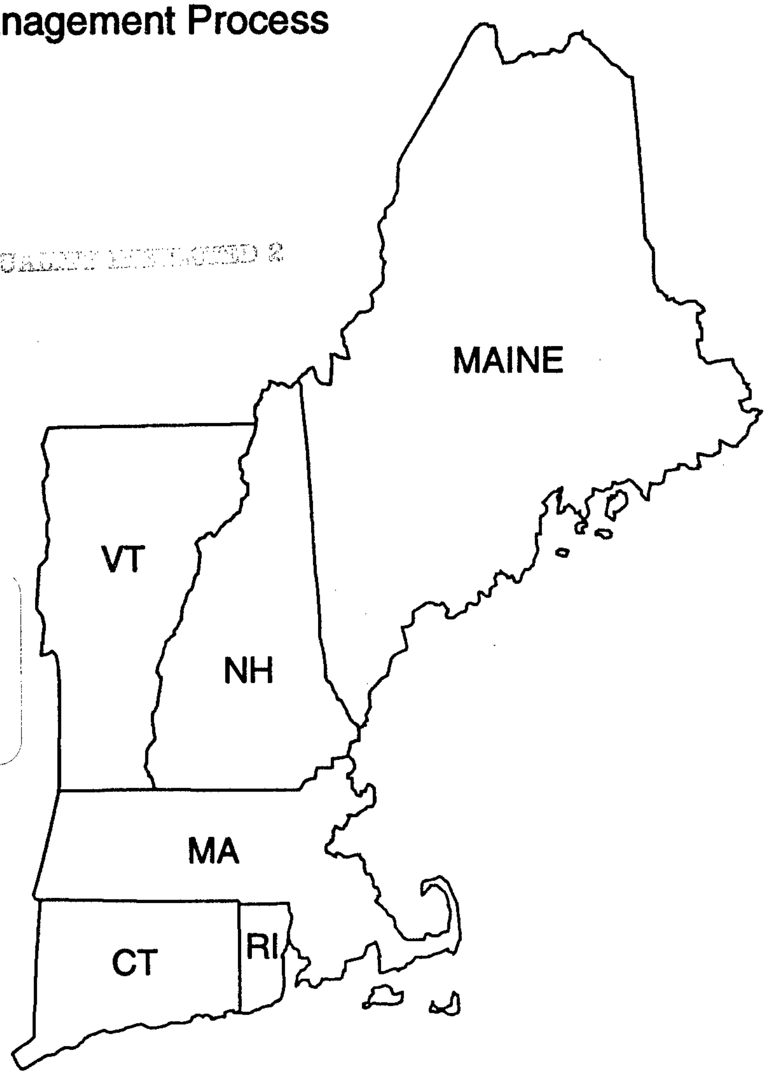
US Army Corps
of Engineers
New England Division

The National Study of Water Management During Drought

THE NEW ENGLAND DROUGHT STUDY: TRIGGER PLANNING:
Intergrating Strategic, Tactical, and Emergency Planning into a Single Water Resources Management Process



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The report documents the consensus of a study team which developed an application of Trigger Planning for enhancing MWRA's decision-making for ensuring that future water sources are adequate to meet the projected demand for Metropolitan Boston, Massachusetts. It is an extension of MWRA's more recently adopted managerial, as opposed to episodic, planning approach to potential shortfalls in supply. MWRA effected demand management measures that helped to preclude the need for new supplies. Trigger Planning is a systematic procedure for deciding what actions should be taken to prevent supply shortfalls, and in the event of a projected shortfall, what project should be built and when preparation for construction should begin. Trigger Planning integrates strategic, drought contingency and emergency planning into a single planning process to the mutual advantage of strategic and drought contingency planning. The process uses the STELLA II software for portraying the water system configuration and functions and a broad range of customized performance measures. STELLA II simulations of the system permits interested citizens and managers alike to view and evaluate the system under different scenarios and performance criteria thereby enhancing their understanding and leading to consensus on the planning and management of the water system.

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The National Study of Water Management During Drought

THE NEW ENGLAND DROUGHT STUDY

TRIGGER PLANNING: Integrating Strategic, Tactical, and Emergency Planning into a Single Water Resources Management Process

EXECUTIVE SUMMARY

BACKGROUND

The New England Drought Study is one of several regional study components or case studies of the National Study of Water Management During Drought (The National Drought Study). The principal objectives of the National Drought Study are to review how water is managed in the United States, to engage the water management community in a number of case studies on specific approaches to the problem and to develop a strategy to improve water management during drought. The National Drought Study has been conducted under the direction and management of the Corps of Engineers' Institute for Water Resources.

The case studies are required to satisfy two objectives:

- to help to achieve the principal objective of the National Drought Study or to develop a better way of managing drought in the United States,
- to leave the region better prepared for drought.

The New England Drought Study has been conducted in the six New England states (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island and Connecticut) in two phases over a three year period beginning in February 1991. Phase I was devoted to the selection of a case study for Phase II. Selection was based on the degree of vulnerability of the entity to drought, the value of the experience nationally in dealing with drought, and the willingness of the state or agency to participate in the study. The study for Phase I recommended that the Massachusetts Water Resources Authority/Metropolitan District Commission (MWRA/MDC) Water System be the case study for Phase II.

During Phase II, two studies have been conducted. TRIGGER PLANNING: Integrating Strategic, Tactical and Emergency Planning into a Single Water Resources Management Process is the object of this report. Water Resources Planning for Metropolitan Boston, Massachusetts is the subject of a separate report.

This study seeks to make a positive contribution to the region and the nation by developing a Trigger Planning methodology to enhance decision- making at the MWRA for ensuring that future that the sources of water supply are adequate in quantity, quality and reliability to meet future demand. In addition, this study has the objective of building consensus among the principal interested parties in strategic and drought contingency planning for the MWRA/MDC Water System in anticipation of presenting the results to the MWRA Advisory Board and the Board of Directors. These parties are MWRA staff and staff and members of the Water Supply Citizens Advisory Committee (WSCAC).

STUDY PROCESS

The report documents the work of a Study Team, consisting of Massachusetts Water Resources Authority (MWRA), the Water Supply Citizens Advisory Committee (WSCAC), and the New England Corps of Engineers (NED) staff to develop techniques to enhance MWRA's decision-making with respect to water resources planning. In particular, the Study Team was entrusted to develop, through consensus, a Trigger Planning process for ensuring that the sources of water supply are adequate to meet projected demand by identifying early actions, favoring lower cost and shorter lead projects, that should be taken to avoid supply inadequacy. Team Members generally met monthly at the MWRA Waterworks Division offices at 100 First Avenue, Boston (Charlestown), Massachusetts, and sometimes more frequently, from the Fall of 1991 to early 1994. Meetings were organized around agendas, meeting minutes and follow-up responsibilities and facilitated by the use of the STELLA II software portrayal of the MWRA/MDC Water System and its functions.

STUDY APPROACH

Historically, long range or strategic planning of water resources by the MWRA and its predecessor agencies has been episodic. It has taken the form of periodic assessments of future demands on the system and of the system's capacity to satisfy these demands followed by system improvements or decisions to postpone improvements. The system would then generally be expected to run on its own. More recent MWRA/MDC planning experience can be characterized as an interventionist managerial approach. Rather than permit a water system to move towards an unknown situation, whether desirable or undesirable, system managers take action to direct the system to a more preferred future. The MWRA/MDC recently has avoided potential shortfalls in supply by effecting demand management measures that helped to preclude the need for new supplies.

The present application of Trigger Planning is an extension of this managerial approach. It is a systematic procedure for deciding what studies and actions should be taken to prevent supply shortfalls and in the event of a projected shortfall, what projects should be built and when preparation for construction should begin. It is a comprehensive decision-making process to assist the MWRA in integrating strategic, tactical, and emergency planning into a single continuous planning process to ensure that future sources of supply are adequate to meet projected water demand. This integration mutually benefits strategic and drought contingency planning. More effective demand reduction responses to drought avails the system of water for successive years. This is of particular significance to the MWRA/MDC Water System which has the capacity to store several years supply. Again more effective strategic planning renders a more robust system that is better able to manage drought.

STUDY METHODOLOGY

The Trigger Planning (Figure 10) process for ensuring supply adequacy has three basic elements: evaluation, monitoring and programming. The word supply is used in this report in the narrower sense to indicate sources of supply and, with one exception, does not consider the adequacy of transmission nor the distribution systems. The maximum carrying capacity of Quabbin Tunnel, which transmits water between the Quabbin and Wachusett Reservoirs, is used in this application of Trigger Planning.

Evaluation of System Capacity

The STELLA II interactive model of the MWRA/MDC Water System portrays the system configuration and the equations that define functional relationships based on operating rules and system behavior. The model makes use of the following:

- Water System Data Base (WSDB),
- Safe Yield Model based on 31 years of hydrological record from October 1949 to September 1980,
- MWRA Drought Management Plan,
- Projections of water system demand to the year 2012 in four scenarios: 230, 260, 285 and 340 mgd in addition to 300 and 320 mgd,
- Customized performance measures and criteria to determine the capacity of the system to meet demand while concurrently evaluating the impacts on the environment, the socioeconomy and consumers.

With respect to evaluation, the methodology relies on a STELLA II software package to model the configuration and functions of the system and permits the introduction of the MWRA Drought Management Plan with different levels of drought management success, alternative demand scenarios and customized performance measures. In effect, drought management is integrated into strategic planning. The exercise produces performance data on the system under different levels of demand, drought management, and performance criteria. System managers are permitted to view the tradeoffs among the different performance criteria and to evaluate the capacity of the system. The results are a better understanding of how the system works in its interaction with demand and possible enhancements to the system. The performance criteria are coupled with economic and other analyses to determine the most cost effective high performance alternative strategic plans. The output of the model is one or more strategies for balancing demand at the end of the planning horizon.

Monitoring of Indicators and Assessment of Demand and Supply

The second element, monitoring, is presented generally and specifically in Figures 10 and 11 in the main report. Indicators and leading indicators of changes in demand and supply are identified and monitored in order to anticipate changes in demand and sources of supply affecting future supply adequacy. Periodic assessments of changes in supply and demand for water are made vis-a-vis trigger points.

Programming of Studies and Actions

Finally a determination is made as to whether or not trigger points are being approached and the program of studies and actions reconfirmed or modified in order to ensure future sources of supply adequacy. For example in the case where a trigger point is being approached, the MWRA may adopt aggressive demand measures in order to reduce the slope of the demand curve and to postpone or avoid triggers for supply augmentation projects. Alternatively the system may proceed with actions needed to augment supply. See Figures 12 to 18 in the main report.

FINDINGS AND CONCLUSIONS

This study concludes that:

- the present application of Trigger Planning to ensure the adequacy of supply clearly demonstrates the advantages of drought management. The model integrates drought planning into long term planning and mutually benefits both strategic and drought planning. Reduction of the demand for water during an impending drought puts additional water at the disposal of the system for long term needs. The result is a system that has been made more robust because of punctual responses to potential drought and which is better prepared to deal with drought when it occurs. A more robust water system is positioned to better manage drought.

- the broadening of the criteria for evaluating system performance and the quick interactive assessments through the use of STELLA II can be considered some of the main achievements of the study.

- the interactive nature of Trigger Planning, through the use of the STELLA II software package for portraying the configuration, functions and simulation exercises of the MWRA/MDC Water System, facilitates consensus among the parties participating in the planning process. In the first instance these have been the MWRA system managers and WSCAC staff and members.

- the MWRA reports annually to its Advisory Board and in turn to the Board of Directors on the status of the MWRA Long Range Water Supply Program (LRWSP), including the adequacy of future supply. Trigger Planning has been conceived as a decision making tool to assist system planners to decide what actions should be taken to ensure the adequacy of supply.

- this application of Trigger Planning has identified the need for three studies, in addition to those included in the MWRA LRWSP, that are prerequisites to planning for water supply adequacy. These are:

    o a program to monitor ecological conditions at Quabbin Reservoir when pool levels fall below the current target pool of 490 feet (BCB) during extreme drought conditions in order to explore the tradeoffs of increased water system yield versus possible ecological, including water quality, deterioration.

    o a study to assesses the impacts on consumers of the different drought actions in order to evaluate the tradeoffs between the benefits and costs to system users of the timing and intensity of drought actions.

    o a study to evaluate the effectiveness of MWRA's demand management program and its components in order to determine where future conservation efforts should be concentrated. This study should also seek to disaggregate the contributions of different factors, such as demand management, the price of water and the changing and depressed economy, to the decline in system water use from 334 mgd in 1987 to 257 mgd in 1992.

FUTURE ACTIONS

The following actions are indicated in order to ensure the institutionalization of Trigger Planning for supply or source adequacy at the MWRA.

1. Adopt the present application of Trigger Planning and integrate it into the MWRA LRWSP process for monitoring and assessing the sufficiency of future supply to meet demand and reporting the results to the Advisory Board and Board of Directors. Eventually the MDC and the Massachusetts Department of Environmental Protection should be apprised of the study and invited to contribute to the process.

2. Ensure the institutionalization of Trigger Planning in the LRWSP by committing the required resources and by assigning the appropriate staff whose performance standards reflect MWRA's commitment to the program.

3. Pursue the development of the components of the LRWSP and Trigger Planning including the:

    - completion and updating of the Water System Data Base,
    - extension of the hydrological input data to the STELLA II Model from October 1980 to the present,
    - refinement of the customized water system performance measures and criteria,

4. Undertake the studies:

    - to monitor ecological conditions at Quabbin Reservoir as pool levels descend below the present target pool of 490 feet (BCB),
    - to assess the impact on consumers of the timing and stringency of drought actions.
    - to estimate the contributions of different factors such as demand management, the price of water and the changing and depressed economy, to the decline in water use from the MWRA/MDC Water System since 1987.

GLOSSARY OF ABBREVIATIONS

BCB - Boston City Base

DEM - Department of Environmental Management (Massachusetts)

DEP - Department of Environmental Protection (Connecticut and Massachusetts)

EIR - Environmental Impact Report

EOEA - Executive Office of Environmental Affairs (Massachusetts)

LRWSS- Long Range Water Supply Study

LRWSP- Long Range Water Supply Program

MA - Massachusetts

MDC - Metropolitan District Commission (Massachusetts)

M&I - municipal and industrial (water supply)

MEPA - Massachusetts Environmental Policy Act

mgd - million gallons per day

MOU - memorandum of understanding

MWRA - Massachusetts Water Resources Authority

National Drought Study - National Study of Water Management During Drought

NED - New England Division, Corps of Engineers

NEPA - National Environmental Policy Act

STELLA- Systems Thinking, Experimental Learning Laboratory, with Animation

TP - Trigger Planning

WRC - Water Resources Commission (Massachusetts)

WSCAC- Water Supply Citizens Advisory Committee

TABLE OF CONTENTS

Chapter 3: TRIGGER PLANNING (Continued)

LIST OF TABLES

MAIN REPORT Page

APPENDIX A

APPENDIX C

LIST OF FIGURES

APPENDIX A

APPENDIX C

Chapter 1
BACKGROUND

THE STUDY

The National Drought Study

The New England Drought Study is one of a number of regional study components or case and topical studies in the National Study of Water Management During Drought (The National Drought Study). The National Drought Study is managed by the U.S. Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources, Fort Belvoir, Virginia. The authority under which this study is conducted requires the preparation of estimates of long term capital needs for water resources programs under the jurisdiction of the Secretary of the Army for Civil Works. The principal objective of the National Study is to develop a strategy to improve water management during drought. The study calls for a review of ways that water is managed in the United States and the engagement of the water management community in a number of case studies using innovative approaches.

The national study is a Corps of Engineers' response to the droughts that occurred throughout the United Stares from 1986 to 1988 and which continue in some regions today. Through a series of questionnaires and workshops, Corps' senior staff and four managers from outside the Corps designed a plan of study to address the greatest regional concerns with respect to water management during drought.

In addition, the Assistant Secretary of the Army (Civil Works), Robert Page, wrote in early 1990 to the governors of the 50 states and Federal agencies with drought responsibilities eliciting their perspectives on drought issues and requesting their participation in and points of contact for the drought study. The point of departure for the New England Drought Study is the responses from the six New England states to the Assistant Secretary's letter.

The New England Drought Study

Phase I of the three year New England Drought Study was devoted to the selection of a case study in the six state New England region for Phase II based on vulnerability to drought, the value of the drought planning experience to other parts of the country and the willingness of staff to participate in Phase II. The report for Phase I, completed in July 1991, recommended the selection of the Massachusetts Water Resources Authority/Metropolitan District Commission (MWRA/MDC) as the focus for Phase II of the study.

Phase II has two components. The first is the subject of a separate report. It is the presentation of the MWRA/MDC water resources planning experience from its initial response to the 1960's drought in seeking to develop new sources of supply to more recent planning based on demand and supply management, which has obviated the need for new supplies while leaving MWRA's 2.5 million customers less vulnerable to drought. The second component is the development of a Trigger Planning Model aimed at the identification and monitoring of leading indicators of potential imbalances of the supply and demand of water in order to schedule the required actions for ensuring that the future supply of water is adequate in quantity, quality and reliability to meet future demand. It is the object of this Phase II report.

STUDY AUTHORITY

The National Drought Study is being conducted under the authority of Sections 707 and 729 of the Water Resources Development Act of 1986. Section 707 entitled, "Capital Investment Needs for Water Resources", authorizes the Secretary of the Army for to prepare and submit to Congress an estimate of the long term capital needs for water resources programs under his jurisdiction, including but not limited to:

- deep draft ports
- inland waterway transportation
- flood control
- municipal and industrial water supply
- hydroelectric power
- recreation
- fish and wildlife conservation

Section 729 regarding the "Study of Water Resources Needs of River Basins and Regions" authorizes the Secretary of the Army for Civil Works, in coordination with the Secretary of the Interior and in consultation with appropriate Federal, State and local agencies, to study the water resources needs of river basins and regions of the United States.

STUDY AREA

The study area for The New England Drought Study is comprised of the six New England States: Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont. The focus for Phase II is the MWRA/MDC Water System. See Figure 1.

STUDY OBJECTIVE

The New England region was selected as one of the case studies for the National Drought Study for several reasons. It represents an area of the country that has not experienced serious widespread drought since the 1960's and may be due for one. Also, New England has a number of water supply systems that are typical of a large number of urbanized communities in the United States with aging municipal and industrial water supply infrastructures, which are not only in need of capital improvements to maintain current services, but must face the challenges of satisfying future demands. In addition, many of these systems are subject to or risk emergency failures because they do not have redundant supply and delivery systems.

According to the guidelines established by the National Drought Study, the case studies must satisfy two objectives:

- to help achieve the principal objective of the National Study of Water Management During Drought, which is to develop a better way to manage water during drought in the United States;

- to leave the region better prepared for drought.

The two components of the New England Drought Study included in Phase II have been designed to respond to the national study objectives. The MWRA/MDC water resources planning experience component aims to describe, analyze, enhance and present the MWRA/MDC strategic, drought contingency and emergency water resources planning experience and to identify water systems where the experience can be applied. It is the subject of a separate report. The Trigger Planning component seeks to make a positive contribution to the region by assisting the MWRA/MDC in extending its current planning experience by developing techniques to enhance decision-making for ensuring that future water supplies are adequate in quantity, quality and reliability to meet future demand. Trigger Planning is the subject of this report.

PRIOR REPORTS

- The U.S. Army Corps of Engineers, Institute for Water Resources (IWR), The National Study of Water Management During Drought - Report of the First Year of Study, May 1991.

- Corps of Engineers, Davis, California, Hydrologic Engineering Center, A Preliminary Assessment of Corps Reservoirs, Their Purposes, and Susceptibility to Drought, September 1991.

- Planning and Management Consultants, Ltd., Carbondale, Illinois, Water Management During Drought; Research Assessment, August 1991.

- Advisory Council on Intergovernmental Relations, Washington, DC, Intergovernmental Coordination for Drought Related Water Resources Management, 1990.

- Resources for the Future, Washington, DC, Integrated Framework for a National Water Management Under Drought Study, Undated.

- U.S. Army Corps of Engineers, New England Division, The Study of the Vulnerability of New England to Drought, Phase I, July 1992.

LAYOUT OF MWRA/MDC WATER SYSTEM

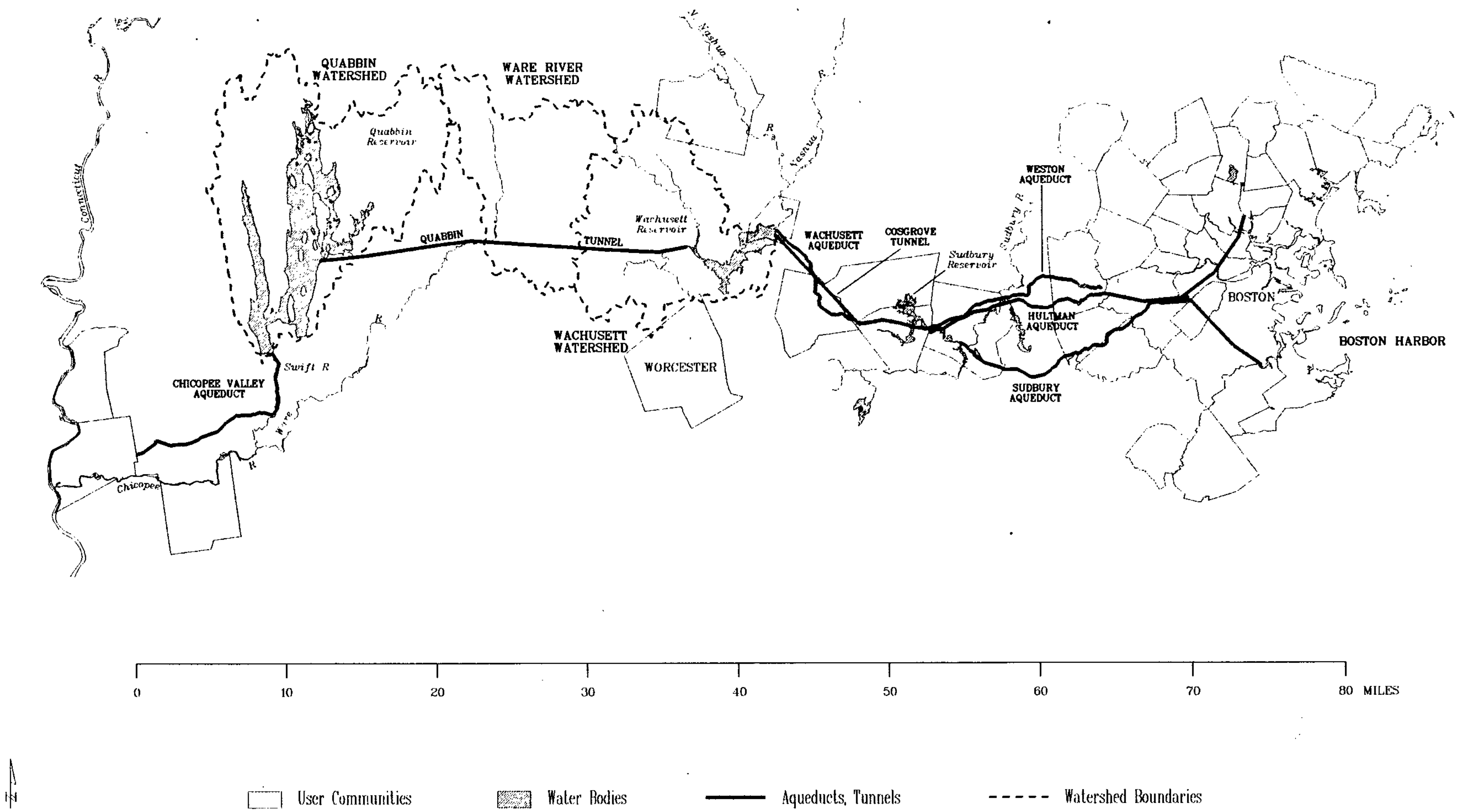

FIGURE 1

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Chapter 2
INTRODUCTION

Trigger Planning is a product of the evolution of the water resources planning experience for the metropolitan Boston area. Local citizen interest in how the metropolitan Boston area plans and manages its water supply system has significantly increased since the drought of the 1960's. The drought raised the possibility of a potential future shortfall in supply and moved the Metropolitan District Commission (MDC) to seek new sources of supply. Among the alternatives under consideration was the importation of water from the Connecticut River, located west of Boston. The proposal was met with strong resistance from citizens' groups representing the Connecticut River Valley. They challenged the need for supply augmentation. They argued that the need for new sources of supply was based on an overestimation of future water demand and significant waste in the system. Failure, on the part of Boston to manage its system efficiently, had posed the threat of unnecessarily transferring water resources to the metropolitan Boston area and removing them from future local use and development. The water resources planning experience for the metropolitan Boston area has evolved from a classical to a managerial approach.

TRADITIONAL WATER SUPPLY PLANNING

Traditional water supply planning determines the increase in supply to meet the expected imbalances in supply and demand i.e. planning efforts are initiated periodically or when a drought has elevated public concern about the reliability of water supply in the future. This approach is episodic. Structural changes in the system are the primary alternatives. Supply can be increased by bringing additional sources into the system. Demand is assumed to have limited variability: it can increase but actions are not undertaken to reduce demand. Demand forecasts are made over a 30-50 year planning horizon and structural solutions are favored to eliminate shortfalls in supply. Towards the end of the planning process, the public reviews proposed solutions to anticipated shortfalls. Public opposition may delay the implementation of proposed solutions. The water system remains relatively unchanged between planning periods.

THE MANAGERIAL APPROACH

The managerial approach is interventionist. System managers intervene to shape demand and supply as future imbalances are anticipated. A two pronged planning approach is undertaken: nonstructural solutions are favored, but managers prepare for the possibility of undertaking structural solutions should they become necessary. Planning for supply adequacy is undertaken on a 15 to 20 year horizon (or the time necessary to develop a new source) and a range of demand projections. The public participates continuously and proactively in the planning process and public opposition to eventual proposals is minimized. In the case of the MWRA/MDC Water System, WSCAC currently provides the public participation.

Because of the potential for reductions in demand, demand management measures are the primary focus for bringing demand and supply into balance. Supply augmentation studies and actions are undertaken to prepare for the exhaustion of non-structural measures and of the necessity to pursue structural solutions to anticipated demand and supply imbalances.

TRIGGER PLANNING

The concept of Trigger Planning was introduced by the Water Supply Citizens Advisory Committee (WSCAC) in 1982 and developed in a paper in 1986 (1). The current application of Trigger Planning in the New England Drought Study was approved by the MWRA Board of Directors in March 1990 (2). The study was initiated as a joint effort of MWRA's Waterworks Division, WSCAC and NED in early 1992.

The present application of Trigger Planning aims to assist the MWRA in integrating strategic, tactical, and emergency planning into a single continuous planning process to ensure that future supplies are adequate to meet projected water demand. Trigger Planning is a comprehensive and systematic procedure for deciding what studies and actions should be taken to prevent supply shortfalls and, in the event of a projected shortfall, what projects should be built and when preparation for construction should begin.

The partnership of the MWRA and citizen interest groups, such as WSCAC, has moved the management of the water supply system towards more realistic water demand forecasts and demand management measures to reduce system water use. Both the managers of the MWRA Water System and WSCAC are concerned that water supply planning provide reliable service while maximizing the use of the water system and preparing to meet future demands.

THE INTERESTED PARTIES

The four interested parties for the Trigger Planning effort are: the Corps of Engineers (Institute for Water Resources (IWR) and the New England Division (NED)); the Massachusetts Water Resources Authority (MWRA); the MWRA service area communities; and WSCAC.

The objectives of the Corps of Engineers, as outlined in the National Drought Study, are *TO DEVELOP A BETTER WAY OF MANAGING DROUGHT IN THE UNITED STATES AND TO ENSURE THAT THE OBJECT OF THE CASE STUDY, WHICH FOR THE NEW ENGLAND DROUGHT STUDY IS THE MWRA/MDC, IS BETTER PREPARED FOR DROUGHT AS A RESULT OF THE STUDY.*

"The MWRA's primary mission is to modernize the metropolitan area water and sewer systems, to conserve water resources and to improve the quality of water in Boston Harbor." (3) The Water System and the Sewerage System have been established to carry out these missions. *THE MISSION OF THE MWRA/MDC WATER SYSTEM IS TO ENSURE THE LEGITIMATE WATER SUPPLY NEEDS, IN TERMS OF QUANTITY, QUALITY AND RELIABILITY FOR THE COMMUNITIES IN THE MWRA SERVICE AREA IN CONFORMANCE WITH CURRENT LAWS AND REGULATIONS.* The MWRA is governed by its eleven member Board of Directors. Its sixty-seven member Advisory Board considers and makes recommendations on matters relating to the budget and MWRA membership.

The MWRA Water System serves 46 communities, 32 of which are fully supplied with water, 14 partially supplied and one community (Dedham) which is entitled to be served by the MWRA but which is not. Twenty-nine of these communities are also provided with sewer services by the MWRA's Sewerage System. Fourteen other communities are also provided sewer services. A total of 60 communities are provided with water and/or sewer services by the MWRA. Both the Board of Directors and the Advisory Board are weighted in favor of representation from the sixty communities in the water and sewer service areas. See Table 14. *MEMBER COMMUNITIES ARE PRIMARILY INTERESTED IN A RELIABLE WATER SUPPLY AT PRICES THAT THE COMMUNITIES CONSIDER APPROPRIATE.* Communities are billed for water and sewer charges on the basis of water use. Population will be factored into future billings. Because of the costs of the cleanup of Boston Harbor and of the investment requirements for the water system due to years of deferred maintenance, MWRA rates have escalated in the past several years. Service communities are particularly concerned with the predictions of even higher rates.

WSCAC is a citizens group, whose expenses are reimbursed by MWRA. WSCAC has been mandated... "to gather, formulate and represent the public position." (4) on public policy concerning the conservation, use and development of the water and related land and other resources affected by the fulfillment of the MWRA/MDC mission. *IN PARTICULAR, WSCAC IS SENSITIVE TO THE IMPACT OF MWRA/MDC POLICY, PLANNING, AND PROJECTS ON RIVER BASINS AND THE ENVIRONMENT, AND TO EQUITABLE WATER AND RELATED RESOURCE USE.*

PRINCIPAL CONCERNS

Historically, long range or strategic planning of water resources undertaken by MWRA and its predecessor agencies has been episodic. It has taken the form of periodic assessments of future demands on the system and of the system's capacity to satisfy these demands followed by system improvements or decisions to postpone improvements. Then the system would generally be expected to run on its own. More recent MWRA/MDC planning experience can be characterized as interventionist. Rather than permit a water system to move towards an unknown situation, whether desirable or undesirable, system managers take action to direct the system to a more preferred future. The MWRA/MDC has recently avoided potential shortfalls in demand by effecting demand management measures that helped to preclude the need for new supplies.

MWRA and WSCAC are concerned:

- that episodic water resources planning practices could lead to a failure of managers to anticipate a shortfall in supply leading to crisis management of the water supply system. In the event of a crisis, discussions may devolve to the political realm and decisions taken that are neither the choices of the system managers nor WSCAC.

- such hasty decisions based on available, but likely, insufficient information, analyses and preparation can lead to less than optimal capital expenditures.

These situations, for example, can result from a failure to monitor the degradation of local sources of water for partially supplied communities, thereby adding to the demand on the system.

Chapter 3
TRIGGER PLANNING

PLANNING HORIZONS

Planning for potential water shortages can be approached in terms of long, medium and short term measures. (5)

Strategic Planning

Strategic measures generally are long term planning procedures that allow for the modification of all water resource elements, whether they be the water system infrastructure itself, institutional and managerial arrangements and existing laws, policy, etc. Traditionally, strategic planning for municipal water systems has taken the form of periodic evaluations of demand versus supply, transmission and distribution capacities of the water system with the aim of ensuring that system capacity is sufficient to satisfy the projected system demand. Demand estimates would be based on forecasts of water use using 20 year but tending towards the 40 to 50 year planning horizons.

Tactical Planning

Tactical measures are planning procedures that are implementable within the framework of existing water system infrastructure, institutional arrangements and laws and which are set in place before a drought occurs. Drought contingency plans are tactical measures.

Emergency Planning

Emergency measures are planning procedures that respond to an immediate threat of water shortage in a water system when other preparations are insufficient. A municipality's response to an earthquake that damages its water system or the sudden contamination of a source would require emergency measures.

OBJECTIVES

The objectives of the present application of Trigger Planning are to conceive and apply a planning process for the MWRA to ensure that future water supply is sufficient to satisfy projected demand and that there is agreement among the interested parties on the process and its application.

Sufficiency of Supply to Satisfy Future Demand

The principal goal of the present application of the Trigger Planning study is to enable the MWRA to determine which of a number of alternative studies, actions and projects to implement and when to implement them to fulfill its mission to meet the legitimate water supply needs of the customers in its service area. In addition to meeting customer needs, the Trigger Planning process would favor the implementation of smaller, cost-effective projects and the avoidance or postponement of expending large sums on major projects. This report focuses on possible shortfalls in supply.

Trigger Planning, which by definition includes drought management, as well as, strategic and emergency planning, would enable the MWRA to more effectively evaluate and act to bring future water supply and demand into balance while alleviating stresses in the system due to potential drought situations. Consequently, the MWRA will have put itself in a better position to deal with drought.

Consensus Building

The interactive nature of Trigger Planning makes the process transparent to the MWRA/MDC staff and both technical and non-technical members of the public. The use of the STELLA II software package permits the portrayal of the configuration and operation of the water system as relates to the source of supply on the computer screen and the simulation of different future conditions to determine their impact on the water system. With respect to the MWRA/MDC Water System, it permits all parties to know how the system works, to view different system futures and their repercussions as a basis for achieving consensus on what actions should be taken today in order to avoid future water supply shortfalls. Consensus building will first be facilitated by NED and involve MWRA and WSCAC staff and then proceed on to the Advisory Board and the Board of Directors.

ELEMENTS

In the development of the Trigger Planning process the following elements were initially considered. A more complete list of the Trigger Planning elements are presented in Chapter 13.

- Water System Data Base (WSDB)
- Safe Yield Model
- MWRA Drought Management Plan
- An interactive dynamic model of the MWRA/MDC Water System portraying the existing infrastructure, inputs to the model, operating rules and system behavior.
- Leading indicators of changes in supply and demand for water.
- Water system performance measures.
- Projections of future water demand.

Water System Data Base (WSDB)

The MWRA Water System Data Base is currently being developed to a) collect and assemble water supply and demand related data in a systematic manner, b) develop standardized and ad-hoc procedures of analyzing the collected data, and c) design graphical visual aids for presentation to the Board of Directors and the general public. The data requirements for the Trigger Planning effort will provide impetus to the collection, assembly and analysis of water use and related socioeconomic data.

Safe Yield Estimation Model

The MWRA has developed a safe yield estimation model of its three current sources of supply: the Quabbin Reservoir/Ware River/ Wachusett System. In the MWRA/MDC Water System, safe yield is defined as the measure of a water system to deliver water during a critical drought and is expressed in million of gallons per day (mgd). For the MWRA system, safe yield is computed at 300 mgd for the period from October 1949 to September 1980. The model includes the 1960,s drought, which is widely considered to be the worst drought of record.

Drought Management Plan

Chapter 21G of the General Laws (The Water Management Act) of the Commonwealth of Massachusetts authorizes the Massachusetts Department of Environmental Protection (DEP) to issue declarations of water emergencies upon request of the water supplier. A condition of this regulation is that the DEP can require the operator of the system to submit a plan for bringing about an expeditious end to the water emergency. Measures that can be considered include, but are not limited to the following:

(1) an approved water resources management plan,
(2) a leak detection program,
(3) a program of auditing water use,
(4) a program of system rehabilitation,
(5) a conservation program for public and private buildings,
(6) a ban or restriction on certain water uses,
(7) a moratorium on the issuance of building permits,
(8) a plan for prioritizing competing uses,
(9) drought management or contingency plans.

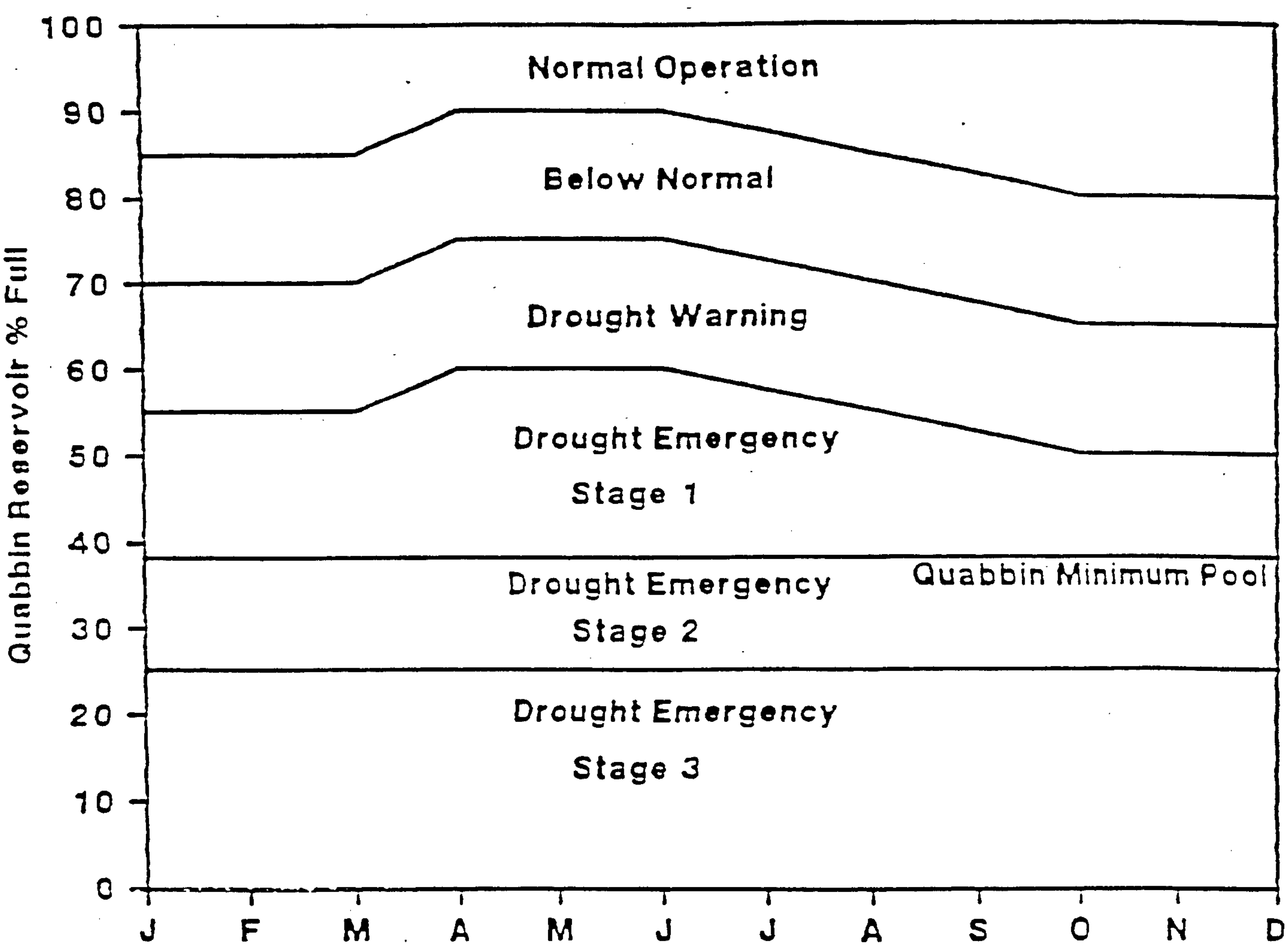
The preparation of the MWRA Drought Management Plan (DMP) was precipitated by a two year below average rainfall and over use of the Quabbin-Ware-Wachusett supply source, which created a potential drought warning situation in early 1989. Based on its observations of the levels of Quabbin Reservoir, MWRA concluded that the drought warning stage had been reached. DEP was requested to issue a Declaration of Water Emergency so that appropriate response actions could be taken. DEP in turn required the MWRA to prepare a drought management plan and to take other emergency actions. The MWRA prepared a DMP, which was finalized and approved by DEP in July 1989.

The plan is the product of a cooperative effort with the MDC which operates the water system watersheds and reservoirs. MWRA staff completed two forecasting models and assisted user communities in developing their own plans. The models permit the analysis of various trade-offs of the postponement of triggered restrictions and their severity. The DMP is principally keyed to monitoring reservoir levels at Quabbin Reservoir, whose watershed contributes more than half to the system's 300 mgd safe yield and whose reservoir stores more than three years of current demand. Figure 2 presents Drought Status Control Diagram for trigger levels at Quabbin Reservoir and Table 1 the target reductions and corresponding response actions for the trigger levels.

Figure 2
The New England Drought Study

Massachusetts Water Resources Authority \ Metropolitan District Commission
Drought Management Plan

DROUGHT STATUS CONTROL DIAGRAM
TRIGGER LEVELS AT QUABBIN RESERVOIR



Source: MWRA, Drought Management Plan, undated, p. 5-4.

Table 1

MWRA/MDC DROUGHT MANAGEMENT PLAN
TARGET USE REDUCTIONS AND MWRA RESPONSE ACTIVITIES

Stage	Trigger Range (Quabbin % Full)	Target Water Use Reduction	MWRA Response Measures
Normal Operation	80 - 100	0	
Below Normal	65 - 90	Previous year's system use	- Advise local officials and media - Distribute MWRA materials - Repair leaks - Rehabilitate meters
Drought Warning	50 - 75	5%	- Identify drought coordinator - Restrict outdoor and municipal use - Request voluntary cuts from large users and visible users (car washes, restaurants, etc.) - Activate Water Bank - Enforcement:fines
Drought Emergency			
Stage 1	38 - 60	10%	- Ban nonessential outdoor, municipal water use - Request more large user cutbacks - Distribute new materials - Continue coordination local actions - Consider rate structure changes
Stage 2	25 - 38	15%	- Increase meter reading frequency - Establish mandatory rationing and enforcement - Distribute info materials and feed back on savings - Modify rate structures - Moratorium on new connections
Stage 3	Below 25	30%	- Revise rationing for 30 % reduction - Continue distribution of materials, organization of local response - implement emergency sources or interconnections

SOURCE: MWRA, Drought Management Plan, undated

An Interactive Model of the System (STELLA II)

Trigger Planning is facilitated by the use of the STELLA II interactive software package which models the configuration and operation of the MWRA/MDC water supply system and permits the simulation of different future strategies and their impacts on the system. The Trigger Planning application of STELLA II permits planners to compress space by portraying the operational features of the water system on the computer screen and to compress time by simulating different futures and instantaneously evaluating their outcomes. The interactive nature of the model facilitates the building of consensus among interested parties such as the managers of the MWRA system and WSCAC and eventually the MWRA Board of Directors and Advisory Board. Appendix B presents the results of the STELLA II modeling.

Leading Indicators

Trigger planning provides a framework for monitoring leading indicators of changes in supply and demand within the context of ensuring future water supply adequacy. These indicators are intended to give advance notice as to whether the system is expected to approach its *CRITICAL POINT* or the point at which future supply would not be adequate to meet projected demand. The *LEAD TIME* is the time necessary to implement a strategy or a series of actions to ensure the adequacy of future supply. A *TRIGGER POINT* is a point in time when a strategy or series of actions is initiated in order to ensure supply adequacy. It is equal to the critical point minus lead time. Monitoring of the leading indicators of changes in supply and demand permits planners to anticipate whether or not trigger points are being approached.

The concept of leading indicators for the MWRA/MDC Water System is more fully developed in Appendix C. An indicator is a quantifiable phenomenon, that is so closely associated with the behavior of a particular condition, that it may be used, in conjunction with other indicators, to identify the occurrence of the condition. A leading indicator is one that anticipates the occurrence of a future condition.

In order to be useful, leading indicators should satisfy four criteria: relevance, timeliness, accessibility and sustainability. Relevance has to do with the historical behavior of the indicator to significantly demonstrate association with the condition. Timeliness is the amount of advance notice that a leading indicator would afford a user in predicting the occurrence of a condition. Accessibility is the availability of data on the leading indicator. Sustainability is the ability of the indicator to be relevant for the period under consideration.

The following indicators have been found to satisfy the four qualities of leading indicators.

1. The Condition of Local Sources in MWRA/MDC Service Communities and Adjacent Communities - If one of the 15 communities currently partially supplied with MWRA/MDC water or one of the 27 communities adjacent to the MWRA/MDC service area were to require full supply from the system because of contamination of local sources, for example, MWRA/MDC demand could suddenly increase by as much as 25 mgd. The condition of local sources is a principal leading indicator because of the suddenness and volatility of potential increases in demand.

2. Events and Proposed Projects Potentially Affecting Demand - Events and proposed projects may significantly affect the demand for water. The MWRA should systematically analyze all events and proposed projects for their potential effect on MWRA/MDC water demand. These effects, for example, can be the direct result of the location of water using industries or more indirectly from the impact on employment and then on water use.

3. Laws, Regulations, and Agreements - Laws, regulations and agreements affect the ways that water and related land resources are used. More recently those that have had the greatest impact on the demand and supply of water in the MWRA/MDC system have been the Safe Drinking Water Act, the Water Management Act, the Interbasin Transfer Act and water exchange agreements. The anticipated approval and application of relevant laws, regulations and agreements should systematically be monitored by the MWRA in terms of their impact on the system.

4. Watershed Conditions and Operational Procedures in MWRA/MDC System - It goes without saying that the MWRA/MDC should monitor the conditions in their watersheds and their operational procedures since they impact directly on the supply and demand for water.

5. Climate, Precipitation and Streamflow - For the same reasons as 4. above, climate, precipitation and streamflow should be monitored.

6. Public Views on Water Resources Management, Conservation and Use - The MWRA/MDC should monitor public issues related to the management, conservation and use of the institution's current and future water and related land resources.

7. Building Permits in the MWRA/MDC Service Area Communities - Private building permits have been shown to have predictive qualities for near future water use in the MWRA/MDC Water System and for identifying early trends of changes in water use. However, these trends may not be sustained. Building permits should therefore be used with caution as a leading indicator of future capacity supply stress in the MWRA/MDC Water System.

Water System Performance Measures and Criteria

The Study Team for the New England Drought Study has developed measures and criteria for assessing the performance of the supply function of the MWRA/MDC Water System. See chapter 8.

Water Demand Projections

The water demand projections are presented in chapter 6.

Chapter 4
MWRA LONG RANGE WATER SUPPLY PROGRAM

Based on the results of its Long Range Water Supply Study (LRWSS), in 1986 the newly created MWRA issued the MWRA Water Supply Policy Statement consisting of a series of policy statements, which were adopted by the Board of Directors. The statements included the approval of nonstructural solutions as a means of balancing future demand and supply. The development of new supplies would be one of last resort; the Board would not review any river diversion option until after 31 December 1989.

Meanwhile, the MWRA initiated the five year MWRA Long Range Water Supply Program (LRWSP) in order to monitor conditions of demand and supply for the water system, to make recommendations on the findings and to report on these to the Board of Directors. The first report entitled, MWRA Long Range Water Supply Program (LRWSP), Program Briefing and Recommendations to the Board of Directors (24 January 1990) recommended that the Board postpone its decision on the development of a new supply until 1995 at the earliest. The report and its annual updates to 1992 specified the pursuit of the following programs, for which additional details are provided in Figure 3.

- Protection of existing supplies,
- Leakage control and water accounting,
- Demand management and conservation,
- Local source capacity enhancement,
- Planning future supply adequacy,
- Education, outreach and reporting.

The most recent annual report on the LRWSP (21 October 1992) concluded that no immediate action on supply augmentation is required. In addition the report expressed satisfaction with the Corps of Engineers assisted Trigger Planning activity to provide the analytical tools aimed at ensuring future supply adequacy.

Figure 3
The New England Drought Study

MWRA/MDC WATER SYSTEM - MWRA LONG RANGE WATER SUPPLY PROGRAM (LRWSP):1990-95 *

PROTECTION OF EXISTING SUPPLIES

MWRA/MDC SOURCES
- Watershed Protection Program
- Sudbury Emergency Suppy

LOCAL COMMUNITY SOURCES
- MWRA Partial Users Assistance
- Cambridge Reservoir Protection Committee
- Contamination Prevention in Non-MWRA Communities

LEAKAGE CONTROL AND WATER ACCOUNTING

LEAK DETECTION AND REPAIR
- MWRA Pipes
- Community Systems

FLOW METERING AND MONITORING
- MWRA System
- Community Retail Meter Accuracy
- Control of Releases in System

DEMAND MANAGEMENT & CONSERVATION

DOMESTIC CONSERVATION
- Device Retrofit Program
- Conservation Information & Outreach
- Promotion Water-Saving Technologies

NON-DOMESTIC CONSERVATION
- Technical Information Dev. & Exchange
- Implementation Assistance Program

MUNICIPAL CONSERVATION
- Public Building Demonstration Program
- Retail Pricing Structures

LOCAL SOURCE CAPACITY ENHANCEMENT

SOURCE IDENTIFICATION & DEVELOPMENT
- Feasibility Assessment of Potential Sources
- Activation Aditional Local Sources

WATER SHARING AND IMPROVED USAGE
- Implementation Needham and Wellesley
- Investigation Other Possibilities

PLANNING FUTURE SUPPLY ADEQUACY

SUPPLY AND DEMAND MONITORING
- Water System Database
- Geographic Information System
- Trigger Planning
- Demand Forecasting

DROUGHT MANAGEMENT PLANNING

ADDITIONAL WATER SUPPLY PROPOSALS

CONDITIONS GOVERNING SERVICE EXTENSION

EDUCATION, OUTREACH AND REPORTING

SCHOOL EDUCATION PROGRAM

WATER SUPPLY CITIZENS ADVISORY COMMITTEE (WSCAC)

PREPARATION OF REPORTS TO BOARD

COMPLETED AND OTHER PROGRAMS

SAFE YIELD DEFINITION

IMPACT OF SAFE DRINKING WATER ACT

REDUNDANCY PLANNING

OPERATIONAL ENHANCEMENTS
- SWIFT RIVER RELEASES
- WACHUSETT CONNECTIONS

* The integration of the LRWSP and Trigger Planning, including the annual assessments, is assumed after 1995.

SOURCES: MWRA, MWRA Long Range Water Supply Program, Program Briefing (24 January 1990) and Progress Briefing and annual updates

Chapter 5
MWRA TWENTY YEAR WATERWORKS MASTER PLAN (1993-2012)

In July 1992, the MWRA Waterworks Division completed the preparation in draft of the Twenty Year Waterworks Master Plan (The Twenty Year Plan), which was updated in September 1993, for identifying and scheduling all of the capital improvements necessary to assure a safe and reliable supply of water to customer communities in the MWRA service area from 1993 through 2012. The capital investment needs aim to address the need to repair, restore and provide enhancements to the water system whose maintenance has been neglected over the years and to meet more stringent federal and quality standards.

The Twenty Year Plan has been articulated to meet seven planning principles.

- provide high quality water
- provide reliable water delivery
- maintain infrastructure in sound condition
- keep water supply and demand in balance
- distribute water at adequate pressures and flow rates
- operate the system efficiently and effectively
- actively plan to control future capital needs

MAJOR PROBLEMS IN THE SYSTEM

The Waterworks Division has identified the following problems which prevent the system from meeting the planning principles articulated in the Twenty Year Plan.

- Lack of aqueduct redundancy
- Pipelines and valves in poor condition
- Covered storage required for treated water
- Inadequate metering in some communities
- Treatment that does not comply with water quality standards
- Potential growth in water demand

CAPITAL REQUIREMENTS

The total capital requirements for the twenty year plan are presented in Table 2 and those specifically addressing supply in Table 3.

Table 2
The New England Drought Study
SUMMARY MWRA CAPITAL IMPROVEMENT PROJECTS
1993-2012
(Costs in million current 1992 dollars)

SYSTEM COMPONENT	93-97	98-02	03-12	Total
Supply	48.91	381.26	35.04	465.21
Transmission	137.28	249.70	272.50	659.48
Distribution	174.79	254.71	279.86	709.36
Operational Support	35.11	5.00	10.00	50.11
	396.09	890.67	597.40	1884.16

Source: MWRA, Twenty Year Waterworks Master Plan, July 1992

Table 3
The New England Drought Study
MWRA CAPITAL IMPROVEMENT PLAN FOR SUPPLY PROJECTS
1993-2012
(Costs in million current 1992 dollars)

	Cost	Schedule
QUALITY ASSURANCE PROJECTS		
Wachusett Water Treatment Plant	397.00	1993-2001
Quabbin Reservoir Treatment	30.00	1994-2004
Weston Disinfection	1.69	1993-1994
Booster Disinfection	2.60	2004-2008
Water Quality Model	0.25	2002-2004
QUANTITY PROJECTS		
Domestic Device Program	9.08	1993-1995
Protect Local Sources	1.29	1993-2002
Develop Local Sources	17.45	1993-2005
Leak Detection Community Systems	5.50	1999-2001
Sudbury Reservoir Watershed Protection	0.10	1995-1996
Water Demand Forecast Support	0.25	1995-1996
Planning Study: New sources	required funds not estimated	
TOTAL	465.21	

Source: MWRA, Twenty Year Waterworks Master Plan, July 1992

IMPLICATIONS OF THE TWENTY YEAR WATERWORKS MASTER PLAN ON DEMAND AND SUPPLY

The term supply is used here to denote the sources of supply, including the Quabbin Tunnel which connects the two principal sources of supply, the Quabbin and Wachusett Reservoirs, and treatment and is distinguished from the transmission and distributions functions of the MWRA/MDC Water System. In order to evaluate the adequacy of future supply to meet the projected demand for water, the study assessed the implications of proposed MWRA projects and actions during the next twenty years on the supply and demand for water. The implementation of projects in the MDC's Twenty Year Waterworks Master Plan would affect the system supply and demand for water. The operations projects were evaluated and were found not to have impacts on supply and demand. Assessments have not been prepared by MWRA on the corresponding impacts of distribution subsystem improvements because issues remain to be resolved between the service communities and regulatory agencies and MWRA. Those projects that potentially will have an impact on the quantity of water supplied or demanded are:

- Wachusett Water Treatment Plant
- Leak Detection in Community Systems Project
- Domestic Device Retrofit Program
- Industrial, Commercial and Industrial Conservation
- Protection and Management of Local Sources Project
- Development of Local Sources Project
- Metro-West Tunnel Project
- Hultman Aqueduct Repair Project
- Wachusett Reservoir Bypass Tunnel

The impacts are summarized in Table 4.

Wachusett Water Treatment Plant

With respect to water quality at Wachusett Reservoir, the MWRA is preparing to comply with the Safe Drinking Water Act (amended in 1986) by continuing to consider the construction of the Wachusett Water Treatment Plant while at the same time attempting to meet the standards by managing the watershed to improve quality. The construction of filtration, disinfection, and corrosion control facilities for Wachusett Reservoir in compliance with the Safe Drinking Water Act is planned for completion in 2001. It is estimated that the plant will require between 1 and 6 mgd of water for its operation.

Leak Detection in Community Systems

The Leak Detection in Community Systems Project would provide a leak detection survey for MWRA service communities at a rate of once in ten years in the periods 1999-2001 and 2009-2011. It is estimated that the detection and the subsequent repairs undertaken by the communities would likely reduce the demand for water on the MWRA system by up to 5 mgd by 2011.

Domestic Device Retrofit Program

Domestic water use accounts for nearly half of water use. The MWRA has initiated a program to reduce domestic water use. The Domestic Device Retrofit Program offers the free installation of water-saving devices to all 730,000 occupied housing units in the service area. Assuming an acceptance rate of 59 percent, approximately 430,000 housing units would be retrofitted during the 1993-95 period resulting in an estimated savings of 3 to 4 mgd by 1996.

Industrial, Commercial and Institutional Conservation

The non-domestic sector includes water used by factories, utilities, businesses, offices and institutions and represents a little less than half of total community water use. Water audits and case studies indicate a significant potential for reducing water use in this sector. Studies indicate that many facilities reduce water use by 20 to 30 percent by adopting measures that can pay for themselves in the third year or less of implementation. It is estimated that the savings in water from this activity would be between 10 and 15 mgd by the year 2012.

Protection and Management of Local Sources

The Protection and Management of Local Sources Project provides technical assistance to local communities in the management of their local sources of water and seeks to control possible additional demands on the MWRA system. In addition, the MWRA continues to develop water exchange agreements with communities having surplus local supplies. The program has already produced exchange agreements with Needham and Wellesley. The possibility of implementing such agreements with Lynn, Worcester, Sharon and Cambridge will be studied in the period 1995-96. It is estimated that the protection of local sources aspect of this project would not affect the future quantity of water available. However, the implementation of the water exchange programs would reduce demand by approximately 0.5 mgd for Needham and Wellesley and by about 10 mgd for the other four communities by 1996.

Development of Local Water Sources

The Development of Local Water Sources Project (1993-2005) seeks to develop new local sources of supply as a means to augment MWRA supplies or to reduce the demand on the system. Three sites (Cochituate Wells, Newton Water Works and the South Arm of the Neponset Aquifer), estimated to have a combined estimated yield of 9.1 mgd, would be examined. A second aspect of the project is the Reactivation of Contaminated Sources at the Canton Wells #3 and #7, the Johnson Street Well in Peabody, and at Lyman Street in Northborough. The reactivation of these wells would reduce demand by a maximum of 3 mgd on the system.

Metro-West Tunnel

A 17-mile long, 500 mgd capacity Metro-West Tunnel pressure tunnel will be constructed from Marlborough to Weston to provide redundancy for the Hultman Aqueduct. This will reduce the risk of widespread service disruption associated with a failure of the Hultman Aqueduct. With the Hultman Aqueduct out of service, leakage would be reduced between 2 and 5 mgd. In addition, a savings of an estimated 2 mgd will be realized since several water users currently served by the Wachusett Reservoir will be served more efficiently with the construction of the Metro-West Tunnel.

Hultman Aqueduct Repair

After the completion of the Metro-West Tunnel, the Hultman Aqueduct will be taken off line for inspection and the repair of leaks and the rectification of other problems. The water savings have been estimated above under Metro-West.

Wachusett Reservoir Bypass Tunnel

The MWRA is considering the construction of a 6 to 8 mile long tunnel under Wachusett Reservoir linking the Quabbin Tunnel at Oakdale to the Cosgrove intake. This would provide flexibility in the delivery of the higher quality Quabbin Reservoir water directly to the metropolitan Boston area without mixing with water in Wachusett Reservoir. The operation of the bypass would result in an, as yet, undetermined amount of spillage at Wachusett Reservoir and a diminution of safe yield.

Table 4
The New England Drought Study
IMPACTS OF MWRA TWENTY YEAR WATERWORKS MASTER PLAN (1993-2012) ON THE QUANTITY OF WATER DEMANDED (mgd)

	Range of Impacts in Quantity Demanded From	To	Year
SUPPLY AND OTHER PROJECTS			
-Wachusett Water Treatment Plant	+1	+6	2001
-Leak Detection in Community Systems	-5	0	2011
-Domestic Device Retrofit Program	-4	-3	1996
-Indust/Commer/Instit Conservation	-15	-10	2012
-Protection and Management of Local Sources			
. Protection	0	0	
. Water Exchange Agreements			
.. Needham, Wellesley	-0.5	0	1992
.. Lynn, Worcester, Cambridge	-5	0	1996
.. Springfield	-5	0	?
-Development of Local Water Sources			
. Cochituate, Newton, Neponset Aquifer	-9.1	0	2005
. Reactivation 4 contaminated sources	-3	0	2005
TRANSMISSION SYSTEM PROJECTS			
-Metro-West Tunnel(CIP #33)			
Savings @ Wachusett Aqueduct	-2	-2	2001
Hultman out of service	-5	-2	2001
-Hultman Aqueduct Repair			2004
See Metro-West above			
-Wachusett Reservoir Bypass Tunnel	0	0	?
PRICE - not assessed			
TOTALS	-52.6	-11	

Table 5
The New England Drought Study
IMPACTS OF MWRA TWENTY YEAR WATERWORKS MASTER PLAN (1993-2012) ON THE QUANTITY OF WATER SUPPLIED (mgd)

	Range of Impacts in Quantity Supplied From	To	Year
-Wachusett Reservoir Bypass Tunnel	negative impact, not quantified		

SOURCE: The New England Drought Study: MWRA and WSCAC Study Team members.

Chapter 6
WATER DEMAND PROJECTIONS

The following scenarios have been prepared by the MWRA in order to provide the basis for four projections of water demand for the service area beginning with 260 mgd in 1992 to 2012. The projections take into account the impacts of the MWRA's Twenty year waterworks Master Plan (July 1992) on demand. The range of these impacts are summarized in Table 11. These impacts range from an increase in water demand between 1 and 6 mgd due to the construction of the Wachusett Water Treatment Plant to a decrease between 10 and 15 mgd as a result of the execution of the Industrial, Commercial, and Institutional Conservation Program. The elements of both the impacts of the Master Plan and the four scenarios are translated into future water demands of 230, 260, 285, and 340 mgd as depicted in Table 6.

SCENARIO 1: STAGNANT ECONOMY WITH GREAT DEMAND MANAGEMENT SUCCESS

In this scenario, the regional economy sputters along during most of the 1993-2012 period with continued losses of employment in the manufacturing sector. Businesses strengthen conservation measures and some develop on-site water sources. Some new building occurs mainly in low water-using sectors. Population in the service area declines slightly. Leak repair and substantial system rehabilitation efforts by the MWRA and communities continue to reduce unaccounted-for water use. A few local sources of supply in the partially-supplied communities and adjacent communities become contaminated, but all are eventually returned to use with treatment. Several communities develop local sources and reduce reliance on the MWRA. The construction of the Wachusett Water Plant is delayed due to improving water quality.

As shown in Table 6, the impacts of projects in the Master Plan is expected to result in a decline in water use of 23 mgd. The assumptions implicit in the description of Scenario 1 would bring about an additional decline in demand of 7 mgd for a total decline in demand of 30 mgd or a water use forecast of 230 mgd in 2012.

SCENARIO 2: PERIODS OF ECONOMIC GROWTH WITH CONTINUED DEMAND MANAGEMENT SUCCESS

In scenario 2, the regional economy bounces around during the 1993-2012 period, with several periods of growth and decline. Some new building occurs, mainly in the low water-using service sectors. Population in the service area remains relatively constant or declines slightly. Strong MWRA conservation efforts continue to reduce water usage per employee and per residence. High water and sewer rates contribute to water conservation. While some local sources of supplies in MWRA partially-supplied and adjacent communities become contaminated, most are eventually returned to use with treatment.

Average water use as a result of projects in the Master Plan would decrease due to a net savings of 18 mgd (demand management programs: -15 mgd; Metro-West Tunnel etc.: -4 mgd; Wachusett Water Treatment Plant: +1 mgd). The assumptions of Scenario 2 contribute an offsetting increase of water use of 18 mgd so that demand remains at 260 mgd in 2012. The fully supplied communities experience lower water use because of population losses, but the growth of the economy causes increased industrial, commercial and institutional use, combined with added use from the partially supplied communities and to adjacent communities joining the system, and to additional Quinapoxet withdrawals.

SCENARIO 3: MODERATE ECONOMIC GROWTH WITH SOME LOCAL SOURCE CONTAMINATION

Scenario 3 envisions the regional economy rebounding during the 1990's and the early part of the twenty-first century. New building occurs in a wide range of the industrial, commercial and institutional sectors. Population in the service area increases by about 5 percent. Strong MWRA conservation efforts continue to reduce water usage per employee and per resident, but begin to show diminishing rates of return. A few local sources of water supply in MWRA partially-supplied and adjacent communities become contaminated and the communities turn to the MWRA for water. The Wachusett Water Treatment Plant is constructed.

The implementation of projects in the Master Plan would result in a net decline in demand of 17 mgd. However, the expectations described above for Scenario 3 would place an additional demand of 42 mgd on the system resulting in a net increase of 25 mgd over the estimated demand of 260 mgd in 1992 and 285 mgd in 2012.

SCENARIO 4: SIGNIFICANT ECONOMIC GROWTH AND CONTAMINATION OF LOCAL SOURCES

In the last scenario, the regional economy strongly rebounds during the 1990's and early twenty-first century. Significant new building occurs, especially in high water using sectors such as bio-tech industries, hospitals and manufacturing. The population in the service area increases by about 10 percent. Conservation efforts continue but reach maximum effectiveness. Leak repair efforts cannot keep up with the deteriorating pipe network. Several major sources of water in the MWRA partially-supplied communities and adjacent communities become contaminated and turn to the MWRA for water. In addition, rapid growth in the adjacent communities force them to make demands for MWRA water. The Wachusett Water Treatment Plant consumes 3 mgd. The construction of the Metro-West Tunnel is delayed while leakage in the Hultman Aqueduct expands.

The net impact of the Master Plan on water demand is a decrease of 10 mgd (Conservation:-13 mgd and Wachusett WTP: +3mgd). The implication of Scenario 4 is an increase in demand of 90 mgd or a net increase of 80 mgd over the estimated 1992 use of 260 mgd or a demand projection of 340 mgd in 2012.

Table 6
The New England Drought Study
MWRA PROJECTED WATER DEMAND SCENARIOS (1993-2012)
(mgd)

	Range of Impacts in Quantity Demanded From	To	SCENARIO 1	2	3	4
IMPACTS ON DEMAND OF TWENTY YEAR MASTER PLAN						
-Wachusett Water Treatment Plant	+1	+6	0	+ 1	+ 2	+ 3
-Leak Detection Community Systems	-5	0	- 2	- 2	- 2	0
-Residential Domestis Device Retr.	- 4	-3	- 4	- 3	- 3	- 3
-Indust/Commer/Instit Conservation	-15	-10	-10	-10	-10	-10
-Protection and Management of Local Sources						
. Protection	0	0	0	0	0	0
. Water Exchange Agreements						
.. Needham, Wellesley	-0.5	0	0	0	0	0
.. Lynn, Worcester, Cambridge	-5	0	0	0	0	0
.. Springfield	-5	0	0	0	0	0
-Development of Local Water Sources						
. Cochituate, Newton, Neponset Aquifer	-9.1	0	- 3	0	0	0
. Reactivation 4 contaminated Sources	-3	0	0	0	0	0
-Metro-West Tunnel(CIP #33)						
Savings @ Wachusett Aqueduct	-2	-2	- 2	- 2	- 2	0
Hultman out of service	-5	-2	- 2	- 2	- 2	0
-Hultman Aqueduct Repair See Metro-West above						
-Wachusett Reservoir Bypass						
TOTALS	-52.6	-11				
IMPACTS OF MWRA SCENARIOS ON DEMAND						
-Residential use						
Fully supplied communities			- 4	- 2	+ 5	+13
Partially supplied communities			- 3	+ 3	+ 6	+11
-Indust/Commer/Instit Use			0	+12	+18	+33
-New Communities			0	+ 2	+ 5	+14
-Other						
Quinapoxet			+ 4	+ 3	+ 3	+ 6
-Unaccounted For Water						
. MWRA			- 2	0	+ 1	+ 6
. Communities			- 2	0	+ 4	+ 7
Sub-Totals			-30	0	+25	+80
WATER DEMAND IN 1992			260	260	260	260
PROJECTED WATER DEMAND 2012			230	260	285	340

SOURCES: Study Team for the New England Drought Study except information on scenarios was provided by Jonathan Yeo, MWRA Waterworks, Boston, Mass.

Chapter 7
PROBLEM IDENTIFICATION AND OPPORTUNITIES

Problem and opportunity statements have been derived from areas of national concern expressed in the National Drought Study and under whose authority this present study is conducted. The statements are also derived from regional concerns advanced by the Massachusetts Water Resources Authority and the Water Supply Citizens Advisory Committee and from the without project condition that would occur in the absence of this study.

STATEMENT OF PROBLEM

The National Drought Study has been designed to address the issue of the management of water resources during drought. The National Study also aims to make a positive difference in water resources management in the entities addressed in the case studies. The MWRA/MDC Water System is one such case study.

With reference to the MWRA system, "The principal objective of our water supply program is to successfully keep supply and demand in balance". (6) Basically the MWRA has adopted a two pronged approach to ensuring that the system is not subject to a future water supply shortfall. On the one hand, the Authority has undertaken a series of demand and supply management actions to reduce water use and to enhance the quality and quantity of water currently available to communities which are currently being served and those which could request service in the future. These actions have been outlined in MWRA's Twenty Year Waterworks Master Plan. On the other hand, the MWRA is applying the Trigger Planning concept "to provide the MWRA with the analytical tools necessary to plan pro-actively to keep supply and demand in balance, and to initiate appropriate actions when needed." (7) However, since present demands are well below the safe yield of the system, managers fear that traditional episodic planning techniques may not anticipate new demands in time to avoid a water supply shortfall. Both the MWRA and WSCAC generally agree that the existing water system should be used to the fullest extent to avoid future water supply shortfalls .

OPPORTUNITIES

The following opportunity statements have been established.

- to ensure the legitimate water supply needs, in terms of quantity, quality and reliability for the 46 communities in the MWRA service area,

- to ensure that the MWRA/MDC is better prepared for drought,
- to contribute to improved water resources planning at the MWRA,
- to avoid future water supply shortfalls,
- to adopt a planning process (Trigger Planning) that avoids the shortcomings of episodic planning,
- to enhance the MWRA decision-making process with respect to water resources planning, while taking into account risk and uncertainty,
- to ensure that future water supply for the MWRA/MDC Water System is adequate to meet future demand by identifying early actions that should be taken in order to avoid supply shortfalls,
- to develop a coherent program of studies for avoiding future supply shortfalls by favoring smaller projects, by reducing project lead time, and by avoiding the expenditure of funds prematurely while minimizing risk and uncertainty
- to develop consensus among the MWRA/MDC and interested citizens and citizens groups on avoiding future supply shortfalls.

Chapter 8
PERFORMANCE MEASURES AND CRITERIA FOR SUPPLY ADEQUACY

Performance measures and criteria have been prepared in order to evaluate the adequacy of the MWRA/MDC Water System as it is expected to exist in the year 2012 (without project condition) to meet projected demand. The performance of the system is evaluated for each of the four demand scenarios defined earlier. Since both a drought management plan and demand management measures will be adopted by the MWRA, the demands on the system are not unrestrained. Demand has been and will be modified by the drought and demand management measures.

PERFORMANCE MEASURES

The Study Team for the New England Drought Study has developed measures for assessing the performance of the supply function of the MWRA/MDC Water System under a series of different demand forecasts and target pools at Quabbin reservoir. The following classical performance measures were considered:

- Safe Yield
- Reliability
- Resiliency
- Vulnerability

They were examined and modified and others introduced to reflect the specific characteristics of the system. Reliability was considered and rejected as an appropriate performance measure in the context of a system with active drought management. A measure called Drought Actions was developed instead. The performance measures adopted permit multifaceted views of the performance of the system. Not only do they provide measures for assessing the ability of the system to satisfy projected demands but also to measure the corresponding impacts on the condition and ecology of Quabbin Reservoir, the socioeconomy of the region and on consumers served by the system as a result of satisfying these demands. The following performance measures have been sorted into <u>QUANTITY</u> or the availability of supply measures and <u>IMPACT</u> related measures.

QUANTITY RELATED MEASURES

SAFE YIELD is the quantity of water that can be supplied on a continuous basis during a critical drought. For planning purposes, the combined safe yield of the three current sources of water (Quabbin and Wachusett Reservoirs and the Ware River) for the MWRA/MDC Water System is 300 mgd at the current target pool of 38 percent full or at an elevation of 490 feet above the Boston City Base (BCB). In this case, the reservoir would not be permitted to dip below the target pool.

SUPPLY SHORTFALL is expressed as the number of months with a shortfall in supply at different levels of demand and stages and degrees of drought response.

IMPACT RELATED MEASURES

SEVERITY is the maximum number of consecutive months that Quabbin Reservoir is below a specific target pool level at a specific water demand during the period under consideration. This measure was developed because the excursion time below the target pool on this very large reservoir affects the growth of shoreline vegetation and the temperature whose changes affect fish habitat. Short term excursions have relatively little environmental impact.

MAXIMUM POOL DESCENT is the maximum deviation of the pool at Quabbin Reservoir below a specific target pool level at a specific water demand during the period under consideration. Maximum pool descent is indicated as the elevation of the pool at the maximum deviation.

RESILIENCY is the ability of the water supply system to recover from an unsatisfactory condition. For the MWRA/MDC Water System, it is defined as the time spent below a target pool level (currently 490 feet (BCB) or 38 percent full) at Quabbin Reservoir, relative to an acceptable stay below the level. Resiliency is expressed as a percentage and is measured as the ratio of the tolerable stay in an unsatisfactory condition to a particular stay times 100. For example, if system managers determine that the MWRA/MDC Water System could tolerate the level of Quabbin Reservoir to be 18 months below the target pool, its resiliency would be 100 percent if the system rebounded from the unsatisfactory state in a maximum of zero to 18 months (zero to 18 months is counted as 18 months in the calculation) and 75 percent if its maximum stay in the unsatisfactory state were 24 months.

VULNERABILITY is the socioeconomic losses associated with SEVERITY. Information does not now exist to permit an estimation of these losses.

DROUGHT ACTIONS, as a water supply system performance measure, is defined for the MWRA/MDC system as the number of months that the reservoir levels at Quabbin Reservoir remain in each of the stages (normal operation, below normal, drought warning and drought emergency stages 1, 2, and 3) in the MWRA Drought Status Control Program (Figure 2) for the period under consideration. Drought response actions corresponding to each stage are given in Table 1.

At the time of the preparation of this report, the Study Team was not fully satisfied with the definition of resiliency. WSCAC representatives had offered an alternative definition of resiliency that tracks the differences between inputs and outputs of the reservoir over the period of record. In effect this is the rate of change in the volume of water in the reservoir and can be calibrated in terms of elevation given an initial value. A positive value indicates increasing elevation, i.e. drought recovery. The recovery rate indicated as a 24-month moving average is plotted against time. While the relationship is of interest in terms of the quality of control of the elevation of the reservoir, it is not clear how it could be used as a measure of the performance of the water system.

PERFORMANCE CRITERIA

Given the iterative nature of the assessment process, the following criteria serve as a first estimation, subject to subsequent modification, of the tolerable limit beyond which system stress and or impacts are unacceptable.

QUANTITY RELATED CRITERIA

SAFE YIELD: implicit in the STELLA II model for the present application of Trigger planning.

SHORTFALL: MWRA/MDC Water System should be capable of delivering 100 % of demand, as modified by drought and demand management measures, with no consideration of target pool.

IMPACT RELATED CRITERIA

SEVERITY: the maximum number of consecutive months below the target pool at Quabbin Reservoir should not be more than 18 months.

MAXIMUM POOL DESCENT: the pool at Quabbin Reservoir should not fall below 470 feet(BCB). At approximately 470 feet a ridge is exposed and the reservoir ceases to behave as a unit.

RESILIENCY: the maximum number of consecutive months, that it is acceptable for the pool at Quabbin Reservoir to be below the target pool, is 18 months and the resiliency should not fall below 90 percent.

VULNERABILITY: not assessed since information on socioeconomic impacts is not available and because the assessment is beyond the scope of the present study.

DROUGHT ACTIONS: drought actions in drought emergency stages 1, 2, and 3 should not exceed 24 months.

PERFORMANCE EVALUATION

Each of the performance measures are evaluated quantitatively against the performance criteria by the simulation of the demand scenarios and system operations using the STELLA II model. The results are presented in Chapter 10, Tables 8 through 11, and summarized in Table 12.

Chapter 9
WITHOUT PROJECT CONDITIONS: MWRA/MDC WATER SYSTEM IN 2012

The four "without project" conditions span the range of likely conditions that are expected to exist in the MWRA Water Supply System at the end of the 20 year planning horizon or in the year 2012. The without project conditions focus on the exploitation of opportunities related to preparing the system to avoid future shortfalls in supply. The other opportunity statements listed in Chapter 7 are implicit in the without project condition. They will be more directly addressed in the risk and uncertainty analysis below.

The without project conditions are the four scenarios. They are simply the existing condition of the system and its projection to the year 2012 based on the MWRA Twenty Year Master Plan and the estimates of future supply and demand. The use of the STELLA II software package permits the integration of strategic, tactical (MWRA Drought Management Plan) and emergency planning into a single interactive model and permits the evaluation of the performance of the water system under different simulated futures.

DEMAND

Table 6 presents a summary of the four previously defined demand scenarios, including the range of impacts of the various actions contained in the Twenty Year Master Plan on the demand for water by the year 2012. The range of impacts of individual actions range from zero to a maximum reduction of 15 mgd for the non-domestic conservation program. The range of total impacts on demand ranges from 11 to nearly 53 mgd. Below in Table 7 is a summary of the projected demands for the four scenarios and the potential additional reductions in demand that are available for exploitation by the MWRA management.

Table 7
The New England Drought Study
DEMAND PROJECTIONS AND POTENTIAL FOR ADDITIONAL DEMAND REDUCTIONS

	Actual 1992 (mgd)	Projected 2012 (mgd)	Potential Additional Reductions In Demand (mgd)
Scenario 1	260	230	30
Scenario 2	260	260	35
Scenario 3	260	285	36
Scenario 4	260	340	43

The reductions in demand, due to the measures in the Drought Management Plan and presented in Figure 2 and Table 1, are explicit in the STELLA II Model of the MWRA/MDC Water System.

SUPPLY

The implementation of projects in the Master Plan is expected to have little, if any, impact on the 300 mgd safe yield of the water system except the Wachusett Reservoir Bypass Tunnel. The operation of the bypass is expected to result in an, as yet, undetermined amount of spillage at Wachusett Reservoir. Since this estimate is within the margin of error of estimates of the safe yield, this study uses a safe yield of 300 mgd for both the existing and the without project condition. The purpose of the bypass is to provide flexibility in the delivery of high quality water to the metropolitan Boston area without mixing with the lower quality water in Wachusett Reservoir. If the Wachusett Reservoir were to be relegated to standby status, then the safe yield of the system would reduce to about 200 mgd. This, however, is not an option that is under serious consideration by the MWRA.

Chapter 10
ASSESSMENT OF SUPPLY ADEQUACY IN 2012: WITHOUT PROJECT CONDITIONS FOR THE FOUR SCENARIOS

INTERACTIVE MODEL OF THE WITHOUT PROJECT CONDITIONS (STELLA II)

The assessment of supply adequacy evaluates the ability of the MWRA/MDC Water System to meet the demand in the without project condition. The without project condition is the most likely condition that is expected to exist in the MWRA/MDC Water System in the absence of projects and actions not currently included in plans to balance demand and supply. There are as many without project conditions as there are alternative projections of demand.

The interactive STELLA II software has been used to model both the supply of and the demand for water in the system. The supply is portrayed by modeling the configuration and functions of the MWRA/MDC Water System as it is projected to exist in the year 2012. A 31 year historical hydrological record extending from October 1949 to September 1980 and including the 1960's drought of record is used. The model is run unrestrained, that is, the Quabbin pool is permitted unlimited drawdown. System demand is represented in the projected loadings for the four scenarios of 230, 260, 285 and 340 mgd in addition to loadings in the vicinity of the current safe yield of the system: 300 and 320 mgd. The system is evaluated for its ability to withstand the 1960's drought.

In addition the model includes performance measures (Chapter 8) and compares them to criteria of minimum acceptability as defined below.

Shortfall:	The model counts the number of months with a shortfall in supply. The shortfall criterion is no shortfall.
Severity:	The model counts the number of consecutive months that the Quabbin Reservoir pool is below a specific target pool. The severity criterion is a maximum of 18 consecutive months below the target pool.
Maximum Pool Descent:	The model indicates the maximum deviation of the Quabbin Reservoir pool in feet which is translated into the elevation of the maximum deviation in feet (BCB). The maximum pool descent criterion is 470 feet (BCB).

Resiliency: The model calculates resiliency based on the maximum number of consecutive months from the severity criterion is taken in conjunction with the acceptable stay below the target pool to calculate resiliency. See definition above in Performance Measures. The resiliency criterion is 98 percent.

Drought Actions: The model counts the number of months that the Quabbin pool is in different stages in the Drought Status Control Diagram. See Figure 2. The drought actions criterion is 24 months in drought emergency stages 1, 2, and 3.

PERFORMANCE

Figures 4 to 8 illustrate the performance of the system as measured at Quabbin Reservoir under different levels of demand and without and with drought management. The STELLA II depiction of the system is based on the Safe Yield Model which covers the 372 month period from October 1949 through September 1980.

Table 8 summarizes the performance of the water system under different demand loadings and other assumptions and with 100 percent drought management success. Tables 9 and 10 respectively demonstrate the performance assuming 50 percent success in drought management and with no drought management. Table 11 presents the impact on drought actions of lowering the target pool from 490 to 485 feet (BCB). The performance of the system at a target pool elevation of 485 feet is included in the tables in order to show the sensitivity of the system to lowering the target pool. However the evaluation of the adequacy of the system does not consider this criterion. Table 12 permits a comparison of the performance of the system and the performance criteria.

PERFORMANCE ASSESSMENT

Given the performance of the MWRA/MDC Water System under the different performance measures and demand loadings, the assessment of the adequacy of supply is an iterative process. It involves the preparation of criteria to define system adequacy, the identification of the critical point at which the water system would no longer be adequate and an assessment of the risks and uncertainty of not pursuing or of postponing strategies to address the potential supply shortfall.

Figure 4

The New England Drought Study

WITHOUT PROJECT CONDITION AT QUABBIN RESERVOIR - DEMAND:285 MGD
WITHOUT AND WITH DROUGHT MANAGEMENT (DM)

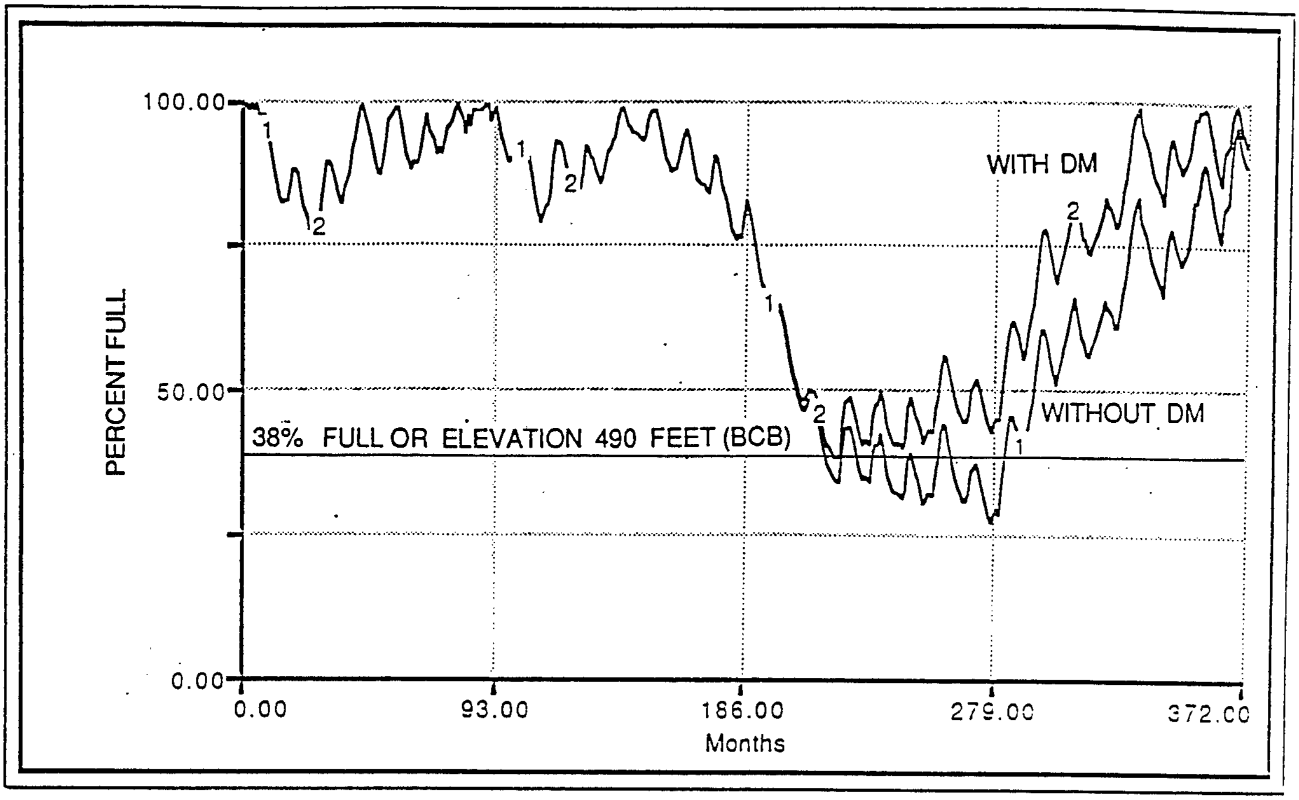


Figure 5

The New England Drought Study

WITHOUT PROJECT CONDITION AT QUABBIN RESERVOIR - DEMAND:300 MGD
WITHOUT AND WITH DROUGHT MANAGEMENT (DM)

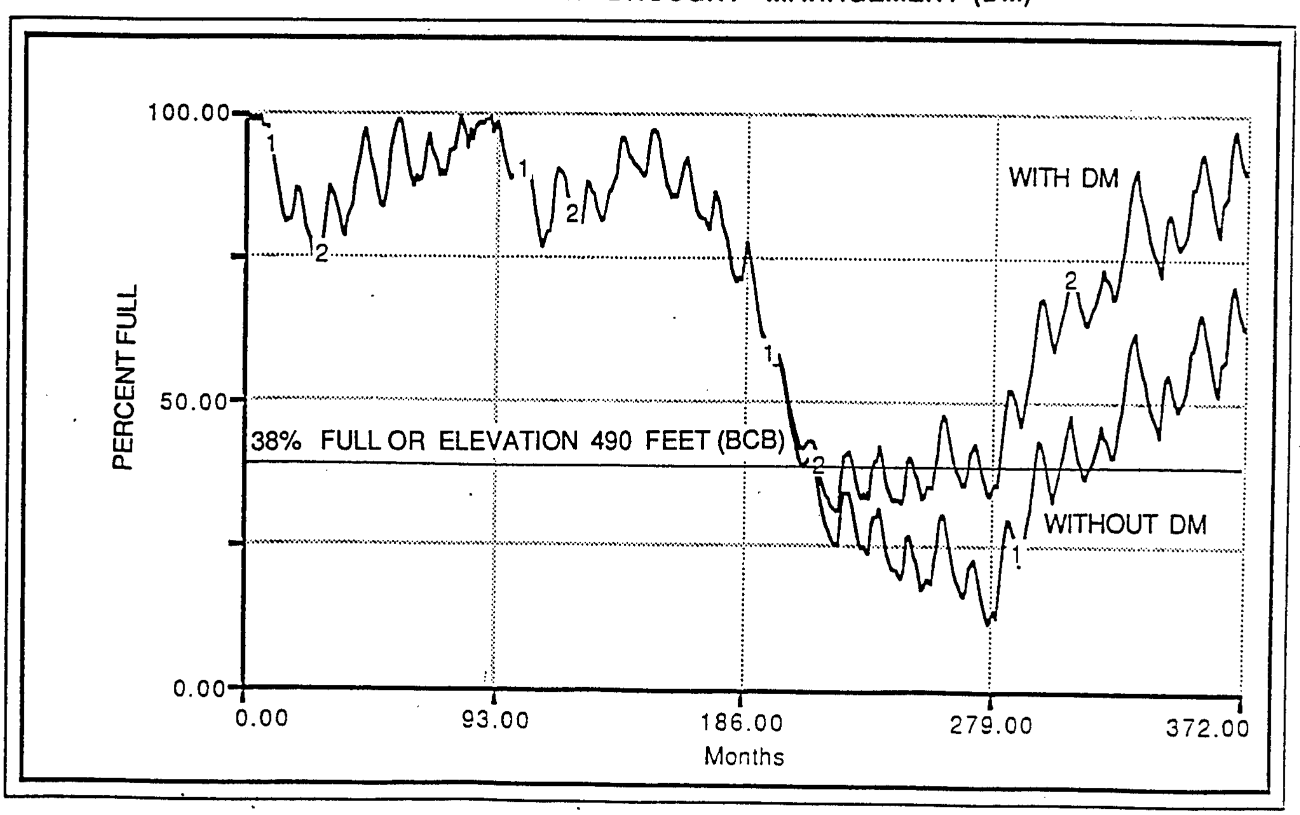


Figure 6

The New England Drought Study

WITHOUT PROJECT CONDITION AT QUABBIN RESERVOIR - DEMAND:285 MGD WITHOUT AND WITH DROUGHT MANAGEMENT (DM)

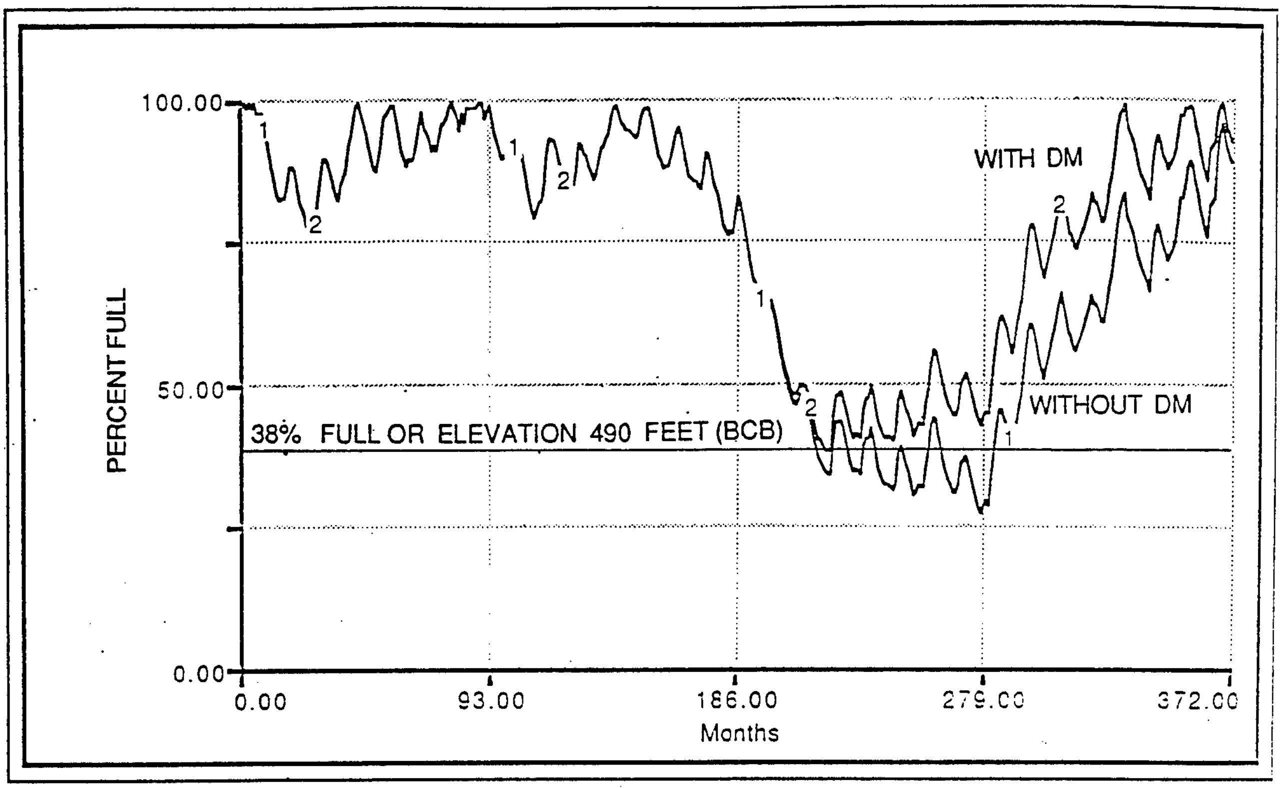


Figure 7

The New England Drought Study

WITHOUT PROJECT CONDITION AT QUABBIN RESERVOIR - DEMAND:300 MGD WITHOUT AND WITH DROUGHT MANAGEMENT (DM)

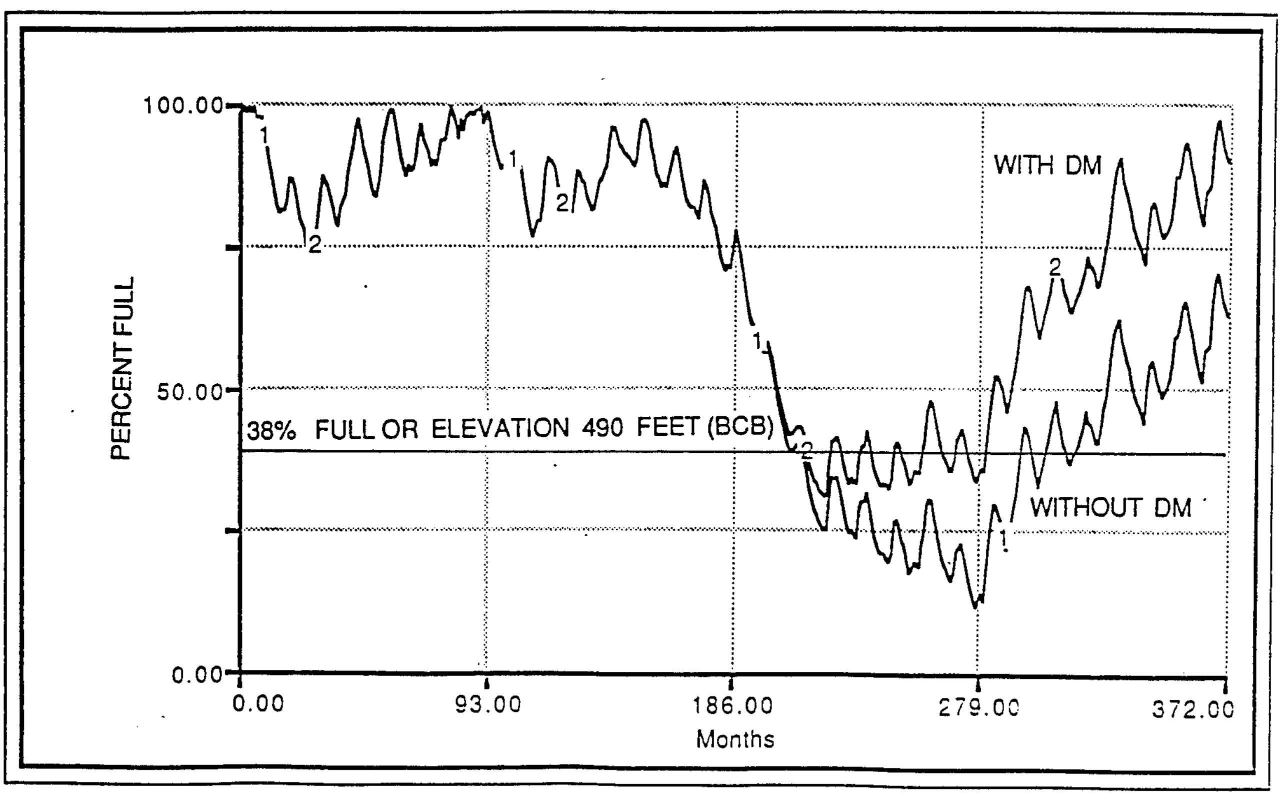
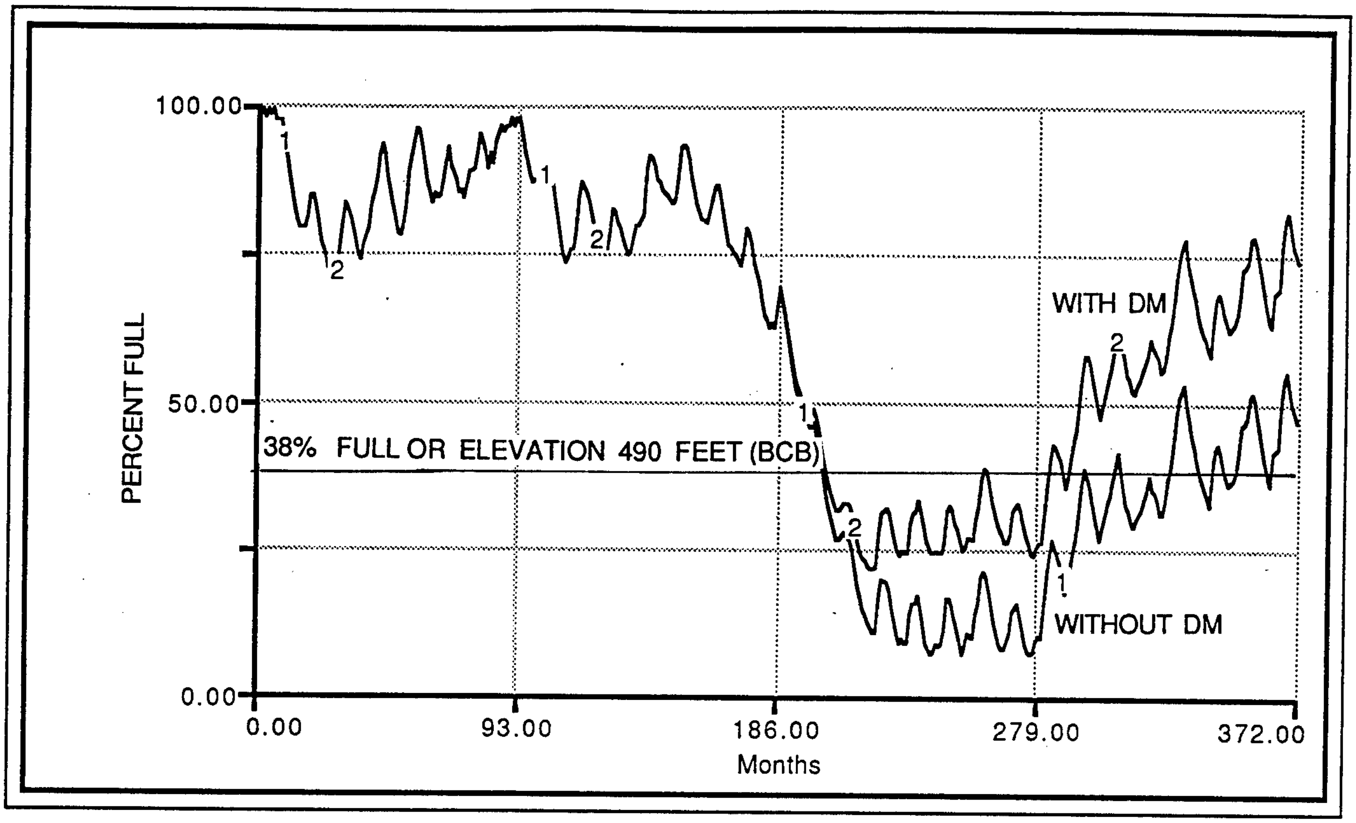


Figure 8

The New England Drought Study

WITHOUT PROJECT CONDITION AT QUABBIN RESERVOIR - DEMAND:320 MGD WITHOUT AND WITH DROUGHT MANAGEMENT (DM)



A gross assessment of the adequacy of supply can be estimated by comparing projected demands to the safe yield of the system, which has been established by the MWRA for planning purposes at 300 mgd. Projected water use forecasts under Scenarios 1, 2, and 3 (230, 260, 285 mgd) indicate demands within the safe yield of the system. Under Scenario 4, Significant Economic Growth and Contamination of Local Sources, which increases system use by 80 mgd over the 1992 system use of 260 mgd or by more than 30 percent, would supply be inadequate. Considering the supplementary projections of 300 and 320 mgd, the system would not be able to meet the latter.

A more complete assessment includes modeling the effects of the implementation of demand management measures and MWRA's Drought Management Plan in order to determine the system's ability to meet different levels of demand in accordance with criteria, which account for the tolerable limits of impacts on the environment, the regional socioeconomy and on those served by the water system. The assessment examines each system performance measure from SHORTFALL to DROUGHT ACTIONS.

An examination of Table 12 indicates the apparent reliability of Quabbin Reservoir to deliver up to 340 mgd with no *SHORTFALL,* if drought management is 100 % successful. However, if drought management were only 50 percent successful, then the system would be capable of supplying up to 320 mgd with no shortfall. Only 300 mgd could be supplied without a shortfall in the absence of drought management. Consideration of the *SHORTFALL CRITERION* alone, leads to the conclusion that the system could supply between 300 and 340 mgd depending on the success of drought management.

The satisfaction of such demand in the range of 300 to 340 mgd would not be without negative repercussions on the reservoir, the socioeconomy of the region and on consumers themselves. Bearing in mind the performance criteria established above, the severity criterion, limiting the Quabbin pool to a maximum of 18 consecutive months below the target pool, would be violated between 300 and 320 mgd with 100 percent drought management success and at about 285 mgd with no drought management. Consideration of the *SEVERITY CRITERION* alone limits the capacity of the system to between 285 and 320 mgd depending on the success of drought management.

The maximum pool descent criterion limits the pool elevation at Quabbin Reservoir to 470 feet (BCB). Consideration of the *MAXIMUM POOL DESCENT CRITERION* alone would limit the capacity of the MWRA/MDC to a range of between 285 and 320 mgd depending on the degree of drought management.

Table 8
The New England Drought Study
SUMMARY OF THE PERFORMANCE OF THE MWRA/MDC WATER SYSTEM IN 2012
(ASSUMING 100 % DROUGHT MANAGEMENT SUCCESS, EXCEPT AS NOTED)

Scenarios (no.)	Demand (mgd)	QUANTITY Safe Yield (mgd)	Shortfall NDM (mo.)	Shortfall DM	ENVIRONMENT Target Pool (Ft.)	Severity (mo.)	Maximum Pool Descent (Elev.Ft.)	Resiliency (%)	CONSUMERS Drought Actions (stage)	(mo)
1	230	300	0	0						
									NO	286
					495	0	507	100	BN	57
					490	0	507	100	DW	29
					485	0	507	100	DE1	0
									DE2	0
									DE3	0
2	260	300	0	0						
									NO	251
					495	0	498	100	BN	34
					490	0	498	100	DW	66
					485	0	498	100	DE1	21
									DE2	0
									DE3	0
3	285	300	0	0						
									NO	195
					495	9	490	100	BN	76
					490	2	490	100	DW	23
					485	0	490	100	DE1	76
									DE2	2
									DE3	0
	300	300	0	0						
									NO	150
					495	52	483	35	BN	93
					490	9	483	100	DN	33
					485	5	483	100	DE1	52
									DE2	44
									DE3	0
	320	300	21	0						
									NO	85
					495	91	473	20	BN	120
					490	56	473	32	DW	56
					485	25	473	72	DE1	30
									DE2	60
									DE3	21
4	340	300	36	0						
									NO	44
					495	101	456	18	BN	121
					490	98	456	18	DW	58
					485	58	456	31	DE1	51
									DE2	31
									DE3	67

* NDM = No Drought Management Plan DM = With Drought Management Plan
** Drought Management Plan Stages at target pool of 490 feet: NO = Normal Operation; BN = Below Normal; DW = Drought Warning; DE1 = Drought Emergency, Stage 1; DE2 = Drought Emergency, Stage 2; DE3 = Drought Emergency, Stage 3. (See Figure 1).

Table 9
The New England Drought Study
SUMMARY OF THE PERFORMANCE OF THE MWRA/MDC WATER SYSTEM IN 2012
(ASSUMING 50 % DROUGHT MANAGEMENT SUCCESS, EXCEPT AS NOTED)

		QUANTITY	ENVIRONMENT						CONSUMERS	
Scenarios (no.)	Demand (mgd)	Safe Yield (mgd)	Shortfall NDM (mo.)	Shortfall DM	Target Pool (Ft.)	Severity (mo.)	Maximum Pool Descent (Elev.Ft.)	Resiliency (%)	Drought Actions (stage)	(mo)
1	230	300	0	0						
									NO	283
					495	0	506	100	BN	58
					490	0	506	100	DW	31
					485	0	506	100	DE1	0
									DE2	0
									DE3	0
2	260	300	0	0						
									NO	249
					495	0	497	100	BN	36
					490	0	497	100	DW	57
					485	0	497	100	DE1	30
									DE2	0
									DE3	0
3	285	300	0	0						
									NO	188
					495	20	488	90	BN	68
					490	6	488	100	DW	34
					485	0	488	100	DE1	58
									DE2	24
									DE3	0
	300	300	0	0						
									NO	131
					495	87	475	21	BN	94
					490	46	475	39	DN	41
					485	10	475	100	DE1	35
									DE2	69
									DE3	2
	320	300	21	0						
									NO	84
					495	94	459	19	BN	98
					490	91	459	20	DW	43
					485	87	459	21	DE1	54
									DE2	30
									DE3	63
4	340	300	36	0						
									NO	41
					495	116	445	16	BN	122
					490	102	445	18	DW	20
					485	94	445	19	DE1	66
									DE2	36
									DE3	87

* NDM = No Drought Management Plan DM = With Drought Management Plan
** Drought Management Plan Stages at target pool of 490 feet: NO = Normal Operation; BN = Below Normal; DW = Drought Warning; DE1 = Drought Emergency, Stage 1; DE2 = Drought Emergency, Stage 2; DE3 = Drought Emergency, Stage 3. (See Figure 1).

Table 10
SUMMARY OF THE PERFORMANCE OF THE MWRA/MDC WATER SYSTEM IN 2012
(No Drought Management)

QUANTITY ENVIRONMENT

Scenarios (no.)	Demand (mgd)	Safe Yield (mgd)	Shortfall NDM (mo.)	Shortfall DM	Target Pool (Ft.)	Severity (mo.)	Maximum Pool Descent (Elev.Ft.)	Resiliency (%)
1	230	300	0					
					495	0	506	100
					490	0	506	100
					485	0	506	100
2	260	300	0					
					495	0	496	100
					490	0	496	100
					485	0	496	100
3	285	300	0					
					495	71	479	25
					490	20	479	90
					485	7	479	100
	300	300	0					
					495	102	456	18
					490	82	456	22
					485	68	456	26
	320	300	21					
					495	128	442	14
					490	93	442	19
					485	90	442	20
4	340	300	36					
					495	*	435 (est)	
					490	*	435 (est)	
					485	*	435 (est)	

* Outside range of STELLA II capability.

Table 11
The New England Drought Study
DROUGHT MANAGEMENT IMPACTS ON CONSUMERS OF LOWERING THE TARGET POOL AT QUABBIN RESERVOIR TO 485 FEET (BCB)

Stage	Demand (mgd)	Drought Actions (Number) Target Pool 490 Ft	485 Ft
	260		
NO Normal Operation		251	251
BN Below Normal		34	34
DW Drought Warning		66	66
DE1 Drought Emergency 1		21	21
DE2 Drought Emergency 2		0	0
DE3 Drought Emergency 3		0	0
	285		
NO Normal Operation		195	195
BN Below Normal		76	76
DW Drought Warning		23	23
DE1 Drought Emergency 1		76	78
DE2 Drought Emergency 2		2	0
DE3 Drought Emergency 3		0	0
	300		
NO Normal Operation		150	145
BN Below Normal		93	93
DW Drought Warning		33	37
DE1 Drought Emergency 1		52	80
DE2 Drought Emergency 2		44	17
DE3 Drought Emergency 3		0	0
	320		
NO Normal Operation		85	84
BN Below Normal		120	119
DW Drought Warning		56	55
DE1 Drought Emergency 1		30	48
DE2 Drought Emergency 2		60	43
DE3 Drought Emergency 3		21	23

Table 12
OVERALL SUMMARY OF THE PERFORMANCE OF THE MWRA/MDC WATER SYSTEM IN 2012 AND THE PERFORMANCE CRITERIA

QUANTITY			ENVIRONMENT					CONSUMER
Scenarios (no.)	Demand (mgd)	Safe Yield (mgd)		Shortfall (mo.)	Severity TP 490 ft (mo.)	Maximum Pool Descent (Elev.Ft.)	Resiliency (%)	Drought Actions Stages DE1-DE2 (mo.)
1	230	300						
			100%DM	0	0	507	100	0
			50%DM	0	0	506	100	0
			NDM	0	0	506	100	1
2	260	300						
			100%DM	0	0	498	100	21
			50%DM	0	0	497	100	30
			NDM	0	0	496	100	55
3	285	300						
			100%DM	0	2	490	100	78
			50%DM	0	6	488	100	82
			NDM	0	20	479	90	91
	300	300						
			100%DM	0	9	483	100	96
			50%DM	0	46	475	39	106
			NDM	0	82	456	22	147
	320	300						
			100%DM	0	56	473	32	111
			50%DM	0	91	459	20	147
			NDM	21	93	442	19	177
4	340	300						
			100%DM	0	98	456	18	149
			50%DM	19	102	445	18	189
			NDM	36	NA	NA	NA	NA
PERFORMANCE CRITERIA		300		0	18	470	98	24

100%DM = 100 percent drought management success
50%DM = 50 percent drought management success
NDM = No Drought Management Plan
TP = Target pool

* Drought Management Plan Stages at target pool of 490 feet: NO = Normal Operation; BN = Below Normal; DW = Drought Warning; DE1 = Drought Emergency, Stage 1; DE2 = Drought Emergency, Stage 2; DE3 = Drought Emergency, Stage 3 (Figure 1).

With respect to the *RESILIENCY CRITERION* of 90 percent, the system would be capable of delivering a maximum of 285 and 300 mgd depending on the extent of drought management.

Respecting the *DROUGHT ACTIONS CRITERION* of restricting drought actions in drought emergency stages 1, 2, and 3 to 24 months would limit the system between 230 and 260mgd depending on drought management success. This situation may be alleviated by adjusting the drought management criteria as a function of the average demand.

Although the drought actions at 100 percent drought management success respectively are 78 at 285 mgd and 96 at 300 mgd, the severity is limited to 2 and 9 consecutive months below the target pool of 490 feet. The severity criterion of 18 consecutive months below the target pool is therefore not violated. At 50 percent drought management success, the drought actions are 82 at 285 mgd, while the severity is only 6 consecutive months.

Taking into account all of the above criteria, except drought actions, the current MWRA Water System, as it is expected to operate in the year 2012, would likely be adequate for meeting demands between 285 and 300 mgd. Success with drought management would likely render the system adequate at 300 mgd. Bearing in mind that the projections of future demand, the assumptions on demand management success are modest. The MWRA estimates that additional reductions in demand, estimated between 30 and 43 mgd, are theoretically available for exploitation by water system managers. (See Table 7)

The fact that the hydrological record for the STELLA II Model of the system is a relatively short 372 months, and that this period includes the 1960's drought of record, has a significant influence on the results of the modeling. Supplementing the model with the more recent hydrological data since 1980 should be undertaken by the MWRA in order to make the model current.

COMPARISON OF STELLA II MODEL TO SYSTEM OPERATION AND OTHER MODELS

The following discussion compares the STELLA II portrayal of the MWRA/MDC Water System to the historical operation of the system and to the system's Safe Yield and Spreadsheet Models currently used by the MWRA.

The Safe Yield Estimation Model

The Safe Yield Estimation Model of the system was developed in the early 1980's with a focus on the evaluation of new water supply sources. For any combination of supply sources, the model estimated the safe yield. The supply modeled for the Trigger Planning study was the Quabbin-Ware-Wachusett system without Sudbury Reservoir and with the minimum pool at Quabbin Reservoir set at 490 feet (BCB). A large volume of input information was collected and synthesized for the model and the time modeled was October 1949 through September 1980. The Safe Yield Model provides a single measure of system performance with Quabbin Reservoir operating above 490 feet(BCB) or 38 percent capacity. For planning purposes, the MWRA considers that the system is able to supply 300 mgd in all but 8 months and without drought management. The model is rigid and does not mirror reservoir operations very well. It is not designed to evaluate operational changes.

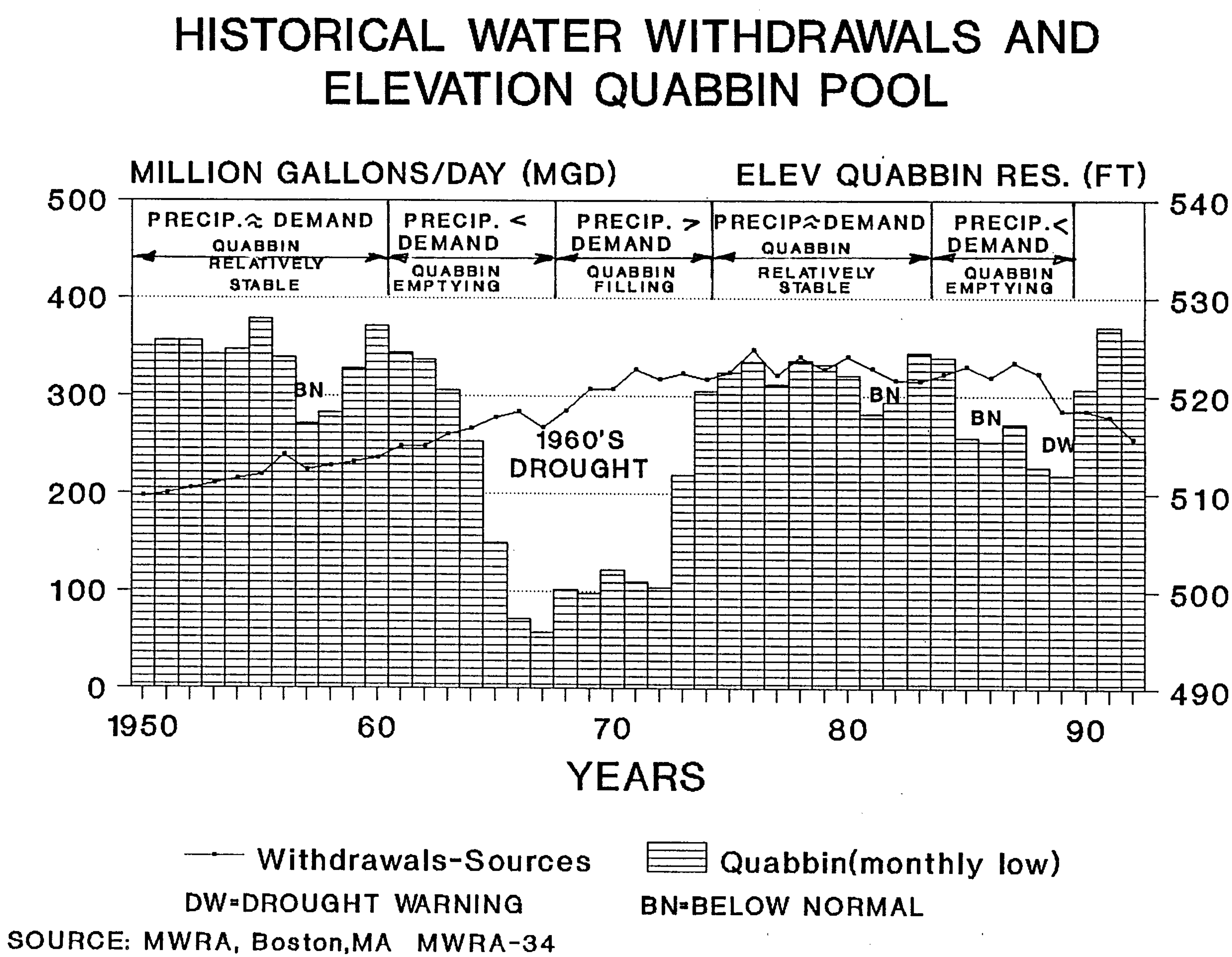
The Drought Management Plan Model (Spreadsheet)

The Drought Management Plan or Spreadsheet Model was created to provide quick answers to the impacts of drought management strategies based on trigger levels at Quabbin Reservoir and associated demand reduction responses. It grossly simplifies the MWRA/MDC Water System and introduces additional sources as the reservoir is drawn down to certain levels. The model measures the performance of the system by counting the number of months that the reservoir spends in the different drought management stages. The latter is also one of the performance measures in the STELLA II Model. Like STELLA II, it is suitable for negotiation and consensus building because of its fast running time and ease in changing inputs. The Spreadsheet Model portrays a more robust water system than the STELLA II Model.

Historical System Operation

Figure 9 presents a graph of historical water use for the MWRA/MDC system since 1950 and minimum monthly pool elevations at Quabbin Reservoir. The graph clearly demonstrstes the incidence of the 1960's drought and the onset of droughts in 1957, 1981, 1985 and 1989. The latter did not develop into full droughts because demand subsequently declined and/or precipitation increased to normal levels. Potential droughts appeared but did not materialize. In terms of demand on the system, from 1969 to 1988, water system use or the quantities of water released from the Quabbin-Ware-Wachusett system has been in excess of 300 mgd and up to a maximum of 347 mgd in 1976. The water system has sustained demands of more than 300 mgd over a continuous 20 year period.

Figure 9
The New England Drought Study



However, the STELLA II Model has additional criteria which recognize stress at demands between 270 and 300 mgd. At these levels of demand, the drought actions criterion of a maximum of 24 months in Drought Emergency Stages 1 to 3 and/or the severity criterion limiting the number of consecutive months to 18 below the target pool of 490 feet (BCB) would be violated depending on the success of drought management responses.

<u>Summary</u>

MWRA Study Team staff explain that the historical data, and in particular the data prior to 1980, is inherently uncertain and that in many cases was arrived at by consensus. In addition, records are incomplete regarding the operation of the system and to what extent standby sources such as Sudbury Reservoir were used. They agree that the STELLA II portrayal of the system combines the best attributes of the Safe Yield Estimation and Spreadsheet Models, it is relatively inexpensive to develop and incorporates a high degree of realism on actual reservoir operation. The model's accuracy and the Water System Data Base are expected to improve over time, which should improve the reconciliation between the model and the historical experience of the system. However, the historical accuracy of the STELLA II Model is not paramount. Its major focus is to evaluate future policy impacts.

Chapter 11
TRIGGER PLANNING METHOLOGY: STUDIES AND ACTIONS TO ENSURE SUPPLY ADEQUACY

DEFINITIONS

The *CRITICAL POINT* for supply adequacy is the point in time at which the future supply would be inadequate to meet projected demand. The *LEAD TIME* is the time needed to implement a strategy or a series of actions to address projected supply inadequacy. The use of the concept of lead time will eventually permit the identification of the *TRIGGER POINT* or the point in time at which action to prevent a shortfall in supply is initiated. (8) Based on studies of previously considered supply augmentation alternatives (Reactivation of Sudbury Reservoir, and the Connecticut, Merrimack and Millers Rivers) between nine and fifteen years would be required to develop a new supply. See Table 13.

METHODOLOGY

The Trigger Planning process for ensuring supply adequacy has three basic elements: evaluation, monitoring and programming.

Evaluation of System Capacity

With respect to evaluation, the methodology relies on a STELLA II software package to model the configuration and functions of the system as it relates to supply or source adequacy and permits the introduction of the MWRA Drought Management Plan with different levels of drought management success, alternative demand scenarios and customized performance measures. See Figure 10. In effect, drought management is integrated into strategic planning. The exercise produces performance data on the source or supply function of the system under different levels of demand, performance criteria, etc. thus permitting system managers to view the tradeoffs among the different performance criteria and to evaluate the capacity of the system, as well as when measures should be considered to modify demand and /or supply. This provides a better understanding of how the system works in its interaction with demand and possible enhancements to the system. The performance criteria are coupled with economic and other analyses to determine the most cost effective high performance alternative strategic plans. The output of the model is the evaluation of one or more strategies for balancing demand and supply at the end of the planning horizon. The model integrates drought planning into long term planning and mutually benefits both strategic and drought planning. The result is a system that has been made more robust because of punctual responses to potential drought and which is better prepared to deal with drought when it occurs.

The STELLA II interactive model of the MWRA/MDC Water System portrays the system configuration and includes the equations that define functional relationships based on operating rules and system behavior. See Figure 13. The model makes use of the following:

- Water System Data Base (WSDB),
- Safe Yield Estimation Model based on 31 years of hydroloical record from October 1949 to September 1980,
- MWRA Drought Management Plan,
- Projections of water system demand to the year 2012 in four scenarios: 230, 260, 285 and 340 mgd in addition to 300 and 320 mgd,
- Customized performance measures and criteria to determine the capacity of the system to meet demand while concurrently evaluating the impacts on the environment, the socioeconomy and consumers,

Monitoring of Indicators and Assessment of Demand and Supply

Meanwhile, indicators of trends in water use (water use itself, population, employment) and leading indicators of changes in demand and supply (condition of local sources, events and proposed projects, laws, regulations, agreements, watershed conditions, climate, precipitation, streamflow, public views and building permits) are identified and monitored to determine whether or not supply adequacy is being affected. Periodic assessments of changes in supply and demand and a determination as to whether or not trigger points are being approached are undertaken. See Figures 10 and 11.

Programming of Studies and Actions

Depending on the outcome of the assessment, a program of studies and actions is reconfirmed or modified in order to ensure future supply adequacy. For example in the case where a trigger point is being approached, the MWRA may adopt aggressive demand measures in order to reduce the slope of the demand curve and to postpone or avoid triggers for supply augmentation projects. See Figures 12 to 14.

Figure 10

The New England Drought Study

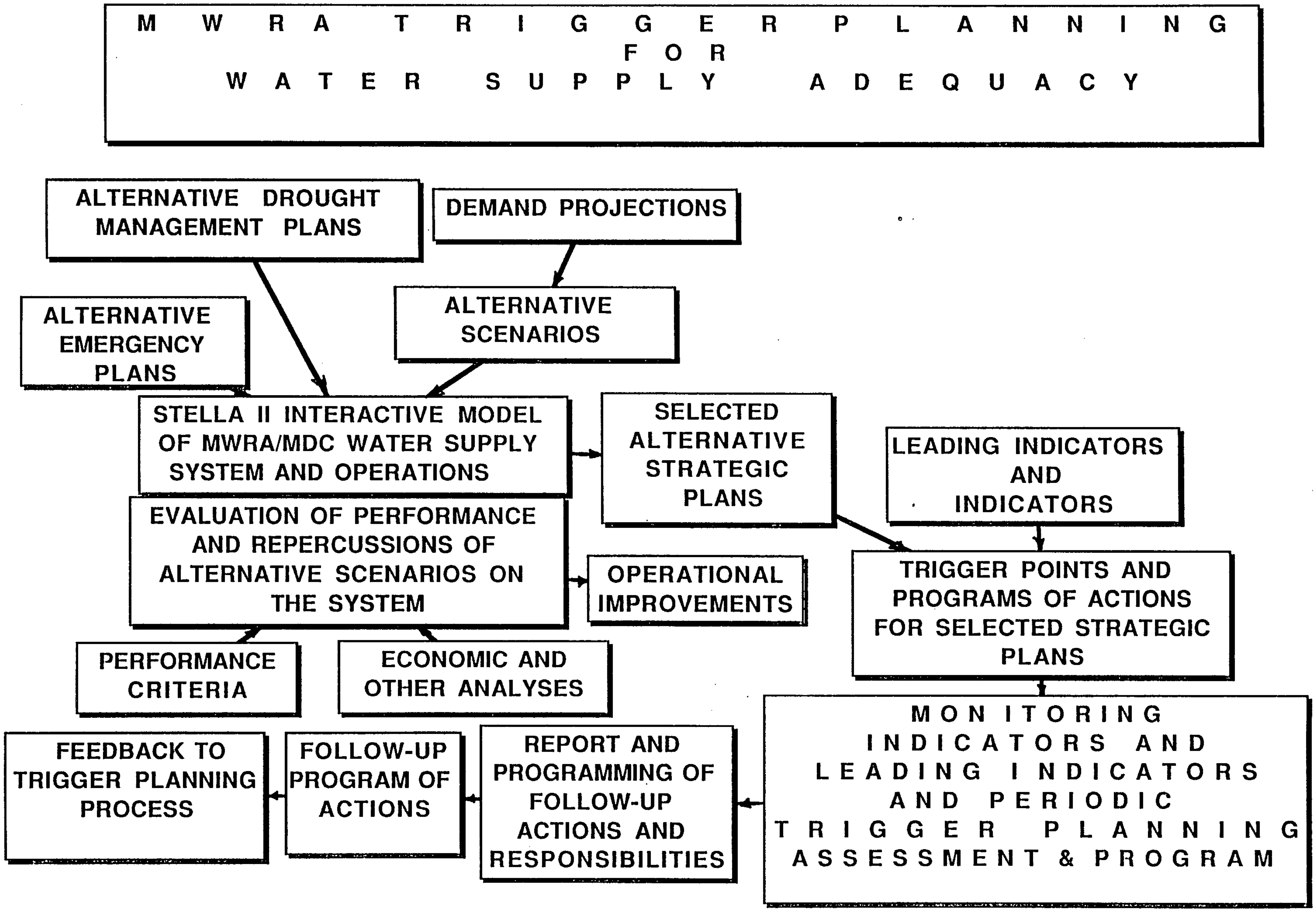


Figure 11
The New England Drought Study

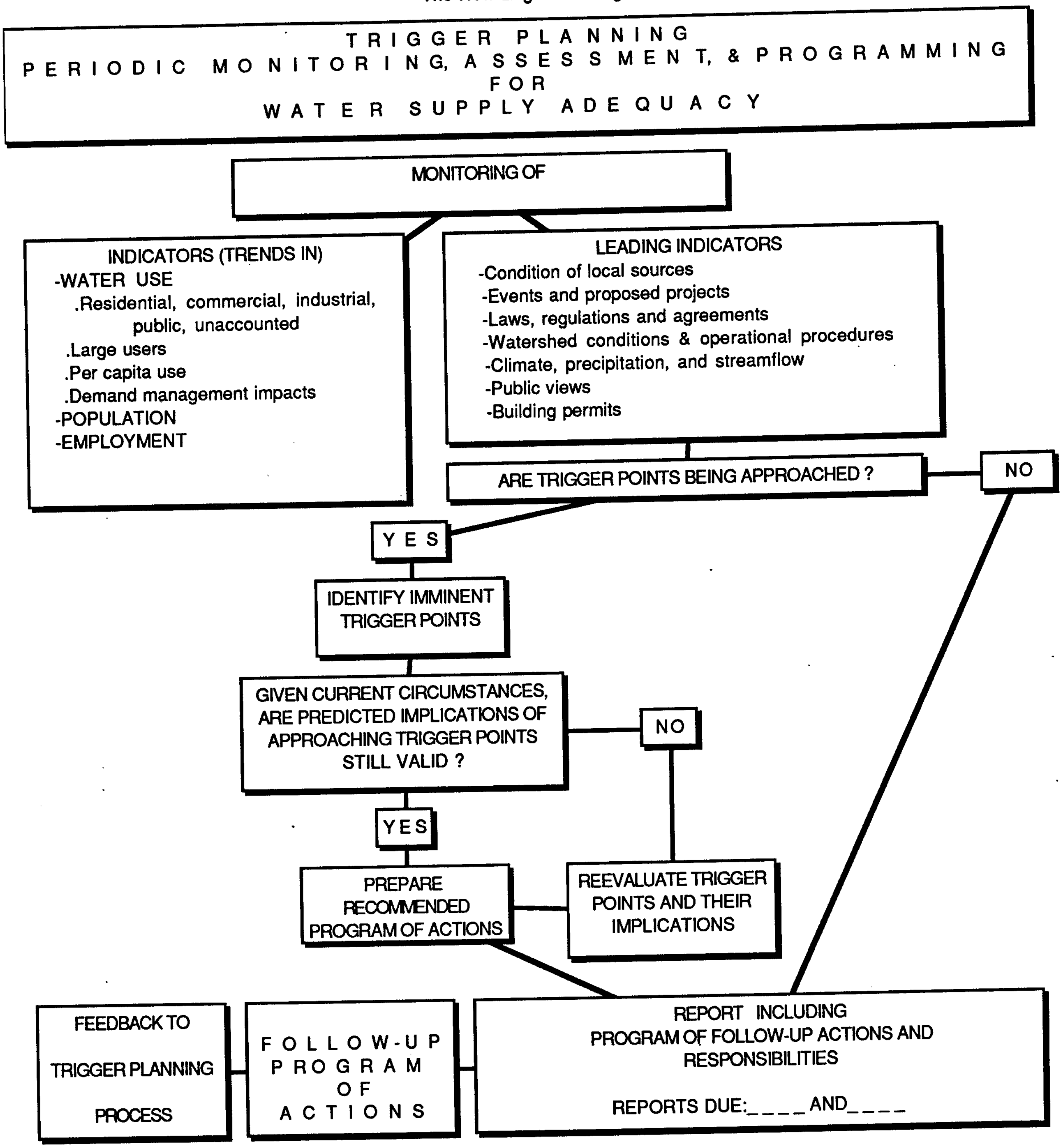


Table 13
The New England Drought Study

ALTERNATIVE PLANS TO BALANCE FUTURE SUPPLY AND DEMAND FOR THE MWRA/MDC WATER SYSTEM

			Implementation	C O S T S			($ Million)	
PLANS		Yield (mgd)	Time (Years)	Capital	O&M	Annual.	Annual/MG	
REACTIVATION SUDBURY RESERVOIR	(1)	16	9	25	1.2	3.5		($1991)
CONNECTICUT RIVER	(2)	63	15	120-220			0.5-0.8	($1989)
MERRIMACK RIVER	(2)	120	15	600			1.6	($1989)
MILLERS RIVER	(2)	38	15	135			0.9	($1989)

(1) Source: MWRA, Waterworks Division, The Future Role of the Sudbury Reservoir and Watershed in the MDC/MWRA Water Supply System - A Review of Alternatives, September, 1992, p. 16.
(2) Source: MWRA, MWRA Long Range Water Supply Program, January 24, 1990.

ADDITIONAL PREREQUISITE STUDIES

The present application of Trigger Planning underscores the need to monitor conditions at Quabbin Reservoir when target pool levels fall below the current target pool elevation of 490 feet (BCB). The monitoring program would follow ecological conditions during periods of drawdown at Quabbin Reservoir, in order to provide information on drawdown options for augmenting the yield of the system vis-a-vis the effects on water quality, and the environmental quality of the reservoir and surrounding area. There is also a need to assess the impact of drought actions on consumers, whether they be residential, industrial/commercial, municipal, etc. in order to evaluate the tradeoffs between the benefits and costs to system users of more stringent drought responses. The first stages of an additional study to evaluate the effectiveness of MWRA's demand management program in order to estimate where future conservation efforts should be concentrated has been completed using IWR MAIN 6.0. IWR MAIN can be used to disaggregate the contributions of different factors such as demand management, the price of water and the changing and depressed economy, in the decline in system water use from 334 mgd in 1987 to 257 in 1992.

ILLUSTRATIVE EXAMPLE

An analysis has been conducted in order to demonstrate the methodology for determining the nature of actions and when they should be taken with respect to ensuring supply adequacy. The methodology consists simply of determining when projected estimates of future supply would be inadequate to satisfy demand and then determining the nature and schedule of studies or actions in order to avoid a supply shortfall. For illustrative purposes, the analysis assumes that the system would be inadequate to meet projected demand or would achieve its critical point at demands of 300 and 320 mgd.

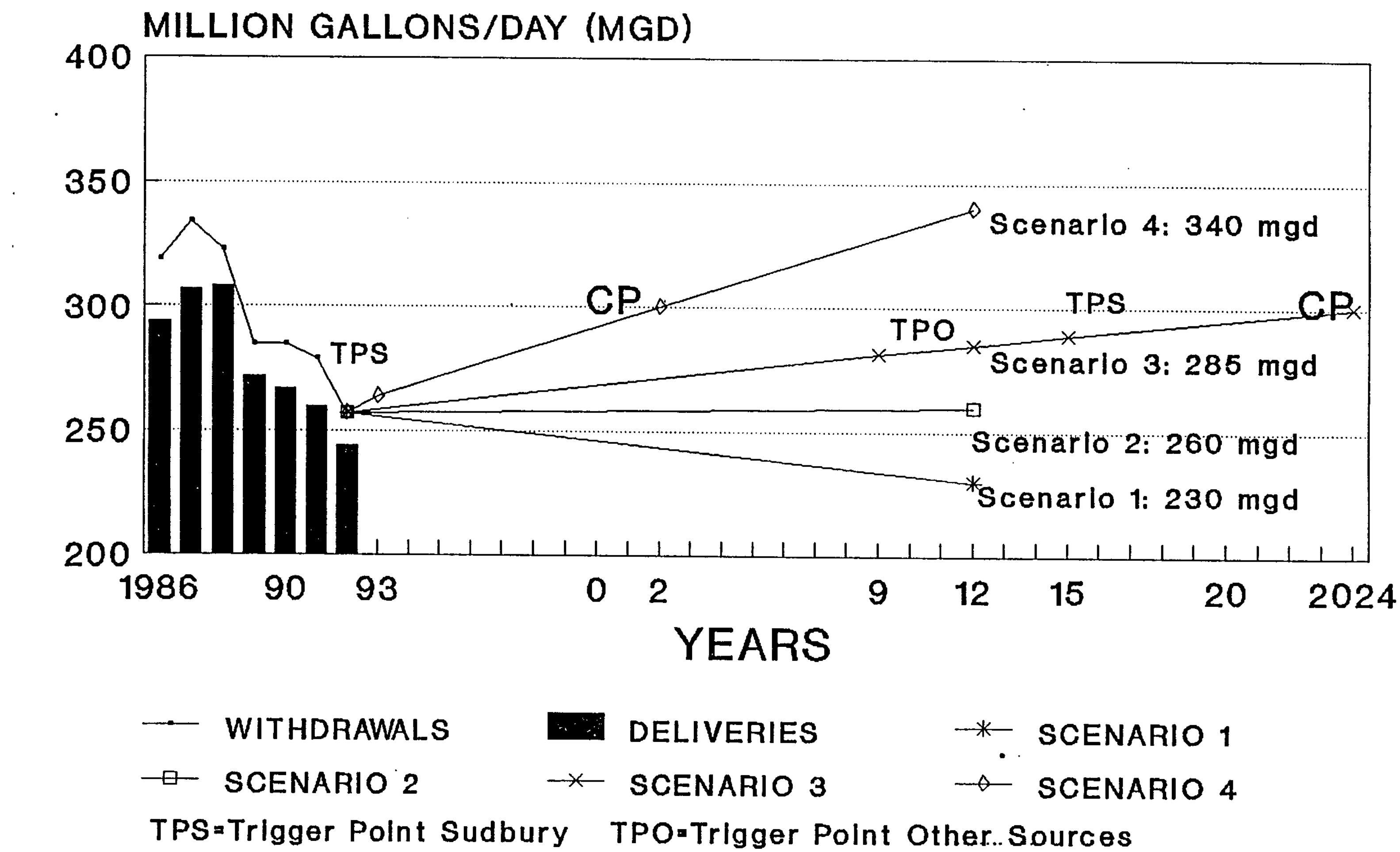
Figure 12 assumes that the critical point for the system is 300 mgd. Under this assumption, Scenarios 1 and 2, with projected demands in the year 2012 of 230 and 260 mgd would never achieve the critical point. Scenario 3, with a projected demand of 285 mgd in 2012 and rising, would achieve a critical point of 300 mgd in the year 2024. Scenario 4, with a projected demand of 340 mgd in 2012, would reach the critical point at 300 mgd in the year 2002.

Figure 13 assumes that the critical point for the system is 320 mgd. Again under this assumption, Scenarios 1 and 2 would never reach the critical point. Scenario 3, with a projected demand of 285 mgd would reach the critical point in the year 2040. Scenario 4, with a projected demand of 340 mgd in 2012, would reach a critical point in the year 2007.

Assuming lead times of 9 and 15 years respectively for the Sudbury alternative and the other alternatives (Connecticut, Merrimack and Miller River Basins), the trigger points for Scenario 3 are well out into the future between the years 2009 and 2031. If demand increases as markedly as the annual rate of 4 mgd in Scenario 4, then there would be sufficient time to implement only the Sudbury alternative.

Figure 12
The New England Drought Study

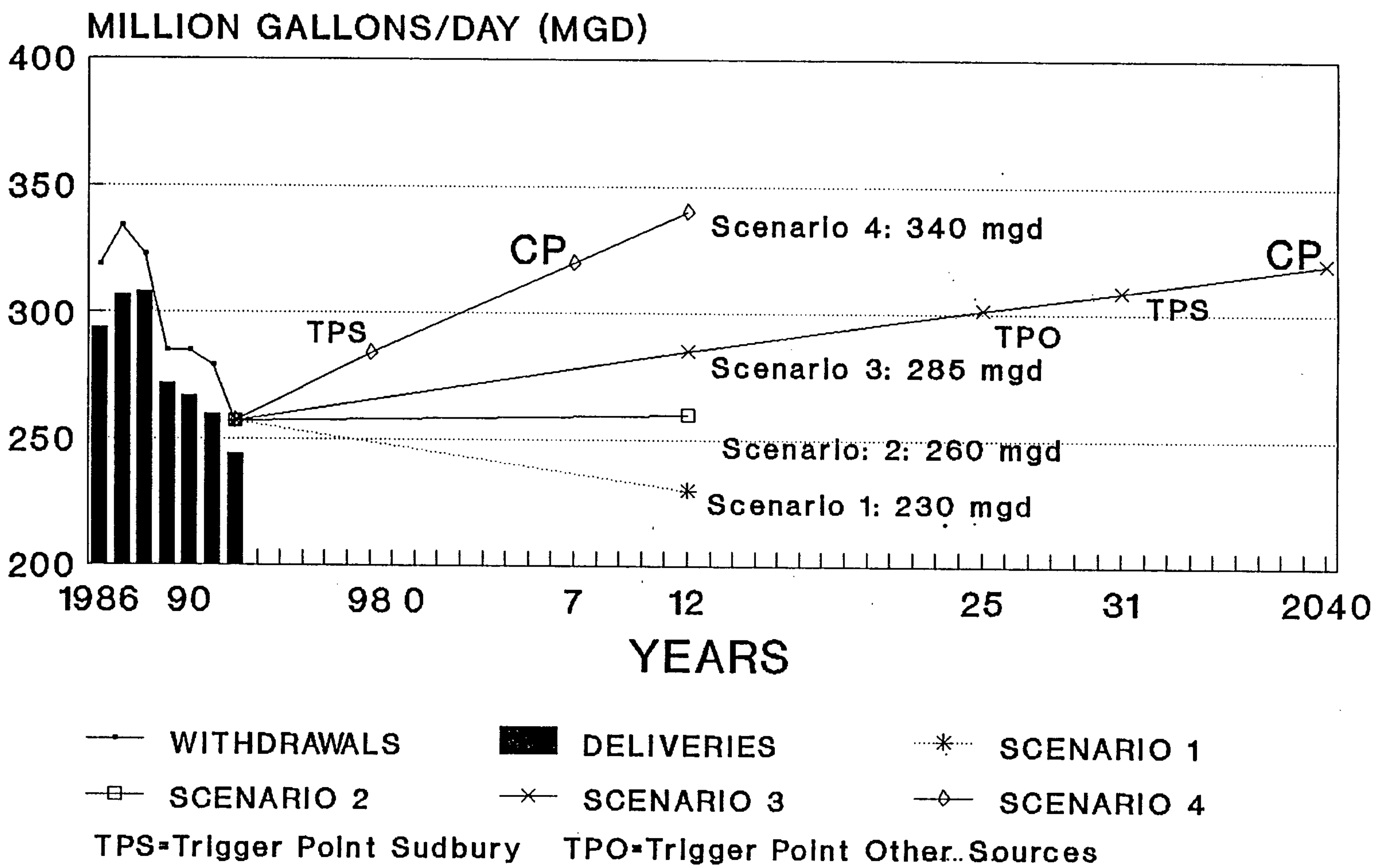
MWRA/MDC WATER DEMAND PROJECTIONS & TRIGGER POINTS ASSUMING CRITICAL POINT (CP) AT 300 MGD



SOURCE:New England Drought Study MWRA32C

Figure 13
The New England Drought Study

MWRA/MDC WATER DEMAND PROJECTIONS & TRIGGER POINTS ASSUMING CRITICAL POINT (CP) AT 320 MGD



SOURCE:New England Drought Study MWRA32B

Aggressive Demand Management

As an initial response to system demand approaching trigger points, the MWRA would launch into more aggressive demand management actions in order to postpone, or possibly avoid, a trigger point for supply augmentation. Figure 14 presumes a situation subsequent to 1992 when water demand is edging towards the assumed critical point of 300 mgd. Beginning in the year 2000, system managers would launch an aggressive demand management program aimed at progressively modifying the slope of the system use away from the critical point.

No Action on Supply Augmentation

Figures 15 presents a summary schematic of the schedule of programs and actions assuming the critical point is far into the future and beyond the lead times of the considered supply augmentation alternatives. In this case the MWRA would pursue the actions in MWRA's Long Range Water Supply Program. Figure 3 provides additional details on the programs.

Continuing Actions for Supply Adequacy

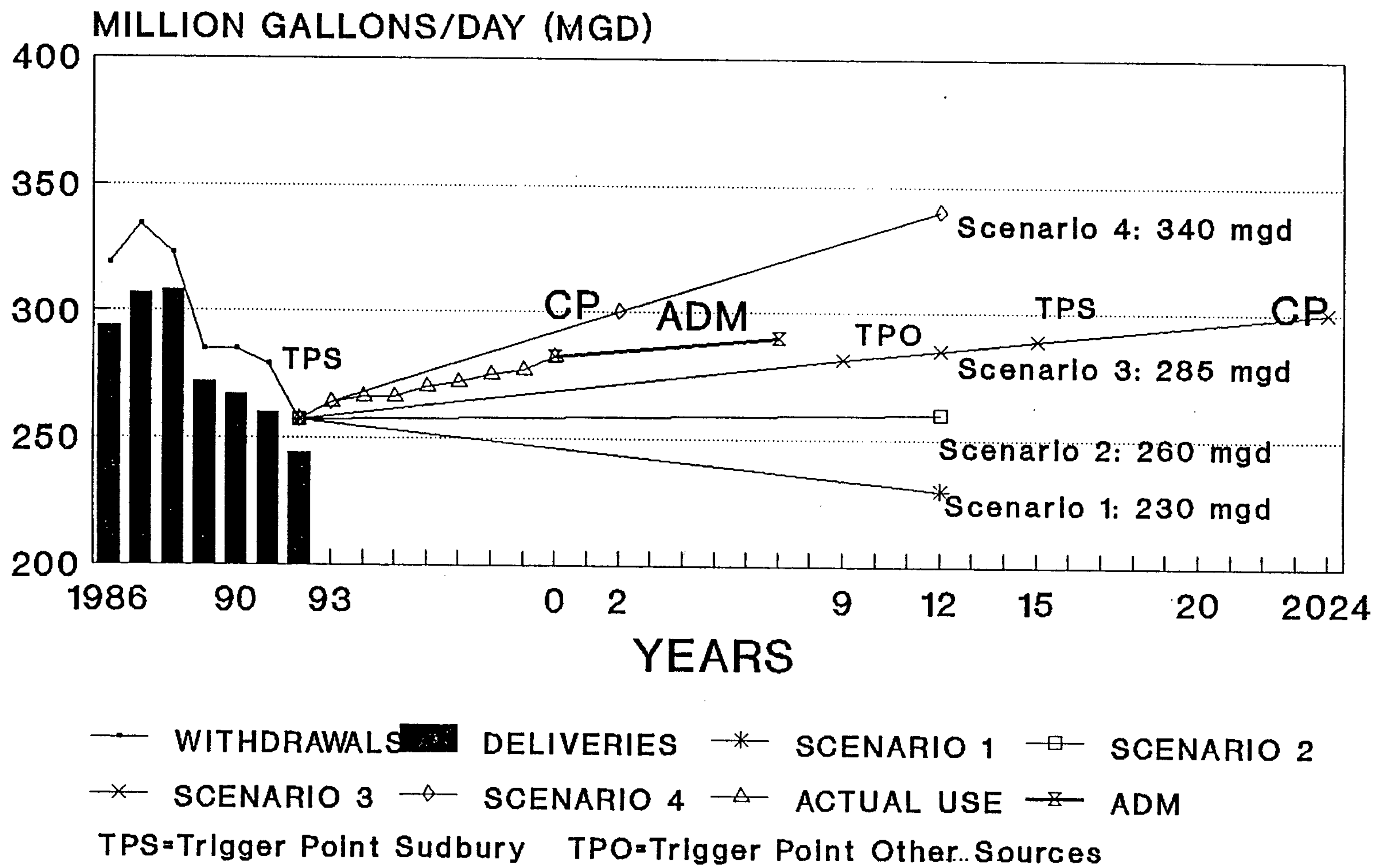
Figure 16 presents the situation in which the supply system is approaching a critical point that is less than fifteen years in the future. Initially MWRA would initiate a more aggressive demand management program, which could lead to the avoidance of the critical point. In this case no action on supply augmentation would be necessary and managers would continue to pursue actions to promote supply adequacy. In the event that the impending critical point cannot be avoided, actions would be undertaken at the trigger point to address the predicted shortfall.

Typical Schedules of Studies

Figures 17 and 18 present schematics for the required studies and actions and lead times for the Sudbury alternative and other alternatives for supply augmentation.

Figure 14
The New England Drought Study

MWRA/MDC WATER DEMAND WITH AGGRESSIVE DEMAND MANAGEMENT (ADM) TO AVOID NEARING ASSUMED CRITICAL POINT (CP) AT 300 MGD



SOURCE:New England Drought Study MWRA32D

Figure 15
The New England Drought Study

MWRA/MDC WATER SYSTEM - SUMMARY SCHEDULE OF STUDIES AND ACTIONS FOR PLANNING FUTURE SUPPLY ADEQUACY

ASSUMING THAT THE CRITICAL POINT IS FAR INTO THE FUTURE AND BEYOND THE LEAD TIMES OF CONSIDERED SUPPLY AUGMENTATION ALTERNATIVES

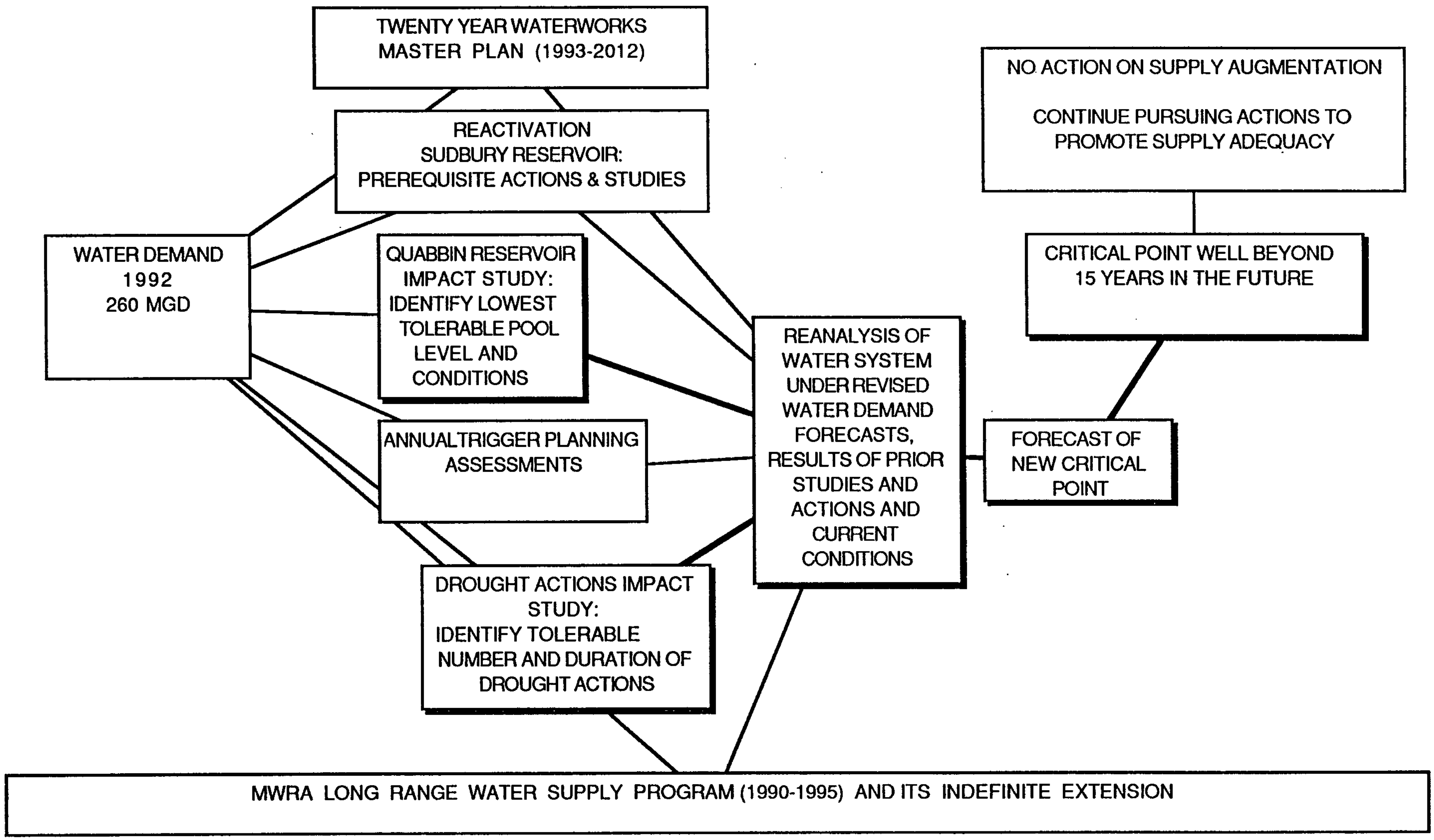


Figure 16
The New England Drought Study

MWRA/MDC WATER SYSTEM - SUMMARY SCHEDULE OF STUDIES AND ACTIONS FOR PLANNING FUTURE SUPPLY ADEQUACY

ASSUMING THAT THE CRITICAL POINT IS LESS THAN 15 YEARS IN THE FUTURE

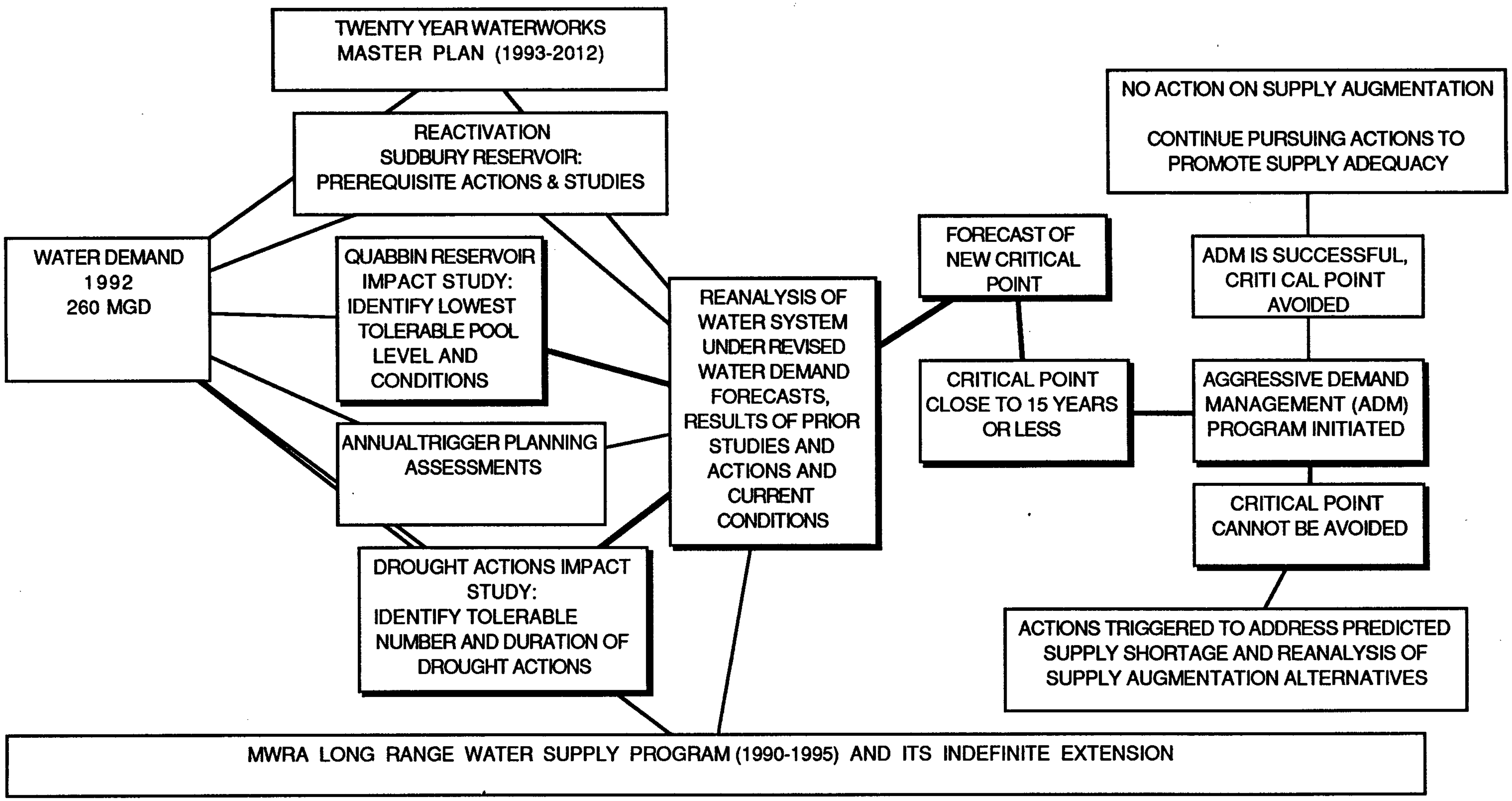


Figure 17
The New England Drought Study

MWRA/MDC WATER SYSTEM - SCHEDULE OF STUDIES AND ACTIONS TO IMPLEMENT REACTIVATION OF SUDBURY RESERVOIR

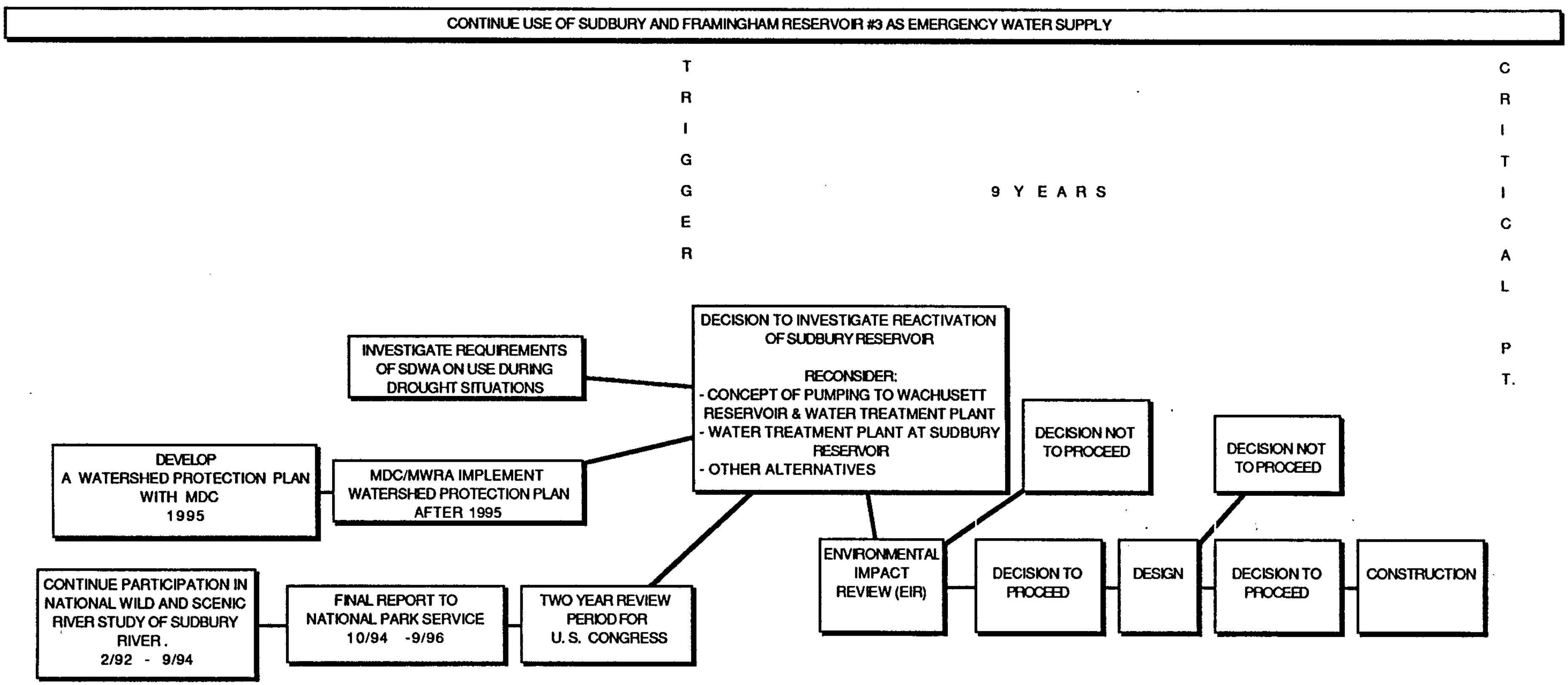
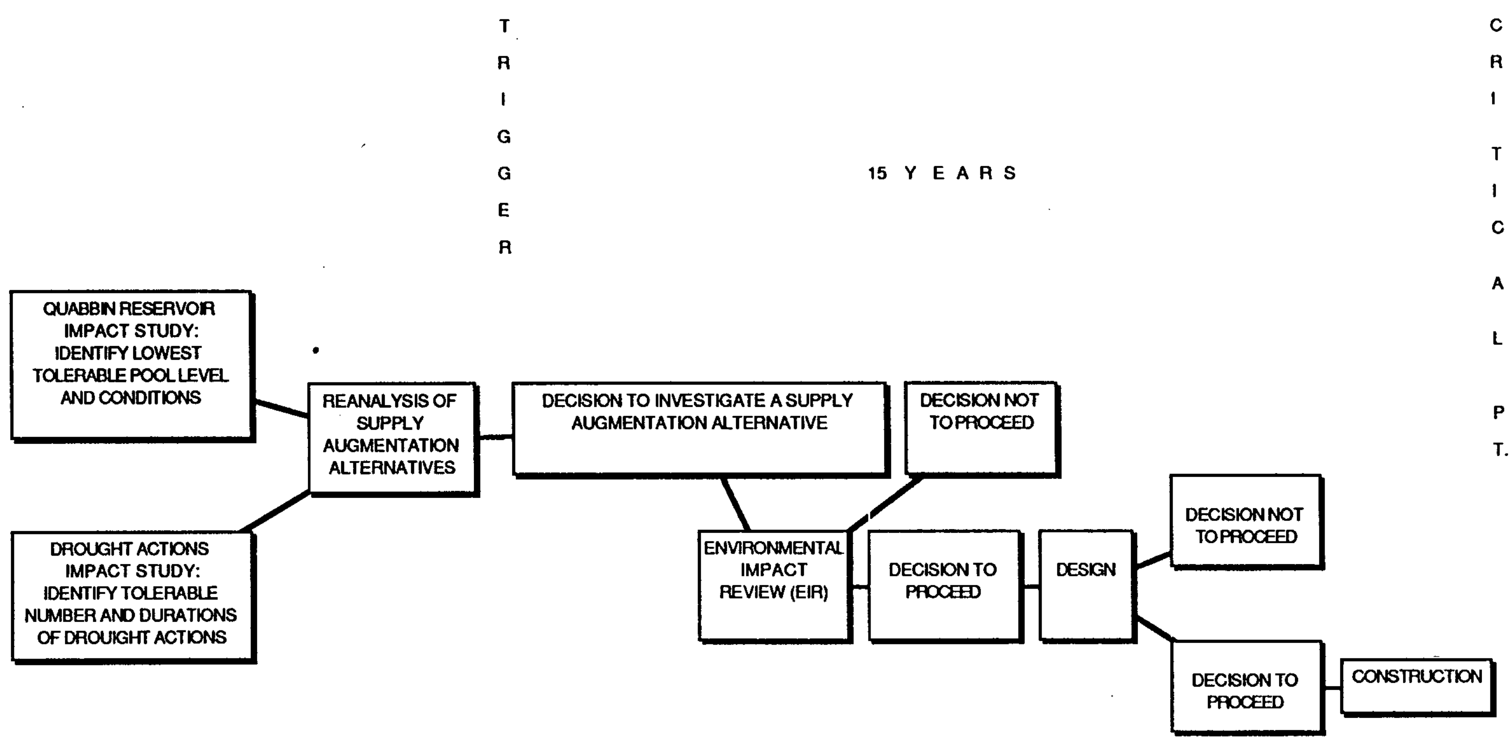


Figure 18

The New England Drought Study

MWRA/MDC WATER SYSTEM - SCHEDULE OF STUDIES AND ACTIONS TO IMPLEMENT A SUPPLY AUGMENTATION ALTERNATIVE



Chapter 12
RISK AND UNCERTAINTY

The present application of Trigger Planning aims to enhance the MWRA/MDC decision-making process relative to the studies and actions required to avoid future supply shortfalls for the MWRA/MDC Water System, while taking into account risk and uncertainty.

The MWRA has adopted the following definitions of risk and uncertainty. (8) *RISK* is defined as the probability of exceedence or non-exceedence of critical values of a particular variable. Since risk exists objectively in nature, in society or in technology based systems, it can be conceived in probabilistic terms whether or not it has been properly conceived by the investigator. Risk is investigator independent. *UNCERTAINTY* is the lack of knowledge on risk properties. Situations of uncertainty cannot be described in objectively known probability distributions. Uncertainty is investigator dependent. These definitions are not inconsistent with those of the Corps of Engineers. EC 1105-2-179 (1 September 1987) describes situations of *RISK* "...as those in which the probability of potential outcomes can be described in statistical terms with a reasonable degree of confidence." With respect to *UNCERTAINTY*, "...the probability of potential outcomes cannot be estimated with the required degree of confidence. Uncertainty is substantially more difficult to include in project analysis than risk."

Risk and uncertainty analysis is a decision framework that attempts to incorporate both the likelihood and the consequences of risk and uncertainty-bearing into the decision making framework. Risk and uncertainty analysis identifies, describes and analyzes potential sources of risk and uncertainty (R&U), applies alternative techniques and tradeoffs for minimizing them, and displays the results in a manner that makes it clear to decision makers the degrees of risk and uncertainty determined to characterize the situations.

POTENTIAL SOURCES OF RISK AND UNCERTAINTY FOR SUPPLY ADEQUACY

The following are potential sources of risk and uncertainty that can affect the adequacy of future supply in the system.

- Supply shortfall:

  - o uncertainty of estimates of future demand,
  - o uncertainty with respect to estimating future sources of supply,
  - o the risk that prerequisite studies and actions will not be undertaken in a timely fashion,

- o the risk that lower cost smaller projects with shorter lead times will not be favored,
- o the risk that drought management may not be as effective as prescribed, thereby adversely affecting the performance of the system and the adequacy of future supply,
- o the risk that demand management success would reduce the amount of water available for drought management with similar repercussions on the system as above,

- The MWRA/MDC and service area communities will not be prepared for drought,

- The consensus reached by the MWRA and WSCAC will not be representative of the interests of the MWRA/MDC entities (Board of Directors, Advisory Board and member communities), citizen and citizen groups and environmental and regulatory agencies.

- Decision-makers will transfer unacceptable levels of risk to certain groups.*

- Unacceptable levels of residual risk and the creation of new risks.*

- Inadequate data and understanding of the data.*

- Data, model, parameter and other types of uncertainty.*

- Adverse effects on environmental, and historical and cultural resources.*

* Not addressed in present study.

RISK AND UNCERTAINTY TECHNIQUES

The Institute for Water Resources prepared a report in two volumes entitled Guidelines for Risk and Uncertainty Analysis in Water Resources Planning (March 1992) the report proposes the following techniques for dealing with risk and uncertainty.

- collect more data to reduce measurement error,

- use more refined analytical techniques,

- increase safety factors in design,

- select alternatives or components of alternatives with better known performance characteristics,

- avoid or reduce irreversible or irretrievable commitments of resources, incremental strategy.

- use sensitivity analysis and risk analysis methods in the evaluation of the benefits and costs of alternatives,
- account for decision-makers' and different publics' propensities to risk,
- explicitly present assumptions used in the analysis and justify their use,
- identify all key variables,
- specify risk and uncertainty objectives,
- use creative display techniques to help analyze risk and uncertainty,
- use probability theory,
- use statistical techniques,
- use sampling techniques
- use forecasting methods,
- use decision rules,
- use decision trees,
- use rules of thumb.

INADEQUATE FUTURE SUPPLY

It is uncertain whether the supply of water to the MWRA/MDC Water System will be sufficient to satisfy demand in the year 2012. This uncertainty stems from the projected estimates of demand and supply and whether the prerequisite studies and actions will be in place to ensure supply efficiency. Because of this uncertainty, there is a risk that the MWRA may not correctly anticipate future system demand, thereby risking a shortfall in supply. In addition, the MWRA has imposed the condition that lower cost and shorter lead actions and projects be favored.

R&U of Estimates of Future Demand and Supply

The average daily water demand on the MWRA system recently has declined from 334 mgd in 1987 to approximately 260 mgd in 1992 as a result of demand management measures undertaken by MWRA, lower water use due to the changing and depressed economy and in response to price increases. This present study has projected demand in the year 2012 under four scenarios:

1	Stagnant economy with great demand management success:	230 mgd
2	Periods of economic growth with demand management success:	260 mgd
3	Moderate economic growth, contamination of local sources:	285 mgd
4	Significant economic growth, contamination of local sources:	340 mgd

The analysis also includes projections at 300 and 320 mgd, which are in the range of estimates of the safe yield of the water system. The estimates are based on the implementation of the MWRA Twenty Year Waterworks Master Plan (1993-2012) which would reduce demand between 11 and 53 mgd, depending largely on the success of the programs to reduce demand on the system (demand management and conservation, improved use of sources, water supply protection, etc.). See Table 4.

Superimposed on MWRA efforts are conditions outside its control due to economic conditions, precipitation patterns and the contamination of a local source of water currently used by one of MWRA's partially supplied communities or by a community adjacent to the current service area. A high risk to supply sufficiency is that the contamination of a local source would cause the community to request full supply from the MWRA. Total water use for the 14 partially supplied communities is approximately 90 mgd of which MWRA supplied only 12 mgd in 1992. The highest individual demands are between 15 and 25 mgd. In addition, 27 communities adjacent to the MWRA service area could possibly request service from the MWRA. A study (9) conducted in 1992 estimated that the combined safe yield of the surface and groundwater sources is about 93 mgd while the average daily demand of these communities is projected to rise from 57 mgd in 1990 to 70 mgd in 2020. The highest adjacent community uses are projected to rise from 4 to 7 mgd for the same period. Three of these communities, in addition to Bedford which is partially supplied through Lexington, have average daily demand to safe yield ratios greater than one and a fourth community is expected to exceed one by 2020.

Possibly the worst single event with respect to the threat of adequacy of supply for the MWRA/MDC Water System would be the contamination of one of the sources in one of the partially supplied communities because of the suddenness with which it could occur. Such an event involving the city of Cambridge would add about 15 mgd to the 1992 demand of 260 mgd for a total of 275 mgd. The contamination of Worcester's sources would augment demand by about 25 mgd taking demand to 285 mgd, but this is very unlikely since the city plans to increase the protection of its supplies. Contamination during a period of rising demand could particularly stress the system. MWRA is currently employing risk management techniques in the form of programs to monitor and protect existing supplies, by providing technical assistance to communities partially supplied by the MWRA for the protection of their supplies and to non-MWRA communities for the prevention of supply contamination.

The risk of a supply shortfall due to a steady increase in demand is also a possibility. The MWRA is currently using techniques to reduce risk and uncertainty by adopting an application of Trigger Planning to manage the water system in order to prevent the need for new sources of supply and concurrently to make timely decisions if shortfalls in supply occur or are likely to occur despite MWRA's best efforts to prevent them. The present application of Trigger Planning includes risk and uncertainty mitigation techniques to closely monitor changes in demand and supply, employ alternative forecasts of demand and supply, and use sensitivity analysis with the help of the STELLA II interactive model of the water system, and to use decision rules and decision trees.

However, MWRA's withdrawal of water from sources has dropped dramatically by 77 mgd from 334 mgd in 1987 to about 257 mgd in 1992. MWRA staff estimates that approximately two-thirds of the decline was due to demand management and the other third to the price of water and changes in the regional economy. If the MWRA were to fail to monitor an increase in demand or to act to avoid an impending shortfall in demand then it is conceivable that demand could rise by 40 to 50 mgd over say a five year period.

Considering the risk and uncertainty management techniques discussed above and assuming their continued employment by the MWRA, there is a very low risk of a supply shortfall due to a gradual or sudden increase in demand on the system. However, failure on the part of the MWRA to use these techniques and to act on them or to provide the appropriate resources to undertake these programs, could substantially increase the risk of shortfalls in supply.

Prerequisite Studies and Actions

There is little risk that the prerequisite studies and actions necessary to ensure supply adequacy will not be undertaken by the MWRA. In 1990, the MWRA Board of Directors adopted the recommendation of the report prepared by the MWRA and entitled, MWRA Long

Range Water Supply Program (LRWSP) to postpone the decision on the development of a new supply until 1995. The Board also approved a five year program to reduce demand and enhance supply: demand management, improved use of existing and new local sources, source protection, and management and planning for the future. MWRA's Waterworks Division reports to the Board yearly on the progress of the program and on the status of demand and supply. The second annual report, dated 21 October 1992, reported that average demand in 1992 had decreased to 260 mgd and that for the third consecutive year demand has remained below the system's safe yield of 300 mgd. "Although it appears that a fairly comfortable margin exists between supply and demand, it would be premature to claim full success and call the job complete based on these short term results." (10)

Meanwhile, the 1992 report reviewed the program of studies listed in the five year program and presented on Figure 3. The implementation of the five year program appears generally to include the full range of studies and actions to reduce demand while protecting and enhancing the sources of water for the system. However, the Trigger Planning effort, which is the object of this present report, has identified the need for two additional studies. The first is to monitor conditions at the Quabbin Reservoir when pool levels fall below the current target pool elevation of 490 feet (BCB). The monitoring program would provide information on drawdown options to increase yield in relation to water quality and ecological conditions at the reservoir and the surrounding area. In addition, there is a need to assess the impact of drought actions on consumers, whether they be residential, industrial, commercial, municipal, etc..Tradeoffs would be evaluated between the benefits to system yield from earlier and more stringent drought responses, and the pain, from these actions, on consumers.

Favoring of Lower Cost and Shorter Lead Time Projects

There is little risk that lower cost, shorter lead time projects will not be favored by the MWRA to promote supply adequacy. The MWRA five year program of studies and actions in its Long Range Water Supply Program: 1990-1995, has been designed specifically to permit the MWRA to undertake less costly non-structural measures to reduce the demand on the system while enhancing supply in order to forestall or preclude the development of costly supply augmentation alternatives. The program adheres to this mandate.

Effectiveness of the Drought Management Plan

The MWRA/MDC Drought Management Plan (see Chapter 3) calls for reductions between 5% and 30% depending on the stage in Quabbin Reservoir. Figures 4 through 8 amply demonstrate the enhanced performance of the MWRA/MDC Water System as a result of the timely application of drought response measures. Given the MWRA/MDC Water System with its over year storage, the success of drought management in conserving water for later periods will effectively permit the system to extend its adequacy to higher levels of demand. Failure to execute or to fully execute the required measures to reduce demand would lower the performance of the system and make it less adequate to satisfy future demand. Tables 8 to 12 present the results of the performance of the water system with 100 percent and 50 percent drought management success and without drought management. For example, the number of consecutive months that the Quabbin pool would be below the target pool of 490 feet would be 9 months with 100 percent drought management success (Table 8) and 82 months without drought management at a system demand of 300 mgd (Table 10).

Demand Management Success

There is a risk that demand management success may diminish the ability of system managers to respond to drought. Certain actions, such as the reduction of water use by large users, are common to both demand and drought management. As demand management becomes part of normal operations of the MWRA/MDC Water System, the amount of water use reduction that could be anticipated from drought actions may be decreased, thereby trimming the potential reductions that could be expected from the implementation of the Drought Management Plan. In order to gain the long term benefits to system adequacy from drought management because of the integration of strategic and drought contingency planning, system managers may call for more frequent and/or more stringent drought actions than are included in the current Drought Management Plan. If reductions in demand are not forthcoming, then the water system will be less capable of meeting future demands at the expected levels of performance.

LACK OF PREPARATION FOR DROUGHT

Trigger Planning integrates strategic, drought contingency and emergency through the use of the STELLA II interactive model of the system into a single managerial strategy aimed to ensure that future sources of water are sufficient to meet demand. The model assumes that both MWRA and community water system managers take the appropriate actions to ensure that demand reductions are actually made as the Quabbin Reservoir enters the different drought stages. The MWRA/MDC Drought Management Plan calls for reductions between 5% and 30% depending on the stage in Quabbin Reservoir. Drought management plans have also been prepared by the system communities, as required by the Department of Environmental Protection (DEP). In Massachusetts, DEP is
responsible for the issuance of declarations of water emergencies. DEP is also authorized to

require that suppliers remedy the causes of water shortages, including improved planning, conservation, demand management, system improvements and temporary restrictions.

The experience of the DEP, MWRA and MDC in responding to three more recent threats to drought (1981, 1985, and 1989), as described in the report, THE NEW ENGLAND DROUGHT STUDY: Water Resources Planning for Metropolitan Boston, Massachusetts (January 1994), demonstrates that procedures are in place to activate the Drought Management Task Force. The Task Force is a ad hoc state-wide committee convened by the Secretary of the Executive Office of Economic Affairs (EOEA) when the need arises. Participants are representatives of the EOEA agencies including DEP, DEM, etc., municipal and industrial water providers such as the MWRA, and those entities likely to be involved drought response actions. As the threat of a potential water shortage, caused by a precipitation deficit or other reason, presented itself, the Task Force would monitor the situation and take action as prescribed in the Drought Management Plan. Given this experience there is little risk that the MWRA and its service communities would be ill-prepared for drought for procedural reasons.

Again the integration of strategic and drought contingency planning permits the strengths and weaknesses of one to be transferred to the other. Ineffective strategic planning can result in a system that is under stress in periods of precipitation adequacy and worse still, a system, that has been so weakened in periods of water shortage, that it is unable to respond effectively to drought.

RISK OF NON-REPRESENTATIVE CONSENSUS

There is a risk that consensus developed early on in the planning process will not hold as communities and interest groups become more involved as actions move closer to implementation. This report on the implementation of the present application of Trigger Planning, in order to ensure future supply adequacy at the MWRA, is the product of a two year collaborative effort among Study Team staff from the MWRA Waterworks Division, WSCAC and NED. Reviews by their respective organizations will ensure consensus among these parties to the limit of their respective organizations.

It is intended that the results of the study be reviewed by the 67- member MWRA Advisory Board, 60 of whom represent all of the communities receiving water and sewer services from the MWRA and later by the 11- member Board of Directors, with 5 MWRA communities being represented directly and up to 3 indirectly through membership on the Advisory Board. The 60 community membership retains 95 percent of the voting strength of the Advisory Board.

See Table 14. Eventually the MDC and the Massachusetts DEP would also be apprised of the results of the study and invited to provide input to the Trigger Planning process.

WSCAC's 1992 roster comprised forty-one members consisting of scientists, attorneys, public policy advocates, elected officials, etc.representing community, regional, state, river basin, academic, environmental, health and private sector interests. Theoretically, it is the broadest based of the interest groups. Geographically, it's membership covers Massachusetts and Connecticut with some members having New England-wide interests and also represents the major Massachusetts river basins. WSCAC is particularly sensitive to the impact of MWRA policy on river basins, the equitable use of water, and on the environment. Its active membership has a particular interest in safeguarding the resources of the Connecticut River Basin. Because of its early intervention in the planning process, the knowledge of its active membership on water resources policy issues and their skill in interacting with the political process, WSCAC plays a significant role in water resources policy-making in Massachusetts and in the MWRA/MDC Water System. Generally, the MWRA and WSCAC develop consensus early in the planning process, while for member communities their influence is most noticeably exerted towards the end of planning and prior to implementation. There is a risk that consensus between the MWRA and WSCAC early in the planning process on issues related to future supply adequacy may not command the attention of communities in the MWRA service area individually, or through their representation on the Advisory Board and Board of Directors and lead to a realization much further along in the planning process, that the prior consensus is not in their interests.

SUMMARY RISK AND UNCERTAINTY ANALYSIS

Table 15 presents a summary of the risk and uncertainty analysis of Trigger Planning for the adequacy of sources of supply for the MWRA/MDC Water System. The proposed Trigger Planning process enhances and systemizes current planning for future supply adequacy. The amount of residual risk of future supply inadequacy is acceptable. However, the successful implementation of Trigger Planning depends on the will of MWRA to institutionalize the program by committing the required resources to the program and assigning the appropriate staff whose performance standards reflect this commitment.

Table 14
The New England Drought Study
MWRA BOARD OF DIRECTORS AND ADVISORY BOARD MEMBERSHIPS

	Total Membership	MWRA Service Community Membership	Other Membership	
Board of Directors	11	5	1	Sect. EOEA
			3	Advisory Board*
			1	Connecticut River Basin
			1	Merrimack River Basin
Advisory Board	67	60**	1	Connecticut River Basin
			1	Quabbin/Ware Watersheds
			1	Wachusett Watershed
			1	Metropolitan Area Planning Council
			1	Environmental Expert
			2	Recreational or Commercial Boston Harbor

Community members could be appointed to the Board of Directors.

** Represent 46 communities provided with sewer and/or water service and 14 communities provided with sewer service only.

Source: MWRA Waterworks Division

Table 15
The New England Drought Study
SUMMARY OF RISK AND UNCERTAINTY (R&U) ANALYSIS
TRIGGER PLANNING FOR SOURCES OF SUPPLY ADEQUACY
FOR THE MWRA/MDC WATER SYSTEM

R&U Issues	Current R&U Reduction Techniques	Additional Trigger Planning Techniques	Residual Risk
INADEQUATE SUPPLY			**ACCEPTABLE IF TRIGGER PLANNING INSTITUTIONALIZED**
- Estimates of future demand and supply	Monitor demand & supply	Water system data base	
	Alternative forecasts	Integration strategic drought emergency planning	
	Worst case scenario	Leading indicators	
	Worst single event	Performance measures and criteria	**UNACCEPTABLE IF TRIGGER PLANNING IS NOT IN PLACE**
		Interactive modeling STELLA II	
		Improved demand projections	
		Consensus building	
		Decision rules and trees	
- Prerequisite studies and actions	See Twenty Year Master Plan		
- Favoring of lower cost shorter lead time projects	See Twenty Year Master Plan		
	See Long Range Water Supply Program: 1990-95		
- Effectiveness of drought mgmt.	See MWRA/MDC Drought Management Plan	See Tables 8 to 12 and Figures 3 to 7 for positive effects of strategic planning	
- Demand management success		Forecast scenarios do not assume high demand management success. See Table 7.	

Table 15 (continued)

NOT PREPARED FOR DROUGHT			**ACCEPTABLE**
	See MWRA/MDC Drought Management Plan	See Tables 8 to 12	
		Integration of strategic, drought, and emergency planning shows positive effects of drought mgmt.	
UNREPRESENTATIVE CONSENSUS			
	WSCAC provides input to water resources planning	Analysis of risk to different parties	**ACCEPTABLE**
	Review of MWRA proposals by Board Directors and Advisory Committee	Identification of need for communities to participate early in the planning process	

Chapter 13
ACKNOWLEDGEMENTS

The New England Division, U.S. Army Corps of Engineers prepared this report under the direction of Colonel Brink P. Miller, Division Engineer, It was prepared by Charles L. Joyce, Project Manager, under the supervision of John Kennelly, Chief, Long Range Planning Branch, John Craig, Chief, Basin Management Division and Joseph L. Ignazio, Director of Planning.

This document reports on the New England Drought Study, which is a component of the National Study of Water Management During Drought directed by Kyle Schilling, Director of the Institute for Water Resources and managed by William Werick with the assistance of Germaine Hofbauer.

The report documents the work of a Study Team, consisting of MWRA, WSCAC and NED staff to develop techniques to enhance MWRA's decision-making with respect to water resources planning. In particular, the Study Team was entrusted, through consensus, to develop a Trigger Planning process for ensuring that water supplies are adequate to meet projected demand by identifying early actions that should be taken to avoid supply inadequacy. Team Members generally met monthly at the MWRA Waterworks Division offices at 100 First Avenue at the Charlestown section of Boston and sometimes more frequently from the Fall of 1991 to early 1994. Meetings were organized around agendas, meeting minutes and follow-up responsibilities and facilitated by the use of the STELLA II software portrayal of the MWRA/MDC Water System and its functions. The following persons served on the Study Team.

<u>MWRA, Waterworks Division, Capital Engineering and Development Dept.</u>
Stephen Estes-Smargiassi, Program Manager
Daniel Nvule, Project Manager,
Jonathan Yeo, Project Manager,
Andrew Hildick-Smith, Resource Conservation and Management Department, participated in several of the monthly team meetings.

<u>WSCAC</u>
William G. Elliott, Co-director,
Robie Hubley, Member,
Eileen Simonson, Co-director

NED
Charles L. Joyce, Project Manager, The New England Drought Study

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This report was prepared for publication by Anna Parfenuk.

NOTES

1. Water Supply Citizens Advisory Committee (WSCAC): Hubley, Robie; Elliott, William; Simonson, Eileen; and Hartman, Elaine, "Description of Trigger Planning" June 1986.

2. Massachusetts Water Resources Authority (MWRA), MWRA Long Range Water Supply Program, Progress Briefing, 12 June 1991.

3. MWRA, "MWRA Water System" Undated brochure.

4. WSCAC, "The WSCAC Perspective", 11 October 1985.

5. U.S. Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources, The National Study of Water Management During Drought, Report of the First Year of Study, Ft. Belvoir , Virginia, February 1991, pp B-3, B-4.

6. MWRA, MWRA Long Range Water Supply Program, Program Briefing, 21 October 1992, p.36.

7. Ibid., p.38.

8. MWRA, "Memorandum: Subject: Trigger Planning Selection Committee Meeting", 8 June 1989. Appendix B, p. B-1.

9. Stone and Webster Civil and Transportation Services, Inc., Study of Local Sources of supply in Non-MWRA Supplied Communities - Summary Report, October 1992, pp1-1 to 3-8.

10. MWRA, MWRA Long Range Water Supply Program, Program Briefing 21 October 1992, p.i.

APPENDIX A

EXISTING CONDITIONS: THE MWRA/MDC WATER SYSTEM

Appendix A
EXISTING CONDITIONS: THE MWRA/MDC WATER SYSTEM

The MWRA/MDC Water Supply System is a wholesaler of potable water currently serving approximately 2.5 million people in 46 communities primarily in the greater Boston area. The system has evolved over the past 350 years from rainwater and spring sources in 1652 serving an estimated 5,000 people in the city of Boston to a complex regional system consisting of reservoirs, transmission aqueducts and tunnels, distribution storage facilities, etc. fully supplying 31 communities and partially providing 15 others.

Since the MWRA became operational in 1985, the water system has been operated as a partnership with the MDC responsible for the watersheds and reservoirs and with the MWRA planning, managing and operating the remainder of the system including the transmission system, pumping and hydroelectric stations, and distribution reservoirs. The communities served own and operate and maintain their own distribution systems.

Figure 1 in the main report presents a map of the principal structural components of the Water System, as well as the communities served by the system. The water supply comes principally from the Quabbin and Wachusett Reservoirs located respectively 65 and 32 miles west of Boston and also the Ware River which has no storage capacity. During emergencies water can be supplied from Sudbury reservoir. The Quabbin Reservoir has a capacity of 412 billion gallons or approximately four years of supply at the current demand of approximately 260 mgd. Storage at Wachusett is about 65 billion gallons. Contributions to the 300 mgd safe yield of the system are approximately 53, 33, and 14 percent each for the Quabbin, Wachusett and Ware River watersheds. Water is transmitted by gravity beginning from a maximum elevation of 530 feet (BCB) at Quabbin Reservoir, and a seasonal supply from the Ware River by the 13-foot diameter, 24.6 mile long Quabbin Aqueduct to Wachusett Reservoir. From here it is delivered by a series of aqueducts and tunnels varying in diameter between 10 and 13 feet to feed fourteen distribution reservoirs or for direct delivery to community distribution systems.

SUPPLY SYSTEM

The supply system consists of three active sources: the Quabbin and Wachusett Reservoirs and the Ware River, and one inactive subsystem: the Sudbury System with four reservoirs and various treatment facilities. The characteristics of these supplies are presented in Table A-1.

Quabbin Reservoir

Table A-1 presents the characteristics of the sources of water for the MWRA\MDC Water System.

Table A-1
The New England Drought Study
MWRA/MDC WATER SYSTEM - WATER SOURCES

Source	**Watershed Area (Sq. Mi.)**	**Reservoir Volume (Billion Gals.)**	**Contribution To Safe Yield (mgd)**	**Status**
Quabbin Reservoir	185.9	412.2	158	Active
Wachusett Reservoir	107.7	65.0	101	Active
Ware River	96.8	None	41	Active
Sudbury System				
Sudbury Reservoir	22.3	7.2		Inactive
Reservoir No. 3	5.4	1.2		Inactive
Reservoir No. 2	46.0	0.5		Inactive
Reservoir No. 1	1.5	0.3		Inactive

Sources: MWRA, Twenty Year Waterworks Master Plan, 1992 and Drought Management Plan, Undated

The largest source of water for the MWRA system is the Quabbin Reservoir with a storage capacity of 412 billion gallons and a contribution of approximately 53 percent to the safe yield of the current system or an estimated 158 mgd. Located 65 miles west of Boston, the construction of Quabbin was completed in 1939 to impound the flow of the Swift River. Its water surface area is approximately 39 square miles and watershed area 186 square miles. Winsor Dam and Goodnough Dike impound water to a maximum elevation of 530 feet BCB (above the Boston City Base).

The principal releases from Quabbin Reservoir are made easterly via the Quabbin Aqueduct through the Wachusett Reservoir towards the major water use centers in the metropolitan Boston area. This aqueduct is also used to convey water westward from the Ware River. Releases are also conveyed through the Chicopee Valley Aqueduct to the fully supplied communities of Wilbraham, Chicopee and South Hadley. Water use for these three communities is about 12 to 14 mgd. The MWRA is also required to release approximately 20 million gallons water per day into the Swift River in accordance with a War Department Permit issued by the U.S. Army Corps of Engineers.

Briefly these requirements are:

Maintain a minimum flow release of 20 mgd (31 cfs) into the South Branch of the Swift River as measured at Bondsville.

In the period between June 1 and November 30, stream flows in the Connecticut River, as measured at Montague City, govern the minimum flow releases from the Quabbin Reservoir into the South Branch of the Swift River as follows:

- Maintain a minimum flow release of 20 mgd (31 cfs) when the flows in the Connecticut River are greater than 4900 cfs.
- Maintain a minimum flow release of 70 cfs (45 mgd) when the flows in the Connecticut River are between 4,900 and 4650 cfs.
- Maintain a release of 110 cfs (71 mgd) when the flows in the Connecticut River are below 4650 cfs.

These releases also generate Hydroelectricity for reservoir facility use or sale to a utility company. The 300 mgd safe yield of the three active sources of water supply for the MWRA/MDC system (Quabbin and Wachusett Reservoirs and the Ware River) is based on a target pool of 38 percent full at Quabbin Reservoir. However there remains the possibility of drawing Quabbin Reservoir down to 2 percent of its capacity via the intake to the Quabbin Aqueduct.

Ware River

Moving east from Quabbin watershed and contiguous to it is the Ware River watershed which serves as a seasonal supply to the MWRA/MDC system. The Ware River Diversion, completed in 1931, has no storage capacity. An intake for the 98 square mile watershed of the Ware River in the Town of Barre permits water to be diverted into the Quabbin Aqueduct and transported westward into the Quabbin Reservoir. Here the Ware River water is directed by a series of baffles away from the aqueduct intake and effectively detained and diluted by the higher quality water from the Quabbin watershed before exiting in diluted form some four years later through the Quabbin intake into the aqueduct. Although the Quabbin Aqueduct has the capacity to direct Ware River water eastward into the Wachusett Reservoir, this is not normally done because of its quality. Diversions from the Ware

River are permitted only between October 15 and June 15 when the flows in the river exceed 85 mgd. Ware River diversions contribute approximately 41 mgd to the system's safe yield.

Wachusett Reservoir

The system's second major supply source is the Wachusett watershed located east and contiguous to the Ware River watershed. The Wachusett Dam, located 25 miles west of Boston, was constructed in 1908 to both collect water from its 117 square mile Nashua River watershed and to receive water conveyed from Quabbin Reservoir and store it up to a capacity of 65 billion gallons and to an elevation of 395 feet (BCB). The reservoir contributes approximately 101 mgd to the system's safe yield. The City of Worcester has water rights to 21 square miles of the watershed.

Hydroelectric power is generated by water entering the reservoir from the west at the Oakdale Power Generator. Power is also generated at facilities located at the intake to the Cosgrove Aqueduct for transmission to the Hultman Aqueduct and at the transfer from Hultman to Weston Aqueducts.

The community of Clinton is fully supplied and that of Leominster and Worcester partially supplied by Wachusett Reservoir.

The intake for the Cosgrove Aqueduct can be used to draw down the Wachusett Reservoir to 50 percent full, while the old Wachusett Aqueduct can be used to draw down the reservoir completely.

Nonactive Sources

Sudbury Reservoir and Framingham Reservoir No. 3 are maintained as standby sources for the MWRA system. They could provide a safe yield of 28 mgd of water of a quality below current standards.

TRANSMISSION SYSTEM

Table A-2 presents the ten conduits that are currently active in the MWRA transmission system. The 13-foot diameter, 24-mile deep rock Quabbin Tunnel transports water eastward from Quabbin Reservoir into Wachusett Reservoir. Quabbin Tunnel is also used to divert water westward from the Ware River when such diversions are permitted. The 14-foot diameter, 8-mile long Cosgrove Tunnel carries virtually all water transmitted eastward from Wachusett Reservoir. The Wachusett Aqueduct is presently used to carry water to supply Northborough and the Westboro State

Hospital. From Cosgrove, water is carried by the 11-12 foot diameter, 18-mile long Hultman Aqueduct. A 3-mile segment of the Hultman, known as the Southborough Tunnel, transmits water under the Sudbury Reservoir. All but 11 to 15 percent of the water passing through the Southborough Tunnel is released to the Hultman for high service use. The remainder is released to the Weston Aqueduct and transmitted to the Weston Reservoir for low pressure use. High pressure transmission continues towards the city of Boston through the City Tunnel and then north to the City Tunnel Extension or south to the Dorchester Tunnel. The Sudbury Aqueduct, which extends from Framingham Reservoir No. 3 to the Chestnut Hill Reservoir, is held on standby.

TABLE A-2
The New England Drought Study
MWRA Transmission Characteristics

Aqueducts and Tunnels	Year Completed	Capacity (MGD)	Diameter (Feet)	Length (Miles)	Type of Construction
Quabbin Tunnel	1939	610	13	24.6	Concrete-Lined Rock
Chicopee Valley Aqueduct	1950	20	3-4	14.8	Concrete/Steel Pipe
Wachusett Aqueduct	1897	350	10	12.0	Brick/Concrete; Part Open Channel; Gravity
Cosgrove Tunnel	1967	600	14	8.0	Concrete-Lined Rock
Hultman Aqueduct	1940	325	11-12	15.0	Concrete/Steel
(Southborough Tunnel)	1940	600	14	3.0	Concrete-Lined Rock
Weston Aqueduct	1903	300	10-12	13.5	Brick and Concrete
Sudbury Aqueduct*	1878	90	7-9	17.4	Brick; Gravity
City Tunnel	1950	300	12	5.4	Concrete-Lined Rock
(City Tunnel Ext.)	1963	200	10	7.0	Concrete-Lined Rock
(Dorchester Tunnel)	1976	200	10	6.4	Concrete-Lined Rock

* Inactive, on standby for use in emergency

Note: All conduits are pressurized except those of the gravity type.

SOURCE: MWRA, Twenty Year Waterworks Master Plan, 1992

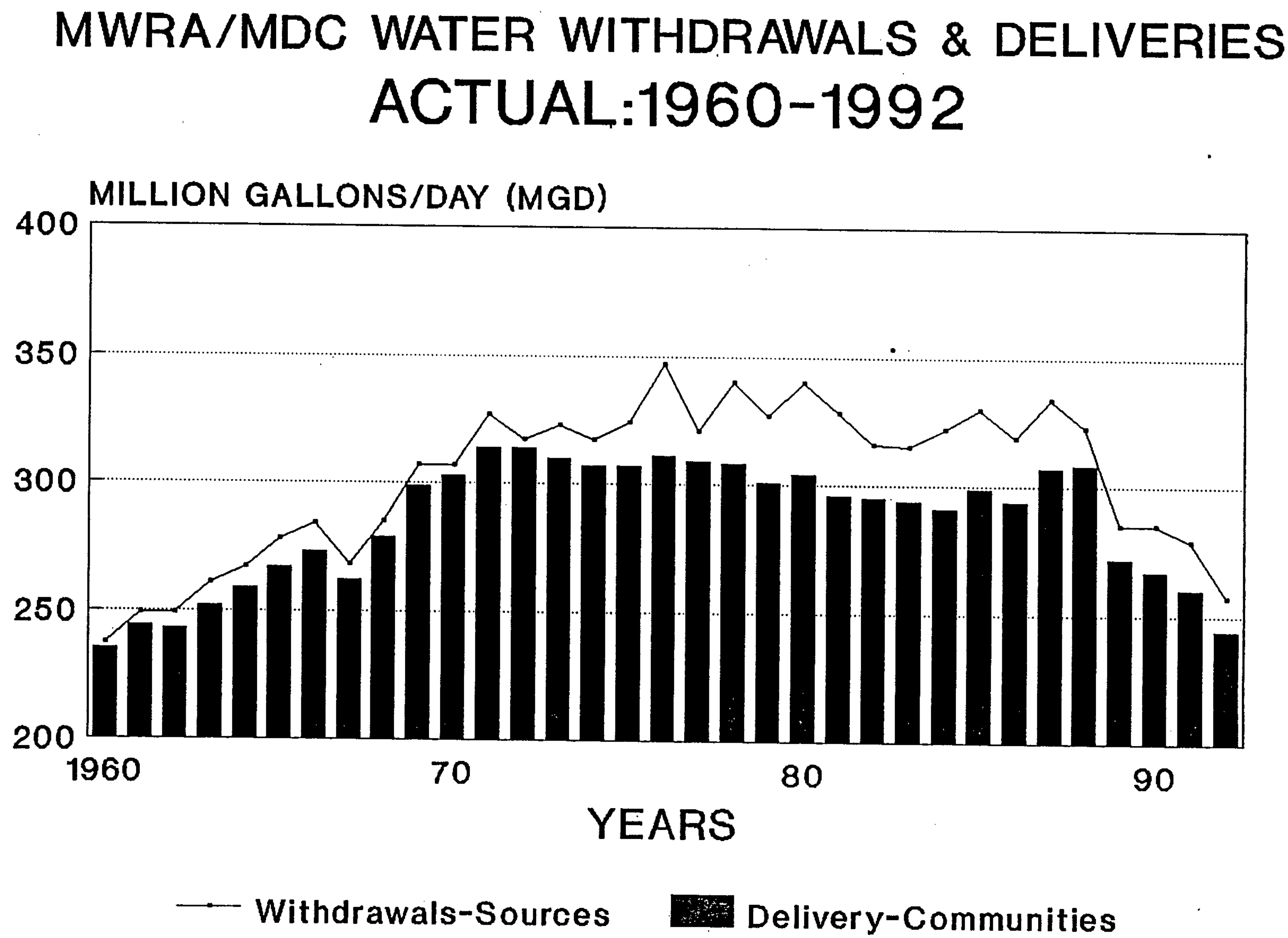
In addition, the 3-4 foot diameter, 14.8 mile long Chicopee Valley Aqueduct exits Quabbin Reservoir from the south to serve the communities of Chicopee, South Hadley and Wilbraham.

HISTORICAL WATER DEMAND

MWRA/MDC Water System demand has increased from 237 mgd in 1960 to 307 mgd in 1979 to a peak of 347 mgd in 1976 and remained above the 300 mgd safe yield of the system until 1989. See Table A-3 and Figure A-1. Since 1990 system use or the volume of water withdrawn from MDC sources has declined steadily to 257 mgd in 1992 and continues to decline in 1993. System unaccounted for water varied from 2 mgd in 1960 to peaks of 36 mgd in the 1970's and has exhibited an uneven decline from 27 mgd to 13 mgd in 1992. The water delivered to the MWRA communities went through a similar but less pronounced pattern from 235 mgd in 1960 to 314 mgd in the early 1970's to 244 mgd in 1992. Water delivered to the communities remained below or within 5 percent of the safe yield of the system for the entire period. The MWRA has conducted a preliminary analysis of the factors responsible for the decline in reservoir withdrawals from 334 mgd in 1987 to 257 mgd in 1992. Approximately two-thirds of the difference has been estimated to be attributable to demand management in the MWRA and community systems, 23 percent to the response of consumers to higher priced water and 10 percent to the changing and depressed regional economy. (1)

Tables A-4 to 7 present the historical water use for the communities fully served by the MWRA/MDC Water System and the partially served communities. Although Dedham is entitled to service, it currently is self-supplied. Since 1990, the fully supplied communities used between 86 and 88 percent of the water withdrawn from the reservoirs and the partially supplied communities about 5 percent. The remaining water is MWRA system unaccounted for water or was provided to the users indicated in Table A-6. Among the latter is an entitlement to the city of Worcester of water from the Quinapoxet watershed which amounted to 4.6 mgd in 1992. In 1990, the total water use by the partially supplied communities was 89.2 mgd of which 14.9 mgd was supplied by MWRA. Among these communities the highest water users in 1990 were Worcester with 24 mgd and Cambridge with 14 mgd, although only 0.07 mgd was supplied by the MWRA to these two communities. Any or all of these communities could theoretically require full service from the MWRA.

Figure A-1
The New England Drought Study



SOURCE: MWRA, Boston,MA MWRA-30

Table A-3
The New England Drought Study
MWRA/MDC WATER SYSTEM- HISTORICAL WATER USE (MGD)

Years	Withdrawals From Sources	Deliveries to Communities	MWRA System Unaccounted
1960	237	235	2
1	249	244	5
2	249	243	6
3	261	252	9
4	267	259	8
5	278	267	11
6	284	273	11
7	268	262	6
8	285	279	6
9	307	299	8
1970	307	303	4
1	327	314	13
2	317	314	3
3	323	310	13
4	317	307	10
5	324	307	17
6	347	311	36
7	321	309	12
8	340	308	32
9	327	301	26
1980	340	304	36
1	328	296	32
2	316	295	21
3	315	294	21
4	322	291	31
5	330	299	31
6	319	294	25
7	334	307	27
8	323	308	15
9	285	272	13
1990	285	267	17
1	279	260	19
2	257	244	13

Source:MWRA Waterworks Division, Boston, Mass.

Table A-4
The New England Drought Study
MWRA FULLY SUPPLIED COMMUNITIES (32) - HISTORICAL WATER USE
(million gallons per day-mgd)

Town or City	1980 Water Use	1990 Water Use	1992 Water Use
Arlington	4.78	4.23	4.09
Belmont	3.03	2.48	2.63
Boston	135.61	110.22	98.70
Brookline	7.17	7.09	6.78
Chelsea	3.39	2.96	3.41
Chicopee	10.35	8.77	7.30
Clinton	1.92	2.01	1.83
Everett	8.48	6.36	4.80
Framingham	7.97	7.80	7.01
Lexington	5.13	4.47	5.29
Lynnfield WD	0.44	0.52	0.39
Malden	5.45	5.06	5.41
Marblehead	2.17	2.22	1.78
Medford	9.00	5.91	5.42
Melrose	2.82	3.47	3.26
Milton	2.99	2.66	2.58
Nahant	0.40	0.46	0.39
Newton	11.14	10.74	10.48
Norwood	4.36	3.92	3.51
Quincy	11.75	10.27	9.98
Revere	4.65	4.56	4.71
Saugus	3.79	3.09	3.12
Somerville	9.82	9.09	8.17
Southboro	0.52	0.66	0.65
South Hadley	2.19	2.05	1.78
Stoneham	3.59	3.43	3.49
Swampscott	1.97	1.83	1.66
Waltham	11.53	8.89	8.47
Watertown	4.73	4.08	3.42
Weston	1.14	1.23	1.23
Wilbraham	0.85	1.07	1.03
Winthrop	2.09	2.06	1.83
TOTAL	285.22	243.66	225.00

Source: MWRA Waterworks Division, Boston, MA

Table A-5
The New England Drought Study
MWRA PARTIALLY SUPPLIED COMMUNITIES (15)
HISTORICAL WATER USE
(million gallons per day-mgd)

Town or City	1980 Total Water Use	1990 Total Water Use	1990 MWRA Supplied Water Use	1992 Total Water Use	1992 MWRA Supplied Water Use
Bedford	1.54	1.57	1.15		?
Cambridge	17.20	14.38	0.07		0.00
Canton	3.03	2.57	1.27		1.44
Dedham . Not currently receiving water from MWRA but has right to service					
Leominster	6.18	4.38	0.31		0.00
Lynn	13.30	13.34	2.47		1.55
Marlborough	4.14	4.40	2.81		3.34
Needham	3.53	3.28	0.53		0.30
Northborough	0.63	1.13	0.42		0.34
Peabody	8.48	6.57	0.10		0.04
Wakefield	2.43	2.77	2.32		2.37
Wellesley	3.06	2.49	0.28		0.24
Winchester	2.99	2.50	0.88		1.06
Woburn	5.66	5.58	2.28		1.82
Worcester	24.20(est)	24.20	0		0.00
TOTALS	97.37	89.16	14.89		12.50

Source: MWRA Waterworks Division, Boston, MA

Table A-6
The New England Drought Study
HISTORICAL WATER USE - SUPPLIED BY MWRA

	1980 (mgd)	1990 (mgd)	1990 (%)	1992 (mgd)	1992 (%)
31 Fully Supplied Communities	285.2	243.7	86	225.0	88
15 Partially Supplied Communities		14.9	5	12.5	5
MWRA System Unaccounted For		17.3	6	13.5	5
Other		9.2	3	* 6.4	2
TOTAL WITHDRAWALS FROM MWRA/MDC SOURCES	340.0	285.1	100	257.4	100

*MDC Parks Division	0.140
MWRA Sewerage System	0.004
Commonwealth of Mass	0.322
Quinapoxet Withdrawals	4.624
U.S. Government	0.064
Westboro State Hospital	0.162
Other Withdrawals	1.070
	6.385

Table A-7
The New England Drought Study
MWRA COMMUNITY HISTORICAL WATER USE (mgd)

	1980	1990	1992
31 Fully Supplied Communities	285.2	243.7	225.0
15 Partially Supplied Communities		89.2	
MWRA System Unaccounted For		17.3	13.5
Other		9.2	6.4
		359.4	
Local Sources		74.3	
TOTAL WITHDRAWALS FROM MWRA/MDC SOURCES	340.0	285.1	257.4

Source: MWRA Waterworks Division, Boston, MA.

INTERACTIVE STELLA II MODEL OF THE EXISTING CONDITIONS

The present application of Trigger Planning integrates strategic, tactical and emergency planning into a single planning concept. It is facilitated by the use of the STELLA II interactive software model which models the MWRA/MDC water supply system physically and operationally and permits the simulation of different future strategies and their impacts on the system. The STELLA II application for Trigger Planning thus permits planners to portray the physical and operational features of the water system on the computer screen and to compress time by simulating different futures and instantaneously evaluating their outcomes. The interactive nature of the model facilitates the building of consensus among interested parties such as the managers of the MWRA system and WSCAC and later the MWRA Board of Directors and their Advisory Board. The STELLA II Model for the system is more completely presented in Appendix B.

The elements of the model are:

the system configuration,

the equations which define the functional relationships between the components of the system,

the estimated yield of the system based on 31 years of hydrological record, extending from October 1949 to September 1980,

the volume to elevation relationships at Quabbin Reservoir,

the MWRA Drought Management Plan and anticipated reductions in demand in accordance with the plan (see Figure 2 and Table 1 in the main report),

the system demand, and

the performance definitions and measures.

Figures A-2 and 3 present the configuration of the MWRA/MDC Water System and the elevation of the pool at Quabbin Reservoir during the 31 year hydrological period. This period includes the 1960's drought of record. The model begins with a full Quabbin Reservoir and a system demand approximating the actual 1992 demand on the system of 260 mgd. Curve 1 is without drought management and curve 2 with drought management.

NOTES - APPENDIX A

1 U.S. Army Corps of Engineers, New England Division, The New England Drought Study: Water Resources Planning for Metropolitan Boston, Massachusetts, January, 1994, pages 27 and 28.

Figure A-2
The New England Drought Study
STELLA MODEL: MWRA/MDC WATER
SYSTEM CONFIGURATION

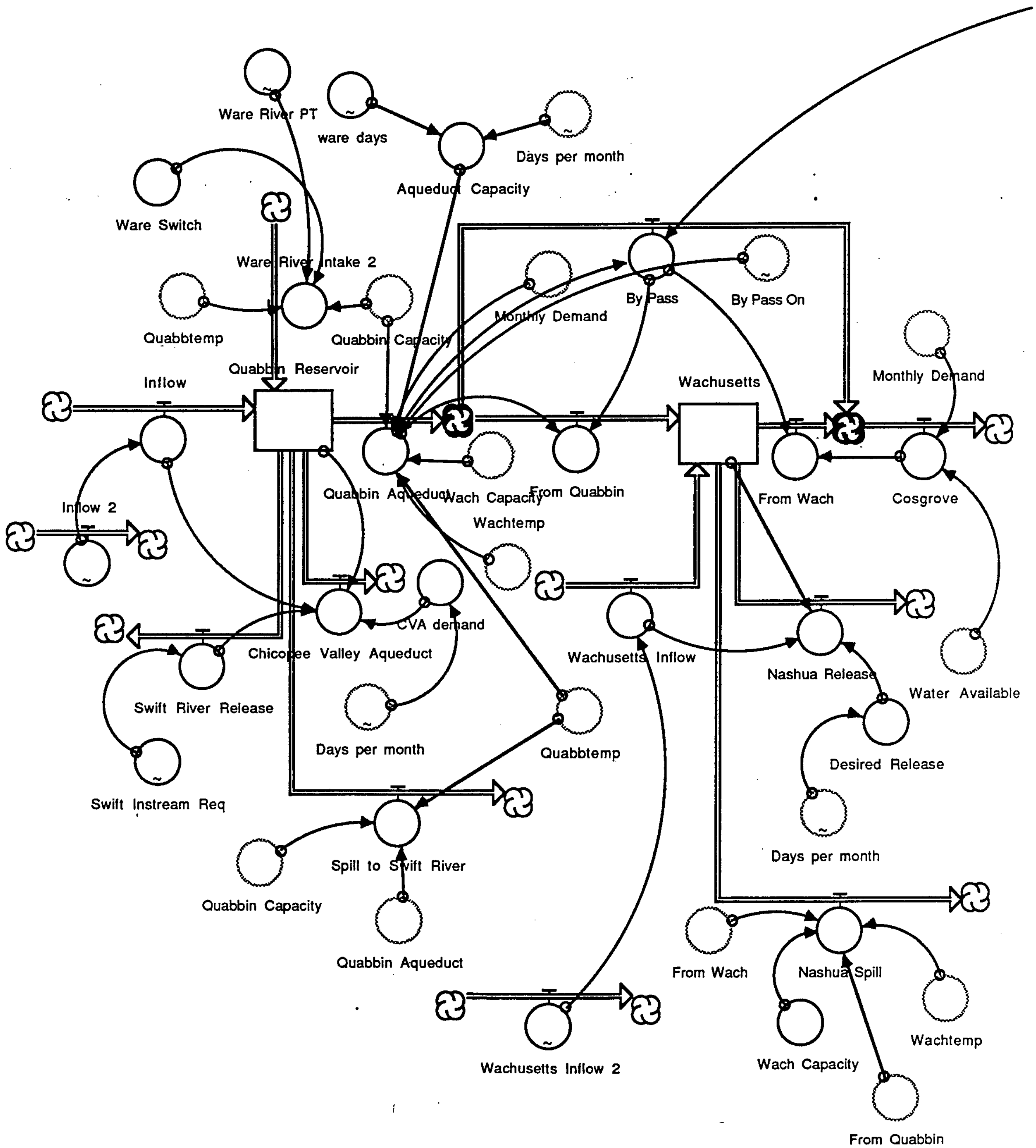
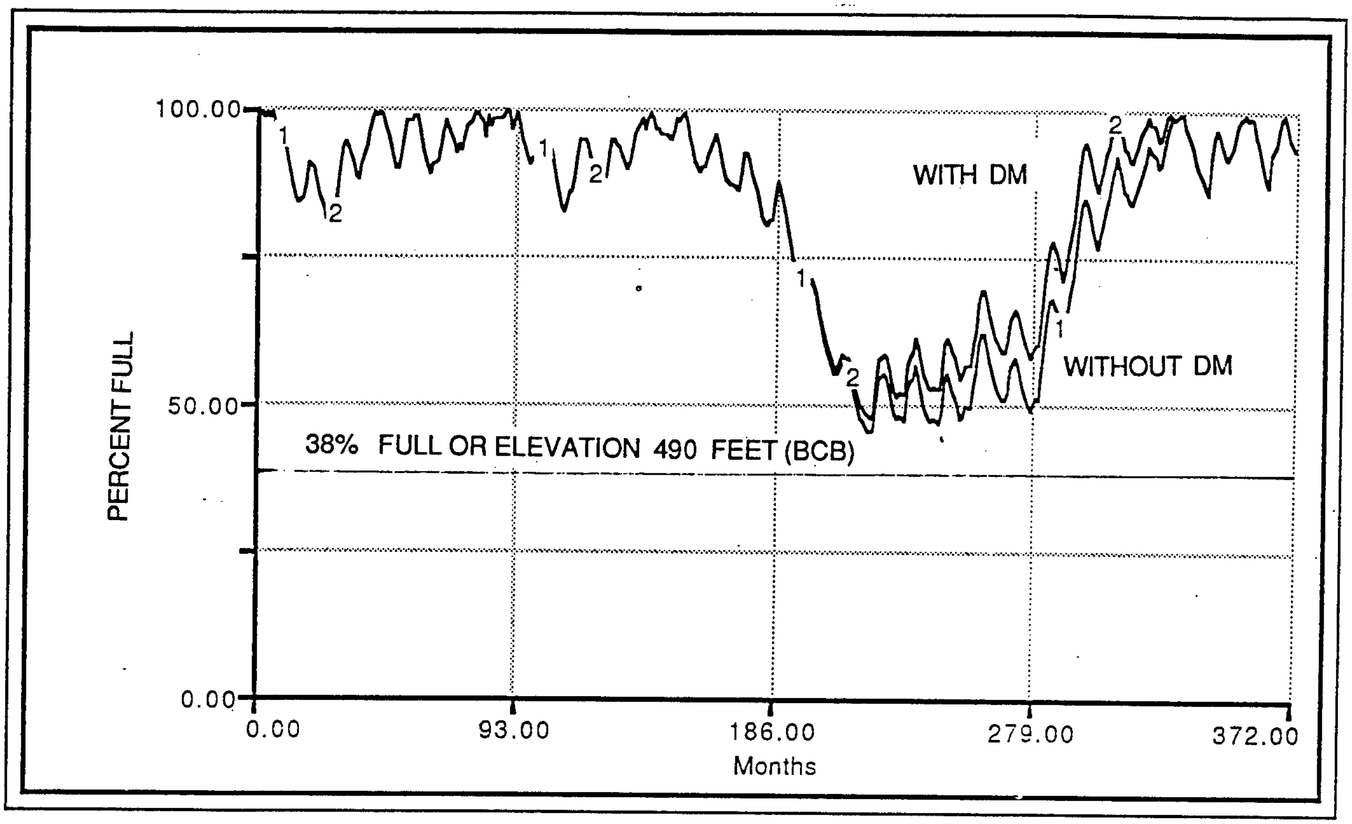


Figure A-3
The New England Drought Study

EXISTING CONDITIONS AT QUABBIN RESERVOIR - DEMAND: 260 MGD WITHOUT AND WITH DROUGHT MANAGEMENT (DM)



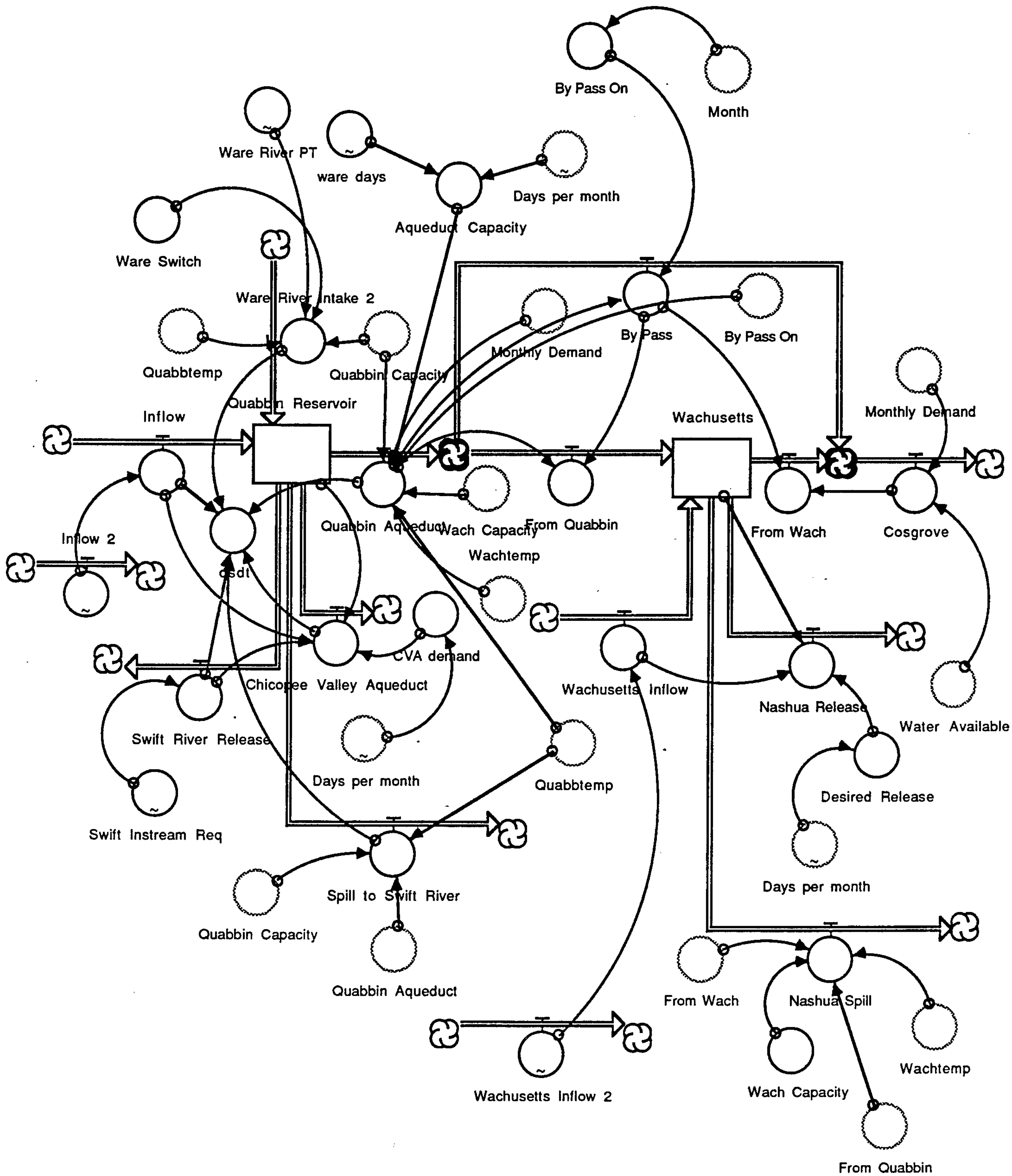
APPENDIX B

STELLA II PORTRAYAL OF THE MWRA/MDC WATER SYSTEM

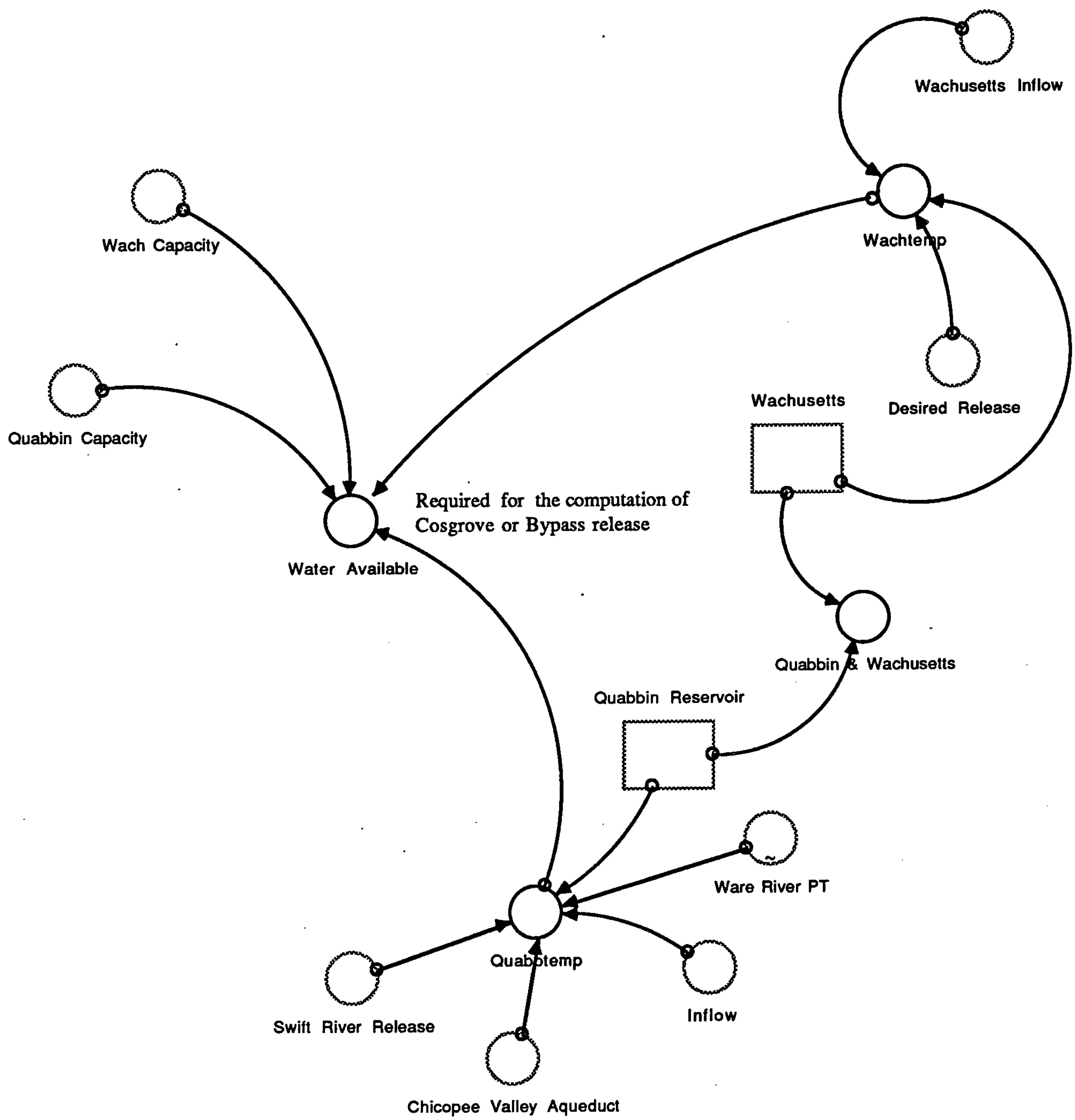
APPENDIX B

STELLA II PORTRAYAL OF THE MWRA/MDC WATER SYSTEM

SYSTEM CONFIGURATION

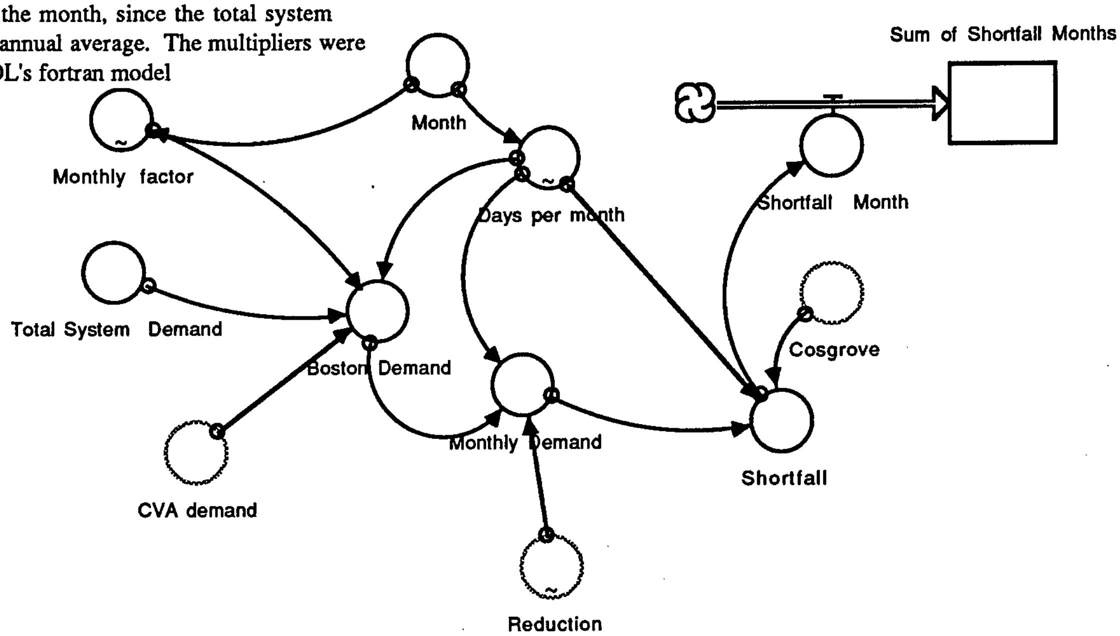


TEMPORARY STORAGES

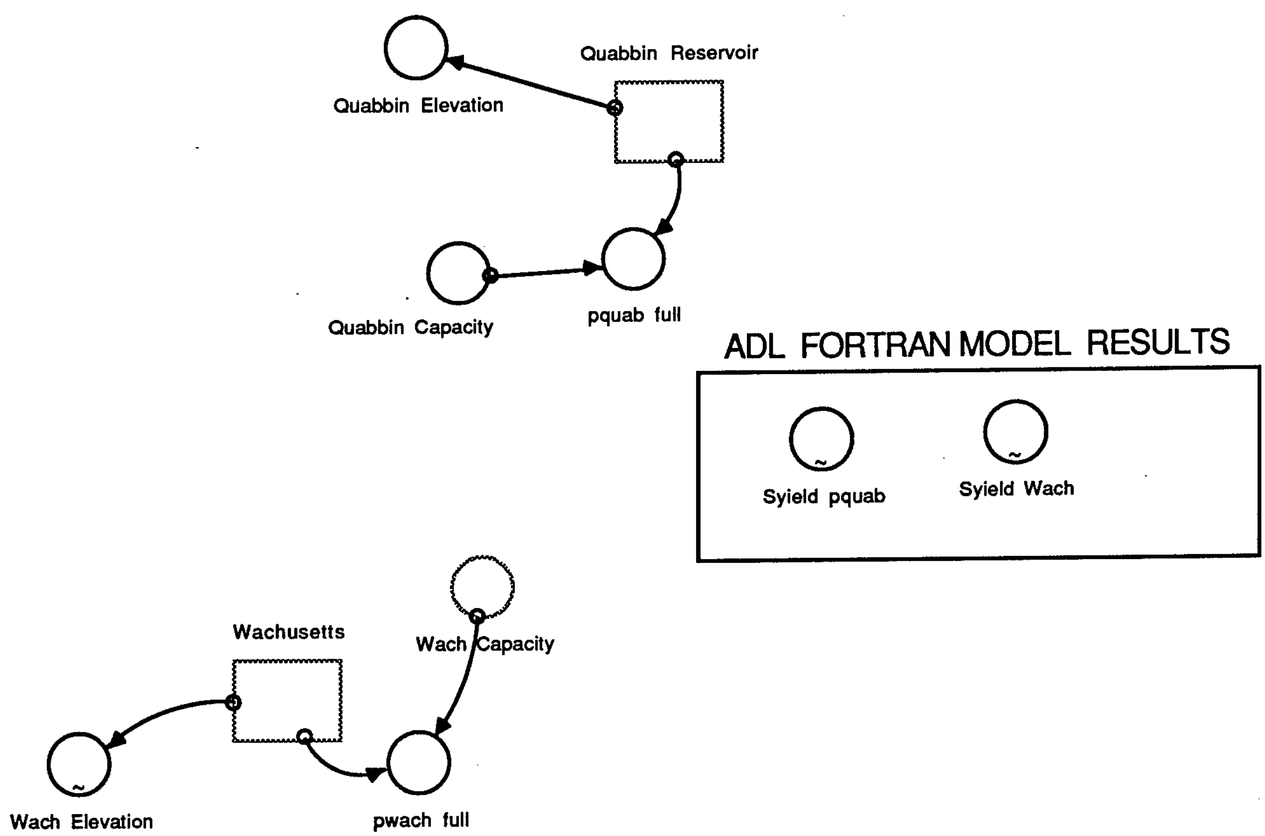


COMPUTATION OF DEMAND

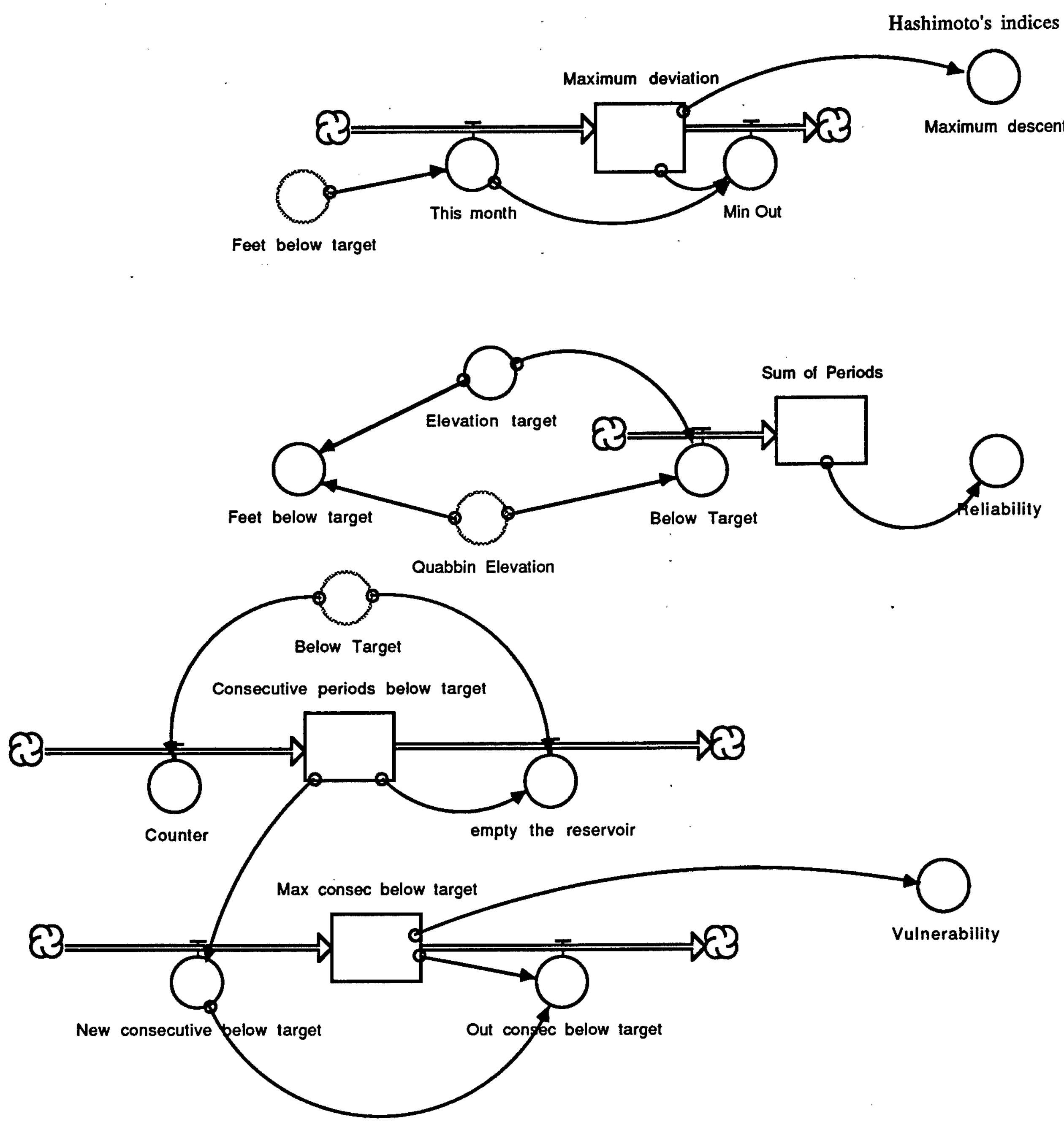
Multiplier for the month, since the total system demand is the annual average. The multipliers were taken from ADL's fortran model

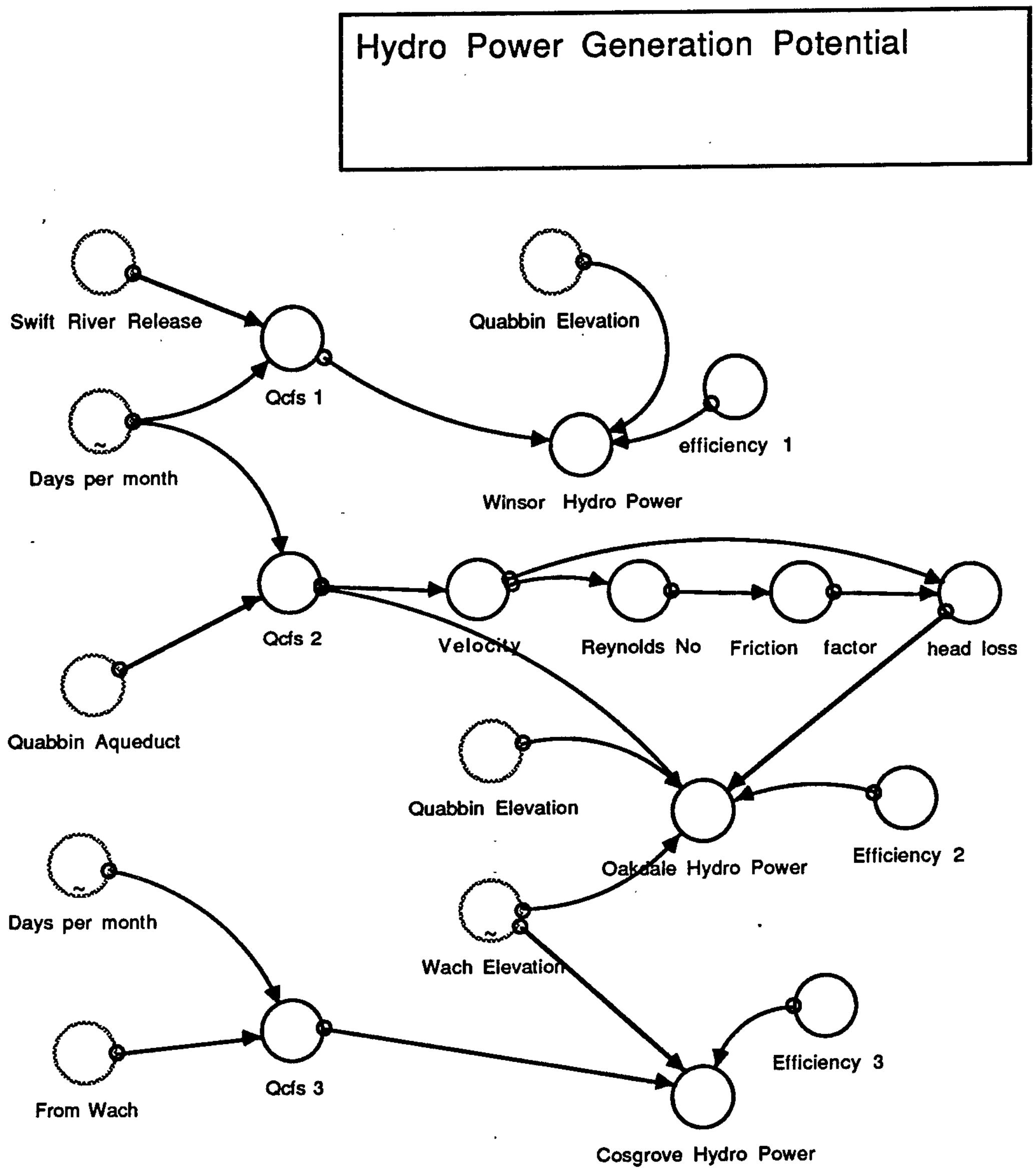


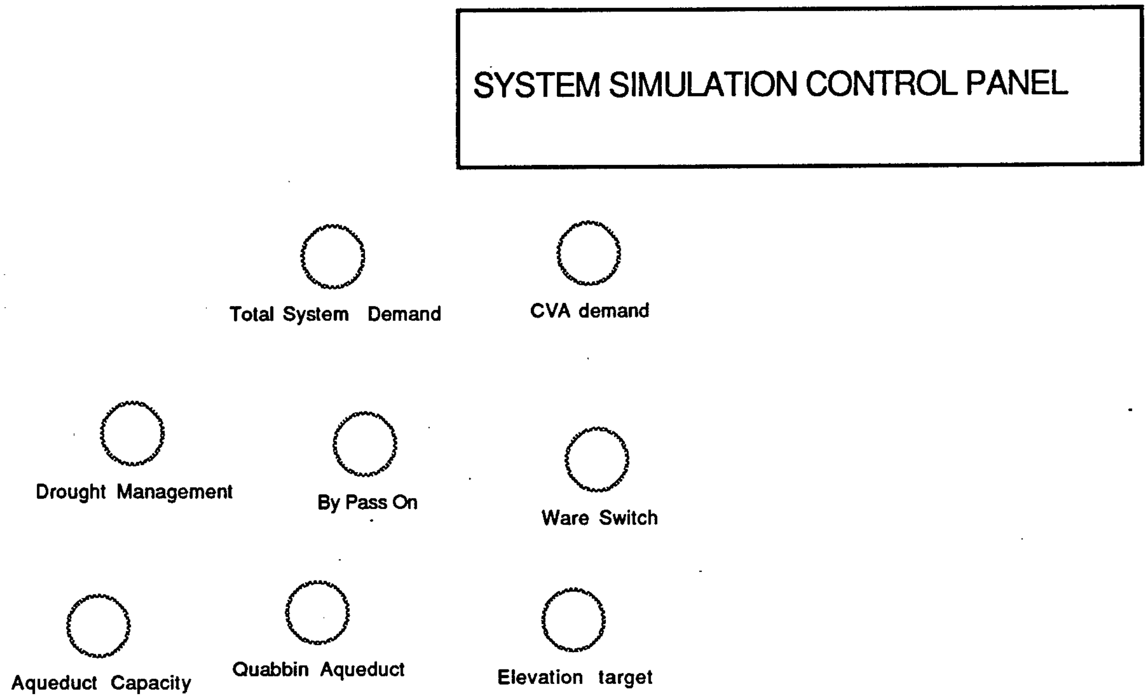
VOLUME TO ELEVATION RELATIONSHIPS



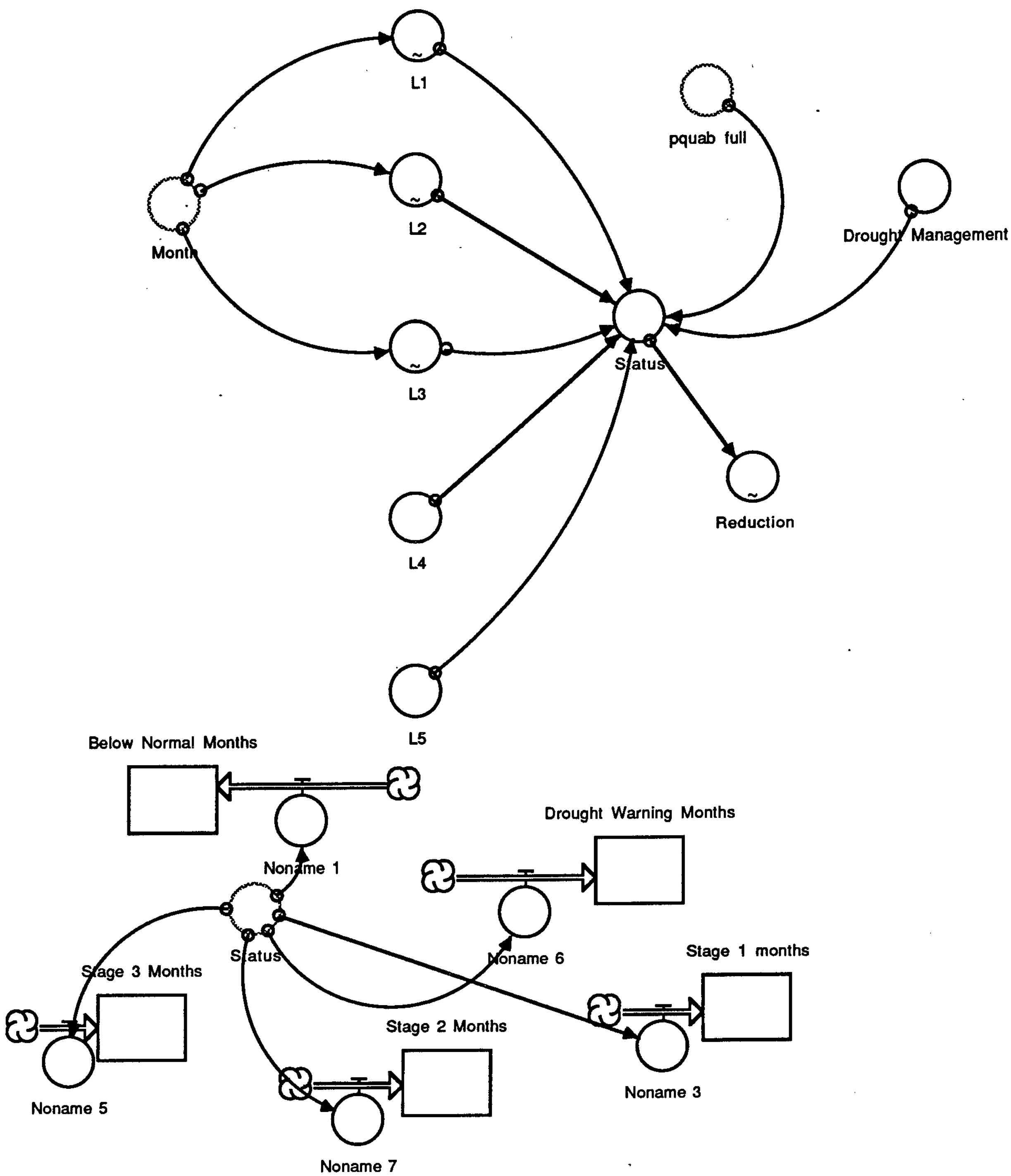
PERFORMANCE FACTORS




Hydro Power Generation Potential
Swift River Release
Qcfs 1
Quabbin Elevation
efficiency 1
Days per month
Winsor Hydro Power
Qcfs 2
Velocity
Reynolds No
Friction factor
head loss
Quabbin Aqueduct
Quabbin Elevation
Oakdale Hydro Power
Efficiency 2
Days per month
Wach Elevation
Efficiency 3
From Wach
Qcfs 3
Cosgrove Hydro Power


SYSTEM SIMULATION CONTROL PANEL
Total System Demand
CVA demand
Drought Management
By Pass On
Ware Switch
Aqueduct Capacity
Quabbin Aqueduct
Elevation target

DROUGHT MANAGEMENT PLAN



INFLOW DATA

Inflow_2 = GRAPH(time

(0, -4.08) (1, 27.98) (2, 13.92) (3, 47.1) (4, 52.31) (5, 41.08) (6, 35.73) (7, 40.77) (8, -4.05) (9, -3.58) (10, -7.84) (11, -2.35) (12, -0.68) (13, -2.05) (14, 17.71) (15, 37.83) (16, 32.1) (17, 49.84) (18, 62.62) (19, 38.82) (20, 28.78) (21, 3.46) (22, 2.8) (23, -7.72) (24, 3.13) (25, 28.41) (26, 35.82) (27, 36.41) (28, 69.5) (29, 67.2) (30, 61.76) (31, 26.71) (32, 17.9) (33, 11.89) (34, 16.23) (35, -2.76) (36, 22.66) (37, 54.55) (38, 48.49) (39, 68.96) (40, 40.09) (41, 49.36) (42, 70.96) (43, 41.45) (44, 25.88) (45, 9.49) (46, 16.25) (47, 12.95) (48, -6.97) (49, 6.31) (50, 18.89) (51, 53.75) (52, 56.41) (53, 99.46) (54, 97.58) (55, 61.71) (56, 10.91) (57, -7.26) (58, -10.38) (59, -9.59) (60, 15.69) (61, 16.02) (62, 45.22) (63, 22.75) (64, 34.72) (65, 44.32) (66, 58.04) (67, 52.05) (68, 15.1) (69, 3.42) (70, 5.7) (71, 27.11) (72, 7.84) (73, 45.43) (74, 38.22) (75, 15.22) (76, 35.85) (77, 55.09) (78, 59.37) (79, 24.71) (80, 19.31) (81, -2.82) (82, 89.88) (83, 5.77) (84, 61.96) (85, 62.72) (86, 11.9) (87, 25.96) (88, 27.74) (89, 45.12) (90, 126.67) (91, 38.84) (92, 27.91) (93, 5.67) (94, -3.84) (95, 13.5) (96, 6.53) (97, 17.55) (98, 36.79) (99, 26.68) (100, 23.67) (101, 29.46) (102, 40.98) (103, 24.9) (104, 15.38) (105, -3.75) (106, -6.64) (107, -5.27) (108, -2.54) (109, 17.12) (110, 43.81) (111, 40.28) (112, 25.62) (113, 45.79) (114, 74.87) (115, 43.81) (116, 7.13) (117, 26.45) (118, 3.25) (119, 8.22) (120, 8.59) (121, 21.85) (122, 12.39) (123, 29.68) (124, 22.28) (125, 55.84) (126, 68.23) (127, 20.99) (128, 16.41) (129, 28.48) (130, 13.17) (131, -1.69) (132, 39.12) (133, 48.83) (134, 49.88) (135, 35.99) (136, 41.38) (137, 36.43) (138, 110.02) (139, 41.83) (140, 33.84) (141, 20.21) (142, 9.11) (143, 34.58) (144, 20.45) (145, 22.94) (146, 22.18) (147, 13.66) (148, 38.25) (149, 63.05) (150, 70.61) (151, 28.12) (152, 33.3) (153, 17.31) (154, 2.21) (155, 2.21) (156, -0.78) (157, 15.61) (158, 13.75) (159, 27.89) (160, 23.1) (161, 37.73) (162, 57.63) (163, 25.6) (164, 8.01) (165, 0.07) (166, 0.09) (167, -1.04) (168, 18.3) (169, 12.11) (170, 15.71) (171, 16.96) (172, 19.48) (173, 49.04) (174, 60.04) (175, 23.24) (176, 14.46) (177, -1.95) (178, -2.15) (179, 2.9) (180, -4.33) (181, 17.85) (182, 12.58) (183, 37.8) (184, 22.99) (185, 61.12) (186, 49.16) (187, 9.98) (188, 1.36) (189, 1.01) (190, -1.86) (191, -10.97) (192, -5.07) (193, -1.49) (194, 13.57) (195, 6.83) (196, 31.44) (197, 21.55) (198, 32.85) (199, 10.95) (200, 7.14) (201, -1.06) (202, 0.17) (203, 2.49) (204, 6.31) (205, 8.79) (206, 13.78) (207, 13.78) (208, 26.03) (209, 46.49) (210, 19.97) (211, 26.47) (212, 12.74) (213, 11.02) (214, 1.91) (215, 12.72) (216, 14.95) (217, 23.57) (218, 16.54) (219, 20.44) (220, 24.63) (221, 35.1) (222, 77.56) (223, 59.99) (224, 30.07) (225, 21.08) (226, 9.85) (227, 3.06) (228, 5.06) (229, 16.81) (230, 37.12) (231, 20.85) (232, 17.85) (233, 74.17) (234, 28.66) (235, 24.49) (236, 46.64) (237, 4.95) (238, 0.75) (239, 1.53) (240, 4.28) (241, 25.16) (242, 33.05) (243, 19.48) (244, 23.95) (245, 37.21) (246, 79.77) (247, 26.03) (248, 16.2) (249, 11.23) (250, 28) (251, 10.79) (252, 5.25) (253, 29.82) (254, 41.97) (255, 18.63) (256, 65.12) (257, 46.18) (258, 71.34) (259, 39.61) (260, 23.13) (261, 8.36) (262, 8.41) (263, 8.31) (264, 6.26) (265, 17.55) (266, 18.86) (267, 17.26) (268, 31.11) (269, 36.62) (270, 58.57) (271, 37.16) (272, 8.69) (273, 12.58) (274, 12.69) (275, 13.03) (276, 13.12) (277, 21.81) (278, 46.35) (279, 31.25) (280, 30.62) (281, 75.39) (282, 69.13) (283, 68.73) (284, 57.87) (285, 17.93) (286, 2.76) (287, 0.68) (288, 6.13) (289, 39.26) (290, 58.38) (291, 54.43) (292, 50.31) (293, 73.41) (294, 77.2) (295, 58.22) (296, 36.58) (297, 16.74) (298, 4.78) (299, -2.97) (300, 3.35) (301, 5.72) (302, 66.94) (303, 43.45) (304, 40.98) (305, 56.71) (306, 43.34) (307, 46.71) (308, 16.14) (309, 7.7) (310, 2.66) (311, 28.71) (312, 4.33) (313, 22.78) (314, 33.42) (315, 40.44) (316, 42.89) (317, 52.15) (318, 39.69) (319, 18.04) (320, 35.44) (321, 31.98) (322, 17.43) (323, 46.23) (324, 57.42) (325, 59.17) (326, 42) (327, 68.84) (328, 77.82) (329, 57.92) (330, 44.58) (331, 43.66) (332, 16.51) (333, 0.9) (334, 16.82) (335, 0.1) (336, 15.38) (337, 18.7) (338, 30.27) (339, 17.07) (340, 18) (341, 102.62) (342, 55.75) (343, 35.33) (344, 20.18) (345, 13.17) (346, 24.3) (347, 23.81) (348, 51.56) (349, 40.23) (350, 53.82) (351, 78.73) (352, 30.07) (353, 47.77) (354, 46.91) (355, 30.97) (356, 20.7) (357, 2.21) (358, 19.62) (359, -4.88) (360, 7.52) (361, 4.67) (362, 18.37) (363, 89.93) (364, 31.52) (365, 107.42) (366, 75.84) (367, 46.09) (368, 2.26) (369, 0.8) (370, 24.36) (371, 24.36)

DOCUMENT: These are actual reservoir yield numbers in MG/Sqmi. Since the historical values are known there is no need in this base case scenario to include precipitation and evaporation.

Wachusetts_Inflow_2 = GRAPH(time
)
(0, 0.36) (1, 24.73) (2, 18.28) (3, 39.85) (4, 48.12) (5, 39.22) (6, 42.87) (7, 26.02) (8, 9.25) (9, 44) (10, 5.73) (11, 0.99) (12, -0.47) (13, 7.26) (14, 9.82) (15, 23.88) (16, 23.88) (17, 56.5) (18, 54.71) (19, 12.58) (20, 13.07) (21, 5.14) (22, 0.89) (23, 4.12) (24, 3.44) (25, 18.23) (26, 27.32) (27, 35.37) (28, 80.03) (29, 68.12) (30, 65.95) (31, 31.4) (32, 20.66) (33, 16.39) (34, 9) (35, 7.47) (36, 14.42) (37, 61.19) (38, 49.51) (39, 77.89) (40, 57.85) (41, 62.6) (42, 70.78) (43, 46.97) (44, 41.99) (45, 7.68) (46, 12.93) (47, 5.6) (48, 5.01) (49, 10.84) (50, 30.85) (51, 55.19) (52, 71.39) (53, 111.5) (54, 127.56) (55, 75.63) (56, 16.96) (57, 5.07) (58, 5.68) (59, 2.94) (60, 8.86) (61, 13.69) (62, 37.5) (63, 25.79) (64, 34.18) (65, 47.39) (66, 54.6) (67, 66.91) (68, 20.68) (69, 10.83) (70, 18.13) (71, 79.75) (72, 29.6) (73, 66.44) (74, 99.7) (75, 42.39) (76, 35.21) (77, 59.75) (78, 54.8) (79, 33.18) (80, 22.33) (81, 9.35) (82, 66.07) (83, 17.9) (84, 86.39) (85, 102.41) (86, 21.43) (87, 74.17) (88, 41.34) (89, 55.06) (90, 143.63) (91, 52.45) (92, 28.26) (93, 13.14) (94, 5.51) (95, 6.33) (96, 8.52) (97, 15.15) (98, 29.09) (99, 32.45) (100, 27.96) (101, 41.55) (102, 48.24) (103, 22.05) (104, 12.56) (105, 4.4) (106, 1.29) (107, 1.27) (108, 2.28) (109, 5.51) (110, 35.64) (111, 55.39) (112, 38.23) (113, 74.66) (114, 134.15) (115, 55.73) (116, 18.63) (117, 14.51) (118, 8.39) (119, 12.74) (120, 16.13) (121, 24.68) (122, 27.96) (123, 38.42) (124, 28.15) (125, 67.38) (126, 82.88) (127, 23.39) (128, 15.4) (129, 35.99) (130, 17) (131, 13.24) (132, 33.96) (133, 51.65) (134, 60.63) (135, 42.04) (136, 48.16) (137, 48.96) (138, 116.4) (139, 54.26) (140, 32.24) (141, 20.54) (142, 9.99) (143, 23.98) (144, 19.99) (145, 31.26) (146, 27.28) (147, 22.44) (148, 39.88) (149, 76.59) (150, 95.83) (151, 42.61) (152, 24.45) (153, 10.83) (154, 2.07) (155, 15.41) (156, 10.55) (157, 16.01) (158, 19.19) (159, 39.69) (160, 30.13) (161, 70.45) (162, 91.19) (163, 40.86) (164, 20.47) (165, 9.66) (166, 10.41) (167, 9.66) (168, 35.7) (169, 39.26) (170, 43.6) (171, 26.66) (172, 22.89) (173, 75.04) (174, 61) (175, 30.71) (176, 12.22) (177, 1.29) (178, -1.34) (179, 1.88) (180, -1.04) (181, 20.92) (182, 22.07) (183, 37.05) (184, 30.86) (185, 67.43) (186, 53.46) (187, 20.8) (188, 9.87) (189, 5.46) (190, 3.16) (191, 0.23) (192, -0.33) (193, 4.48) (194, 15.05) (195, 13.35) (196, 21.31) (197, 32.98) (198, 38.63) (199, 17.88) (200, 13.8) (201, 7.44) (202, 6.53) (203, 6.33) (204, -0.61) (205, 1.69) (206, 2.94) (207, 6.2) (208, 20.14) (209, 39.12) (210, 26.49) (211, 21.74) (212, 9.52) (213, -2.87) (214, -1.29) (215, 1.88) (216, 0.64) (217, 13.56) (218, 9.25) (219, 14.86) (220, 17.69) (221, 30.4) (222, 93.83) (223, 76.55) (224, 28.22) (225, 13.85) (226, 3.81) (227, 3.7) (228, 4.57) (229, 4.73) (230, 31.25) (231, 18.86) (232, 26.4) (233, 114.66) (234, 37.59) (235, 33.89) (236, 70.3) (237, 19.67) (238, -1.01) (239, -1.62) (240, 1.11) (241, 17.01) (242, 32.05) (243, 18.32) (244, 22.64) (245, 60.55) (246, 100.08) (247, 31.39) (248, 10.72) (249, 8.39) (250, 7.26) (251, 6.08) (252, -0.5) (253, 37.05) (254, 54.36) (255, 27.37) (256, 91.34) (257, 54.43) (258, 85.26) (259, 39.35) (260, 23.93) (261, 3.72) (262, 2.12) (263, 2.17) (264, 3.41) (265, 6.8) (266, 6.62) (267, 8.12) (268, 19.12) (269, 57.44) (270, 79.26) (271, 55.07) (272, 17.67) (273, 5.84) (274, 4.83) (275, 5.94) (276, 5.77) (277, 8.76) (278, 15.88) (279, 37.9) (280, 36.46) (281, 107.23) (282, 93.67) (283, 76.64) (284, 61.36) (285, 25.3) (286, 5.84) (287, 4.41) (288, 7.23) (289, 60.2) (290, 66.8) (291, 28.71) (292, 66.42) (293, 82.44) (294, 86.72) (295, 57.02) (296, 31.63) (297, 22.64) (298, 9.77) (299, 3.88) (300, 4.97) (301, 10.03) (302, 75.63) (303, 54.9) (304, 51.27) (305, 62.13) (306, 59.02) (307, 39.45) (308, 17.19) (309, 6.55) (310, 4.5) (311, 13.85) (312, 16.09) (313, 20.72) (314, 51.53) (315, 46.92) (316, 39.5) (317, 57.59) (318, 60.3) (319, 24.43) (320, 9.47) (321, 9.3) (322, 5.14) (323, 21.36) (324, 50.38) (325, 60.65) (326, 41.22) (327, 59.75) (328, 78.93) (329, 54.19) (330, 34.51) (331, 18.44) (332, 7.42) (333, 1.82) (334, 6.66) (335, -0.24) (336, -1.06) (337, -4.9) (338, -0.45) (339, 0.87) (340, 4.85) (341, 90.73) (342, 70.59) (343, 41.85) (344, 10.95) (345, 2.54) (346, 10.69) (347, 8.27) (348, 40.46) (349, 53.98) (350, 62.62) (351, 76.22) (352, 35.28) (353, 60.3) (354, 80.74) (355, 37.24) (356, 19.01) (357, 2.15) (358, 2.92) (359, -5.54) (360, -0.85) (361, 1.34) (362, 12.83) (363, 97.98) (364, 40.86) (365, 101.09) (366, 61.31) (367, 37.61) (368, 14.88) (369, 10.86) (370, 18.14) (371, 18.14)

FUNCTIONAL RELATIONSHIPS

- Aqueduct_Capacity = 600*(Days_per_month-ware_days)
  DOCUMENT: This is the monthly hydraulic capacity of aqueduct between Quabbin Reservoir and Wachusett Reservoir. I.e. it forms the upper constraint of this transfer

- Boston_Demand = (Total_System__Demand-CVA_demand/Days_per_month)*Monthly_factor
- By_Pass_On = If (Month = 9 or Month = 10 or Month = 11 or Month = 12) then 0 else 0
- Cosgrove_Hydro_Power = Qcfs_3*(Wach_Elevation-316)*efficiency_3/11.81
- CVA_demand = 13*Days_per_month
- Desired_Release = 1.8 *Days_per_month
- Drought_Management = 1
- dsdt = Inflow+Ware_River_Intake_2-Swift_River_Release-Spill_to_Swift_River-Chicopee_Valley_Aqueduct-Quabbin_Aqueduct
- efficiency_1 = 0.85
- Efficiency_2 = 0.85
- Efficiency_3 = .85
- Elevation_target = 530
- Feet_below_target = max(0,Elevation_target-Quabbin_Elevation)
- Friction__factor = If Reynolds_No < 2000 then 64/Reynolds_No else 0.0136
  DOCUMENT: Manning's coefficient for tunnel is 0.013

  Friction factor obtained from n using the following equation:

  f = n^2 * 8g /(R^0.333) (SI units) , for an R of 3.021 ft and n=0.013,
  f = 0.0136 (3.281 ft = 1m)

- head_loss = If Velocity > 0 then Friction__factor*(129935/11)*Velocity*Velocity/(2*32.2) else 0
  DOCUMENT: Hydraulic head loss in the Quabbin Aqueduct

- L4 = 38
  DOCUMENT: Minimum Pool. Reservoir levels between L3 and L4 correspond to Drought Emergency Stage 1 (Status 3). Reduction in demand is 10%.

- L5 = 25
  DOCUMENT: Lower boundary for Drought Emergency Stage 2. Stella model Status 4. Reduction in demand 15%.

- Maximum_descent = Maximum_deviation
- Month = MOD(Time,12) + 1
- Monthly_Demand = Days_per_month*Boston_Demand*((100-Reduction)/100)
- Oakdale_Hydro_Power = Qcfs_2*(Quabbin_Elevation-Wach_Elevation-head_loss)*Efficiency_2/11.81

- pquab_full = (Quabbin_Reservoir/Quabbin_Capacity)*100
  DOCUMENT: Volume of Quabbin Reservoir expressed as a percentage of maximum capacity.

- pwach_full = (Wachusetts/Wach_Capacity)*100
- Qcfs_1 = (Swift_River_Release*133681)/(Days_per_month*24*3600)
  DOCUMENT: Conversion from MG per month to cubic feet per second.

- Qcfs_2 = (Quabbin_Aqueduct*133681)/(Days_per_month*24*3600)
  DOCUMENT: Conversion from MG per month to cubic feet per second.

- Qcfs_3 = (From_Wach*133681)/(Days_per_month*24*3600)
  DOCUMENT: Conversion from MG per month to cubic feet per second.

- Quabbin_&_Wachusetts = Wachusetts+Quabbin_Reservoir
- Quabbin_Capacity = 412000
  DOCUMENT: This is the maximum capacity of Quabbin Reservoir in
  Million Gallons

- Quabbin_Elevation =
  (36561.5+SQRT(36561.5^2-4*42.1227*(7958351-Quabbin_Reservoir)))/(2*42.1227)
  DOCUMENT: This is the root of the quadratic equation that is the functional form of Q Vs E. The actual equation is
  Q=7958351-36561.5E+42.1227E*E Where
  Q= Volume in MG and
  E = Elevation in BCB feet

  Good in the range of about 6% full to 100%

- Quabbtemp =
  Quabbin_Reservoir+Inflow-Chicopee_Valley_Aqueduct-Swift_River_Release+Ware_River_PT
- Reliability = 100-(Sum_of_Periods/(TIME+1))*100
- Reynolds_No = (Velocity*11)/(0.00001217)
- Shortfall = (Cosgrove-Monthly_Demand)/Days_per_month

- Status = If Drought_Management = 1 THEN
  (If pquab_full >= L1 then 0 else
  If (pquab_full < L1 and pquab_full >=L2) then 1 else
  If (pquab_full < L2 and pquab_full >=L3) then 2 else
  If (pquab_full < L3 and pquab_full >=L4) then 3 else
  If (pquab_full < L4 and pquab_full >=L5) then 4 else 5) ELSE 0
  DOCUMENT: Stella model status. Included for model development convenience and does not correspond with the 3 drought emergency levels found in MWRA literature.

- Total_System__Demand = 285
- Velocity = Qcfs_2/127.649
  DOCUMENT: Tunnel velocity in ft/s

- Vulnerability = (12/Max_consec_below_target)*100
- Wachtemp = Wachusetts+Wachusetts_Inflow-Desired_Release
- Wach_Capacity = 65000
  DOCUMENT: This is the maximum capacity of Wachusett Reservoir

○ Ware_Switch = 1
DOCUMENT: Value of 1 indicates that we can transfer whereas for a value of 0 there are no transfers. Included here to demonstrate the impact of the transfers on the system.

○ Water_Available = If Wachtemp > 0.85*Wach_Capacity then (Wachtemp-0.85*Wach_Capacity) + (Quabbtemp-.1*Quabbin_Capacity) else
(Quabbtemp-.1*Quabbin_Capacity)

○ Winsor__Hydro_Power = Qcfs_1*(Quabbin_Elevation-380)*efficiency_1/11.81
DOCUMENT: Power in KW

I hp = 745.737 watts

⊘ Days_per_month = GRAPH(Month
)
(0.00, 0.00), (1.00, 31.0), (2.00, 30.0), (3.00, 31.0), (4.00, 31.0), (5.00, 28.0), (6.00, 31.0), (7.00, 30.0), (8.00, 31.0), (9.00, 30.0), (10.0, 31.0), (11.0, 31.0), (12.0, 30.0)
DOCUMENT: Note that simulation is done based on a hydrologic year that begins with October. Leap days for February (month=5) are ignored.

⊘ L1 = GRAPH(Month)
(1.00, 79.0), (2.00, 79.0), (3.00, 79.0), (4.00, 85.0), (5.00, 85.0), (6.00, 85.0), (7.00, 90.0), (8.00, 90.0), (9.00, 90.0), (10.0, 87.0), (11.0, 85.0), (12.0, 82.0)
DOCUMENT: Lower boundary for Normal Operation given as a percent full for Quabbin Reservoir. If level is between 100% and L1 status is 0 and there is no reduction in demand.

⊘ L2 = GRAPH(Month)
(1.00, 65.0), (2.00, 64.0), (3.00, 64.0), (4.00, 70.0), (5.00, 70.0), (6.00, 70.0), (7.00, 75.0), (8.00, 75.0), (9.00, 75.0), (10.0, 72.0), (11.0, 68.0), (12.0, 67.0)
DOCUMENT: This is the lower boundary for below normal operation. Reservoir levels between L1 and L2 correspond to status 1. No reduction in demand.

⊘ L3 = GRAPH(Month)
(1.00, 49.0), (2.00, 49.0), (3.00, 49.0), (4.00, 55.0), (5.00, 55.0), (6.00, 55.0), (7.00, 60.0), (8.00, 60.0), (9.00, 60.0), (10.0, 56.0), (11.0, 55.0), (12.0, 52.0)
DOCUMENT: Lower boundary for Drought Warning. If Reservoir levels are between L2 and L3 then Status 2. Reduction in demand is 5%

⊘ Monthly_factor = GRAPH(Month)
(0.00, 0.00), (1.00, 0.98), (2.00, 0.96), (3.00, 0.95), (4.00, 0.97), (5.00, 0.96), (6.00, 0.95), (7.00, 0.94), (8.00, 0.97), (9.00, 1.05), (10.0, 1.12), (11.0, 1.11), (12.0, 1.04)

⊘ Reduction = GRAPH(Status)
(0.00, 0.00), (1.00, 0.00), (2.00, 5.00), (3.00, 10.0), (4.00, 15.0), (5.00, 30.0)
DOCUMENT: Demand reductions corresponding to level status. The drought plan includes a series of actions to be taken to achieve the indicated reductions.

Swift_Instream_Req = GRAPH(TIME)
(0.00, 2201), (1.00, 982), (2.00, 620), (3.00, 620), (4.00, 560), (5.00, 620), (6.00, 600), (7.00, 620), (8.00, 1210), (9.00, 2150), (10.0, 2124), (11.0, 1671), (12.0, 1997), (13.0, 906), (14.0, 620), (15.0, 620), (16.0, 560), (17.0, 620), (18.0, 600), (19.0, 620), (20.0, 753), (21.0, 1742), (22.0, 1946), (23.0, 1363), (24.0, 1563), (25.0, 1059), (26.0, 620), (27.0, 620), (28.0, 560), (29.0, 620), (30.0, 600), (31.0, 620), (32.0, 804), (33.0, 824), (34.0, 1079), (35.0, 880), (36.0, 773), (37.0, 600), (38.0, 620), (39.0, 620), (40.0, 560), (41.0, 620), (42.0, 600), (43.0, 620), (44.0, 651), (45.0, 1383), (46.0, 1946), (47.0, 1900), (48.0, 1996), (49.0, 1415), (50.0, 620), (51.0, 620), (52.0, 560) ...

Syield_pquab = GRAPH(TIME)
(0.00, 97.6), (1.00, 97.4), (2.00, 96.5), (3.00, 97.9), (4.00, 99.8), (5.00, 99.2), (6.00, 99.0), (7.00, 99.3), (8.00, 97.2), (9.00, 94.6), (10.0, 91.9), (11.0, 89.7), (12.0, 87.4), (13.0, 85.6), (14.0, 84.6), (15.0, 85.0), (16.0, 85.1), (17.0, 87.0), (18.0, 89.7), (19.0, 89.7), (20.0, 89.2), (21.0, 87.0), (22.0, 84.7), (23.0, 82.3), (24.0, 80.4), (25.0, 80.2), (26.0, 80.5), (27.0, 81.0), (28.0, 84.9), (29.0, 88.0), (30.0, 91.1), (31.0, 91.0), (32.0, 90.2), (33.0, 88.8), (34.0, 87.3), (35.0, 85.3), (36.0, 84.6), (37.0, 87.1), (38.0, 88.7), (39.0, 92.3), (40.0, 93.9), (41.0, 95.8), (42.0, 98.0), (43.0, 98.0), (44.0, 98.1), (45.0, 96.3), (46.0, 94.8), (47.0, 93.1), (48.0, 90.8), (49.0, 89.2), (50.0, 88.9), (51.0, 90.8), (52.0, 93.7) ...
DOCUMENT: This is the percentage full of Quabbin Reservoir as computed by Arthur D. Little's Fortran Safe Yield Model using the same inputs as Stella. It is used to compare Stella results with those computed by an alternative method as a first cut at model calibration.

Syield_Wach = GRAPH(TIME)
(0.00, 61720), (1.00, 61720), (2.00, 61720), (3.00, 60429), (4.00, 64415), (5.00, 61318), (6.00, 60231), (7.00, 61720), (8.00, 61720), (9.00, 58471), (10.0, 58471), (11.0, 58471), (12.0, 58471), (13.0, 58471), (14.0, 58471), (15.0, 58471), (16.0, 58471), (17.0, 58471), (18.0, 56740), (19.0, 58128), (20.0, 58471), (21.0, 58471), (22.0, 58471), (23.0, 58471), (24.0, 58471), (25.0, 58471), (26.0, 58471), (27.0, 58471), (28.0, 59827), (29.0, 59203), (30.0, 58682), (31.0, 58471), (32.0, 58471), (33.0, 58471), (34.0, 58471), (35.0, 58471), (36.0, 58471), (37.0, 57903), (38.0, 55274), (39.0, 55537), (40.0, 55223), (41.0, 55223), (42.0, 55223), (43.0, 55223), (44.0, 61720), (45.0, 61720), (46.0, 58471), (47.0, 58471), (48.0, 58471), (49.0, 58471), (50.0, 58471), (51.0, 58471), (52.0, 58897) ...
DOCUMENT: This Wachusetts volume as computed by ADL's Fortran Safe Yield Model. Used for initial Calibration purposes.

Wach_Elevation = GRAPH(Wachusetts)
(44175, 378), (45008, 379), (45841, 380), (46674, 380), (47507, 381), (48340, 382), (49173, 383), (50006, 383), (50839, 384), (51672, 385), (52505, 385), (53338, 386), (54171, 387), (55004, 387), (55837, 388), (56670, 389), (57503, 389), (58336, 390), (59169, 391), (60002, 391), (60835, 392), (61668, 393), (62501, 393), (63334, 394), (64167, 394), (65000, 395)
DOCUMENT: Elevation above Boston City Base.
Points were obtained from Metropolitan Water Works Wachusett Reservoir tables of November 1908

⊘ ware_days = GRAPH(TIME)
(0.00, 0.00), (1.00, 9.00), (2.00, 2.00), (3.00, 27.0), (4.00, 15.0), (5.00, 30.0), (6.00, 27.0), (7.00, 18.0), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 5.00), (15.0, 20.0), (16.0, 8.00), (17.0, 20.0), (18.0, 30.0), (19.0, 18.0), (20.0, 6.00), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 6.00), (26.0, 14.0), (27.0, 21.0), (28.0, 28.0), (29.0, 31.0), (30.0, 30.0), (31.0, 14.0), (32.0, 1.00), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 3.00), (37.0, 29.0), (38.0, 31.0), (39.0, 31.0), (40.0, 28.0), (41.0, 30.0), (42.0, 30.0), (43.0, 30.0), (44.0, 8.00), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 3.00), (50.0, 9.00), (51.0, 18.0), (52.0, 28.0) ...
DOCUMENT: No of days in month transfer from Ware river is possible. During these days there is no flow from Quabbin to Wachusett

⊘ Ware_River_PT = GRAPH(TIME)
(0.00, 0.00), (1.00, 1450), (2.00, 230), (3.00, 2707), (4.00, 5900), (5.00, 2022), (6.00, 8500), (7.00, 1057), (8.00, 0.00), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00), (12.0, 0.00), (13.0, 0.00), (14.0, 201), (15.0, 1019), (16.0, 310), (17.0, 2669), (18.0, 4059), (19.0, 588), (20.0, 253), (21.0, 0.00), (22.0, 0.00), (23.0, 0.00), (24.0, 0.00), (25.0, 1253), (26.0, 1008), (27.0, 950), (28.0, 4922), (29.0, 4189), (30.0, 4559), (31.0, 590), (32.0, 5.17), (33.0, 0.00), (34.0, 0.00), (35.0, 0.00), (36.0, 58.2), (37.0, 3859), (38.0, 2564), (39.0, 4778), (40.0, 2155), (41.0, 2421), (42.0, 4372), (43.0, 1204), (44.0, 889), (45.0, 0.00), (46.0, 0.00), (47.0, 0.00), (48.0, 0.00), (49.0, 71.1), (50.0, 606), (51.0, 2309), (52.0, 3588) ...
DOCUMENT: Potential transfer volume (MG) that can be diverted from the Ware river. This is precomputed from the Ware river time series.

Diversion from the Ware River is limited to periods when Ware flow is greater than 85 mgd and is prohibited between June 15 and October 15

☐ Below_Normal_Months(t) = Below_Normal_Months(t - dt) + (Noname_1) * dt
INIT Below_Normal_Months = 0
INFLOWS:
Noname_1 = If Status = 1 then 1 else 0

☐ Consecutive_periods_below_target(t) = Consecutive_periods_below_target(t - dt) + (Counter - empty_the_reservoir) * dt
INIT Consecutive_periods_below_target = 0

INFLOWS:
Counter = Below_Target
OUTFLOWS:
empty_the_reservoir = if Below_Target=0 then Consecutive_periods_below_target else 0

☐ Drought_Warning_Months(t) = Drought_Warning_Months(t - dt) + (Noname_6) * dt
INIT Drought_Warning_Months = 0
INFLOWS:
Noname_6 = If Status = 2 then 1 else 0

☐ Maximum_deviation(t) = Maximum_deviation(t - dt) + (This_month - Min_Out) * dt
INIT Maximum_deviation = 0
INFLOWS:
This_month = Feet_below_target
OUTFLOWS:
Min_Out = Min(This_month,Maximum_deviation)

☐ Max_consec_below_target(t) = Max_consec_below_target(t - dt) + (New_consecutive_below_target - Out_consec_below_target) * dt
INIT Max_consec_below_target = 0

INFLOWS:
New_consecutive_below_target = Consecutive_periods_below_target
OUTFLOWS:
Out_consec_below_target = min(Max_consec_below_target,New_consecutive_below_target)

☐ Quabbin_Reservoir(t) = Quabbin_Reservoir(t - dt) + (Inflow + Ware_River_Intake_2 - Chicopee_Valley_Aqueduct - Spill_to_Swift_River - Swift_River_Release - Quabbin_Aqueduct) * dt
INIT Quabbin_Reservoir = Quabbin_Capacity

INFLOWS:
Inflow = Inflow_2*186
DOCUMENT: Inflow data has to be converted from Million Gallons Per Month Per Square mile by multiplying by Quabbin's drainage area of 186 Sq miles

Ware_River_Intake_2 = If Ware_Switch = 1 AND (Quabbtemp-Ware_River_PT) < 0.98*Quabbin_Capacity then min(Ware_River_PT,(0.98*Quabbin_Capacity - Quabbtemp-Ware_River_PT))
Else IF Ware_Switch = 1 AND (Quabbtemp-Ware_River_PT) > 0.98*Quabbin_Capacity THEN 0
ELSE 0
OUTFLOWS:
Chicopee_Valley_Aqueduct = IF Quabbin_Reservoir - Swift_River_Release+Inflow>=CVA_demand Then CVA_demand ELSE Quabbin_Reservoir+Inflow -Swift_River_Release

Spill_to_Swift_River = IF Quabbtemp-Quabbin_Aqueduct>Quabbin_Capacity then Quabbtemp-Quabbin_Aqueduct-Quabbin_Capacity else 0

Swift_River_Release = Swift_Instream_Req
DOCUMENT: mgd
This release is required by law for low flow augmentation

Quabbin_Aqueduct = IF By_Pass_On = 0 THEN
If ((Wachtemp-Monthly_Demand)/Wach_Capacity)>.95
or
(Quabbtemp/Quabbin_Capacity)<.05 then 0
else min(Aqueduct_Capacity,.90*Wach_Capacity-Wachtemp+Monthly_Demand)
ELSE
Min(Monthly_Demand, (Quabbtemp-.1*Quabbin_Capacity))

DOCUMENT: Transfers done when Wachusett is below 95%.
Try to keep Wachusett's target pool at 90% capacity

Stage_1_months(t) = Stage_1_months(t - dt) + (Noname_3) * dt
INIT Stage_1_months = 0
INFLOWS:
Noname_3 = If Status = 3 then 1 else 0

Stage_2_Months(t) = Stage_2_Months(t - dt) + (Noname_7) * dt
INIT Stage_2_Months = 0
INFLOWS:
Noname_7 = If status = 4 then 1 else 0

Stage_3_Months(t) = Stage_3_Months(t - dt) + (Noname_5) * dt
INIT Stage_3_Months = 0
INFLOWS:
Noname_5 = If status = 5 then 1 else 0

Sum_of_Periods(t) = Sum_of_Periods(t - dt) + (Below_Target) * dt
INIT Sum_of_Periods = 0
INFLOWS:
Below_Target = IF Quabbin_Elevation<Elevation_target THEN 1 Else 0

Sum_of_Shortfall_Months(t) = Sum_of_Shortfall_Months(t - dt) + (Shortfall__Month) * dt
INIT Sum_of_Shortfall_Months = 0
INFLOWS:
Shortfall__Month = if Shortfall = 0 then 0 else 1

Wachusetts(t) = Wachusetts(t - dt) + (Wachusetts_Inflow + From_Quabbin - Nashua_Release - Nashua_Spill - From_Wach) * dt
INIT Wachusetts = Wach_Capacity
INFLOWS:
Wachusetts_Inflow = Wachusetts_Inflow_2*108

DOCUMENT: Convert from MGM/Sq.mi to MGM by multiplying with Wachusetts Drainage area of 108 Sq miles

From_Quabbin = Quabbin_Aqueduct-By_Pass
OUTFLOWS:
Nashua_Release = IF Wachusetts+Wachusetts_Inflow>=Desired_Release THEN Desired_Release ELSE Wachusetts_Inflow+Wachusetts
Nashua_Spill = IF Wachtemp+From_Quabbin-From_Wach>Wach_Capacity then Wachtemp+From_Quabbin-From_Wach-Wach_Capacity else 0

From_Wach = Cosgrove-By_Pass

UNATTACHED:

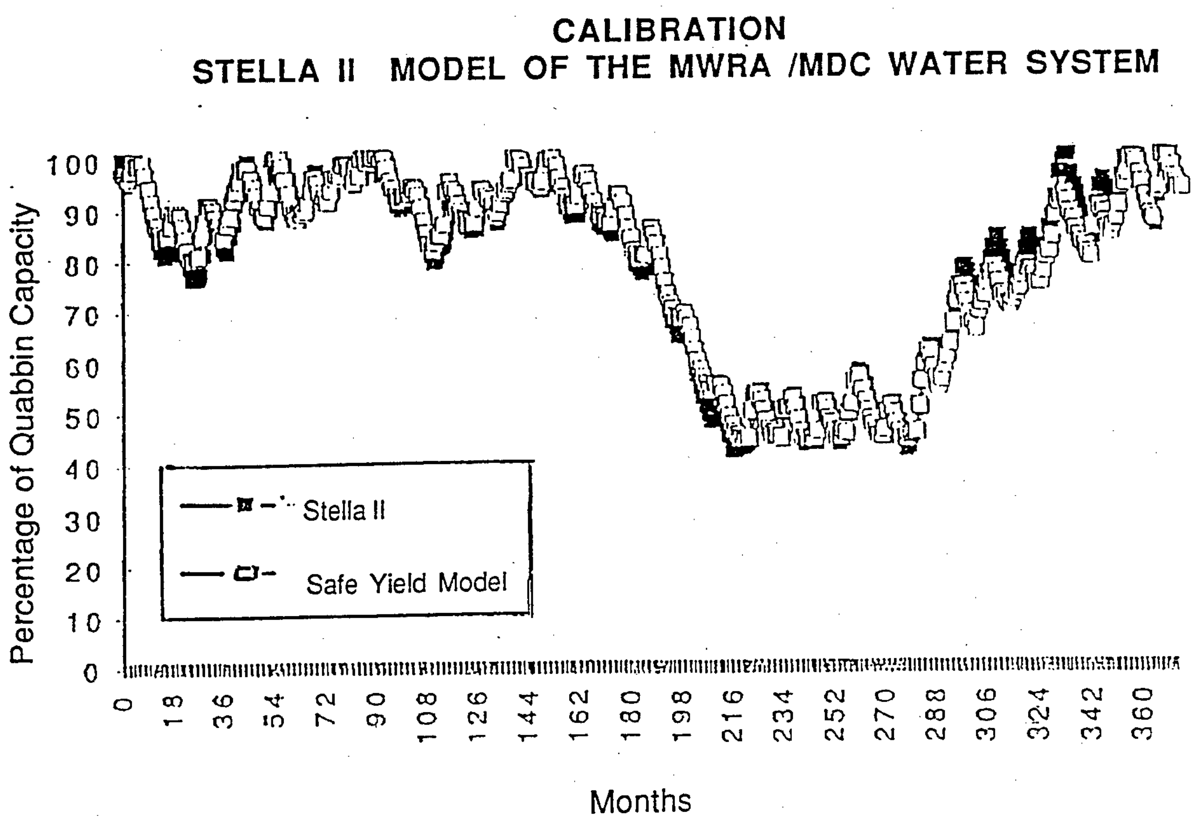
By_Pass = If By_Pass_On = 1 then Quabbin_Aqueduct else 0
DOCUMENT: Bypass expected to be constructed in 2001 AD. Included in the system configuration in order to enable computing its impact on the performance of the system.

Cosgrove = Min(Monthly_Demand,Water_Available)

MODEL CALIBRATION

MODEL CALIBRATION

The STELLA II Model of the MWRA/MDC Water System was calibrated by comparing its outputs to those of the MWRA Safe Yield Model. The time modeled was that of the Safe Yield Model or the period October 1949 through September 1980 for the Quabbin/Ware/Wachusett system without Sudbury Reservoir .The target pool was set at 490 feet (BCB) and the demand at 280 mgd. According to the MWRA, the rationale for comparing the STELLA II to the Safe Yield Model is the latter had gained credibility in terms of the operation of the system. If the STELLA II Model were to duplicate its results, it shall be considerred sufficiently calibrated. The following graph demonstrates that the STELLA II Model closely duplicates the Safe Yield Model and therefore reasonably represents the operation of the MWRA/MDC Water System.



APPENDIX C

LEADING INDICATORS FOR TRIGGER PLANNING

Appendix C
LEADING INDICATORS FOR TRIGGER PLANNING

BACKGROUND

Trigger Planning, a concept introduced by the Water Supply Citizens Advisory Committee in 1982, is currently being applied and further developed in the New England Drought Study. In this application, it is a decision-making tool to assist the MWRA/MDC in integrating strategic, drought contingency and emergency water resources planning into a single planning concept to ensure that the future water supplies are adequate to meet projected water demand. The outcome would be a systematic procedure for deciding what studies and actions should be undertaken to prevent supply shortfalls and, in the event of a projected shortfall, what projects should be built and when preparation for construction should begin.

Trigger Planning is facilitated by the use of the STELLA II interactive software which models the configuration and operation of the MWRA/MDC water supply system and permits the simulation of different future strategies and their impacts on the system. The STELLA II application of Trigger Planning thus permits planners to compress space by portraying the water system on the computer screen and to compress time by simulating different futures and instantaneously evaluating their outcomes. The interactive nature of the model facilitates the building of consensus among interested parties such as the managers of the MWRA system and the citizens group, WSCAC and eventually the MWRA Advisory Board and other interested parties.

Within the context of ensuring that future water supply is adequate to meet projected demand for water in the MWRA/MDC system, trigger planning provides a framework for monitoring indicators of changes in supply and demand. These indicators are intended to give advance notice as to whether the system is expected to approach its CRITICAL POINT or the point at which future supply would not be adequate to meet demand. The LEAD TIME is the time necessary to implement a strategy or a series of actions to ensure the adequacy of future supply. These actions can require upwards to 9 to 15 years for the implementation of large scale supply augmentation projects. Monitoring of the indicators of changes in supply and demand would permit planners to anticipate whether or not TRIGGER POINTS, or points at which actions to prevent a shortfall should be initiated, are being approached. Figure 10 in the main text presents a scheme for the overall trigger planning concept including the identification and monitoring of leading indicators and annual trigger planning assessments. Figure 11 presents a decision tree for these assessments.

INTRODUCTION

An indicator is a quantifiable phenomenon, that is so closely associated with the behavior of a particular condition, that it may be used, in conjunction with other indicators, to identify the occurrence of the condition. A leading indicator is one that would point toward the occurrence of a future condition. One of the more commonly known uses of leading indicators is for forecasting economic conditions. The National Bureau of Economic Research has pioneered this forecasting method which exploits observed historical timing relationships through the use of certain variables that in the past have given advanced notice of economic events. In economic terms, "A leading indicator is a variable that, experience has shown, normally turns down before recessions start and turns up before expansion begins." (1)

Accordingly, leading indicators should satisfy three criteria: relevance, timeliness, and accessibility. (2) RELEVANCE has to do with the historical behavior of the indicator to significantly demonstrate association with the condition. TIMELINESS is the amount of advance notice that a leading indicator would afford a user in predicting the occurrence of a condition. ACCESSIBILITY is the availability of data on the leading indicator.

The aspect of time determines whether the indicator is a lagging, coincident or leading one. Leading indicators may give false signals. Their signals should therefore be confirmed by comparison with those of other leading and coincident indicators.

The present application of Trigger Planning considers a planning horizon of twenty years and lead times of nine to fifteen years to implement to implement a large scale supply augmentation project. The leading indicators should therefore also have the quality of SUSTAINABILITY, or the ability to be relevant for the period under consideration.

MUNICIPAL AND INDUSTRIAL (M&I) WATER SYSTEMS

The primary use of indicators and leading indicators in the present application of Trigger Planning is to provide water resources planners and managers with a bundle of indices for making decisions on issues concerning the demand on and the supply capacity of the MWRA/MDC water system. Those indicators that move with the demand and the supply capacity are coincident indicators and are used in concert with others to confirm changes in demand and capacity. Leading indicators anticipate changes in demand and supply and can be monitored to give advance notice to water resources managers of impending stresses between the supply and demand for water. The present Trigger Planning exercise is concerned primarily with signals of changes in demand and supply that may lead to a supply shortfall.

Concerning possible future water supply shortfalls, it is essential that the determinants of demand and supply, and the factors that give advance notice of changes in these determinants and in turn changes in the supply or demand for water, be identified.

DETERMINANTS AND INDICATORS FOR THE MWRA/MDC SYSTEM

HISTORICAL WATER USE

The quantities of water released from MWRA/MDC system reservoirs ranged from 237 mgd in 1960 to a peak of 347 mgd in 1976 to 257 mgd in 1992. Water delivered by the MWRA/MDC to communities in the service area for the same period has risen from 235 (mgd) in 1960 to a peak of 314 mgd in 1971 and 1972 then declined to 243 mgd in 1992. The differences between the releases and deliveries is MWRA/MDC's "unaccounted water" consisting, among others, of leakage. In addition, the individual water systems also have "unaccounted water". Figures C-1 and 2 graphically present the historical water deliveries to the MWRA/MDC communities, the city of Boston and the remaining communities in the service area as well as the evolution of water deliveries to Boston and five other mature communities in the metropolitan area (Arlington, Chelsea, Everett, Somerville and Watertown) using in excess of 2.5 mgd and experiencing a decline in water use between 1960 and 1991. Boston represented about one-half of all deliveries in 1960 and 47 percent at the system's peak demand in 1971 and 1972 and 40 percent in 1991. Boston and the five other declining water users represented approximately 62 percent of deliveries in 1960 and about one-half in 1991.

MWRA has estimated unaccounted water in the early 1980's as representing about one third of all water released from its reservoirs and local sources. Since that time the MWRA and member communities have undertaken aggressive leak detection and repair and other demand management measures so that by 1990 unaccounted water was reduced to 20 percent. (3) These reductions will tend to mask the reductions attributable to the different determinants of demand.

DETERMINANTS OF WATER USE

With respect to water demand, the IWR-MAIN Water Use Forecasting System (IWR-MAIN) projects the level and pattern of municipal water use in the following categories: (4)

- Residential water use
- Commercial/Institutional water use
- Industrial water use
- Public/Unaccounted Water Use

Projections of water demand in these categories is accomplished on the basis of demographic, socioeconomic, and climatic characteristics in the service area. These determinants are:

- Resident and seasonal population
- Number, market value and types of housing units
- Employment in service industries
- Manufacturing employment and output
- Water and wastewater prices and rate structure
- Irrigated acreage, residential and commercial/institutional use
- Personal income
- Climate
- Weather conditions
- Water-using appliances
- Conservation activities

All of these determinants are directly observable and therefore serve the dual role of determinant and indicator. Theoretically, they could serve as surrogates of water use in the above four water use categories. A comparison of historical behavior of these individual indicators and corresponding water use categories would be useful. Unfortunately, MWRA time series water use data is not disaggregated in the four categories. In addition to the determinants of water demand, there may be other parameters that anticipate the behavior of the determinant and in turn water use.

Also, there are other determinants of water demand peculiar to particular municipal water systems. For the MWRA/MDC system, these are related to the extent of the service area and the condition of local supplies of water for communities that are currently partially supplied by the MWRA and communities adjacent to the current service area.

LEADING INDICATORS FOR THE MWRA/MDC SYSTEM

Leading indicators of changes in the future water supplies of the MWRA/MDC system are those that provide lead time in anticipating changes in the quantity and quality of water available. Again leading indicators must satisfy four basic criteria: relevance, timeliness, accessibility and sustainability. Table C-1 presents the determinants/ indicators and leading indicators in terms of the demand and the supply of water and subcategories. Some determinants/indicators may also be leading indicators.

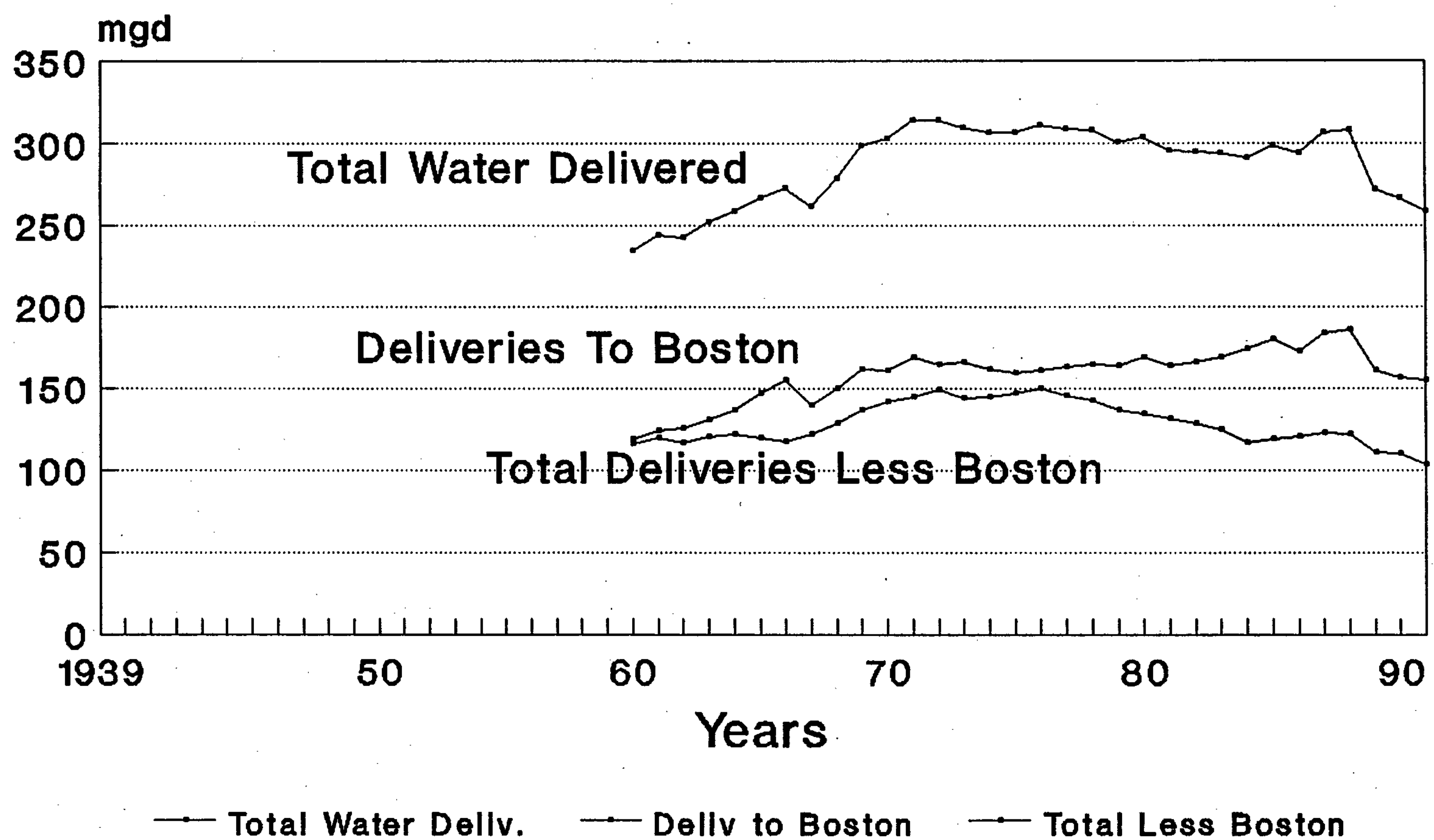
CUSTOMERS SERVED

All of the determinants in Table C-1 listed in the category: number of communities in the service area and the condition of sources, satisfy the four conditions for leading indicators. The number of communities in the MWRA/MDC service area increased from 22 cities and towns using 143 mgd in 1940 to 42 communities, using 300 mgd in 1970, to 44 and 46 communities respectively in 1980 and

Figure
C-1

THE NEW ENGLAND DROUGHT STUDY

WATER DELIVERED
MWRA/MDC SERVICE AREA

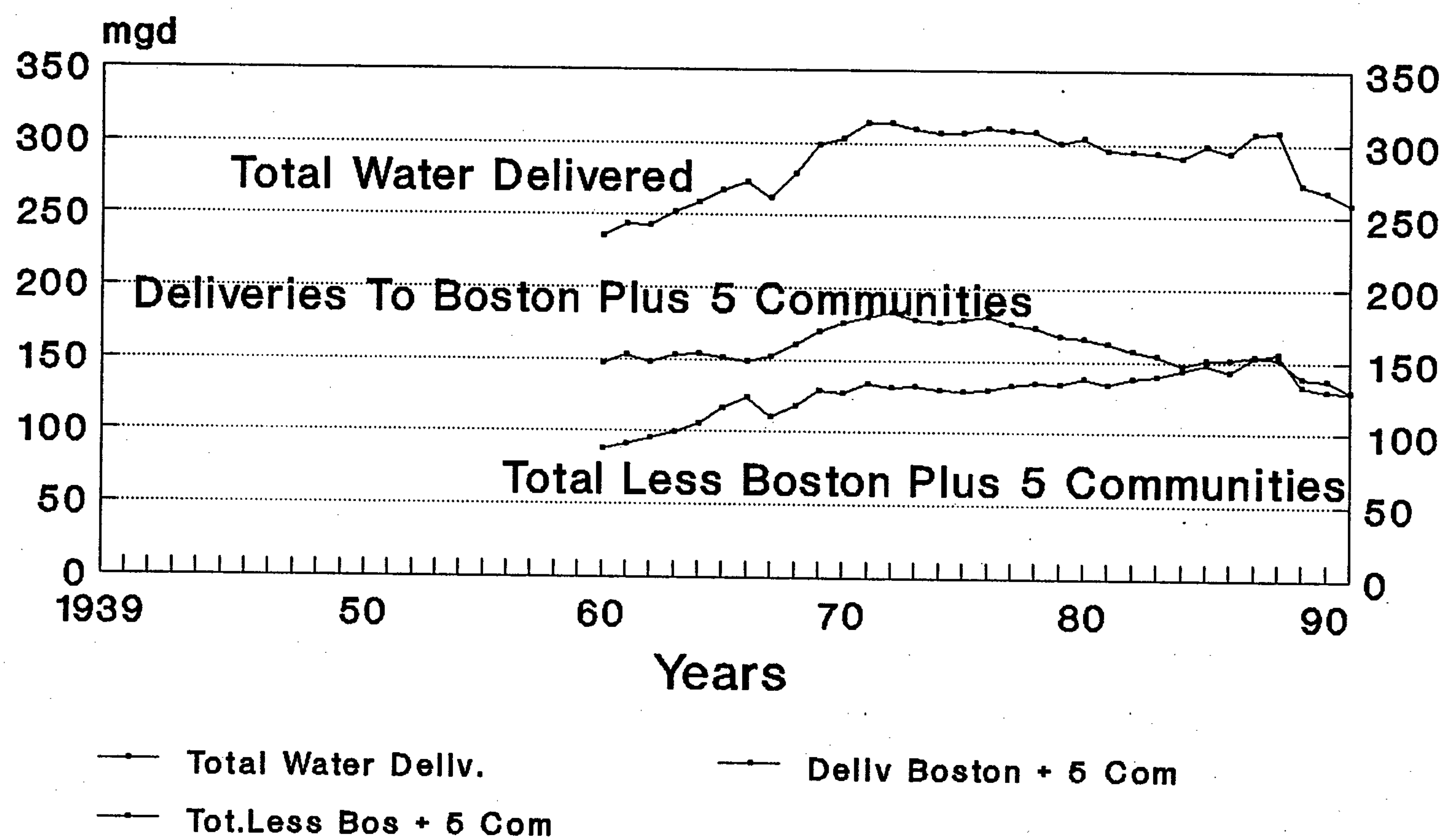


Source: MWRA,Waterworks,Bos.,MA. MWRA-24

Figure
C-2

THE NEW ENGLAND DROUGHT STUDY

WATER DELIVERED
MWRA/MDC SERVICE AREA



Source:MWRA,Waterworks,Bos.,MA. MWRA-26

1992. In 1990, the 15 communities partially supplied with water from the MWRA/MDC used nearly 90 mgd of which approximately 74 mgd was withdrawn from local sources and 16 mgd from the MWRA/MDC system. If one of these communities were to lose its water supply, an additional demand of 25 mgd could be put on the MWRA/MDC Water System. The MWRA has identified 27 communities, located adjacent to the MWRA service area, whose supplies may be in danger of contamination. Average daily water demand for these communities is nearly 60 mgd. The largest users among these communities consume 4 to 7 mgd. The possibility that communities in the region may view the MWRA/MDC as the supply of last resort makes projections of future water use sensitive to the condition of the sources used by these communities and particularly those communities that are already partially served or adjacent to the current service area. The change in the number of communities in the MWRA service area and the condition of local sources of supply in and adjacent to the MWRA service area are therefore leading indicators of future water demands. Although the MWRA monitors these factors, the condition of these resources and changes in the MWRA/MDC service communities should be integrated into the trigger planning process as leading indicators.

RESIDENTIAL POPULATION SERVED

Several conditions deter the MWRA from tracking water use through population and housing data for the MWRA service area. MWRA does not generate time series residential water use data to permit an analysis of the linkage to residential population and residential housing statistics. Reliable population and housing statistics are not available except from the national census which is undertaken every ten years. However, system managers should monitor socioeconomic conditions in the service area including population projections undertaken by regional agencies in order to project future water use.

Residential building permits fulfill all of the conditions for leading indicators except sustainability. Data for new privately owned housing units authorized in permit issuing places is compiled by the U.S. Bureau of Census and available on a monthly basis at the community and county levels. An estimated 82 to 95 percent lead to construction. Figure C-3 presents time series data for private building permits issued for twenty-five of the communities fully supplied with water by the MWRA/MDC from 1966 to 1992 and corresponding water use data. (5) Between 82 and 95 percent of the permits are estimated to lead to building construction. Building permit data has shown itself to be a be a somewhat reliable and early and volatile indicator of changes in near future water use. The annual reportings for the twenty-five communities anticipated an upturn in water use by two years in 1983 and a downturn by two years in 1987. The permit data is however of limited use for predicting water use some nine to twenty years in the future. The data on private building permits authorized in permit issuing places has been shown to have predictive qualities for near future water use in the MWRA/MDC Water System. However these trends may not be sustained. Building permits should therefore be used with caution as a leading indicator for future capacity stress.

Housing start data is collected nationally using sampling techniques by the Bureau of the Census and released for the four U.S. regions (Northeast, Midwest, South and West) and forty metropolitan areas not including Boston. Because of the lack of disaggregation to the community level, housing start data cannot be considered as a leading indicator of water use for the MWRA/MDC system.

INDUSTRIAL WATER USE

The determinants of industrial water use are employment and production. Time series industrial water use data is not available to permit the correlation of the latter with industrial water use for the MWRA communities. In the absence of directly relevant data, relationships have been investigated between some more remote parameters to water use. Figures C-4 to 8 graphically present available data for total and some forms of disaggregated water use and employment. Unfortunately, the tracking of any of the employment parameters would not permit managers to know in advance of impending changes in the demand for water.

RATE OF WATER USE

Concerning those determinants of the rate of water use: climatic patterns, water and wastewater prices and rate structure and demand management practices, and based on available data, no leading indicators have, as yet, been identified. However, studies of the responses of water demand to changes in the price of water and to demand management measures would be useful for water use projections.

CHANGES IN WATER USE AND QUANTITY OF WATER AVAILABLE TO MWRA/MDC SYSTEM

With respect to changes in water use and on the supply side, quantity of water available to the MWRA/MDC system, monitoring of both local attitudes on water resources and events and proposed projects for their impact on water supply and demand, can provide municipal water users with advance notice on changes in the demand and supply of water. Climate, precipitation and streamflow, system operating procedures, regulatory definitions, and water exchange agreements offer indications of the quantity of water that would be available in a water supply system. The systematic monitoring of these factors within the trigger planning model can, in combination with other leading indicators, serve as predictors of changes in water supply and demand.

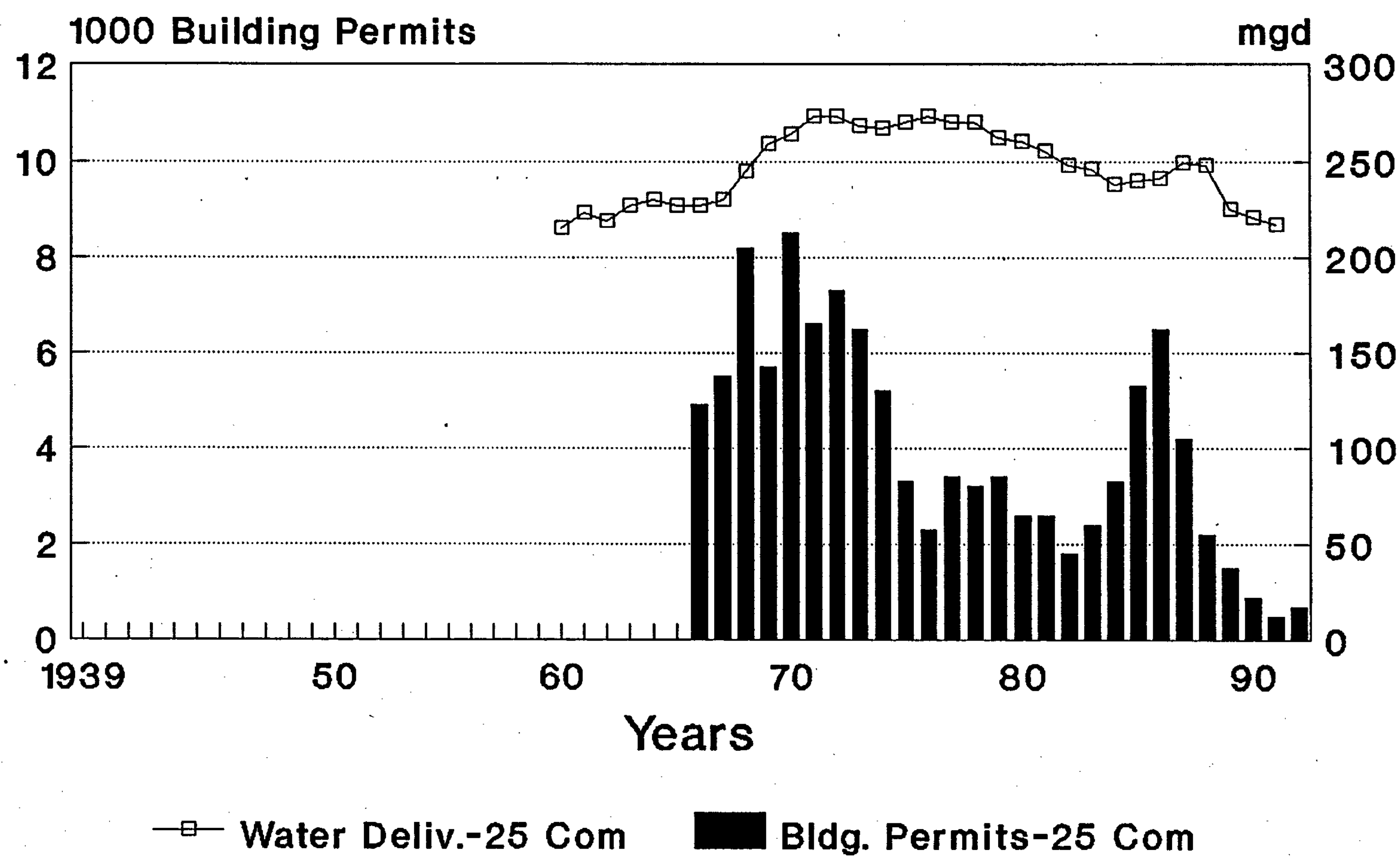
QUALITY OF WATER IN MWRA/MDC SYSTEM

The monitoring of watershed conditions will permit planners to undertake improved estimates of the quality of the water for future supply without and with treatment.

Figure
C-3

THE NEW ENGLAND DROUGHT STUDY

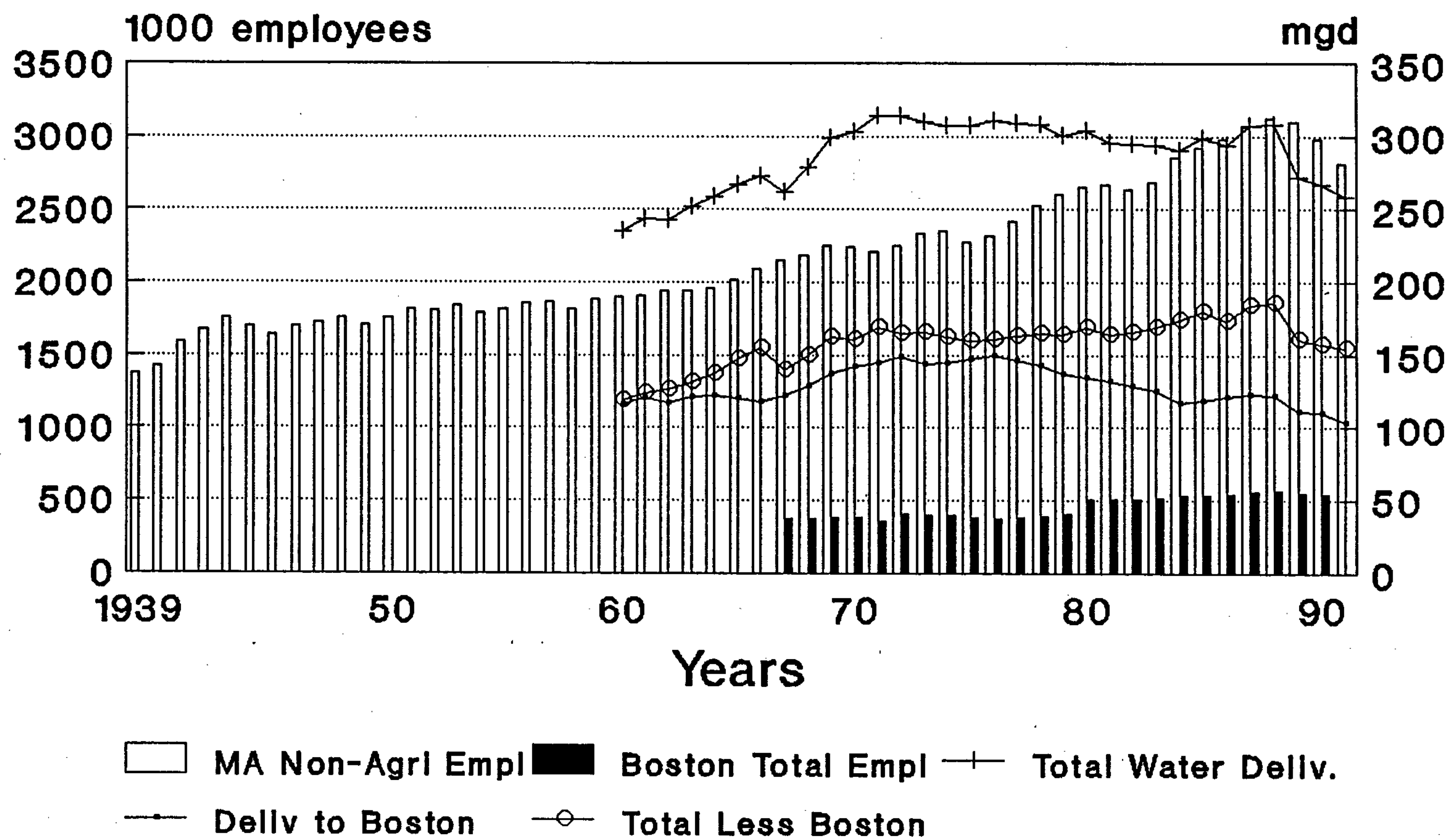
BUILDING PERMITS AND WATER DELIVERIES 25 MWRA/MDC COMMUNITIES



Sources: MWRA, US Dept Commerce MWRA-19B

Figure
C-4

WATER USE AND EMPLOYMENT MWRA/MDC SERVICE AREA

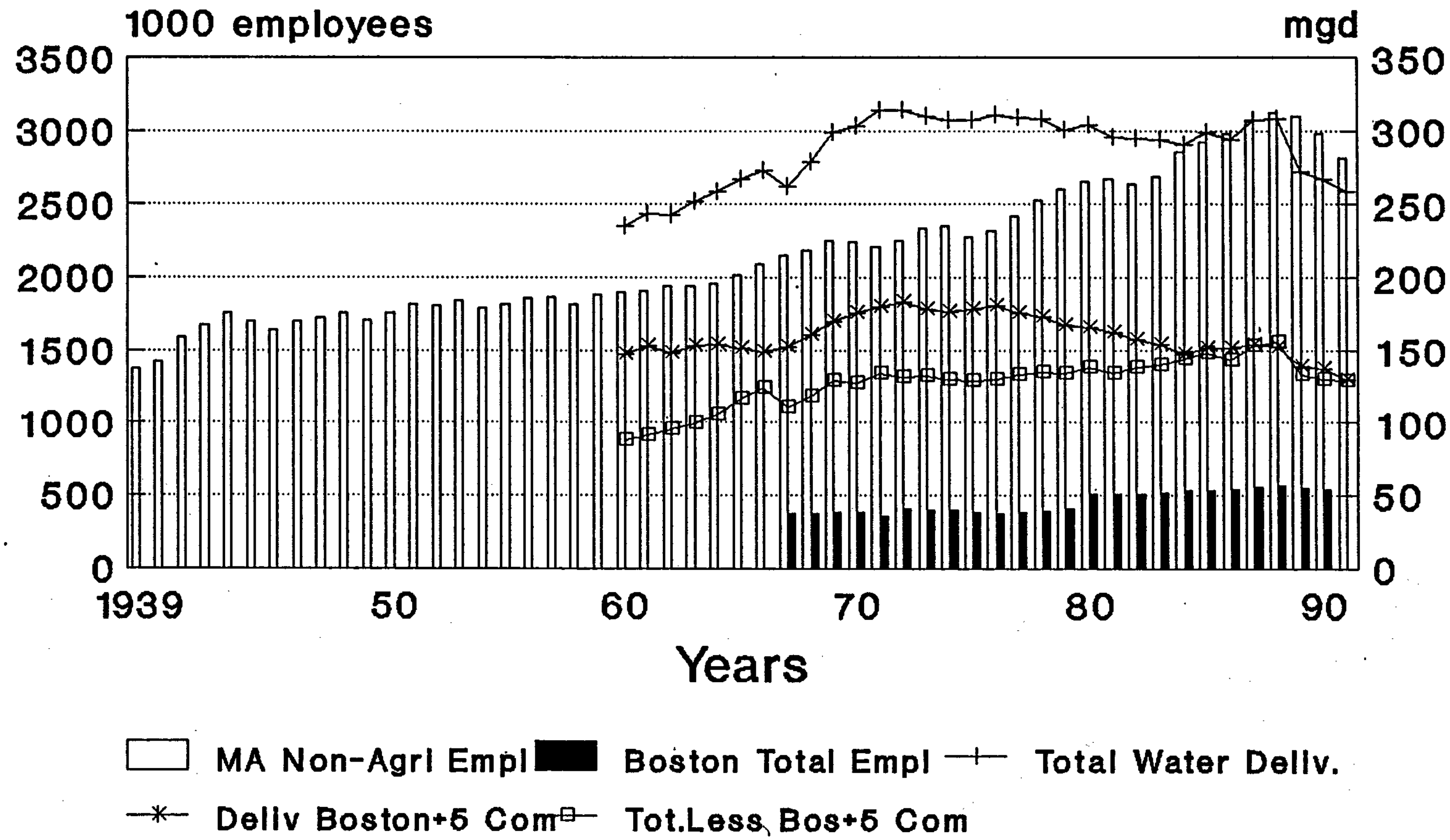


Sources:MWRA, MA DET, US BLS MWRA-15

Figure
C-5

THE NEW ENGLAND DROUGHT STUDY

WATER DELIVERED & EMPLOYMENT MWRA/MDC SERVICE AREA

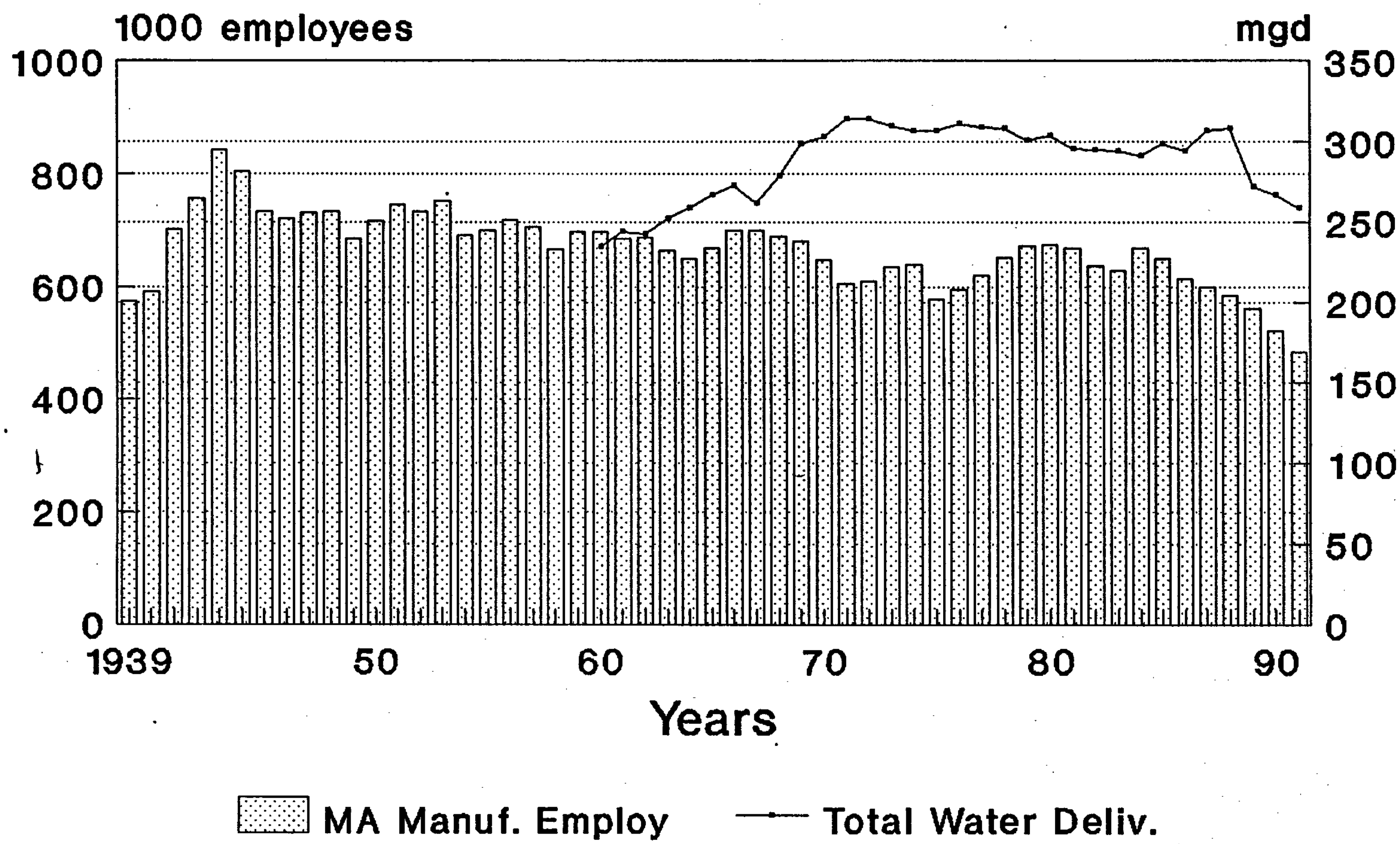


Sources:MWRA,MA DET,US BLS MWRA-27

Figure
C-6

THE NEW ENGLAND DROUGHT STUDY

WATER USE AND EMPLOYMENT
MWRA/MDC SERVICE AREA

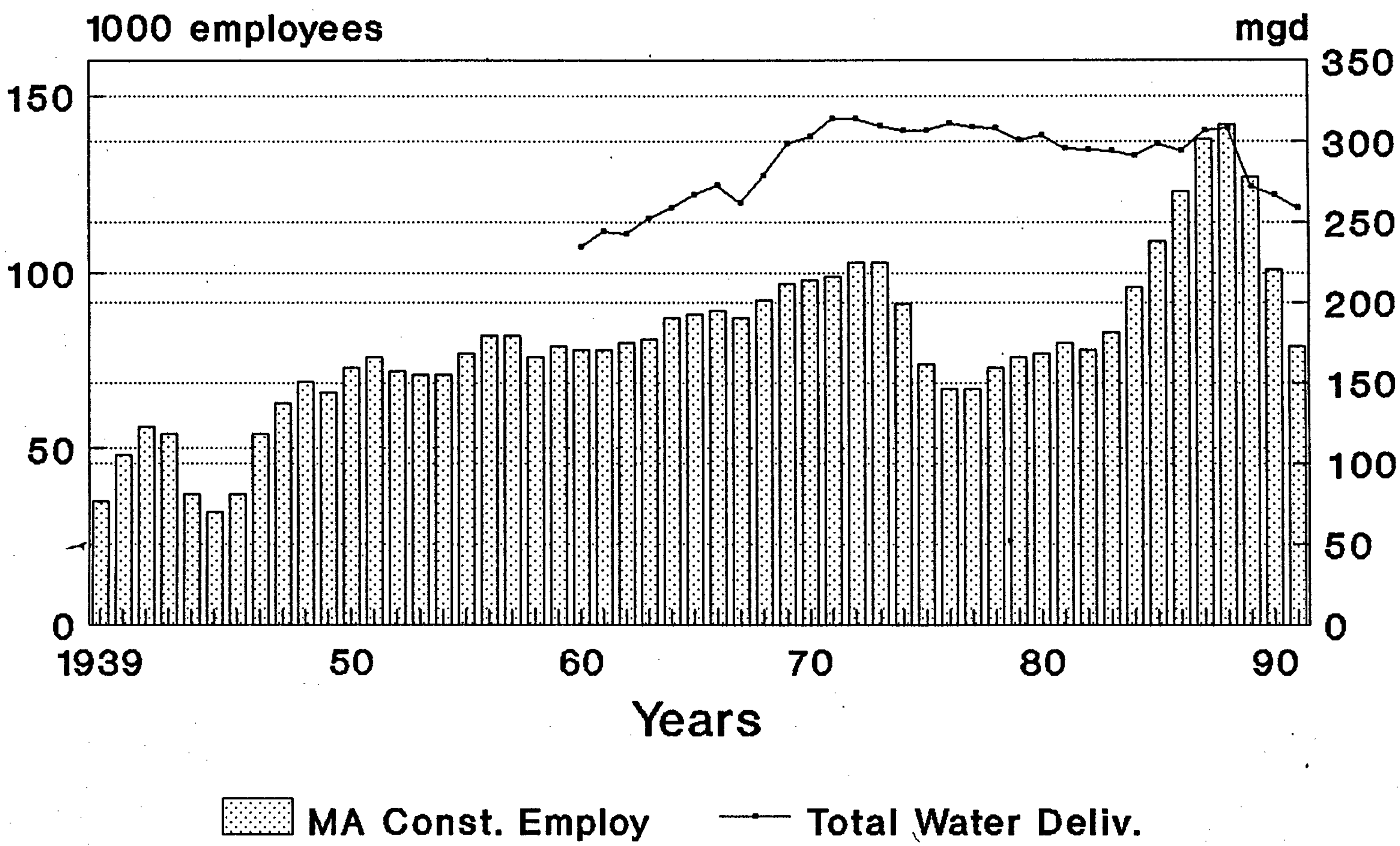


Sources: MWRA,MA DET, US BLS   MWRA-17

Figure
C-7

THE NEW ENGLAND DROUGHT STUDY

WATER USE AND EMPLOYMENT
MWRA/MDC Service Area

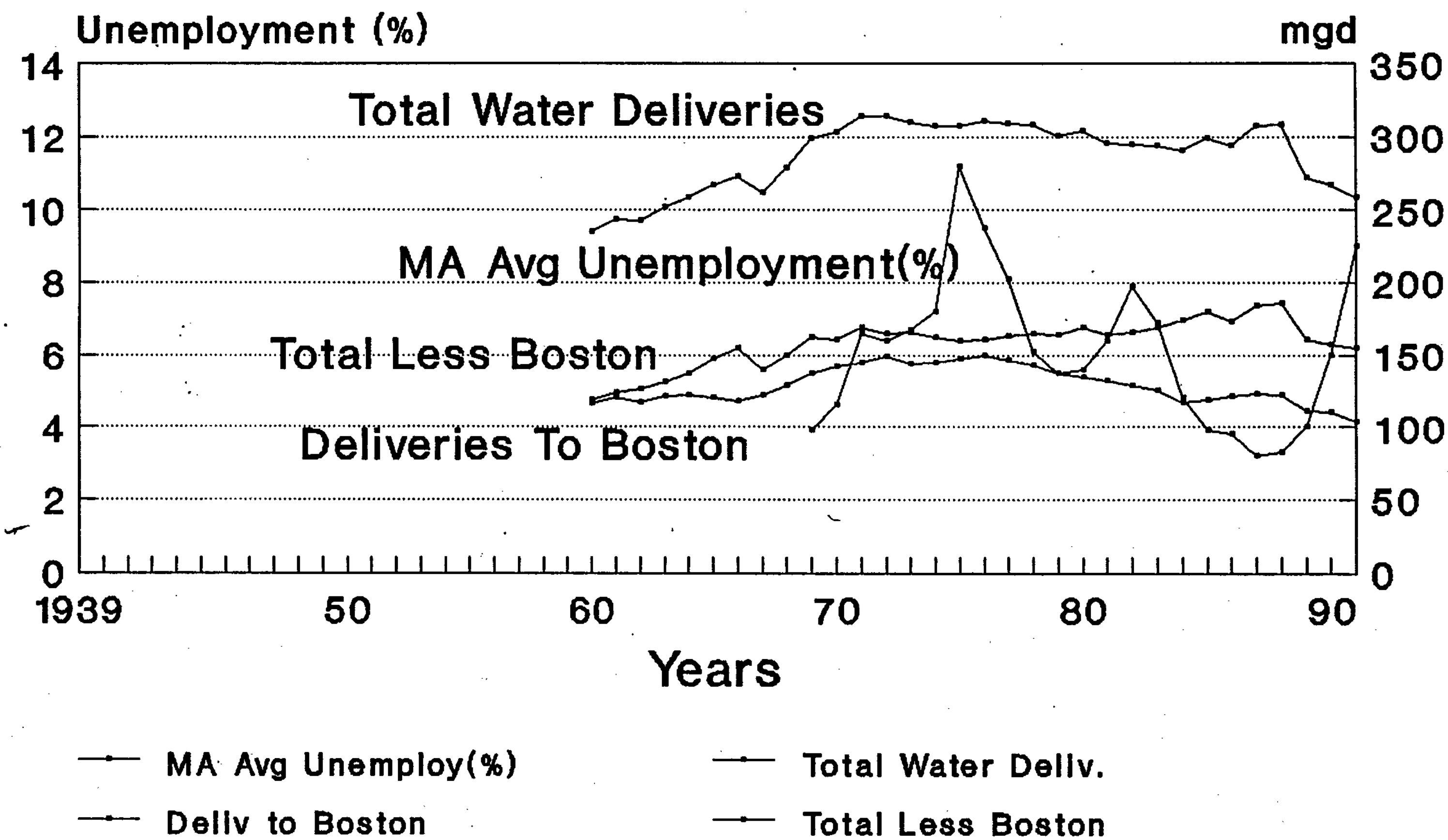


Sources: MWRA,MA DET, US BLS   MWRA-16

Figure
C-8

THE NEW ENGLAND DROUGHT STUDY

WATER USE AND UNEMPLOYMENT MWRA/MDC SERVICE AREA



Sources:MWRA, MA DET, US BLS MWRA-21

Table C-1

The New England Drought Study

DETERMINANTS, INDICATORS AND LEADING INDICATORS OF CHANGES IN THE SUPPLY AND DEMAND FOR WATER IN MWRA/MDC SERVICE AREA

DETERMINANTS\INDICATORS	LEADING INDICATORS
<u>DEMAND SIDE</u>	
<u>Customers served</u>	
- number of communities in MWRA service area	- changes in number of communities in MWRA service area
- condition of sources in the MWRA partially supplied communities	- condition of sources in the MWRA partially supplied communities
- condition of sources in communities adjacent to the MWRA service area	- condition of sources in communities adjacent to the MWRA service area
- condition of sources for self-supplied users in the MWRA service area	- condition of sources for self-supplied users in the MWRA service area
<u>Residential population served</u>	
- population	
- number, value and types of housing units	- building permits
<u>Industries served</u>	
- employment	
<u>Rate of water use</u>	
- climatic patterns	
- water and wastewater prices and rate structure	
- demand management practices	
<u>Changes in water use</u>	
- events and proposed projects that may have significant impacts on the demand for water in the MWRA service area	- events and proposed projects that may have significant impacts on the demand for water in the MWRA service area
- local views on water resources management, conservation, and use	- local views on water resources management, conservation & use

Table C-1 (Continued)

DETERMINANTS\INDICATORS	LEADING INDICATORS
SUPPLY SIDE	
Natural and human-made quality of water in MWRA/MDC system	
- watershed conditions and development	- watershed conditions and development
Quantity of water available to MWRA/MDC system	
- climate	- climate
- precipitation and streamflow	- precip. and streamflow
- operational procedures	- operational procedures
- regulatory definitions and requirements	- regulatory definitions and requirements
- water exchange agreements	- water exchange agree.
- species representation in the watersheds	
- events and proposed projects that may have significant impacts on the availability of water to serve the MWRA service area	- events and proposed projects that may have significant impacts on availability of water
- local views on water resources management, conservation and use	- local views on water resources management, conservation and use

CONCLUSIONS

There is no substitute for the real time monitoring of the two principal factors in predicting potential imbalances in the supply and demand for water for the MWRA/MDC Water Supply System: THE DEMAND FOR WATER and THE SUPPLY OF WATER. The relationship of supply to demand is sensitive to factors that affect supply and demand. The supply and demand for water are subject to the vagaries of human behavior and conditioned by how the society decides to manage, use and conserve its resources and what will be produced. On a routine basis the MWRA should monitor water use patterns and trends in the following categories and other variables in addition to leading indicators.

WATER USE

- Large users whether industrial, commercial or institutional
- Communities and particularly the larger communities
  - .where demand is increasing
  - .where demand is stable or declining
- Demand by community disaggregated in the following categories: residential, commercial, institutional, industrial, etc.
- Per capita water use
- Impacts of demand management

EMPLOYMENT

POPULATION

The following indicators satisfy the four conditions of relevance, timeliness, accessibility and sustainability for leading indicators as predictors of capacity supply stress. Building permits have been included although they may not be sustainable for use in longer term predictions of water use.

- The condition of local sources
- Events and proposed projects
- Laws, regulations and agreements
- Watershed conditions and operational procedures
- Climate, precipitation and streamflow
- Public views
- Building permits

1. <u>The Condition of Local Sources in MWRA/MDC Service Communities and Adjacent Communities</u> - If one of the 15 communities currently partially supplied with MWRA/MDC water or one of the 27 communities adjacent to the MWRA/MDC service area were to require full supply from the system because of contamination, for example, demand could suddenly increase by as much as 25 mgd. The condition of local sources is a principle leading indicator because of the suddenness and volatility of potential increases in demand.

2. Events and Proposed Projects Potentially Affecting Demand - The MWRA should systematically analyze all events and proposed projects for their potential effect on MWRA/MDC water demand. These effects can be the direct result of the location of water using industries or more indirect from the impact on employment and then water use, for example.

3. Laws, Regulations, and Agreements - Laws, regulations and agreements affect the ways that water and related land resources are used. More recently those that have had the greatest impact on the demand and supply of water in the MWRA/MDC system have been the Safe Drinking Water Act, the Water Management Act, the Interbasin Transfer Act and water exchange agreements. The approval and application of relevant laws, regulations and agreements should systematically be monitored by the MWRA in terms of their impact on the system.

4. Watershed Conditions and Operational Procedures in MWRA/MDC System - It goes without saying that the MWRA/MDC should monitor the conditions in their watersheds and their operational procedures since they impact directly on the supply and demand for water.

5. Climate, Precipitation and Streamflow - For the same reasons as 4. above, climate, precipitation and streamflow should be monitored.

6. Public Views on Water Resources Management, Conservation and Use - The MWRA/MDC should monitor public issues related to the management, conservation and use of the institution's current and future water and related land resources.

7. Building Permits in the MWRA/MDC Service Area Communities - Private building permits have been shown to have predictive qualities for near future water use in the MWRA/MDC Water System. However, the trends indicated by building permits may not be sustained. Building permits should therefore be used with caution as a leading indicator.

NOTES - ATTACHMENT C

1. Baumol, William J. and Binder, Alan S., Economics - Principles and Policy (Harcourt Brace Jananovich, Publishers, Fifth Edition, 1991) p.228

2. Nelson, Charles L., The Investors Guide to Economic Indicators (John Wiley and Sons, 1987) p.3

3. MWRA, MWRA Long Range Water Supply Program, Program Briefing and Recommendations to the Board of Directors 24 January 1990, p.33.

4. Planning and Management Consultants, Ltd., IWR-MAIN Water Use Forecasting System - Version 5.1 (Carbondale, Illinois, Revised August 1991) pp. II 3-18

5. The twenty five fully served communities are: Arlington, Belmont, Boston, Brookline, Chelsea, Everett, Lexington, Lynnfield, Malden, Marblehead, Medford, Melrose, Milton, Nahant, Newton, Norwood, Quincy, Revere, Saugus, Somerville, Stoneham, Swampscott, Waltham, Watertown, and Winthrop.