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Water Supply Yield for the Wachusett Reservoir

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Abstract

This project provides a system of decision making tools which serves to more efficiency monitor and understand the hydrologic behavior of the Wachusett Reservoir in Massachusetts. A mass balance Excel model and working reservoir model in Stella were designed that incorporate analyses of the hydrologic flows in the system. This project served as a basis for the MA Department of Conservation and Recreation to re-evaluate the current methods for calculating yields in the Wachusett Reservoir.

Executive Summary

The Department of Conservation and Recreation (DCR) and the Massachusetts Water Resource Authority (MWRA) supply one-third of Massachusetts residents with clean drinking water. The Wachusett Reservoir system has supplied a demand as high as 300 MGD in the past, and due to modern conservation efforts current demand is around 220MGD. The possibility of supplying a larger population with clean drinking water requires a more accurate yield analysis of the Wachusett Reservoir system. The goal of this project was to better understand and quantify the water that flows in and out of the Wachusett Reservoir so that recommendations could be presented to improve yield analysis.

To quantify the reservoir yield commonly used methods for the hydrological cycle, watershed characteristics, and yield analysis were examined to identify all of the natural parameters that would influence the Wachusett Reservoir. The Quabbin Aqueduct, Quinapoxet River, Stillwater River, Ware River Diversion, Wachusett Aqueduct, and the Nashua River Release are gauged components which are specific to the Wachusett Reservoir system and had to be accounted for in the reservoir yield analysis. The sleeve release on the Wachusett Dam is the control mechanism that the DCR can use to control the Wachusett Reservoir water elevation. The demand for water is not a constant value and varies throughout the year. Consumers tend to use more water in the summer and less in the winter; this creates a yearly demand curve for the population. One area of investigation in this project concerned analysis on increasing this demand curve.

The major natural inflow to the reservoir system is precipitation that enters the reservoir from direct runoff, through waterways, or from direct precipitation. Direct precipitation and flow from the major waterways are accurately gauged and easy to quantify. This project determined direct runoff by using the known flow of the Quinapoxet River to configure a Wachusett watershed runoff equation using the NRCS method. This modified method was applied to the Stillwater River, Thomas Basin, and Reservoir District Subbasin. ArcGIS and the MassGIS information system were used to find the areas, slopes, soils, and land use data for the subbasins so that Curve Numbers (CN) could be generated for use in the modified NRCS method. The other significant natural inflow is contribution due to groundwater, which revealed to be a major

outflow in the summer. The groundwater flow into and out of the reservoir is directly connected to fluctuations in the groundwater table and the constant water elevation maintained in the reservoir. The monthly contributions to the Wachusett Reservoir due to groundwater flow were estimated using the groundwater table and the reservoir mass balance.

The Quabbin Aqueduct transfers water from the Quabbin Reservoir to the Wachusett Reservoir to help meet demand in times of low flow natural conditions. The flow in this aqueduct is controllable and used to maintain the level of the Wachusett Reservoir in a safe range, while still meeting the consistent demand despite the non-consistent flows of natural hydrologic conditions

Water evaporates off of the Wachusett Reservoir into the atmosphere from surface area of the reservoir. Using local pan evaporation data and applying commonly used evaporation methods, the average monthly evaporation rate was generated for the Wachusett Reservoir. The reservoir spillway is a required outflow that releases water to the Nashua River only when the reservoir reaches a certain level to assure that the water level does not rise to a hazardous level.

All available gauged flow measurements and data concerning the constraints of the hydrological cycle were quantified. The remaining parameters were investigated and accurate ways of generating flows from the available data were developed and designed. Using the 2002-2005 data record, a Microsoft Excel model was built to generate a reservoir yield that was consistent with historically observed conditions; thus verifying the Excel model mass balance results as accurate.

Using the Stella modeling program, a second model was developed for the Wachusett Reservoir system. The model demonstrates the optimal operation conditions for the Wachusett Reservoir and provides the capability to better understand various components within the system. Using the Stella model the Quabbin Aqueduct and releases to the Nashua River can be controlled to manage and optimize reservoir operation. This model serves a design tool to enhance the evaluation of reservoir yields for the Wachusett Reservoir.

Several recommendations were developed based on the various model simulations and hydrological research presented in this project. The results demonstrated that the accuracy of reservoir models directly correlates to the quality of reservoir data. Accurate stream flow monitoring for all of the waterways around the reservoir would improve the precision of calculated runoff volumes. Frequent local pan evaporation data collection would increase the accuracy of the surface evaporation from the reservoir. The report also determined groundwater flow to be a significant component to the reservoir system and further understanding of this process would enhance any evaluation of reservoir yield.

Acknowledgements

This Major Qualifying Project was completed by Michael Bellack and Ryan Lizewski, in cooperation with Worcester Polytechnic Institute, The Department of Conservation and Recreation (DCR), The Massachusetts Water Resource Authority (MWRA), and Professor Paul Mathisen to investigate the Water Supply Yield for the Wachusett Reservoir.

The Wachusett Reservoir system, like most natural hydrologic systems, is an incredibly dynamic and complex arrangement processes. To assure that all of the components of this intricate system were accounted for we received help, guidance, and data from a variety of people and organizations.

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1.0 Introduction

Sufficient water supply is an increasing concern for the exponentially growing population of our finite planet. Currently, 1.1 billion people lack access to clean water around the world (McCarthy, 2005). While the majority of water scarcity issues lie in developing countries, we may soon all find ourselves reevaluating our water consumption. Clean safe water is crucial for the health and wellbeing of all the inhabitants of the earth.

For two million Massachusetts residents, water is supplied through the Department of Conservation and Recreation (DCR) – Massachusetts Water Resource Authority (MWRA) system. Over the past 100 years the system has met increased demand through the addition of a network of reservoirs. The Quabbin, Wachusett and Sudbury reservoirs, in addition to the Ware watershed, are all part of the DCR-MWRA system which is responsible for a sufficient and sanitary water supply to the Boston area.

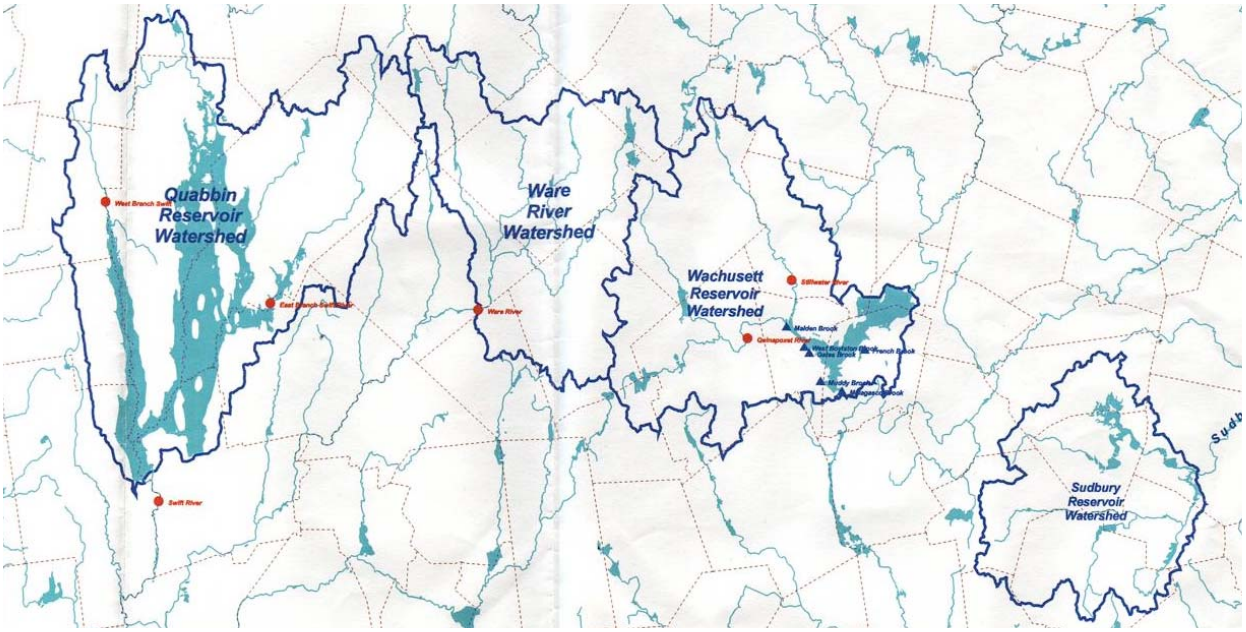


Figure 1: DCR-MWRA Water Supply System

Reservoir yield is the rate of flow which can be drawn from the reservoir while still maintaining proper operating conditions (NDWR, 2003). Through a variety of conservation efforts over the past decades, demand in the DCR-MWRA system has been reduced from 300 MGD to around 220MGD. As a result, the reservoir has been yielding more water than demand requires and large volumes of water are being released from the reservoir. Although the reservoir yield for the Wachusett Reservoir is high enough to meet the required demand there are many towns throughout Massachusetts which face water supply problems. For several communities not within the system, excessive withdrawals from groundwater aquifers and prevalent contamination emphasize the importance in averting future water scarcity issues.

Many of these communities require expansion of their water supply methods and show desire to join the DCR-MWRA system. Due to successful conservation work, many DCR and MWRA officials believe the system can handle in increased demand. The volume of water in the system is vast and the increased demand could successfully be handled by the system. Additionally, extra ratepayers could produce further resources to finance the operation of the system. Still, many environmentalists are opposed to the additional stress on the reservoir through incorporating more communities. If demand peaks over the reservoir safe yield, the water level will begin to drop. This will expose shoreline and small islands which will attract thousands of birds. The bird’s waste is detrimental to water quality which will cause taste and odor problems in the consumers water supply. Also, if water levels recede too much then the danger arises of not having enough water to meet demand needs.

As a result, DCR has shown interest in reevaluating the current method of calculating reservoir yield and identify key hydrological components to the reservoir. The safe yield for the reservoir is often debatable with many studies suggesting a varying range of safe yields. In order to better understand the behavior of the reservoir, a method for calculating yield based of hydrological components should be developed. Safe yields should also be defined and tested through a variety of scenarios to ensure proper operating conditions and aqueduct drought protection.

The goal of this project was to work with the MA Department of Conservation and Recreation (DCR) to reevaluate the existing system for calculating reservoir yields through the identification of the hydrological components of the watershed and reservoir. Our study quantified the hydrologic behavior of the Wachusett Reservoir assisted through the design of two models in reference to safe yield and storage analysis. A series of recommendations were also designed as to the implementation of a monitoring program to help more efficiently supervise and understand the behavior of the Wachusett Reservoir.

This project satisfies the capstone design requirement for the Major Qualifying Project (MQP) at Worcester Polytechnic Institute. As declared in the Statement of Design, located in Appendix 21, this engineering project involves analysis and synthesis of the hydrological components of the Wachusett Reservoir. The design of this project includes a decision making process through the conceptualization, testing and validating models and conclusions.

2.0 Literature Review

To understand the operation and behavior of this watershed system we must first look at reservoir behavior and hydrology; first in general and then in other water supply systems. A basic understanding of hydrology and of reservoir system dynamics is an important step in determining our own recommendations for the Wachusett Reservoir.

2.1 Hydrology

Water is a vital requirement for all living organisms on this planet. For centuries people have been examining where water comes from and where it goes. Hydrology provides an understanding of the distributions, movement and quality of water above, on, and below the earth (Wanielista, 1997). Principles and concepts of hydrologic processes facilitate understanding and design of water management systems. In fact, a good understanding of the hydrologic processes is important for the evaluation of the water resources in accordance to management and conservation both on global and regional scales.

2.1.1 Hydrologic Cycle

The hydrologic cycle is an accounting of the relations of meteorological, biological, chemical, and geological phenomena which keeps water in constant motion. (Wanielista, 1997). These processes consist of evaporation, condensation, precipitation, interception, transpiration, infiltration, storage, runoff, groundwater flow. Some of these processes can be seen in action in Figure 2.

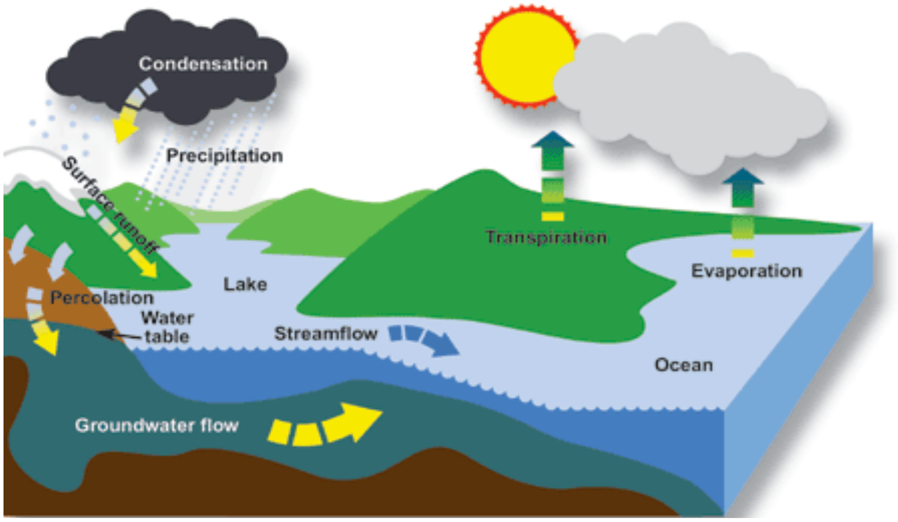


Figure 2: Hydrological Cycle

The flowing definitions and terminology are according to the United State Geological Survey (USGS) and the Nevada Division of Water Resources.

2.1.2 Evapotranspiration

Evapotranspiration (ET) is actually the sum of the two hydrologic processes of evaporation and transpiration from a given land area. Evaporation (E) is the cooling process of liquid water becoming water vapor including vaporization from water surfaces, land surfaces and snow fields. To quantify evaporation one may take measurements from evaporation pans, estimated from an accurate water budget in which all other variables are known, or use correlations with climatic data.

Transpiration (T) is the second process in which water moves for the soil or ground water into the atmosphere via the stomata in plant cells. The factors affecting transpiration are similar to those of evaporation in addition to the physical plant morphology. If evapotranspiration rates can be calculated and evaporation rates are known then transpiration is easily determined.

2.1.3 Precipitation

Precipitation (P) is the downward movement of water in liquid or solid phase from the atmosphere due to cooling of the air below the dew point. Precipitation can come in the liquid form as rainfall or solid form as snow and ice.

Rainfall is usually quantified by use of a network of rain gauges. Three principle gauges are commonly used: tipping bucket, weight and float gauges. (Wanielista, 1997) The tipping bucket operates on the principle that once a small bucket of known volume is filled the bucket tips and the number of tips is recode trough a computer. A weighing-type gauge simply measures the weight of rain, snow and ice that accumulates in a bucket. The float gauges record rainfall depth by use of a flotation mechanism which relays information to a computer.

2.1.4 Runoff and Stream flow

Runoff (R) is the portion of precipitation that moved from land to surface water bodies that is neither intercepted by vegetation, absorbed into the soil, nor evaporated into the atmosphere. The local land uses, percent impervious cover, and vegetation all affect the time it takes runoff to reach a surface water body.

Often surface runoff will travel along favorable topographical features until the water is fed into a stream. Streamflow itself is the discharge that occurs though a channel into a receiving water body. Base flow of the stream is often maintained through groundwater; however, stream levels can severely fluctuate according to precipitation changes and especially drought conditions.

2.1.5 Surface and Ground Water Flow

Subsurface flow is the water which infiltrates the ground surface and travels underground, often in large aquifers, until a water body is reached. These aquifers are often recharged through precipitation; however, ground water levels may drop in times of high water demand, drought conditions, and as a result of seasonal variability. This is often evident through the fluctuations of depth to the water table throughout the year.

2.2 Watershed Characteristics

A watershed consists of the area of land which contributes to water drainage along topographical slopes draining to a stream or river. Eventually these streams and rivers will flow into a water body and may even contribute to a larger watershed system. Such a large watershed system can be made up of several subbasins for each of the smaller tributary streams and rivers, Figure 3.

Figure 3: Nest Watersheds (CGIS)

A reservoir watershed can consist of several large watersheds for major stream inflows. Each of these watersheds can consist of a network of smaller subbasins for each of the tributaries to the larger stream. The streams follow a basin order where streams can be ranked according to the degrees of separation from the main channel. (Marsh, 2005). A fourth order basin would mean the main channel is of the fourth order, indicating a nest hierarchy of three stream orders, Figure 4.

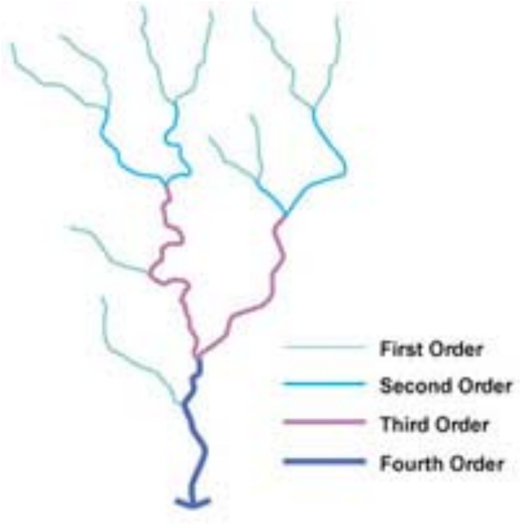


Figure 4: Stream Order Classification (CGIS)

2.2.1 Land Use

Land use can severely alter and change a watershed system and the drainage networks. A high percentage of imperious surfaces can alter and change runoff conditions which will adversely affect the watershed. The canalizing and piping of streams which hinder human development, lead to severe alteration to the behavior of the watershed. This is often called “pruning” of the natural channels and is an effect of urbanization (Marsh, 2005). Even though a natural drainage network can be pruned the overall networks are often enlarged and intensified. Lower infiltration rates, extensive impervious over, coupled with pruning will lead to increase in the volume of runoff, a decrease in the quality of surface water runoff, and shorter times of concentration.

2.3 Yield

According to the Army Corps of Engineers the yield for a reservoir system is the volume or schedule of supply at one or more specified locations usually in terms of volume of water per time period (Fredrich, 1975). However, we must not only look at the maximum amount of water we can take but we must determine a safe yield which accounts for certain risks. The safe yield for a reservoir is the demand that can successfully be met under certain drought conditions (OWASA, 2001)

2.3.1 Water Budgets and Reservoir Yields

The water budget is the culmination of all the inputs and outputs into the system. A typical water budget for a reservoir may look like Figure 5.

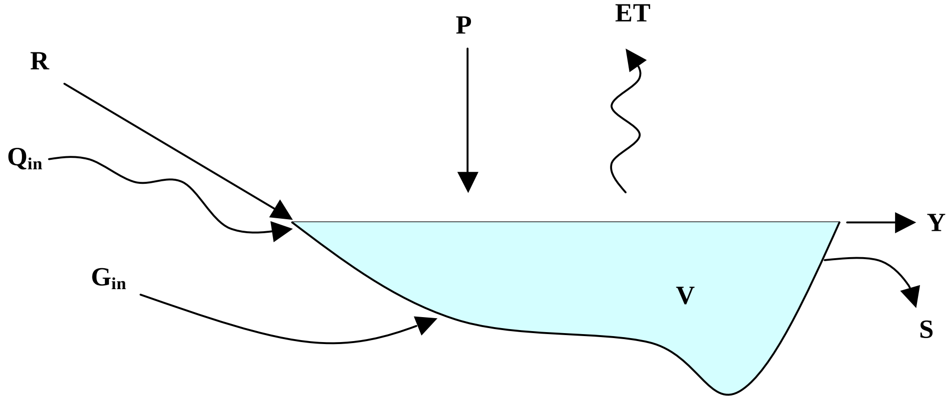


Figure 5: Water Budget

Where
P = Precipitation
V = Volume
Q_{in} = Surface inflow
G_{in} = Groundwater inflow
ET = Evapotranspiration
Y = Yield
R = Runoff
S = Seepage

Often with a reservoir system we are interested in determining the yield, for the volume is usually known. Equation 1 shows a typical mass balance to solve for the yield of a reservoir.

$$Y = V + P + Q_{in} + R + G_{in} - ET - S \qquad \text{Equation 1}$$

Of course it is not advisable to operate a reservoir system at maximum yield for a sudden drought or operation failure could lead to disastrous consequences.

2.3.2 Risk Assessment and Reservoir Yields

It is dangerous for water systems to operate at maximum capacity for slight variations in natural conditions can have adverse effects on the water system. Reservoir levels may drop leading to severe environmental degradation in addition to water quantity and quality problems. For these reasons it is important to determine the appropriate volume of water which can be taken from the reservoir while still maintaining the acceptable degree of risk.

Often the risk willing to be taken will include a judgment as to the appropriate storage-performance-yield relationships (Philipose, 1995). Within these relationships a degree or reliability and vulnerability is formulated. Reliability is often the ratio of the number of times the demand for water is satisfied to the overall number of times the system was operated. Meeting the target demand is crucial and a reservoir system which is taxed beyond its limits will fail to satisfy the demand creating a multitude of problems from the consumers and to the watershed ecosystem itself. The degree of impact the problems will have is called the vulnerability. In the event of a failure to vulnerability of the reservoir system can hint on how severe the reservoir will respond. A system which possesses a high degree of vulnerability may experience drastic failures and consequences from the slightest operational malfunction, while those with a lower vulnerability may experience few significant consequences.

2.3.3 Drought Conditions and Safe Yields

The event which can cause the most detrimental effects for a water system is a drought. Droughts are often used to determine how well the system will operate under severe environmental conditions. The safe yield for a reservoir is the demand which can be met under specified drought conditions (Pretto, 1997). For example, a 20-year safe yield is the yield which can be met under drought conditions which would occur on average once in every twenty years or have a one a twenty chance of occurring.

To determine the base line conditions to measure their safe yield many water supply system will utilize the “drought of record” (RWSA, 2004). The drought of record is simply the most server drought which has occurred on record for the water supply system. However, some area may experience more serve droughts then others or have incomplete data making the ranges for a drought of record vary greatly. Other systems may only determine safe yield for a 20 or 30 year drought. However, it may be best to evaluate safe yields of a system for a variety of drought conditions for varying occurrence intervals.

3.0 Background

The DCR - MWRA reservoir system includes the Wachusett and Quabbin Reservoirs with additional transferable water from the Ware River. This system is operated to deliver adequate high quality water to its customers from the reservoirs; both of which are classified as Class A water bodies. (MWRA, 2001) Additionally, the reservoir system must provide adequate flood protection, maintain minimum releases to rivers, and the potential for hydropower generation in three locations.

3.1 Wachusett Reservoir

The Wachusett reservoir was built between 1897 and 1908 when the Nashua River was blocked with the Wachusett Dam. Parts of Boylston, West Boylston, Clinton, and Sterling were flooded to create a new water supply to meet the increasing water demands from Boston.

Figure 6: Wachusett Reservoir

The Wachusett Watershed is 107 square miles, 70% of which is protected through DCR land ownership and other regulations. The Wachusett Reservoir is significantly more developed than the Quabbin reservoir with only 70% of the watershed classified as forest or open space.

Land Use	Forest & Open	Agric.	Low Res.	Med. Res.	High Res.	Com.	Ind. & Trans	Water & Wetland	Impervious
Wachusett Watershed	**70%**	**6%**	**8%**	**4%**	**1%**	**1%**	**2%**	**9%**	**3.90%**

Table 1: Wachusett Watershed Land Use (DCR)

It has been estimated that the Wachusett watershed contributes to 34% of the total system yield (MWRA, 2001).

There are many hydrologic components to the Wachusett watershed. Runoff across the upper watershed form small streams which network until they develop into larger rivers which flow into the reservoir. The majority of Wachusett inflow, over 90%, enters the reservoir at the western tip in Thomas Basin, which also receives water from the Quabbin Reservoir via the Quabbin Aqueduct (MWRA, 2001). Direct runoff also contributes, to a lesser degree, on the southern and northern portions of the reservoir.

The releases from the Wachusett Reservoir consist of withdrawals to meet demand, to maintain required releases downstream and any overflows in periods of high reservoir volume. However the withdrawals from MWRA count for over 90% of the water leaving the system; the rest predominantly constitute releases to the Nashua River (NWRA, 2003). Once the water is withdrawn it travels. Water supply was once discharged through the Wachusett Aqueduct; however, the aqueduct is currently used as a reserve tunnel in case of damage or construction on the Cosgrove Tunnel. The only release required for the Wachusett Reservoir mandates a discharge of 1.71 MGD to the Nashua River, as stated in Chapter 488 of the Acts of 1895.

3.2 Quabbin Reservoir

The Quabbin Reservoir was built from 1926-1946 by damming the Swift River and submerging the towns of Dana, Enfield Greenwich and Prescott. At the time the Quabbin was the largest manmade reservoir in and world and still currently the largest one devoted entirely to water supply (MWRA, 2001).

The Quabbin Reservoir has a maximum storage capacity of 412 billion gallons which is recharged from a watershed of 186 square miles. This gigantic watershed is approximately 90% forest or wetlands and is remarkably well preserved. A major tenet of the management of the Quabbin Reservoir is protection through ownership of watershed land, have which 45% is DCR owned (DCR, 2005). The average yield of the Quabbin Watershed is estimated to be 159 MGD. To increase this yield, water from the Ware River may also be diverted to the Quabbin Reservoir.

Figure 7: Quabbin Reservoir

Discharge from the reservoir mainly leaves through the Quabbin Aqueduct. This tunnel is made from 270 miles of pipe which delivers water from the Quabbin Reservoir, by gravity, to the Wachusett Reservoir. (Westphal, 2003) The Chicopee Valley Aqueduct also draws water from Quabbin to supply approximately 11 MGD to three communities west of the reservoir. A release to the Swift River must also receive 45 MGD - 70 MGD according to water levels in the Connecticut River, as stated in the 1929 War Department Requirement.

3.3 Ware River Watershed

Water from the Ware River can be diverted to either the Quabbin or Wachusett Reservoirs, according to certain met criteria. The first mode is referred to as the “Limited Ware” scenario. This is when reservoir levels are below their seasonal norms, this usually occurs when the Quabbin Reservoir falls below 98% of its capacity. The “Full Ware” scenario occurs only if demand on the system surpasses 270 MDG. (MWRA, 2001) This continues until the Quabbin Reservoir returns to its normal operating range.

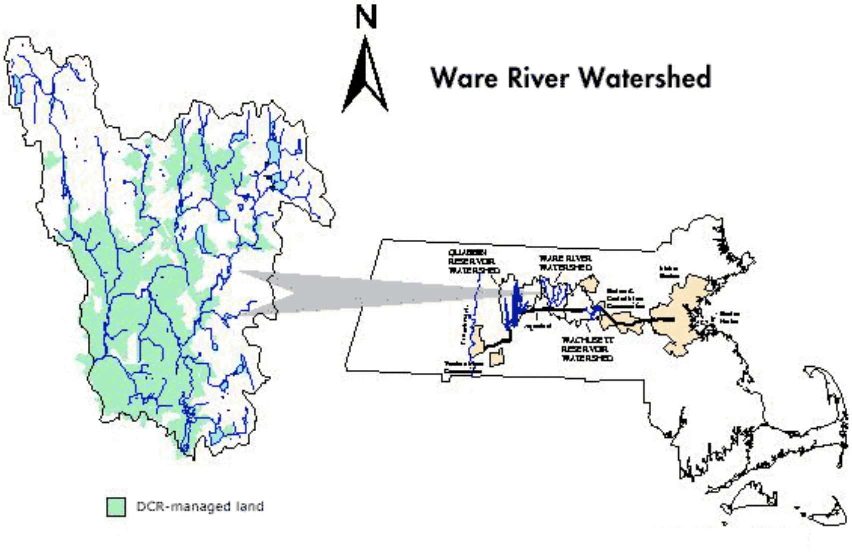


Figure 8: Ware River Watershed

3.4 Existing Demand

The water demand for the system followed an increasing trend until the 1980's when a long-range study projected water demand to reach 340 MGD in 2020. This resulted in an intense push to reduce water usage through a variety of conservation efforts and reduces water loss through leakage. This reduced average daily demand from 326 MGD in 1987 to 285 MGD in 1990. The current average daily demand for the system is approximately 251 MGD, according to 1997-2001 MWRA data.

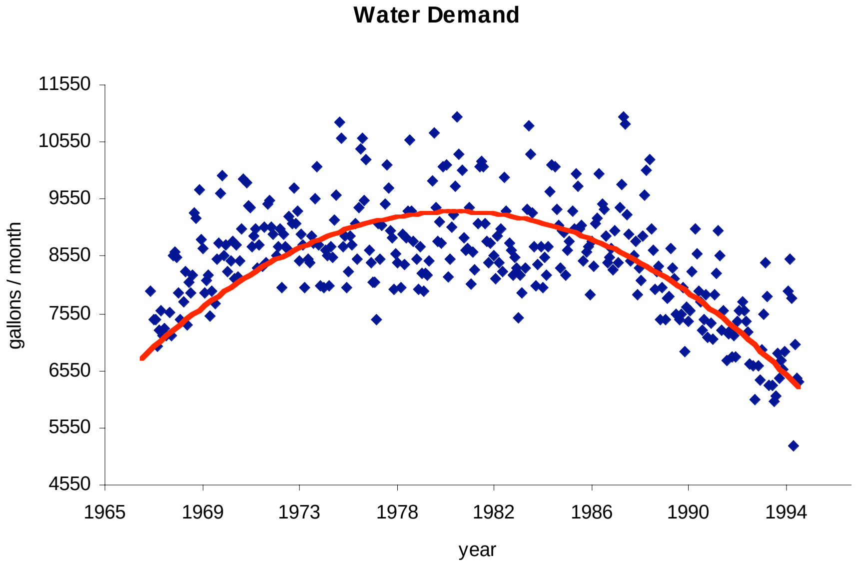


Figure 9: Water Demand

The DCR-MWRA system supplies 46 fully and partially served communities in Massachusetts. The 21 fully supplied communities receive all their water from the DCR- MWRA system and maintain an average annual water demand of 208 MGD. The partially supplied communities receive a portion of the water to supplement locally owned wells and surface waters. Many of these communities use the system as a back up in case of an emergency and normally do not draw water from the system; in 2001 the demand from partially supplied users was 23 MGD. A list of communities that are served or are capable of being served is located in Appendix 1.

3.5 Projected Water System Expansion

Whether the system can safely handle additional communities has always been an issue of debate. Several inquires have been presented to expand the system for communities with inadequate or contaminated water sources. According to the Metropolitan Area Planning Council

(MAPC) projections for 2025 population and unemployment growth, future demands can be estimated.

Projections of Demand in the MWRA Water Service Area		
Baseline Demand of 251 MGD		
Total Demand in 2025		
High Estimate	Medium Estimate	Low Estimate
264 MGD	**246 MGD**	**234 MGD**

Table 2: Water Demand Projections

MAPC also identified 15 communities which withdrawals were already occurring below permitted rate in accordance to the Water Management Act. An additional 13 communities are projected to reach their current permitted withdrawal rates by 2025. Communities who have proposed expansion inquires include: Stoughton, Reading, Wilmington, Dedham-Westwood Water District, Holden, in addition to the MAPC projected shortfall communities.

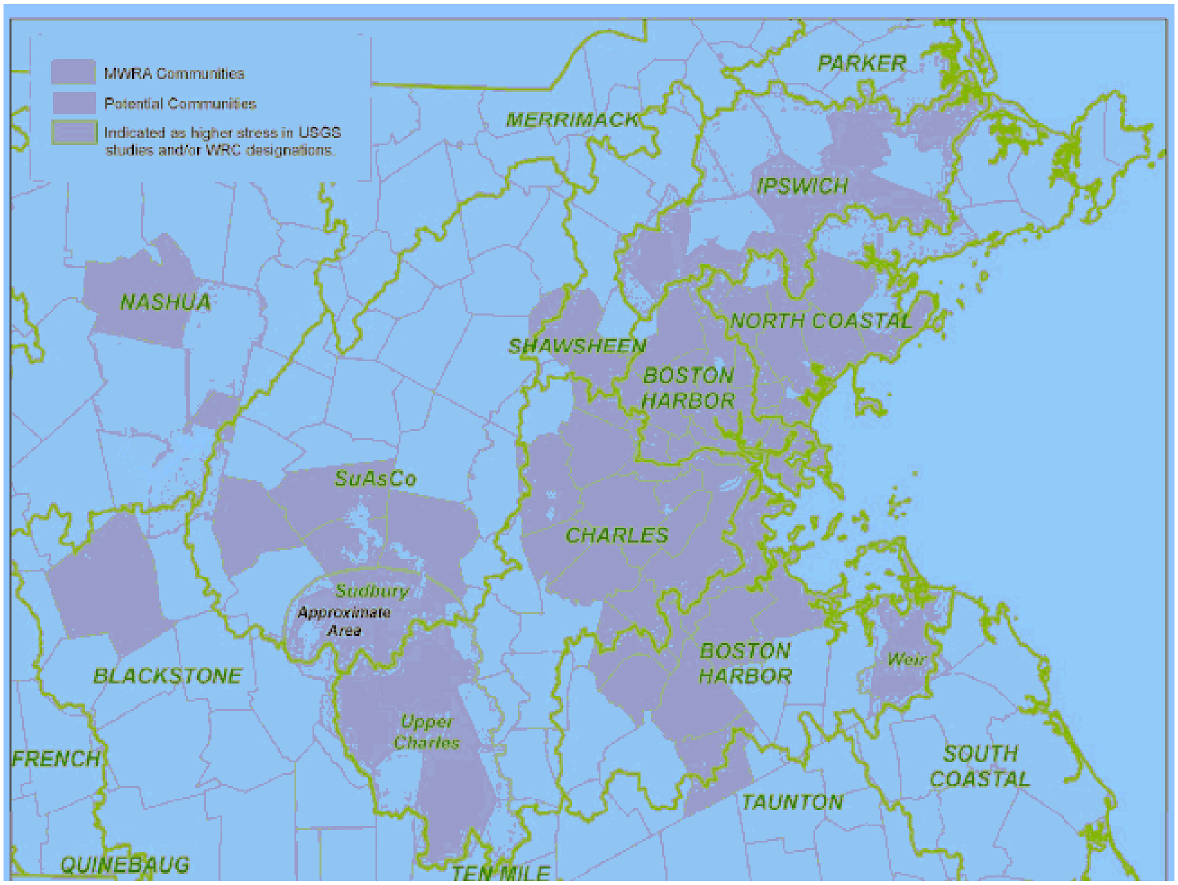


Figure 10: Potential Water System Expansion

3.3 US Army Corps of Engineers: Hydraulic Engineering Methods for Water Resources Development

The US Army Corps of Engineers published this volume to provide a guide to the procedures used in determining the storage-yield of a reservoir.

The storage-yield is determined by collecting all necessary hydraulic data then determining the physical and hydraulic constraints on the reservoir system. The data and constraints are then compiled and put into a simulation over a selected time interval to produce a storage-yield result.

The data used in the simulations must be analyzed and organized. Streamflow data consists of the streams and waterways which flow directly into the reservoir; the volume of water can be measured by calculating the flow rate and depth. Any losses from the reservoir must be calculated to assure accurate mass-balance data. This loss includes evaporation, precipitation and runoff; the sum of these parts is the average net reservoir loss. Demand data is used in the simulation to account for seasonal or other possible fluctuations in water demand. The local climatology is also factored into the simulation to account for accurate evaporation and snowmelt data.

Understanding the data from the time interval that is used in the simulations is essential. The simulations must account for possibilities that the limited time of data collection did not produce. The physical constraints of the reservoir system such as maximum flows and storage capabilities must be included in the simulations to produce an accurate storage-yield, this must also account for the low-flow regulations downstream. A shortage index must be developed to assure that the storage yield will be sufficient to assure that shortages are controlled.

The compiled data is run through the simulations to create a mass balance curve. The mass balance curve is combined with simulations of minimum, maximum and average streamflow data to illustrate how the mass-balance reservoir system will react to the fluctuations of flow.

The US Army Corps of Engineers stresses that having accurate data and understanding how to interpret it is the best way to produce accurate reservoir simulations.

3.6 OWASA Raw Water Supply Facilities: Safe Yield Analysis

CH2M Hill conducted a study for the Orange Water and Sewer Authority to determine an accurate storage-yield of University Lake and Cane Creek Reservoir, Carrboro, NC, to analyze the possibility of expanding the service area. Background research showed a 1997 report that estimated a possible yield of 13.5 mgd with some saying as high as 16 mgd.

The characteristics and constraints of the reservoir are presented, and all the inflows, outflows, and major losses are identified. The characteristics of each of the constraints is presented and integrated with the simulation data. The flow data is analyzed and simplified to find the average operation conditions of the OWASA's reservoir system. Combining the flow data and storage capabilities produces a mass-balance curve for the reservoir that is then used in a simulation predict the reservoir's behavior in times of high flow or drought. Applying the data from sample time periods can confirm that the simulation model produces accurate storage-yield results.

A series of drought related simulations are run to assure that the reservoir will be able to handle the demand during a low input time period. Analyzing the data from the drought simulations produced a 30-year safe yield of 11.2 mgd for OWASA's reservoir system.

Methodology

The goal of our project is to work with the Department of Conservation and Recreation (DCR) to reevaluate the existing system for calculating reservoir yields through the identification of the hydrological components of the watershed and reservoir. Our study quantified the hydrologic behavior of the Wachusett Reservoir assisted through the design of two models in reference to safe yield and storage analysis. A series of recommendations were also designed as to the implementation of a monitoring program to help more efficiently supervise and understand the behavior of the Wachusett Reservoir.

To achieve our goal we have completed the following objectives for our project:

- *Perform literature and background research*
- *Investigate available information on the reservoir system*
- *Identify and evaluate hydraulic inputs*
- *Develop and test reservoir yield model*
- *Produce design recommendations concerning reservoir operation*
- *Produce report and present recommendations*

4.1 Literature and background research

Literature and background research concerning hydrology and reservoir behavior was at the forefront of our project. Investigation of similar situations, papers, and projects facilitated our understanding of the Wachusett Reservoir system and how it functions. A basic hydrologic understanding was needed in order to properly assess the components of the DCR-MWRA system. Background research included a brief history, as well as a description, of the Wachusett and Quabbin reservoirs, their watersheds, inflows, outflows, and transfers. Additional interviews with DCR and MWRA officials presented us with an insight of how the reservoir system is operated and the measures to which the Wachusett Reservoir is monitored. This research provided us with an understanding of the hydrologic processes and characteristics of a reservoir system. From here we assessed the components of the system and the data which was available.

4.2 Assessment of available information on the reservoir system

To accurately calculate the yield of the Wachusett reservoir system, a complete record of the system and all of its processes are necessary. DCR is currently collecting hydrologic data from several of the flows in and out of the Wachusett Reservoir. Additionally other organizations and past research provided valuable data and observations for our project. We identified, investigated, researched, and analyzed each of the variables to assure that the data used in the yield calculation is accurate.

- ***Gauged Flows***

  Many of the controllable elements of the system are closely monitored and gauged. The volume of water transferred from Quabbin is monitored and controlled; data was available through DCR-MWRA records. Water supplying the Nashua River includes the release, sleeve valve and the spillway; these are all monitored and recorded. The release to the Nashua River is regulated and water flowing over the spillway is calculated and recorded. Additionally, to reduce a sudden discharge to the Nashua the sleeve valve is opened to lessen the volume of spill.

- ***Precipitation***

Precipitations measurements were obtained from the DCR precipitation database. The data base is a monthly record of rainfall in 203 locations across Massachusetts; several of which are within watershed boundaries. For our analysis we used precipitation data from the West Boylston gauge location, the closest to the Wachusett Reservoir.

- ***Runoff***

  Two major basins of the Wachusett Watershed, Thomas Basin and Reservoir District, drain directly into the reservoir. To quantify the volume of water coming off the basins we analyzed how the land is developed and the volume of precipitation and used the NRCS TR – 55 method. Land use data was provided through USGS ArcView Data layers and from DCR records.

- ***Streamflow***

  The Quinapoxet and Stillwater Rivers are two major tributaries for the Wachusett Reservoir. Streamflow from these rivers is monitored through USGS streamflow monitoring gauges at the mouths of both rivers. However, accuracy of the Stillwater data cannot be completely verified for backwater from beaver activity downstream frequently disrupts the gauge readings. Data from the Quinapoxet gauged was be used to develop and calibrate the models and data from the Stillwater gauged was used to verify the accuracy of our methods

- ***Evaporation***

  Searching for a complete record concerning evaporation for the New England area proved to be challenging. One climatology station in Kingston, RI recorded pan evaporation data for the months of May though October. In addition, evaporation values utilized in other studies and reports were also analyzed. DCR and the Geotechnical, Rock and Water Resources Library presented estimations and values used to quantify evaporation in Massachusetts.

- ***Demand***

  Demand data is supplied by the MWRA and consists of daily demand values for each of the communities receiving water from the system.

Once gathered, this information provided our group with the most feasibly complete and accurate data record for the Wachusett Reservoir. Any concern of inaccuracy in the instrumentation or data collection methods utilized was evaluated. From our collected information, we can identify and analyze holes and inconsistencies within the data. Subsequently, developing an appropriate method to accurately quantify and evaluate hydrologic nature of the system.

4.3 Identification and evaluation of hydrologic variables

The analysis of methods and instrumentation will allow us to accurately account for all the water entering and leaving the system. Once we have identified and investigated the constraints on the entire reservoir system, we can pinpoint discrepancies in the current procedure for calculating yield and determine a more appropriate approach. The data collected in the previous objective was evaluated as to its importance and place in our analysis. Acquiring accurate and appropriate data is crucial, for any model we produce will be based and calibrated using this information.

4.4 Development and verification of reservoir yield models

After updating and confirming the reservoir demand and hydrologic data, we established working reservoir models to determine reservoir behavior. The models incorporated the entire data record for the desired time period and formed the basis into a sophisticated mass balance for the Wachusett Reservoir system. After the design and development of the models, verification against the existing data record was conducted to confirm their accuracy.

An initial model in Excel was designed in order to evaluate the data and establish a preliminary yield. We combined all of the reservoir inflows and outflows for 2002 – 2005 into an Excel spreadsheet and built a mass balance model that generates flow data from given precipitation data to generate a reservoir yield. This yield is then verified with the observed yields in those years to confirm our data and results were accurate. We generated averages and trends from the four sample years and came up with characteristic sets of data for dry, normal, and wet years. These methods and data were then ready to export to our next model.

The Stella software package provided an excellent way to design a model of the system in a manner we deemed appropriate. The model we created can be run multiple times to simulate possible results, identify key locations in the watershed, and demonstrate optimal operating conditions. The model is designed to run on only inputs of precipitation and temperature, from which a reservoir yield can be predicted. Utilizing the program we can alter and change the characteristics for the system and see how the reservoir behaves under certain changes. Also, we can establish and discover relationships within the system itself to better understand the mechanics of the reservoir.

4.5 Development of design recommendations concerning reservoir operation

The design of our models demonstrates the hydrologic behavior of the Wachusett Reservoir and analyzes ranges of operating conditions; assessing the vulnerability of particular circumstances. Many reservoirs may only be designed for droughts with occurrence intervals of 20 or 30 years. We determined certain ranges in which the reservoir can successfully operate and associate the appropriate risks of such operation. Droughts were our main concern and performances of the reservoir model during particular drought conditions were evaluated. A recommendation to whether the system can handle increased demand is based on analysis and performance of our models and reservoir data.

4.6 Produce report and present recommendations

The report was produced with an updated reservoir yield analysis based on our data record, performance of our models, and determination of safe yield methods. Recommendations were developed concerning the ability of Wachusett reservoir to supply water to additional communities without causing any detrimental environmental impacts. Additionally, recommendations will be presented to DCR concerning the implementations of future monitoring programs. Execution of these programs will address issues to help more efficiently monitor the Wachusett watershed; in interest of both hydrologic activity and water quality.

5.0 Watershed Analysis

Investigation into the hydrologic components of the Wachusett Reservoir yielded an abundance of data. This large data record went back in part to the 1940's and continues until the present day. However, this data record is by far inclusive and contains discrepancies and holes. In order to evaluate the data, a data range must be selected in which the record is complete. To ensure sufficient data to compare and evaluate, a four-year data range was selected. The years from 2002-2005 had a complete data record for the reservoir. Therefore, this data range was used to construct and calibrate the models. Also, use of more recent years allows for more up to date land use data to use in the models.

This chapter presents a breakdown of the hydrologic characteristics for the Wachusett Reservoir. Results are presented to illustrate the natural mechanisms within the hydrologic reservoir behavior; rainfall, evaporation, streamflow, and runoff. Presented within the watershed analyses are the characteristics of these hydrologic components which include; the NRCS method, baseflows, land use, soils, and antecedent moisture conditions. The complete operation including controlled releases and transfers are analyzed in the subsequent modeling section of the report.

5.1 Rainfall

One of the most important parameters when assessing the hydrologic characteristics of a subbasin in developing a reservoir yield is rainfall. Rainfall data were easily attainable through the DCR network of rain gauge stations that are located in 150 gauges across Massachusetts as can be seen in Figure 11. These data are available on the DCR website and is updated monthly, rainfall data are found Appendix 2.

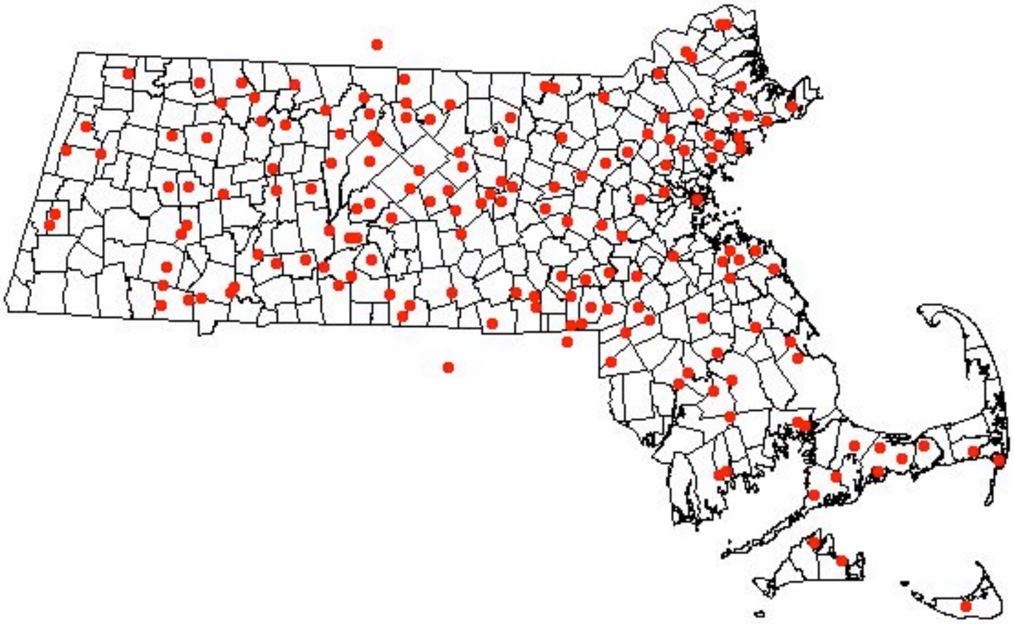


Figure 11: Rain Gauge Network (DCR)

Stations within the watershed are located in Holden, Boylston, Princeton, Rutland and West Boylston. For this analysis, the rain gauge data in West Boylston will be used due to its close proximity to the Wachusett Reservoir and its lengthy data record, which goes back to 1945.

As can be seen in Figure 12, the rainfall distribution across the watershed is relatively uniform. Seasonal variations in precipitation remain minor with an average monthly precipitation of approximately 4 inches. Differences between the various gauged readings within the watershed also remain minimal, since similar trends can been seen in rain gauge locations across the watershed.

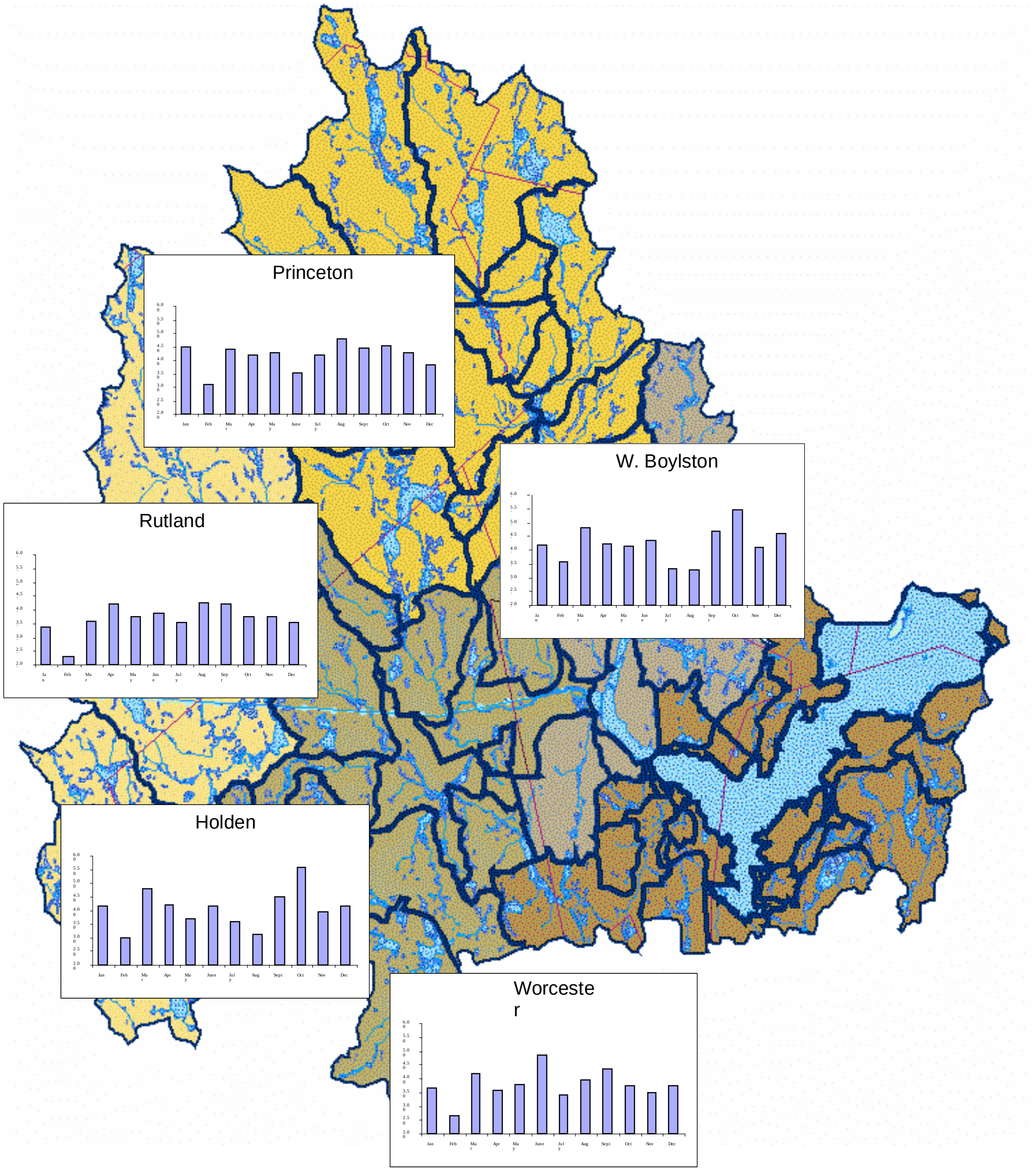


Figure 12: Watershed Rainfall Distribution

5.2 Evaporation

Complete and accurate evaporation data for the New England Area proved to be a challenge to find. However, one climatology station in Kingston, RI contains a record of limited pan evaporation data from the months of May to October. Additionally, other research papers and documents allowed us to analyze past methods utilized for quantifying evaporation.

The Public Access Management Plan Update for the Quabbin Reservoir suggested a pan evaporation value between 39 inches per year for central Massachusetts; estimating an annual evaporation value for the reservoir to be 22 inches (DCR, 2005). Additionally, evaporation maps for the United States contoured particular rates of evaporation across the country. As shown in Figure 13, the map from the Geotechnical Rock and Water Resources Library suggests annual pan evaporation around 35 inches.

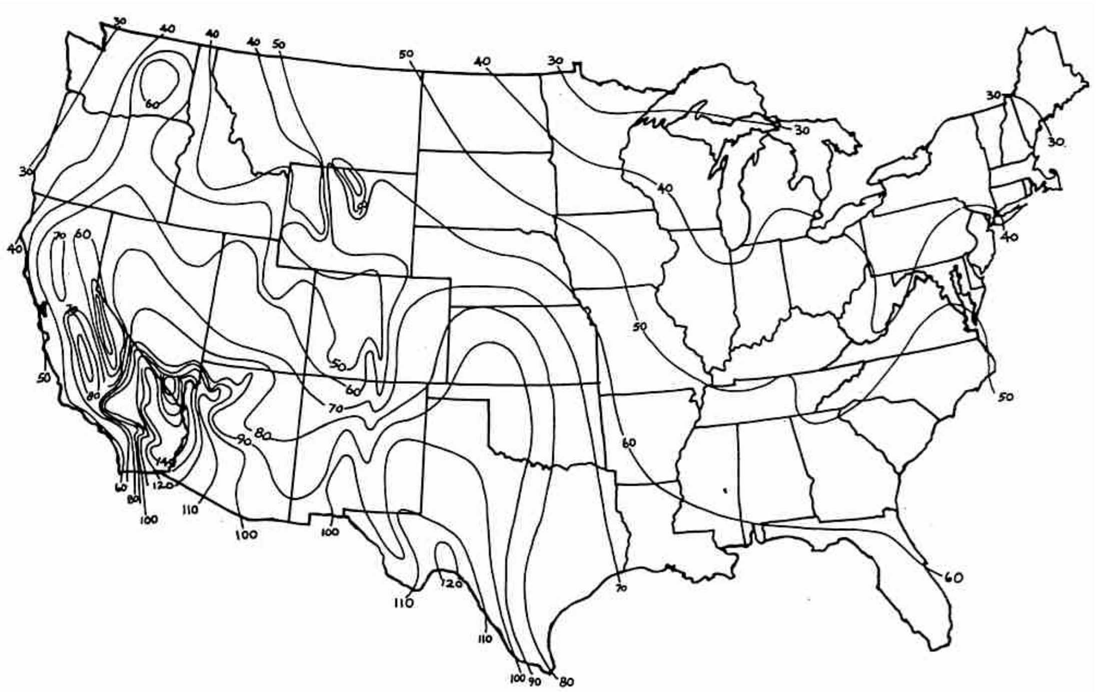


Figure 13: Pan Evaporation Data for the United States (GROW, 2004)

Fortunately, evaporation rates within the New England Area remain relatively uniform with slight variations. As the contour lines within Figure 13 show, evaporation can vary greatly in the Western and Southwestern United States with rates doubling as you travel latitudinally across California. Such a change in evaporation rates on the Eastern Seaboard can only be seen when comparing values over the distance between from Maine and Florida

Several equations can also be implemented to estimate evaporation values. One of the more intense and accurate equations are the Penman Equation:

$$PE = \left(\frac{\Delta}{\Delta + \gamma}\right) * Q_{ET} + \left(\frac{\gamma}{\Delta + \gamma}\right) * E_{at} \text{ (mm/day)} \qquad \text{Equation 2}$$

However, this equation requires numerous parameters and is overly complicated for the relative scope of evaporation within the system. Another equation which exists and requires known parameters is the Dunne Equation (Bedoya, 2005):

$$E = \left(0.0013 + 0.00016u^2\right) * e_a * \left[{(100 - R_h)}/{100} \right] \qquad \text{Equation 3}$$

Where:
E = average daily evaporation in cm/day
u^2 = average daily wind velocity in km/day
e_a = saturation vapor pressure of air in millibars
R_h = average relative humidity given as percent

In order to quantify surface evaporation from the Wachusett Reservoir an approach must be developed which incorporates both evaporation equations and recorded data. Implementation of the Dunne equation, using data acquired from the National Oceanic and Atmospheric Administration, yields relatively large evaporation rates but provides a good estimate of annual evaporation trends. The entire evaporation data set is located in Appendix 3. The data record from the climatology station in Kingston, RI is partial; however, the gaps can be closed by extrapolating the trends established from the Dunne equation to the missing data. This approach used is indicated by Equation 4.

$$\frac{C_{D_{i+1}}}{C_{D_i}} = \frac{C_{R_{i+1}}}{C_{R_i}} \qquad \text{Equation 4}$$

Where
$C_{D\,i}$= Dunne Equation Evaporation in month *i*
C_{Di+1} = Dunne Equation Evaporation in month *i+1*
C_{Ri} = Real Evaporation in month *i*
C_{Ri+1} = Real Evaporation in month *i+1*

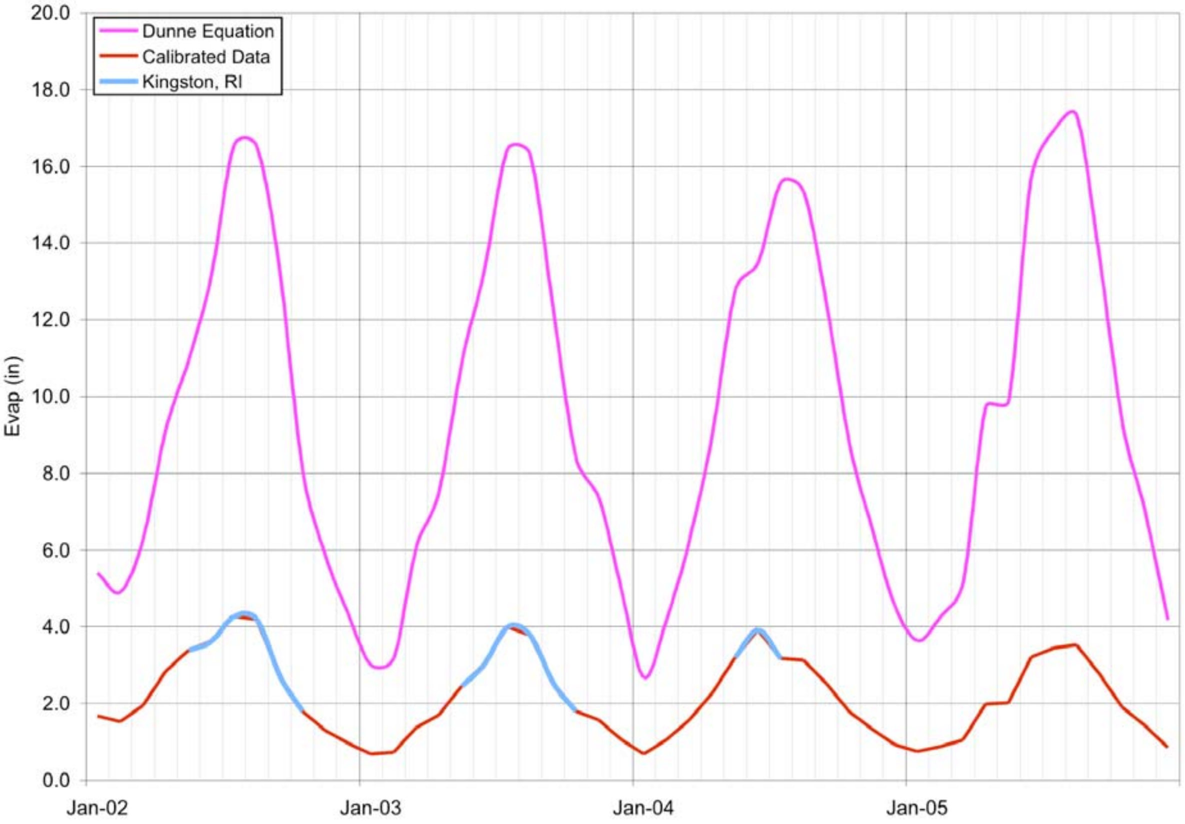


Figure 14: Evaporation Data

As Figure 14 shows, the Dunne equation overestimated the volume of evaporation when compared to the evaporation reading in Kingston, RI. However, this is acceptable for the interest is in the rate of change of evaporation volumes calculated throughout the year. The trend of the Dunne Equation was used to extrapolate the limited evaporation data to complete the year. The values calculated were then checked with the literature to verify that an accurate and acceptable range was developed. The calculated evaporation rates for the four year data set ranged from 24 – 30 inches per year with an average of 26 inches.

5.3 Runoff

To generate accurate runoff flows, the available data was analyzed to develop runoff equations for the Wachusett Reservoir basin. The NRCS curve number method was chosen to determine the direct runoff in the Wachusett reservoir subbasins. The total stream flow (Q_t) for each month was broken down into a base flow (Q_b) and a runoff flow due to precipitation (R).

$$Q_t = Q_b + R \qquad \text{Equation 5}$$

Using the known stream flow from the Quinapoxet River and data from the Quinapoxet and Worcester subbasins, the NRCS method was used to determine the curve numbers (CN) for each subbasin to find the runoff flow (R).

5.3.1 Base Flow

The low flow records for both the Quinapoxet and Stillwater Rivers were analyzed and the base flow was determined to be the lowest flow point during a dry period for each month. Any water that was not part of the base flow was considered to be runoff due to precipitation. Figure 15 and

Figure 16 demonstrates the variation in monthly base flow throughout the year for the Quinapoxet and Stillwater Rivers. Descriptions on the gauges are presented in Appendix 8 and Appendix 9

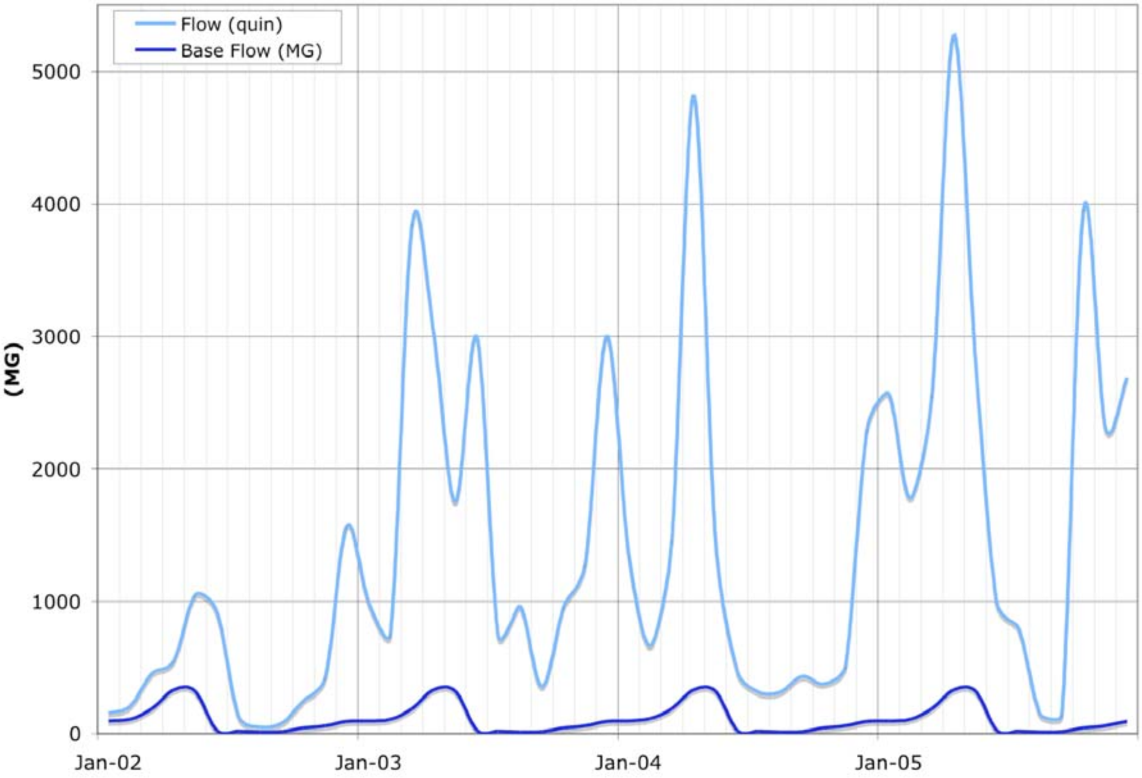


Figure 15: Quinapoxet Base Flow

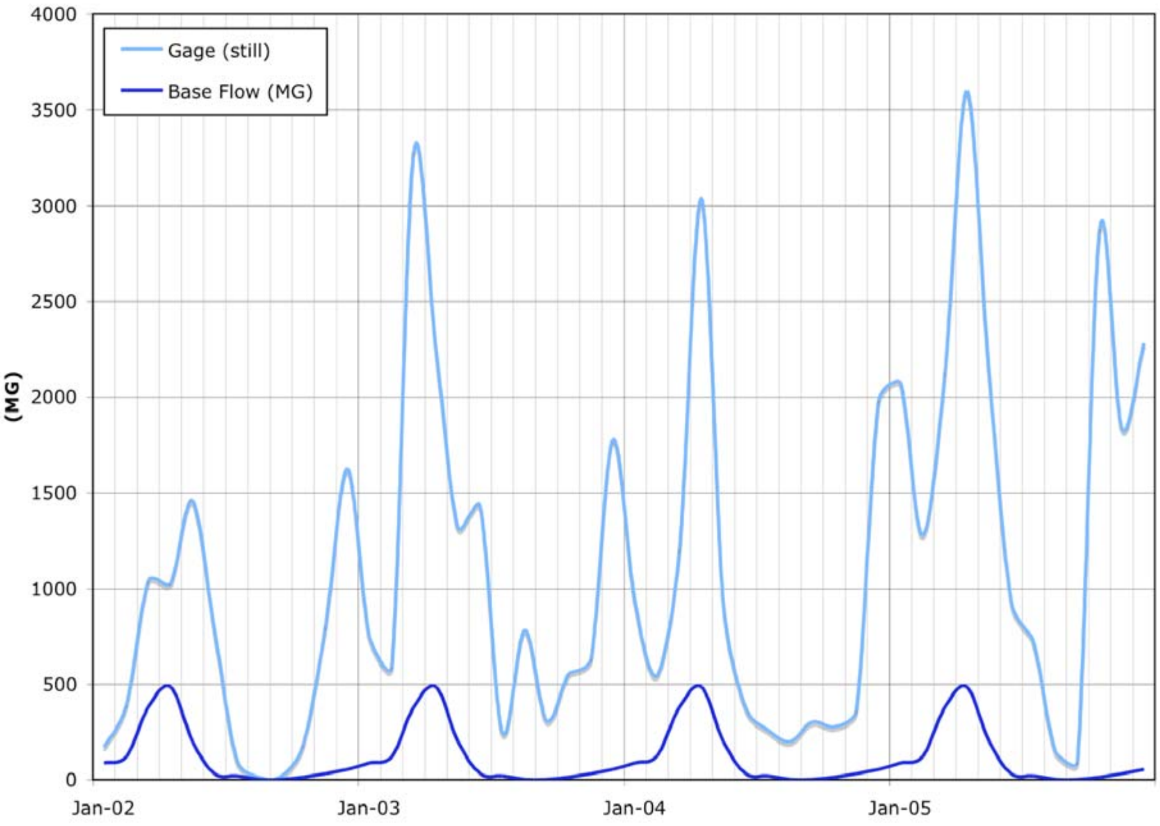


Figure 16: Stillwater Base Flow

To determine the runoff (R) for each subbasin the differences in infiltration had to be quantified for each subbasin. MassGIS maps in ArcGIS were used to compile the slope data, land use data, and the areas of each subbasin to produce curve numbers (CN) as per the NRCS method. This allowed us to see the differences in the runoff for each subbasin.

5.3.2 NRCS Method

Originally developed by the Soil Conservation Service (SCS), presently the Natural Resources Conservation Service (NRCS), the Curve Number Method is an empirical description for estimating infiltration and rainfall excess. During a rainfall event, precipitation falls at a certain intensity, which normally is larger than the storage capacity of the soil. Rainfall excess will equal rainfall intensity once watershed storage approaches the potential saturation value and infiltration rate equals zero. Assuming an initial abstraction of 0.2S':

$$S' = (1000/CN) - 10 \qquad \text{Equation 6}$$

and

$$R = \frac{(P - 0.2S')^2}{(P + 0.8S')} \qquad \text{Equation 7}$$

Where:
S'= Storage at Saturation (in)
CN = NRCS Curve Number
P = Precipitation (in)
R = Runoff Excess (in)

5.3.2.1 Soils

The NRCS Curve Numbers are derived from the hydrologic soil group and land use of the subbasin. There are thousands of classified soils which are put into hydrologic soils groups based on their infiltration characteristics. The following are the classified hydrologic soil groups:

Soil Group	Description	Infiltration Rate	Soil Texture
A	Low runoff potential	8 - 12 mm/h	Sand, sandy loam
B	Moderate infiltration	4 - 8 mm/h	Silt loam, loam
C	Low infiltration	1 - 4 mm/h	Sandy clay, loam
D	High runoff potential	0 - 1 mm/h	Clay loam, clay

Table 3: Hydrologic Soil Groups

The Soil Conservation Service has classified soils within Worcester County. The soil types within the Wachusett Watershed have different infiltration rates and found at varying slopes. These variables affect the volume of runoff, which will be seen coming off from the subbasins.

Portions of the watershed soils are glacial drift and have a high runoff potential. Figure 17 displays the typical soils distribution neighboring the Wachusett Reservoir.

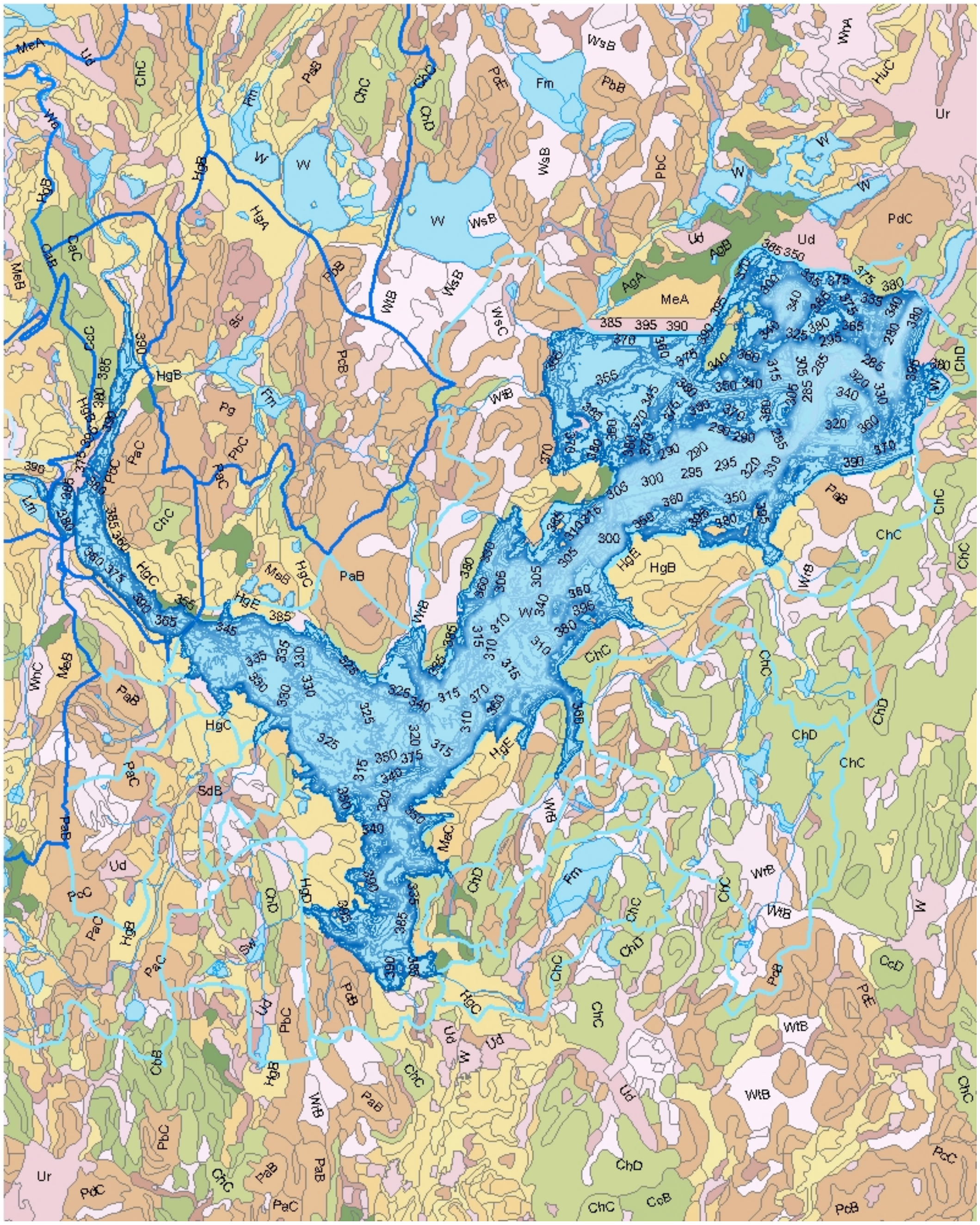


Figure 17: Soils along the Wachusett Reservoir

5.3.2.2 Land Use

Once an appropriate soil group has been determined, the CN number can be derived based on the classified land uses of the subbasin. USGS provided land use data for the region in ArcGIS data layers; these are shown in Figure 18 on the following page. The DCR also maintains records of the classified land uses in the watershed which are shown if Table 4.

Land Use	Reservoir	Thomas Basin	Quinapoxet	Stillwater	Worcester
Forest/Open	0.71	0.62	0.75	0.78	0.75
Agriculture	0.04	0.07	0.05	0.07	0.09
Residential Low	0.07	0.10	0.07	0.1	0.06
Residential Med	0.07	0.08	0.08	0.02	0.01
Residential High	0.01	0.02	0.00	0.00	0.01
Commercial/Industrial	0.02	0.06	0.03	0.01	0.01
Water/Wetland	0.08	0.07	0.02	0.03	0.07
Impervious	0.106	0.064	0.108	0.076	0.066

Table 4: Subbasin Land Use (DCR)

Depending on the hydrologic soils type and the land use of a subbasin, a curve number can be assigned to that basin. The higher the imperious surface, the higher the CN number for the basin. The typical runoff curve numbers for certain land uses can be found in

Appendix 5.

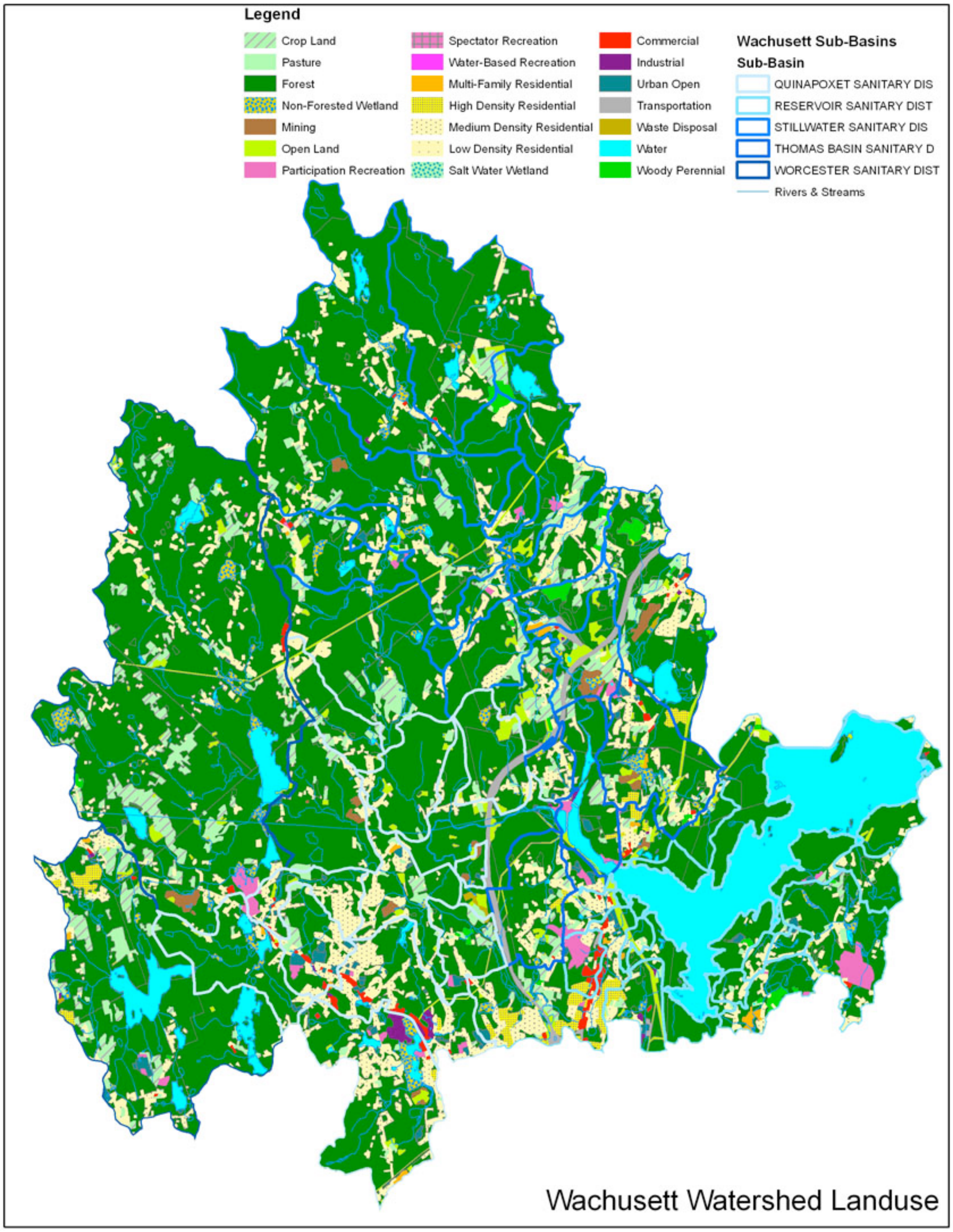


Figure 18: Wachusett Watershed Land Use

5.3.2.3 Runoff Excess

The runoff from the NRCS method can be compared against the USGS gauged readings on the Stillwater and Quinapoxet Rivers. Having previously established base flow conditions and subtracting these volumes from the gauged readings will yields the monthly runoff from the subbasin. Comparing this data with the calculated runoff from the NRCS curve number method demonstrates very different trends. For the Quinapoxet River, shown in Figure 19, the runoff estimated from the NRCS method is extremely high. For the Stillwater River the NRCS predictions underestimate the volume of runoff during the summer, Figure 20.

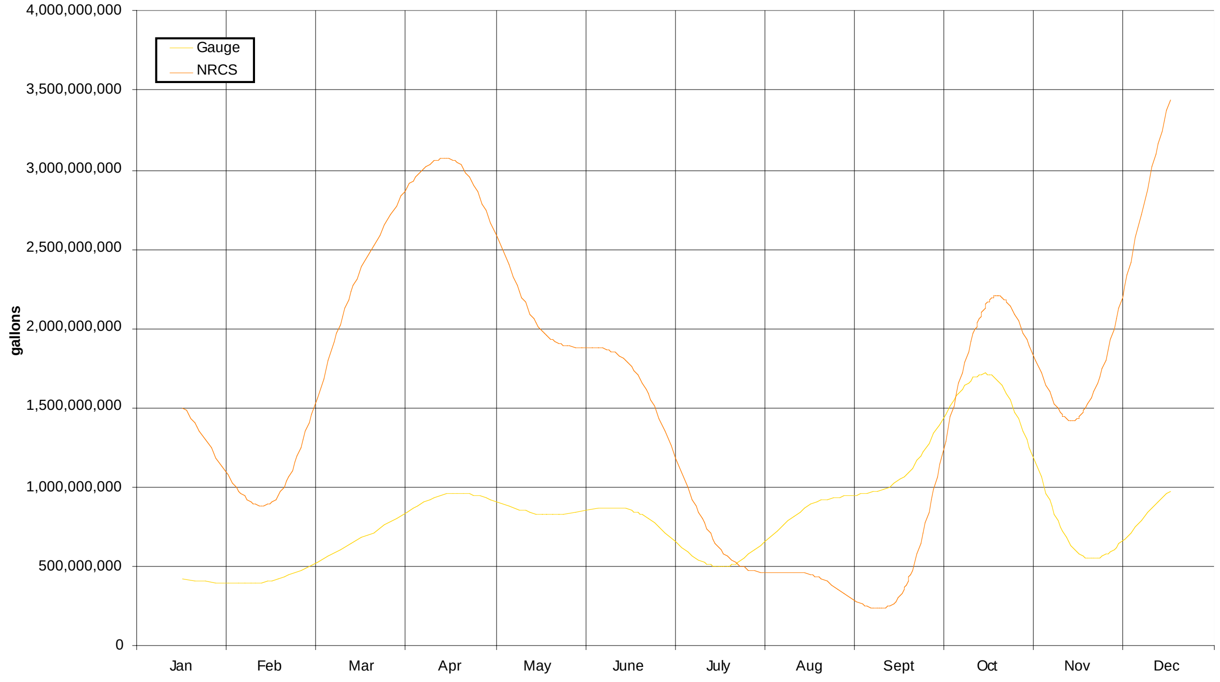


Figure 19: Quinapoxet Runoff-NRCS

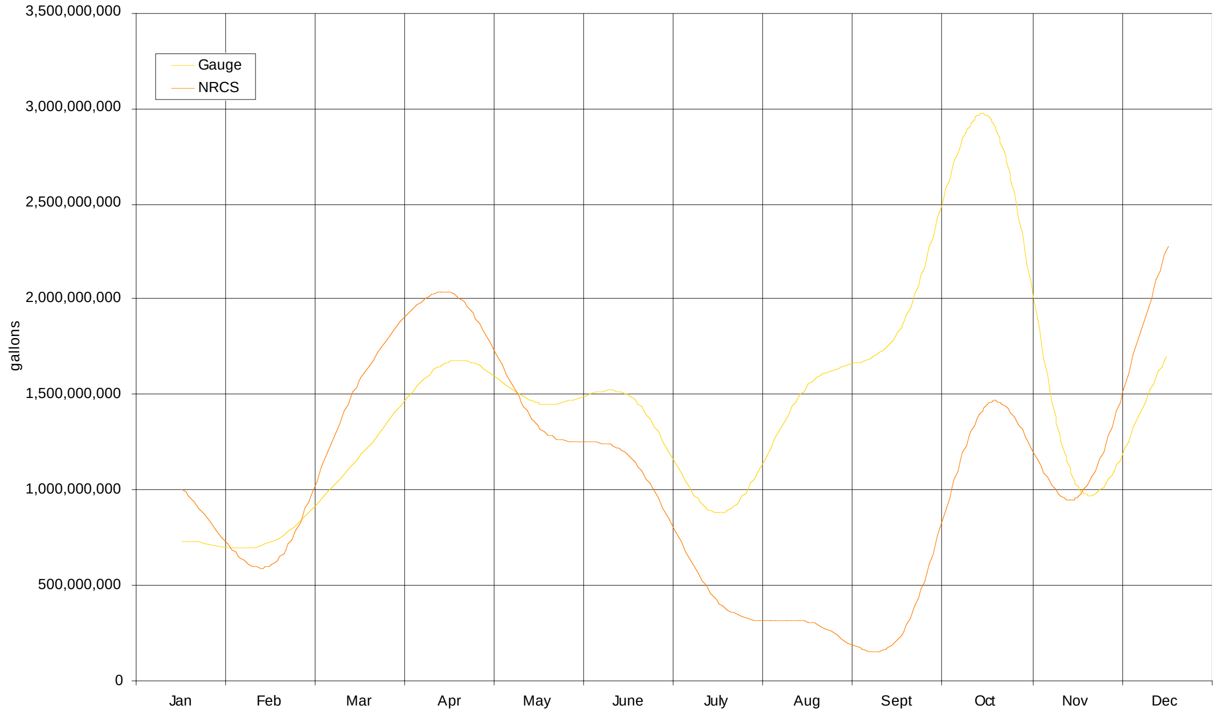


Figure 20: Stillwater Runoff-NRCS

As the can be seen in the data, using one curve number of an entire basin cannot accurately account for the seasonal variation of runoff. The NRCS method is a tool used to quantify runoff for one particular storm event over a basin. Using the method to derive values on a monthly timescale may seem too inaccurate if utilizing only a single curve number. However, to capture the true annual fluctuation of soil conditions and runoff behavior, a monthly varying curve number system may be implemented.

In order to adjust the curve numbers for wet and dry conditions three antecedent moisture conditions have been established by the NRCS.

Condition	Description
1	Dry, high infiltration rate
2	Normal, often assumed
3	Wet, high runoff potential

Table 5: Antecedent Moisture Conditions

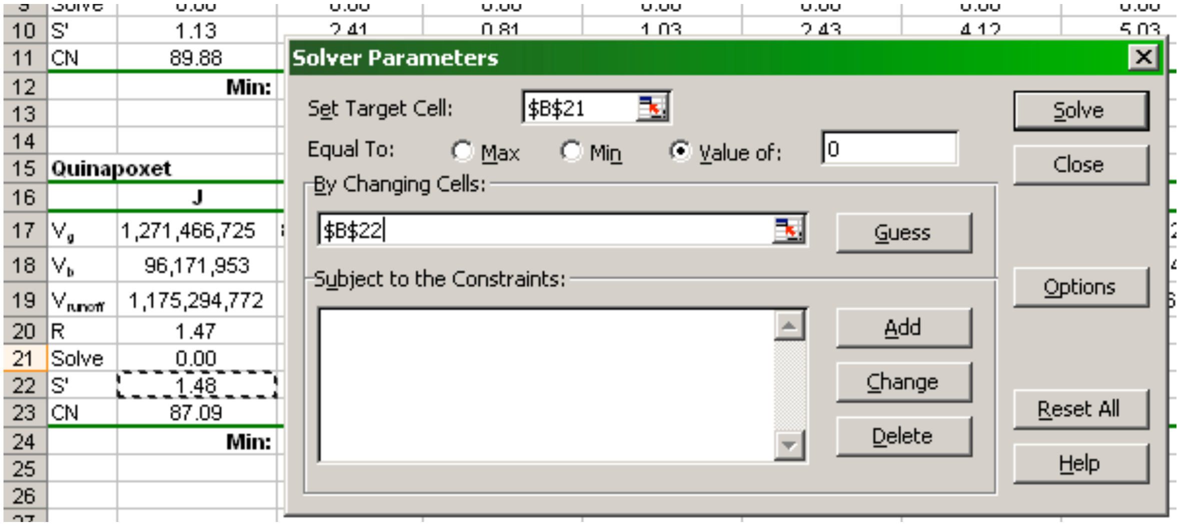
These conditions provide a method to scale CN values depending on the varying moisture of the soils. For the initial development of the curve numbers the assumption was made for condition 2 with an initial abstraction of 0.2S'.

5.3.3 Modification to the NRCS Method

As a result of the seasonal variability seen in the subbasin characteristics, a monthly variable curve number was developed for each major subbasin. USGS gauges on the Quinapoxet and Stillwater Rivers were analyzed by extrapolating base flow and runoff volumes. Since precipitation data (P) is available and the volume of runoff is known, S' can be solved for in the original rainfall excess equation:

$$R = \frac{(P - 0.2S')^2}{(P + 0.8S')} \qquad \text{Equation 8}$$

Excel includes a solve function which iterates values approaching a desired solution and resets the cells according to the new values; screen shot shown in Figure 21. This is extremely helpful since solving for S' in the previous runoff equation would prove to be a challenge otherwise.



10	S'	1.13
11	CN	89.88
12		**Min:**
13		
14		
15	**Quinapoxet**	
16		**J**
17	V_g	1,271,466,725
18	V_b	96,171,953
19	V_{runoff}	1,175,294,772
20	R	1.47
21	Solve	0.00
22	S'	1.48
23	CN	87.09
24		**Min:**
25		
26		

Solver Parameters

Set Target Cell: B21

Equal To: ○ Max ○ Min ● Value of: 0

By Changing Cells: B22

Subject to the Constraints:

Figure 21: Excel Solver Function

Once each monthly S' and CN for the Quinapoxet and Stillwater Subbasins have been generated, they are extrapolated to the ungauged basins. A method to scale CN values between the gauged Quinapoxet and Stillwater Subbasins to the ungauged Reservoir and Thomas Subbasins was developed using the relationship in Equation 9.

$$\frac{CN_{xi}}{CN_x} = \frac{CN_{Qi}}{CN_Q} \qquad \text{Equation 9}$$

Where:

CN_{xi} = Monthly curve number for ungauged subbasin (unknown)

CN_x = NRCS curve number for ungauged subbasin

CN_{Qi} = Monthly curve number for known (Quinapoxet) subbasin

CN_Q = NRCS curve number for ungauged subbasin

The purpose for this relationship is to scale the determined CN values to the ungauged basins. This is based on the ratio between the derived CN value based on the NRCS for the subbasin and the backtracked curve number previously solved. Equation 9 is not an evaluation to determine explicit CN values but more of an estimation on the assumption that the difference between monthly CN values and the "real" CN value is the same for each subbasin across the watershed, illustrated in Figure 22.

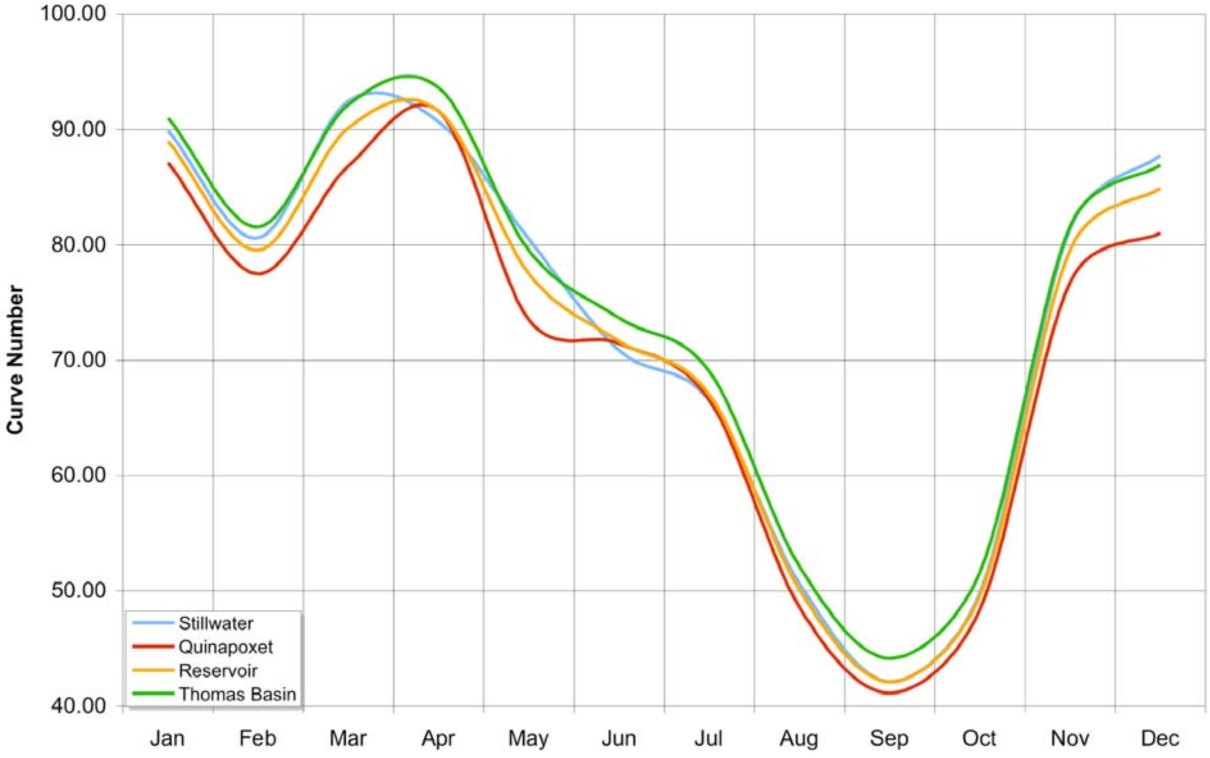


Figure 22: Subbasin Curve Numbers

As shown, the CN values for the subbasins vary slight with one another. However, the seasonal variation can be great, with spring CN values in the low 90's and summer lows in the low 40's.

5.3.3.1 Streamflow

To determine the volume of water which flows off the Wachusett Reservoir Watershed, the USGS gauged flow from the Quinapoxet River is multiplied by a runoff constant for the individual subbasin. This runoff constant is based on the variable C_{dr}, which uses the NRCS method to determine monthly volumes of water. The derivation of Equation 10 can be found in

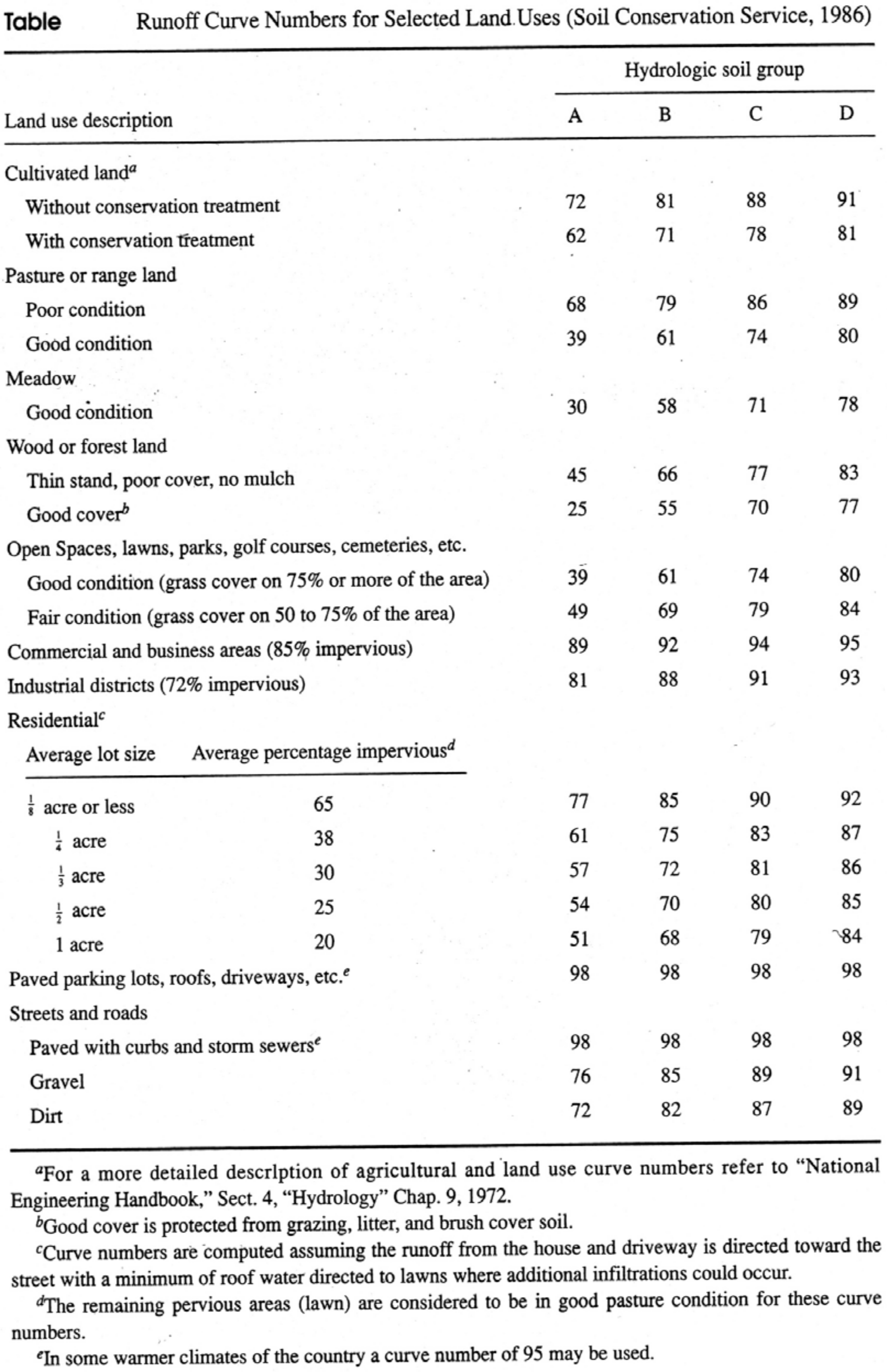


Table Runoff Curve Numbers for Selected Land Uses (Soil Conservation Service, 1986)

		Hydrologic soil group			
Land use description		A	B	C	D
Cultivated land[a]					
Without conservation treatment		72	81	88	91
With conservation treatment		62	71	78	81
Pasture or range land					
Poor condition		68	79	86	89
Good condition		39	61	74	80
Meadow					
Good condition		30	58	71	78
Wood or forest land					
Thin stand, poor cover, no mulch		45	66	77	83
Good cover[b]		25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.					
Good condition (grass cover on 75% or more of the area)		39	61	74	80
Fair condition (grass cover on 50 to 75% of the area)		49	69	79	84
Commercial and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential[c]					
Average lot size	Average percentage impervious[d]				
$\frac{1}{8}$ acre or less	65	77	85	90	92
$\frac{1}{4}$ acre	38	61	75	83	87
$\frac{1}{3}$ acre	30	57	72	81	86
$\frac{1}{2}$ acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[e]		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers[e]		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89

[a] For a more detailed description of agricultural and land use curve numbers refer to "National Engineering Handbook," Sect. 4, "Hydrology" Chap. 9, 1972.

[b] Good cover is protected from grazing, litter, and brush cover soil.

[c] Curve numbers are computed assuming the runoff from the house and driveway is directed toward the street with a minimum of roof water directed to lawns where additional infiltrations could occur.

[d] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[e] In some warmer climates of the country a curve number of 95 may be used.

Appendix 6.

$$C_{dr} = \frac{\left[\left(P^{2}\right) - \left(I_{a} S_{S} P\right) + \left(\left(1 - I_{a}\right) S_{S} P\right)\right]}{\left[\left(P^{2}\right) - \left(I_{a} S_{Q} P\right) + \left(\left(1 - I_{a}\right) S_{Q} P\right)\right]} \tag{Equation 10}$$

$$C_{dr} \frac{A_{S}}{A_{Q}} = K \tag{Equation 11}$$

$$Q_{S} = Q_{Q} K \tag{Equation 12}$$

Where:
P = Precipitation (in)
I_a = Initial Abstraction (in)
S'_i = Monthly S’ value for Subbasin *i* (in)
Q_S = Flow from Stillwater Subbasins (gal/month)
Q_Q = Gauged Flow from Quinapoxet River (gal/month)

These equations provide us with a method to quantify flows coming off the ungauged subbasins based on the USGS gauged readings from the Quinapoxet and on the storage infiltration values for the ungauged subbasin. The Stillwater USGS gauge provided the means to test the Equation 12 and then verify it against the gauged reading of the river. Applying the calibrated NRCS model to the Stillwater River subbasin Stillwater River flow was generated and was compared to the known gauged flow. Figure 23.

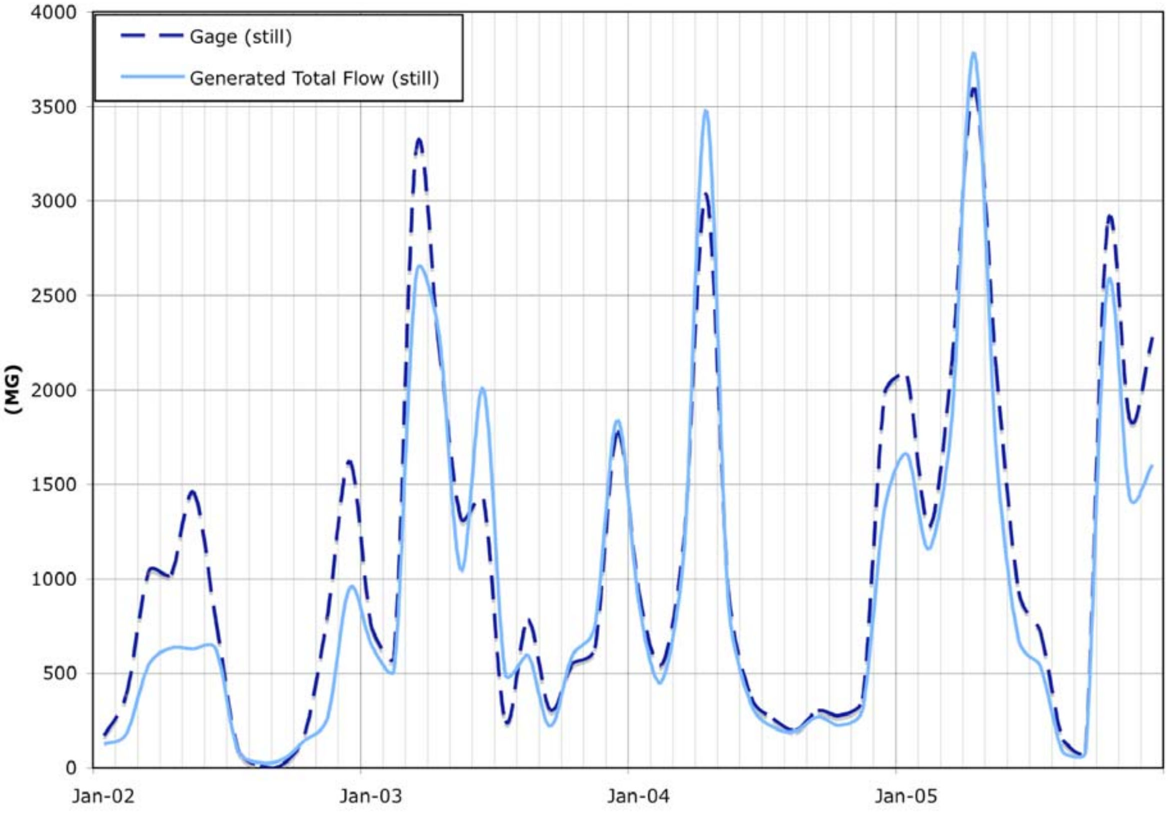


Figure 23: Stillwater Generated Data

The plotted data shows the generated flow closely follows the gauged readings of the Stillwater River. Occasionally this method will underestimates peak flows; however, the degree by which the method deviates is acceptable.

5.3.3.3 Direct Runoff

Thomas and Reservoir Subbasins are located along the reservoir and thus overland runoff flows directly into the Wachusett Reservoir. Small streams exist in these subbasins; however, a fair amount of water flows directly into the reservoir. To determine the direct runoff into the reservoir from the Thomas and Reservoir Subbasins, the flow from the Quinapoxet River is multiplied by a runoff constant, as previously described. This constant is derived from the NRCS method using the monthly variable curve numbers and subbasin areas. The following equations are the same as Equations 10-12; however, variables are changed for direct runoff.

$$C_{dr} = \frac{\left[\left(P^{2}\right) - \left(I_{a} S_{R,T} P\right) + \left(\left(1 - I_{a}\right) S_{R,T} P\right)\right]}{\left[\left(P^{2}\right) - \left(I_{a} S_{Q} P\right) + \left(\left(1 - I_{a}\right) S_{Q} P\right)\right]} \qquad \text{Equation 13}$$

$$C_{dr} \frac{A_{R,T}}{A_{Q}} = K \qquad \text{Equation 14}$$

$$Q_{R,T} = Q_{Q} K \qquad \text{Equation 15}$$

Where:
$Q_{R,T}$= Flow from Thomas and Reservoir Subbasins.

Applying the curve numbers for the Thomas and Reservoir Subbasins to the modified NRCS runoff equation generated the direct runoff volumes shown in Figure 24.

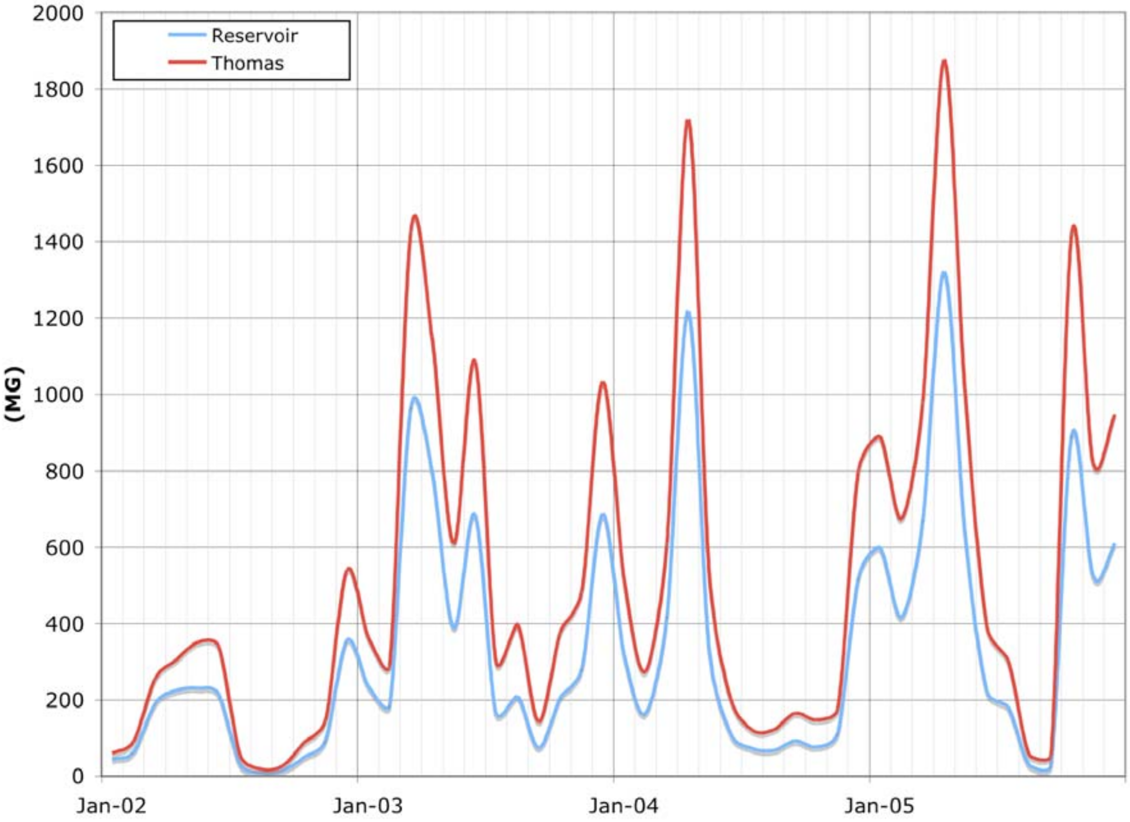


Figure 24: Direct Runoff

The graph shows similar trend between the two subbasins; although, a higher volume of runoff is demonstrated in the Thomas Basin. The following Figure 25 shows the estimated total streamflow contribution into the Wachusett Reservoir for each of the subbasins, from 2002-2005.

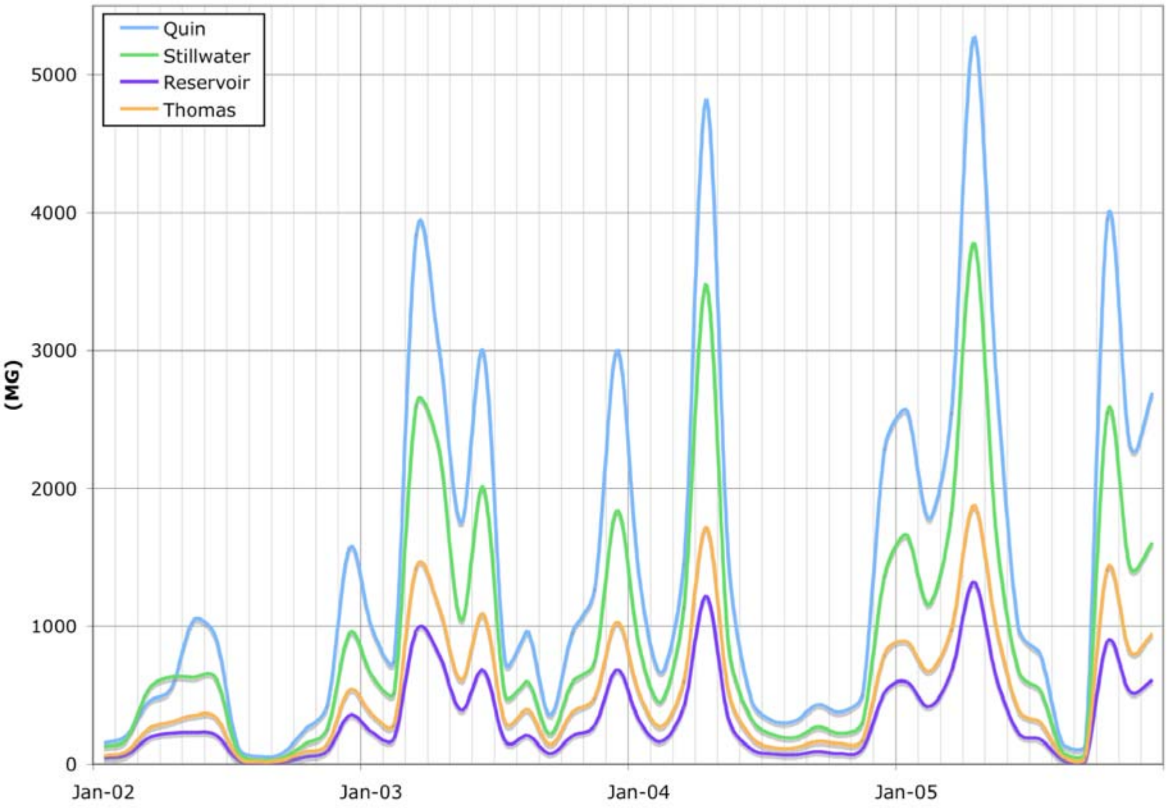


Figure 25: Total Runoff

6.0 Hydrologic Modeling

In order to properly analyze the data and hydrological research, a mass balance model in Excel was designed. This model proved the basis for establishing all the flows coming into and out of the Wachusett Reservoir for the 2002-2005 data record. The second model was designed using the Stella modeling program. This objective of this model is to provide an analysis tool concerning water supply yield and reservoir operation through conducting various simulations.

6.1 Configuring the Wachusett Reservoir Model in Excel

To generate an accurate Wachusett Reservoir yield it was necessary to configure the reservoir model to assure every parameter was accounted for. Microsoft Excel was used to catalog and quantify all of the reservoir inflows and outflows and to develop the model equations that would produce an accurate reservoir storage-yield. The following chapter illustrates the hydrologic mass balance for the Wachusett Reservoir.

6.1.1Quantiffication of Inflows

There are many inflows to the Wachusett Reservoir; some flows are natural, streamflow and runoff, and some flows are controlled, Quabbin Transfer and the Ware diversion. The following is a breakdown of the inputs into the Wachusett Reservoir. Some of the following variables have previously been established in the prior Watershed Analysis chapter of this report.

6.1.1.1 Direct Precipitation (P_{direct})

To calculate the direct precipitation onto the Wachusett Reservoir, the local precipitation (P) was multiplied by the reservoir surface area (SA), which generated the volume of water that fell directly on the reservoir. Appendix 2

$$P_{direct} = P * SA \qquad \text{Equation 16}$$

6.1.1.2 Ware River Diversion (Q_{WRD})

The Ware River diversion flow is a gauged flow that only flows when the Ware River is experiencing high flow events. In the four sample years the Ware River diversion only received flow in the high rain events of October 2005. Appendix 7

6.1.1.3 Quinapoxet River (Q_Q)

The Quinapoxet River is the larger of the two major rivers which flow into the Wachusett Reservoir. The Quinapoxet River is accurately metered by the USGS with a water-stage recorder with telephone telemeter. This metered flow is entered directly into the Excel reservoir model and is demonstrated in Figure 15. Appendix 8

6.1.1.4 Stillwater River (Q_S)

The Stillwater River is the smaller of the two major rivers that flow into the Wachusett Reservoir. It is monitored by a USGS water-stage recorder with telephone telemeter, but the gauged flows are not considered accurate due to beaver activity on the river. The modification to the NRCS method utilizing a monthly curve number was used to produce a runoff constant K, which when multiplied by the Quinapoxet gauge flow, generates the flow from the Stillwater

River. This is the same process which was described in the Section 5.3.3.1 of the Watershed Analysis chapter. Appendix 9

$$Q_S = Q_Q K \qquad \text{Equation 17}$$

6.1.1.5 Direct Runoff (Q_{DR})

The direct runoff flow off of the Thomas and Reservoir Subbasins into the Wachusett Reservoir is fairly unmonitored. These two subbasins contain some small streams but a fair amount of water runs off directly into the reservoir. The NRCS method modification was used as described in the Section 5.3.3.2 of the Watershed Analysis chapter, Equation 17. Appendix 10

$$Q_{R,T} = Q_Q K \qquad \text{Equation 17}$$

6.1.1.7 Quabbin Aqueduct (Q_U)

The Quabbin Aqueduct conveys water from the Quabbin Reservoir into the Wachusett Reservoir and supplies most of the water that is used to meet demand. The aqueduct is 24.6 miles long, making it only 0.5 mile shorter than the longest tunnel in the world. The Quabbin Aqueduct can supply up to 400 cfs which is entirely feed by a natural siphoning action. The flow in the Quabbin Aqueduct is controllable but limited by the water level in the Quabbin Reservoir. This flow is gauged by DCR-MWRA and the gauged flow was used in the Excel reservoir model, plotted in Figure 26 and contained in Appendix 12

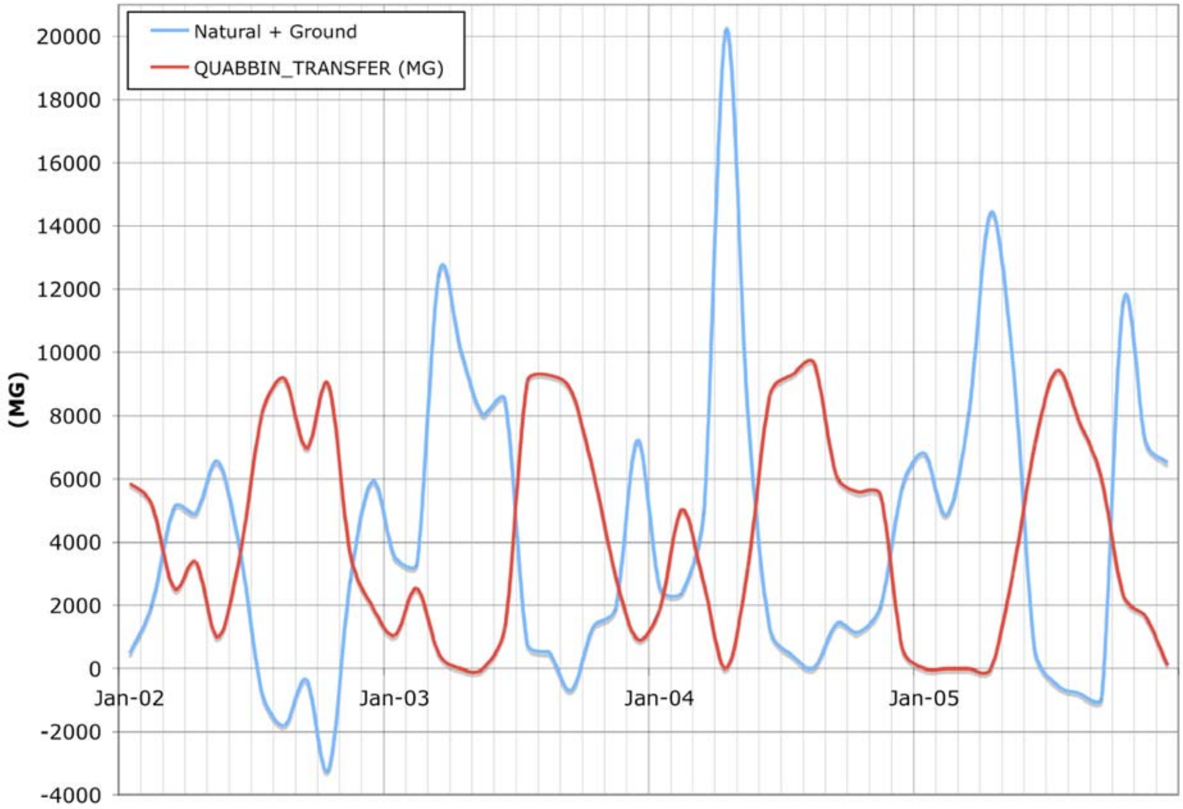


Figure 26: Quabbin Transfer and Natural Flows

The Quabbin Aqueduct is normally activated when the natural inflows to the Wachusett Reservoir are lower than the desired demand. Figure 26 shows the oscillating nature of the two flows and how their peaks alternate depending on the season. In the summer season, the volume of water which is supplied by the watershed drops significantly and additional water is required to maintain proper operating conditions.

6.1.2 Quantification of Outflows

The majority of the outflows to the system are regulated or gauged. Evaporation and effluent subsurface flow are the only two natural processes by which water will leave the system. Since backtracked S’ values were estimated from the gauged streamflow readings, evapotranspiration values are effectively included into the S’ value for each subbasin.

6.1.2.1 Evaporation (E)

The evaporation values previously derived in Section 5.2 of the Watershed Analysis Chapter were used in the Excel model. The method of extrapolating the available Kingston, RI data to the Dunne Equation curve is shown in Equation 9 and was described in the Section 5.2. Appendix 3

$$\frac{CN_{xi}}{CN_x} = \frac{CN_{Qi}}{CN_Q} \qquad \text{Equation 18}$$

6.1.2.2 Reservoir Spillway ($Q_{spillway}$)

When the volume in the Wachusett Reservoir exceeds capacity, the excess water is released over the spillway. The volume of water which is spilled is calculated and recorded. The spillway elevation is normally set at 395 feet above sea level; however, this elevation can be changed for construction or maintenance. Appendix 14

6.1.2.3 Nashua River Release (Q_{nashua})

The Nashua River Release is a gauged flow that releases the mandated 1.8MGD to the Nashua River to supply the river with a steady minimum flow. The Nashua River Release gauged flow was applied to the Wachusett Reservoir Excel model. Appendix 15

6.1.2.4 Sleeve Release (Q_{sleeve})

The sleeve value is a controlled release which discharges water to the Nashua River. The four 42” valve pipes permit preventative releases in order to avoid large volumes of reservoir overflow, which could endanger downstream development. Appendix 16

6.1.2.5 Wachusett Aqueduct ($Q_{aqueduct}$)

The Wachusett Aqueduct is the former tunnel which used to supply demand from the Wachusett Reservoir. It is currently maintained as a back up in the event of maintenance or failure in the Cosgrove Tunnel, which currently supplies demand. Appendix 17

6.1.2.6 Demand (Yield) (Y)

The demand (yield) is the amount of water that is used by the supply the consumer demand. The flow to demand is gauged in the Cosgrove Tunnel which can handle a maximum flow of 600MGD. The demand varies throughout the year and follows a steady curve on an annual basis. The average withdrawal to meet demand is currently around 220 MGD.

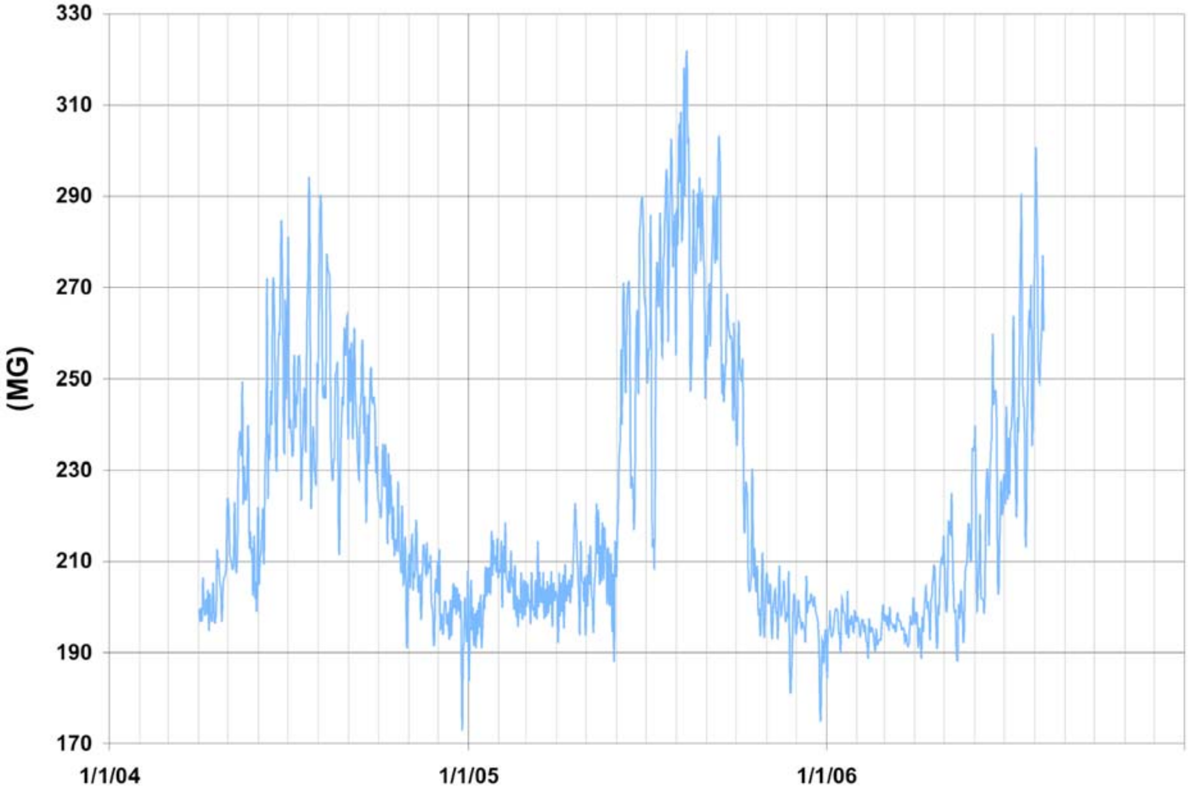


Figure 27: Daily Average Demand

Demand data from the system is accurately measured and this recorded data were used in the Wachusett Reservoir Excel model; shown in

Figure 27, data available in Appendix 18

6.1.3 Reservoir Mass Balance

The basic concept of a mass balance is the change in volume is equal to the sum of the inflows minus the sum of the outflows; this is demonstrated in Equation 20

$V = [\sum inflows]-[\sum outflows]$ Equation 20

Looking specifically at the mass balance for the Wachusett Reservoir, Equation 20 shows all the components into the hydrological system of the reservoir.

$$V = \left[P_{direct} + \left(Q_{WRD} + Q_{Q} + Q_{S} + Q_{U}\right) + Q_{DR}\right] - \left[E + Q_{spillway} + Q_{nashua} + Q_{sleeve} + Q_{aqueduct} + Y\right] \pm G$$

Equation 21

6.1.3.1 Ground Water *(G)*

The volume of water that was still unaccounted for in the mass balance was primarily attributed to groundwater. The volume of the reservoir was known and the only variable that was still undetermined was the contribution from groundwater. The groundwater that flows into the reservoir in the winter and spring and out of the reservoir in the fall and winter is one of the major parameters in quantifying the reservoir storage-yield. In addition, the groundwater flow into and out of the Wachusett Reservoir is directly related to the elevation of the groundwater.

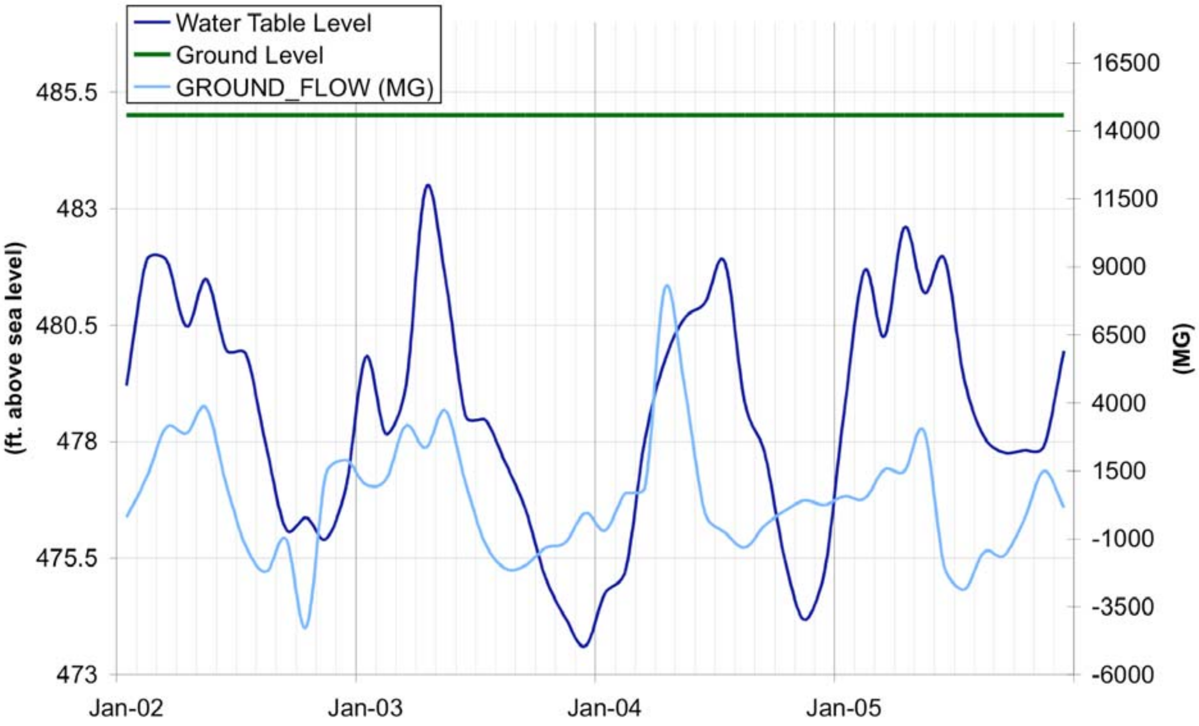


Figure 28: Groundwater Elevation and Estimated Groundflow

Figure 28 demonstrates the seasonal variations in the groundwater elevation (USGS, 2007). On average the groundwater table around the reservoir may fluctuate as much at 10 feet, and these trends are mirrored in the volumes of water, which are estimated to flow through the Wachusett Reservoir. Analysis of the contours surrounding the reservoir, limited groundwater and soil information available yielded a ground water elevation contour map shown in Figure 29.

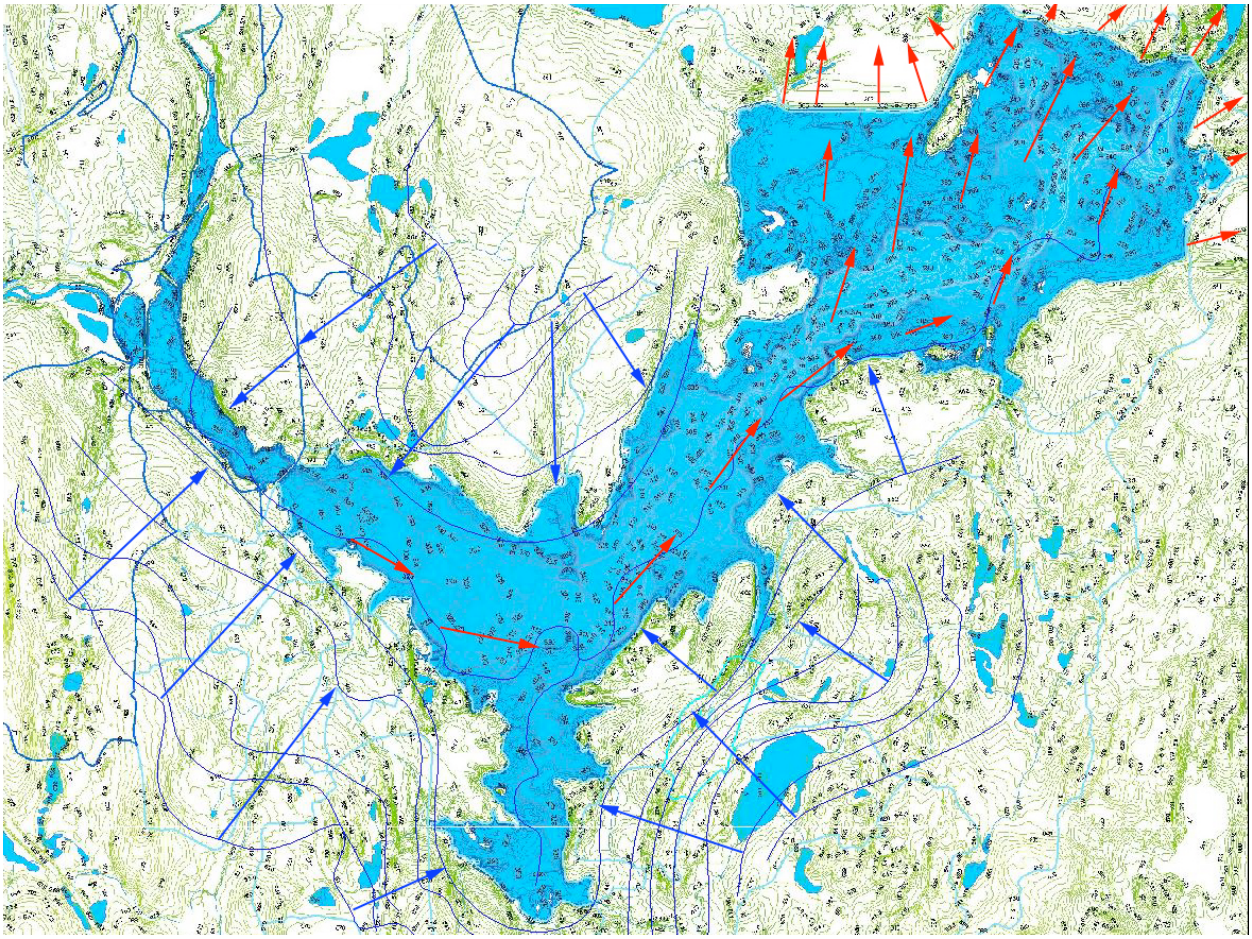


Figure 29: Groundwater Contour and Flow Map (Sketch)

As Figure 29 shows, constant flow from the reservoir to the groundwater aquifer exists in the area surrounding the Wachusett Dam; sketched with red arrows. This is largely due to the small operating band which the Wachusett Reservoir is maintained, causing the hydraulic head around the dam to constantly push water into the aquifer. Upstream from the dam, groundwater flow begins to change from flow into the aquifer to flow into the reservoir; sketched with blue arrows. As previously determined, the elevation of the water table fluctuates. This fluctuation changes the flow rate of groundwater, which enters the upper portion of the reservoir seasonally. In the summer months when the water table is at its lowest, the volume of water, which contributes to yield, is also at it's lowest; as demonstrated in the data in Appendix 11

6.1.4 Inflow Summary

Figure 30 shows the contribution of each variable to the inflows for the Wachusett Reservoir from 2002 – 2004 using the Excel model.

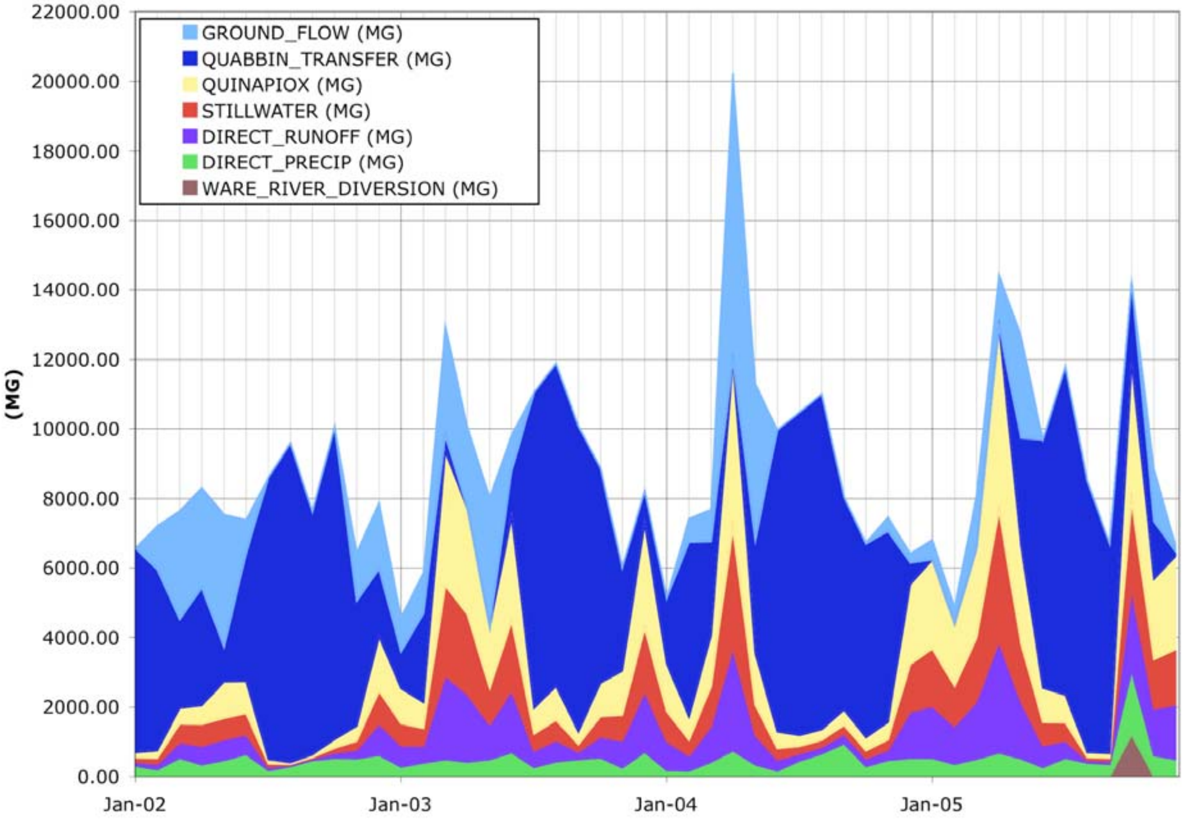


Figure 30: Inflows to the Wachusett Reservoir

6.1.5 Outflow Summary

Figure 31 shows the contribution of each outflow to the Wachusett Reservoir from 2002 – 2005 using the Excel model.

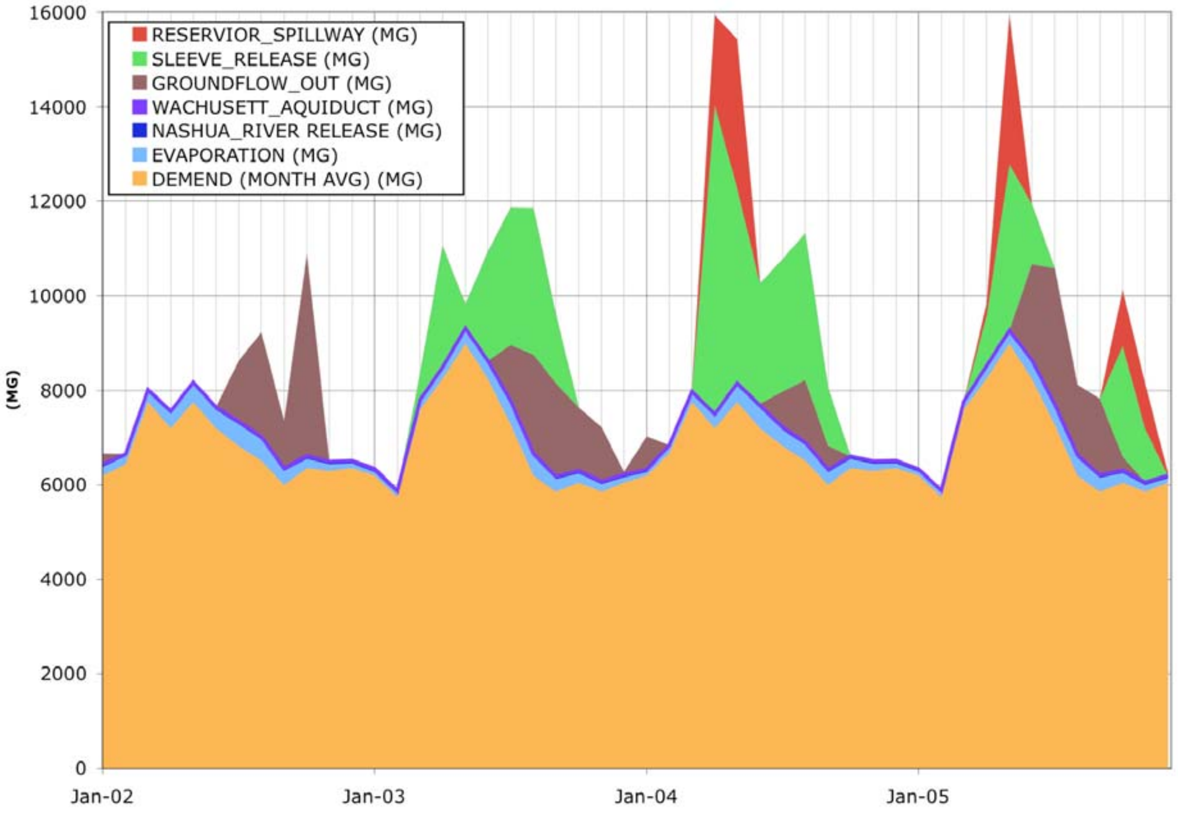


Figure 31: Outflows to the Wachusett Reservoir

6.2 Wachusett Reservoir Model in Stella

The Stella modeling package is a powerful and flexible modeling program which provides an excellent way to map out and simulate the Wachusett Reservoir system. Through data analysis and hydrologic observations a conceptual model was designed concerning the hydrologic behavior of the reservoir. From this conceptual model, the actual mathematical model was designed using Stella. This model was calibrated and tested against our 2003 data set to ensure each parameter was properly assigned and the simulation was running in an appropriate manner. Once the mathematical model was verified, it was analyzed against the entire four year data set, 2002-2005. This procedure validates our model to run simulations for predictions and hydrologic analysis. Finally to test the model under drought conditions, the drought during 1963-1967, a one in three hundred year drought, was used.

6.2.1 Conceptual Model

The dominate processes within the Wachusett Reservoir consist of the hydrologic characteristics of the watershed, releases, demand, and water transfers. All these processes contribute to the enormous mass balance for the reservoir. The variables in the conceptual model can basically be categorized into four major flows as illustrated in Figure 32.

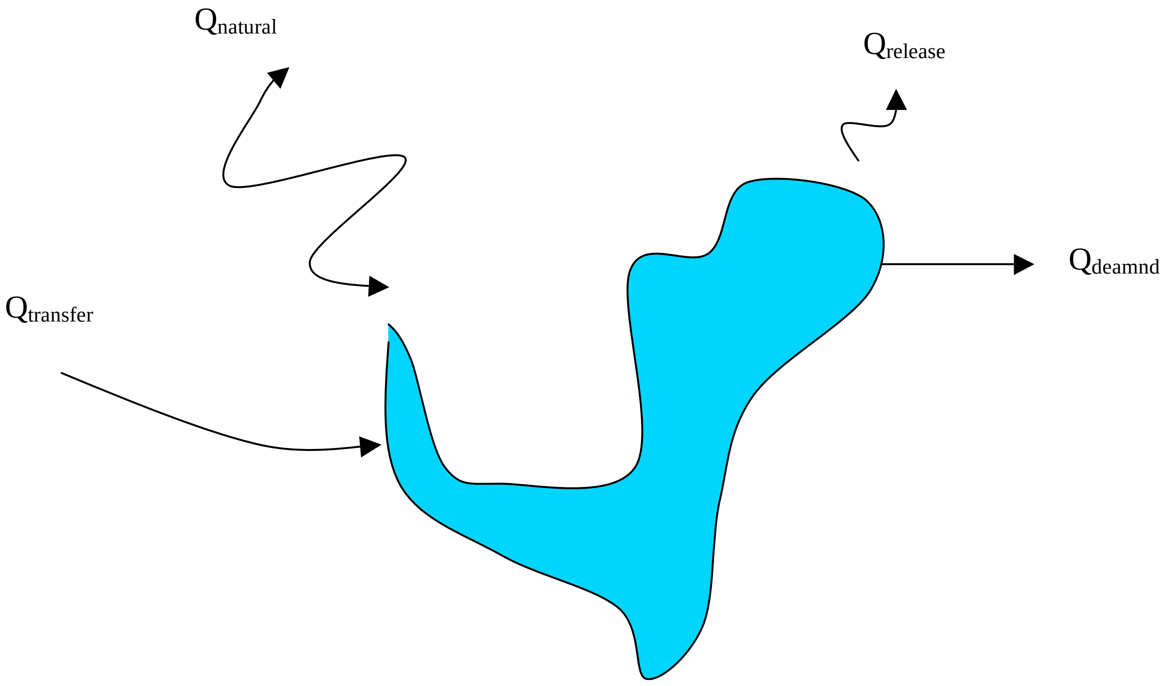


Figure 32: Conceptual Reservoir Model

These components include the Quabbin transfer, withdrawals to meet demand, releases to the Nashua River, and the sum of all the “natural” inflows into the reservoir. The natural flows constitute streamflow, runoff, evaporation, and groundwater flow. In the Stella model these variables operate in similar fashion as was described in the Excel model.

6.2.2 Mathematical Model

To develop a numerical model, values have to be assigned to each of the contributions to the Wachusett Reservoir system. These volumes are calculated through set values or an equation which requires inputs from other variables. There are many sections of operation within our model which all contribute to the overall simulation of the reservoir. The main portion consists of the mapped water balance which shows the inflows and withdrawals of the system. A separate page is dedicated to developing runoff values for the four major subbasins in the watershed. In order to run the model in an accurately simulated environment, a time and climate generation system is an integral part of the reservoir model and permits the generation of monthly temperature and rainfall values based on seasonal averages. Finally, a method was needed to verify and validate our model; as a result, the user can input desired rainfall and Quinapoxet streamflow data. This user interface acts as the control panel for the reservoir model, which all operations and data entry can be controlled. From these processes, the model can generate the remaining values for the system which can be cross referenced with our data record.

6.2.2.1 Water Budget Model

The model has a formal skeletal structure which resembles a typical water budget; as can be seen in Figure 33. The reservoir is located in the center of the model and has designed flows which deliver water through the system.

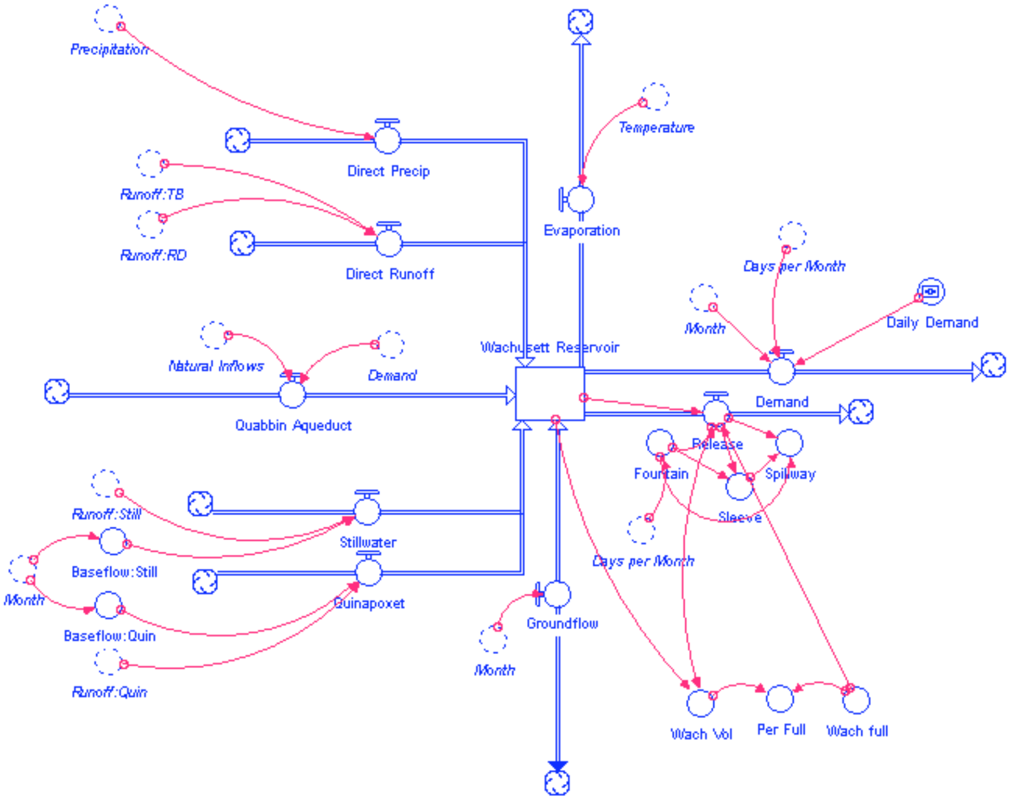


Figure 33: Stella Model Water Budget

The series of flows from the reservoir are functions which bring volumes of water into and out of the system; these flows include natural, gauged, ungauged and regulated flows. The following is a breakdown of each flow within the model. These processes are functions of equations and basic programming entered into the model. A copy of the entire model and corresponding equations are found in Appendix 20.

- **Direct Precipitation**

  The rainfall for the month is multiplied across the 6.5 mi^2 surface area of the reservoir to obtain a monthly volume of rainfall which fell on the surface water.

- **Evaporation**

  A curve was fitted to the evaporation values previously derived in Section 5.2 of the Watershed Analysis chapter. This curve is solely based on temperature and generates evaporation values which match the seasonal trends. The relatively small volume of water which leaves the reservoir validates the curve which has a correlation coefficient of 0.95 based on the 2002-2005 data.

- **Groundflow**

  Since an equation for groundwater flow cannot be developed and verified from the available data record, monthly averages based on the data produced in the Excel model were used. The scope of this project did not include the development of a relationship between any other variables in the data record. The averages previously developed are a good indicator to the typical amount of water which enters and leaves the system on a seasonal basis.

- **Streamflow and Runoff**

  Streamflow in the model constitutes the baseflows of the Quinapoxet and Stillwater rivers, plus any addition of flow due to runoff. The runoff from the Quinapoxet, Worcester and Stillwater Subbasins are assumed to reach one of the two rivers before entering the reservoir. The runoff for the Thomas Basin and Reservoir District subbasins contribute to the direct runoff volumes of the model and are assumed to travel straight into the reservoir. Runoff is calculated in the same fashion as described in Chapters 5 and 6, by multiplying the gauged Quinapoxet flow by a runoff coefficient to determine the ungauged flows, Equation 24.

$$C_{dr} = \frac{\left[\left(P^2\right) - \left(I_a S_i P\right) + \left(\left(1 - I_a\right) S_i P\right)\right]}{\left[\left(P^2\right) - \left(I_a S_Q P\right) + \left(\left(1 - I_a\right) S_Q P\right)\right]} \qquad \text{Equation 22}$$

$$C_{dr} \frac{A_i}{A_Q} = K \qquad \text{Equation 19}$$

$$Q_i = Q_Q K \qquad \text{Equation 20}$$

where:
S'_i = S’ value for subbasin *i*
S'_Q = S’ value for the Quinapoxet Subbasin
I_a = initial abstraction
Q_i = Flow from subbasin *i*
Q_Q = Gauged Flow from the Quinapoxet River

This process section of the model can be seen in Figure 34.

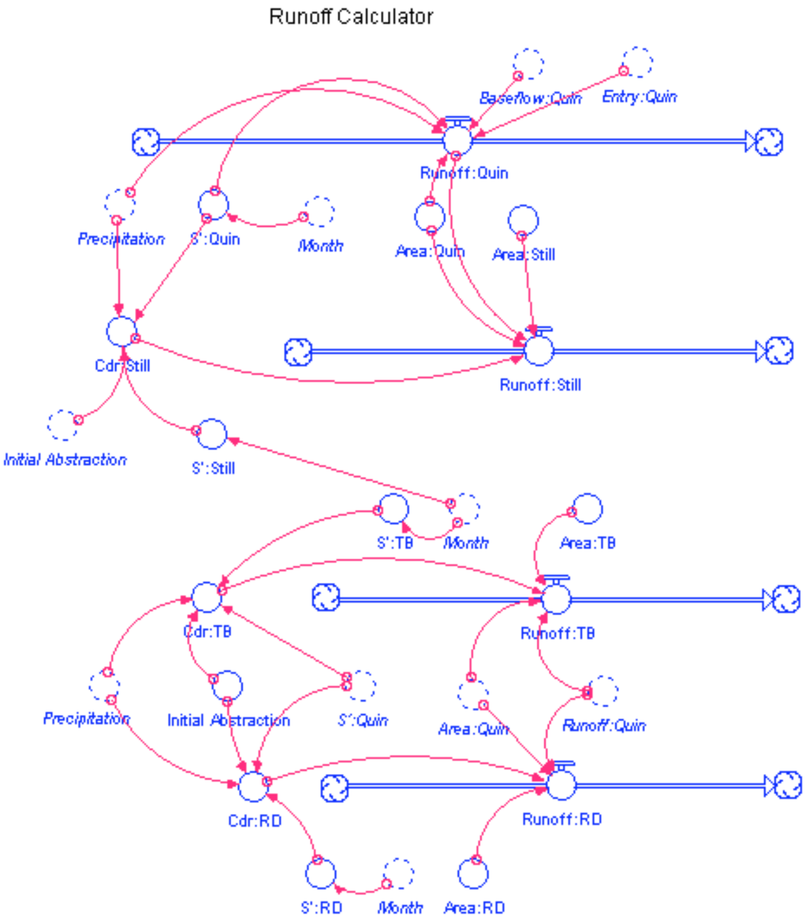


Figure 34: Stella Model Runoff Calculator

As the figure demonstrates, monthly S’ values are assigned to each subbasin. Quinapoxet streamflow data is entered by the user, which includes baseflow, and is scaled to the remaining subbasins using this projects derivation on the NRCS method. If no Quinapoxet data is entered, the model calculates volume of runoff on the Quinapoxet and Worcester Subbasins using the original NRCS equations. This will be the volume which is subsequently scaled to the remaining basins.

- **Releases**

  The releases for the Wachusett Reservoir include the regulated fountain which provides water to the Nashua River, the controlled sleeve value to prevent excess spill, and the spillway in situations of high volume. The fountain releases the mandatory 1.8 MGD to the Nashua River. The spillway simply dumps the excess water when the reservoir volume is above 100%.

- **Demand**

  The seasonal water demand curve is based on the monthly demand averages for the 2002-2005 data sets. This curve takes the average daily water demand and calculates a monthly volume to be withdrawn from the reservoir.

- **Quabbin Transfer**

  To maintain proper operating conditions in the Wachusett Reservoir, water from Quabbin is transferred through the Quabbin Aqueduct. In the model, the Quabbin Aqueduct is activated when the natural inflows into the reservoir is exceed by the demand. This process keeps the volume in the Wachusett Reservoir controlled and within the optimal range. Since the volume of water which can be drawn from Quabbin requires its own hydrologic model, close consideration is given to transfer water. No maximum limit is set and any yield analysis should be made on the volume of water which is required by Quabbin to maintain proper conditions for the Wachusett Reservoir.

6.2.2.2 Climate Generation

To develop a self sufficient hydrologic model, temperature and precipitation data can be randomly generated, Figure 35, and scaled based on seasonal norms and extremes. The monthly temperatures are randomly assigned based on the regional average maximum and minimum temperatures. A scaling factor can be assigned by the user in order to generate temperature for varying atmospheric conditions. Similarly, precipitation data is generated based on monthly rainfall averages; including a scaling factor to test the Wachusett Reservoir under dry or wet conditions.

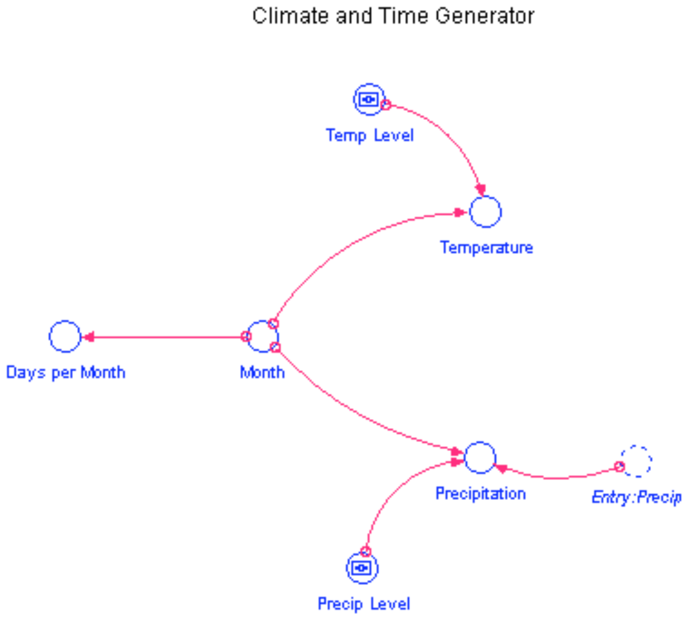


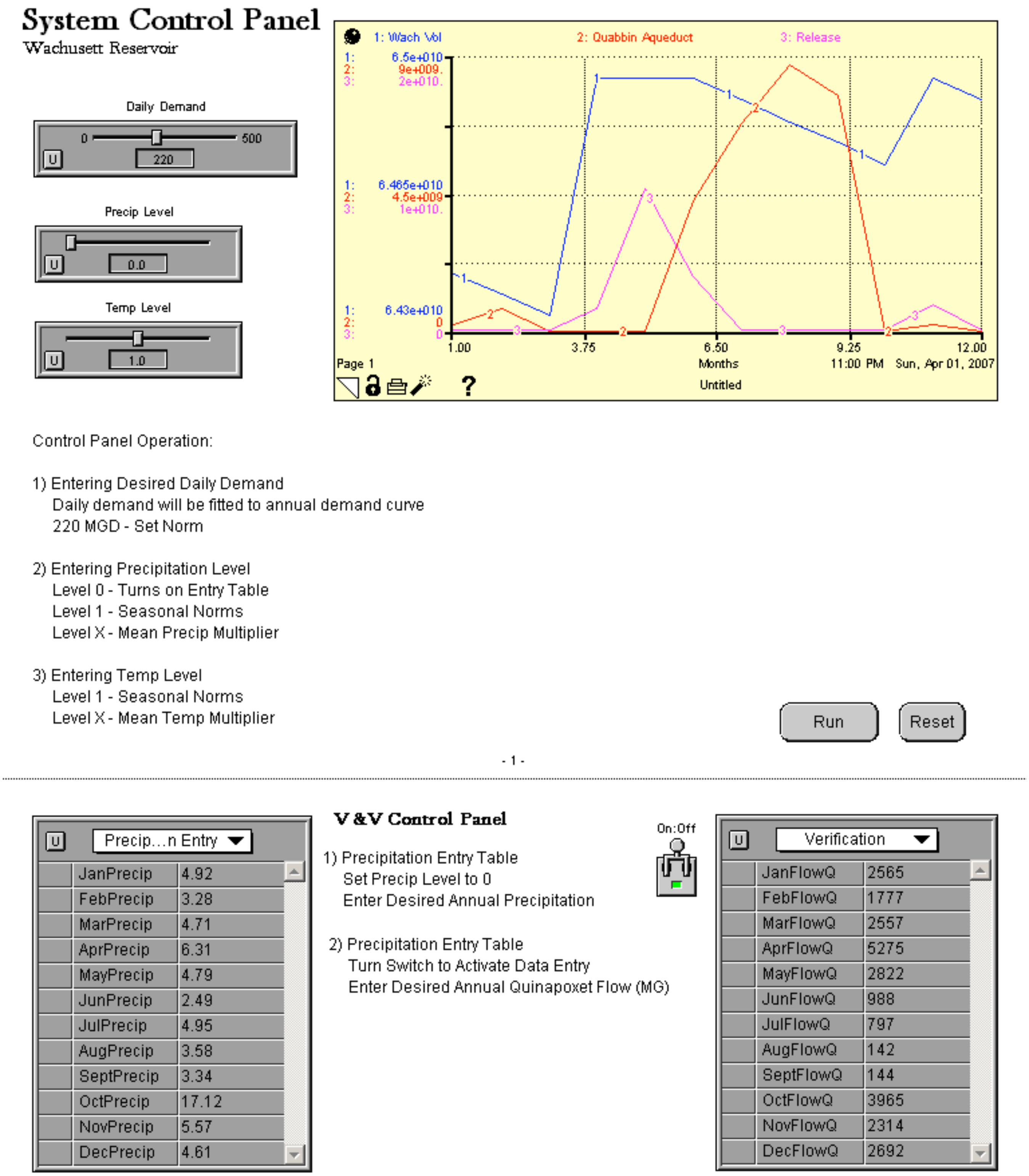
Figure 35: Stella Model Climate and Time Generator

6.2.2.3 Verifying the Model

To assure the model is operating in the designed manner, data entry tables are utilized in order to verify the results against the Excel model and data record. These tables are located on the interface of our model; the entire model is designed to run almost entirely on precipitation and Quinapoxet flow data.

6.2.2.4 User Interface

In order to properly interact with the model, an interface with a system control panel was designed, illustrated in Figure 36. A series of three slider bars can be found in the upper left section of the system control panel. The user can select the desired average daily water demand in the first slider bar; this input is then fit to the annual demand curve.



Control Panel Operation:

1) Entering Desired Daily Demand
   Daily demand will be fitted to annual demand curve
   220 MGD - Set Norm

2) Entering Precipitation Level
   Level 0 - Turns on Entry Table
   Level 1 - Seasonal Norms
   Level X - Mean Precip Multiplier

3) Entering Temp Level
   Level 1 - Seasonal Norms
   Level X - Mean Temp Multiplier

JanPrecip	4.92
FebPrecip	3.28
MarPrecip	4.71
AprPrecip	6.31
MayPrecip	4.79
JunPrecip	2.49
JulPrecip	4.95
AugPrecip	3.58
SeptPrecip	3.34
OctPrecip	17.12
NovPrecip	5.57
DecPrecip	4.61

1) Precipitation Entry Table
   Set Precip Level to 0
   Enter Desired Annual Precipitation

2) Precipitation Entry Table
   Turn Switch to Activate Data Entry
   Enter Desired Annual Quinapoxet Flow (MG)

JanFlowQ	2565
FebFlowQ	1777
MarFlowQ	2557
AprFlowQ	5275
MayFlowQ	2822
JunFlowQ	988
JulFlowQ	797
AugFlowQ	142
SeptFlowQ	144
OctFlowQ	3965
NovFlowQ	2314
DecFlowQ	2692

Figure 36: Stella Model User Interface

The temp and precip levels help evaluate the model under a range of atmospheric conditions. As previously described in the climate generation process, these levels multiply the generated value by a desired scale. To evaluate a year with 50% less than average rainfall, the precipitation level should be set at 0.5. A year which is 10% hotter than average would have a temperature level input of 1.10.

To the right of the slider bars is a graph of the reservoir volume, the Quabbin Aqueduct, and the releases from the Wachusett Reservoir. This graph is automatically generated when the model is run to help establish an immediate sense as to the result of a trial run. To run a simulation, buttons are located on the bottom right corner of the control panel, run and reset. These buttons are also located on the bottom left corner of the Stella program window.

The data entry tables previously mention can be seen at the bottom of Figure 36. The left hand table is for monthly precipitation, in inches, for a year of rainfall data; to activate this table the precip level should be set to zero. To the right is the verification table in which monthly Quinapoxet flow, in million gallons, is entered into the model. To activate this model the On:Off switch should be activated so the green light is on, as shown in Figure 36.

6.2.3 Validation

While the Stella model utilizes many of the equations and values established and tested in the Excel model; the validity of the Stella model to accurately simulate reservoir behavior should be examined. The entry tables allow the user to perform such a test on the model. Data from the year 2003 was used to evaluate the accuracy in Stella in duplicating data from the Excel model and data record.

Since the method used to evaluate runoff was the same in Excel as is in the Stella model, the values should match up. Additionally the values from both models should mirror the gauged reading to the degree of acceptability previously established in the Excel Chapter, Figure 37 demonstrates these relationships.

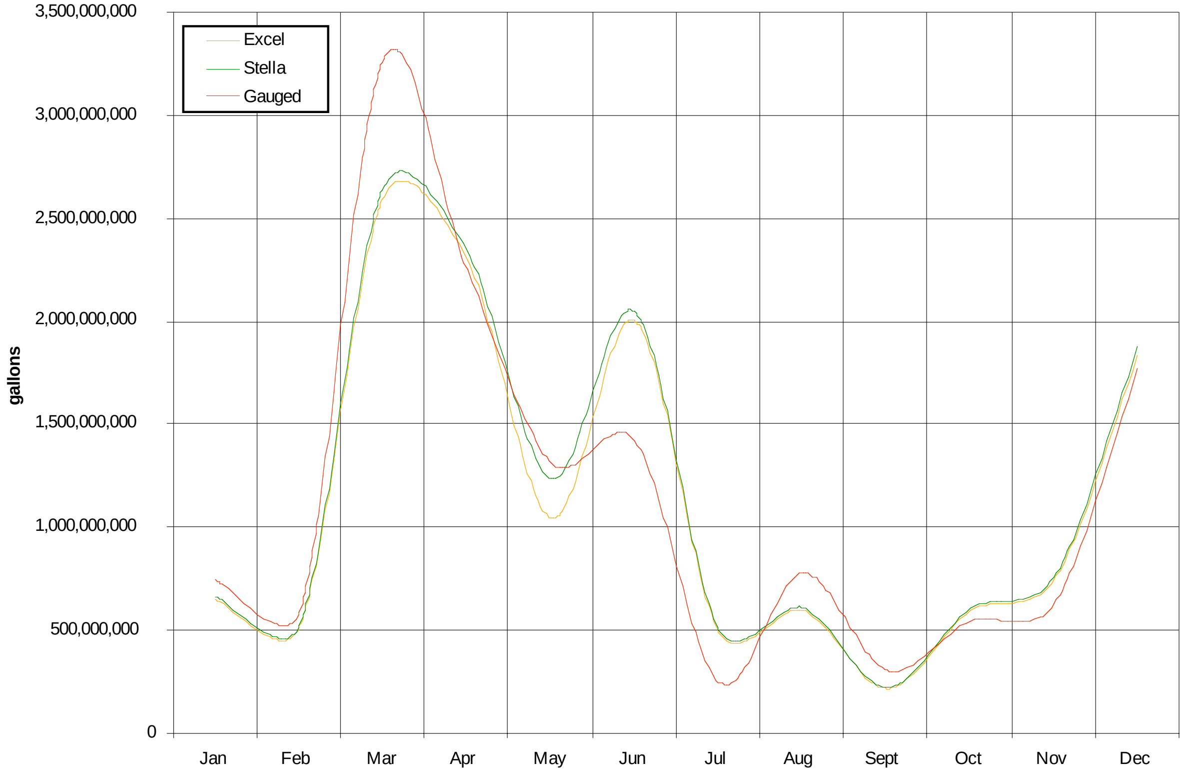


Figure 37: Stella 2003 Simulation, Stillwater Flow

The Stella model predicts volumes of water entering the reservoir from the Stillwater River which includes baseflow and runoff. As the graph reveals, the Stella and Excel model match and the synthesized Stillwater streamflow adequately mirrors the gauged readings. The Stella model for the Wachusett Reservoir simulated the volume coming through the Stillwater River within 1.3% of the actual gauged readings.

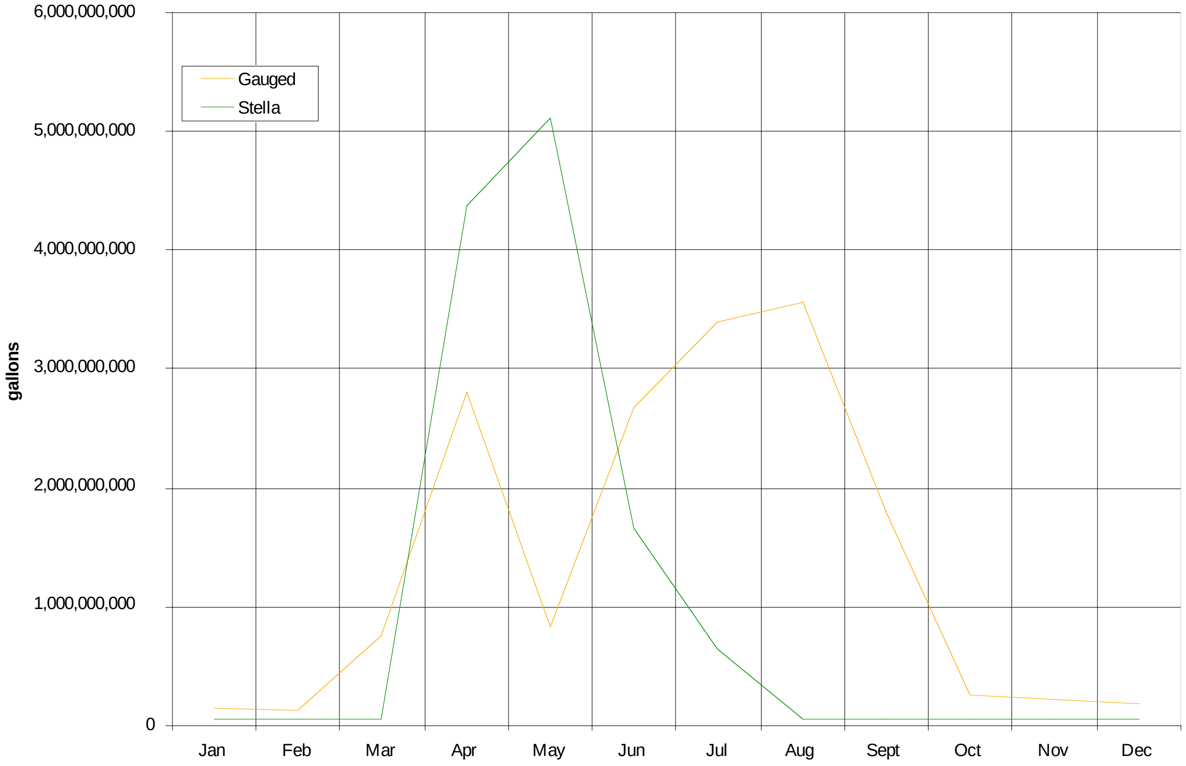


Figure 38: Stella 2003 Simulation, Release Volumes

The release program in the model is defined to start operating when the volume of the reservoir begins to exceed the maximum storage capacity. Since there are no operating decisions to make as to when/if to turn on the sleeve valve, the expected volume of release is the necessary volume of water dictated by the model. The gauged and modeled releases are plotting in Figure 38.

As shown in Figure 38, the releases from the model have higher peaks than the peaks of the actual measured releases. However since the model has the ability to efficiently maintain reservoir level, water release is kept to the bare minimum. The releases from the model in April – June simply represent the excess natural inflow which occurs through the melting of snow pack, the heavier spring rains and the reduced capacity for infiltration due to saturation in the soil. Overall the model released 27% less water than the water released by the actual reservoir operation; 4.5 billion gallons.

The Quabbin transfer is an inflow which supplies the Wachusett Reservoir with a constant supply of water to maintain operation standards. The water level in the Wachusett Reservoir dictates when the transfer is activated. The maximum volume which can be drawn is naturally based on the Quabbin Reservoir volume and hydrologic behavior. However, the Stella model conveys water from Quabbin once the natural inflows into the system are exceeded by the demand and draw as much water as needed. Figure 39 shows the close similarity the model has to actual volumes transferred.

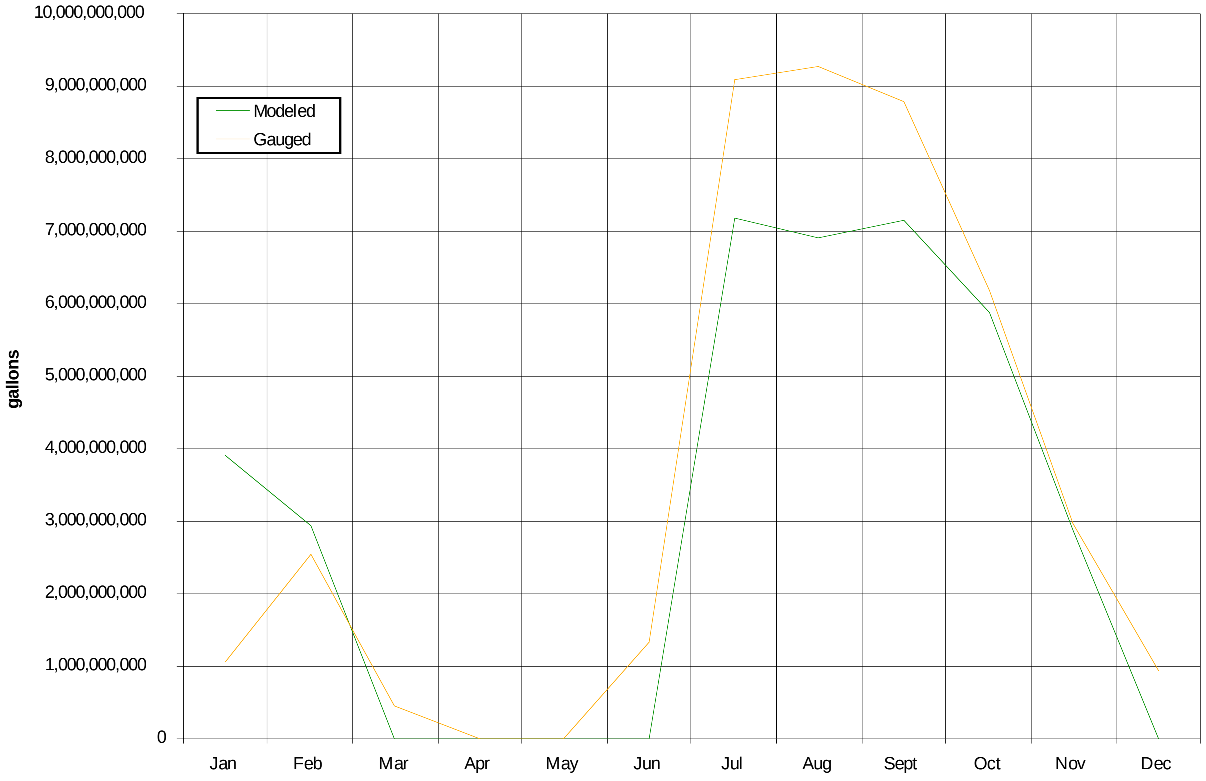


Figure 39: Stella 2003 Simulation, Quabbin Transfer Volumes

The volume of water transferred by our model is smaller compared to the actual amount transferred in 2003. Over the course of the year the model drew 14% less water; 5.8 billion gallons would have been conserved in the Quabbin Reservoir. This water would have normally been released over the Wachusett Dam and decreased the overall efficiency of the system yield.

6.2.4 Model Simulations

Once the model has been tested and verified, predictive simulations can be completed. First, the accuracy and validity of the model needed to be tested, so the complete data set from 2002-2005 was simulated using the model. Second, the drought of record was simulated to test the model against drought conditions. These simulations provide an insight into the volumes of water required to maintain optimal conditions of reservoir operation.

6.2.4.1 Stella Model Simulation: 2002-2005

Analysis of the Stella model using data record from 2002-2005 provided a data set to test the model. The complete data record allows all variables within the model to be completely verified against multiple years of average weather conditions. It is recognized that the 2003 data set, which was used to calibrate and verify the model, is included in the simulation. However, the addition of three years of reservoir data reduces any discrepancies with this data synthesis.

The key variable for analysis in the model simulation is the Quabbin Transfer. Figure 40 shows the volumes of water required by the model to maintain proper operating conditions as compared to the gauged transfer.

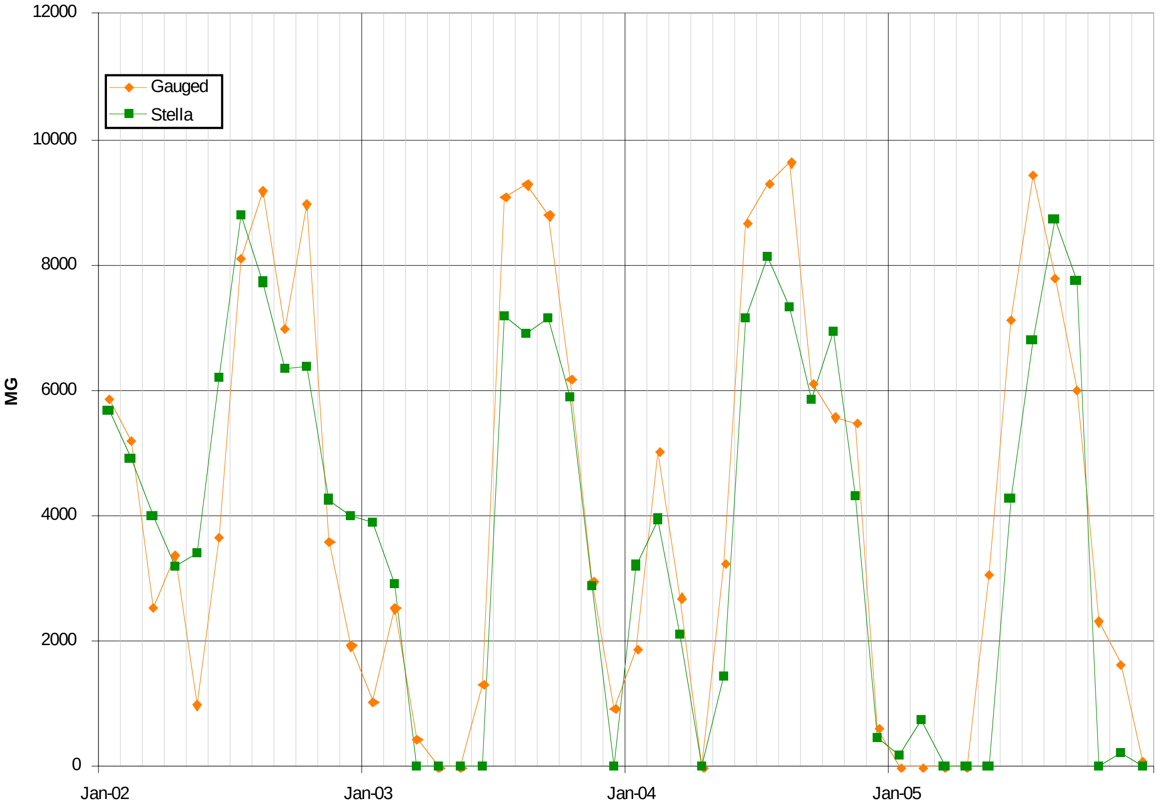


Figure 40: Quabbin Aqueduct, 2002-2005 Simulation

As illustrated in the graph, the model mirrored the gauged transfer readings exceedingly well. Many of the trends and peaks which occurred in the actual operation can also be seen in the simulation. Across the data set, the simulation required 8% less water from the Quabbin Reservoir over the four year data set. This increases the reservoir yield by 4 billion gallons per year according to the reservoir model.

Another parameter of interest is the release from the Wachusett Reservoir which is plotted in Figure 41. The modeled release to the Nashua River was nearly half of the gauged release from the Wachusett Reservoir.

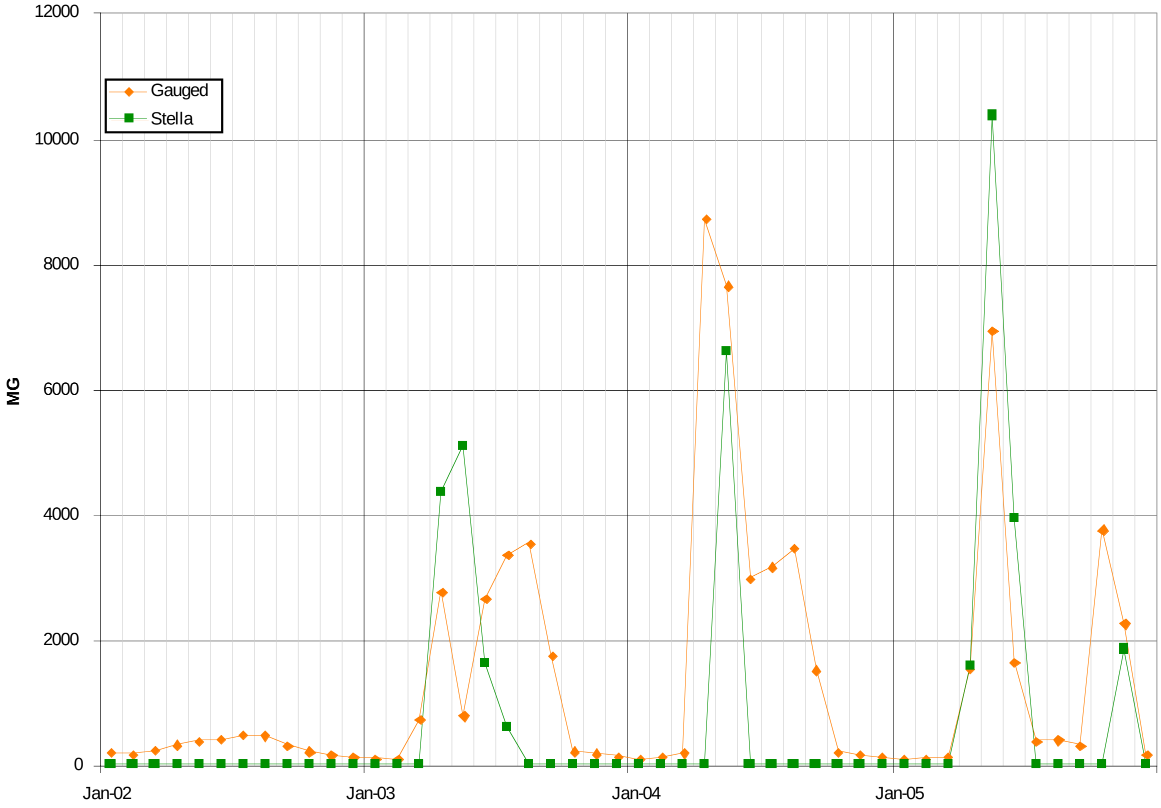


Figure 41: Wachusett Releases, 2002-2005 Simulation

The reservoir model released water to the Nashua River in similar fashion as measured by the gauged release. Some of the peaks in the simulation tend to be slightly higher than what was observed; this has been attributed to the monthly time step used in the model. However, the volume of release from the Wachusett Reservoir is on average releasing 7 billion gallons a year more than the required by the model.

6.4.2.2 Stella Model Simulations: 1963-1967

Testing the model against the drought of record provides analysis as to the volumes of water which were required to maintain proper operating conditions. The MWRA provided reservoir data dating back to the 1940's; precipitation from the 1963-1967 drought period was used as the model input. This drought is often considered to be a 1-300 year drought and data from this time is useful to compare the model simulations.

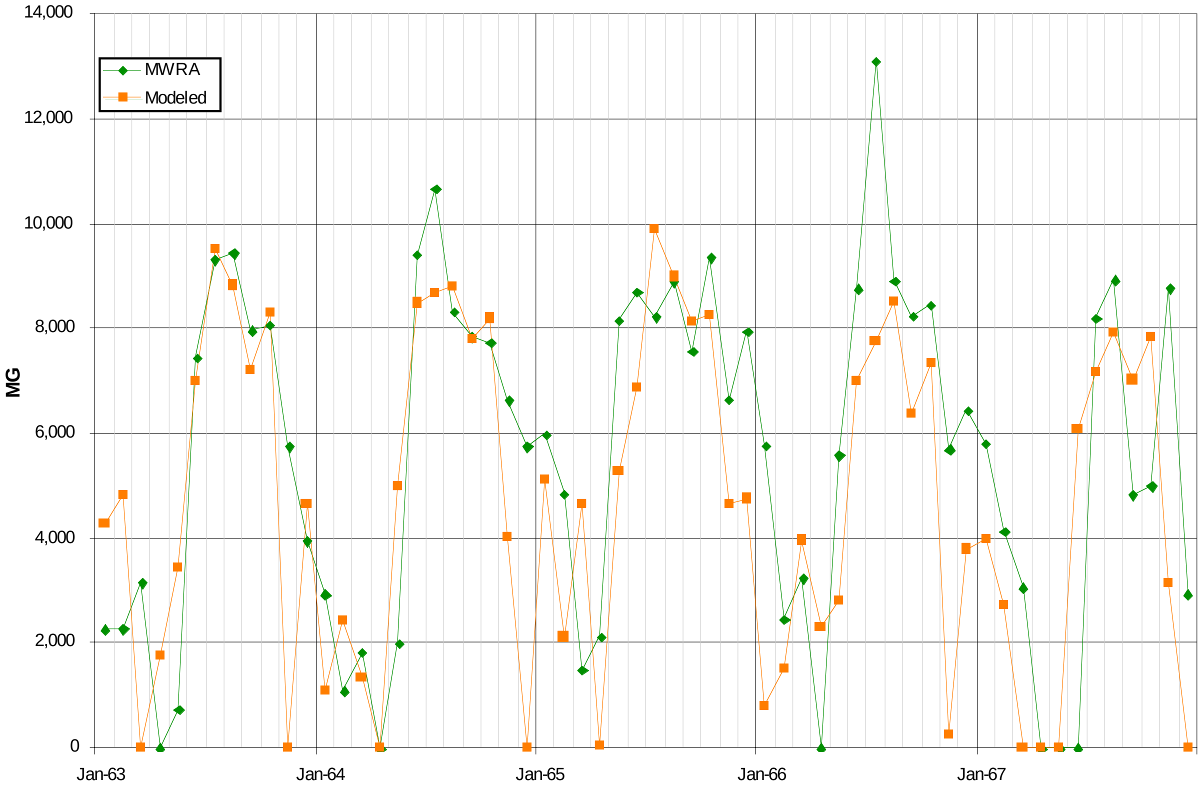


Figure 42: Quabbin Aqueduct, 1963-1937 Simulation

As illustrated in Figure 42, the Stella model mirrored the trends of transfer water from Quabbin during the drought. The overall volume of water required by the model was 15% less than the observed readings; saving 50 billion gallons over the course of the drought. Conserving this much water in the Quabbin reservoir during drought conditions would have raised the yield of the reservoir by 26%.

7.0 Conclusions and Recommendations

The project described in this report included the development of a model which helps provide the ability to quantify the hydrologic components associated with the Wachusett Reservoir and help estimate and understand reservoir yields. The various inflows to the Wachusett Reservoir include streamflow, runoff, precipitation, and transferred water from Quabbin Reservoir or the Ware River. The outflows from the reservoir include evaporation, releases to the Nashua River and withdrawals to meet demand. These inflows and outflows were quantified using data analysis in the Excel mass balance and evaluated reservoir operation through data synthesis in the Stella model. The model was calibrated with the 2003 data set and verified with the complete data record from 2002-2005. The Stella model was also tested for prediction analysis of various conditions by simulating the drought of record. The model mirrored real world data adequately for all cases simulated.

7.1 Recommendations

The conclusions derived from the model development and application led to several recommendations that can be made on methods to better monitor and understand the hydrologic behavior of the Wachusett Reservoir. First, additional monitoring of the Wachusett Reservoir and its watershed can be used to more accurately quantify the flows which were previously discussed. This monitoring program should be a comprehensive data collecting system in which the various components to the Wachusett Reservoir are accurately measured in hopes of increasing the efficiency of reservoir operation. Having the capability to utilize the results and models presented in the report can help predict the behavior of the Wachusett Reservoir.

7.1.1 Monitoring Program

It is recommended that the monitoring program should include all the major components to the Wachusett Reservoir, which are quantified and recorded. Having an accessible database of hydrological components provides the ability to evaluate the each flow and more efficiently determine yields for the reservoir. Several areas of interest arose through the research and analysis completed in this report. One area of importance which data proved hard to collect, was seasonal evaporation rates for the New England Area. Additionally, groundwater monitoring was limited in the area surrounding the Wachusett Reservoir and complicated accurate and precise quantification of groundwater contributions to the reservoir. Finally, limited monitoring and data collection concerning the runoff and baseflows of streams in the Thomas and Reservoir Subbasins prevented cross reference with modeled data.

7.1.1.1 Pan Evaporation Data

Data concerning monthly evaporation rates for the New England Area proved a challenge to quantify. Annual evaporation totals remain relative uniform across the Northeast and data concerning yearly volumes of evaporation were available. However, measurements on a monthly timescale could not be found. If there is a determined need to evaluate the function of evaporation for the Wachusett Reservoir throughout the year, then pan evaporation data should be collected.

Predominately used to collect evaporation data is a Class A evaporation pan. The pan is nearly 4 feet in diameter and almost a foot deep. The pan can be part of an entire weather monitoring system; humidity, wind speed, temperature, evaporation, precipitation, or it can be a standalone component. Additionally, various sensors and data loggers can be installed to the evaporation pan which will automatically collect and download evaporation data.

However, if the need exists to measure evaporation and the cost of an official evaporation pan are too high there can be other methods. Graduate evaporation cylinders, hook gauges, and still wells are all possible to measure the evaporation of water into the atmosphere; although some are more accurate than others. Even with some innovation, there are many ways to design instruments to measure evaporation.

7.1.1.2 Direct Runoff and Streamflow Monitoring

One of the most difficult flows to quantify into the Wachusett Reservoir is the runoff from the Thomas Basin and Reservoir District Subbasins. The method developed in the report took streamflow from the gauged Quinapoxet River and extrapolated them to the other basins. This assumption is based on the fact that reservoir characteristics throughout the watershed are similar and thus flows coming through the Quinapoxet should be representative of the other subbasins; scaled according to land use and subbasin area. This process could be verified and improved if there was a system of stream gauge measurements or flow meters on the streams flowing into the reservoir from the Thomas and Reservoir Subbasins.

Currently, several staff gauges are placed on many of the streams in the two direct runoff subbasins. However, a data collection and analysis system should be utilized to evaluate readings from these staff gauges. Compiling the data into a uniform database of watershed hydrologic measurements would improve the understanding of the variations of seasonal flows. This data would provide beneficial to determine the affect of the Thomas Basin and Reservoir District Subbasins on the Wachusett Reservoir; in terms of water quantity and quality.

7.1.1.3 Groundwater Flow Monitoring

After quantifying all the flows entering and leaving the reservoir system there was a large volume of unaccounted water remaining. Since groundwater data were unavailable, the contributions of groundwater flow through the reservoir could not be defined. Therefore, the assumption was made that all other variables of the hydrologic cycle were accurately accounted for and the remaining water was due to groundwater flow. The rates of groundwater flow estimated for the project were consistent with rates documented in the literature.

The results of the project indicated that groundwater may account for a large portion of the natural flow to the Wachusett Reservoir and groundwater flow should be considered in any reservoir analysis. Having a complete knowledge of the contributions which groundwater makes to the overall reservoir yield can help enhance the operation of the reservoir system. Groundwater is continuously flowing into and out of the reservoir and identifying these flow rates and how they vary throughout the year will more accurately complete the total understanding of the Wachusett Reservoir.

7.1.2 Predictions for Reservoir Operation

The water which is held in the DCR-MWRA system is on a basic level a product; and as in any business and manufacturing process, it is good practice to prevent waste of good product. The water which is released over the dam and excess water drawn from Quabbin can decrease the total yield of the reservoir system. As model simulations from the 2002-2005 data record demonstrate, billions of gallons of water can be conserved in a single year.

The Wachusett Reservoir Stella model demonstrates the potential conservation of water in the system. Since the model evaluates how much water is flowing into the reservoir through streamflow, groundwater, evaporation and all other hydrologic variables, the amount of water transferred from Quabbin is the optimal volume required to maintain proper operating conditions.

Having an appropriate and comprehensive monitoring program permits higher accuracy in the quantification of the flows which enter and leave the reservoir system. Once these variables have been properly assessed; groundwater, direct runoff, evaporation, it becomes easier to predict the nature of the Wachusett Reservoir and its watershed. Further investigation into these parameters would lead to greater accuracy within the models and enhance the ability evaluate yields for the reservoir. It is recommended that additional work be completed to extend this effort such that it includes the Quabbin Reservoir.

Possessing knowledge in the behavior of the Wachusett Reservoir can increase efficiency in reservoir operation and provide adequate insight into the volumes of water which are required from Quabbin. Likewise, minimizing the amount of excess spill over the dam also leads to an overall increase in the yield for the Wachusett Reservoir. If additional communities wish to join the system, maximizing water use within the system can provide the appropriate coverage to maintain the DCR-MWRA system as one of the premier water supply sources in the world.

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Appendix 1: MWRA Customer Communities

MWRA CUSTOMER COMMUNITIES

Community	Services provided by MWRA
Arlington	Water and Sewer
Ashland	Sewer
Bedford	Water (partially supplied), Sewer
Belmont	Water and Sewer
Boston	Water and Sewer
Braintree	Sewer
Brookline	Water and Sewer
Burlington	Sewer
Cambridge	Water (emergency backup only), Sewer
Canton	Water (partially supplied), Sewer
Chelsea	Water and Sewer
Chicopee	Water
Clinton	Water and Sewer
Dedham	Water (partially supplied), Sewer
Everett	Water and Sewer
Framingham	Water and Sewer
Hingham	Sewer
Holbrook	Sewer
Lancaster	Sewer
Leominster	Water (emergency back-up only)
Lexington	Water and sewer
Lynn (GE only)	Water (partially supplied)
Lynnfield Water District	Water
Malden	Water and Sewer
Marblehead	Water
Marlborough	Water (partially supplied)
Medford	Water and Sewer
Melrose	Water and Sewer
Milton	Water and Sewer
Nahant	Water
Natick	Sewer
Needham	Sewer, Water (partially supplied)
Newton	Water and Sewer
Northborough	Water (partially supplied)
Norwood	Water and Sewer
Peabody	Water (partially supplied)
Quincy	Water and Sewer
Randolph	Sewer
Reading	Water and Sewer
Revere	Water and Sewer
Saugus	Water
Somerville	Water and Sewer
Southborough	Water

South Hadley Fire District #1	Water
Stoneham	Water and Sewer
Stoughton	Sewer, Water (partially supplied)
Swampscott	Water
Wakefield	Sewer, Water (partially supplied)
Walpole	Sewer
Waltham	Water and Sewer
Watertown	Water and Sewer
Wellesley	Sewer, Water (partially supplied)
Weston	Water
Westwood	Sewer, Water (partially supplied)
Weymouth	Sewer
Wilbraham	Water
Wilmington	Sewer
Winchester	Sewer, Water (partially supplied)
Winthrop	Water and Sewer
Woburn	Water (partially supplied), Sewer
Worcester	Water (emergency back-up only)

Appendix 2: Rain Gauge Network Data

Holden

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1995	3.29	3.05	2.06	2.25	2.87	2.12	4.57	1.90	3.15	10.66	5.35	2.09
1996	8.91	3.77	3.66	8.37	3.48	3.08	7.51	3.01	7.01	7.14	3.86	7.99
1997	3.36	1.90	6.02	3.63	2.34	1.78	3.16	4.69	1.22	2.35	6.61	2.52
1998	5.75	3.42	6.00	3.31	7.08	8.48	2.01	1.31	1.47	5.25	2.43	1.70
1999	6.42	4.10	4.46	0.79	2.65	1.00	1.71	1.77	8.73	3.24	3.00	2.57
2000	3.72	3.25	4.36	6.69	3.04	6.49	4.27	2.38	3.22	2.11	3.60	3.78
2001	2.22	3.29	8.23	1.08	1.87	6.23	3.01	2.99	3.74	0.70	1.31	3.07
2002	2.85	1.82	4.92	3.13	4.39	5.95	1.68	2.74	4.38	4.98	4.80	5.70
2003	2.63	3.61	4.55	3.83	4.59	6.50	2.46	3.95	4.53	5.08	2.33	6.62
2004	1.70	1.48	3.84	6.93	3.15	1.51	4.27	6.12	8.85	2.70	4.32	4.88
2005	4.92	3.28	4.71	6.31	4.79	2.43	4.95	3.58	3.34	17.12	5.57	4.61
AVE	4.16	3.00	4.80	4.21	3.66	4.14	3.60	3.13	4.51	5.58	3.93	4.14

Princeton

1990	4.30	5.53	2.11	4.86	7.25	1.27	1.67	8.00	2.07	7.50	3.28	5.25
1991	3.83	2.25	4.25	4.25	4.50	5.60	4.99	9.75	6.36	2.75	6.53	3.75
1992	2.87	2.47	4.00	2.50	4.72	4.91	4.00	7.01	2.29	2.25	5.78	4.50
1993	3.68	2.80	7.43	4.80	1.76	1.48	2.09	1.66	6.67	4.91	4.30	5.25
1994	4.48	2.13	4.01	3.23	5.18	2.00	6.12	6.63	4.50	1.39	3.00	6.00
1995	3.75	3.13	1.90	2.30	3.29	1.75	2.64	2.23	2.93	9.70	5.75	2.50
1996	7.30	3.00	3.87	8.00	4.08	3.36	8.45	1.05	6.96	6.90	3.23	5.34
1997	3.50	2.30	4.34	5.00	3.75	2.00	3.75	5.84	1.60	2.91	6.83	2.15
1998	6.22	3.97	5.86	3.03	6.59	9.01	1.26	2.39	1.79	5.76	2.10	1.74
1999	6.10	2.74	5.65	0.99	2.57	1.21	2.89	5.09	9.26	3.29	2.55	1.84
2000	3.28	3.66	5.01	6.75	3.09	6.25	8.04	2.82	4.51	2.61	3.47	4.00
AVE	4.48	3.09	4.40	4.16	4.25	3.53	4.17	4.77	4.45	4.54	4.26	3.85

West Boylston

1995	3.53	3.51	2.95	4.07	3.29	2.20	4.02	1.70	3.29	9.40	6.06	2.23
1996	8.99	1.97	3.38	7.90	5.61	3.62	4.11	3.29	7.37	6.79	3.01	7.89
1997	4.52	2.57	7.96	3.98	2.90	1.83	2.81	4.81	1.95	2.58	6.78	3.97
1998	6.53	3.96	6.71	3.09	8.29	10.56	3.05	1.58	1.77	5.57	2.54	1.69
1999	6.40	4.59	4.32	1.27	2.12	0.82	1.48	2.02	9.01	3.69	3.08	2.58
2000	3.58	4.11	5.91	5.44	2.98	5.91	5.32	2.18	3.23	1.93	4.18	5.41
2001	1.46	3.28	6.79	1.35	2.71	5.66	3.47	2.46	4.43	0.91	1.09	3.20
2002	2.10	2.67	4.58	3.64	5.31	5.78	1.65	2.72	4.35	5.45		5.68
2003	2.91	3.94	3.96	3.94	5.28	7.41	3.11	4.87	5.58	6.11	2.24	4.96
2004	0.93	1.61	1.26	6.29	3.18	1.64	5.14	7.14	7.96	2.32	4.78	3.94
2005	4.76		5.05	5.37	3.60	2.43	2.32	3.36	2.40	15.22	3.16	
AVE	4.16	3.58	4.81	4.21	4.12	4.35	3.32	3.28	4.67	5.45	4.10	4.62

Worcester

1994	5.11	1.86	5.38	2.73	5.87	2.48	3.09	7.64	4.84	1.24	4.54	4.81

1995	3.71	2.86	1.85	1.30	2.39		4.17	1.62	3.15	8.65	4.61	1.30
1996	6.70	2.83	2.16	6.44	3.26		6.49		6.07	5.81	2.93	
1997	3.25	1.71	4.66	3.22	2.72	1.60	2.97	4.34	1.44	2.11	5.50	2.32
1998	4.59	3.17	5.82	3.30	5.89	9.68	1.76	2.38	1.69	4.93	2.28	1.46
1999	6.01	3.38	4.09	0.92	2.80	0.32	3.63	1.87	8.83	3.57	3.38	2.55
2000	3.11	2.60	3.82	6.85	3.52	5.85	3.85	2.10	3.02	2.06	3.61	3.62
2001	1.64	3.07	6.68	0.75	2.26	6.28	1.92	2.41	3.42	0.70	1.36	2.77
2002	2.47	1.43	4.20	3.58	5.57	4.85	2.65	2.95	3.59	4.39	3.82	4.51
2003	2.41	4.43	4.06	3.43	4.13	6.16	2.05	5.34	4.26	5.42	2.19	5.71
2004	1.43	1.45	3.35	6.57	3.27	1.45	4.84	5.07	7.52	2.22	3.93	4.78
AVE	3.68	2.62	4.19	3.55	3.79	4.83	3.40	3.97	4.35	3.74	3.47	3.76

Rutland

1991	3.04	1.96	3.93	4.37	4.38	2.79	4.22	8.26	6.35	3.36	4.28	3.51
1992	2.14	1.90	3.97	1.96	4.43	4.32	3.92	7.52	2.32	2.16	6.17	5.64
1993	3.14	2.18	6.18	3.94	1.93	1.50	2.49	2.29	7.18	4.73	4.83	5.24
1994	5.61	2.08	5.34	2.88	4.75	3.07	5.56	6.89	5.34	1.25	3.02	5.28
1995	2.71	3.24	1.56	1.91	2.94	2.22	3.09	2.03	3.19	11.12	4.62	1.43
1996	3.61	2.07	2.49	7.54	3.80	2.98	2.55	7.85	6.70	6.80	2.28	3.22
1997	3.40	1.26	2.01	3.66	2.38	1.53	5.03	4.64	0.99	2.30	5.67	2.10
1998	3.49	1.71	2.01	3.58	7.32	8.19	0.81	1.30	1.72	3.97	2.40	0.66
1999	4.70		3.75	0.81	2.78	1.26	2.14	1.64	8.55	1.91	2.64	1.03
2000	3.33	3.22	1.45	7.14	3.59	6.63	7.06	0.96	0.75	3.05	4.04	3.53
2001	1.97	1.24	6.42		2.96	7.88	2.09	3.63	3.22	0.33	1.10	
AVE	3.38	2.32	3.56	4.20	3.75	3.85	3.54	4.27	4.21	3.73	3.73	3.52

Appendix 3: Evaporation Data Set

Date		Mean Mo. Temp F	Mean Mo. Temp C	Daylight Hours h	Dew Point F	Dew Point C	Wind Speed MPH	Wind Speed km/d	Saturated Vapor Pressure mb	Actual Vapor Pressure mb	Relative Humidity	Dunne Equation cm/d	Dunne Equation in	Recorded Evaporation in	Total Mo. Evap in		
Jan-02	31	31.8	-0.1	9.5	19.0	-7.2	11.7	451.9	6.1	3.6	0.6	0.4	5.4		1.67		
Feb-02	28	32.1	0.1	10.5	20.0	-6.7	11.6	448.0	6.1	3.7	0.6	0.4	4.9		1.52		
Mar-02	31	36.0	2.2	12.0	21.0	-6.1	11.5	444.2	7.2	3.9	0.5	0.5	6.3		1.95		
Apr-02	30	47.7	8.7	13.3	32.0	0.0	11.0	424.9	11.3	6.1	0.5	0.8	9.2		2.83		
May-02	31	54.2	12.3	14.5	39.0	3.9	10.0	386.2	14.3	8.1	0.6	0.9	11.0	3.39	3.39		
Jun-02	30	63.4	17.4	15.5	54.0	12.2	8.9	343.8	19.9	14.2	0.7	1.1	13.1	3.61	3.61		
Jul-02	31	70.8	21.6	14.8	61.0	16.1	8.4	324.4	25.7	18.3	0.7	1.4	16.6	4.27	4.27		
Aug-02	31	71.1	21.7	13.8	63.0	17.2	8.3	320.6	25.9	19.6	0.8	1.4	16.5	4.19	4.19		
Sep-02	30	64.7	18.2	12.5	54.0	12.2	8.6	332.2	20.8	14.2	0.7	1.1	13.3	2.73	2.73		
Oct-02	31	47.7	8.7	11.0	36.0	2.2	9.4	363.1	11.3	7.2	0.6	0.7	8.1	1.79	1.79		
Nov-02	30	37.6	3.1	10.0	30.0	-1.1	10.4	401.7	7.6	5.6	0.7	0.5	5.9		1.30		
Dec-02	31	28.1	-2.2	9.0	16.0	-8.9	10.9	421.0	5.2	3.1	0.6	0.4	4.3		0.96	30.20	**Total (in)**
Jan-03	31	17.7	-7.9	9.5	8.0	-13.3	11.7	451.9	3.4	2.2	0.7	0.2	3.0		0.68		
Feb-03	28	21.6	-5.8	10.5	10.0	-12.2	11.6	448.0	4.0	2.4	0.6	0.3	3.2		0.72		
Mar-03	31	35.0	1.7	12.0	23.0	-5.0	11.5	444.2	6.9	4.2	0.6	0.5	6.0		1.36		
Apr-03	30	42.5	5.8	13.3	27.0	-2.8	11.0	424.9	9.2	5.0	0.5	0.6	7.5		1.70		
May-03	31	54.0	12.2	14.5	42.0	5.6	10.0	386.2	14.2	9.1	0.6	0.9	10.9	2.45	2.45		
Jun-03	30	63.8	17.7	15.5	53.0	11.7	8.9	343.8	20.2	13.7	0.7	1.1	13.3	3.03	3.03		
Jul-03	31	70.6	21.4	14.8	59.0	15.0	8.4	324.4	25.5	17.0	0.7	1.3	16.5	4.00	4.00		
Aug-03	31	70.7	21.5	13.8	62.0	16.7	8.3	320.6	25.6	18.9	0.7	1.3	16.3	3.78	3.78		
Sep-03	30	62.5	16.9	12.5	53.0	11.7	8.6	332.2	19.3	13.7	0.7	1.0	12.3	2.54	2.54		
Oct-03	31	48.7	9.3	11.0	37.0	2.8	9.4	363.1	11.7	7.5	0.6	0.7	8.4	1.79	1.79		
Nov-03	30	43.4	6.3	10.0	29.0	-1.7	10.4	401.7	9.6	5.4	0.6	0.6	7.4		1.57		
Dec-03	31	31.3	-0.4	9.0	23.0	-5.0	10.9	421.0	5.9	4.2	0.7	0.4	4.9		1.05	24.65	**Total (in)**
Jan-04	31	15.1	-9.4	9.5	4.0	-15.6	11.7	451.9	3.0	1.8	0.6	0.2	2.7		0.67		
Feb-04	29	27.4	-2.6	10.5	10.0	-12.2	11.6	448.0	5.1	2.4	0.5	0.4	4.2		1.05		
Mar-04	31	35.9	2.2	12.0	26.0	-3.3	11.5	444.2	7.1	4.8	0.7	0.5	6.3		1.57		
Apr-04	30	47.3	8.5	13.3	32.0	0.0	11.0	424.9	11.1	6.1	0.6	0.8	9.0		2.26		
May-04	31	58.4	14.7	14.5	43.0	6.1	10.0	386.2	16.7	9.4	0.6	1.0	12.8	3.20	3.20		
Jun-04	30	64.1	17.8	15.5	49.0	9.4	8.9	343.8	20.4	11.8	0.6	1.1	13.5	3.91	3.91		
Jul-04	31	69.0	20.6	14.8	57.0	13.9	8.4	324.4	24.2	15.9	0.7	1.3	15.6	3.17	3.17		
Aug-04	31	68.9	20.5	13.8	59.0	15.0	8.3	320.6	24.1	17.0	0.7	1.3	15.3		3.12		
Sep-04	30	62.7	17.1	12.5	52.0	11.1	8.6	332.2	19.4	13.2	0.7	1.0	12.4		2.52		
Oct-04	31	49.9	9.9	11.0	39.0	3.9	9.4	363.1	12.2	8.1	0.7	0.7	8.8		1.79		
Nov-04	30	40.6	4.8	10.0	30.0	-1.1	10.4	401.7	8.6	5.6	0.7	0.6	6.6		1.34		
Dec-04	31	29.4	-1.4	9.0	19.0	-7.2	10.9	421.0	5.5	3.6	0.6	0.4	4.6		0.93	25.54	**Total (in)**
Jan-05	31	22.2	-5.4	9.5	12.0	-11.1	11.7	451.9	4.1	2.6	0.6	0.3	3.6		0.74		
Feb-05	28	28.6	-1.9	10.5	15.0	-9.4	11.6	448.0	5.3	3.0	0.6	0.4	4.3		0.87		
Mar-05	31	30.9	-0.6	12.0	21.0	-6.1	11.5	444.2	5.8	3.9	0.7	0.4	5.1		1.04		
Apr-05	30	49.3	9.6	13.3	30.0	-1.1	11.0	424.9	12.0	5.6	0.5	0.8	9.7		1.98		
May-05	31	51.4	10.8	14.5	39.0	3.9	10.0	386.2	12.9	8.1	0.6	0.8	9.9		2.01		
Jun-05	30	68.6	20.3	15.5	58.0	14.4	8.9	343.8	23.8	16.4	0.7	1.3	15.7		3.20		
Jul-05	31	71.5	21.9	14.8	62.0	16.7	8.4	324.4	26.3	18.9	0.7	1.4	17.0		3.45		
Aug-05	31	72.5	22.5	13.8	63.0	17.2	8.3	320.6	27.2	19.6	0.7	1.4	17.3		3.53		
Sep-05	30	65.4	18.6	12.5	52.0	11.1	8.6	332.2	21.3	13.2	0.6	1.2	13.6		2.77		
Oct-05	31	51.5	10.8	11.0	42.0	5.6	9.4	363.1	13.0	9.1	0.7	0.8	9.3		1.90		
Nov-05	30	42.1	5.6	10.0	30.0	-1.1	10.4	401.7	9.1	5.6	0.6	0.6	7.0		1.42		
Dec-05	31	27.2	-2.7	9.0	19.0	-7.2	10.9	421.0	5.0	3.6	0.7	0.3	4.2		0.85	23.76	**Total (in)**

Appendix 4: Wachusett Reservoir Subbasin Curve Numbers

	Stillwater			**Quinapoxet**			**Reservoir**		**Thomas Basin**	
	CN: 84.69			CN: 84.15			CN: 84.91		CN: 86.94	
	% imp 0.076			*% imp 0.082*			*% imp 0.106*		*% imp 0.064*	
	S'	*CN*		*S'*	*CN*		*S'*	*CN*	*S'*	*CN*
Jan	1.13	89.88	5.19	1.48	87.09	2.94	1.24	88.98	0.99	91.01
Feb	2.41	80.59	-4.10	2.90	77.50	-6.65	2.57	79.53	2.26	81.56
Mar	0.81	92.49	7.80	1.52	86.83	2.68	1.09	90.15	0.85	92.18
Apr	1.03	90.65	5.96	0.92	91.56	7.41	0.92	91.60	0.68	93.63
May	2.43	80.48	-4.21	3.61	73.49	-10.66	2.91	77.47	2.58	79.50
Jun	4.12	70.83	-13.86	4.00	71.44	-12.71	3.96	71.62	3.58	73.65
Jul	5.03	66.51	-18.18	5.02	66.57	-17.58	4.92	67.03	4.48	69.06
Aug	9.76	50.60	-34.09	10.59	48.57	-35.58	9.97	50.08	9.19	52.11
Sep	13.73	42.15	-42.54	14.32	41.12	-43.03	13.74	42.13	12.65	44.16
Oct	10.05	49.86	-34.83	10.66	48.40	-35.75	10.15	49.62	9.36	51.65
Nov	2.27	81.49	-3.20	3.02	76.79	-7.36	2.56	79.63	2.25	81.66
Dec	1.39	87.77	3.08	2.34	81.02	-3.13	1.78	84.89	1.51	86.92

Appendix 5: NRCS Curve Numbers

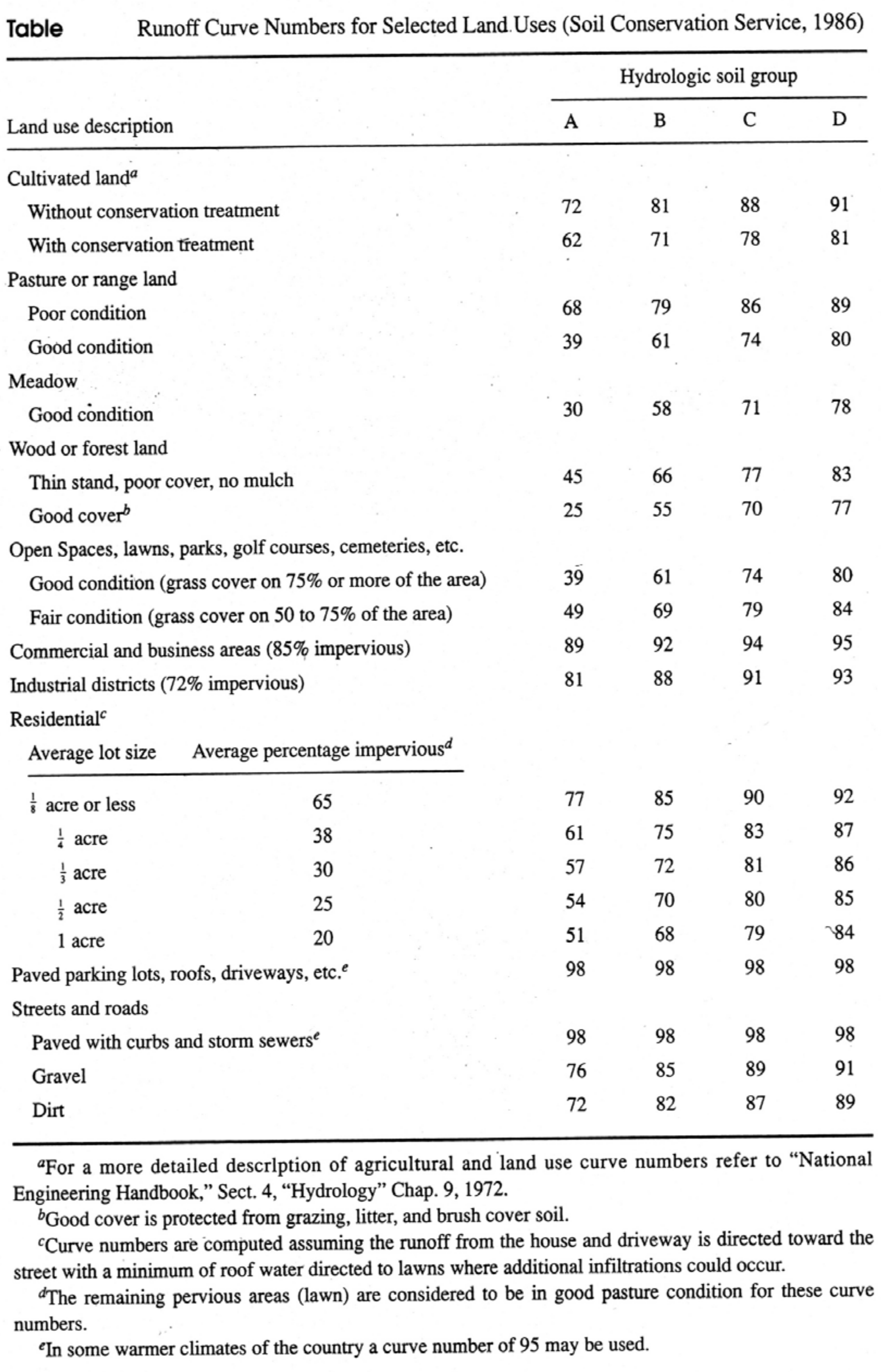


Table Runoff Curve Numbers for Selected Land Uses (Soil Conservation Service, 1986)

Land use description		Hydrologic soil group			
		A	B	C	D
Cultivated land[a]					
Without conservation treatment		72	81	88	91
With conservation treatment		62	71	78	81
Pasture or range land					
Poor condition		68	79	86	89
Good condition		39	61	74	80
Meadow					
Good condition		30	58	71	78
Wood or forest land					
Thin stand, poor cover, no mulch		45	66	77	83
Good cover[b]		25	55	70	77
Open Spaces, lawns, parks, golf courses, cemeteries, etc.					
Good condition (grass cover on 75% or more of the area)		39	61	74	80
Fair condition (grass cover on 50 to 75% of the area)		49	69	79	84
Commercial and business areas (85% impervious)		89	92	94	95
Industrial districts (72% impervious)		81	88	91	93
Residential[c]					
Average lot size	Average percentage impervious[d]				
$\frac{1}{8}$ acre or less	65	77	85	90	92
$\frac{1}{4}$ acre	38	61	75	83	87
$\frac{1}{3}$ acre	30	57	72	81	86
$\frac{1}{2}$ acre	25	54	70	80	85
1 acre	20	51	68	79	84
Paved parking lots, roofs, driveways, etc.[e]		98	98	98	98
Streets and roads					
Paved with curbs and storm sewers[e]		98	98	98	98
Gravel		76	85	89	91
Dirt		72	82	87	89

[a] For a more detailed description of agricultural and land use curve numbers refer to "National Engineering Handbook," Sect. 4, "Hydrology" Chap. 9, 1972.

[b] Good cover is protected from grazing, litter, and brush cover soil.

[c] Curve numbers are computed assuming the runoff from the house and driveway is directed toward the street with a minimum of roof water directed to lawns where additional infiltrations could occur.

[d] The remaining pervious areas (lawn) are considered to be in good pasture condition for these curve numbers.

[e] In some warmer climates of the country a curve number of 95 may be used.

Appendix 6: Derivation of Equation 10

$$R = \frac{(P - .2S')^2}{(P + .8S')}$$

R = Runoff Excess
R_U= Runoff in Ungauged Subbasin
R_G= Runoff in Gauged Subbasin

Assuming and Initial Abstraction of 0.2S':

$$\frac{R_U}{R_G} = \frac{(P - 0.2S_U{}')^2}{(P - 0.2S_G{}')^2} * \frac{(P + 0.8S_U{}')}{(P + 0.8S_G{}')}$$

$$\frac{R_U}{R_G} = \frac{P^2 - 0.2S_U{}'P + 0.004S_U{}'}{P^2 - 0.2S_G{}'P + 0.004S_G{}'} * \frac{(P + 0.8S_U{}')}{(P + 0.8S_G{}')}$$

$$\frac{R_U}{R_G} = \frac{P^2 - 0.6S_U{}'P}{P^2 - 0.6S_G{}'P}$$

Assuming an Undetermined Initial Abstraction:

$$C_{dr} = \frac{R_U}{R_G} = \frac{\left[\left(P^2\right) - \left(I_a S_{R,T} P\right) + \left(\left(1 - I_a\right) S_{R,T} P\right)\right]}{\left[\left(P^2\right) - \left(I_a S_Q P\right) + \left(\left(1 - I_a\right) S_Q P\right)\right]}$$

Appendix 7: Ware River Diversion

WARE_RIVER_DIVERSION (MG)

	2002	2003	2004	2005
Jan	0.00	0.00	0.00	0.00
Feb	0.00	0.00	0.00	0.00
Mar	0.00	0.00	0.00	0.00
Apr	0.00	0.00	0.00	0.00
May	0.00	0.00	0.00	0.00
Jun	0.00	0.00	0.00	0.00
Jul	0.00	0.00	0.00	0.00
Aug	0.00	0.00	0.00	0.00
Sep	0.00	0.00	0.00	0.00
Oct	0.00	0.00	0.00	1216.13
Nov	0.00	0.00	0.00	0.00
Dec	0.00	0.00	0.00	0.00
				1216

Appendix 8: Quinapoxet River Flow

USGS 01095375 QUINAPOXET RIVER AT CANADA MILLS NEAR HOLDEN, MA

http://waterdata.usgs.gov/nwis/dv/?site_no=01095375&agency_cd=USGS&referred_module=sw

LOCATION.--Lat 42^{o}22'22", long 71^{o}49'43", Worcester County, Hydrologic Unit 01070004, on left bank 300 ft upstream from bridge on Harris Street at Canada Mills, 2.1 mi north of Holden, and about 3.5 mi upstream from mouth at Wachusett Reservoir.
DRAINAGE AREA.--46.3 mi^2.

WATER-DISCHARGE RECORDS

PERIOD OF RECORD.--November 1996 to current year.
GAGE.--Water-stage recorder with telephone telemeter. Elevation of gage is 560 ft above National Geodetic Vertical Datum of 1929, from topographic map.
REMARKS.--Flow occasionally regulated by Quinapoxet Reservoir.

WATER-QUALITY RECORDS

PERIOD OF RECORD.--April 1997 to current year.

INSTRUMENTATION.--Water temperature and specific conductance monitor.

COOPERATION BY.--Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection

Appendix 9: Stillwater River Flow

USGS 01095220 STILLWATER RIVER NEAR STERLING, MA

http://waterdata.usgs.gov/ma/nwis/uv/?site_no=01095220&PARAmeter_cd=00065,00060

LOCATION.--Lat 42^{o}24'39", long 71^{o}47'30", Worcester County, Hydrologic Unit 01070004, on left bank at downstream side of bridge on Muddy Pond Road, 1.5 mi upstream from mouth and 2.5 mi southwest of Sterling.
DRAINAGE AREA.--29.1 mi^2.

WATER-DISCHARGE RECORDS

PERIOD OF RECORD.--Low-flow partial record measurements in water years 1971-73, 1991-93. Continuous stage data recorder April 1994 to current year.
GAGE.--Water-stage recorder with telephone telemeter. Elevation of gage is 400 ft above National Geodetic Vertical Datum of 1929, from topographic map. Telephone gage-height telemeter at station.
REMARKS.--Stage-discharge relation affected by seasonal backwater from aquatic vegetation and occasional backwater from beaver dams. Adjustments for backwater are included in the computed record.

WATER-QUALITY RECORDS

PERIOD OF RECORD.--Water temperature and specific conductance, April 1998 to current year; precipitation October 1998 to current year.
INSTRUMENTATION.--Water temperature and specific conductance monitor and heated tipping-bucket precipitation gage.
COOPERATION BY.--Massachusetts Department of Conservation and Recreation, Division of Water Supply Protection.

Appendix 10: Direct Runoff

	sq mi							sq mi						
Reservoir	10.79						**Thomas**	14.79						
S'	**CN**	**Cdr**	**Cdr A_S / A_Q**	**Runoff**	**Flow (MG)**	**Flow**	**S'**	**CN**	**Cdr**	**Cdr A_S / A_Q**	**Runoff**	**Base Flow (MG)**	**Flow**	**Direct Runoff**
1.32	88.32	0.97	0.23	13	31	44	2.19	82.03	1.11	0.36	20	40	61	105
2.59	79.42	0.95	0.22	22	42	64	4.29	69.97	1.23	0.40	39	53	92	156
1.35	88.08	0.98	0.23	61	129	190	2.24	81.69	1.07	0.34	92	165	257	447
0.82	92.40	0.98	0.23	51	175	225	1.36	88.01	1.07	0.34	76	229	305	530
3.22	75.65	0.96	0.23	164	68	231	5.33	65.23	1.16	0.37	270	82	352	583
3.57	73.70	0.97	0.23	203	11	214	5.91	62.86	1.14	0.36	327	14	340	555
4.48	69.06	0.93	0.22	24	7	32	7.42	57.40	1.31	0.42	47	9	56	87
9.45	51.42	0.92	0.22	9	1	10	15.65	38.99	1.33	0.43	18	1	19	28
12.77	43.91	0.93	0.22	14	1	15	21.16	32.09	1.32	0.42	27	1	28	42
9.51	51.25	0.94	0.22	45	5	50	15.76	38.83	1.27	0.41	83	6	89	139
2.70	78.76	0.97	0.23	84	11	95	4.47	69.12	1.13	0.36	134	13	147	242
2.09	82.71	0.98	0.23	338	18	356	3.46	74.28	1.09	0.35	518	23	540	896
1.32	88.32	0.97	0.23	205	31	237	2.19	82.03	1.12	0.36	324	40	364	601
2.59	79.42	0.96	0.23	145	42	187	4.29	69.97	1.16	0.37	238	53	290	478
1.35	88.08	0.98	0.23	840	129	969	2.24	81.69	1.08	0.35	1266	165	1431	2399
0.82	92.40	0.99	0.23	626	175	800	1.36	88.01	1.06	0.34	922	229	1151	1952
3.22	75.65	0.97	0.23	323	68	391	5.33	65.23	1.15	0.37	529	82	611	1002
3.57	73.70	0.97	0.23	673	11	684	5.91	62.86	1.13	0.36	1073	14	1087	1771
4.48	69.06	0.94	0.22	159	7	166	7.42	57.40	1.26	0.40	292	9	301	467
9.45	51.42	0.93	0.22	208	1	209	15.65	38.99	1.29	0.41	395	1	396	605
12.77	43.91	0.93	0.22	74	1	75	21.16	32.09	1.31	0.42	143	1	144	219
9.51	51.25	0.94	0.22	201	5	206	15.76	38.83	1.27	0.41	371	6	377	583
2.70	78.76	0.95	0.22	272	11	283	4.47	69.12	1.21	0.39	473	13	486	769
2.09	82.71	0.98	0.23	668	18	686	3.46	74.28	1.08	0.35	1011	23	1033	1719
1.32	88.32	0.96	0.23	287	31	318	2.19	82.03	1.16	0.37	475	40	515	833
2.59	79.42	0.94	0.22	120	44	164	4.29	69.97	1.26	0.40	221	54	275	439
1.35	88.08	0.98	0.23	292	129	421	2.24	81.69	1.09	0.35	446	165	611	1032
0.82	92.40	0.99	0.23	1042	175	1217	1.36	88.01	1.04	0.33	1491	229	1720	2937
3.22	75.65	0.96	0.22	259	68	327	5.33	65.23	1.19	0.38	444	82	527	853
3.57	73.70	0.93	0.22	99	11	110	5.91	62.86	1.29	0.41	188	14	201	311
4.48	69.06	0.96	0.22	66	7	73	7.42	57.40	1.20	0.38	113	9	122	195
9.45	51.42	0.95	0.22	67	1	68	15.65	38.99	1.24	0.40	121	1	122	189
12.77	43.91	0.95	0.22	92	1	93	21.16	32.09	1.24	0.40	165	1	166	259
9.51	51.25	0.92	0.22	72	5	77	15.76	38.83	1.34	0.43	142	6	148	225
2.70	78.76	0.97	0.23	102	11	112	4.47	69.12	1.14	0.37	164	13	177	289
2.09	82.71	0.98	0.23	503	18	521	3.46	74.28	1.11	0.35	782	23	805	1326
1.32	88.32	0.98	0.23	568	31	599	2.19	82.03	1.07	0.34	849	40	889	1488
2.59	79.42	0.96	0.23	375	42	417	4.29	69.97	1.17	0.37	623	53	675	1093
1.35	88.08	0.98	0.23	544	129	673	2.24	81.69	1.08	0.35	818	165	983	1656
0.82	92.40	0.99	0.23	1146	175	1321	1.36	88.01	1.04	0.33	1646	229	1875	3196
3.22	75.65	0.97	0.23	565	68	633	5.33	65.23	1.15	0.37	921	82	1003	1636
3.57	73.70	0.95	0.22	213	11	224	5.91	62.86	1.23	0.40	381	14	395	619
4.48	69.06	0.96	0.22	175	7	182	7.42	57.40	1.18	0.38	295	9	303	485
9.45	51.42	0.93	0.22	28	1	29	15.65	38.99	1.31	0.42	55	1	55	85
12.77	43.91	0.92	0.22	27	1	28	21.16	32.09	1.34	0.43	55	1	56	84
9.51	51.25	0.97	0.23	889	5	894	15.76	38.83	1.13	0.36	1419	6	1425	2320
2.70	78.76	0.97	0.23	513	11	524	4.47	69.12	1.12	0.36	807	13	820	1344
2.09	82.71	0.97	0.23	592	18	610	3.46	74.28	1.11	0.36	925	23	948	1558
				14058	1997	16055					22230	2544	24775	40829

1.32	88.32	0.97	0.23	268	31	300	2.19	82.03	1.12	0.36	417	40	457	757
2.59	79.42	0.95	0.22	166	43	208	4.29	69.97	1.20	0.39	280	53	333	541
1.35	88.08	0.98	0.23	434	129	563	2.24	81.69	1.08	0.35	655	165	820	1383
0.82	92.40	0.99	0.23	716	175	891	1.36	88.01	1.05	0.34	1034	229	1263	2154
3.22	75.65	0.96	0.23	328	68	395	5.33	65.23	1.16	0.37	541	82	623	1019
3.57	73.70	0.96	0.22	297	11	308	5.91	62.86	1.20	0.38	492	14	506	814
4.48	69.06	0.95	0.22	106	7	113	7.42	57.40	1.24	0.40	187	9	195	309
9.45	51.42	0.93	0.22	78	1	79	15.65	38.99	1.29	0.41	147	1	148	227
12.77	43.91	0.93	0.22	52	1	53	21.16	32.09	1.30	0.42	97	1	98	151
9.51	51.25	0.94	0.22	302	5	307	15.76	38.83	1.25	0.40	504	6	510	817
2.70	78.76	0.97	0.23	243	11	253	4.47	69.12	1.15	0.37	395	13	408	661
2.09	82.71	0.98	0.23	525	18	543	3.46	74.28	1.10	0.35	809	23	832	1375

Appendix 11: Groundwater Flow & Groundwater Elevation

USGS 422341071464901 MA-WSW 26 WEST BOYLSTON, MA
Worcester County, Massachusetts
Latitude 42°23'41", Longitude 71°46'49" NAD27
Land-surface elevation 485 feet above sea level NGVD29
The depth of the well is 16.8 feet below land surface.
This well is completed in the Sand and gravel aquifers (glaciated regions) (N100GLCIAL) n
This well is completed in the STRATIFIED DEPOSITS, UNDIFFERENTIATED (112SRFD) local

Date	Depth to Water Table (ft)					Well 1	Averages
1/28/04	5.8	479.2	485	0	January-02	4.83	4.38
3/1/04	3.11	481.89	485	0	February-02	4.71	4.17333
3/30/04	3.1	481.9	485	0	March-02	4.52	3.76
4/22/04	4.53	480.47	485	0	April-02	4.47	3.95667
4/26/04	3.52	481.48	485	0	May-02	4.03	3.79
5/27/04	5.03	479.97	485	0	June-02	4.25	4.0075
6/20/04	5.13	479.87	485	0	July-02	4.64	4.2175
7/19/04	7.11	477.89	485	0	August-02	4.72	4.335
8/30/04	8.88	476.12	485	0	September-02	4.56	3.84
9/30/04	8.63	476.37	485	0	October-02	4.05	3.62
10/21/04	9.08	475.92	485	0	November-02	3.56	3.605
11/29/04	7.96	477.04	485	0	December-02	3.95	4.18333
12/23/04	5.18	479.82	485	0	January-03	4.09	4.38
1/30/05	6.83	478.17	485	0	February-03	3.58	4.17333
2/27/05	5.84	479.16	485	0	March-03	3.52	3.76
3/27/05	1.55	483.45	485	0	April-03	3.83	3.95667
4/26/05	3.52	481.48	485	0	May-03	3.46	3.79
5/31/05	6.45	478.55	485	0	June-03	3.6	4.0075
6/27/05	6.53	478.47	485	0	July-03	3.81	4.2175
7/26/05	7.46	477.54	485	0	August-03	3.07	4.335
8/24/05	8.44	476.56	485	0	September-03	4.18	3.84
9/26/05	9.91	475.09	485	0	October-03	3.91	3.62
10/31/05	10.77	474.23	485	0	November-03	3.41	3.605
11/27/05	11.38	473.62	485	0	December-03	3.93	4.18333
12/27/05	10.24	474.76	485	0	January-04	4.22	4.38
1/26/06	9.78	475.22	485	0	February-04	4.23	4.17333
2/26/06	6.95	478.05	485	0	March-04	3.24	3.76
3/27/06	5.24	479.76	485	0	April-04	3.57	3.95667
4/24/06	4.34	480.66	485	0	May-04	4.04	3.79
5/7/06	4.01	480.99	485	0	June-04	4.23	4.0075
5/17/06	3.15	481.85	485	0	July-04	4.25	4.2175
6/25/06	6.17	478.83	485	0	August-04	4.06	4.335
7/16/06	7.24	477.76	485	0	September-04	3.93	3.84
8/28/06	9.52	475.48	485	0	October-04	4.31	3.62
9/25/06	10.82	474.18	485	0	November-04	3.79	3.605
10/29/06	9.76	475.24	485	0	December-04	3.39	4.18333
11/27/06	6.3	478.7	485	0	January-05	4.38	4.38
12/28/06	3.32	481.68	485	0	February-05	4.17333	4.17333
2/26/07	4.74	480.26	485	0	March-05	3.76	3.76
3/23/07	2.4	482.6	485	0	April-05	3.95667	3.95667
4/26/07	3.8	481.2	485	0	May-05	3.63	3.79
5/25/07	3.07	481.93	485	0	June-05	3.95	4.0075
6/23/07	5.64	479.36	485	0	July-05	4.17	4.2175
7/27/07	6.9	478.1	485	0	August-05	4.43	4.335
8/25/07	7.23	477.77	485	0	September-05	4.51	3.84
9/28/07	7.18	477.82	485	0	October-05	2.58	3.62
10/26/07	7.1	477.9	485	0	November-05	3.23	3.605
11/24/07	5.05	479.95	485	0	December-05	3.54	4.18333
12/25/07	3.77	481.23	485	0			
1/25/08	5.45	479.55	485	0			
2/23/08	6.95	478.05	485	0			
3/28/08	5.85	479.15	485	0			
4/20/08	2.34	482.66	485	0			
5/21/08	5.35	479.65	485	0			
6/24/08	7.13	477.87	485	0			
7/23/08	8.27	476.73	485	0			
8/21/08	9.37	475.63	485	0			
9/24/08	6.75	478.25	485	0			
10/28/08	5.78	479.22	485	0			
11/23/08	6.16	478.84	485	0			
12/22/08	4.07	480.93	485	0			
2/25/09	4.19	480.81	485	0			
3/25/09	5.07	479.93	485	0			
4/26/09	2.99	482.01	485	0			
5/26/09	4.99	480.01	485	0			
6/22/09	6.09	478.91	485	0			
7/21/09	6.78	478.22	485	0			
8/30/09	8.1	476.9	485	0			
9/22/09	8.99	476.01	485	0			
10/27/09	1.78	483.22	485	0			
11/22/09	3.8	481.2	485	0			
12/20/09	4.09	480.91	485	0			
1/25/10	2.87	482.13	485	0			
2/23/10	4.18	480.82	485	0			
3/28/10	6.2	478.8	485	0			
4/27/10	6.51	478.49	485	0			
5/24/10	3.29	481.71	485	0			
6/28/10	4.86	480.14	485	0			
7/27/10	6.94	478.06	485	0			
8/24/10	8.05	476.95	485	0			
9/26/10	8.79	476.21	485	0			
10/24/10	8.68	476.32	485	0			
11/28/10	3.29	481.71	485	0			
12/19/10	4.9	480.1	485	0			

Appendix 12: Quabbin Transfer

	2002	2003	2004	2005
Jan	5874	1056	1884	0
Feb	5209	2539	5028	0
Mar	2546	461	2704	0
Apr	3375	0	0	0
May	996	0	3247	3084
Jun	3659	1323	8682	7137
Jul	8104	9085	9297	9431
Aug	9184	9287	9639	7810
Sep	6983	8798	6125	6022
Oct	8975	6184	5580	2325
Nov	3601	2955	5487	1650
Dec	1943	931	625	100
				198925

Appendix 13: Total Inflows

	2002	2003	2004	2005
Jan	6344	4582	4443	6806
Feb	7216	5855	7422	4865
Mar	7637	12974	7678	8089
Apr	8304	10064	20231	14438
May	7543	8016	11300	12685
Jun	7383	9832	9924	7670
Jul	7309	9868	9717	8909
Aug	7383	9795	9678	7029
Sep	6626	8112	7536	5080
Oct	5787	7540	6735	13946
Nov	6442	4859	7467	8837
Dec	7886	8156	6411	6610
				399017

Appendix 14: Reservoir Spillway

	2002	2003	2004	2005
Jan	0	0	0	0
Feb	0	0	0	0
Mar	0	0	0	0
Apr	0	0	1917	254
May	0	0	3156	3156
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0
Sep	0	0	0	0
Oct	0	0	0	1185
Nov	0	0	0	954
Dec	0	0	0	56
				10676.9

Appendix 15: Nashua River Release

	2002	2003	2004	2005
Jan	55.80	55.80	55.80	55.80
Feb	50.40	50.40	50.40	50.40
Mar	55.80	55.80	55.80	55.80
Apr	54.00	54.00	54.00	54.00
May	55.80	55.80	55.80	55.80
Jun	54.00	54.00	54.00	54.00
Jul	55.80	55.80	55.80	55.80
Aug	55.80	55.80	55.80	55.80
Sep	54.00	54.00	54.00	54.00
Oct	55.80	55.80	55.80	55.80
Nov	54.00	54.00	54.00	54.00
Dec	55.80	55.80	55.80	55.80
				2628

Appendix 16: Sleeve Release

	2002	2003	2004	2005
Jan	0	0	0	0
Feb	0	0	0	0
Mar	0	558	0	0
Apr	0	2563	6523	1050
May	0	500	4118	3521
Jun	0	2300	2535	1280
Jul	0	2900	2800	0
Aug	0	3100	3100	0
Sep	0	1450	1224	0
Oct	0	0	0	2345
Nov	0	0	0	1131
Dec	0	0	0	0
				42998.27

Appendix 17: Wachusett Aqueduct

	2002	2003	2004	2005
Jan	0.0	14.0	1.3	0.0
Feb	0.0	0.0	1.5	0.0
Mar	0.0	0.0	3.4	0.0
Apr	0.0	0.0	0.0	0.0
May	0.0	0.0	0.0	0.0
Jun	0.0	0.0	0.0	0.0
Jul	0.0	2.4	0.0	0.0
Aug	0.0	6.1	0.0	0.0
Sep	3.9	4.6	0.0	0.0
Oct	5.2	5.6	2.2	0.0
Nov	0.0	1.6	3.8	0.0
Dec	0.0	4.2	4.4	0.0
				64.16

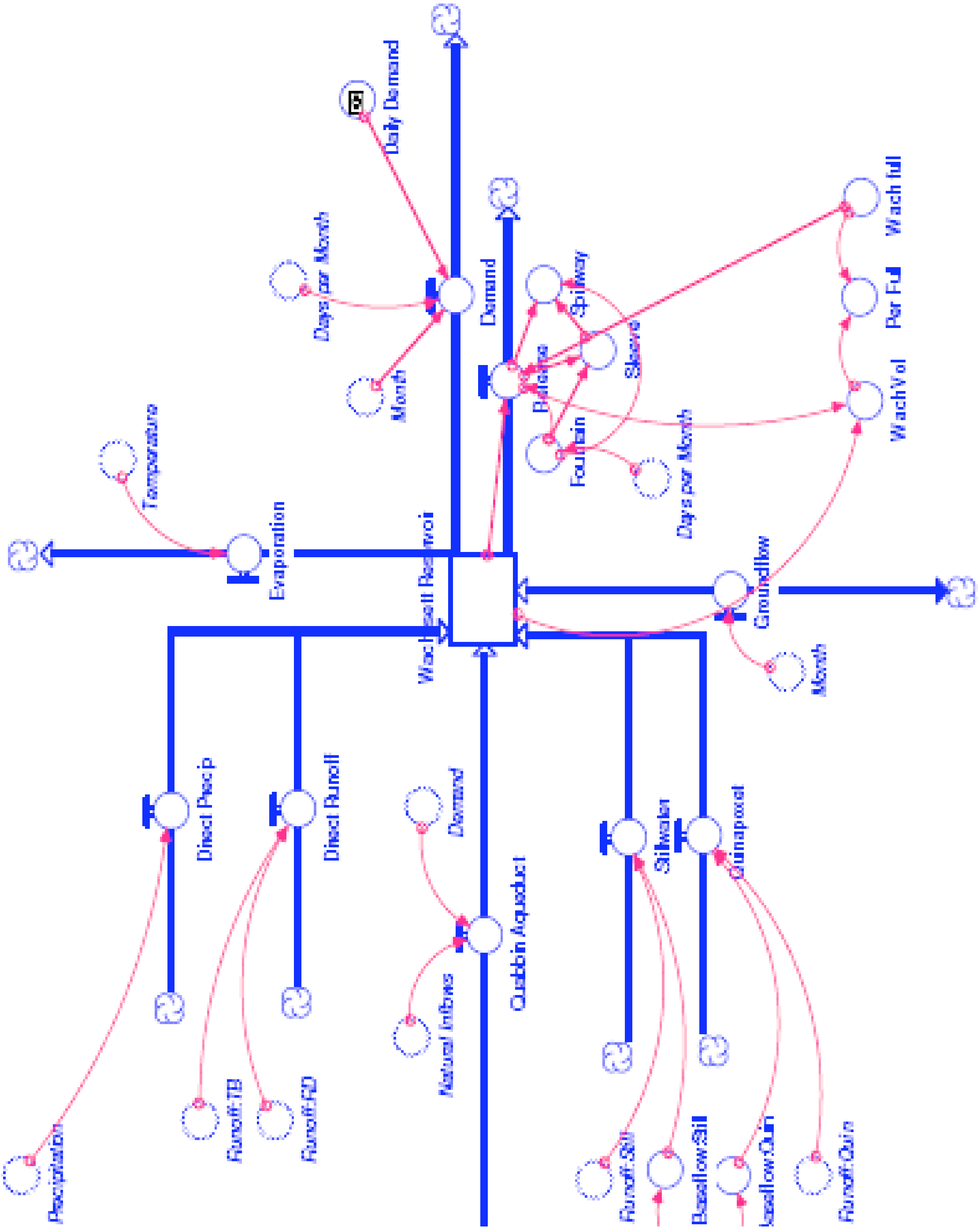
Appendix 18: Natural Outflows

	2002	2003	2004	2005
Jan	236	143	129	135
Feb	214	128	165	144
Mar	266	760	228	168
Apr	359	2799	8737	1572
May	421	820	7674	6949
Jun	443	2681	3011	1679
Jul	516	3389	3197	427
Aug	507	3569	3492	436
Sep	352	1782	1549	353
Oct	254	254	251	3791
Nov	194	224	203	2293
Dec	159	173	160	203
				67587

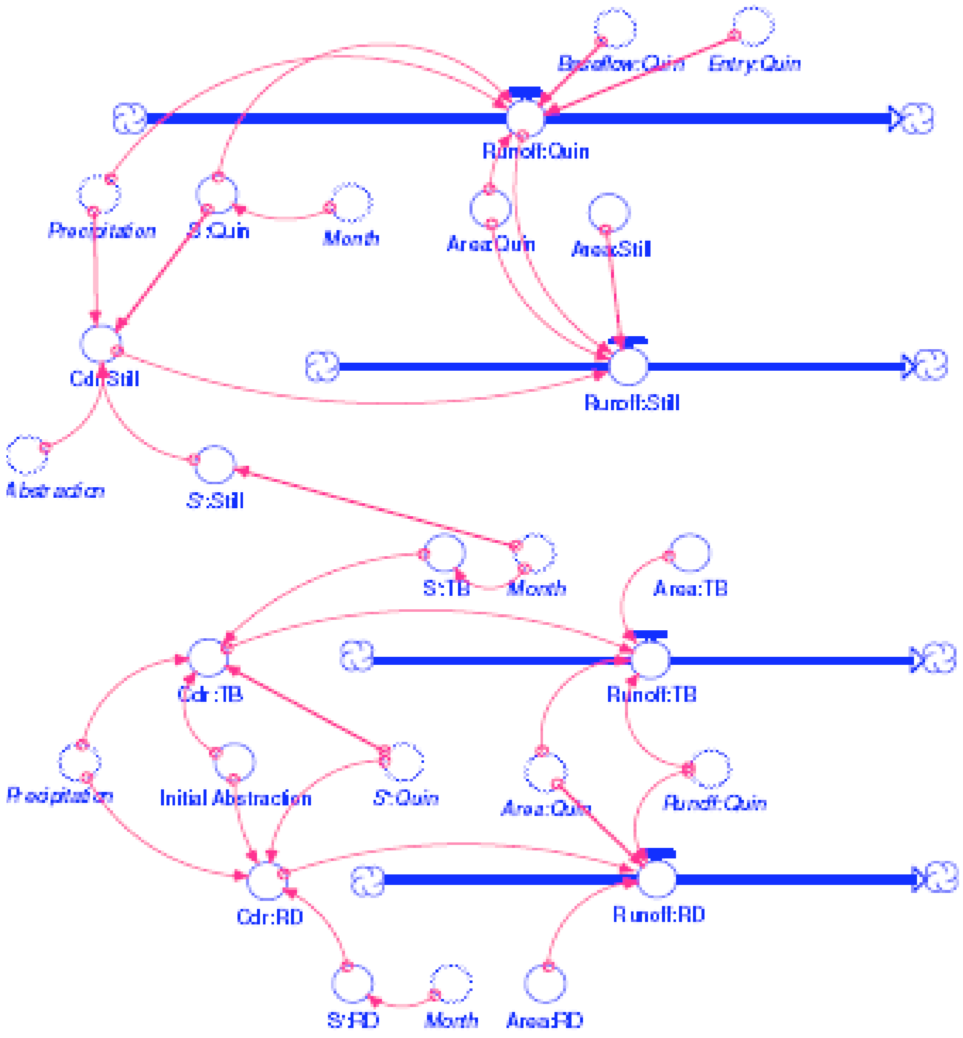
Appendix 19: Demand

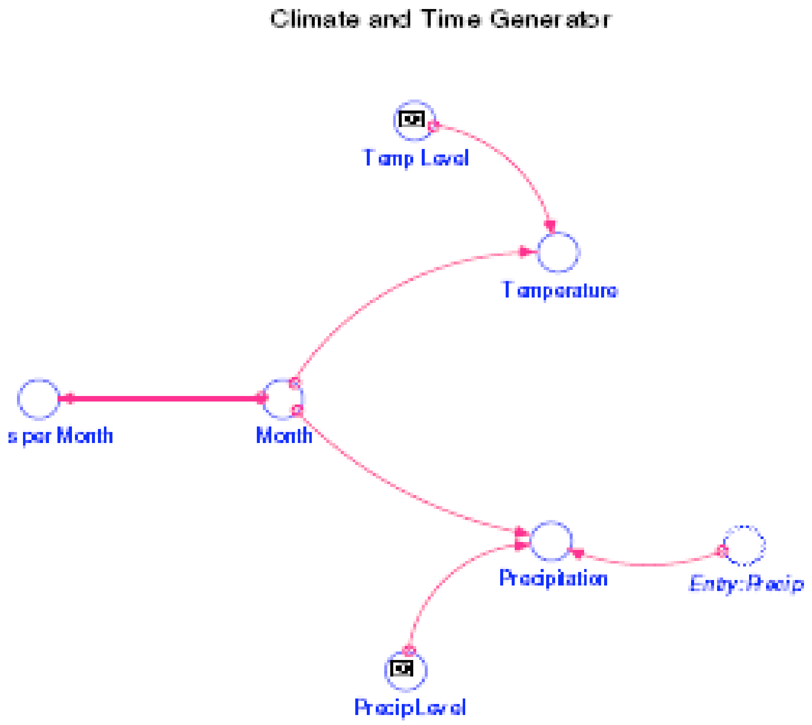
	2002	2003	2004	2005
Jan	6200	6200	6200	6200
Feb	6440	5740	6670	5740
Mar	7750	7595	7750	7595
Apr	7200	8250	7200	8250
May	7750	8990	7750	8990
Jun	7200	8250	7200	8250
Jul	6820	7285	6820	7285
Aug	6510	6200	6510	6200
Sep	6000	5850	6000	5850
Oct	6355	6045	6355	6045
Nov	6300	5850	6300	5850
Dec	6355	6045	6355	6045
				326590

Appendix 20: Stella Model & Equations



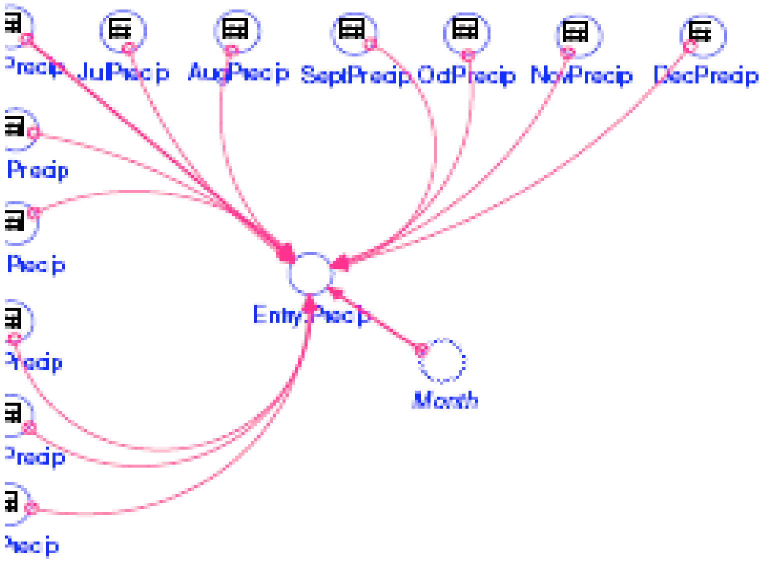
Runoff Calculator

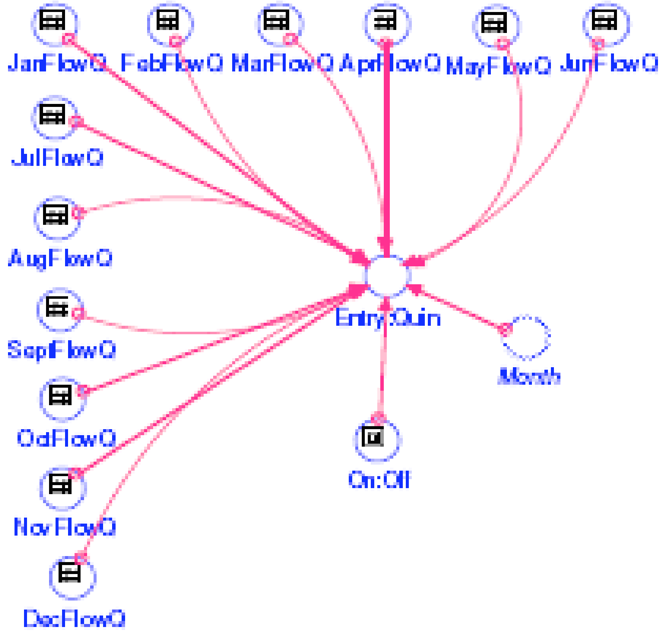


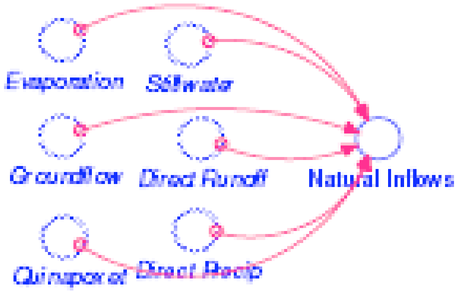


Climate and Time Generator
Temp Level
Temperature
s per Month
Month
Precipitation
Entry:Precip
PrecipLevel

erification Station





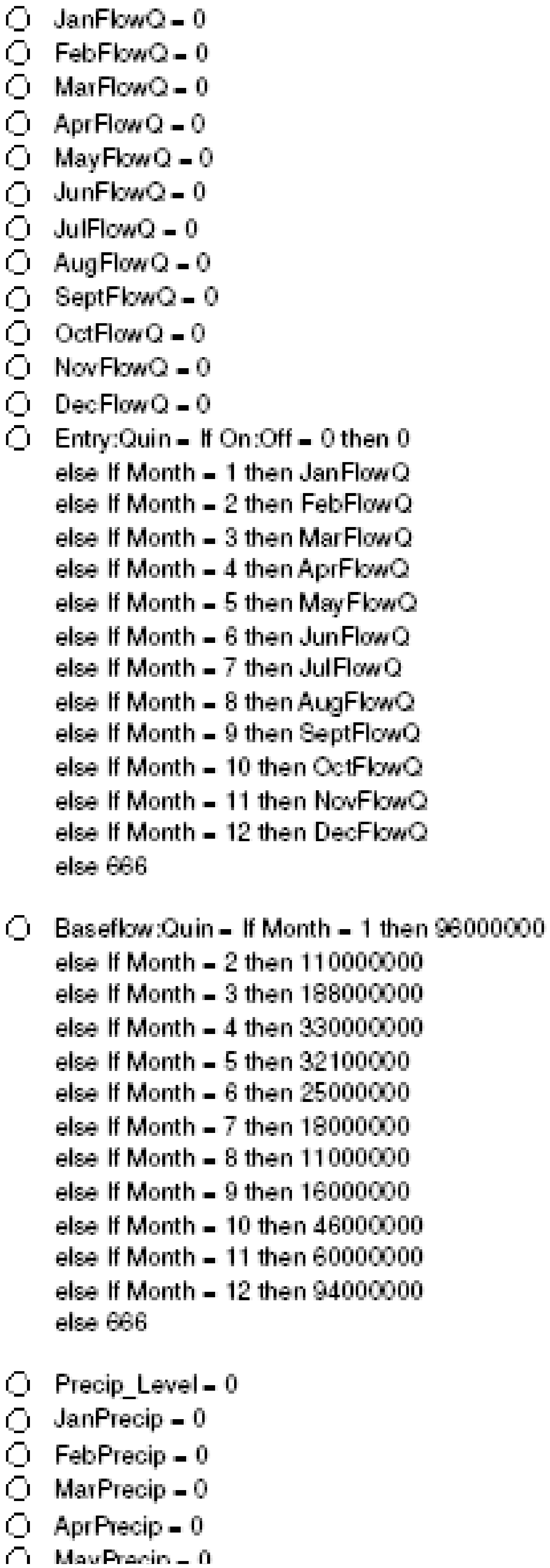


```
{ INITIALIZATION EQUATIONS }

□   INIT Wachusett_Reservoir = 64500000000
○   Month = If (Time-int(Time/12)*12) = 0 then 12
    else If Time > 12 then (Time-int(Time/12)*12)
    else Time
○   Daily_Demand = 300000000
○   Days_per_Month = If Month = 1 then 31
    else If Month = 2 then 28.25
    else If Month = 3 then 31
    else If Month = 4 then 30
    else If Month = 5 then 31
    else If Month = 6 then 30
    else If Month = 7 then 31
    else If Month = 8 then 31
    else If Month = 9 then 30
    else If Month = 10 then 31
    else If Month = 11 then 30
    else If Month = 12 then 31
    else 666

⇨   Demand = If Month = 1 then Daily_Demand*.89*Days_per_Month*10^6
    else if Month = 2 then Daily_Demand*.97*Days_per_Month*10^6
    else if Month = 3 then Daily_Demand*1.10*Days_per_Month*10^6
    else if Month = 4 then Daily_Demand*1.15*Days_per_Month*10^6
    else if Month = 5 then Daily_Demand*1.20*Days_per_Month*10^6
    else if Month = 6 then Daily_Demand*1.16*Days_per_Month*10^6
    else if Month = 7 then Daily_Demand*1.03*Days_per_Month*10^6
    else if Month = 8 then Daily_Demand*.92*Days_per_Month*10^6
    else if Month = 9 then Daily_Demand*.90*Days_per_Month*10^6
    else if Month = 10 then Daily_Demand*.89*Days_per_Month*10^6
    else if Month = 11 then Daily_Demand*.90*Days_per_Month*10^6
    else if Month = 12 then Daily_Demand*.89*Days_per_Month*10^6
    else 666

○   Baseflow:Still = If Month = 1 then 90000000
    else If Month = 2 then 121000000
    else If Month = 3 then 381000000
    else If Month = 4 then 485000000
    else If Month = 5 then 200000000
    else If Month = 6 then 31000000
    else If Month = 7 then 20000000
    else If Month = 8 then 2000000
    else If Month = 9 then 2000000
    else If Month = 10 then 14000000
    else If Month = 11 then 31000000
    else If Month = 12 then 54000000
```



```
○ JanFlowQ = 0
○ FebFlowQ = 0
○ MarFlowQ = 0
○ AprFlowQ = 0
○ MayFlowQ = 0
○ JunFlowQ = 0
○ JulFlowQ = 0
○ AugFlowQ = 0
○ SeptFlowQ = 0
○ OctFlowQ = 0
○ NovFlowQ = 0
○ DecFlowQ = 0
○ Entry:Quin = If On:Off = 0 then 0
  else If Month = 1 then JanFlowQ
  else If Month = 2 then FebFlowQ
  else If Month = 3 then MarFlowQ
  else If Month = 4 then AprFlowQ
  else If Month = 5 then MayFlowQ
  else If Month = 6 then JunFlowQ
  else If Month = 7 then JulFlowQ
  else If Month = 8 then AugFlowQ
  else If Month = 9 then SeptFlowQ
  else If Month = 10 then OctFlowQ
  else If Month = 11 then NovFlowQ
  else If Month = 12 then DecFlowQ
  else 666

○ Baseflow:Quin = If Month = 1 then 96000000
  else If Month = 2 then 110000000
  else If Month = 3 then 188000000
  else If Month = 4 then 330000000
  else If Month = 5 then 32100000
  else If Month = 6 then 25000000
  else If Month = 7 then 18000000
  else If Month = 8 then 11000000
  else If Month = 9 then 16000000
  else If Month = 10 then 46000000
  else If Month = 11 then 60000000
  else If Month = 12 then 94000000
  else 666

○ Precip_Level = 0
○ JanPrecip = 0
○ FebPrecip = 0
○ MarPrecip = 0
○ AprPrecip = 0
○ MayPrecip = 0
```

```
○ AugPrecip = 0
○ SeptPrecip = 0
○ OctPrecip = 0
○ NovPrecip = 0
○ DecPrecip = 0
○ Entry:Precip = If Month = 1 then JanPrecip
  else If Month = 2 then FebPrecip
  else If Month = 3 then MarPrecip
  else If Month = 4 then AprPrecip
  else If Month = 5 then MayPrecip
  else If Month = 6 then JunPrecip
  else If Month = 7 then JulPrecip
  else If Month = 8 then AugPrecip
  else If Month = 9 then SeptPrecip
  else If Month = 10 then OctPrecip
  else If Month = 11 then NovPrecip
  else If Month = 12 then DecPrecip
  else 666

○ Precipitation = If Precip_Level= 0 then Entry:Precip
  else If Month = 1 then Random(3.07,5.07)*Precip_Level
  else If Month = 2 then Random(3.10,5.10)*Precip_Level
  else If Month = 3 then Random(3.23,5.23)*Precip_Level
  else If Month = 4 then Random(2.92,4.92)*Precip_Level
  else If Month = 5 then Random(3.35,5.35)*Precip_Level
  else If Month = 6 then Random(3.02,5.02)*Precip_Level
  else If Month = 7 then Random(3.19,5.19)*Precip_Level
  else If Month = 8 then Random(3.09,5.09)*Precip_Level
  else If Month = 9 then Random(3.47,5.47)*Precip_Level
  else If Month = 10 then Random(3.67,5.67)*Precip_Level
  else If Month = 11 then Random(3.34,5.34)*Precip_Level
  else If Month = 12 then Random(2.80,4.80)*Precip_Level
  else 666

○ S':Quin = If Month = 1 then 1.48
  else If Month = 2 then 2.9
  else If Month = 3 then 1.52
  else If Month = 4 then .92
  else If Month = 5 then 3.61
  else If Month = 6 then 4.00
  else If Month = 7 then 5.02
  else If Month = 8 then 10.59
  else If Month = 9 then 14.32
  else If Month = 10 then 10.66
  else If Month = 11 then 3.02
  else If Month = 12 then 2.34
  else 666
```

```
⇒ Runoff:Quin = If Entry:Quin>0 then Entry:Quin*10^6-Baseflow:Quin
  else ((Precipitation-.2*S':Quin)^2/(Precipitation+.8*S':Quin)*17378742.78*Area:Quin)
○ Initial_Abstraction = .2
○ S':Still = If Month = 1 then 1.13
  else If Month = 2 then 2.41
  else If Month = 3 then .81
  else If Month = 4 then 1.03
  else If Month = 5 then 2.43
  else If Month = 6 then 4.12
  else If Month = 7 then 5.03
  else If Month = 8 then 9.76
  else If Month = 9 then 13.73
  else If Month = 10 then 10.05
  else If Month = 11 then 2.27
  else If Month = 12 then 1.39
  else 666

○ Cdr:Still =
  (Precipitation^2-(Initial_Abstraction*S':Still*Precipitation)+((1-Initial_Abstraction)*S':Still*Precipitation))/(Precip
  itation^2-(Initial_Abstraction*S':Quin*Precipitation)+((1-Initial_Abstraction)*S':Quin*Precipitation))
○ Area:Still = 30.48
⇒ Runoff:Still = Runoff:Quin*Cdr:Still*(Area:Still/Area:Quin)
⇒ Stillwater = Baseflow:Still+Runoff:Still
⇒ Quinapoxet = Baseflow:Quin+Runoff:Quin
⇔ Groundflow = If Month = 1 then 162000000
  else If Month = 2 then 901000000
  else If Month = 3 then 2185000000
  else If Month = 4 then 3746000000
  else If Month = 5 then 3749000000
  else If Month = 6 then -11000000
  else If Month = 7 then -1527000000
  else If Month = 8 then -1773000000
  else If Month = 9 then -1271000000
  else If Month = 10 then -1461000000
  else If Month = 11 then 539000000
  else If Month = 12 then 569000000
  else 0
```

```
○  Temperature = If Month = 1 then Random(15.8,31.4)*Temp_Level
   else If Month = 2 then Random(17.8,34.1)*Temp_Level
   else If Month = 3 then Random(25.6,43)*Temp_Level
   else If Month = 4 then Random(35.5,54.4)*Temp_Level
   else If Month = 5 then Random(46.2,66.3)*Temp_Level
   else If Month = 6 then Random(55.0,74.4)*Temp_Level
   else If Month = 7 then Random(60.8,79.3)*Temp_Level
   else If Month = 8 then Random(59.5,77.1)*Temp_Level
   else If Month = 9 then Random(51.3,69.0)*Temp_Level
   else If Month = 10 then Random(40.7,58.4)*Temp_Level
   else If Month = 11 then Random(32,47.1)*Temp_Level
   else If Month = 12 then Random(21.6,36.2)*Temp_Level
   else 666

⇨  Evaporation = 51.147*exp(0.0293*Temperature)*10^6
○  S':RD = If Month = 1 then 1.24
   else If Month = 2 then 2.57
   else If Month = 3 then 1.09
   else If Month = 4 then .92
   else If Month = 5 then 2.91
   else If Month = 6 then 3.96
   else If Month = 7 then 4.92
   else If Month = 8 then 9.97
   else If Month = 9 then 13.74
   else If Month = 10 then 10.15
   else If Month = 11 then 2.56
   else If Month = 12 then 1.78
   else 666

○  Cdr:RD =
   (Precipitation^2-(Initial_Abstraction*S':RD*Precipitation)+((1-Initial_Abstraction)*S':RD*Precipitation))/(Precipi
   ation^2-(Initial_Abstraction*S':Quin*Precipitation)+((1-Initial_Abstraction)*S':Quin*Precipitation))
○  Area:RD = 10.79
⇨  Runoff:RD = Runoff:Quin*Cdr:RD*(Area:RD/Area:Quin)
○  S':TB = If Month = 1 then .99
   else If Month = 2 then 2.26
   else If Month = 3 then .85
   else If Month = 4 then .68
   else If Month = 5 then 2.58
   else If Month = 6 then 3.58
   else If Month = 7 then 4.48
   else If Month = 8 then 9.19
   else If Month = 9 then 12.65
   else If Month = 10 then 9.36
   else If Month = 11 then 2.25
```

```
○  Cdr:TB =
   (Precipitation^2-(Initial_Abstraction*S':TB*Precipitation)+((1-Initial_Abstraction)*S':TB*Precipitation))/(Precipi
   ation^2-(Initial_Abstraction*S':Quin*Precipitation)+((1-Initial_Abstraction)*S':Quin*Precipitation))
○  Area:TB = 14.79
⇨  Runoff:TB = Runoff:Quin*Cdr:TB*(Area:TB/Area:Quin)
⇨  Direct_Runoff = Runoff:RD+Runoff:TB
⇨  Direct_Precip = Precipitation*107717490
○  Natural_Inflows = Stillwater+Quinapoxet+Groundflow-Evaporation+Direct_Runoff+Direct_Precip
⇨  Quabbin_Aqueduct = Demand-Natural_Inflows
○  Fountain = 1800000*Days_per_Month
○  Wach_full = 65000000000
⇨  Release = IF Wachusett_Reservoir > Wach_Full then Fountain+Wachusett_Reservoir-Wach_Full
   else Fountain
○  Sleeve = If Release > Fountain AND Release < Fountain+100000000 then Release-Fountain
   else if Release>Fountain+100000000 then 100000000
   else 0
○  Spillway = If Sleeve = 100000000 then Release-Sleeve-Fountain
   else 0
○  Wach_Vol = (Wachusett_Reservoir-Release)
○  Per_Full = Wach_Vol/Wach_full

   { RUNTIME EQUATIONS }
□  Wachusett_Reservoir(t) = Wachusett_Reservoir(t - dt) + (Groundflow + Direct_Precip + Direct_Runoff +
   Quinapoxet + Stillwater + Quabbin_Aqueduct - Demand - Evaporation - Release) * dt
○  Month = If (Time-int(Time/12)*12) = 0 then 12
   else If Time > 12 then (Time-int(Time/12)*12)
   else Time
○  Days_per_Month = If Month = 1 then 31
   else If Month = 2 then 28.25
   else If Month = 3 then 31
   else If Month = 4 then 30
   else If Month = 5 then 31
   else If Month = 6 then 30
   else If Month = 7 then 31
   else If Month = 8 then 31
   else If Month = 9 then 30
   else If Month = 10 then 31
   else If Month = 11 then 30
```

```
Demand = If Month = 1 then Daily_Demand*.89*Days_per_Month*10^6
else if Month = 2 then Daily_Demand*.97*Days_per_Month*10^6
else if Month = 3 then Daily_Demand*1.10*Days_per_Month*10^6
else if Month = 4 then Daily_Demand*1.15*Days_per_Month*10^6
else if Month = 5 then Daily_Demand*1.20*Days_per_Month*10^6
else if Month = 6 then Daily_Demand*1.16*Days_per_Month*10^6
else if Month = 7 then Daily_Demand*1.03*Days_per_Month*10^6
else if Month = 8 then Daily_Demand*.92*Days_per_Month*10^6
else if Month = 9 then Daily_Demand*.90*Days_per_Month*10^6
else if Month = 10 then Daily_Demand*.89*Days_per_Month*10^6
else if Month = 11 then Daily_Demand*.90*Days_per_Month*10^6
else if Month = 12 then Daily_Demand*.89*Days_per_Month*10^6
else 666

○ Baseflow:Still = If Month = 1 then 90000000
else If Month = 2 then 121000000
else If Month = 3 then 381000000
else If Month = 4 then 485000000
else If Month = 5 then 200000000
else If Month = 6 then 31000000
else If Month = 7 then 20000000
else If Month = 8 then 2000000
else If Month = 9 then 2000000
else If Month = 10 then 14000000
else If Month = 11 then 31000000
else If Month = 12 then 54000000
else 666

○ Entry:Quin = If On:Off = 0 then 0
else If Month = 1 then JanFlowQ
else If Month = 2 then FebFlowQ
else If Month = 3 then MarFlowQ
else If Month = 4 then AprFlowQ
else If Month = 5 then MayFlowQ
else If Month = 6 then JunFlowQ
else If Month = 7 then JulFlowQ
else If Month = 8 then AugFlowQ
else If Month = 9 then SeptFlowQ
else If Month = 10 then OctFlowQ
else If Month = 11 then NovFlowQ
else If Month = 12 then DecFlowQ
```

```
○ Baseflow:Quin = If Month = 1 then 96000000
  else If Month = 2 then 110000000
  else If Month = 3 then 188000000
  else If Month = 4 then 330000000
  else If Month = 5 then 32100000
  else If Month = 6 then 25000000
  else If Month = 7 then 18000000
  else If Month = 8 then 11000000
  else If Month = 9 then 16000000
  else If Month = 10 then 46000000
  else If Month = 11 then 60000000
  else If Month = 12 then 94000000
  else 666

○ Entry:Precip = If Month = 1 then JanPrecip
  else If Month = 2 then FebPrecip
  else If Month = 3 then MarPrecip
  else If Month = 4 then AprPrecip
  else If Month = 5 then MayPrecip
  else If Month = 6 then JunPrecip
  else If Month = 7 then JulPrecip
  else If Month = 8 then AugPrecip
  else If Month = 9 then SeptPrecip
  else If Month = 10 then OctPrecip
  else If Month = 11 then NovPrecip
  else If Month = 12 then DecPrecip
  else 666

○ Precipitation = If Precip_Level= 0 then Entry:Precip
  else If Month = 1 then Random(3.07,5.07)*Precip_Level
  else If Month = 2 then Random(3.10,5.10)*Precip_Level
  else If Month = 3 then Random(3.23,5.23)*Precip_Level
  else If Month = 4 then Random(2.92,4.92)*Precip_Level
  else If Month = 5 then Random(3.35,5.35)*Precip_Level
  else If Month = 6 then Random(3.02,5.02)*Precip_Level
  else If Month = 7 then Random(3.19,5.19)*Precip_Level
  else If Month = 8 then Random(3.09,5.09)*Precip_Level
  else If Month = 9 then Random(3.47,5.47)*Precip_Level
  else If Month = 10 then Random(3.67,5.67)*Precip_Level
  else If Month = 11 then Random(3.34,5.34)*Precip_Level
  else If Month = 12 then Random(2.80,4.80)*Precip_Level
  else 666
```

```
○ S':Quin = If Month = 1 then 1.48
  else If Month = 2 then 2.9
  else If Month = 3 then 1.52
  else If Month = 4 then .92
  else If Month = 5 then 3.61
  else If Month = 6 then 4.00
  else If Month = 7 then 5.02
  else If Month = 8 then 10.59
  else If Month = 9 then 14.32
  else If Month = 10 then 10.66
  else If Month = 11 then 3.02
  else If Month = 12 then 2.34
  else 666

⇨ Runoff:Quin = If Entry:Quin>0 then Entry:Quin*10^6-Baseflow:Quin
  else ((Precipitation-.2*S':Quin)^2/(Precipitation+.8*S':Quin)*17378742.78*Area:Quin)
○ S':Still = If Month = 1 then 1.13
  else If Month = 2 then 2.41
  else If Month = 3 then .81
  else If Month = 4 then 1.03
  else If Month = 5 then 2.43
  else If Month = 6 then 4.12
  else If Month = 7 then 5.03
  else If Month = 8 then 9.76
  else If Month = 9 then 13.73
  else If Month = 10 then 10.05
  else If Month = 11 then 2.27
  else If Month = 12 then 1.39
  else 666

○ Cdr:Still =
  (Precipitation^2-(Initial_Abstraction*S':Still*Precipitation)+((1-Initial_Abstraction)*S':Still*Precipitation))/(Precip
  itation^2-(Initial_Abstraction*S':Quin*Precipitation)+((1-Initial_Abstraction)*S':Quin*Precipitation))
⇨ Runoff:Still = Runoff:Quin*Cdr:Still*(Area:Still/Area:Quin)
⇨ Stillwater = Baseflow:Still+Runoff:Still
⇨ Quinapoxet = Baseflow:Quin+Runoff:Quin
⇔ Groundflow = If Month = 1 then 162000000
  else If Month = 2 then 901000000
  else If Month = 3 then 2185000000
  else If Month = 4 then 3746000000
  else If Month = 5 then 3749000000
  else If Month = 6 then -11000000
  else If Month = 7 then -1527000000
  else If Month = 8 then -1773000000
  else If Month = 9 then -1271000000
  else If Month = 10 then -1461000000
  else If Month = 11 then 539000000
```

```
○ Temperature = If Month = 1 then Random(15.8,31.4)*Temp_Level
  else If Month = 2 then Random(17.8,34.1)*Temp_Level
  else If Month = 3 then Random(25.6,43)*Temp_Level
  else If Month = 4 then Random(35.5,54.4)*Temp_Level
  else If Month = 5 then Random(46.2,66.3)*Temp_Level
  else If Month = 6 then Random(55.0,74.4)*Temp_Level
  else If Month = 7 then Random(60.8,79.3)*Temp_Level
  else If Month = 8 then Random(59.5,77.1)*Temp_Level
  else If Month = 9 then Random(51.3,69.0)*Temp_Level
  else If Month = 10 then Random(40.7,58.4)*Temp_Level
  else If Month = 11 then Random(32,47.1)*Temp_Level
  else If Month = 12 then Random(21.6,36.2)*Temp_Level
  else 666

  Evaporation = 51.147*exp(0.0293*Temperature)*10^6
○ S':RD = If Month = 1 then 1.24
  else If Month = 2 then 2.57
  else If Month = 3 then 1.09
  else If Month = 4 then .92
  else If Month = 5 then 2.91
  else If Month = 6 then 3.96
  else If Month = 7 then 4.92
  else If Month = 8 then 9.97
  else If Month = 9 then 13.74
  else If Month = 10 then 10.15
  else If Month = 11 then 2.56
  else If Month = 12 then 1.78
  else 666

○ Cdr:RD =
  (Precipitation^2-(Initial_Abstraction*S':RD*Precipitation)+((1-Initial_Abstraction)*S':RD*Precipitation))/(Precipi
  ation^2-(Initial_Abstraction*S':Quin*Precipitation)+((1-Initial_Abstraction)*S':Quin*Precipitation))
  Runoff:RD = Runoff:Quin*Cdr:RD*(Area:RD/Area:Quin)
○ S':TB = If Month = 1 then .99
  else If Month = 2 then 2.26
  else If Month = 3 then .85
  else If Month = 4 then .68
  else If Month = 5 then 2.58
  else If Month = 6 then 3.58
  else If Month = 7 then 4.48
  else If Month = 8 then 9.19
  else If Month = 9 then 12.65
  else If Month = 10 then 9.36
  else If Month = 11 then 2.25
  else If Month = 12 then 1.51
  else 666
```

⇨ Runoff:TB = Runoff:Quin*Cdr:TB*(Area:TB/Area:Quin)
⇨ Direct_Runoff = Runoff:RD+Runoff:TB
⇨ Direct_Precip = Precipitation*107717490
○ Natural_Inflows = Stillwater+Quinapoxet+Groundflow-Evaporation+Direct_Runoff+Direct_Precip
⇨ Quabbin_Aqueduct = Demand-Natural_Inflows
○ Fountain = 1800000*Days_per_Month
⇨ Release = IF Wachusett_Reservoir > Wach_Full then Fountain+Wachusett_Reservoir-Wach_Ful
else Fountain
○ Sleeve = If Release > Fountain AND Release < Fountain+100000000 then Release-Fountain
else if Release>Fountain+100000000 then 100000000
else 0
○ Spillway = If Sleeve = 100000000 then Release-Sleeve-Fountain
else 0
○ Wach_Vol = (Wachusett_Reservoir-Release)
○ Per_Full = Wach_Vol/Wach_full

Appendix 21: Statement of Design

The Major Qualifying Project (MQP) is the capstone requirement for graduating students at Worcester Polytechnic Institute (WPI). It demonstrates the culmination of the entire WPI program and displays the student's knowledge and skills in their designated discipline. While all the projects vary greatly, they all must contain enough demonstrated design content.

This project satisfies the capstone design requirement for the Department of Civil and Environmental Engineering at WPI. The MQP presented here investigates the hydrologic nature of the Wachusett Reservoir and its watershed. To meet the design requirement, this project included the design of a system which serves as a tool to enhance the development of reservoir yields.

This project included data synthesis based in the design of two models founded on hydrological data analysis. These models provide a design tool in order to evaluate the hydrologic function of various components to the Wachusett Reservoir. The models simulate the operation of the Wachusett Reservoir at optimal conditions and thus provide the capability to better understand and control specific functions within the reservoir system. The approach included the evaluation of a variety of conditions for incorporating hydrologic inputs and developing the models. A useful design tool was developed by including inputs into the model, validating the model against real world data and demonstrates its use for predictions.

Additionally through various model simulations and hydrologic research, several recommendations were developed as to the design of a monitoring program for the Wachusett Reservoir. These recommendations, presented to the MA Department of Conservation and Recreation, provide a basis for determining reservoir yield and effectively enhancing reservoir operation. This project, especially since it helps evaluate expanding water supply to communities, incorporates considerations for environmental sustainability, as well as, social and political issues.