alexander, Narragansett Bay: A Marine Use Profile (Washington: Office of Naval Research, 1966), p. 75; C. E. Knox and T. J. Nordenson, Average Annual Runoff and Precipitation in the New England-New York Area (Washington: U. S. Geological Survey Department of the Interior, n.d.), p. 3; New England River Basins Commission, Narragansett Bay Planning Area Report (Boston: New England River Basins Commission, 1975), cover; Water Resources Board, Rhode Island River Basins Part I (Providence: Water Resources Board, 1971), p. xi.

[30]The geology of the Bay region is based upon the following three studies: A. W. Quinn, "Bedrock Geology of Rhode Island," U. S. Geological Survey Bulletin 1295 (1971); B. K. Emerson, "Geology of Massachusetts and Rhode Island," U. S. Geological Survey Bulletin 597 (1917); A. W. Quinn, Rhode Island Geology for the Non-Geologist (Providence: Rhode Island Department of Natural Resources, 1973).

MAP I

NARRAGANSETT BAY DRAINAGE BASIN AND MAJOR CITIES



erosion. The Blackstone formation constitutes the oldest rocks and substructure found in the Basin.

Much of western Rhode Island consists of the same type of rock as found in the Blackstone basin, but granite is especially abundant. One major difference is that the rocks of this area are not as old as those found to the north. Because they are igneous in nature they also erode very slowly.

The third major geological feature of the study area is the sedimentary rocks of the Narragansett basin. They are found north of the Bay and throughout the eastern section of the drainage basin where coal seams, estimated to be 300,000,000 years old are located. Rapid weathering has occurred in parts of this area. Coal mining once was conducted in this area but is proved to be unprofitable.

Lastly, the far southern part of the drainage basin consists of granitic rocks of the Post-Pennsylvanian period with an overburden of glacial deposits. It was during this period of glacial deposition, prior to 12,000 years before present, that isostatic down warping occurred. As the glacier retreated the ocean advanced over the lowered land to form Narragansett Bay. Other glacial effects in the area consist of till deposits, moraines, outwash plains, and eskers.

Surficial Drainage

As indicated on Map 2 three major streams drain the bulk of the basin. The eastern portion is drained by the Taunton River. Starting in Brockton and east of Plymouth, the Taunton Flows southwesterly to Fall River where it empties into Mount Hope Bay. A key stream in this section is the Wading River which drains the western portion of the Taunton River Basin. This is the area of the Narragansett coal seams.

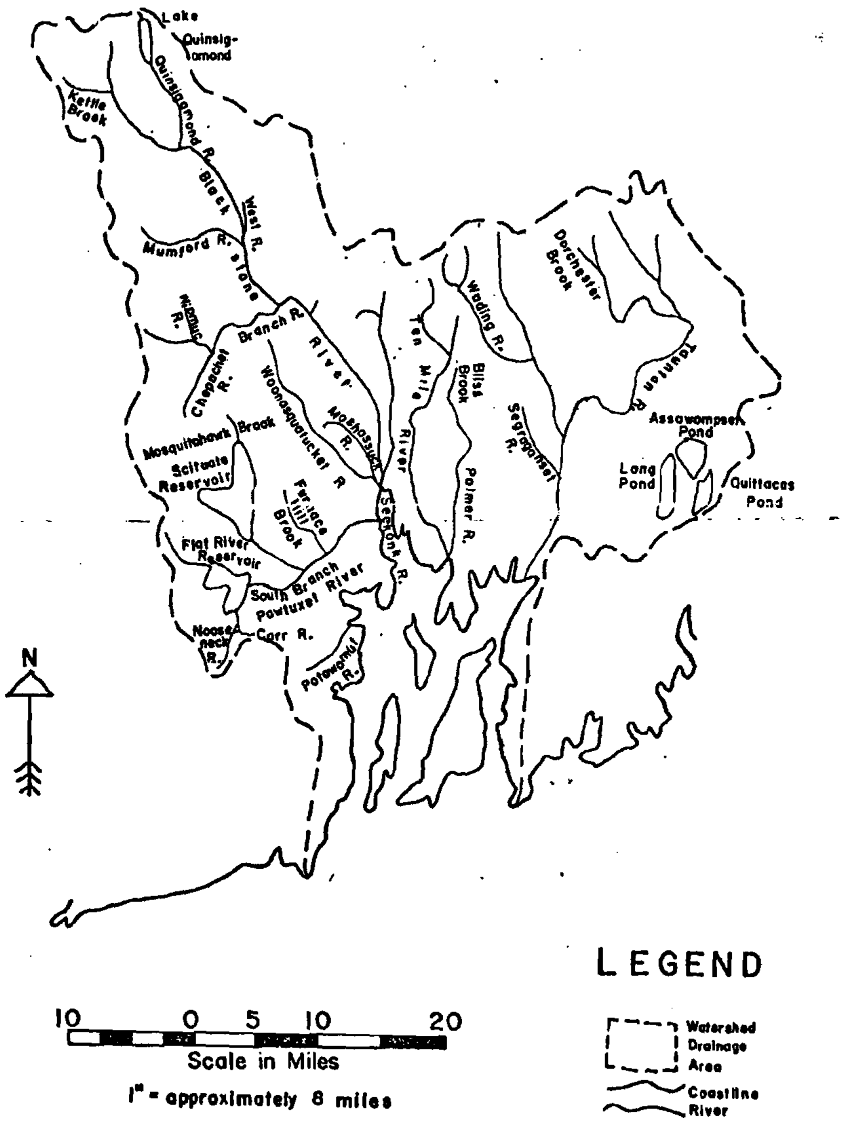
The Blackstone River drains the area north and west of the Bay. Starting in Worcester, the source of water includes Lake Quinsigamond. The stream crosses into Rhode Island at Woonsocket and flows south toward Pawtucket where it becomes the Seekonk River. The Seekonk is a tidal extension of the Bay. Two major streams that flow into the Blackstone are the Mumford River in Massachusetts and the Chepachet/Branch River system in Rhode Island.

Central Rhode Island is drained by the Pawtuxet River. The northern branch flows out of the Scituate Reservoir, while the southern branch drains the Flat River Reservoir area. The two branches meet in West Warwick, and then the Pawtuxet flows through Cranston and empties into the Seekonk River at Warwick.

In addition to the above major river systems four minor streams drain a portion of the land area. The Ten Mile River drains the area between the Taunton and

MAP 2

MAJOR RIVERS OF THE NARRAGANSETT BAY DRAINAGE BASIN



Blackstone River basins. The Moshassuck and Woonasquatucket Rivers drain the area between the Blackstone and Pawtuxet Rivers, flowing into the Seekonk River at Providence. And the area south of the Pawtuxet River is drained by the Potowomut River.

The remainder of the Narragansett Basin is drained by small rivers and streams that do not have significant headwaters. This area includes the islands that are within the Bay itself as well as those areas immediately adjacent to the Bay that have not been previously described.

Regional Climatology

Important in the runoff regime of a stream are the amount of precipitation an area receives and the amount of moisture that is available to evaporate and transpire to the atmosphere. According to the Thornthwaite climate classification[31] this area has a humid moist climate with a surplus of moisture on a yearly basis. Under the Koppen classification the study area has a moist climate with cool summers and cool winters. These regional classifications indicate that the area throughout the year receives an adequate amount of precipitation which is distributed quite equally among all months. There is a temperature range of

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[31] C. W. Thornthwaite, "An Approach Toward a Rational Classification of Climate," Geographical Review, 38 (January, 1948), 77.

about 40°F between the warmest and coldest months of the year.

Average annual temperatures in the Basin decrease away from the southern coastal areas toward the higher elevations of the northwest quarter.[32] Annual temperatures along the south coast average about 51°F while in inland Rhode Island and adjacent Massachusetts they average about 49°F. The northwest quarter is the coolest section with temperatures averaging about 48°F. The eastern section of the Basin has temperatures averaging about 50°F.

Although precipitation in the area is distributed quite equally during the year, summers tend to be slightly drier than the other seasons. However, a major characteristic is the fact that climatologically the basin does not experience a series of significantly dry or wet months. During a particular year, however, precipitation can be quite variable. A very wet month, with precipitation in excess of seven inches, can be followed by a month with less than two inches. Occasionally heavy rains can occur repeatedly for several months. For example, the year 1972 was one of the wettest on record with annual precipitation totals in the basin generally more than 60 inches. Conversely, a series of dry years, such as the mid-sixties, can also occur.

[32] Unless otherwise stated the temperature and precipitation data were taken from the following source: U. S. Department of Commerce, Climates of the States, vol. 1 Eastern States (Washington: National Oceanic and Atmospheric Administration, 1974).

Spatially the average annual precipitation is distributed fairly uniformly over the basin. The lowest precipitation occurs in the immediate area of the Bay with totals on the order of 40 inches. Away from the Bay precipitation increases, reaching totals of 48 inches in the far west-central portion of Rhode Island. Over much of the remainder of the drainage basin annual precipitation is generally between 43 and 45 inches. Knox and Nordenson found similar results in their precipitation study which covered the years 1930-1949.[33]

The precipitation values for the period of record used in this study indicates that the above figures, which are based on the years 1931-1960, are slightly lower. The area around the Bay averaged about 44 inches of precipitation yearly while westward precipitation increased to 47 inches and then to 50 inches in the "wet" portion of the study basin. The precipitation for the remainder of the basin averaged between 44 and 46 except for a dry area southwest of Worcester.

There have been four distinct periods of yearly precipitation amounts within the 35 year study period. A fairly dry period occurred during the 1940's with precipitation in the Worcester area on the average in the upper thirties. In the area of the Bay and eastward precipitation

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[33]Knox and Nordenson, p. 5.

was slightly over 40 inches. Precipitation increased westward from the Bay to 43 inches then to a peak of 47 inches in west-central Rhode Island.

During the 1950's precipitation increased throughout the Basin. Western Rhode Island received well over 50 inches while the area adjacent to Narragansett Bay averaged about 47 inches. The remainder of the Basin averaged between 47 and 48 inches.

The years 1963-1966 were a period of less than average precipitation. The majority of the Basin averaged between 34 and 36 inches of precipitation for those four years. The northwest quarter, though, averaged closer to 37 inches. Central Rhode Island averaged 38 inches of precipitation while the western section averaged 42 inches of precipitation for those years.

The period following 1966 has been particularly wet. The Bay area has received about 47 inches of precipitation annually with totals in western Rhode Island up to 56 inches. The remainder of the drainage Basin has averaged about 48 to 50 inches annually.

Groundwater

The groundwater that exists is the precipitation that percolates to the water table.[34] It is this water that

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[34] Quinn, p. 83.

feeds streams year around and the important source of river water during dry periods. As was stated above soil is important in the amount of water the ground can hold and transmit. At many places within the study area the groundwater can be seen at the surface as lakes and swamps. Other places have poor water bearing soils that diminish the ability of wells to supply water to consumers.

One of the important sources of water within the Basin is water that is stored in ponds and lakes. Two in Rhode Island are significant: the small Flat River Reservoir and the Scituate Reservoir (see Map 2). The latter is the water supply for the city of Providence and covers about 4,000 acres of central Rhode Island. There are two important areas of water in the Massachusetts portion. One is the Long Pond/Quittacas Pond/Assawompsett Pond area located in the southeast corner of the Basin. Another source of surface water is Lake Quinsigamond which commences in the Worcester area. Both areas are identified in Map 2.

The major feature of the area is the Narragansett Bay itself. The water area of the Bay is about 174 square miles (451 square kilometers).[35] It has an irregular coastline of about 250 miles (402 kilometers). Identified on Map 1 are the three major islands within the Bay: Prudence Island, Conanicut Island, and Aquidnick Island.

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[35]Alexander, p. 83.

The Urban Setting

Man has entered the region, changing and modifying the landscape. He cleared the land of its natural vegetation and introduced cities and towns. Even though many people live within the drainage basin half of the area is forest covered. This area consists mostly of maples, birches and oak trees with occasional pine. These trees tend to be deep rooted which increases the water holding capacity of this soil. The soil within the region has a high enough water holding capacity to permit some agriculture.

According to the 1970 census there are approximately 1,575,000 people residing within the Narragansett drainage Basin. The population is concentrated in the following five areas.[36]

Almost all of the city of Worcester is included within the Basin. The city itself has a population of about 175,000 which represents a decline in the past 20 years of 13 percent. Its four southern suburbs have been increasing in population within this period.

Brockton is one of the fastest growing cities in Massachusetts, and it presently is becoming a suburb of Boston. According to the 1970 census it had a population of 89,040, an increase of 42 percent in a twenty year period.

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[36] The population statistics were culled from the remote sensing volumes cited in Chapter 1.

Taunton is an industrial city which has shown a small but steady increase in population of 9 percent in twenty years. It has about 44,000 within its boundaries while the surrounding communities have a much smaller population but a steadily increasing one.

Woonsocket, on the Blackstone River in northeastern Rhode Island, is exhibiting a decreasing population. With about 47,000 people, it is an old industrial community.

Providence, too, has shown a decreasing population, presently about 179,000. But the trend here is to its suburbs, northeast into Pawtucket and Attleboro, Massachusetts, and southwest to Cranston, Warwick and West Warwick. The population of the Providence Standard Metropolitan Statistical Area (the city and its suburbs) is over 910,000 according to the 1970 census.

There are two other areas of significant population. First is Aquidnick Island (Newport, Middletown, Portsmouth) which had a 1970 population of over 75,000. This has been an area of increasing population, which could be arrested due to the closing of major components of the Naval base. The other major city is Fall River. It contains over 95,000 people but not all are necessarily within the drainage basin as the line of runoff runs through the far western section of the city. But this small area is highly urbanized and contains many residents. The other communities not mentioned are much smaller with varying amounts of population. Map 1 includes those cities and towns that form the land areas to be analyzed in Chapter 6.

A few general trends are apparent from the above section. There is a major trend in the country to leave large urban areas. For the large, highly industrial communities of the drainage basin population is increasing slowly, or in many cases declining. With the trend to the suburbs, neighboring communities are absorbing population increases. This is causing small towns to grow rapidly and increases the land in the community that is being used for urban purposes. One exception to this trend would appear to be Brockton. But its new population is based upon the migration from greater Boston.

As population increases services to the residents must increase. The result here is land being used for commercial, industrial, and residential purposes at an increasing rate.

The foregoing has been a brief look at the physical condition and population distribution of the Narragansett Drainage Basin. The physical features and environment are important in the runoff process. As man changes the environment, or physical processes work naturally, the result will be changes in all aspects of life within an area.

CHAPTER 3

THE HYDROLOGY OF A DRAINAGE BASIN

There are many factors connected with the amount of water that runs off the land and into the sea. Several have already been mentioned. Precipitation is the major component in the amount of water that is to fill the streams. It is apparent from the Thornthwaite water budget that temperatures play the crucial roll in the amount of water that is to evaporate and transpirate. The slope of the land and surface cover is important in the quantity and timing of the runoff. It is the hydrology of the basin that defines the amount and type of runoff.

General Hydrology

The water that runs off into Narragansett Bay is basically the result of precipitation within the drainage area. There are no major groundwater supplies emptying within the basin with their sources outside of it. Some water, though, is brought in from outside the drainage basin to be used as drinking water by an urban area. A good example of this is the city of Worcester's water supply which lies outside of the drainage basin. The use of this extra source could increase the runoff from certain areas.

The precipitation that falls is intercepted at the surface. Some of it becomes trapped above the ground by the trees and vegetation.[37] A very light rain may never reach the ground as it is caught and later evaporated from surface vegetation. Urban areas also trap precipitation.[38] Roofs, gutters and some drains collect rain, often trapping it and preventing it from adding to the surface runoff. Asphalt parking lots, holes and other low lying areas of the surface can trap the water forcing it to evaporate rather than run off. Most often in urban areas the precipitation that does fall is collected by the storm drainage system and transported to an area where it is released and allowed to flow naturally. This method applies to rainfall, but snow acts as a delay in runoff. Very little runs off and interception from vegetation may be much less.[39] The bulk of the runoff occurs when the temperatures are warm enough for the melting process. In urban areas it is imperative that snowfall be removed quickly as it is a disruptive factor. Snowfall on streets is often removed to

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[37] J. P. Bruce and R. H. Clark, Introduction to Hydrometeorology, (Oxford, England: Perganon Press Ltd., 1966), p. 34.

[38] R. C. Ward, Principles of Hydrology (London: McGraw-Hill, 1967), p. 184.

[39] Deciduous trees would hold little snow while a coniferous forest would trap the snow and evaporate it, with time.

a dumping location, which could possibly be outside the watershed on which it fell. As with rain, some areas of the city trap snow and it evaporates before it has the chance to increase the runoff. The urban environment is usually warmer than the countryside and this quickens the melting of the urban snowpack.

Part of the rainfall infiltrates the ground and percolates through the soil until the soil is saturated. The movement of the water into the soil depends upon the porosity of the soil: the larger and more frequent the pores, the quicker the water will percolate. A soil that has been compacted can cause a lag in the infiltration process. Surface conditions are a major influence on the amount to be percolated. Vegetation increases the amount added into the soil, as opposed to bare soil which usually is compact with small porous surfaces.[40] Agricultural crops and grassy areas can have highly variable amounts of infiltration.[41] The impervious surface of an urban area causes infiltration to be virtually zero. The water that is available to infiltrate can not due to the changed surface and is carried away by a drainage system. This is one way that urbanization has drastically influenced the hydrology of an area.

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[40] Bruce and Clark, p. 184.

[41] _Ibid._, p. 40.

The water percolates through the soil until it becomes part of the groundwater. The type of soil becomes the important factor in whether it will bear water. The more porous the soil the more air spaces there are that can be filled with water. This type of soil, called permeable, will hold much water and acts as the groundwater. Usually there is an underlying confining layer consisting of impermeable material, possibly some type of clay soil, which retards the movement of water any farther. The result is a reservoir of water within the ground.

The action within the layer is important. The input[42] usually comes from the precipitation on the surface that percolates down to that layer (although it is possible to have sources for the water table up to 200 miles away). The water table often intercepts surface water bodies. Recharge of the water table can come when water is added to it by surface water bodies (rivers, lakes, oceans). In some areas water moves from leakage of the different types of soils, in this case adding water to a certain area. Artificial recharge is less frequent. It involves the adding of water to the ground for irrigation, forcing recharge water into the ground, or land modification that changes the surface so that there is a new source of water for the water table.

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[42] Ward, <u>Hydrology</u>, p. 225.

There are five major methods of discharging water from the groundwater supply.[43] First, there is the evapotranspiration of surface vegetation. It was mentioned above that plants and trees catch precipitation and evaporate the moisture back to the atmosphere. Another source of moisture comes from transpiring the moisture it receives from the ground. The roots of crops and trees usually penetrate the area near the water table drawing from it necessary moisture. Some crops are short rooted and need their moisture supply close to the surface. Large trees can penetrate much deeper into the soil to extract its moisture. Should the water table for some reason be lowered to the point where the vegetation receives little moisture, the plants would wither. It is important that the water table be recharged effectively for the surface vegetation to thrive.

The second form of discharge is groundwater that can seep deeper into the ground. The impermeable layer is not water tight and a certain amount of loss can occur here.

The third method of loss is water that is artificially extracted from the soil by wells. Communities as well as individual homes, depend upon the groundwater for their drinking water. This action can have serious effects on the height of the water table and can result in lowering the

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[43] _Ibid._, p. 256.

height of the water table and can result in lowering the height of the water table if over used.

The fourth and fifth types of groundwater loss occur in two types of contact zones with the surface. Springs usually occur when the water table interacts with the land. This case has water flowing from the ground onto the surface and running off. The last type of loss is when the water table interacts with surface water. Water seeps through the soil and is added to a lake, river or possibly the ocean.

Therefore, part of the water that runs off through the rivers into the Bay does occur from the groundwater. The other major input into a river is the water that runs off the land. As it rains water collects in surface channels and small streams (or urban drains) and flows over the surface and into local streams. The rate of fall of precipitation is a key factor in the surface runoff. A light, steady rain has a good chance of infiltrating the soil, decreasing the amount of surface runoff. A hard, driving rain in a short period of time that leaves much water will not percolate through the soil. It will collect rapidly on the surface and move quickly along low surface channels and into local streams. Its rapid movement does not give it time to seep into the ground.

Surface structure influences surface runoff. In highly sloped areas rain will runoff quickly downhill and have little time to infiltrate. Urban areas, which allow for virtually no infiltration, will create much surface runoff.

Surface runoff, along with the groundwater (which is really delayed runoff), are the two most common sources of river water.

Two minor, but important, sources also occur within a drainage basin. Some of the surface runoff does enter the soil and can flow laterally (within a few feet of the surface) toward a stream.[44] This water does not reach the water table and can not be considered surface runoff. The other factor is precipitation that occurs directly upon a river or its tributaries. All of this water would naturally flow along with the river water.

Within the Narragansett Bay drainage Basin this process occurs many times until the rivers flow into the Bay. This has been the description of the ideal flow of a river. But there are subtleties, some major, that can have varying effects upon the runoff regimen. Some of the changes that can occur (climatic, urban and others) will be stressed as other investigators have found that changes in the environment of a basin can abruptly change the hydrology.

Climatic Hydrology

The weather plays a major role in the runoff regime of a river. As has been stated previously precipitation is

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[44] Bruce and Clark, p. 45.

the key factor. An excess amount of rain will obviously increase runoff. Periods of no rain will result in groundwater being the major source of stream water. It is important to look further at these two situations to interpret their effect on runoff.

Heavy rains add much water to a stream often creating floods for low lying areas. This is the major result of excess precipitation. In some cases, the rain is heavy and has little time to infiltrate the soil. The result is rapid surface runoff.

The threat of floods exists in the Narragansett Bay drainage Basin. Strong coastal storms can cause severe flooding in those areas that are in close proximity to the Bay. A severe rain storm can cause the rivers and streams to overflow. Such was the case with the hurricane of 1938 which caused thousands of dollars of damage within the drainage Basin with its high winds, heavy rains, and flood waters.[45] Floods can be of various magnitudes and with a large population near rivers their forecast becomes important. Flood control stations within the Basin regulate the river flow, preventing possible damage upstream as well as downstream.

With every storm a river reaches the point of maximum

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[45] J. H. Patric, "River Flow Increases in Central New England after the Hurricane of 1938," Journal of Forestry, 72 (January, 1974), 21.

discharge. Peak flows can vary dependent upon the amount and type of storm. The cresting point of river water during a flood would be the peak flow of a particular storm. Often there is a lag time between the most intense portion of a storm and the peak flow. At this point the surface conditions play the important role of delaying the storm water. As will be seen later differing surfaces can increase or decrease the lag time.

It is also possible for a river to demonstrate the effects of a storm several years after it has occurred. The hurricane of 1938 destroyed much vegetation in the area. As a result it was discovered that river flow in New England was at a higher level for about the next five years, before it returned to the pre-hurricane levels.[46]

Several years of low rainfall can result in a much smaller discharge. The water that is being supplied to the river is from the groundwater supply, which is a continuous contributor to runoff. But even groundwater is finite, and it must be recharged so that it will continue its steady flow. In periods of no precipitation plants transpire moisture from the ground and in some cases local wells further deplete the groundwater. This low recharge period decreases the amount being runoff.

As with peak flows the surface conditions have much to

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[46] Ibid., p. 21.

do with low flows. In a study conducted in Ohio on small watersheds with different types of land use it was found that under dry conditions less groundwater was being contributed to the base flow.[47] The study also found that a farm woodlot greatly reduced the amount of runoff when compared to an agricultural area.[48]

Land use has a definite effect on the runoff regime in New England. Patric and Gould[49] used as a study area four small river basins in Massachusetts to determine the effects of the transition of farmland to forest acreage to impervious surface over the past 100 years. None of the four are in the Narragansett Basin but are situated in a northerly semi-circle around Worcester. Precipitation and runoff data were plotted on a cumulative basis by double-mass analysis. The main trend determined was that runoff in these areas decreased at about the same time that land use was changing from agricultural to woodland.[50] The Quaboag watershed which reverted to forest later than the eastern basins exhibited its change in runoff at that time. The Lake

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[47] D. L. Brakensiek and C. R. Amerman, "Evaluating Effect of Land Use on Streamflow," Agricultural Engineer, 3 (March, 1960), 161.

[48] Ibid., p. 167.

[49] J. H. Patric and E. M. Gould, "Shifting Land Use and the Effects on River Flow in Massachusetts," American Water Works Association, 68 (January, 1976), 42.

[50] Ibid., p. 42.

Cochituate basin has been increasing in urban acreage since 1950 with the trend being higher runoff per amount of precipitation.[51] This resulted in the conclusion that "increasing annual flow accompanied urbanization, beginning about 1950. Apparently, greater proportions of the rainfall were diverted to overland flow, with correspondingly decreased evaporative losses. Even though the annual water yield increased during urbanization, streams probably tended to unwanted flashiness caused by lack of infiltration opportunity during storms."[52]

Less significant, but an important factor is the temperature over a basin. Generally the warmer the temperature the greater the amount of water that evaporates or transpires. On a yearly basis this may not be necessarily so. The bulk of evaporation occurs in summer. But if that season averages cooler weather, while the winter months are warmer, the temperature may not reflect the possible decrease in evapotranspiration.

If temperatures are cold enough runoff can be retarded by frozen conditions. This situation tends to delay runoff more than decrease the amount.

But as a rule, the warmer the temperatures the higher the water loss. As will be seen in Chapter 4 several other

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[51] *Ibid.*, p. 44.

[52] *Ibid.*, p. 45.

factors are major contributors to evapotranspiration.

Urban Hydrology

Man, by altering the environment of the drainage basin, alters the hydrology of the basin. By starting communities to building large cities, man changes the face of the earth, putting new and different materials where vegetation, swamp, or desert once were. This change in landscape affects by many methods the general hydrology of the drainage area.

Water Quantity

An urban area can change the surface runoff in many ways. One of the most important is the peak flow of water. With the impervious layer of the city water runs off more rapidly; meaning that peak flows occur much quicker. Brater and Sangal[53] question whether this means an increase in runoff. If the characteristic of the land changed little with urbanization (soil generally impervious) then the timing or amount of surface runoff would hardly change. They also have concluded that the more rapid peak flow may be beneficial to the area. If all streams in an area peaked at the same time a large flood could be expected; but with the quicker urban runoff the peak flow could be much less.[54]

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[53] E. F. Brater and S. Snagal, "Effects of Urbanization on Peak Flows," in Effects of Watershed Changes on Streamflow, ed. W. Moore and C. Morgan (Austin: University of Texas Press, 1969), p. 166.

[54] Ibid., p. 212.

The effect of urbanization on recharge is significant. Because there is little infiltration due to the impervious surface, the result is a possible decrease in the amount of water replenishing the soil. This should hold true for large urban areas that use storm drains for rain water removal. With less water being allowed to replenish the groundwater, it would be expected that periods of low flows would become lesser than previously. In a study conducted in central New Jersey an increase in low flows was discovered. In one instance, water was being provided from outside of the drainage area, used by the community and placed into the ground by the sewage treatment plant. The result was increased ground water and a higher low flow due to the urbanization of the area.[55]

Long Island, New York, has seen extensive investigations of the effect urbanization has had on its hydrology. With the populace of New York City moving to the suburbs areas of once natural vegetation are now sewered cities. Investigations have centered on the East Meadow Brook drainage area, a small basin in Nassau County, lying partially in the Hempsteads. It has been found that the hydrology of this area has been greatly affected over the past forty years.

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[55]E. G. Miller, "Effects of Urbanization on Low Flow," U. S. Geological Survey Professional Paper 550-A (1966), 166.

In the mid-1930's little urbanization had occurred. By comparing runoff figures for thirty years later Seaburn discovered increases in runoff through the years.[56] Precipitation increased only slightly during the period so that the runoff could not be attributed to that factor. In fact, when looking at the runoff from various storms pre- and post-sewering of the basin, the runoff per amount of precipitation had increased greatly.[57] Overall, the increase in the runoff could be attributable to the storm sewer lines that channeled the rain water.

Although there has been no evapotranspiration study conducted on Long Island, it has been speculated that the ground water level has been decreasing. With the recharge being from precipitation combined with the fact that direct runoff is increasing leads Seaburn to suspect that the groundwater is not being recharged as formerly.[58] Sawyer in an earlier study compared East Meadow Brook with a nearby stream and concluded that the base flows at the former had decreased by two percent, possibly indicating a similar

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[56]G. E. Seaburn, "Effects of Urban Development on Direct Runoff to East Meadow Brook, Nassau County, Long Island, N. Y.," U. S. Geological Survey Professional Paper 627-B (1969), 8.

[57]Ibid., p. 11.

[58]Ibid., p. 15.

decrease in the amount of recharge.[59]

The evapotranspiration of the basin is affected by urbanization. Vegetation is the major component in evapotranspiration and by replacing it with impervious surface less moisture will be available to evapotranspire. Even though an urban area has higher temperatures and lower hunidities, the lack of plant life will cause a decrease in evapotranspiration over nearby vegetated areas.[60]

With urban runoff increasing in certain areas problems can develop in the effective removal of storm water. It has been found that impervious land has an effect on channel enlargement.[61] An important characteristic is the steepness of slope of the area, which can increase the runoff and therefore the channel size.[62]

As cities grow, the demand for water becomes great. Water often has to be supplied from foreign drainage basins and then possibly added to a new one. Occasionally, it is dumped out to sea and never added to the runoff. The drinking water comes from two sources: surface water or

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[59] R. M. Sawyer, "Effect of Urbanization on Storm Discharge and Groundwater Recharge in Nassau County, N. Y.," U. S. Geological Survey Professional Paper 475-C (1963), 187.

[60] Bruce and Clark, p. 288.

[61] T. R. Hammer, "Stream Channel Enlargement Due to Urbanization," Water Resources Research, 8 (June, 1972), 1540.

[62] Ibid., 1539.

well water. A lake is set aside so that the purity of the water can be maintained (Scituate Reservoir) and safe drinking water can supply everyone's needs. The tapping of the groundwater with wells can often cause disastrous effects. If the water is pumped out faster than it can be resupplied by infiltration, the land may subside, replacing the area the groundwater once occupied.[63] Sometimes near ocean water, salt water may intrude on the supply and destroy the quality of the groundwater. It becomes imperative that a city provide for its people an adequate supply of drinking water.

Water Quality

Urbanization can affect the runoff water quality in two ways. Disposal of the urban sewage is an important matter. If the polluted material is discharged immediately to rivers and streams, the pollution that occurs will begin to destroy the flora and fauna of the stream. And if a city downstream depends upon the river for its water supply, it will eventually have to search for a new one. River pollution has become a major problem that is evident in the study basin. Man is becoming more conscious of water quality and regulation of dumping and disposal of sewage

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[63] J. Savini and J. C. Kammerer, "Urban Growth and the Water Regimen," U. S. Geological Survey Water Supply Paper 1591-A (1961), 36.

into streams is in effect.

Disposal of urban sewage in rivers is not the only method of water pollution. If the local sewage treatment plant disposes of waste through wells, it is possible for it to contaminate the local water supply and pollute it beyond use.[64] Even a sanitary landfill, in the proper location, can contaminate the groundwater when the normal action of precipitation filters through the rubble and seeps into the ground.

The other method of adversely affecting the water quality is by increasing the amount of sediment in the water. When building construction is in progress land is usually barren with loose soil in the area. The surface runoff can pick up heavy loads of sediments and transport them to a river and then downstream. This sediment is eventually deposited, decreases the ability of the stream to carry water, and thereby increases the probability of floods.[65] Urbanization also may disrupt the natural flow of surface runoff, forcing it to erode new channels and to increase sediment in this manner.

In summary, the foregoing describes the hydrology of a typical basin and the effects that urbanization can have

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[64] Ibid., p. 29.

[65] Ibid., p. 35.

upon it. Not all of the factors apply to all basins but most of it is typical of the hydrology of the Bay's drainage Basin. The region is active in its precipitation and runoff. Over a million people call its confines their home. What kinds of effects are they having upon the amount of runoff draining into the Bay?

CHAPTER 4

THE THORNTHWAITE WATER BUDGET

The hydrologic cycle describes the process of how precipitation interacts with the earth.[66] Some of the precipitation immediately runs off the surface, into lakes and streams. If precipitation falls as snow it is stored on the surface waiting for warmer temperatures to melt it back to a liquid state. Some of the precipitation percolates into the ground to become part of the groundwater storage which feeds streams even when there have been many days without rainfall. Temperature plays an important part in the evaporation of water from lakes or puddles where water has become trapped. Transpiration occurs when plants, trees and other vegetation lose water to the atmosphere, again with a major factor being the temperature.

The research in this process has been in determining the amount of evapotranspiration. It is the most difficult of factors to determine as it consists of the amount of water evaporating from lakes and ponds and the amount of

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[66] R. G. Barry, "The World Hydrologic Cycle," in Water, Earth, and Man, ed. R. J. Chorley (London: Methuen and Co. Ltd., 1969), p. 11.

moisture lost to the atmosphere from vegetation. The measurement of actual evapotranspiration is usually accomplished by one of two methods. There is the use of evaporation pans in which by careful measurement the amount of water loss on a particular day is determined.[67] This method does not consider transpiration. Transpiration is best measured by a lysimeter which is a cased section of soil which holds a variety of vegetation. This segment of land is weighed periodically so as to determine the amount of water loss.[68]

Since these two processes are expensive and frequently impractical researchers have attempted to estimate the amount of evapotranspiration. Penman[69] developed a formula based upon the energy balance and aerodynamics. The result is the equation

$$PE(MM/DAY) = \frac{\frac{\Delta}{\lambda}\frac{R_N}{L} + E_A}{\frac{\Delta}{\lambda} + 1} \qquad (1)$$

where PE is the potential evapotranspiration in millimeters per day, $\frac{\Delta}{\lambda}$ is Bowen's ratio which deals with the psychometric constant and the change of saturation vapor pressure,

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[67] Bruce and Clark, p. 94.

[68] *Ibid.*, p. 98.

[69] H. L. Penman, "Estimating Evapotranspiration," *Transactions of the American Geophysical Union*, 37 (February, 1956).

R_N the net radiation, L is the latent heat of the vaporization of water, and E_A is based upon the wind speed and vapor pressure.[70]

Budyko, on the other hand, has centered his analysis of evaporation slightly differently but dependent upon the same functions. His equation states that

$$R_A - S = L_p D(q_s - q_a) + (PC_p D + 4s\sigma T_a^3)(T_s - T_a) \qquad (2)$$

where R_A is the net radiation, S is the heat flux to the soil, $D(q_s-q_a)$ is a function of wind speed, C_p is the specific heat of the air, and $4s\sigma T_a^3$ and T_s-T_a a calculated net radiation.[71]

These equations consider the major components of evapotranspiration to be wind speed, the vapor pressure and humidity of the atmosphere, and radiation. Only in conjunction with special experiments can these parameters be measured. They leave the average user with much difficulty in their practical application. As a result C. W. Thornthwaite devised an easier bookkeeping method of determining evapotranspiration and, consequently, runoff.

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[70] R. G. Barry, "Evaporation and Transpiration," in Water, Earth, and Man, ed. R. J. Chorley (London: Methuen and Co. Ltd., 1969), p. 174.

[71] C. W. Thornthwaite and F. K. Hare, "The Loss of Water to the Air," Meteorological Monographs, 6 (July, 1965), 174.

Theory and Limitations

Particularly interested in the amount of water needed to produce a good harvest, Thornthwaite devised the water budget for a particular area based on the equation:

$$P = AE + RO + \Delta S \qquad (3)$$

where precipitation (P) equals actual evapotranspiration (AE) plus runoff (RO) plus the change in storage (ΔS).[72] This equation can be transposed to the form

$$RO = P - AE - \Delta S \qquad (4)$$

and used as an estimator of the runoff of a locality.

The emphasis is upon actual evapotranspiration, the amount of water that will evaporate and transpire from the earth's surface. Thornthwaite bases this upon the calculation of potential evapotranspiration which is the amount of water that will evaporate and transpire if there is an adequate water supply to do so. Potential evapotranspiration (PE) is calculated from the equation

$$PE = 1.6L(10T_a/I)^m \text{ cm per month} \qquad (5)$$

where

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[72] C. W. Thornthwaite and J. R. Mather, Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance (Centerton, N. J.: Laboratory of Climatology, 1957), p. 186.

$$I = \sum_{1}^{12} i = \sum_{1}^{12} (\bar{T}_a/5)^{1.514} \qquad (6)$$

and where L is a day length correction factor, T_a is the Celsius mean air temperature for the month, and m is a cubic function of the denominator of I, the heat index.[73] The term $\bar{T}_a$ in the heat index is the climatological normal temperature for the year.

The heat index is the first value to determine. Monthly averages for the year are calculated and added giving an indication of the continentality of the station. The warmer the temperature is the higher the heat index figure will be.

Next, the observed monthly temperature is multiplied by the heat index number for this temperature. To adjust this number for a specific station, each monthly value is multiplied by a latitudinal correction factor that incorporates the monthly duration of possible sunlight.[74] These have been predetermined for most of the latitudes and are a simple input of pre-calculated values of the length of the days for a particular month.[75] These calculations determine

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[73]Thornthwaite and Hare, p. 172.

[74]The Thornthwaite system as described here uses average monthly temperatures, which is based upon daily maximum and minimum temperatures for that month. It is possible to execute the budget on a daily basis particularly if one is interested in irrigating crops.

[75]Thornthwaite and Mather, pp. 206-207.

the potential evapotranspiration (PE), the maximum amount of moisture, given an indefinite supply of water, that will evapotranspirate to the atmosphere for a specific latitude.[76]

Thornthwaite considers 32°F to be the threshold of evapotranspiration, below this temperature no moisture will be lost at the surface. Therefore, PE is automatically zero for any month that averages below freezing.

Monthly precipitation data are used to adequately determine the actual evapotranspiration (AE). AE is how much moisture is to be drawn away from the surface. If precipitation, as the incoming factor, is greater than PE then the potential will equal AE as the qualifications have been met. If any water is left over it will either replenish the soil deficit, raise the groundwater table or run off.

When the precipitation is less than the potential evapotranspiration the remainder must be made up from what is stored in the soil. Different types of soil and vegetation can hold differing amounts of moisture. Shallow sand can only hold an inch or two of water while a deep well-aerated silt loam can hold over twelve inches of water. The

[76]This method of estimating evapotranspiration was originally introduced in Thornthwaite, "Classification of Climate,"; later modifications are contained in C. W. Thornthwaite and J. R. Mather, The Water Balance (Elmer, N. J.: Laboratory of Climatology, 1955); and Thornthwaite and Hare, "Loss of Water."

equation used to determine the remaining soil moisture is:

$$STORAGE = WHC^{(SUM/WHC)} \qquad (7)$$

where SUM is the accumulated negative difference between the precipitation and PE, WHC is the water holding capacity of the soil, and STORAGE is the amount of water remaining in the ground.[77] This equation is essential as the deeper one goes into the soil the more difficult it is to take moisture out of it.

In this case the moisture taken from the soil is added to the precipitation and becomes the variable AE of the equation (4). The actual amount of evapotranspiration never can be greater than the potential. If the actual is less than PE then not enough moisture was taken from the soil due to the difficulty of evapotranspiration. This is considered a deficit period. When precipitation again exceeds the potential evapotranspiration, the excess water percolates into the soil, until it again reaches its water holding capacity.

There are two other factors that can influence the runoff amount determined by Thornthwaite's water budget. First, it is assumed that only fifty percent of the moisture

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[77] L. A. Stone, "Water Balance Computer Program Using Consecutive Monthly Data," in Computer Programs for the Climatic Water Balance, ed. L. A. Stone, J. C. Albrecht, and G. A. Yoshioka (Elmer, N. J.: Laboratory of Climatology, 1971), p. 5.

available for runoff actually runs off in any given month. The remainder is carried over to the next month to be added to any surplus. Therefore, even with months of deficit there will be some runoff with the Thornthwaite water budget. Second, if the monthly average temperature is at or below 31°F the surplus, if any, is considered to be stored on the surface in the form of snow or ice and not added to the runoff until the first month with temperatures above 31°F, the assumption being that daily temperatures were warm enough to release all precipitation in a liquid state.

This, in simplified form, is an explanation of the Thornthwaite water budget. The process does have practical applications to runoff studies.

Sanderson calculated the runoff in the Lake Ontario Basin by using the budget method.[78] The Thornthwaite system was found to be an adequate estimator of runoff and useful for her purpose of determining the runoff of the humid northeastern North America. She also brings up the question of the amount of runoff an urbanizing area would contribute.

Ward tested the Thornthwaite budget in three forms,

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[78] M. Sanderson, "Variability of Annual Runoff in the Lake Ontario Basin," Water Resources Research, 7 (June, 1971), 555.

one of which was on a monthly basis.[79] He did find occasional slight deviations when comparing the budget to actual runoff but overall it was a useful indicator of runoff from a small drainage basin. His main concern was with the estimation of evapotranspiration and his investigation found that Thornthwaite was adequate.[80]

Application to the Narragansett Bay Drainage Basin

A computer program, originally written by L. A. Stone,[81] was adapted for use here, and was used to compute the water budget for the stations within the study area.

Runoff statistics were used as a comparison with actual runoff from gauges that drain the area within which they appear. There are a few weaknesses with Thornthwaite's estimated runoff. The concept of no added runoff from a month with temperatures averaging below 31°F may not be wise for much of the area. Warm spells are usually warm enough to melt much snow and in coastal and southern New England precipitation occasionally falls as rain with subfreezing temperatures following the storm. The result is that the calculated runoff is held as snow even though it

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[79] R. C. Ward, "Estimating Streamflow Using Thornthwaite's Climatic Water-Balance," Weather, 27 (February, 1972), 76.

[80] Ibid., p. 81.

[81] Stone, p. 1.

is possible that there is no snow on the ground at all. Consideration should be given to evaluating coastal areas with slightly different criteria or lower the threshold temperatures.

Because of the delay in the amount of water running off there are times when the amount of actual runoff at the end of the year is higher than the predicted. This would occur in a situation similar to the one described above with December averaging below freezing and the precipitation stored as snow. Therefore, the yearly total of runoff would tend to be lower than the actual. But, eventually, this will be added to the runoff figures during the next year and would appear in the totals for the following year. One method of circumventing this situation would be to determine runoff by the water year months of October to September, which is used by the U. S. Geological Survey.

With this carry-over of fifty percent of the amount available to runoff, there is an amount moved from December to January. The exception would be the first year of study when there is no excess from a preceeding December. For the first year runoff may be slightly lower than the observed runoff from water recording stations. From analysis of the data it appears that after a year or two the predicted amount of runoff accurately reflects the actual runoff.

There are a few other problems with estimating runoff.

These will become apparent and discussed in the following chapters.

The runoff data from the Thornthwaite budget will be evaluated on a monthly basis but used on a yearly basis. This will tend to eliminate any monthly anomalies such as more runoff during one month due to heavy precipitation or the assumption that water in the winter months is held back due to cold weather.

The runoff data from the Thornthwaite water budget will give an indication as to how much water can be expected to flow through the river gauge stations. By using this as an estimate one can observe if the predicted level of runoff corresponds with the actual runoff or if the actual increases with time. Various trends can be observed in comparing the amount of rain with the amount that runs off. By using the water budget for a station near a river gauge, within a basin, or adjacent to a basin one will be able to estimate the amount of runoff for a basin and if that estimation is accurate or too low. If the estimated is below the observed then other factors may be increasing or influencing the amount of runoff. It will be possible to determine by how much the runoff is increasing over the estimated values.

By comparing the observed and estimated runoff it will be possible to look further for explanations as to why certain differences occur. The estimated runoff is a function of temperature; the higher the temperature the more evapotranspiration therefore less water is available for runoff. If the observed runoff has been decreasing in recent years, or increasing at a slower rate, this could be an indication of warmer temperatures increasing the evapotranspiration. By analyzing the potential evapotranspiration on a yearly basis one will be able to indicate if a trend of increasing temperatures is decreasing the amount of runoff in relation to precipitation. If the evapotranspiration is decreasing, its relation to other climatological factors could prove significant in the amount of runoff.

The Thornthwaite water budget necessitated the use of certain data peculiar to the stations being studied. The figures that were employed will be discussed further in Chapter 5.

The major problem that arose was the choice of the soil moisture index. It is important to select a comparable choice for two reasons. One, it will be easier to take water out of a soil that has a very high water holding capacity so that the actual evapotranspiration will be great. Second, the higher the amount of water the soil can hold, the longer it will take to replenish when there is a deficit.

It was decided to keep the water holding capacity constant over the whole drainage basin. This, in effect, would keep all points under a constant factor. It was also decided that a six inch water holding capacity would suffice as it is the capacity of a soil type from which grows shallow rooted crops which is typical in parts of the study area. Also, the six inches would be the approximate capacity of those basins with a high amount of urban acreage which has a very low water holding capacity. If the water holding capacity is ever above this figure runoff would tend to be slightly lower. Therefore the estimated amount of runoff may be less than the actual.

In Hartmann's study, the six inch water holding capacity was used for agricultural areas.[82] He calculated that using a larger water holding capacity would not have made a significant difference in his study.[83]

The Thornthwaite method is only one measure of the water budget. But, by far, Thornthwaite is one of the easiest to use. It can be easily set up for almost any location, but it is especially suited for the northeastern United States. Its accurate estimation of evapotranspiration makes the runoff statistics comparable to the actual basin runoff. Combined with the facts that the variables are readily available and it is easily calculated, the Thornthwaite water budget is a practical and valuable tool as a predictor.

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[82]Hartmann, p. 58.

[83]*Ibid.*, p. 58.

CHAPTER 5

THE DATA STATIONS

The use of the Thornthwaite water budget and the runoff figures for the basin involved the gathering of three separate sets of statistics: precipitation, temperature and runoff. There were some obvious problems with the gathering of the data since some stations only began recording after 1940, and in some cases have been in operation for only a few years. A few ceased operation during the study period, and in some cases there was a radical shift in station site. These and other problems to be described below were handled in a method to best diminish any errors or upset the continuity.

To calculate the Thornthwaite water budget a few other statistics were determined based upon station characteristics. The average monthly temperature was calculated for each station, and from those figures the average heat index was determined. Plotting this average on the unadjusted potential evapotranspiration table supplied by Thornthwaite[84] the unadjusted PE for each half degree from 32° to 100°F

[84]Thornthwaite and Mather, Potential Evapotranspiration, 210-211.

was determined. Depending upon a particular month's temperature the unadjusted PE was calculated and then multiplied by the latitudinal correction factor. This was taken from Thornthwaite[85] and rounded off to the nearest whole degree Fahrenheit.

Precipitation

Precipitation is the most important part of the Thornthwaite equation. It is also a highly variable factor. One of the problems with precipitation is its accurate measurement. The position of the gauge and surrounding terrain may affect greatly the receipt of precipitation. High trees or other obstructions may cause either eddying of the wind such that precipitation can be carried away or even toward the gauge giving an unreliable figure of precipitation. High winds during the storm can cause precipitation to miss the gauge resulting in a deficient reading.[86] The fact of the matter is that only a small point of the region is being measured and the assumption must be made that this fall is representative of the whole area.[87]

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[85] Ibid., p. 237.

[86] L. L. Weiss, "Securing More Nearly True Precipitation Measurements," Journal of the Hydraulics Division, 89 (March, 1963), 17.

[87] J. R. Mather, Climatology: Fundamentals and Applications (New York: McGraw-Hill, 1974), p. 51.

During the winter months the water content of the fallen snow is important to determine since spring floods may result. Error in the measurement of precipitation throughout the year may lead to misrepresentative totals.

Between stations a new factor is taken into account, rainfall is highly variable. A coastal storm could bring much rain to one part of the Narragansett Bay drainage Basin while leaving an opposite location with little if any. Even more dramatic is the summer thunderstorm which can hit one community with a heavy shower and nothing for a place only miles away.

Even though there is difficulty in recording precipitation it is accurate enough for analysis. One can not go back and measure the precipitation of July 1948, so that what has been recorded is taken as factual. The bulk of the stations within or immediately surrounding the Basin were gathered from the annual summary of the volume Climatological Data: New England published by the National Oceanic and Atmospheric Administration covering the years 1940-1974.[88] Occasionally monthly data for some stations were estimated and printed. These figures were assumed to be accurate and used as such.

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[88]National Oceanic and Atmospheric Administration, Climatological Data: New England (Asheville, N. C.: U. S. Department of Commerce, 1940-1974).

Occasionally some stations had a month or series of months missing from the data source. The problem arose as to how to treat these breaks in the record. It was decided that the best method would be to calculate the correlation coefficient with a nearby station or stations in order to determine how precipitation at one station was related to a nearby station. At the same time the linear regression line was computed to find the line that best fit the distribution of data. The station that had the highest correlation for a particular month when compared with the station with the missing data was selected, and the regression line was used as an estimate of the precipitation. The correlation coefficients, as presented in Table 1, were generally between .88 and .97 and rarely was the standard error of the estimate above one inch. Due to the possible error involved only in a few cases were several months estimated for some stations.

The water supply for the city of Providence is the Scituate Reservoir located in the central part of Rhode Island. For their own records, they keep precipitation amounts from five gauges around the reservoir. It appears that two are significant enough to be included in the study.[89] They are Hopkins Mills and Gainer Dam. Their use

[89]Data was gathered from a visit to the reservoir where access was available to the annual summary published by the Water Supply Board. Within the volumes are the published amounts of precipitation recorded for the five gauges.

TABLE 1

PRECIPITATION CORRELATIONS

Station	Compared To	Month	Correlation Coefficient	Standard Error of Estimate
Brockton	Mansfield	Oct	0.95	0.67
	Mansfield	Nov	0.95	0.66
Franklin	Northbridge	Jan	0.96	0.49
	Northbridge	Feb	0.90	0.55
	Northbridge	Mar	0.93	0.71
	Northbridge	Apr	0.94	0.56
	Mansfield	May	0.95	0.55
	Mansfield	Jun	0.93	0.59
	Mansfield	Jul	0.79	1.08
	Northbridge	Aug	0.97	0.87
	Northbridge	Sep	0.95	0.93
	Northbridge	Oct	0.94	0.71
	Mansfield	Nov	0.93	0.66
	Mansfield	Dec	0.92	0.71
Middleboro	Brockton	Feb	0.90	0.55
	Brockton	May	0.95	0.73
	Mansfield	Oct	0.93	0.86
	Taunton	Dec	0.96	0.48
Segregansett	Taunton	Jan	0.89	0.75
	Fall River	Feb	0.89	0.62
	Fall River	Mar	0.94	0.74
	Taunton	Apr	0.95	0.54
	Taunton	Jun	0.91	0.80
	Taunton	Jul	0.94	0.56
	Taunton	Aug	0.92	1.23
	Taunton	Sep	0.96	0.57
	Fall River	Dec	0.89	0.92
Taunton	Middleboro	Mar	0.88	0.72
Worcester City	Worcester Air	Aug	0.99	0.50
Greenville	Providence Air	Feb	0.74	0.86

is significant as this part of the study area has the highest annual precipitation (about 50 inches).

Important in the gathering of the data is knowledge of the position of the gauge and if it has been transferred. During the study period both Worcester and Providence moved their recording stations from downtown locations to outlying airports, thus causing a break in their records. Precipitation statistics were affected to an extent, but as one will see later, the change was more important in recording the temperature. Because of the switch two records for each city were used. In February of 1964 the Northbridge station was moved slightly but it appears not to have affected the recording of the precipitation. The same is true with the slight shift of the Gainer Dam station near the Scituate Reservoir. Table 1 in the Appendix provides various information about the stations: the name, period of record, and the months, if any, of data estimation by linear regression.

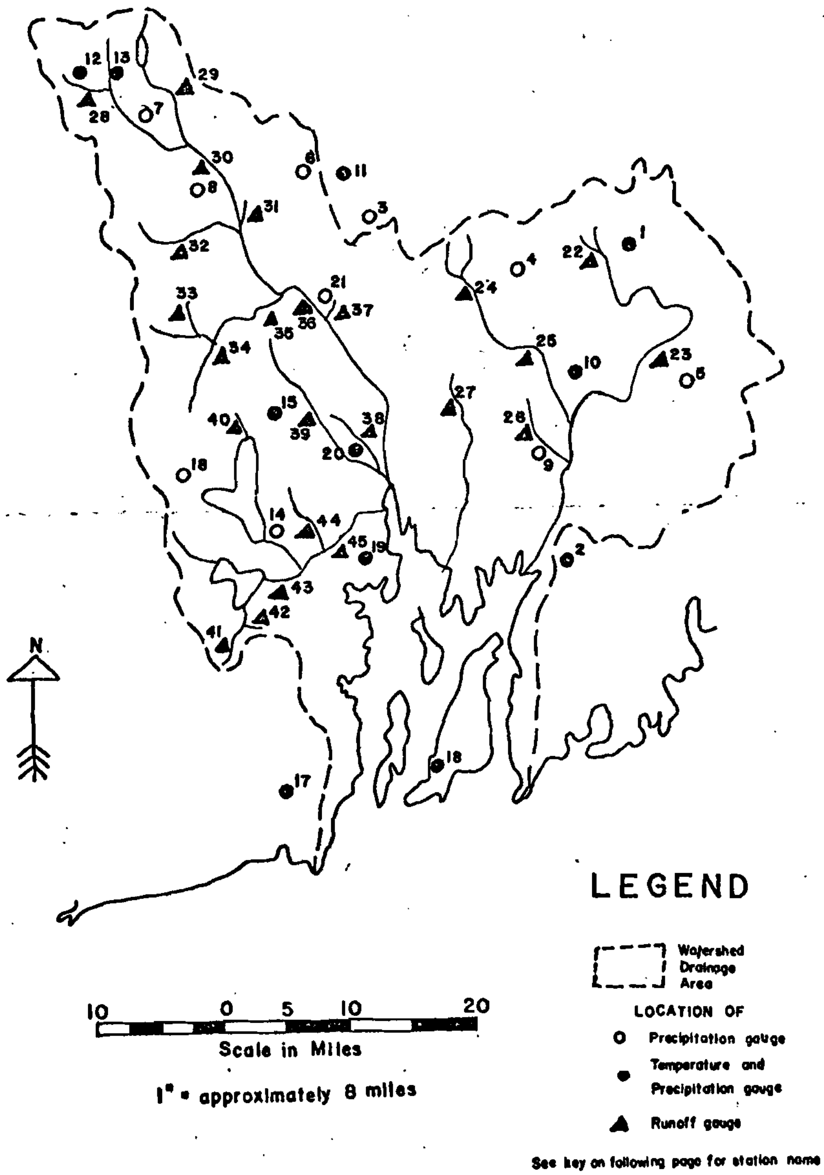
Map 3 shows the position of the precipitation recording stations within the Basin or on the perimeter. It also includes the temperature and river recording stations which will be discussed below.

Temperature

Unfortunately, not all of the stations that are equipped to record precipitation measure the air temperature. About half of them record temperature with only three

MAP 3

PRECIPITATION, TEMPERATURE AND RUNOFF STATIONS



KEY TO MAP 3

Climate Stations

1. Brockton
2. Fall River
3. Franklin
4. Mansfield
5. Middleboro
6. Milford
7. Millbury
8. Northbridge
9. Segreganset
10. Taunton
11. West Medway
12. Worcester Airport
13. Worcester City
14. Gainer Dam
15. Greenville
16. Hopkins Mills
17. Kingston
18. Newport
19. Providence Airport
20. Providence City
21. Woonsocket

Runoff Stations

22. Brockton
23. Bridgewater
24. West Mansfield
25. Norton
26. North Dighton
27. Rehoboth
28. Worcester
29. North Grafton
30. Northbridge
31. Uxbridge
32. East Douglas
33. Harrisville
34. Chepachet
35. Forestdale
36. Woonsocket 1
37. Woonsocket 2
38. Providence
39. Centerdale
40. North Scituate
41. Nooseneck 1
42. Nooseneck 2
43. Washington
44. Cranston 1
45. Cranston 2

having a continuous and complete record covering the study period. As was the case with the rain gauges, Worcester and Providence began recording temperatures at a new location. With thermometers away from the artificial heat sources of the city colder temperatures are being recorded now. For Worcester the case is dramatic. The yearly temperatures are now about 1°F colder at the 1,000 foot high airport than at the former location. This switch caused the new heat index to drop by 2.50 points. The Providence change was not as drastic as the heat index difference is over a third of a point.

Temperatures at other stations did not cover the whole study period and made comparisons difficult. The problem of months with missing data also occurred with temperatures. It was decided to follow the same procedure of correlation coefficients and plotting the estimate along the regression line. By this method one discovers that temperature is less variable than precipitation. As can be seen in Table 2 only a few months had a correlation coefficient below .90 and many were between .95 and .97. The standard error of the estimate was above one degree in a couple of cases but was usually centered around .80. Unfortunately many months had to be estimated in some cases so that complete records could be analyzed and compared.

The problem arose as to how to treat the eleven stations that lacked temperature data. Average temperature

TABLE 2

TEMPERATURE CORRELATIONS

Station	Compared To	Month	Correlation Coefficient	Standard Error of Estimate
Brockton	Taunton	Jan	0.98	0.96
	Taunton	Feb	0.96	0.96
	Taunton	Mar	0.96	0.64
	Taunton	Apr	0.94	0.94
	Taunton	May	0.96	0.84
	Taunton	Jun	0.90	0.87
	Taunton	Jul	0.90	0.93
	Taunton	Aug	0.94	0.82
	Taunton	Sep	0.89	1.17
	Taunton	Oct	0.94	1.01
	Taunton	Nov	0.97	0.65
	Taunton	Dec	0.99	0.74
Worcester City	Worcester Air	Sep	0.98	0.48
	Worcester Air	Nov	0.96	0.66
	Worcester Air	Dec	0.99	0.56
Greenville	Taunton	Jan	0.98	0.97
	Worcester City	Feb	0.97	1.06
	Worcester City	Mar	0.97	0.69
	Worcester City	Apr	0.94	0.71
	Worcester City	May	0.97	0.61
	Worcester City	Jun	0.96	0.70
	Worcester City	Jul	0.95	0.87
	Worcester City	Aug	0.96	0.58
	Worcester City	Sep	0.97	0.70
	Worcester City	Oct	0.96	0.62
	Worcester City	Nov	0.93	0.74
	Worcester City	Dec	0.98	0.84
	Providence Air	Jan	0.98	0.89
	Providence Air	Feb	0.97	0.94
	Providence Air	Mar	0.96	0.69
	Providence Air	Apr	0.95	0.73
	Providence Air	May	0.96	0.72
	Providence Air	Jun	0.95	0.59
	Providence Air	Jul	0.94	0.75
	Providence Air	Aug	0.93	0.78
	Providence Air	Sep	0.97	0.61
	Providence Air	Oct	0.96	0.76
	Providence Air	Nov	0.97	0.54
	Providence Air	Dec	0.99	0.63

TABLE 2 (Continued)

Station	Compared To	Month	Correlation Coefficient	Standard Error of Estimate
Newport	Kingston	Jan	0.98	0.67
	Kingston	Feb	0.93	0.84
	Kingston	Mar	0.96	0.70
	Kingston	Apr	0.91	0.84
	Kingston	May	0.84	1.25
	Fall River	Jul	0.62	0.85
	Kingston	Aug	0.90	0.83
	Kingston	Oct	0.94	0.78

maps for New England give only January and July averages. But from these it was observed that the average temperature for Taunton was about the average for most of the stations in question. To decide how much of a difference this would make two sample runs of the Thornthwaite water budget were computed with the stations with the highest and lowest heat index. In determining how important is a 6 point difference in the heat index the precipitation for Fall River for 1949-1974 was held constant for that city and Worcester airport while each station kept its own recorded temperatures. All other factors were held constant.

As expected, the results showed that Fall River averaged a higher potential and actual evapotranspiration than Worcester, and the excess precipitation run off at Worcester. There was a 2.5 inch difference in the potential evapotranspiration and a 1.7 difference in the actual evapotranspiration, both in favor of Fall River. The estimated runoff for Worcester was 1.7 inches higher than for Fall River. These are yearly averages for the extreme stations. By using the Taunton temperatures, which has a smaller heat index by 2.5 points and keeping in mind that the elevation of the Worcester Airport affects its temperatures, any differences in estimated runoff and actual evapotranspiration would not cause any major problems.

With this in mind temperatures were assigned to precipitation stations that were lacking. The Worcester city temperatures were assigned to Millbury due to the proximity of these two places. Several months were estimated for Greenville and that data were given to Gainer Dam and Hopkins Mills. The Taunton data were assigned to the remainder.[90] As with precipitation, the temperature data were culled from the Climatological Summary.[91]

Table 2 in the Appendix indicates the stations that recorded the temperature, the years of record, the heat index assigned to that station and the months for which data were estimated. Map 3 shows the location of available temperature data for the Basin.

Runoff

Runoff data were taken from the various publications of the Department of the Interior that contained the streamflow records for the Northeast.[92] Recorded for use was the amount of water that flowed through the gauge in

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[90]Franklin, Mansfield, Middleboro, Milford, Northbridge, Segregansett, and Woonsocket.

[91]National Oceanic and Atmospheric Administration.

[92]U. S. Department of the Interior Geological Survey, "Part 1-A North Atlantic Slope Basins, Maine to Connecticut," Geological Survey Water Supply Paper 1301 (1954); U. S. Department of the Interior Geological Survey, "Part 1-A North Atlantic Slope Basins, Maine to Connecticut," Geological Survey Water Supply Paper 1721 (1964); Geological Survey, Surface Water Records of Massachusetts, New Hampshire, Rhode Island, and Vermont (Washington: U. S. Department of the Interior, 1961-1969); Geological Survey, Water Resources Data for Massachusetts, New Hampshire, Rhode Island, and Vermont (Washington: U. S. Department of the Interior, 1970-1974).

relation to the area of the basin. Data were available on a monthly basis, but only yearly totals were necessary. At no time was it necessary to estimate data.

Again, one is at the mercy of the positioning of these gauge stations. There are few monitoring stations on the same river at different locations and fewer at the mouths of the various major streams draining the basin. Even the positioning of the climatological data in relation to river gauging stations is erratic. But the positioning of the two key factors is adequate for the comparisons necessary.

Table 3 in the Appendix summarizes the record of the water gauging stations: the community, river, and basin, years of record and the square miles of the drainage basin.

This concludes the gathering and estimation of the data available. It would be most appropriate if more had been available, more complete, or in a better location for analysis. Enough data has been gathered and in a sufficient quantity to reveal some significant findings.

CHAPTER 6

ANALYSIS OF THE DRAINAGE BASIN

The runoff data supplied by the various gauging stations comprise the element analyzed in studying the basin. The stations are in four major drainage basins and were studied to determine runoff changes within that drainage area. In order, the four are the Taunton, Blackstone, the Providence area, and the Pawtuxet. Analysis consists of comparisons of changes within basins and the possible relation to increases in urbanization.

The method of study consists of the analysis of the slope values of the best fit lines for a period of years as determined from the double-mass analysis. The slope values for a calculated vs. actual runoff analysis theoretically should be close to 1.00000 as this indicates that the actual and calculated runoff values are identical. Fluctuations greater than 1.00000 mean that the actual runoff is greater than the calculated. Conversely, if the slope is less than 1.00000, the actual runoff is less than the Thornthwaite calculated value. The slope values from the actual runoff vs. precipitation graphs can also be thought of as the percent of precipitation that runs off. For various determined periods these slopes will indicate changes in the amount of runoff in relation to the precipitation. The slope values are around 0.50000; if slope values are higher than this value it means that runoff is higher per amount of precipitation; if less than this value then the actual runoff is decreasing per amount of precipitation. Comparisons between drainage areas will take into account the differences in the slopes for a period. If through the four periods the difference is increasing in favor of one station, the increasing runoff may be due to a higher rate of urbanization.

Urban acreage statistics of 1951 and 1971 will be calculated and compared to indicate by how much urbanization is increasing in the study basins. The difference in the amount of increase of percent of urban acreage between two basins is an indication of a higher rate of urbanization in one basin. This rate will be compared with the change in runoff slopes for that study area. If there has been an increase in the difference in runoff slope in the beginning of the study period when compared to the difference of the last period then there should be an increase for that basin in the rate of percent of urban acres.

The first in depth comparison between two basins will stress the method of analysis as well as the tendency in runoff.

The Taunton Drainage Basin

The Taunton River is the outlet for runoff from the eastern section of the drainage basin. Gauging stations within the area are few but their positioning provides an excellent situation for analysis. From the precipitation records it was shown that the basin averages about forty-five inches of precipitation annually. Therefore when a certain station is chosen for the calculated runoff, corrections will not have to be made for varying amounts of precipitation within a drainage area.

A complete runoff record is available for the Bridgewater station and this section drains an area in which there is increasing urbanization. The Brockton record is not as complete but does cover a time of increasing population. On the Wading River there are two stations with long records. The West Mansfield station drains an area consisting of Foxboro and Mansfield with the Norton station farther downstream draining the town and environs of Norton. These three areas have had increases in acres of urban land between 1951 and 1971 but this acreage still comprises about a fifth of the land.[93]

When comparing these two records by double mass analysis a similarity exists. Using the Mansfield station to

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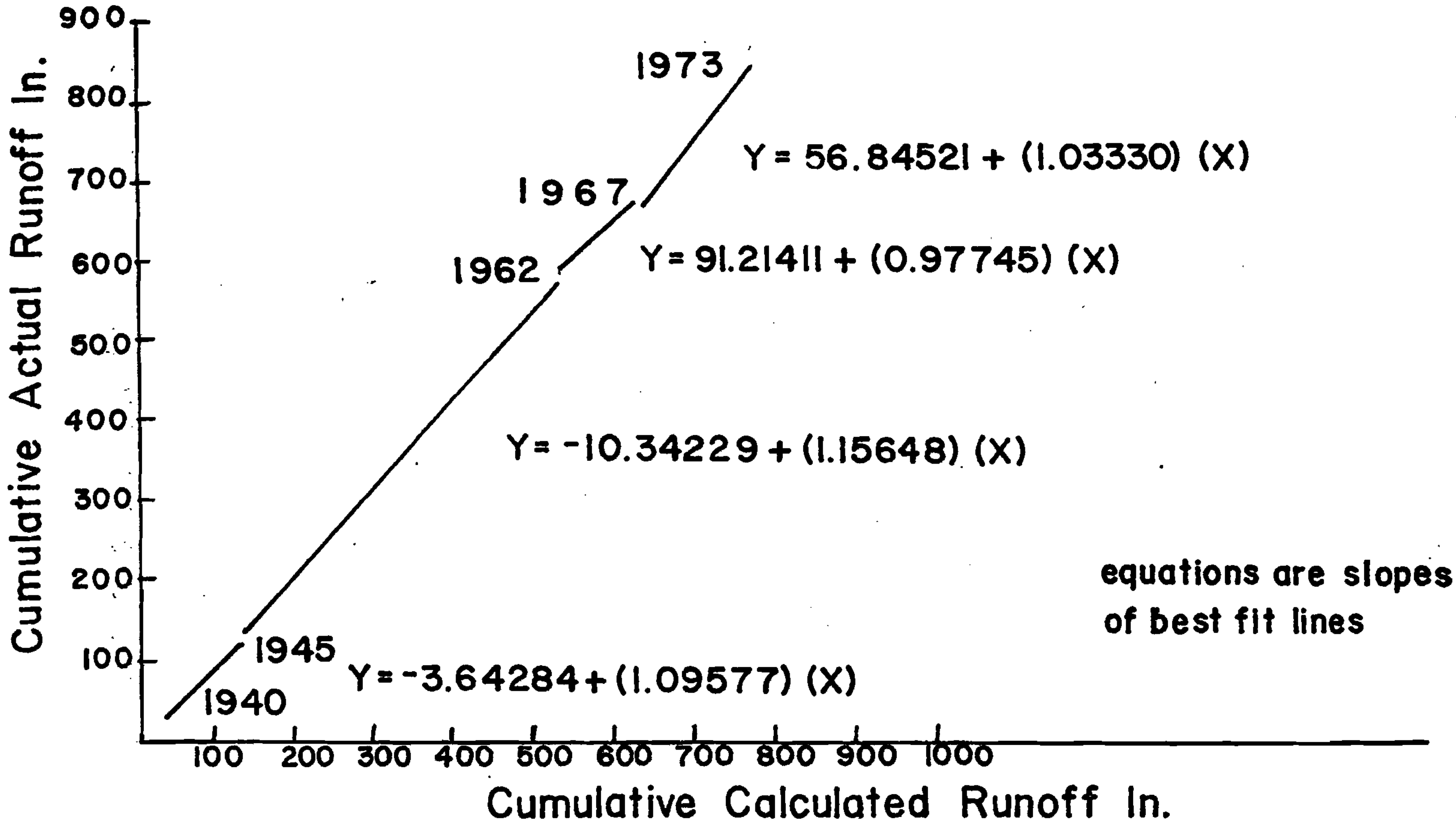
[93] Increases in urbanization in individual towns are as follows: Foxboro 9 percent to 20 percent, Mansfield 9 percent to 17 percent and Norton 6 to 13 percent.

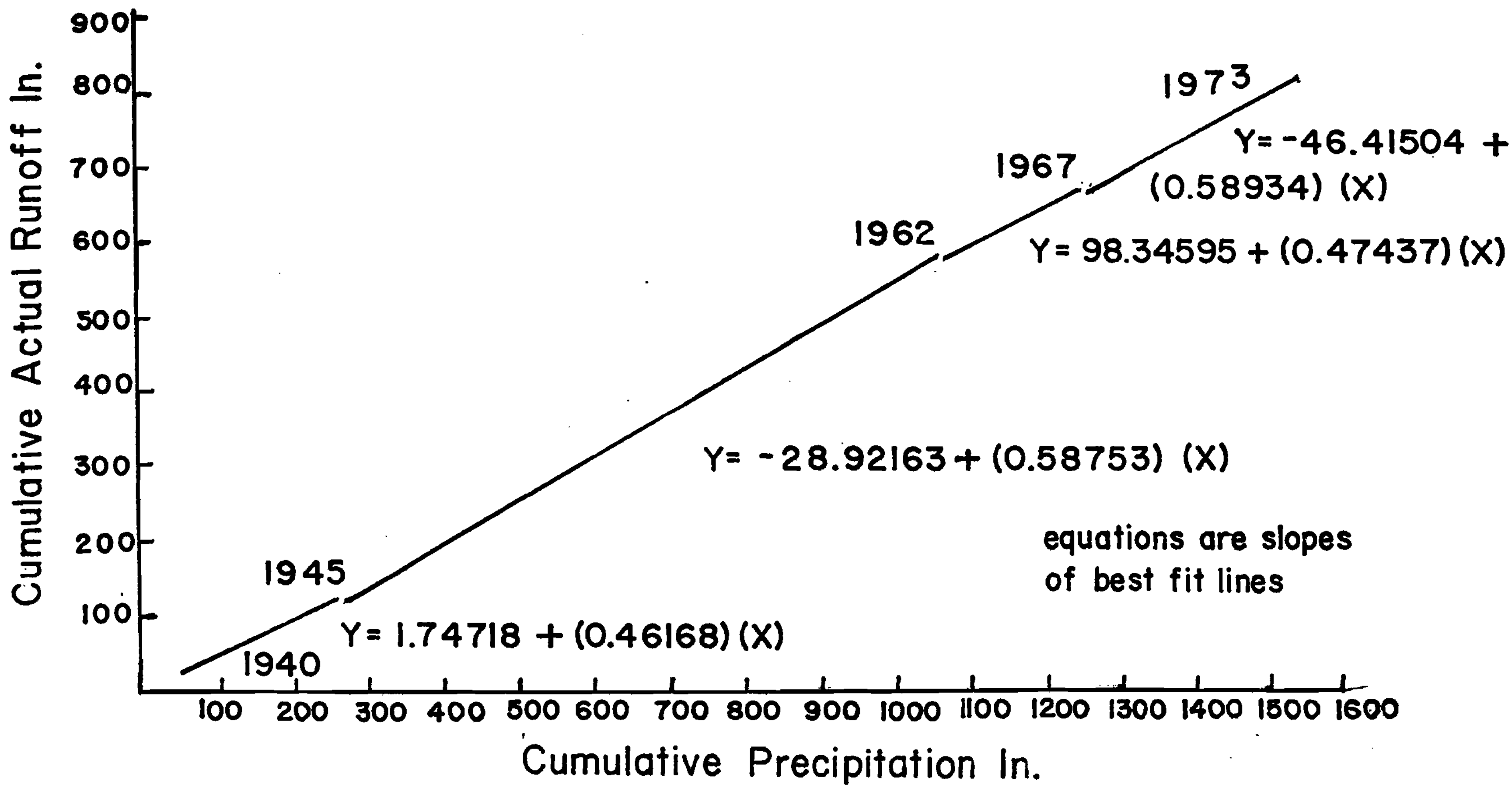
GRAPH 2

DOUBLE MASS OF CALCULATED RUNOFF—Bridgewater



GRAPH 3

DOUBLE MASS—PRECIPITATION VS. RUNOFF—Bridgewater



calculate runoff and plotting it against the observed runoff the slopes are 1.00693 for Norton and 0.99556 for West Mansfield for 1954-1973. It is concluded that the runoff for these two stations is adequately predicted by the estimated. It appears that urbanization has had little influence upon increasing the runoff from this area.

The double mass analysis for precipitation and observed runoff finds similar results. Using precipitation for Mansfield the slope for West Mansfield is 0.50864 and for Norton 0.51443 over the same period. In other words about 51 percent of the precipitation became runoff. Since these two basins exhibit similar runoff characteristics and appear to be accurate indicators of actual runoff with little increases it is possible to use the Norton station as an added comparison with the Brockton drained area.

The Bridgewater and Norton data are presented in two forms: the type of graphs used to determine the breaks in the record and Table 3 which contains the slope values to be evaluated. Two facts begin to complicate the analysis, one strictly regional and the other apparent throughout the total drainage Basin. First, note the gradual increase in slopes up to 1962, followed by a decrease in the mid-sixties then, in the case of Bridgewater, an increase. The decrease for 1962-1967 is common to all stations. These were the dry years mentioned in Chapter 2. As a result of decreased precipitation more rainfall was contributed to

TABLE 3

COMPARISON OF DOUBLE MASS SLOPES FOR BRIDGEWATER AND NORTON

		Bridgewater	Norton	Difference
Calculated Runoff vs. Actual Runoff	1940-1945	1.09577	1.00223	0.09354
	1945-1962	1.15648	1.02523	0.13125
	1962-1967	0.97745	0.97010	0.00735
	1967-1973	1.03330	0.91314	0.12016
Precipitation vs. Actual Runoff	1940-1945	0.46168	0.42295	0.03873
	1945-1962	0.58753	0.52819	0.05934
	1962-1967	0.47437	0.45627	0.01810
	1967-1973	0.58934	0.52665	0.06269

TABLE 4

DOUBLE MASS SLOPES FOR BROCKTON

		Brockton
Calculated Runoff vs. Actual Runoff	1963-1967	1.07621
	1967-1973	1.06841
Precipitation vs. Actual Runoff	1963-1967	0.50421
	1967-1973	0.58442

evapotranspiration than runoff. The Thornthwaite runoff calculates higher values of runoff than observed and the amount of runoff in relation to precipitation decreases. This change in slopes in the graphs means that continuous analysis of runoff from the beginning to end is impossible due to the decline. But comparisons are possible with the period of years that follow.

The other anomaly is in the calculated vs. observed analysis for Norton after 1967, with the decrease continuing. But when comparing actual runoff with yearly precipitation there is an appropriate increase.[94] The error appears to be in the calculated runoff as it suddenly ran much higher than the observed. The temperatures were based upon Taunton data which if they recently became lower than the actual temperature in the Norton area, would decrease evapotranspiration resulting in increased runoff. They appear to have changed the amount of runoff as that appears to have returned to previous levels. The data for the upstream West Mansfield station exhibits the same characteristics. Therefore, the problem here appears to be with a change in the calculated runoff.

This factor makes the latter part of the Norton record difficult to use but the three earlier periods of the record are significant. For the first three series of years the

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[94]For the Mansfield station for the same period the slopes dropped from 0.93881 to 0.89183 while the slopes for precipitation vs. runoff increased from 0.44189 to 0.51435.

actual vs. calculated runoff slopes are higher for Bridgewater than for Norton. There is a marked decrease between the two for the mid-sixties to a value of 0.00735 but Bridgewater remains higher. There is some recovery in the slope for Bridgewater but the decrease for Norton precludes direct analysis.

The runoff vs. precipitation data is more striking. There is a difference with the first to second series of years of 0.03873 to 0.05934 or an increase of from four to six percent more runoff within the Taunton Basin. The difference decreases for the sixties, with more runoff through Bridgewater. Runoff in the last period increased within both areas. For Norton, the runoff of 0.52665 did not equal the second period, but for Bridgewater the runoff slope of 0.58934 increased slightly so that now there is a difference of slightly over six percent between the two stations. This would indicate increasing runoff from the Bridgewater area when compared to the Norton area which has had small changes in urbanization.

The analysis of the Brockton data which are from a station upstream of Bridgewater gives an indication where the increase in runoff is coming from. In comparing the 1963-1967 period for Brockton with the 1962-1963 period for Bridgewater in Table 4 the calculated slopes for Brockton are much higher. But during the last period the Brockton data decreases slightly with the Bridgewater data increasing.

The decrease is similar to what was observed for Norton but not as large. The precipitation vs. runoff slopes show the rebound in runoff for Brockton but it is now lower than the Bridgewater data.

The population and acreage data are inconclusive as an indicator of this sudden change in runoff. The sole argument that can be made is that the population density for the Brockton basin increased at a higher rate than the rest of the basin but has a much lower population density, thereby indicating a higher population in the remainder of the basin.

This anomaly could also be rooted in other factors, but one factor is apparent from this comparison: runoff is higher within the Bridgewater basin than the Norton area. In comparing the urban acreage statistics, both have doubled in twenty years but the Bridgewater basin urbanized from 12.9 to 25.0 as opposed to the increase in the Norton basin of 7.9 to 16.3 percent. The increase of urban area by 12,474 acres in the Bridgewater section saw an increase in runoff within the period. The difference in runoff increased for Bridgewater by 0.02396 or for every 100 inches of precipitation two inches more was added to runoff. Norton had an 8.4 increase in percent of urban acreage within the twenty years while in the Bridgewater basin the increase was in the order of 12.1 in percent of urban acres. Urbanization did not increase as rapidly in the Norton basin which was surpassed by the Bridgewater area by 3.7 percentage points. It is apparent that for every two percent increase in urban acreage runoff is increased by one inch for every one hundred inches of precipitation. This does not quite satisfy the Bridgewater data, but the higher urbanization could tend to increase the runoff.

From this last data it also becomes apparent that the Bridgewater drainage area is urbanizing at a faster rate than the Norton area as there is about a half an inch more of annual runoff in the former.

From the available data it does appear that runoff in the past few years has increased over the 1940's. This factor relates to an increasing amount of urbanization indicating that this type of land use (along with other possible effects from human activities) account for an increase in runoff.

The Blackstone Drainage Basin

The Blackstone River is the major source of runoff water into Narragansett Bay. Starting in Worcester it drains the northwest quarter of the basin, eventually flowing into the Seekonk River near Pawtucket, Rhode Island. The analysis will deal with the area north of the last gauging station on the river which is in Woonsocket. Most of this drainage area is Massachusetts. This area also drains the northwest corner of Rhode Island which will add to the analysis. Precipitation is much more variable in this basin especially in the Rhode Island section. This complicates analysis especially when studying large drainage areas. Due to the number and variety of stations and records it will be best to divide the basin into sections.

Worcester

There are two gauging stations for this general area, one on Kettle Brook (the source of the Blackstone) in Worcester and the other on Quinsigamond River in nearby Grafton. The Worcester station drains part of that city, almost all of Auburn, and a bit of Millbury, while the Grafton station receives runoff from most of Shrewsbury, plus part of Worcester, which includes Lake Quinsigamond. The climatological data is not homogeneous as it consists of two overlapping records with the change in measurements from downtown Worcester to the airport. Data from both periods were analyzed for the two river stations.

Data from both periods are in Table 5. A slightly different trend is apparent here as the calculated runoff is much closer to the actual runoff during the fifties as compared to the forties. The comparison of the two climatic stations shows that the colder airport temperatures increased runoff slightly so that there is a decline in the slopes for the two stations. The data, though, are comparable. It appears the drought greatly affected runoff as the slopes are very low for the mid-sixties indicating much lower runoff than predicted. There is rebound for the last period

TABLE 5

COMPARISON OF DOUBLE MASS SLOPES FOR WORCESTER AND GRAFTON

		Worcester	Grafton	Difference
Based upon Worcester City Data				
Calculated Runoff vs. Actual Runoff	1940-1952	1.09438	1.06544	0.02894
	1952-1962	1.04546	1.04977	-0.00431
Precipitation vs. Actual Runoff	1940-1952	0.49613	0.48290	0.01323
	1952-1962	0.55485	0.55754	-0.00269
Based upon Worcester Airport Data		Worcester	Grafton	Difference
Calculated Runoff vs. Actual Runoff	1949-1962	1.03804	1.03698	0.00106
	1962-1967	0.79644	0.75050	0.04594
	1967-1973	0.94305	0.85391	0.08914
Precipitation vs. Actual Runoff	1949-1962	0.56103	0.56052	0.00051
	1962-1967	0.37060	0.34880	0.02180
	1967-1973	0.51346	0.46555	0.04791

but not up to the calculated as it remained slightly higher than the actual runoff.

Important here are the differences between the two stations. In the forties the calculated runoff was more accurate for the Grafton station than for Worcester. During the fifties it appears that the situation reversed, meaning significant changes in runoff in the Worcester drainage area. The differences between the two increased up to the last period of study.[95]

The runoff vs. precipitation information gives a better indication of the amount of water running off. The drought affected the area significantly as runoff decreased to less than forty percent of the amount of precipitation. But important is the trend between the two. During the forties the runoff from Worcester was higher than for Grafton by 0.01323 but by the end of the study period the Worcester runoff was higher by 0.04791 for a difference of 0.03468. This means that there is about three and a half inches more runoff per 100 inches of precipitation for the Worcester watershed over the Grafton area. The runoff appears to have been about equal during the fifties, maybe due to the higher amounts of precipitation in those years.

The large difference in the latter years could be due

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[95]Grafton is the better indicator of runoff in the early part of the study, but the difference with Worcester is becoming much greater.

to two reasons. The urban acreage for the Grafton basin has been increasing in the twenty year analysis period. Just Shrewsbury is used for this basin as partial statistics for Worcester do not exist. In comparing this with the Worcester basin, which is considered as being only Auburn, the urban land for this area has been increasing at a greater rate. The Worcester basin has gone from 13.6 to 33.9 percent while the Grafton area from 13.5 to 28.3 percent. The increase in urbanization has been in the order of 5.5 percent.

The difference in runoff is reflected by the urbanization statistics. At the end of 1952 the slope difference was 0.01323 in favor of Worcester and by the end of the period the difference had grown to 0.04791. This means that in recent years runoff has increased to about three and a half inches for every one hundred inches of precipitation in the Worcester basin. This corresponds with the Taunton basin as there is about one inch extra runoff for every two percent increase in urbanization. Again, it is slightly higher, possibly due to the larger amount of urban acreage within this particular basin.

The other possible reason for an increase in difference in runoff is that the Grafton runoff has not increased at an equal rate due to water use in that basin. Lake Quinsigamond plus the groundwater supply could be recharging after the mid-sixties. But it is also speculated that this effect is minimal especially eight years after the period of deficit precipitation.

Comparison of the increase in runoff from before the period to the end of the study period is difficult as the amount of runoff has not increased to the pre-deficit levels. But in a comparison with the Taunton basin one sees the great decline in runoff for the mid-sixties but recovery rates are comparable. The Norton area increased by 0.07 while the Bridgewater basin jumped to about 0.115. The Grafton basin which has a slightly higher urbanization compared to Bridgewater increased by about 0.12 while the Auburn area recovered with a 0.14 higher slope.

The Worcester area is the source of water for the Blackstone River. There are two more gauging stations on the stream which should reflect the increasing runoff from this area.

Northbridge

This station is the next one downstream on the Blackstone River. Downstream on nearby tributaries are two gauging stations with short records. The Northbridge data are difficult to work with because of the precipitation that has been recorded in that town. It averages less than the apparent precipitation of the basin. Climatological data for Worcester airport were compared with the Northbridge data and slopes were calculated. The runoff using the

Worcester data proved to be a better predictor of runoff by a slight margin for 1949-1958 but a larger margin in the later years. For the precipitation data the runoff is about equal for the first period but there is a slightly higher amount of runoff per amount of precipitation data that is less than the basin average.

Because the climate data are complete it is best to use the Northbridge data. The slopes for the calculated vs. actual runoff in Table 6 indicate the effect of the smaller precipitation. Except for the first period the slopes are higher when compared to the Worcester data. Even the slow recovery rate is evidenced, though the drop off is about the same. From the predicted slopes it appears that between 1940-1962 there was a definite change in the basin as a whole as the Worcester station which began urbanizing was predicting the runoff more accurately than the Northbridge statistics and up to the present the difference was becoming greater.

The slopes for the amount of runoff per the amount of precipitation shows a marked increase after the first eleven years of study to the typical drop in the mid-sixties. A rebound almost equal to the fifties occurs during the last few years. When comparing this with the Worcester basin the urbanization acreage does not increase. With a difference in runoff of 0.12972 from the first to last period the Northbridge urbanization of 23.5 to 37.3 percent

TABLE 6

COMPARISON OF DOUBLE MASS SLOPES FOR NORTHBRIDGE AND WORCESTER

		Northbridge	Difference Compared to Worcester
Calculated Runoff vs. Actual Runoff	1940-1950	0.94700	-0.14738
	1950-1963	1.19859	0.16055
	1963-1967	0.95167	0.15523
	1967-1973	1.11026	0.16721
Precipitation vs. Actual Runoff	1940-1950	0.44002	-0.05611
	1950-1963	0.61841	0.05738
	1963-1967	0.41997	0.04937
	1967-1973	0.58707	0.07361

TABLE 7

DOUBLE MASS SLOPES FOR DOUGLAS AND UXBRIDGE

		Douglas	Uxbridge
Calculated Runoff vs. Actual Runoff	1940-1950	1.08997	---
	1963-1967	---	0.82757
	1967-1973	---	1.02817
Precipitation vs. Actual Runoff	1940-1950	0.50647	---
	1963-1967	---	0.36512
	1967-1973	---	0.54368

is at a lesser rate than the Worcester basin which went from 13.6 to 33.9 percent. One factor here is the low amount of runoff per precipitation for the years of 1940-1950 for Northbridge. Even by ignoring this there still is a slight increase in runoff in the Northbridge area over Worcester. But the rate of increase in urbanization in the Worcester area is greater than the Northbridge basin. It is speculated that the resulting increase and intensity in acres, not the percentage, may be the key. Urban acreage for the total area went from 17,268 to 27,472 acres while the Worcester basin (which is a part of the larger) went from 1420 to 3544.[96] The higher amount of urban acres which will be concentrated in areas could cause higher runoff especially for the city of Worcester which is included only in the Northbridge basin. Worcester's percent of urban acreage went from 47.8 to 61.3. This high concentration of impervious surface would increase runoff into the Blackstone River.

The other two drainage areas near Northbridge show a couple of trends in Table 7. The data for Douglas are inclusive as all it shows is that runoff for an eleven year period was higher for the Douglas drainage area. The Uxbridge basin shows the effects of the dry sixties by the decrease in

[96]The Northbridge basin consists of Worcester, Shrewsbury, Auburn, Millbury and Grafton.

runoff per precipitation and by the actual runoff being much lower than the calculated. These data are a little less than what was observed for Northbridge, indicating a larger amount of water that runs off in the bigger drainage area. Noteworthy is that the calculated vs. actual runoff slope increased by a higher rate of 0.04201 to the present period for the less urbanized Uxbridge basin.

On the surface it appears that the runoff is increasing at the Northbridge station, but comparisons with urban acreage statistics do not necessarily confirm this. It will be shown later on with further comparisons that there is a noticeable increase.

Woonsocket

The gauge on the Blackstone River in Woonsocket offers the look at three areas of analysis, the drainage area of northern Rhode Island, a small tributary in Woonsocket, and the Blackstone itself which flows mostly in Massachusetts. Again precipitation becomes a problem especially in the Rhode Island area where annual precipitation is high. Due to this variability the climatic data will vary with the station.

As the western part of Rhode Island has a very high amount of rainfall it becomes important to have data that will reflect this effect. Due to the apparent high runoff the climatological data of Gainer Dam was used. It was estimated that the rainfall for this central Rhode Island station would more nearly reflect the total precipitation of the basin. The slopes for Forestdale in Table 8 indicate this fact as the runoff slopes for the calculated are close to being accurate. There is a decline for the period of below normal precipitation as can be expected with a rebound to previous levels. The amount of precipitation that runs off has been steadily increasing with a drop for the mid-sixties that is not as drastic as what has occurred at other stations.

It is impossible to investigate the change in urbanization for Rhode Island as has been done for Massachusetts due to the fact that similar studies do not exist. Only two studies somewhat similar to that previously used do exist and both were completed in the early seventies. Population density statistics are not necessarily accurate indicators of urban acreage.[97] This area consists of the two towns of Burrillville and Glocester which have been increasing in population density from 103 to 113 to 138, according to the U. S. Census starting in 1950. This increase of a third coincides with an increase in runoff of about one inch per one hundred inches of precipitation. The urban acreage is now at 6 percent of the land, an

[97]The Northbridge drainage area appears to have increased runoff, but when population density statistics were analyzed the migration from Worcester was much larger than the increasing population in the nearby towns in the basin. Worcester's urban acreage increased even though there was a population decrease.

TABLE 8

DOUBLE MASS SLOPES FOR FORESTDALE

		Forestdale
Calculated Runoff vs. Actual Runoff	1941-1950	1.03257
	1950-1963	0.98903
	1963-1967	0.83161
	1967-1973	1.02088
Precipitation vs. Actual Runoff	1941-1950	0.50615
	1950-1963	0.55070
	1963-1967	0.41479
	1967-1973	0.56039

indication that any runoff increases would possibly be small in nature.

The climatic data for Woonsocket must take into account the higher precipitation in a portion of the basin. Good long records are lacking. Northbridge's small annual rainfall was not considered which left the data from Franklin, a station nearby with precipitation nearly equal to Woonsocket, and fairly representative of the basin.

In Table 9 one can see the same general trend that has been observed upstream is apparent again. The predicted runoff does not increase to the pre-deficit levels. There is also the sharp drop in the slope for the deficit years which makes it equivalent to the stations upstream on the Blackstone. The Thornthwaite method appears to be a good estimator of annual runoff with the slopes around 1.00 for most analysis.

Again the calculated runoff reflects the amount of runoff per amount of precipitation. There is a general increase in runoff with a sharp drop for the mid-sixties and a recovery reflective of that observed upstream.

Comparison with the Worcester station proves interesting. Assuming that the Rhode Island area of the Blackstone basin with its urban acreage at 6 percent in 1970 increased at a steady but small rate the acreage statistics are

TABLE 9

DOUBLE MASS SLOPES FOR WOONSOCKET WITH BASIN COMPARISONS

		Woonsocket	Difference Compared to Worcester	Difference Compared to Northbridge	Difference Compared to Forestdale
Calculated Runoff vs. Actual Runoff	1940-1950	1.03638	-0.05800	0.08938	0.00381
	1950-1963	1.14585	0.10781	-0.05274	0.15682
	1963-1967	0.75874	-0.03770	-0.19293	-0.07287
	1967-1973	0.96964	0.02659	-0.14062	-0.05124
Precipitation vs. Actual Runoff	1940-1950	0.47516	-0.02097	0.03514	-0.03099
	1950-1963	0.58501	0.02398	-0.03340	0.03431
	1963-1967	0.37924	0.00864	-0.04073	-0.03555
	1967-1973	0.54408	0.03062	-0.04299	-0.01631

revealing. The Woonsocket basin[98] increased from 11.0 to 20.3 percent while the Worcester basin increased from 13.6 to 33.9 percent meaning that the urban acreage increased by a rate of 11 percentage points in the Worcester basin when compared to the total basin. From the runoff statistics one notices that for the first period runoff was higher through Worcester by a slope difference of 0.02097 but by the last period it was higher in the Woonsocket area by 0.03062 so that there is a runoff difference of 0.05159 within the study period. The theory that by increasing the runoff by one inch per one hundred inches does not apply as there is surplus runoff through Woonsocket.

A comparison with Northbridge indicates that there is a runoff increase of 0.07813 during the study period for the Northbridge station. There was a 5.5 increase in urban acreage percent for the Northbridge station in relation to Woonsocket. According to this, for every one percent increase in acreage the runoff increased by about 1.5 inches for every one hundred inches of precipitation, a very high runoff rate.

In comparing the Forestdale slopes with Woonsocket there is an unusual occurrence. The second period shows the runoff higher for the Woonsocket basin while the other

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[98]This basin consists of the communities in the Northbridge basin plus Upton, Northbridge, Sutton, Milford, Hopedale, Mendon, Blackstone, Millville, Uxbridge, Douglas, and Franklin.

periods the Forestdale runoff is slightly higher. These data lead to a few possible conclusions. The Forestdale basin has about 6 percent of the land in urban acres while the Woonsocket area has 20 percent. It is possible that an urbanizing basin will increase runoff in wet years while in dry years the runoff per amount of precipitation may decrease to an extent. The Forestdale basin also has a higher amount of precipitation in comparison with the Woonsocket area. The runoff statistics are fairly equal. This may result with runoff from an unurbanized basin with high precipitation equalling the runoff from an area of small precipitation but higher urbanization. It is also speculated that the Forestdale basin could be reverting from agricultural land to forest acreage during this period. This would result in a decrease in runoff.

An attempt will be made to clarify some of the apparent inconsistencies in the Blackstone basin data in a section below.

In the small Woonsocket basin one finds that the Woonsocket data do a poor job in estimating the runoff for this small basin. Forty-five percent of the precipitation runs off as opposed to higher quantities in other basins. As a result it is most likely that the basin characteristics are highly influential in the runoff process of this area.

In conclusion, the Woonsocket basin does not consistently follow the relationship between runoff and urbanization. In comparison with other areas it does not fit the theory that a certain amount of urbanization leads to a certain amount of added runoff. But there are indications that runoff is high for this basin particularly for that part of the basin that drains Massachusetts. Proof of this fact led to the following analysis.

The Northbridge Cutoff

It is possible that as the basin becomes much larger the runoff tendencies become a bit difficult to detect as urban acreage increases but there is also more area available to absorb, store, and evapotranspire precipitation which can distort urban percentages. It was decided to shorten the Woonsocket basin as much as possible. The amount of runoff was calculated for the Forestdale and Northbridge basins and subtracted from the runoff from the total Woonsocket basin. This resulted in a basin with a drainage area of 183.7 square miles, about twice as large as Forestdale and about a third larger than the Northbridge basin. Comparable slopes and Table 10 were prepared using the Northbridge climatological data.

Urban acreage increased from 4.7 to 11.6 percent within the cutoff basin while in the Northbridge basin it increased from 23.5 to 37.3 for a difference of 6.9 percent. Checking the slope differences one notices that increasing urbanization may have come late to the cutoff area and is a

TABLE 10

DOUBLE MASS SLOPES FOR NORTHBRIDGE CUTOFF WITH BASIN COMPARISONS

		Cutoff	Difference Compared to Northbridge	Difference Compared to Forestdale
Calculated Runoff vs. Actual Runoff	1941-1950	1.00567	0.05867	-0.02690
	1950-1963	1.17006	-0.02853	0.18103
	1963-1967	0.86185	-0.08982	0.03024
	1967-1973	1.08097	-0.02929	0.06009
Precipitation vs. Actual Runoff	1941-1950	0.47741	0.03039	-0.02874
	1950-1963	0.56417	-0.05824	0.01347
	1963-1967	0.38009	-0.57158	-0.03470
	1967-1973	0.57179	-0.01528	0.01140

relatively new development. The difference in slope from the beginning to end of the period is 0.050267 so that runoff increased by five inches for every one hundred inches of precipitation in the Northbridge basin over the cutoff area. This results in an 1.5 inch increase in runoff for every one percent difference in urbanization. This is still much higher than the average for other basins but some of the increase is due to the higher as well as more densely settled area in the northern portion. This more densely settled section is obviously increasing the runoff at a higher proportion.

Analysis with the Forestdale section is without definite urban acreage statistics but there is a trend toward increased runoff from the cutoff area, indicating the higher amount of urbanization. The Thornthwaite calculated runoff shows that as the periods passed the calculated runoff for the cutoff became less accurate. This would also indicate that urbanization was gradually increasing within the cut-off basin.

This method also indicates that the calculated runoff for the Northbridge basin became a less accurate indicator of runoff than the cutoff section. All of this points to the increased urban acreage in the northern portion of the study area over the southern.

Although the cutoff analysis does not resolve the idea that urban acreage increases runoff at a certain rate, it is a good indicator of the higher percentage of land under urban use in the northern area. This trend is visible in the calculated runoff as well as in the specific amount being added to runoff. The cutoff area also shows that the years of deficit precipitation were just as severe in this section as in the Northbridge basin, but that the responding rebound was greater for the cutoff.

Blackstone Conclusions

A few general trends are apparent from the preceeding analysis. The primary result is that increased urban acreage has increased runoff within the basin. Use of the cutoff basin showed that runoff is much greater over the Northbridge basin than within the cutoff area. Comparison with the highly unurbanized Forestdale section with the calculated runoff showed a decrease in the reliability of the cutoff to predict runoff. This is an indication of the increase in urban land in the cutoff area. The total Woonsocket record corresponds with the Northbridge data as runoff is increasing at a much higher rate in the northern basin.

One reason the Woonsocket data may not agree with the Worcester data is that the former is such a large and varied basin. There is probably much input from urban areas either clustered near the stream or with outlets into the Blackstone or its tributaries. The Worcester data are significant in the fact that the Worcester basin is urbanizing faster than the Grafton data and the relative runoff slopes indicate that fact. The Grafton data exhibit a large drop in slope during the mid-sixties with a slow recovery afterwards. It is believed that other land use factors, possibly increased water storage or usage, are decreasing the amount available for runoff.

The question of whether urbanized areas decrease the amount of runoff in dry years and gradually increase it in wet years can be determined by an analysis of slope differences between the fifties, mid-sixties, and early seventies. Table 11 indicates no real pattern that holds throughout. It is interesting to note that two stations with small decreases and large post-deficit increases are the least urbanized stations. Forestdale with the smallest area in urban acreage had a higher slope at the end of the study period than at the beginning. The cutoff area which has a little more urbanization almost recovered to the fifties rate.

Woonsocket had a very high drop off rate with a high recovery rate but it still left a large deficit. The same is true for the Grafton basin. This makes specific analysis impossible but the trend appears to be one of larger deficits for urban areas coming into dry years with smaller increases in slopes in the following wetter years. It is possible that the increase in runoff has gradually lowered

TABLE 11

CHANGE IN SLOPES FOR CALCULATED VS. ACTUAL RUNOFF DUE TO THE DROUGHT YEARS

	Amount of Decrease	Amount of Increase	Difference	Percent of Urban Acres
Worcester	-0.24160	0.14661	-0.09499	33.9
Grafton	-0.28648	0.10341	-0.18307	28.3
Northbridge	-0.24692	0.15859	-0.08833	37.3
Forestdale	-0.15859	0.18927	0.03185	5.7
Woonsocket	-0.38711	0.21090	-0.17621	20.3
Cutoff	-0.23024	0.21912	-0.01112	11.6

the water table, thereby decreasing runoff in dry years. The subsequent small recovery may be due to the natural recovery of the water table. This idea will be explored later when data from all basins are available.

Further comparisons and conclusions will follow in Chapter 7.

The Providence Drainage Basin

This is the smallest basin area with only two stations available. One station is on the Woonasquatucket in Centerdale, while the other consists of a very short record for Providence. Very little comparison can take place with the data inconclusive.

Slightly different study times were used with the analysis for Centerdale starting in 1949. In this manner one is able to use solely the climatological data of the Providence airport in Warwick.

The use of this data in Table 12 showed that the calculated runoff was a good estimator of runoff. There was a drop in the mid-sixties and recovery almost returned to the pre-deficit period.

The urban acreage within the basin appears to be about 13.2 percent of the land.[99] The Centerdale basin failed to recover to the previous slope by -0.01895. This result is

[99] It consists of North Smithfield and Smithfield.

TABLE 12

DOUBLE MASS SLOPES FOR CENTERDALE AND PROVIDENCE

		Centerdale	Providence
Calculated Runoff vs. Actual Runoff	1949-1955	1.02839	---
	1955-1964	1.01779	---
	1964-1967	0.86352	1.25887
	1967-1973	0.99884	1.04059
Precipitation vs. Actual Runoff	1949-1955	0.56412	---
	1955-1964	0.54774	---
	1964-1967	0.43215	0.51014
	1967-1973	0.54835	0.52099

fairly consistent with the same type of data previously mentioned for the Blackstone basin.

The runoff per amount of precipitation statistics also suggests that the runoff is relatively consistent with a gradual increase. The period of deficit precipitation was not as severe as in some cases as the drop was only 0.115. It is questionable whether the slight drop in runoff during the late fifties is significant. Slopes were calculated using the Greenville station which is near this basin. The slopes for the first two periods were 0.56300 and 0.57439 indicating a slight increase within this period. There is a possibility that runoff actually decreased during the period due to a land use change from agricultural to forest land. But the population in this basin has almost doubled to 22,817 and there is a slight trend in the increasing runoff slope that would indicate urbanization is slowly increasing the basin runoff.

The use of the Providence airport climatological data for the Providence basin is inconclusive. The predicted value for the dry years is much higher than for the last few years. Actual runoff was much higher than the predicted, which is contrary to the other stations. Also the runoff per amount of precipitation does not exhibit a significant decrease as it is consistently a little over 50 percent.

In conclusion, there is very little of significance due to the scarcity of data. The Woonasquatucket, though, does exhibit some of the characteristics of a basin that has a small but increasing amount of urban acreage.

The Pawtuxet Drainage Basin

Central Rhode Island is drained by the Pawtuxet River which includes the Scituate Reservoir. This basin is proof of the fact that runoff is based primarily upon the average precipitation of the basin. This basin drains an area of highest precipitation of the whole study area and this factor tends to increase runoff within the basin. Climatological data for the basin will be applied to two basins with relatively long records along with a few others with a few years of records.

The Washington station on the South Branch of the Pawtuxet has a long record of data. Fitting climatological data with this station had to take into consideration the amount of precipitation within the basin. Slopes were plotted using the Hopkins Mills and Gainer Dam and records presented in Table 13. The results showed that runoff was a little higher than the calculated for the Gainer Dam record while just the opposite was found for the Hopkins Mills data. Therefore, it appears that average runoff is somewhere between these two figures for this basin. Since the Hopkins Mills station appears to be a better fit, this data will be analyzed.

These particular stations show an increase for the

TABLE 13

DOUBLE MASS SLOPES FOR WASHINGTON USING DIFFERENT CLIMATOLOGICAL STATIONS

		Gainer Dam Data	Hopkins Mills Data
Calculated Runoff vs. Actual Runoff	1941-1949	1.15131	0.97595
	1949-1963	1.11765	1.05323
	1963-1967	0.98004	0.81538
	1967-1973	1.02244	0.93553
Precipitation vs. Actual Runoff	1941-1949	0.56042	0.51453
	1949-1963	0.61893	0.59817
	1963-1967	0.48920	0.43519
	1967-1973	0.56128	0.53234

fifties with a sharp drop for the mid-sixties followed by an increase not yet reaching the 1940's rate. According to the 1970 statistics only 5.1 percent of the basin was considered urbanized.[100] The recovery from the period of dry years appears to be very slow, or water has since been diverted for other purposes.

The actual runoff rates show that the runoff has recovered to a figure higher than the one observed for the forties. The period of deficit precipitation appears to have been severe but there is not as drastic a change as in other stations.

There are two small gauged areas upstream of Washington in the Nooseneck area that measure tributaries of the Pawtuxet. The data from these areas in Table 14 are inconclusive. For the Nooseneck 1 station the estimated runoff is very high while the Nooseneck 2 station has much smaller slopes. These two areas are close to one another and exhibit a great variability in runoff. This undoubtedly is due to the topography of the region rather than a great variability in precipitation. The Nooseneck 2 station drains a swampy area while there is a higher topography within the Nooseneck 1 station. This could result in the slower rate and smaller amount of runoff in the former against the higher amounts for the latter.

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[100] The basin is primarily in Coventry and West Greenwich.

TABLE 14

DOUBLE MASS SLOPES FOR TWO NOOSENECK STATIONS

		Nooseneck 1	Nooseneck 2
Calculated Runoff vs. Actual Runoff	1964-1967	1.01836	0.71424
	1967-1973	1.16649	0.94715
Precipitation vs. Actual Runoff	1964-1967	0.51192	0.35836
	1967-1973	0.64040	0.52005

Due to the extreme variability of runoff within this basin, along with the shorter record it is difficult to perform any comparisons. It does appear to reflect the runoff that occurs in Washington.

The other major gauging station is situated in the city of Cranston and drains the bulk of the basin including the Scituate Reservoir area. This particular area poses distinct problems.

The use of climatological data is an excellent example that the average precipitation of the basin is necessary when computing the Thornthwaite runoff. Data for the station nearest the gauging station, Providence airport, proved to be a poor estimator of runoff with the calculated much lower than the actual. The figures for Gainer Dam, within the basin and probably closest to the actual basin average in precipitation, also had slightly high slopes. Finally the Hopkins Mills statistics were computed. This resulted in slightly lower slopes but statistics that are comparable with stations previously investigated. It appears that Hopkins Mills is the most accurate predictor of the runoff through Cranston.

This is one way in which the runoff is affected by the Scituate Reservoir area. The amount being taken out of the reservoir and others within the basin result in the Cranston data being adjusted to take into account what is lost from these sections of the basin. Even though in some cases this water may be put back into the runoff regime by individual cities, it is presumed that not all left the basin. Between the high amount of precipitation within a portion of the basin, and the degree of regulation that occurs in reservoirs, the runoff statistics of this basin may not be extremely accurate.

One other factor causing the Hopkins Mills data to be an accurate indicator is the high evapotranspiration from the Scituate Reservoir. There will be a large moisture loss within this area and one method of compensating for this fact is to begin with high values for yearly precipitation. This situation contributes to the need for the use of precipitation data similar to Hopkins Mills.

The slopes for the runoff per amount of precipitation presented in Table 15 become very high for the mid-fifties with a sharp drop for the deficit years. The recovery for the past few years nearly equals the point of the fifties. Runoff through this whole period appears high even though the figures which deal with the highest amount of precipitation were used.

Data from a stream within Cranston, and upstream from the Pawtuxet station provide a brief comparison. The Gainer Dam climatological data was used for the Furnace Brook station with the Thornthwaite estimate fairly accurate, resembling the slope for the Cranston data. This proves that the precipitation data are an accurate indicator of

TABLE 15

DOUBLE MASS SLOPES FOR CRANSTON WITH BASIN COMPARISON

		Cranston 2	Cranston 1	Difference Compared to Washington
Calculated Runoff vs. Actual Runoff	1941-1949	0.95056	---	-0.02539
	1949-1963	1.05950	---	0.00627
	1963-1967	0.83459	---	0.01921
	1967-1973	1.04068	1.04539	0.10515
Precipitation vs. Actual Runoff	1941-1949	0.50121	---	-0.01332
	1949-1963	0.60169	---	0.00352
	1963-1967	0.44491	---	0.00972
	1967-1973	0.59146	0.57276	0.05912

basin characteristics. Significantly, the runoff is higher in the whole Pawtuxet vs. the Furnace Brook area. From urban acreage statistics it appears that the Furnace Brook area is not highly urbanized.

This leaves the comparisons of the two drainage areas with the longest records, Washington and Cranston. The actual runoff against the precipitation for the basin shows that runoff has been increasing for the total basin. The large increase though does not appear to reflect the difference of about 1.4 percent in urban acreage in 1970.[101] What is more important than overall basin average is the concentration of urban area. Only 6.5 percnet of the basin consisted of urban acreage in 1970. Part of the basin drains a portion of Cranston, near the gauging station, with its higher intensity of urbanization. The river also borders West Warwick and drains most of that city which is 48.5 percent urbanized. The facts are that the area receives about 47 inches of precipitation annually, the Gainer Dam station very accurately predicts runoff in a small basin near this station, while it is the high precipitation of Hopkins Mills that predicts and reflects the Cranston runoff. It would appear that the intensive urbanization in the eastern section is causing runoff to be slightly higher than can naturally be expected.

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[101]This is based upon data for Coventry, West Greenwich, Scituate, Foster and West Warwick.

Upon observing the calculated slopes for the mid-sixties it appears that the total basin recovered much better than the Washington area. Both dropped to about the same level from about the same level, but the slope became 0.10 higher in the Cranston basin. This difference could be due to two factors, first the increase in runoff particularly in the Cranston-West Warwick area and a decrease in the actual runoff in the Washington basin, possibly due to a return to natural vegetation increasing the evapotranspiration.

The analysis of this basin is based primarily upon the accuracy of the adjusted runoff statistics provided by the Geological Survey. If their calculated figures of the change of water in the reservoir watersheds are inaccurate this particular study will not reflect the runoff process. It does seem reasonable to state that there is increased runoff over a portion, and it is due primarily to increased urbanization.

Summary

The Bridgewater basin, when compared to a slower urbanizing basin in Norton, has experienced an increase in the amount of water running in the Taunton River. This is probably due to the increase in urban area by four percent over the Norton area. Comparison with the small Brockton basin showed about an equivalent amount of runoff. This small basin, though, drains only a small amount of Brockton which has increased in urban area from 38 to 64 percent in the twenty year period. As a result the increased runoff through the Bridgewater station would be due primarily to this fairly recent increase.

In the total Blackstone basin runoff was found to be increasing in certain sections. The urban increases in the Worcester basin is causing more runoff, particularly when compared to the less urbanized Grafton basin. Analysis of the large drainage areas become complex with combinations of factors influencing runoff. In particular, runoff through Woonsocket is influenced by high precipitation amounts in the Forestdale area. There is a high amount of runoff from the Forestdale basin which roughly equals the total basin runoff. Most revealing was the comparison with the Northbridge cutoff area. With the cutoff section it was discovered that runoff was much higher in the Northbridge drainage area when compared to the cutoff. This corresponded with the higher amount of urbanization in the upper portion of that drainage basin. The data also matched well with the Forestdale section as it has less urban acreage and runoff would increase at a slower rate than the cutoff area. It would appear again that runoff increases are due to urbanization, with the bulk of the increase occurring in the upper portions of the basin.

There appears to be a small increase in the runoff in the Centerdale area, but the Providence basin and its small amount of data is inconclusive. Any increase is on a small scale due to the small rate of urbanization.

Lastly, the Pawtuxet basin is dependent upon the high precipitation in the source region. Runoff is on the increase in the Pawtuxet through Cranston when compared to the slightly urbanized Washington district. The higher urbanization is concentrated in the eastern portion of the basin, which may be the reason for the calculated runoff being based on a high amount of annual precipitation. The high evapotranspiration from the Scituate Reservoir contributes to the use of high annual precipitation statistics to compensate for the water loss. If the measured runoff from the Reservoir is accurate, the large runoff rate is due in part to the high precipitation in one section of the Cranston basin and the high concentration of urban land in the other.

The analysis brought up certain questions and possible comparisons that can further indicate any increases in the runoff regime. These involve further analysis of previously presented data along with the runoff relationships of different basins.

CHAPTER 7

ANALYSIS OF THE NARRAGANSETT BAY DRAINAGE BASIN AS A WHOLE

The four study areas of the Narragansett Bay Drainage Basin each exhibited certain intrabasin characteristics that allow for interbasin analysis. Most importantly runoff appears to be increasing within the Basin with high rates of urban acreage increases, but not necessarily at a set rate of runoff increasing for a set rate of urbanization. Two basins were compared in the Taunton basin and in the Worcester area. Each had a basin that increased runoff by one percent for every two percent increase in urban acreage. The particular factor, though, did not hold true for the remainder of the study area. Other basins appeared to increase runoff at a higher percentage when compared to the relative increase in urban area.

Interbasin Comparisons

It is apparent that from comparisons within a drainage basin that runoff is increasing in relation to an increase in urban acreage. It is important to compare stations from the basins as a whole to determine if these conclusions are valid for the total study area of the Narragansett Bay Drainage Basin.

The analysis of data in this section will be by the periods of which slopes were determined for Chapter 6. These do not necessarily correspond exactly to specific years but the general periods were represented: the first period is the forties, the second is the fifties, the third is the years of deficit precipitation of the sixties and the fourth is the period from the mid-sixties to 1973.

Analysis of the Forestdale and Bridgewater basins, in Table 16 reveals an unusual tendency. The tendency in runoff from both categories of slopes is that runoff is increasing for part of the period within the Bridgewater basin, but the Forestdale section is presently increasing its amount of runoff. It would appear that the tendencies in runoff between these two stations would be due in part to the increasing urban area in the Bridgewater and a possible change from farm land to forest area in the Forestdale section. The present trend of increasing runoff in Forestdale may be due to an increase in impermeable land increasing runoff.

The Bridgewater basin increased urbanization from 12.9 percent to 25.0 percent during the past 20 years while the Massachusetts section of the Woonsocket increased from 11.0 to 20.3 percent. The difference in the accuracy of the predicted runoff fluctuates wildly and indicates little

TABLE 16

COMPARISONS OF DOUBLE MASS SLOPES

		Bridgewater Minus Forestdale	Bridgewater Minus Woonsocket	Norton Minus Cutoff
Calculated Runoff vs. Actual Runoff	First Period	0.06320	0.05939	-0.00344
	Second Period	0.16745	0.01063	-0.14483
	Third Period	0.14584	0.21871	-0.10825
	Fourth Period	0.01242	0.06366	-0.16783
Precipitation vs. Actual Runoff	First Period	-0.04447	-0.01348	-0.05446
	Second Period	0.03683	0.00252	-0.03598
	Third Period	0.05958	0.09513	0.07618
	Fourth Period	0.02895	0.04526	-0.04514

change in the ability to predict runoff. The actual runoff vs. precipitation shows an increase through the years of about 0.06 indicating increased runoff from the Bridgewater basin. The rate of urbanization and increase of runoff indicate that for every one percent increase in urbanization there is an increase in runoff of about one and a third inches for every 100 inches of precipitation.

Norton and the cutoff area are two small basins with steadily increasing urbanization, Norton going from 7.9 to 16.3 percent while the cutoff area has increased from 4.7 to 11.6 percent. The calculated runoff is not accurate for Norton, as mentioned previously in Chapter 6, but the slopes for the precipitation vs. runoff are revealing. Runoff has increased in the Norton basin, drastically for the mid-sixties, and are presently running slightly higher than the first general time period. Urban acreage has increased at a slightly quicker rate in the Norton basin with a change of 1.5 in percent of urban acreage. This would fit the slow increase in runoff that is evidenced in this comparison.

The long record for the station in Cranston allows for speculative comparison due to the lack of urban acreage statistics for the early fifties. The rough estimate for urbanization in this basin is 6.5 percent for 1970. What is missing from this figure is the concentration of urban acres in the West Warwick portion which is close to fifty percent. When compared to three highly urbanized sections in Table 17 the differences during various periods show trends of increased runoff.

The calculated runoff depicts the importance of the intensity of urbanization. In the case of Bridgewater and Woonsocket the calculated runoff slope for Cranston was becoming higher by the last period. This means that, in relation to Bridgewater and Woonsocket, Cranston was becoming a less accurate predictor of runoff through the years. There was more change in this basin through this period which is indicated by the successively higher slopes for Cranston. The exception is for the Northbridge station, but even in this case the slopes over the last twenty years are beginning to show an increase in runoff in the Cranston basin.

The precipitation vs. runoff slopes for nearly all cases indicate a higher percent of runoff within the Cranston basin. The trend in the three cases is for an increase in runoff in the other three basins when compared to the Cranston station. The higher runoff in the Cranston basin would be due primarily to the intense urbanization in one section and the higher precipitation in another section. The increasing runoff in the other basins would be due to the higher rate of urban acres in those basins. From these two comparisons it is apparent that a higher amount of precipitation leads to a larger amount of runoff. There is

TABLE 17

COMPARISONS OF DOUBLE MASS SLOPES

		Cranston Minus Bridgewater	Cranston Minus Northbridge	Cranston Minus Woonsocket
Calculated Runoff vs. Actual Runoff	First Period	-0.14521	0.00356	-0.08582
	Second Period	-0.09698	-0.13909	-0.08635
	Third Period	-0.14286	-0.11708	0.07585
	Fourth Period	0.00738	-0.06958	0.07104
Precipitation vs. Actual Runoff	First Period	0.03953	0.06119	0.02605
	Second Period	0.01416	-0.01672	0.01668
	Third Period	-0.02946	0.02494	0.06567
	Fourth Period	0.00212	0.00439	0.04738

not a set ratio indicating the exact amount of precipitation that will run off. There is a higher rate of runoff in rainier years.

Any other interbasin comparisons appear irrelevant, due to the length of record or size and complexity of the basin. It does appear that the general trend of increasing urban acres increasing runoff is a general regional trend.

Analysis of the Mid-Sixties

The available data offer one other analysis that is worthy of study. For the Blackstone basin the fact became apparent that the deficit of the mid-sixties appear to have been more severe in parts that are draining urban areas. Due to the significance of this the statistics were calculated for the remaining basins with adequate length of records. The data in Table 18 are directly comparable to what was presented in Table 11. The Norton data were omitted when plotting correlation coefficients and graphs due to the continued decrease in the present period. Although a specific trend is lacking a general picture is apparent. As is shown in Graph 4, areas of small urban acreage had a much higher rebound from the deficit, while the basins with greater than 20 percent of the land as impervious surface had a poor recovery rate. The one remaining exception is the Washington basin with its low urbanization and slow recovery following the mid-sixties.

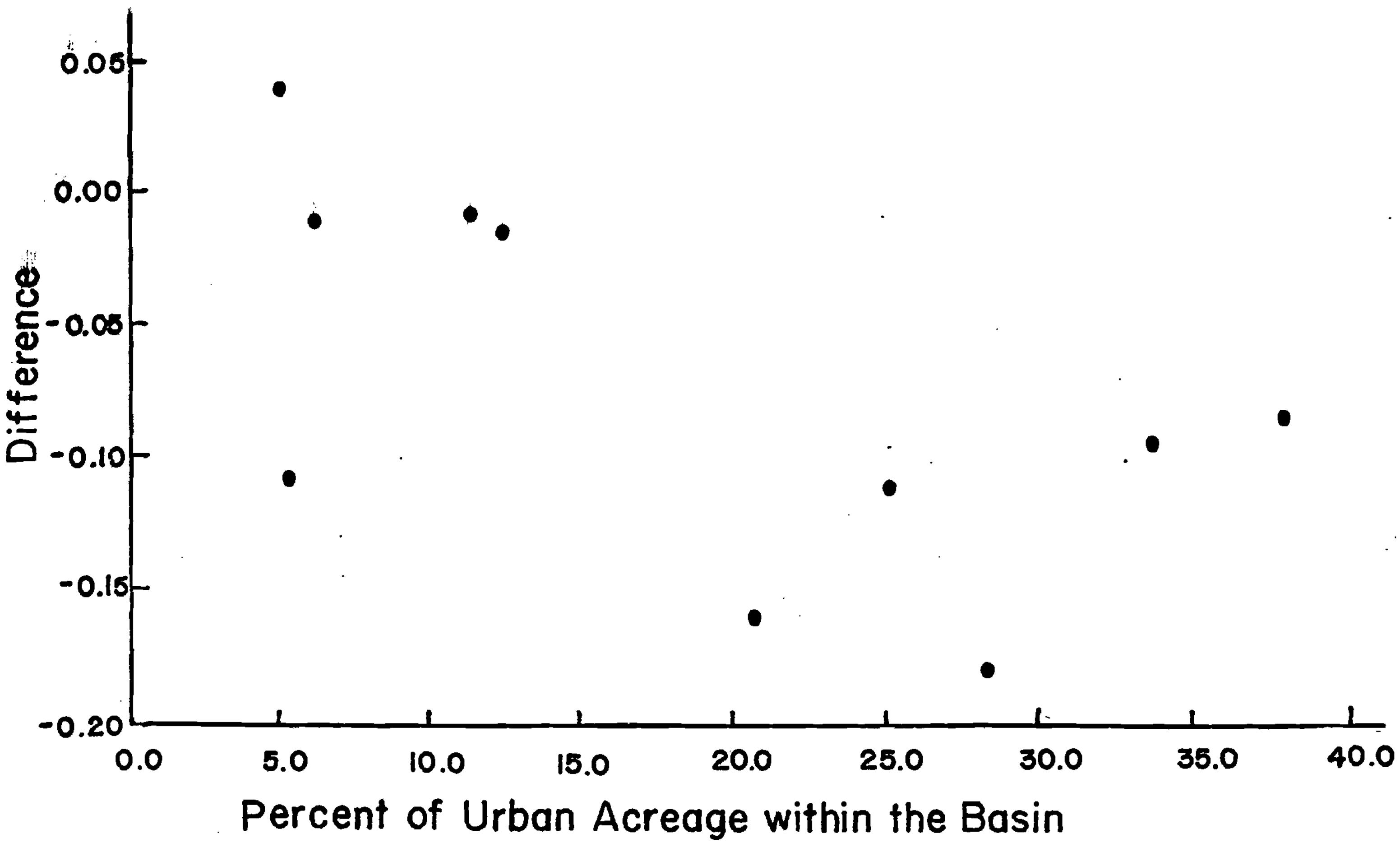
TABLE 18

CHANGE IN SLOPES FOR CALCULATED VS. ACTUAL RUNOFF DUE TO THE DROUGHT YEARS

	Amount of Decrease	Amount of Increase	Difference	Percent of Urban Acres
Bridgewater	-0.17903	0.05585	-0.12318	25.0
Norton	-0.05513	-0.05696	-0.11209	16.3
Centerdale	-0.15427	0.13592	-0.01895	13.2
Washington	-0.23785	0.12015	-0.11770	5.1
Cranston	-0.22491	0.20609	-0.01882	6.5

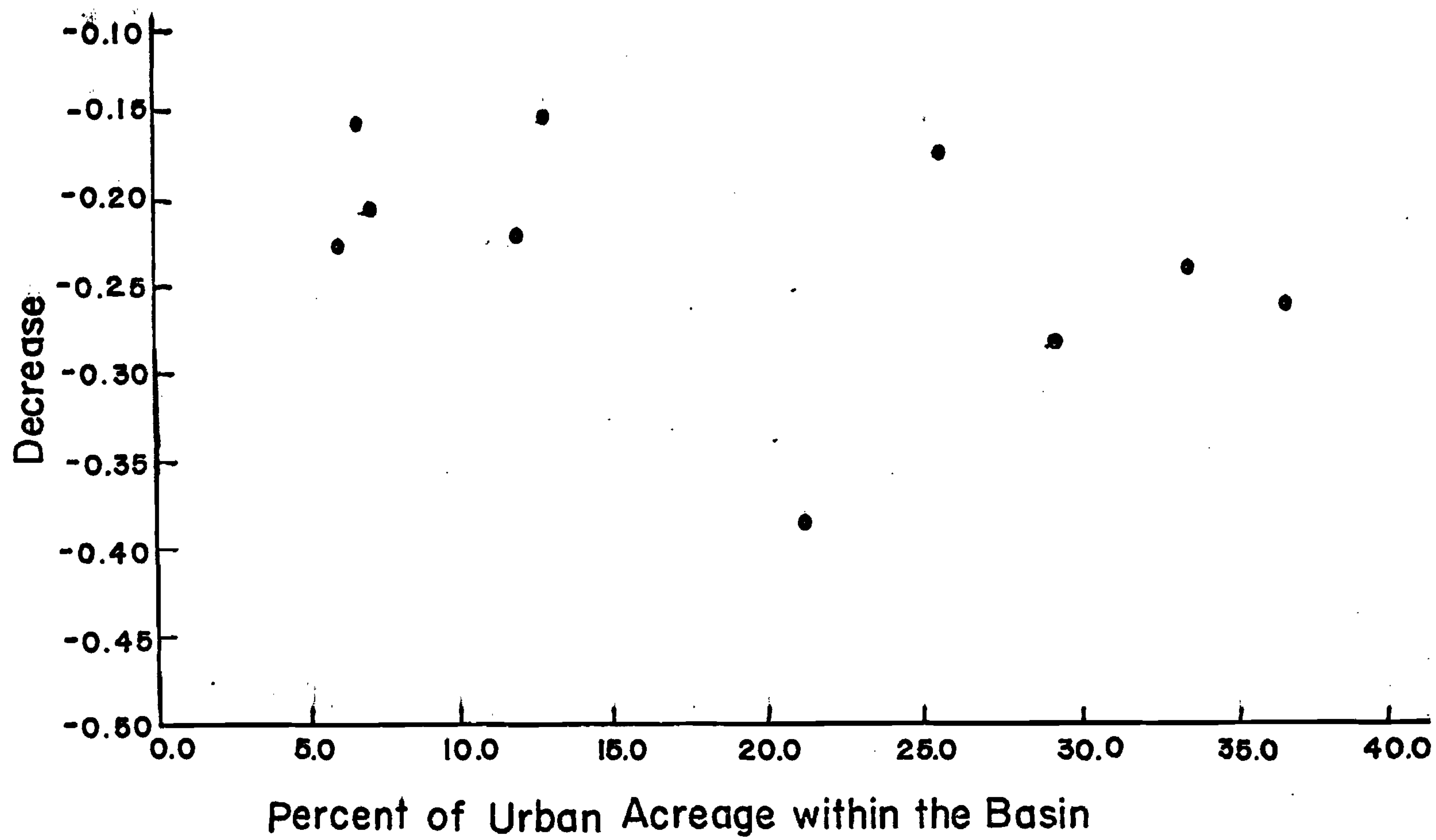
GRAPH 4

Runoff Relationship between Deficit Years and Urban Acreage



GRAPH 5

Runoff Relationship between Decrease and Urban Acreage



The fact that urban areas tend to decrease the base flows in deficit periods is apparent in the analysis of the decrease in slope occurred in the Woonsocket basin which had about 20 percent of the land in urban acreage. The three other areas upstream (Forestdale, Northbridge and the Cutoff area) all had a less pronounced decrease in runoff. One can only speculate that such a great decrease was due to the cumulative effects of drought on the runoff as it traveled downstream from Worcester or possibly a water loss from the Blackstone River that was not detected. The general trend appears to be that areas of higher urban acreage had a greater deficit period.

Therefore, it appears that the urban areas of the Narragansett Bay Drainage Basin can cause a decrease in runoff during certain periods. The base flows are affected by a drier period in areas of higher amounts of impervious surface causing less runoff for these areas. The recovery period is less consistent but the differences between the two periods indicate that urbanized sections are more severely affected. This could be due in part to the decrease in base flows during the period of deficit precipitation and possibly the slow recharge of the groundwater in the following period. The urban deficit in the combination of the two runoff periods shows an unexpected effect of the runoff regime in the basin. It shows that urbanization does not necessarily increase runoff under certain climatic conditions.

CHAPTER 8

CONCLUSIONS AND PROPOSALS

Several factors are significant in the runoff into the Bay. The amount of precipitation is the major factor in the amount of runoff that occurs. Higher than average amounts of precipitation tend to increase the amount in streamflow. As in previous studies, it is discovered that the percent of impervious surface is related to the amount of runoff in two ways: it tends to increase the amount running off and appears to lower the rate of runoff during periods of no precipitation.

Ramifications for the Narragansett Bay Drainage Basin

The overall climate of the Basin throughout the period, combined with urban acreage, caused a decrease in runoff for a part of the study period. The period of deficit precipitation of the mid-sixties and subsequent recovery were most severe for the more urbanized areas. This is shown by a fairly large drop in the actual runoff when compared to the calculated runoff. Urban areas tend to decrease base flows, which is what occurred in the sixties. The recovery to a rate less than the fifties would seem to indicate that the recharge of the groundwater is a slow process, due to the poor infiltration property of impervious surfaces. The effects of the dry mid-sixties appear to be in slight evidence today with a smaller runoff rate in some areas. The combination of high urban acreage and a period of below normal precipitation can create a period of decreased runoff.

Comparisons were made between basins for four periods of years. Thus it was possible to indicate basins with increasing runoff, relating it to increasing urbanization. It was found that runoff has been increasing in the more urbanized basins. In a few cases it was found that for every two percent difference in urban acreage increases, runoff in the basin increased by one percent. In other cases a ratio of over one inch of runoff for a percent increase in urbanization was found. Although no specific increase in runoff was found for a specific amount of urban acreage, the trend is in this direction. One of the two factors which appear to weigh heavily is the size of the basin. Large basins, containing more acreage make the runoff regime a complex proposition. Another key factor is the intensity. If much of a basin is unurbanized, but with impervious surface concentrated in a small area, the river flow is increased.

Through this study it is quite evident that the climate and the land use within the drainage basin of Narragansett

Bay affects the fresh water that flows into the Bay. Further increase in runoff may lead to an enlargement of a river channel. This would be necessary for years rainier than normal. But, as has been seen, the deplenished groundwater supply causes a decrease in runoff in dry periods. Larger streambeds may not be necessary at all times. Runoff into the Bay in post-deficit periods may be slow to re-reach to the runoff levels previously registered.

Two possible outcomes of changes in urbanization and precipitation might easily upset the ecological balance of the Bay. Periods of high or increased runoff could result in a higher concentration of fresh water within the Bay, diluting the naturally briny composition. Years of below normal precipitation, occurring with increasing urban land, might tend to reduce the runoff, with the result of salt water intrusion in the rivers themselves. And the increase or decrease of salt water in the Bay can easily influence the quality and quantity of marine life in the Bay.

This study was conducted for only those rivers with adequate gauging records. It constitutes slightly over half of the total drainage basin. Several sections were omitted since there were no runoff records available. From this study it is believed, however, that the same process would be applicable in the remaining areas. Any increases in urban acreage will tend to exhibit the same runoff characteristics that have been demonstrated here, with the exact amount dependent upon climatological and non-climatological factors.

Reflections on Thornthwaite's Water Budget

The Thornthwaite water budget as an estimator of runoff was quite useful. There were occasional instances where his method appeared to indicate certain changes that other data did not and only further investigation into all aspects of the variables could indicate which were actually influencing the slopes. Although these types of situations were rare in such cases the Thornthwaite budget was a good indicator.

On a yearly basis it provided positive results except for the first year of data. Due to the lack of a "carry over" amount for the first month, the first year usually resulted in an underestimation of runoff. Any further use of the first year data, other than conducted here, could be suspect. This would include analysis on a monthly basis.

The Thornthwaite system though was not a consistently accurate system of estimation. It is imperative that the precipitation totals that are used are most nearly the basin average. Otherwise, there will be a poor estimation of the basin runoff. The same applies for the use of temperatures; they should come as close to the basin average as possible.

A major problem was to account for the great range in precipitation. In wet years the predicted value was lower than the observed basin runoff. In the dry sixties actual runoff was much lower than predicted due to the fact that less precipitation runs off during periods of below normal precipitation. For future use it may be best to perform other studies to determine the effect lower than average precipitation has on runoff and correct the Thornthwaite runoff calculations. In this way slope changes due to the climate may be avoided thereby allowing for analysis of the effects of land use change on a year by year basis.

If the user is aware of such limitations and possible shortcomings of the Thornthwaite system he can predict accurately the basin runoff. The key factor is precipitation and it must reflect as closely as possible the basin average.

Recommendations for Future Study

This paper has investigated and determined the effect urban areas have on the amount of runoff into the Bay. In general the higher the amount of impervious surface the larger the runoff. In dry years, though, runoff drops severely and is slowly recovering to the levels found before 1963.

Any future studies of this situation should determine more accurately the amount of urban acreage. Through an intensive investigation of original land use maps it should be possible to gather the exact acreage figures for a particular basin. The land use statistics on the latest series of maps also should be utilized with great emphasis on all forms of land use. If this is done the possible effects of decreased farm land and increases in abandoned fields may be detected. The runoff regime is really a product of all forms of land surfaces.

Unfortunately, it is not possible to determine past rainfall for areas poorly gauged. Nor is it possible to determine the exact amount of all runoff into the Bay. Ideally, several climatological stations should be set up at intervals within the basin, with runoff records kept at a selected point on the major stream that drains the area. This could be feasible for a small drainage basin. In fact many studies have been conducted as such. It may not be practical on a large scale, such as the study just conducted here due to increased expense and operation.

Any large drainage basin studies, however, can be conducted with a little extrapolation of data. A system similar to the one used by Solomon et al.[102] for Newfoundland may be possible to determine the basin rainfall. A better gauged river basin is also a distinct possibility as a better indicator of where runoff is increasing and by how much. With this process completed it could be possible to

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[102] S. I. Solomon, J. P. Denouvilliez, E. J. Chart, J. A. Woolley, and C. Cadou, "The Use of a Square Grid System for Computer Estimation of Precipitation, Temperature, and Runoff," Water Resources Research, 4 (October, 1968).

determine the average basin precipitation and temperature and then calculate the expected runoff.

Conducting a large basin study is difficult but worthwhile. From these investigations it is possible to determine the results of land use and changes in the areal climate on the runoff of a study area. It is not as easy to control factors, but the outcome can be more significant than for a small basin.

It has been shown that runoff has been affected by urban acreage in the past and it will continue to do so in the future. Any further land use changes should take into account all aspects of the environment, including the groundwater resources and surface runoff. The changes miles from the Bay could have detrimental effects upon it.

Future studies of this type for this area can better determine the actual runoff within the basin. In this way a more exact figure of the increase in runoff may be determined particularly in relation to the concentration of impervious surface and by taking the climate into account along with the influence of land use, specifically urban acreage, on stream runoff in Narragansett Bay.

As has been seen, runoff into the Bay is not a constant factor. There are fluctuations due to the climate and land use. As a result the water quantity into Narragansett Bay may be significantly altered, with possibly damaging consequences in the quality of its environment.

It is hoped by the writer that more studies of land-sea relationships will be made. The increasing population along seaboards and the pressure upon resources, particularly water, seem to warrant such studies.

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APPENDIX

DATA STATION INFORMATION

TABLE 1

PRECIPITATION STATIONS

Station	Years of Record	Months Estimated
Brockton	1948-1974	Oct, Nov 1950
Fall River	1940-1974	None
Franklin	1940-1974	Apr 1949, Apr, May, Jun, Aug, Sep, Nov, Dec 1951, All Year 1952
Mansfield	1940-1974	None
Middleboro	1940-1974	Feb, May, Oct, Dec 1957
Milford	1940-1974	None
Millbury	1940-1959	None
Northbridge	1940-1974	None
Segreganset	1946-1974	Jul 1949, Feb, Apr 1950, Mar, Jun, Dec 1951, Jan, Mar, Aug, Sep 1956
Taunton	1940-1974	Mar 1951
West Medway	1957-1974	None
Worcester Airport	1949-1974	None
Worcester City	1940-1962	Aug 1950
Gainer Dam	1941-1973	None
Greenville	1948-1970	Feb 1951
Hopkins Mills	1941-1973	None
Kingston	1940-1974	None
Newport	1958-1974	None

TABLE 1 (Continued)

Station	Years of Record	Months Estimated
Providence Airport	1949-1974	None
Providence City	1940-1952	None
Woonsocket	1956-1974	None

TABLE 2

TEMPERATURE STATIONS

Station	Years of Record	Heat Index	Months Estimated
Brockton	1948-1974	43.82	Sep, Oct, Nov, Dec 1950, All Year 1951, 1952, Jan, Feb, Mar, Apr, May, Jun, Jul 1953, Jun, 1960, May, Jun, Jul 1965
Fall River	1940-1974	46.72	None
Taunton	1940-1974	44.02	None
West Medway	1957-1974	42.70	None
Worcester Airport	1949-1974	39.45	None
Worcester City	1940-1962	42.02	Sep, Nov, Dec 1948, Nov, Dec 1962
Greenville	1940-1974	43.73	All Months 1940-1947, Aug, Sep 1953, Mar 1963, Feb, Apr, May 1967, Mar 1968, Dec 1970, All Year 1971, Jan, Feb, Mar, Apr, May, Jun, Nov 1972, Jan, Feb, Mar, Apr, May, Jun, July, Aug, Sep, Oct 1973, Sep, Oct, Nov, Dec 1974
Kingston	1940-1974	41.72	None
Newport	1958-1974	44.81	Oct 1962, Jan, Feb 1963, Jul, Aug 1969, May 1970, Mar, May 1972, Mar, Apr 1974
Providence Airport	1949-1974	45.19	None
Providence City	1940-1952	45.57	None

TABLE 3

RUNOFF STATIONS

Community	River	Basin	Years of Record	Sq. Mi. of Drainage Basin
Brockton	Dorchester Brook	Taunton	1963-1973	4.67
Bridgewater	Taunton	Taunton	1940-1973	260
West Mansfield	Wading	Taunton	1954-1973	19.2
Norton	Wading	Taunton	1940-1973	42.4
North Dighton	Segreganset	Taunton	1967-1973	10.6
Rehoboth	Bliss Brook	Palmer	1963-1973	31.3
North Grafton	Quinsigamond	Blackstone	1940-1973	25.5
Northbridge	Blackstone	Blackstone	1940-1973	139
Uxbridge	West	Blackstone	1963-1973	27.9
East Douglas	Mumford	Blackstone	1940-1950	27.8
Harrisville	Nipmuc	Blackstone	1965-1973	16.0
Chepachet	Chepachet	Blackstone	1965-1973	17.4
Forestdale	Branch	Blackstone	1940-1973	91.2
Woonsocket 1	Blackstone	Blackstone	1940-1973	416
Woonsocket 2	Blackstone Trib.	Blackstone	1966-1973	2.31
Providence	Moshassuck	Moshassuck	1964-1973	23.1
Centerdale	Woonasqua-tucket	Woonasqua.	1942-1973	38.3

TABLE 3 (Continued)

Community	River	Basin	Years of Record	Sq. Mi. of Drainage Basin
North Scituate	Mosquito-hawk Brook	Pawtuxet	1966-1973	3.06
Nooseneck 1	Nooseneck	Pawtuxet	1964-1973	8.23
Nooseneck 2	Carr	Pawtuxet	1964-1973	6.73
Washington	South Branch Pawtuxet	Pawtuxet	1941-1973	63.8
Cranston 1	Furnace Hill Brook	Pawtuxet	1966-1973	4.19
Cranston 2	Pawtuxet	Pawtuxet	1940-1973	200