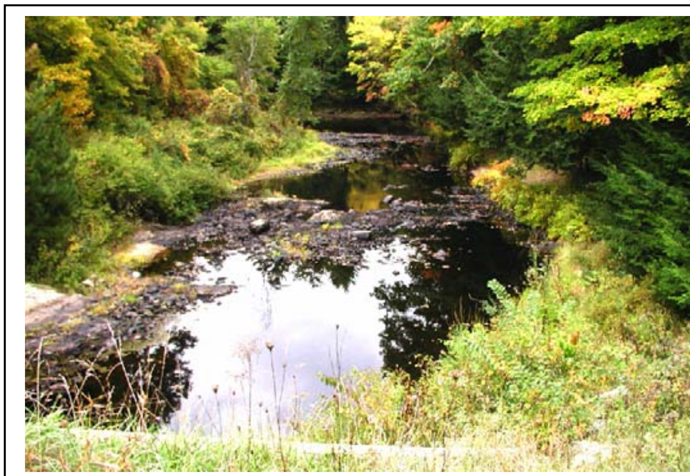
Aquarion Water Company of New Hampshire

Safe Yield Analysis: Exeter Water Supply System

April 2003



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Executive Summary

To support decisions about an interconnection between the water system of Hampton, NH (operated by the Aquarion Water Company of New Hampshire) and that of Exeter, New Hampshire, CDM assessed the safe yield of the Exeter system. CDM gathered information about Exeter's system, projected demand, used hydrologic and system simulation models to estimate the safe yield under various conditions, and estimated the reliability that can be expected under the various conditions. The study concluded that an interconnection would benefit both parties.

Background

Aquarion provides water service for about 8,500 customers in Hampton, North Hampton, and Rye, New Hampshire. In 2001, the average annual demand on the system was about 2.38 million gallons per day (mgd). During the droughts of the late1990s and 2002, Aquarion struggled to meet high summertime demands, which are attributed in part to the seasonal tourist population at Hampton Beach. During July, when demand for water is typically the highest, demand can exceed 3.5 mgd. Accordingly, the New Hampshire Department of Environmental Services (DES) has placed a moratorium on new connections. Thus Aquarion cannot extend distribution mains to serve new residential or commercial developments.

Previous Studies

In 2001, Aquarion engaged CDM to evaluate the feasibility of an interconnection between the Aquarion and Exeter water systems, to provide additional water during emergencies. The two distribution systems are about 2.5 miles apart, and, under average conditions, each system has adequate capacity to provide water to the other. The 2001 study indicated that an interconnection would be feasible and identified the necessary facilities and pipe routing.

The Exeter Reservoir

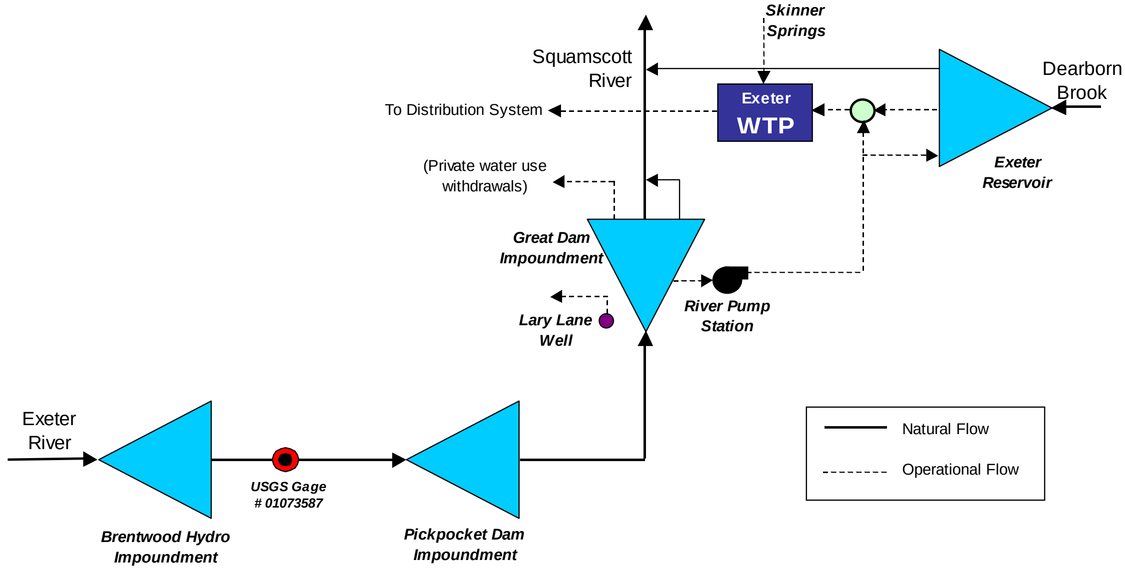
Although the interconnection was originally envisioned for emergency use, subsequent discussions indicated that Exeter might be willing to consider selling surplus water to Aquarion. This additional supply would help mitigate Aquarion's seasonal water supply deficits. CDM's *'Water System Evaluation Study'* (CDM, 2002), prepared at the request of Exeter, indicated that Exeter may have additional water supply available. This evaluation was based on approximate regionalized methods for estimating system yield, and the report recommended that a more rigorous analysis of system yield be conducted. Aquarion subsequently engaged CDM to conduct the detailed safe yield study presented in this report.

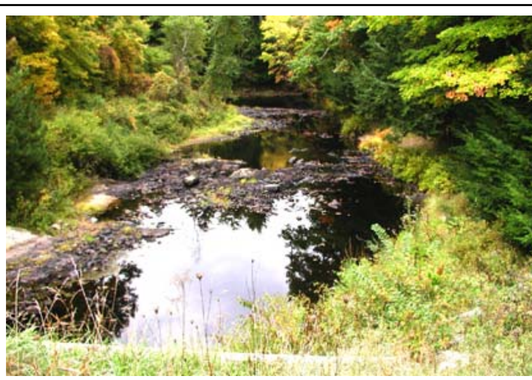
Exeter Water Supply System

As Figure E-1 shows, Exeter relies on a combination of surface water and groundwater to meet system demands, which averaged about 1.16 mgd in 2001. The primary source for the Exeter system is the Exeter River. The town also uses the Exeter Reservoir, located adjacent to the water treatment plant; the reservoir is fed by Dearborn Brook but also is supplemented with flows from the Exeter River. Exeter's groundwater sources include Skinner Springs (water from which is pumped to the treatment plant) and Lary Lane Well (water from which is pumped directly to the distribution system).

Figure E-1: Exeter Water Supply System

EXETER WATER SUPPLY SYSTEM SCHEMATIC





The Exeter River near the USGS gage station

Looking upstream at Great Dam in Exeter

Study Objectives and Methods

The purpose of this study is to provide accurate estimates of the sustainable yield from Exeter's water supply sources. Specifically, the study has the following objectives:

- Estimate the sustainable yield of Exeter's water supply sources during drought years;
- Estimate the sustainable yield of Exeter's water supply sources during normal years;
- Quantify the reliability of the safe yield over a range of withdrawal rates; and
- Quantify the sensitivity of the safe yield to other factors, such as operations of dams within the study area and other water users.

To accomplish these objectives, CDM developed two linked models: a hydrologic model to simulate flow in the Exeter River and the Exeter Reservoir, and a system simulation model to simulate the effects of storage, dam operating procedures, system withdrawals, and system constraints.

These models were used to simulate various demand scenarios that have occurred during the period for which we have climate records, including three major droughts (the mid-1960s, 1980, and 2002). The modeling results were used to estimate the withdrawal rates that could be sustainable if such droughts occurred again, and to estimate the likelihood of system failure if these sustainable withdrawal rates were exceeded. The model was also used to simulate the effects of changes to certain operational procedures, to help determine if instituting the changes would increase the yield.

Results Summary

The primary results of the study are the predicted rates of withdrawal that could be sustained (that is, safe yield rates) during droughts and under normal conditions. The sensitivity of these rates to many factors was assessed, and the rates were found to be most sensitive to the operating procedures of the Exeter Mills Apartments. This apartment complex is adjacent to the Exeter River and withdraws water from the Great Dam impoundment for cooling and irrigation. The apartments do not recycle the cooling water, but with certain operational changes, most of the cooling water could be re-captured for water supply purposes (depending on hydraulic constraints at the reservoir and treatment plant).

Table E-1 summarizes the withdrawal rates that could be sustained during the three drought scenarios and during a normal year. It presents the sustainable rates for two alternative sets of operational procedures pertaining to the Exeter Mills Apartments:

- Cooling water used by the Exeter Mills Apartments is not recycled
- Cooling water is recycled and the hydraulic constraints at the Exeter Reservoir are eliminate (as planned during the WTP re-construction)

Table E-1.
*Safe Yield Rates for Drought and Normal Years**

	Average Annual mgd			
	1966 Drought	**1980 Drought**	**2002 Drought**	**1998 (normal year)**
Safe yield **without** recycling	1.7	1.2	1.4	4.3
Safe yield **with** recycling, and **with** removal of hydraulic constraints at the WTP	2.7	2.2	2.4	5.3

**Based on assumptions of Section 6.1, except for Exeter Mills cooling water.*

This report also estimates how reliable the system would be (that is, how often the active storage would be depleted) if the withdrawal rates listed in Table E-1 were exceeded. Also, the sensitivity of the values to various operating protocols is analyzed and presented.

The results suggest that Exeter's projected demand of 1.92 mgd in 2020 (at full build-out, with 100% of the town serviced by the supply system) is within the safe yield of the system. The analysis also suggests that if an additional 0.5 mgd were transferred annually to Hampton, the system would still be nearly 100% reliable, but that (approximately) once in a ten year period, full demand might not be satisfied for roughly 25 days. That is, full demand would be satisfied more than 99% of the time.

The system can reliably supply 0.5 mgd to Hampton even with maximum projected future demand in Exeter.

Furthermore, in the simulation, the failures most frequently occurred during September and October, when demand in Hampton is normally reduced due to lower seasonal tourist populations. However, simulation did not assume the demand of 0.5 mgd would be reduced. The analysis also suggests that if demand restrictions are invoked (as described in Section 6), the reliability rate increases to over than 99.5%.

The yield and reliability of the system could likely be further increased if the unused hydropower dam in Brentwood is removed. This dam impounds a portion of the contribution from approximately 55% of the watershed during low flow periods, when the supply system experiences the greatest stress. An analysis of streamflow records reveals that during low flow periods, the effect of the Brentwood Hydro Dam is equivalent to a reduction in total basin drainage area of approximately 20%.

Conclusions

An interconnection could benefit both systems.

An interconnection between the Hampton (Aquarion) and Exeter systems could benefit both systems. It could provide additional supply to Aquarion during emergency conditions and peak summer demands. The additional supply could also allow Aquarion to allow its groundwater wells to rest during off-peak times. For Exeter, an interconnection could provide improved fire flows in the eastern part of town and emergency supply in the event of a failure at the water treatment plant. Additionally, there is the potential for Exeter to generate additional revenue through water sales or cost sharing of the new water treatment plant.

Section 1
Introduction

1.1 Motivation for the Safe Yield Study

Aquarion Water Company of New Hampshire (Aquarion, formerly Hampton Water) currently provides water service for approximately 8,500 customers in the communities of Hampton, North Hampton, and Rye, New Hampshire. Based on 2001 records, the average annual demand is approximately 2.38 million gallons per day (mgd). During the droughts of the late-1990s and 2002, Aquarion has struggled to meet high summertime demands, the result of seasonal tourist population at Hampton Beach. During July, which is typically the highest demand month, the monthly demands are in excess of 3.5 mgd. Accordingly, Aquarion is currently under a moratorium from the New Hampshire Department of Environmental Services (DES) on new connections. As a result, Aquarion can not extend distribution mains to serve new residential or commercial developments.

In 2001, Aquarion engaged CDM to evaluate the feasibility of a water system interconnection between Aquarion and Exeter, NH. The existing distribution systems are located approximately 2.5 miles apart and, under average conditions, each system has adequate capacity to provide water to the other. Past experience has shown that there have been occasions when both Aquarion and Exeter would have benefited from an interconnection, most notably in the fall of 1996 and during the summer droughts in 1999 and 2002. In 1996 Exeter's water treatment plant was flooded and the Town relied on limited groundwater supplies and water tanker trucks to meet demand. Aquarion was not impacted by the flooding and had additional supply capacity during this period. During the droughts in the summers of 1999 and 2002, groundwater levels dropped and Aquarion's groundwater wells were not able to maintain typical production rates. The reduced groundwater withdrawals combined with high customer demand led to water use restrictions. Exeter's surface water supply was not impacted as severely by these droughts and Exeter had additional water supply capacity during this time.

The interconnection was originally envisioned as an emergency interconnection, to be used during severe conditions. However, as Aquarion has been under moratorium on new connections since 2001 due to a supply deficit, they are actively seeking new supplies. Exeter's 'Water System Evaluation Study' (CDM, 2002) included a safe yield evaluation, based on regional empirical methods, which indicated that Exeter may have surplus supply available. Additionally, Exeter has expressed potential interest in selling excess supply to Aquarion. Aquarion subsequently engaged CDM to conduct the detailed safe yield study that is the focus of this report.

1.2 Study Objectives

The purpose of this study is to provide accurate estimates of the sustainable yield from the Exeter water supply system. Specifically, the study has the following objectives:

Estimate the sustainable yield of the Exeter water supply system during drought years. Using historic droughts of record, evaluate the sustainable yield of Exeter's system, considering other withdrawals and constraints on the river, and compare to Exeter's projected future demand rates. This is an estimate of the 'worst-case' condition that may occur within Exeter's system.

Estimate the sustainable yield of the Exeter water supply system during normal years. Based on average precipitation years, determine the sustainable yield of Exeter's system, considering other withdrawals and constraints on the river, and compare to Exeter's projected future demand rates. This is an estimate of the typical conditions that are likely to occur within Exeter.

Quantify the reliability of the safe yield over a range of withdrawal rates. Exeter's future 2020 average water demands are estimated to be approximately 1.92 mgd. These demands would increase if Exeter elects to sell water outside its boundaries. Therefore, this analysis evaluates the reliability of the system as a function of Exeter's withdrawals.

Quantify the sensitivity of the safe yield to other factors, such as operations of dams within the study area and other water users. There are other water users who withdraw water directly from the Exeter River Basin. Additionally, there are three dams on the Exeter River that affect the flow available for Exeter's water supply. This analysis evaluates the impact of these system factors.

1.3 Definition of Safe Yield

For the purposes of this study, "Safe Yield" is defined as the average daily withdrawal from a water supply system that can be sustained through the drought(s) of record without entirely depleting the system storage. The drought of record for most of New England is normally considered to be the prolonged drought that occurred during the mid-1960s. However, since the Exeter water supply system is very sensitive to sudden changes in within-year precipitation patterns, assessing the sustainability of supply during a prolonged drought such as that of the 1960s may not actually account for worst-case conditions. Hence, two other prominent short-term droughts were also considered during this study: the drought of 1980, and the recent drought of 2002. Safe yield estimates will therefore be presented for the droughts of the 1960s, 1980, and 2002, along with years during which normal precipitation patterns prevailed. These results can be interpreted as *maximum sustainable average daily withdrawals through the droughts of record without system failure,* that is, without drawing water levels down below intake levels.

Results of extended continuous simulation (from 1963 through 2002) will also be presented. Instead of applying the "no failure" criteria to this analysis, however, results will be presented in terms of failure frequency that can be expected for various levels of average daily withdrawals. These results are intended to augment the safe yield (no failure) results by offering insight into the reliability of the system for withdrawal rates that may exceed the estimated safe yield.

The yield estimates presented in this study comply with all applicable regulations. The system draws water only from active storage reserves, that is, only water above the intakes to the river pump station and the treatment plant is simulated as being available for withdrawal in this study. Hence, even when active storage is depleted in the impoundments, there is still water below the intakes; nearly 10 million gallons in the Exeter River impoundment, and nearly 9 million gallons in the Exeter Reservoir. Hence, neither impoundment would be physically emptied as a result of the sustainable yield rates presented in this report. Water would continue to flow into the impoundments (river flow would be unaffected upstream of the pump station), although water levels would decrease and flow would not pass through Great Dam.

This study has focused on the hydrologic availability of water and the hydraulic constraints associated with the Exeter water supply system. The yield values reported are based on operational compliance with known regulations. Additional guidance information is presented so that yield can be evaluated in the context of aesthetic and environmental constraints that may be related to water surface elevations. Withdrawals from the Exeter River do not reduce the river flow except for the short reach between the pump station and Great Dam, and the reach downstream of Great Dam (the Squamscott River), which is essentially tidal. Instead, withdrawals reduce the water surface elevation upstream of Great Dam. For this reason, a sensitivity analysis is presented in which the safe yield is re-computed for incremental reductions in allowable storage depletion in the Exeter River.

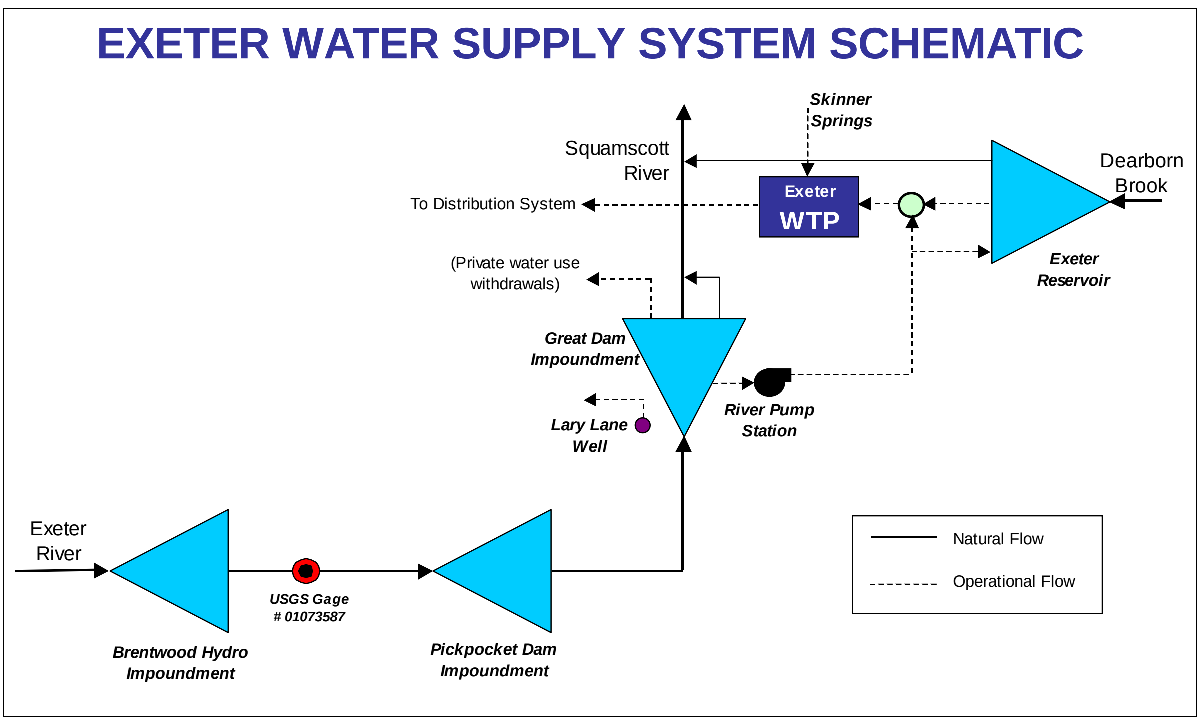
Section 2
Exeter Water Supply System Description

2.1 Water Supply Sources

The Town of Exeter draws its water supply from four sources, as shown in Figure 2-1 and listed below (Figure 2-1 is included in the pocket at the end of this section). A full schematic of the system and its existing interconnections is shown in Figure 2-2.

- Exeter River
- Exeter Reservoir
- Lary Lane Well
- Skinner Springs

Figure 2-2: Exeter Water Supply System Schematic



2.1.1 Exeter River

The Exeter River is the primary source of water supply for the Town of Exeter. The watershed is mostly rural and forested, and covers an area of approximately 106 square miles, as shown in Figure 2-1.

The Exeter River is impounded behind Great Dam, which was acquired by the Town of Exeter in 1981. Documents relating to the acquisition are included in the *Water System Evaluation Study*, Appendix B (Camp Dresser & McKee Inc., 2002). Downstream of Great Dam, the river changes name to the Squamscott River, and it is tidally influenced from the Dam to the ocean. The dam is equipped with a fish ladder. Any water that passes over the dam or through the fish ladder is lost from the supply system. The dam and fish ladder are shown in the photograph of Figure 2-3.

In 1972, the Town of Exeter constructed a pump station on the east bank of the river, near the athletic fields of Phillips Exeter Academy. The pump station consists of a single constant speed pump that can transfer approximately 2.1 mgd from the Exeter River to either the Town's water treatment plant or the Exeter Reservoir, depending on operating objectives. The pump draws water from the impoundment behind Great Dam through a pipe with an invert elevation of 15 feet (NGVD). For comparison, the crest of Great Dam is at 22.5 feet (NGVD). Available storage behind the dam is discussed in Section 2.3.

There are two other significant impoundments on the Exeter River upstream of Great Dam. The Pickpocket Dam (also acquired by the Town of Exeter in 1981) is located at Cross Road near the corporate boundary between Exeter and Brentwood (see Figures 2-2 and 2-4). The drainage area upstream of the Pickpocket Dam is approximately 74 square miles. This dam is normally not operated by the town, and can be characterized as a "run-of-the-river" dam. It is equipped with a fish ladder and release gates, should they be needed, although any water passing through these facilities is retained in the water supply system and flows downstream to the Great Dam Impoundment. Water impounded behind Pickpocket Dam is effectively stored in the water supply system, and can become available for supply augmentation if necessary. This will be discussed further in Section 6.0.

Further upstream in the Town of Brentwood, another dam impounds the river. Referred to herein as the "Brentwood Hydro Dam," the dam was previously used to generate hydropower at an adjoining power generation facility (see Figures 2-2 and 2-5). The drainage area upstream of the dam is approximately 59 square miles. The dam is no longer operated, although it is still privately owned, and has fallen into disrepair. A visual field inspection conducted as part of this study confirmed that both the dam face and the forebay channel leak badly. In theory, then, while the dam may prevent some of the river flow from passing during low-flow periods, it still allows water to pass downstream even when no water passes over the spillway. This will be further discussed in Section 4.0.

The United States Geological Survey (USGS) operates a streamflow gage (#01073587) on the Exeter River between the Brentwood Dam and the Pickpocket Dam (see Figures 2-2 and 2-6). The drainage area upstream of the gage is listed by the USGS as 63.5 square miles. The gage has been in service since June of 1996, and is located at the site of a natural hydraulic control in the form of a rocky barricade. In a personal communication dated October 18, 2002, the USGS indicated that the accuracy of the gage was rated as "good" for low flow levels (on the order of 1 cfs), with an estimated accuracy of +/- 10%.

Figure 2-3: Great Dam and Fish Ladder

Figure 2-4: Pickpocket Dam

Figure 2-5: Brentwood Hydro Dam

Figure 2-6: USGS Gage – Natural Control

2.1.2 Exeter Reservoir

The Exeter Reservoir (Figure 2-7) is fed by Dearborn Brook, and drains an area of approximately 1.7 square miles of predominately undeveloped land. Because the contributory area of the reservoir represents less than 2% of the total contributory area of the water supply system, the basin itself does not provide a large percentage of the water supply. However, water from the Exeter River can be pumped into the reservoir (in lieu of pumping directly to the water treatment plant) for temporary storage. A storage summary for the reservoir is presented in Section 2.3.

Water can be withdrawn from the reservoir directly to the treatment plant. When water spills from the reservoir over the spillway (Figure 2-8), it is lost from the water supply system and flows through a concrete channel into Wheelwright Creek and eventually into the Squamscott River. Flashboards can be installed at the spillway to raise or lower the reservoir surface level as needed.

Figure 2-7: Dam at Exeter Reservoir

Figure 2-8: Spillway at Exeter Reservoir

2.1.3 Lary Lane Well

The Lary Lane Well is located on the northwest bank of the Exeter River near the southern border of Exeter. It extends 94 feet into a gravel layer after penetrating an overlying layer of clay. Water pumped from the well is delivered directly to the water distribution system (after chemical treatment for disinfection and iron/manganese control), and does not pass through the water treatment plant. The well was constructed in 1958, and is equipped with a single constant speed pump. CDM has estimated that the capacity from the well is 0.3 – 0.5 mgd (Camp Dresser & McKee Inc., 2002), but the pump is not normally operated for 24 hours, and daily well withdrawals in recent years have been closer to 0.1 mgd.

2.1.4 Skinner Springs

The Skinner Springs area in Stratham was developed as a supplementary water source for Exeter in 1929. The facility includes production wells, a collector well, and a 10-inch raw water transmission main to the Water Treatment Plant. The original construction included six production wells and the collector well, all at depths of 20-25 feet. The existence of one deep artesian well installed in the bedrock is mentioned in a 1935 letter in the Town's files. Weston & Sampson (1968) indicated there were eight production wells. Whitman & Howard (1986) cites six 30-inch diameter wells, two 42-inch diameter wells, and a 30-foot diameter collector well. The produced water flows by gravity from the Skinner Springs collector well to the Water Treatment Plant.

2.2 Storage Summary

Surface water is stored at three locations within the water supply system: in the impoundment behind Great Dam, in Exeter Reservoir, and in the impoundment behind Pickpocket Dam. Each impoundment was analyzed during this study to identify the percentage of total storage at each location that would be physically available for withdrawal into the water supply system. For example, water that is pooled below the intake pipes cannot be physically extracted, even though it is impounded. For the purposes of this report, water that can be physically extracted from storage will be referred to as "Active Storage," and water that is below the level of the associated intake pipe will be referred to as "Inactive Storage." Figure 2-9 illustrates this nomenclature.

Figure 2-9 depicts the threshold between active and inactive storage very generally as the elevation of the invert of the intake pipe. System-specific head losses or configurations that require additional head in order to provide sufficient flow over a weir (for example) usually result in a threshold that is located above the invert of the intake pipe. These effects will be discussed in detail with respect to individual impoundments for the Exeter System in the following sections.

Figure 2-9: Active vs. Inactive Storage

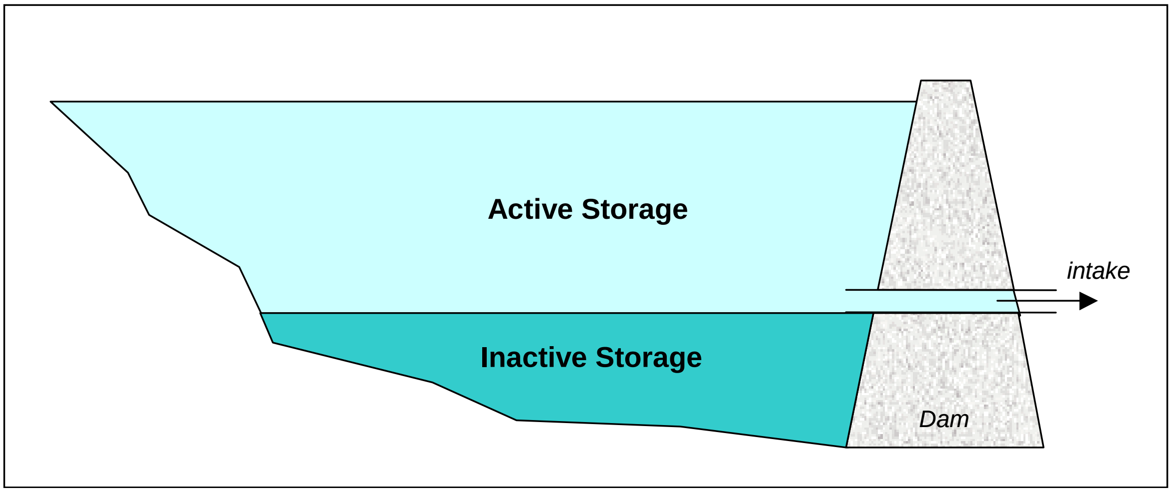
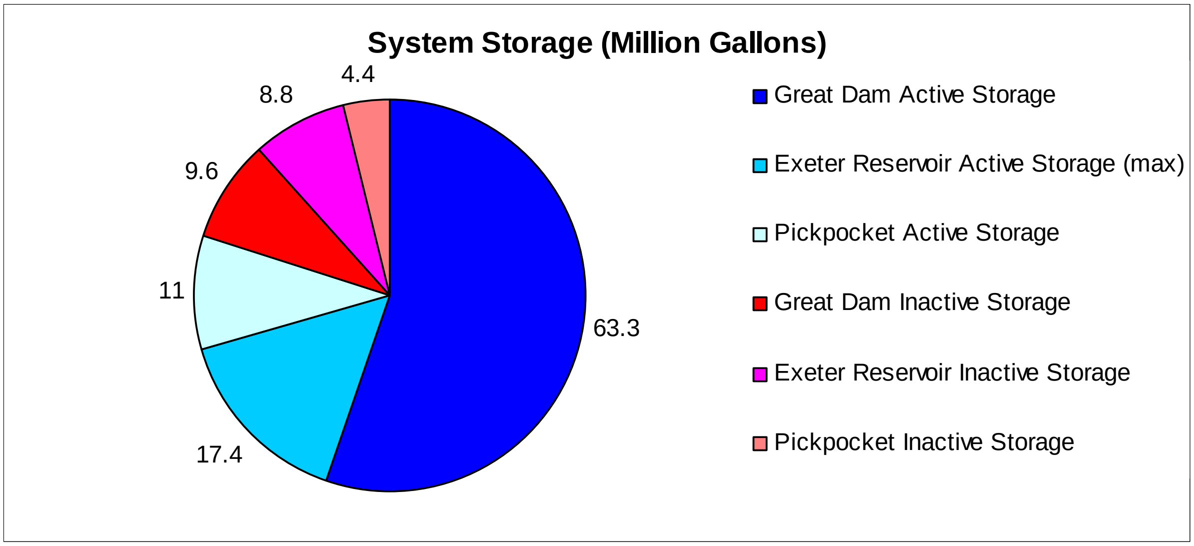


Figure 2-10 illustrates the contributions of each impoundment to the active and inactive storage within the system. The total storage in the system is estimated at 115 million gallons. Approximately 80% of the total system storage is available for withdrawal, and just 20% is below the limiting hydraulic infrastructure. The active and inactive storage values for each impoundment are described in the following sections.

Figure 2-10: Contributions to Total System Storage



2.2.1 Storage Behind Great Dam

A bathymetric survey was conducted as part of this study to characterize the geometry of the Exeter River channel upstream of Great Dam. River channel transect measurements were obtained at 11 stations upstream of the dam over a reach of approximately 2 miles. The results were augmented by data used by the Federal Emergency Management Agency (FEMA) for a HEC-2 open channel model used to conduct a flood insurance study (FIS) for the Town of Exeter in 1981 (FEMA, 1981).

The survey yielded two important results:

- A longitudinal profile of the channel invert
- Lateral cross sectional geometry from which volumetric estimates could be obtained

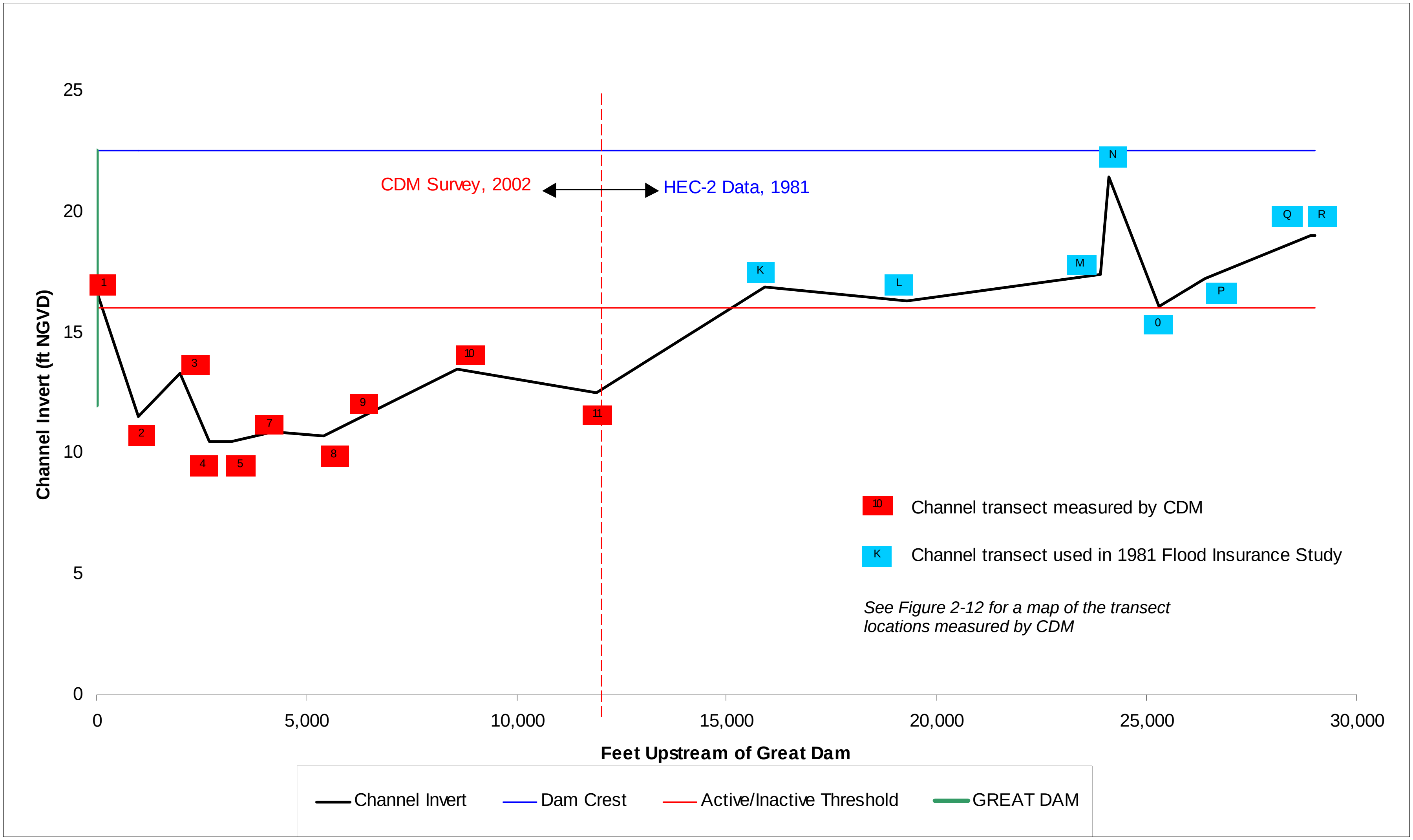
Results of the survey indicated that the impoundment behind Great Dam is a significant component of the overall system storage. The impoundment stretches approximately 6 miles behind the dam, roughly to the intersection of the river with the Boston and Maine Railroad tracks in the southwest corner of the town. It is not until further upstream that the invert of the channel rises above the dam crest.

The intake to the river pump station is a submerged pipe that has an invert elevation of 15 feet NGVD. Water flows by gravity through the pipe into a wet well, from which it is pumped to either the water treatment plant or the Exeter Reservoir. In order to provide at least 4 mgd of flow in the pipe, approximately one foot of head is required above the pipe invert. Hence, for the purposes of this study, the lowest elevation of active storage in the impoundment behind Great Dam is estimated to be 16 feet. This elevation is 6.5 feet below the dam crest, as illustrated in Figure 2-11. The location of channel transects is also illustrated in Figure 2-12.

The transect measurements were used to estimate cross-sectional area at each river station, and from these values, estimates of channel volume and corresponding water surface area were computed for a range of water surface elevations (channel geometry was linearly interpolated between transect stations). Transect graphs are included in Appendix B. The results of the analysis are shown graphically as stage-volume and stage-area curves in Figures 2-13 and 2-14. The volume represents the total volume in the impoundment, and a line is drawn on the figure to segregate active storage from inactive storage.

From these measurements, it is estimated that the Great Dam impoundment has an active storage capacity of approximately 63 million gallons. When the water level is at the dam crest, the estimated surface area of the impounded water is approximately 44 acres.

Figure 2-11: Channel Invert Profile for Great Dam Impoundment



CDM

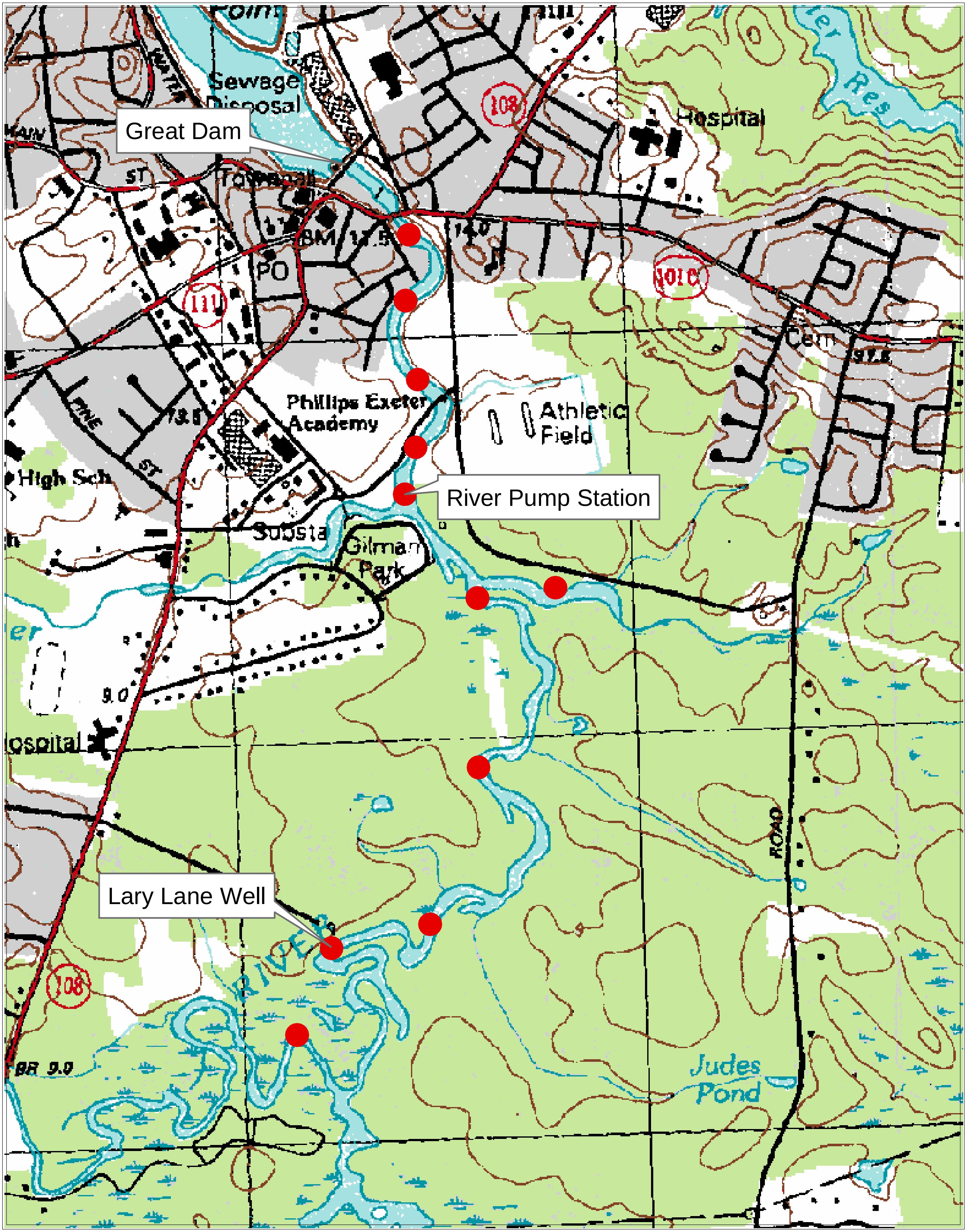

Great Dam
River Pump Station
Lary Lane Well
Sewage Disposal
Hospital
Phillips Exeter Academy
Athletic Field
High Sch
Gilman Park
PO
Cem
Judes Pond
ROAD
108
111
101C

Figure 2-13: Stage-Volume Curve for Great Dam Impoundment

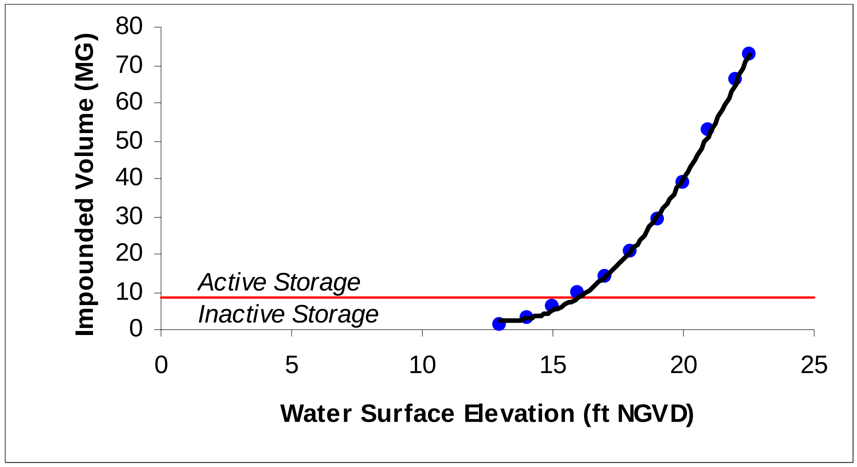
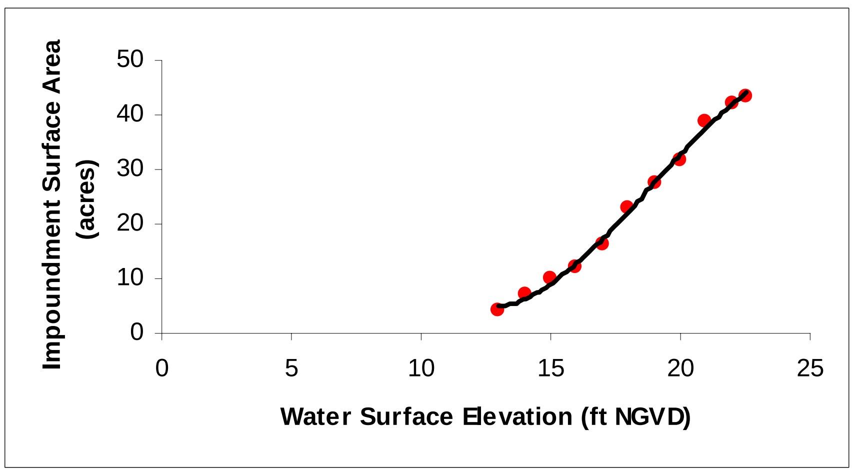


Figure 2-14: Stage-Area Curve for Great Dam Impoundment



2.2.2 Exeter Reservoir Storage

Very little data exist on the bathymetry of the Exeter Reservoir. CDM reports several values of storage and elevation in the 2002 evaluation of the Exeter water system (Camp Dresser & McKee Inc., 2002), obtained primarily from other sources. From these data, stage-volume and stage-elevation curves were estimated, as shown in Figures 2-15 and 2-16.

The estimated spillway capacity of the reservoir when stoplogs are in place is 26 million gallons at a corresponding water surface elevation of 22.95 feet NGVD. The surface area of the reservoir at the spillway level is estimated as 18 acres. Water flows by gravity into the treatment plant and is then pumped through the treatment system. Before reaching the pump, water flows by gravity over a weir at elevation 17.55 feet NGVD. Below this elevation, the storage is considered to be inactive. A capacity of approximately 8 million gallons is classified as inactive storage, which means that only 18 of the 26 million gallons of total capacity is considered to be active storage for the existing water supply system.

The volume of active storage is reduced further depending on the intake flow rate to the treatment plant. Numerous restrictions in the piping system require a significant amount of hydraulic head in the reservoir above the weir elevation of 17.55 feet. For example, for a flow of 2 mgd into the plant, an estimated 1 foot of head in the reservoir (above the weir) would be required, effectively reducing the active storage from 18 MG to 16 MG. Similarly, a flow of 3 mgd into the treatment plant would effectively reduce the active storage to approximately 13 million gallons. The effect of intake flow on the threshold between active and inactive storage in shown in Figure 2-17. Calculation sheets are included in Appendix C.

Figure 2-15: Estimated Stage-Volume Curve for Exeter Reservoir

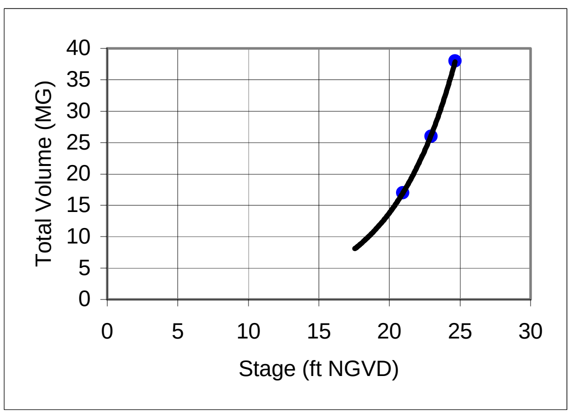


Figure 2-16: Estimated Stage-Area Curve for Exeter Reservoir

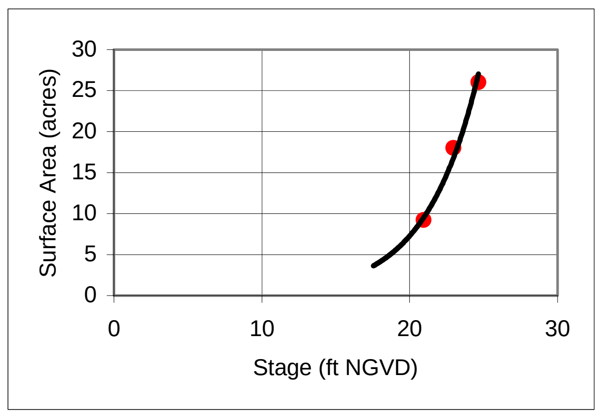
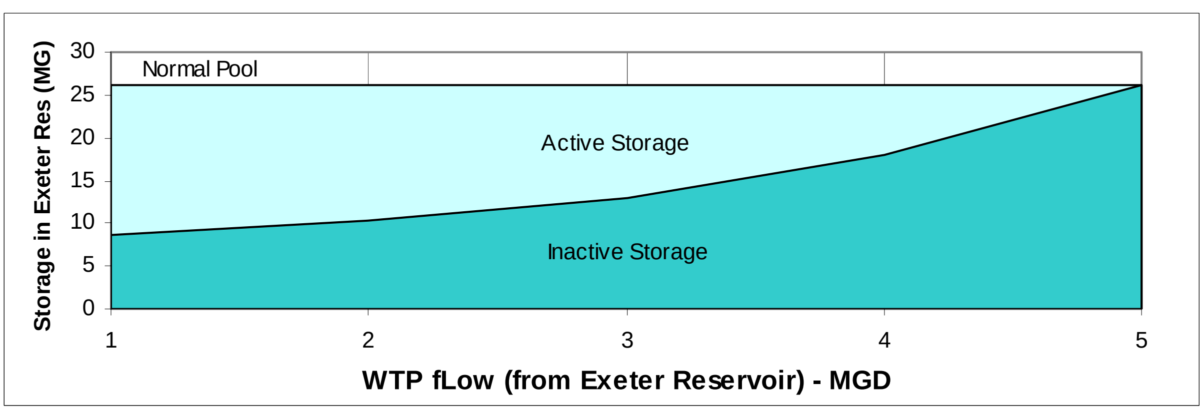


Figure 2-17: Effects of Intake Flow Rate on Active Storage Capacity



2.2.3 Storage Behind Pickpocket Dam

Since the Town of Exeter owns the Pickpocket Dam, operators could open gates at the dam to release stored water downstream toward the Great Dam impoundment. The effectiveness of such operational action is evaluated in Section 6.0.

In order to estimate the storage capacity behind Pickpocket Dam, transect records that were used in a HEC-2 model for a FEMA flood insurance study for the Town of Brentwood were obtained (FEMA). Transect area and surface width were computed for various water surface elevations, and these results were used to estimate channel volume and surface area for each water level. Channel geometry was linearly interpolated between transect stations.

The channel invert is plotted in Figure 2-18, and the stage-volume and stage-area curve for the impoundment are plotted in Figures 2-19 and 2-20, respectively. The Pickpocket Dam impounds an estimated 15 million gallons, 11 million gallons of which are considered active storage. The threshold between active and inactive storage at this dam was determined to be the elevation of the channel invert immediately behind the dam (approximately 54.5 feet NGVD), which is only 2.5 feet below the dam crest of 57 feet. The impoundment extends approximately 2.5 miles upstream of the dam, and when water is at the spillway crest, the estimated impounded surface area is 15 acres.

Figure 2-18: Channel Invert Profile for Pickpocket Dam Impoundment

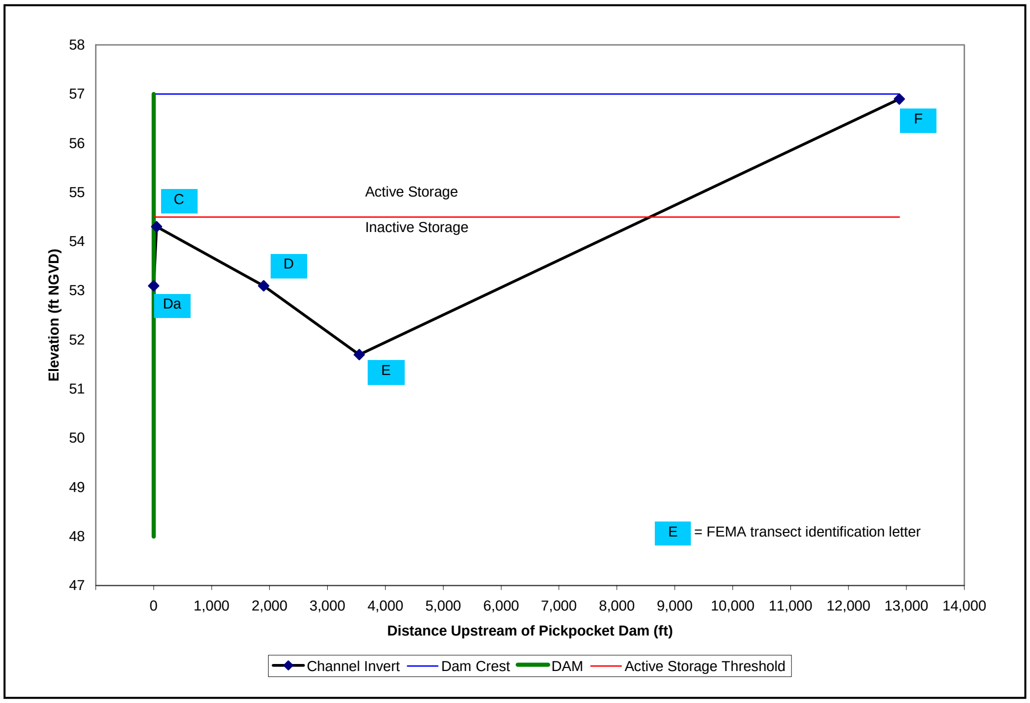


Figure 2-19: Stage Volume Curve for Pickpocket Dam Impoundment

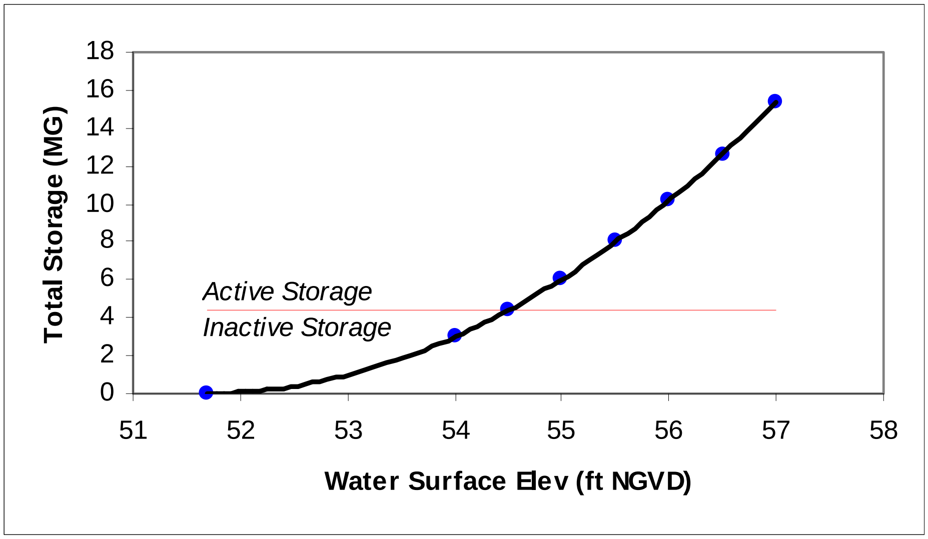
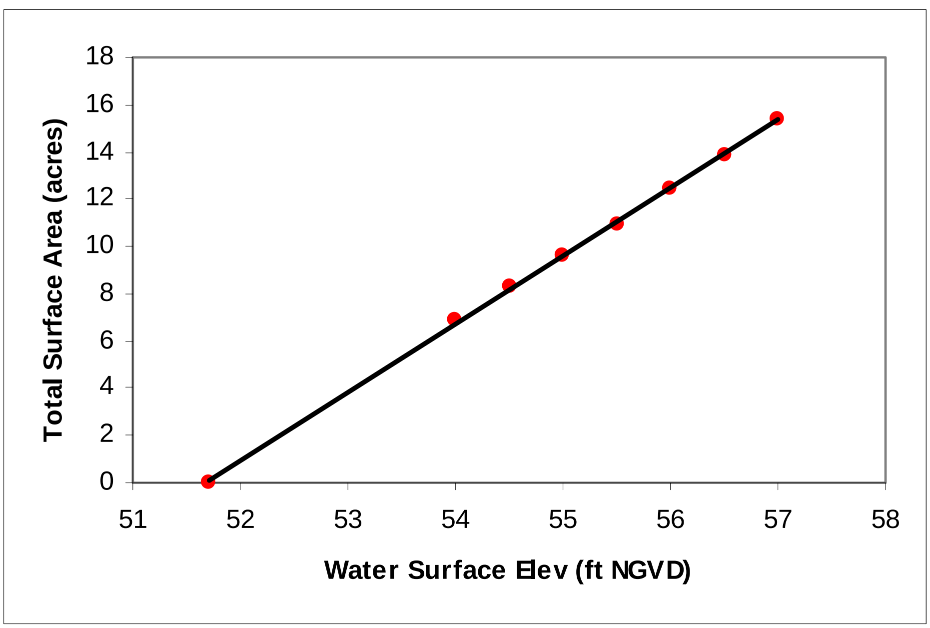


Figure 2-20: Stage-Area Curve for Pickpocket Dam Impoundment



2.3 Interconnections and Operating Protocols

Interconnections within the Exeter water supply system are illustrated in Figure 2-2. Water from the Great Dam Impoundment can be pumped directly to the water treatment plant or into the Exeter Reservoir. Water from the reservoir can only be withdrawn into the treatment plant. Water from the Pickpocket Dam Impoundment can be released downstream to the Great Dam Impoundment, but the Town of Exeter has not historically operated the Pickpocket Dam in this way. Neither the Town of Exeter nor the Town of Brentwood have operational jurisdiction over the Brentwood Hydro Dam, which is privately owned but no longer operated.

Historically, the Town of Exeter has relied solely on the Exeter River as the primary source of supply from April through October, and during these months, water is pumped directly from the river to the treatment plant (overflow volume spills into the Exeter Reservoir). From November through March, the Town typically draws water from the Exeter Reservoir, and water from the river is pumped into the reservoir to augment the supply.

Both the Pickpocket Dam and Great Dam are equipped with fish ladders. When questioned on the regulatory requirements for these fish ladders, the New Hampshire Department of Environmental Services (NHDES) indicated that, on average, approximately 20 cfs flows through the fishways between mid-April and mid-June each year. However, NHDES indicated that under extreme low flow conditions, there are no regulatory requirements to maintain flow in the fish ladders, since fish are not expected to swim upriver during such conditions. Therefore, release requirements through the fish ladders will not affect this safe yield study.

The state of New Hampshire had originally planned to require minimum flow levels in the portion of the Exeter River designated under the Rivers Management and Protection Programs (RMPP), namely the area upstream of the confluence with Great Brook. However, at the time of this writing, NHDES has suspended this effort for the Exeter River, and no information is available on whether or not the river might be subject to instream flow requirements in the future. The timeframe estimated for a decision on this issue is five to ten years in the future. Even if the instream flow rules are invoked in the future, the river pump station is downstream of the area designated in the RMPP. For these reasons, the impacts of any future instream flow rules have not been accounted for in this study.

Section 3
Water Demands in the Exeter River Basin

3.1 Introduction

While Exeter is the only community that relies on the Exeter River as the source for a municipal water supply, Exeter is not the only water user along the river. Several other entities withdraw flow from the river for uses ranging from cooling systems to irrigation. Accordingly, this section summarizes the current water withdrawals from the Exeter River.

3.2 Town of Exeter Water Supply

3.2.1 Average Annual Demands

The average annual demand in Exeter is currently about 1.16 mgd, based on 2001 water production records. As part of Exeter's *Water System Evaluation Study* (CDM, 2002) Exeter's population and corresponding water demands are expected to increase approximately 1.4% per year. Additionally, water demands are expected to increase as the system is extended to serve all areas of the Town. Currently, only about 77% of the Town's population is served by the municipal water system. Table 3-1 summarizes the current and projected average annual water demands.

Table 3-1: Exeter's Current and Projected Water Demands

Year	Average Annual Demand (mgd)
2001	1.16
2010	1.67*
2020	1.92*

**Assumes service to entire town.*

3.2.2 Monthly Demand Variability

When conducting safe yield evaluations, it is important to know not only the average yearly water demand but also how the demand rates are distributed during the year. For many New England communities, the highest monthly demands occur in the summer, during the irrigation season. However, this high water usage period also typically corresponds to the period when river flows are at their lowest. Conversely, in the spring when water demands are relatively low, river flows at typically at their highest. Table 3-2 summarizes Exeter's monthly demand fluctuations based on recent records. The fluctuations assumed throughout this study correspond to the average fluctuations from January 1995 through June 2002. Records from just 2002 are shown for comparison, and generally follow the same pattern as the average values from 1995-2002, although peak summer demand was higher than average in 2002.

Table 3-2: Monthly Demand Variability

Month	% of Average Yearly Demand assumed for all years in this study (based on Jan. 1995 – Jun. 2002)	2002 Records (total demand, million gallons) (for reference)	% of 2002 Average Monthly Demand (for reference)
January	95%	29.3	85%
February	95%	27.4	79%
March	90%	28.5	82%
April	91%	30.9	89%
May	105%	36.7	106%
June	110%	36.1	104%
July	119%	45.1	130%
August	119%	48.2	139%
September	107%	37.2	107%
October	99%	35.5	102%
November	88%	30.9	89%
December	91%	30.0	87%

3.3 Other Water Uses

There are four other entities that withdraw water directly from the Exeter River or indirectly via groundwater wells located within the Exeter River basin. For the purposes of this study, CDM assumed that groundwater withdrawn within the Exeter River basin is a direct withdrawal from the river. Studies have shown that in the short-term (over weeks or months) this is a conservative approach. However, over an extended period (years) this is an accurate representation, as the groundwater that is withdrawn from the basin is not available to recharge the river.

3.3.1 Phillips Exeter Academy

Phillips Exeter Academy (PEA) is a private high school located in Exeter. Water from both the Exeter River and adjacent groundwater wells is used to irrigate the

Academy's fields during the summer. Additionally, PEA withdraws approximately 1.5 mgd from the river for use in its ice rink condenser. The condenser is a flow-through system and all the water that is taken from the Exeter River is returned, via Little River, a tributary of the Exeter River.

3.3.2 Fish Ladders

The New Hampshire Department of Fish and Game operate two fish ladders on the Exeter River, at the Pickpocket Dam and at Great Dam. The fish ladder at the Great Dam is of the greatest importance to this study because the water passing through this ladder is 'lost' for Exeter's water supply purposes. The water passing through the fish ladder at the Pickpocket Dam is still retained within the impoundment behind the Great Dam, thus it is still available for Exeter's water supply.

According to Fish and Game, the fish ladders are operated between April and mid-June at a maximum flow of about 50 cfs (average flow rate of approximately 20 cfs), although the actual flow rate will vary depending on which species of fish is migrating. Migrating fish are attracted upstream by high river flows and, according to Fish and Game, during low flow periods the fish will not migrate up the Exeter River. Therefore, under low flow conditions, Exeter would not be required to reduce their water withdrawals in order to maintain flows in the fish ladder.

3.3.3 Mobile Home Parks

There are two mobile home parks located within Exeter that rely on groundwater wells for water supply purposes. These groundwater wells are located within the Exeter River basin and have an average demand of approximately 0.13 mgd, based on NHDES records.

3.3.4 Exeter Mills Apartments

The Exeter Mills Apartments, luxury apartments in a converted mill building, are located on the bank of the Squamscott River, just downstream of the Great Dam. When the mills were operated for manufacturing, water was supplied from the Exeter River via a penstock leading from the Great Dam. The apartment complex still relies on water from the penstock for irrigation, fire suppression and cooling purposes. In the summer, when water is flowing over Great Dam, approximately 0.025 mgd is used for irrigation. When the Exeter River drops below the crest of Great Dam, the apartments curtail their usage. The fire suppression system is also connected to the penstock and, in the event of a fire, draws flows from here.

The largest usage by the apartments is during the summer for the cooling system, the cooling system is a flow-through system that withdraws flow from the penstock and discharges to the Squamscott River. The usage extends from approximately May until October (the season when air conditioning is necessary) at the rate of about 0.5-1.0 mgd, via a variable speed pump. Since the cooling water is discharged to the Squamscott, the flow is essentially lost to Exeter for water supply purposes. While the apartments have the ability to recycle this flow back into the penstock, the system is not operated in this manner because the existing recycling pipe can only discharge water near the cooling system intake, where it is immediately drawn back into the cooling system before equalizing in temperature with the cooler river water. This "short-circuiting" results in a gradual increase in the water temperature, which makes it ineffectual for cooling purposes. Accordingly, to prevent this from occurring, the water is not recycled.

For the purposes of this report, CDM has assumed that the water currently used by the apartments for cooling will be recycled back to the impoundment at the Great Dam in the future. By extending the current recycle line from the base of the penstock approximately 350 feet to the impoundment, the "short-circuiting" problem could be eliminated. Additionally, the Town of Exeter is investigating the rights of the apartments to take this water.

Section 4
Hydrologic Modeling of Water Supply Sources

4.1 Hydrologic Modeling Objectives

To effectively and defensibly estimate the safe yield of a water supply system, the response of the system to hydrologic and operational patterns must be assessed during periods in which the system is highly stressed. According to Section 1.3, safe yield is defined for this study as the average daily withdrawal from a water supply system that can be sustained through the drought(s) of record without entirely depleting the system storage.

The State of New Hampshire does not have a published guidance document for safe yield analysis. However, the state of Massachusetts has published a guidance document for safe yield analysis (MADEP, 1996). For safe yield studies in the State of Massachusetts, this document mandates that *"…the analysis include streamflow and precipitation data from the 1960s drought-of-record."* While this guidance applies specifically to studies conducted on Massachusetts water supply systems, its prudence is evident in the fact that it supports conservatism by conditioning sustainable yield estimates on the most severe historic conditions. This study is based on this guidance.

The drought that occurred between 1964 and 1967 is widely considered to be the most severe drought of record for the New England region. However, for small water supply systems, such as the Exeter system, it was unclear whether the prolonged gradual reduction in cumulative precipitation that occurred during the mid-1960s would be as severe as a more sudden, but less lengthy, reduction in precipitation. Therefore, in addition to analyzing the drought of the 1960s, it was decided to analyze the system response to other significant droughts as part of this study, specifically the droughts of 1980 and 2002.

The Massachusetts guidance document also recommends that safe yield studies should be conducted using a monthly timestep (as a maximum). However, if system response times (for complete drawdown) are on the same order of magnitude as the timestep, it follows that further resolution is needed to simulate the within-month variability in inputs and outputs. The Exeter system relies on limited storage, which can be depleted within a period of 1-2 months during severe droughts, and hence, a more refined timestep was required for this analysis. A daily timestep was selected since the system response time is much greater than a single day, and since this resolution was compatible with USGS streamflow records.

Unfortunately, streamflow records for the Exeter River date back only to 1996, and no data exist on hydrologic inputs to the Exeter Reservoir. In order to simulate the system response to hydroclimatic conditions during the 1960s and 1980 droughts, synthetic streamflow data were required. Both empirical models and physically-based models were evaluated in order to identify and develop a mathematical tool that would adequately reproduce rainfall-runoff relationships within the system. Primary emphasis was placed on generating reliable estimates of streamflow during the low-flow periods that limit the sustainable yield.

Therefore, the primary hydrologic modeling objectives were:

- Generate a continuous synthetic record of daily streamflow in the Exeter River dating back to 1964.
- Ensure that the model provides reasonably accurate and credible estimates of low flow, both in terms of magnitude and duration
- Keep the model(s) as simple as possible to avoid unnecessary computational complexity and uncertainty

This section of the report explains the methods used to develop and calibrate hydrologic models of the Exeter River watershed and the Exeter Reservoir watershed. The model was used to generate input for the system simulation model discussed in Section 5.0.

4.2 Exeter River Model

4.2.1 USGS Records Summary

The USGS operates a streamflow gage (#01073587) on the Exeter River in the Town of Brentwood, NH (se Section 2.1.1). The drainage area upstream of the gage is listed by the USGS as 63.5 square miles. The gage has been in service since June of 1996, and is located at the site of a natural hydraulic control in the form of a rocky barricade. In a personal communication dated October 18, 2002, the USGS indicated that the accuracy of the gage was rated as "good" for low flow levels (on the order of 1 cfs), with an estimated accuracy of +/- 10%.

Since this streamflow gage was not in service during the 1980 drought nor during the 1960s drought, records from other streamflow gages in the region were compared to the Exeter River records to determine if any similar river in the area, with records dating back to the 1960s, could be used as a good predictor of flow in the Exeter River. Table 4-1 lists the data collected for the comparative study:

Table 4-1: Summary of USGS Streamflow Records Near Exeter

River/Gage Location	USGS Gage ID	Drainage Area (mi^2)	Years of Record
Exeter River near Brentwood NH	01073587	63.5	1996-2002
Lamprey River near Newmarket NH	01073500	183.0	1934-2002
Cocheco River near Rochester NH	01072800	85.7	1995-2002
Oyster River near Durham NH	01073000	12.1	1934-2002
Salmon Falls River at Milton NH	01072100	108.0	1968-2002
Dudley Brook near Exeter NH	01073600	4.97	1962-1985

4.2.2 Regional Correlation Study

Since the record for the gage on the Exeter River only extends back to 1996, synthetic data (based on streamflow records from similar watersheds or simulation models) were required in order to simulate the hydrology of the Exeter River basin through the droughts of the 1960s and 1980. Streamflow records for other regional rivers, as listed in Table 4-1, were compared to the existing data for Exeter (1996 through 2002) to determine if historic flow in the Exeter River could be reliably predicted from other sources. Records were compared at daily time intervals.

Only the flow in the Lamprey River appeared to be well correlated to the flow in the Exeter River – all other rivers exhibited very poor correlation with flows in the Exeter River. High flows in the Lamprey River were very well correlated to high flows in the Exeter River, but low flows (less than 20 cfs) were not as well correlated. Figure 4-1 illustrates the predictive strength of data from the Lamprey River in the form of a linear regression model that was fit to the Exeter River data. A split regression was applied to try to identify a relationship that applied specifically to low flows, but the rivers are clearly not well correlated in this regime. In fact, if a linear relationship is assumed, the low-flow data from the Lamprey River clearly overestimate the extreme low flow levels observed in the Exeter River. Figures 4-2 and 4-3 confirm that the high flows are well correlated, but that the low flows are not.

Figure 4-1: Regression Model for Exeter River Using Lamprey River As Predictor

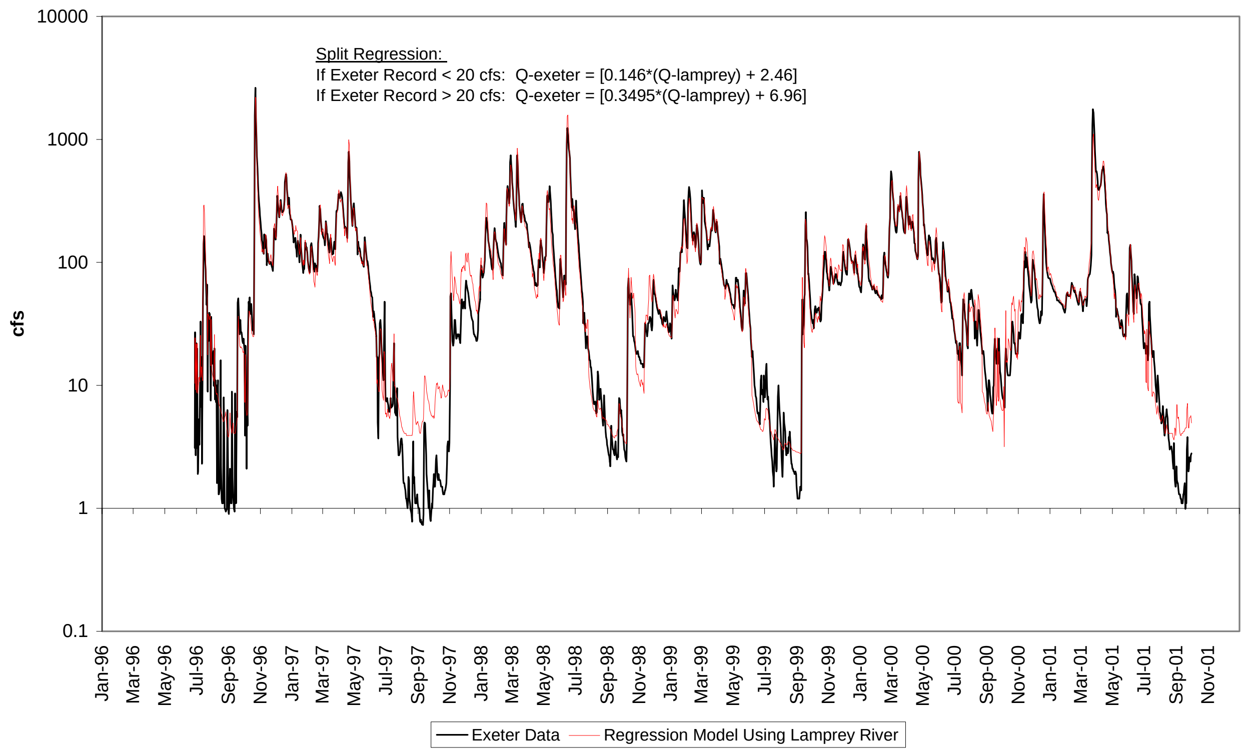


Figure 4-2: Correlation between Lamprey and Exeter Rivers for daily flows <u>above 20 cfs</u>

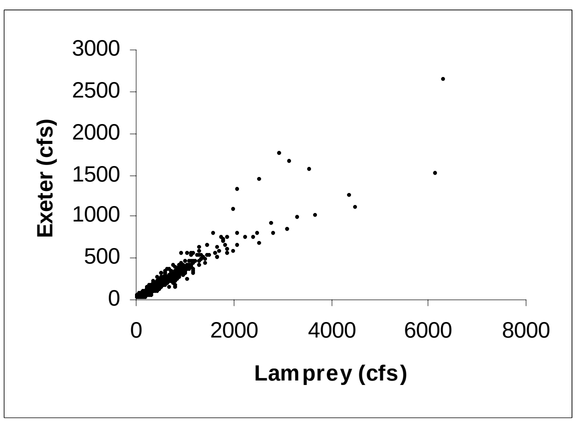
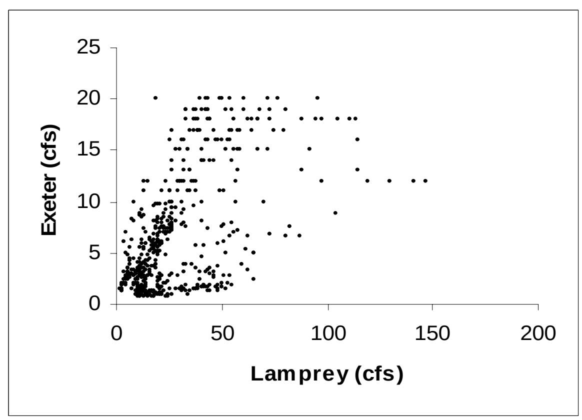


Figure 4-3 Correlation between Lamprey and Exeter Rivers for daily flows <u>below 20 cfs</u>



Because this study depends on accurately simulating low flows in the Exeter River, the Lamprey River data were not considered as a viable predictive tool. Using the Lamprey River to estimate flow in the Exeter River results in overestimating the low flow, and this would lead to overestimating the safe yield from the system.

For continuous simulation, however, it is useful to include a continuous streamflow record that includes both high flows and low flows. Therefore, for flows above 20 cfs (for which the Lamprey River can be used to linearly predict flow in the Exeter River with high accuracy), the regression model illustrated in Figure 4-1 was used (this is discussed again in Section 4.2.5 with respect to the complete synthesized timeseries of flow in the Exeter River). For flows below 20 cfs, another method of estimating flow in the Exeter River was required (see Section 4.2.3).

4.2.3 A Hydrologic Model for Low-Flow Simulation

Because regional transposition methods were inadequate for predicting the low flows in the Exeter River (needed for extending the daily record through the 1960s and 1980 droughts), a physically-based precipitation-runoff model was developed. The model structure and equations are described in detail in **Appendix A**. This section discusses some of the generalities of the model. The following sections (4.2.4 and 4.2.5) present the results of model calibration and verification and also explain how the model was used to generate a synthetic time series of flow for the Exeter River.

Three hydrologic models were investigated for use in this study:

- EPA StormWater Management Model (SWMM) – Runoff Block. Number of hydrologic parameters: >10

- IHACRES Model – *Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (*Beven, 2001; Jakeman *et al.*, 1990). Number of hydrologic parameters: 3

- *abcd* Model (Thomas, 1981) – named for its four parameters ("a, b, c & d"). Number of hydrologic parameters: 4.

Only the *abcd* model was capable of reproducing observed flows in the Exeter River under low flow conditions. The other two models did not faithfully represent the magnitude and duration of low flows during the late summer. Hence, the abcd model was identified as the most appropriate tool for this study. A more complete list of the model attributes and selection criteria is included in **Appendix A.**

The *abcd* model predicts daily flow from climatic inputs of daily precipitation, daily minimum temperature, and daily maximum temperature. In terms of basic fluid mechanics, the model establishes the entire basin as a control volume, and by the principle of continuity (conservation of mass), balances the water coming into and moving out of the basin.

The model computes the values of two storage variables for each time step; soil moisture and groundwater storage. Precipitation is directed into the soil, and soil infiltration is divided between evapotranspiration, runoff , groundwater recharge, and remaining soil moisture. Groundwater is then depleted by discharging to the river at rates proportional to aquifer storage. The flows are computed at a daily level using calibrated parameters and climate input. Total flow into the river is the sum of runoff and groundwater flow (baseflow).

The model was modified to simulate the effects of the hydropower dam in Brentwood. The dam is no longer operated and for high flows, the model assumes that the dam has no impact on streamflow (all flow is passed through the dam). During low flow periods, however, the dam may impound some flow and prevent immediate passage downstream, despite high observed leakage rates. To simulate the reduction of flow in the river caused by the Brentwood Dam during low flow periods, a calibrated parameter was added to the model that effectively reduces the contributing drainage area upstream of the USGS gage by 38% (or approximately 20% of the overall basin area) when simulated flow in the previous timestep drops below 6 cfs. Note that this does not represent a true ratio of drainage areas. The area upstream of the dam is approximately 59.1 square miles, while the area upstream of the gaging station is 63.5 square miles. However, because of the high rates of observed leakage through the dam, the complete removal of the hydrologic contribution from upstream of the dam would have been unrealistic.

The model was also modified to account for losses due to surface evaporation from the impoundment upstream of the Brentwood Dam. The surface area of the impoundment was estimated to be approximately 19 acres.

The losses at the Brentwood Hydro Dam due to evaporation, and more importantly, the apparent impoundment of water during periods of low flow, suggest that the removal of this dam may increase the system yield by providing additional water during the critical low flow periods.

4.2.4 Model Calibration and Verification

The model was calibrated specifically to reproduce flows below 20 cfs (above this level, the regression model discussed in Section 4.2.2 can adequately predict river flow). However, while the focus was on low flow simulation, the model was checked to ensure that high flows were also simulated with reasonable accuracy, so that the overall water balance would be credible.

The model was calibrated by tuning the four physically-based parameters (described in **Appendix A**). This process was accomplished using nonlinear optimization techniques that identified appropriate groupings of parameter values and by manually fine-tuning the results of the optimization program. The objectives of the calibration were to:

- minimize the sum of errors for flows below 20 cfs

- reproduce the duration of low flows with reasonable accuracy

The USGS data from 1996 through 1999 were used for calibration of the model. Data from 2000-2002 were used for model verification (the parameters calibrated to the data from 1996 through 1999 were not adjusted, and were tested to evaluate the true predictive strength of the model over a period that was independent of the calibration period). Figures 4-4 and 4-5 illustrate the model performance over both the calibration and verification periods. Figure 4-4 presents the model performance over the complete flow range on a logarithmic scale (although it was calibrated specifically to flow levels below 20 cfs), and Figure 4-5 presents the model performance in greater detail (normal scale) for flows below 20 cfs only.

As evidenced by Figures 4-4 and 4-5, the model appears to reproduce low flow levels in the Exeter River with reasonable accuracy in terms of overall timing and magnitude. However, a more complete evaluation of the performance must account for the duration of low flows, since the duration of low-flow periods is a primary consideration in evaluating the reliability of a water storage system. Figures 4-6 through 4-9 illustrate the ability of the model to reproduce the cumulative effect of continuous low flows (in addition to predicting the actual magnitude of the low flow levels). In general, the model does not appear to be biased upward or downward, and on average, can be considered a reliable predictor of low flow magnitude and duration for this study. The large apparent discrepancy in minimum 30-day flow in 2002 (Figure 4-9) is attributed to the fact that records were only available through mid-summer of that year at the time the model was calibrated, and the annual recession in streamflow was just beginning to occur (as shown in Figures 4-4 and 4-5).

Figure 4-4: Hydrologic Model Calibration and Verification

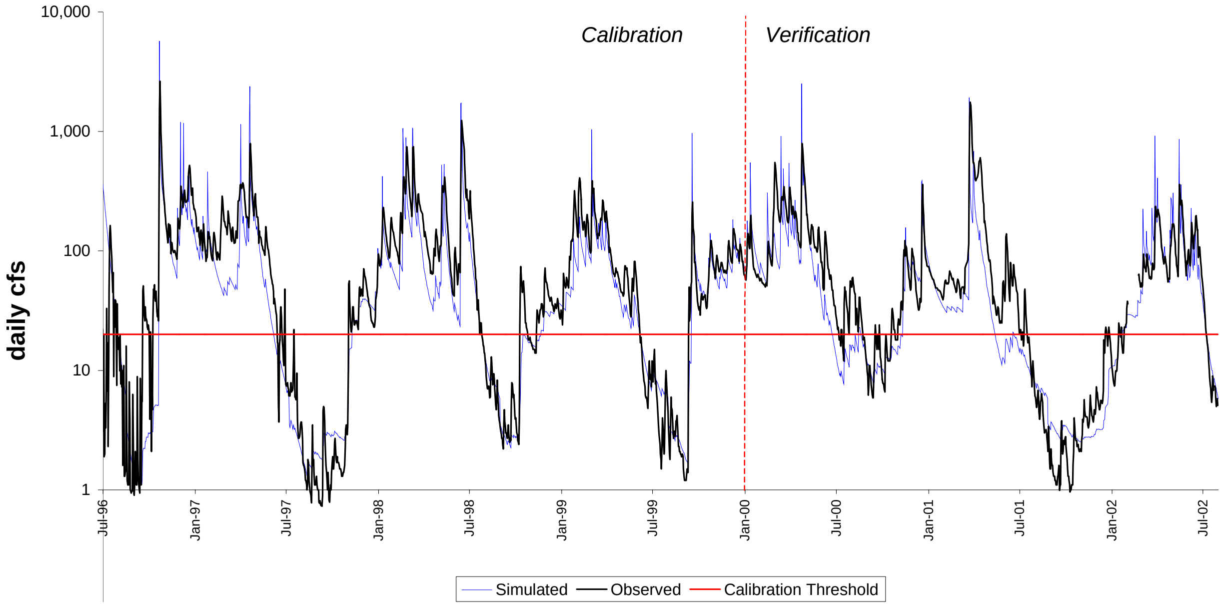


Figure 4-5: Hydrologic Model Performance for Low Flow Periods

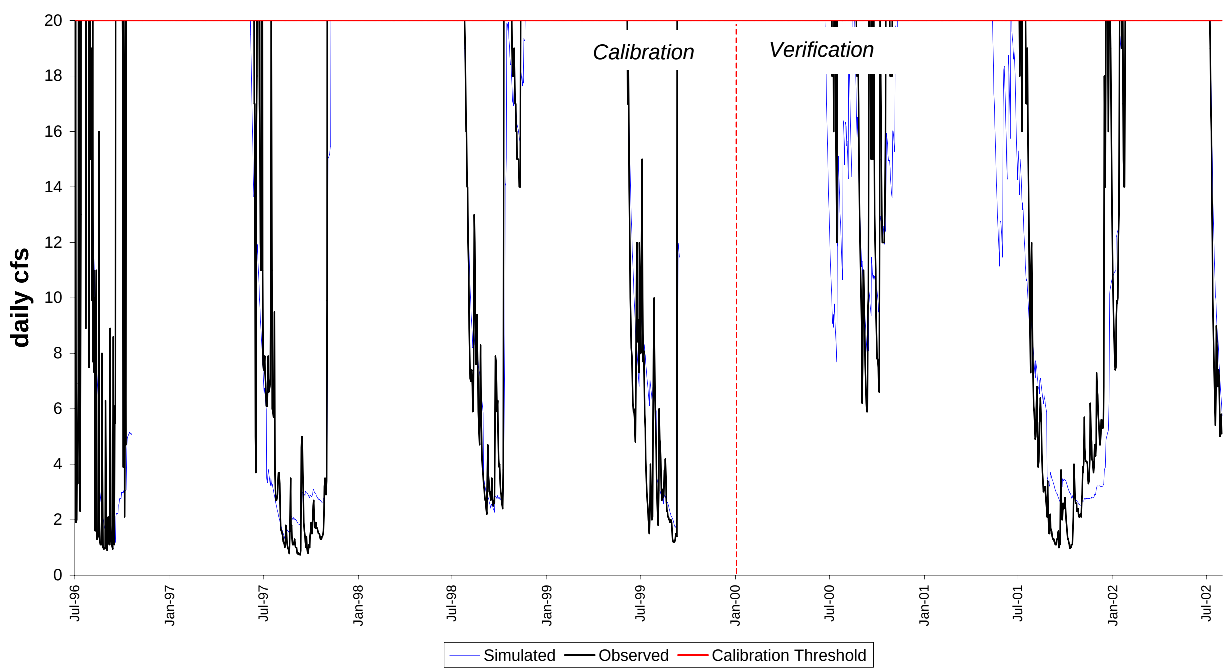


Figure 4-6: Lowest Daily Flow During Each Year of Record

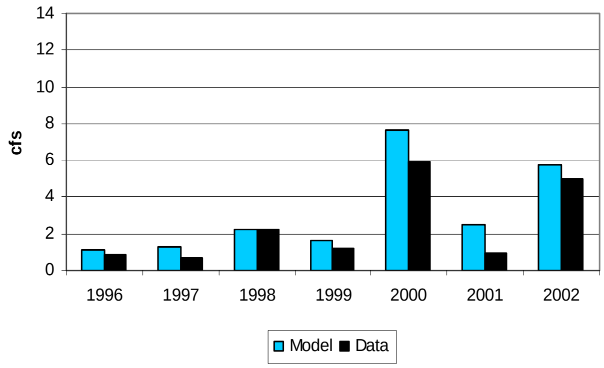


Figure 4-7: Average Daily Flow when Less than 20 cfs

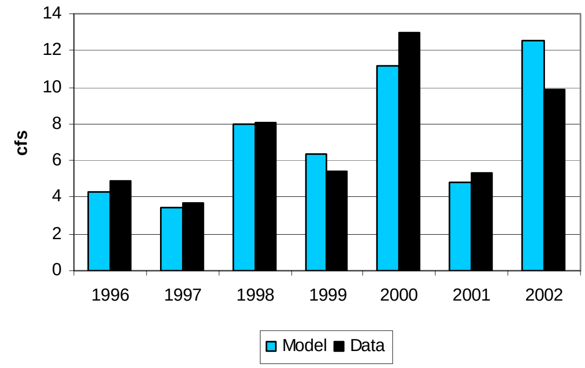


Figure 4-8: Minimum 7-day Average Flow

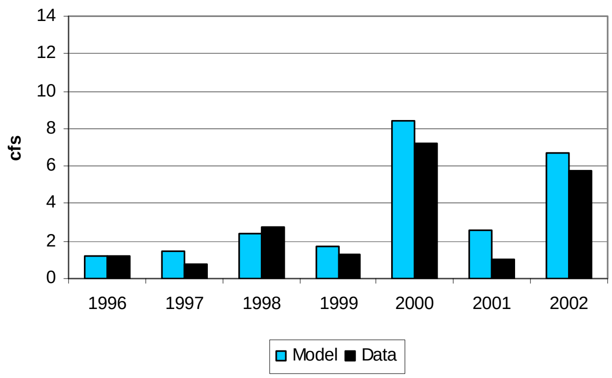
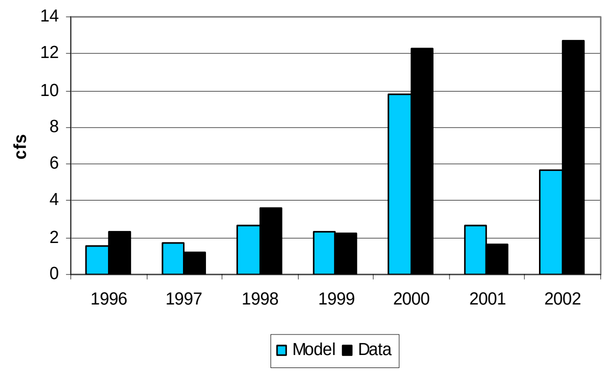


Figure 4-9: Minimum 30-day Average Flow

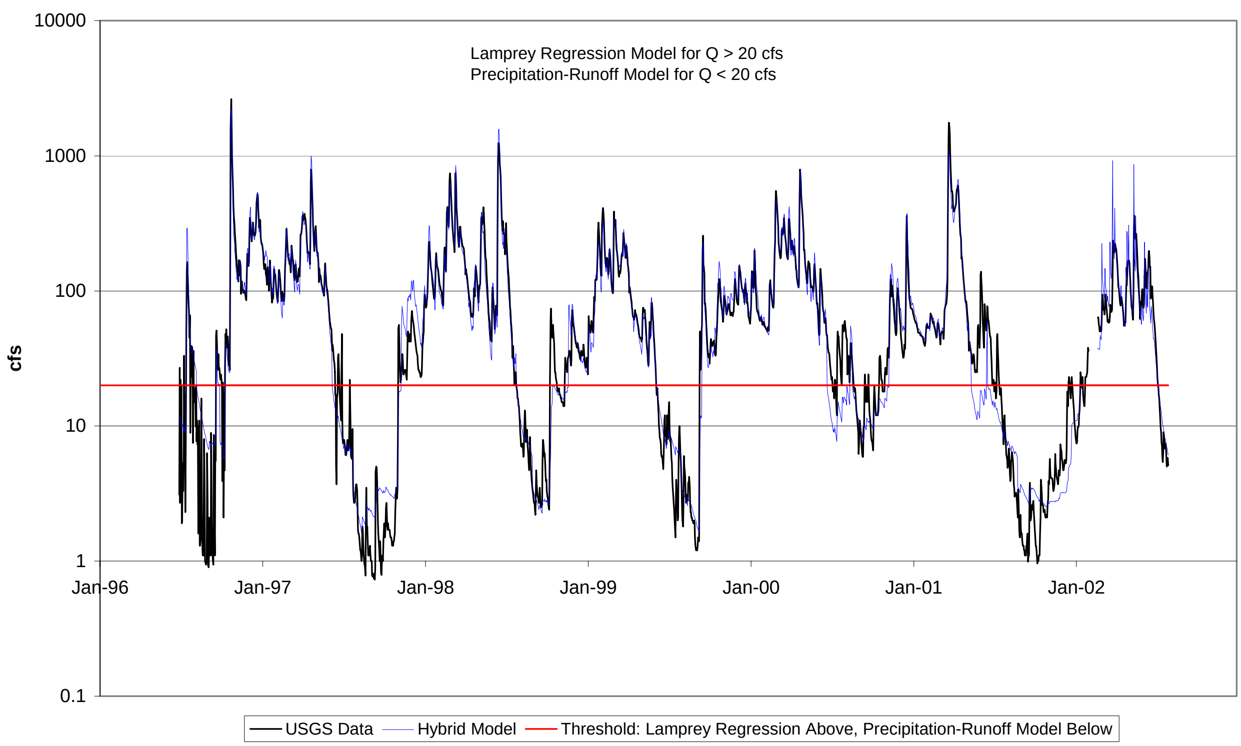


4.2.5 Synthesis of Extended Streamflow Timeseries for the Exeter River

To ensure that the safe yield estimated in this study is a reliable value that can be sustained through the severe droughts of record, the modeling tools discussed above were used to generate a synthetic series of flow in the Exeter River from 1964 through 1996. The objective was to generate a continuous series of daily flow so that the droughts of record, as well as any other years of interest, could be analyzed with respect to various withdrawal patterns.

A hybrid approach was used, since different sources were determined to be more reliable for different flow regimes. Flows above 20 cfs were simulated using the regression relationship developed using data from the Lamprey River (see Section 4.2.2). Flows below 20 cfs were simulated using values estimated by the calibrated precipitation-runoff model described in Sections 4.2.3, 4.2.4, and Appendix A. The hybrid model is compared to USGS gage data in Figure 4-10.

Figure 4-10: Hybrid Model Compared to USGS Gage Data



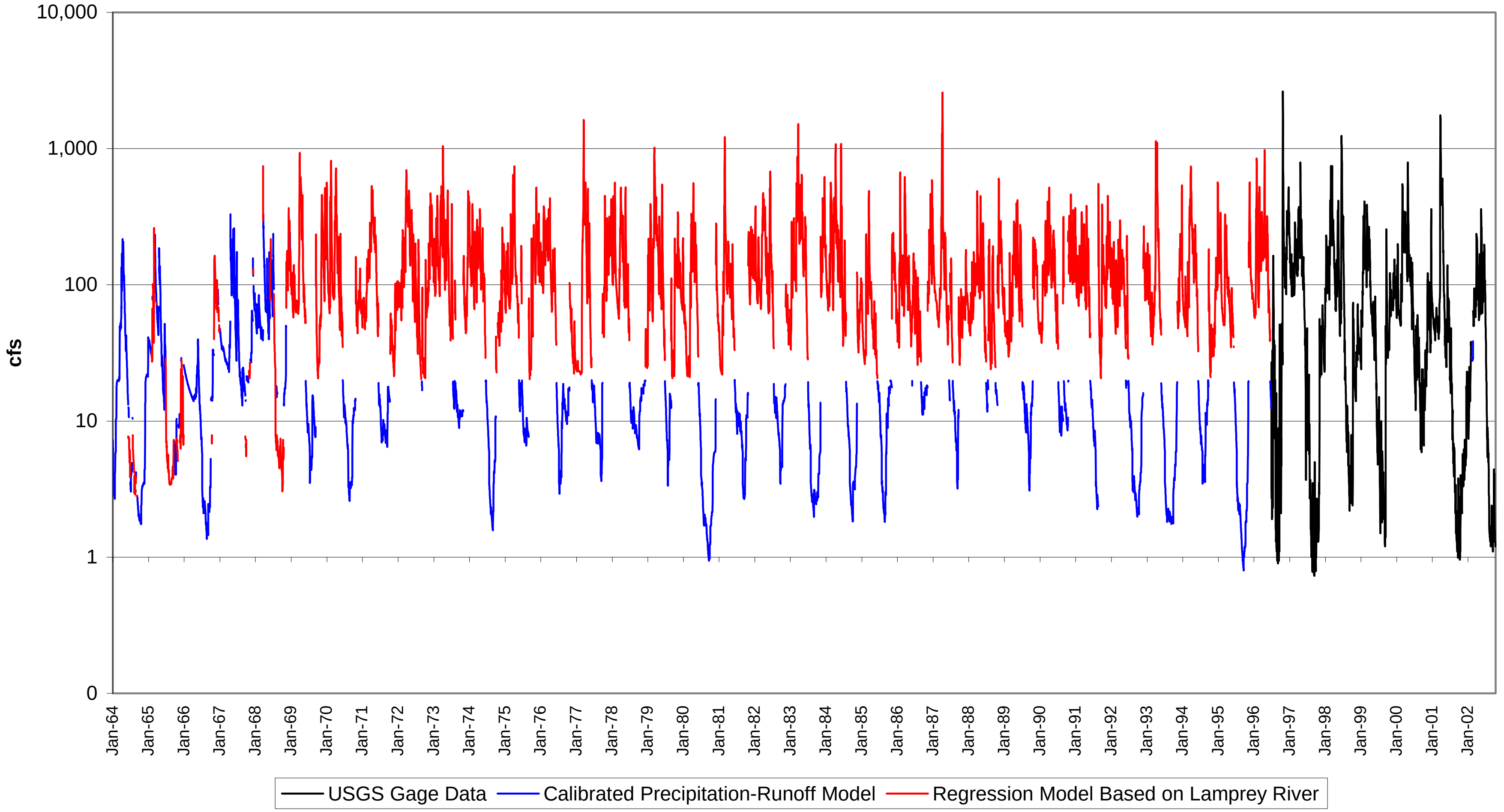
**Estimates for 1996 may differ from calibration results due to assumptions of initial conditions and model stabilization period.*

The only exception to the association of one method with each flow regime was that during the drought of the 1960s, each daily flow value was generated by applying the lower of the two estimates (regression model or precipitation-runoff model). This was done to ensure the most conservative estimate possible for this extended period of drought, since the regression model actually predicted lower values than the precipitation-runoff model on certain days. During all other low-flow periods, the precipitation-runoff model predicted lower flow levels than the regression model, and hence it is the more conservative estimator during low flow periods (and more accurate, based on the figures presented in this section). After June of 1996, actual data from the USGS record was available to complete the timeseries through 2002.

The final synthetic timeseries of flow in the Exeter River (at the USGS gage station) is presented in Figure 4-11. The various sources of the flow estimates are distinguished by different colors.

Of note in Figure 4-11 is the fact that flows during the 1990s appear to reach lower levels than flow during the 1960s, which is normally considered the drought of record for New England. The low flow levels during the 1990s are more comparable to the low flow level of 1980. These results are consistent with known hydrologic records. The drought of the 1960s was characterized by prolonged periods of gradual reduction in cumulative precipitation rates followed by gradual recovery, but not by sudden or dramatic climatic changes. Conversely, the drought of 1980 represented a very sudden and severe reduction in precipitation, with an equally fast recovery, a similar pattern to those observed several times through the 1990s. The impact of the 1960s drought is apparent in the estimated reduction in net annual flow, and not necessarily in extremely low minimum flow levels, and hence, it is reasonable that the model predicts higher minimum flows during the 1960s than it does for the 1980 drought, and also higher minimum flows than were observed several times throughout the 1990s. This pattern is verified by the observed flow records for the Lamprey River.

Figure 4-11: Synthetic Timeseries of Flow in Exeter River at USGS Gage Station



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4.3 Exeter Reservoir Model

As mentioned previously, there are no data available for inflows to the Exeter Reservoir, nor are there extended operational records of reservoir elevation to which a hydrologic model could be calibrated. Hence, another synthetic record was required.

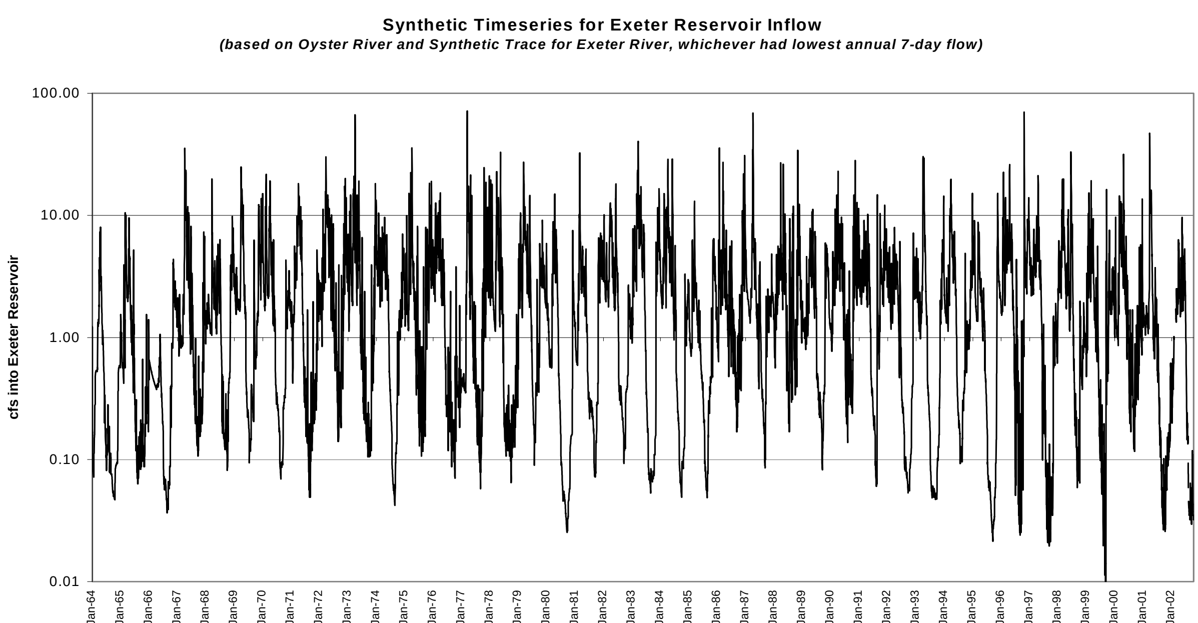
Since the Exeter Reservoir contributes very little to the overall system yield (drainage area of 1.7 square miles compared to 106 square miles for the Exeter River), a conservative approach was applied so that the analysis does not unreasonably overestimate the safe yield.

Two approaches were considered for simulating the flow into the Exeter Reservoir:

- Transpose the synthetic record of the Exeter River flow (see Section 4.2.5) by multiplying each daily value by the ratio of drainage areas
- Transpose the USGS record for the Oyster River near Durham, NH (USGS gage number 01073000) by drainage area ratio

The Oyster River was identified as a candidate for transposition because of its geographic proximity and because it drains an area of only 12.1 square miles, which more closely approximates the drainage area of the Exeter Reservoir than does the Exeter River. However, to ensure a conservative estimate, a timeseries for each year was generated using the transposed data (either from the Exeter River or the Oyster River) with the lower minimum 7-day average flow. The timeseries is shown in Figure 4-12.

Figure 4-12: Synthetic Record of Exeter Reservoir Inflow



Section 5
Development of a System Model for Operational Simulation

5.1 System Model Configuration

A simulation model of the water supply system was developed in order to evaluate the effects of storage, operations, and hydrologic inflow on the system yield. The model uses flows from the hydrologic timeseries described in Section 4 as input, and routes flow through the system hydrologically. Mass balance computations are performed at each storage reservoir (except the Brentwood Hydro impoundment), and the calculations include withdrawals, leakage, surface precipitation, surface evaporation, etc.

Operating rules are programmed into the model to replicate actual operating procedures and decision processes used by Exeter and other water users. For example, the model simulates Exeter's use of the river during the summer and the reservoir during the winter. Additionally, withdrawals by irrigation users are simulated only during the summer. The operating logic for the model is described in detail in Section 5.2.1.

The model was programmed to perform mass balance computations using a daily time step. This time interval was selected for two reasons:

- A daily timestep for the system model is compatible with the daily timestep of the hydrologic models described in Section 4, and which are used to provide input to the system model

- The active storage in the system can be drawn down within a period of 1-3 months, and a monthly timestep would not provide the necessary resolution for an effective study of the Exeter system.

The model was programmed on a spreadsheet using Microsoft Excel. A schematic representation of the flows and storage reservoirs is shown in Figure 5-1. The flows can be categorized as either natural or operational, and each is described in Table 5-1.

For simplicity and conservatism, all demand is assumed to be satisfied by water from the treatment plant (drawn from the Exeter River or the Exeter Reservoir). Neither the Lary Lane well nor Skinner Springs is simulated. It is assumed that water that might be consumed by Lary Lane well remains in the river, (since the well is in the Exeter River Basin), so this assumption has no impact on the estimate of system yield. Skinner Springs is outside the Exeter River Basin, but the contribution from these wells to overall supply is very small, and this assumption will have a negligible impact on the study.

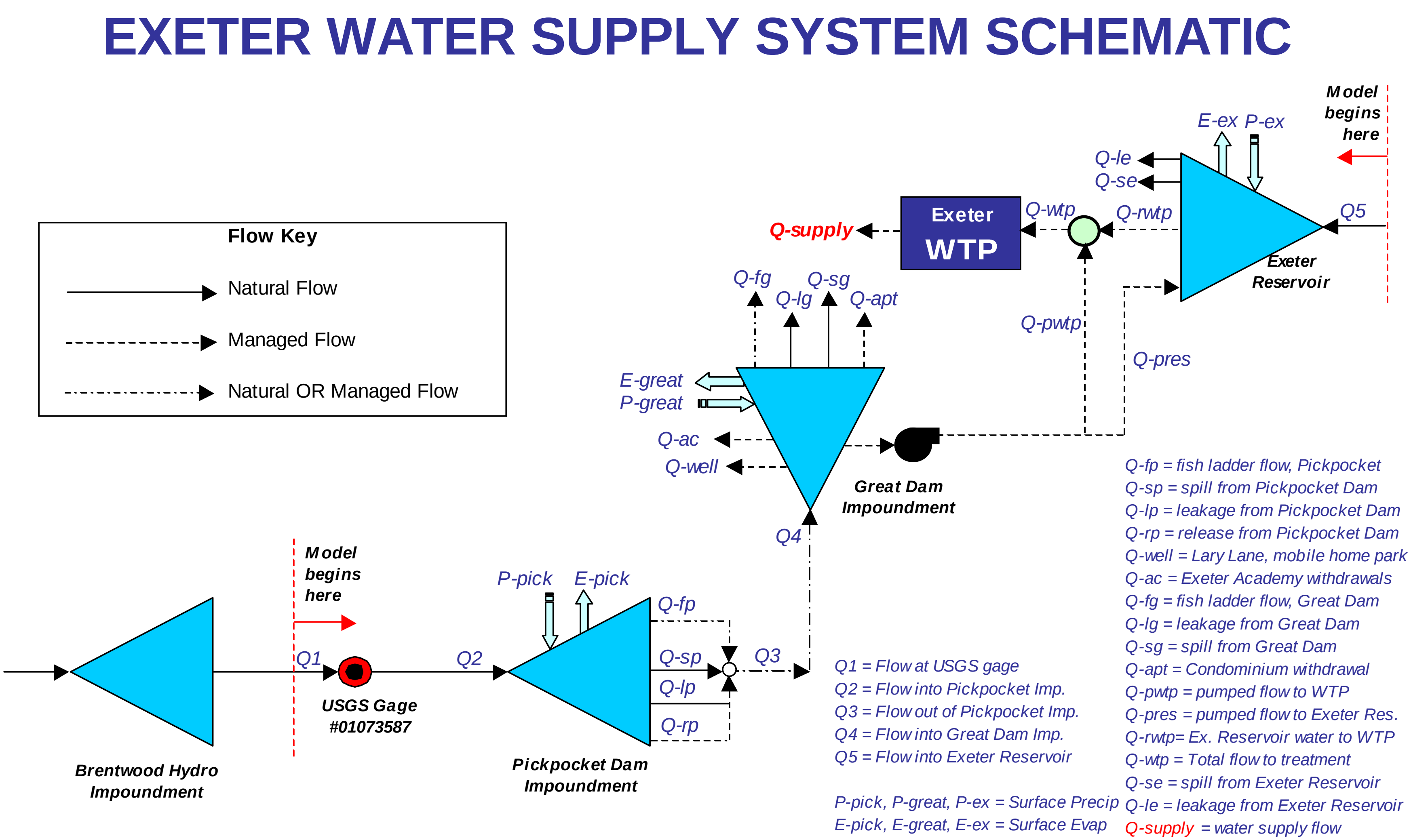
Table 5-1: Flows Simulated in System Model

Flow ID*	Description	Flow Type**	Notes (See also Section 5.2: *Simulated Operating Logic)*
Q1	Streamflow at USGS gage	Natural	Per hydrologic model described in Section 4
Q2	Streamflow into Pickpocket Imp.	Natural	Scaled from Q1 by drainage area ratio
Q3	Streamflow past Pickpocket Dam	Natural/OP	a) Sum of flows past dam, or b) net inflow (see 5.2)
Q4	Streamflow into Great Dam Imp.	Natural/OP	Q3 + [Q1 scaled to drainage area between Q3 and Q4]
Q5	Streamflow into Exeter Res.	Natural	Per hydrologic model described in Section 4
P_x	Direct precip. on reservoir surface	Natural	Function of reservoir area
E_x	Surface evap. from reservoirs	Natural	Function of reservoir area
Q_{fp}	Fish ladder flow at Pickpocket	Natural/OP	Minimum of [20 cfs from 4/15 – 6/15] or [net inflow]
Q_{sp}	Spill at Pickpocket Dam	Natural	Net inflow in excess of storage capacity is spilled d/s
Q_{lp}	Leakage at Pickpocket Dam	Natural	Est. at 0.055 mgd based on leaks measured elsewhere
Q_{rp}	Release from Pickpocket Dam	OP	See Section 5.2: *Simulated Operating Logic*
Q_{well}	Well withdrawals from basin	OP	Includes Lary Lane (if desired) and mobile home park
Q_{ac}	Withdrawal by Phillips Exeter Ac.	OP	Varies seasonally from 0.004 mgd to 0.088 mgd
Q_{fg}	Fish ladder flow at Great Dam	OP	Minimum of [20 cfs from 4/15 – 6/15] or [net inflow]
Q_{lg}	Leakage at Great Dam	Natural	Measured at 0.044 mgd, but can be "turned off".
Q_{sg}	Spill at Great Dam	Natural	Net inflow in excess of storage capacity is spilled
Q_{apt}	Withdrawal by Exeter Mills Apts.	OP	Up to 1.03 mgd, but 1 mgd can be recycled
Q_{pwtp}	Flow from Pump station to WTP	OP	See Section 5.2: *Simulated Operating Logic*
Q_{pres}	Flow from Pump station to Res.	OP	See Section 5.2: *Simulated Operating Logic*
Q_{rwtp}	Flow from Exeter Res. to WTP	OP	See Section 5.2: *Simulated Operating Logic*
Q_{wtp}	Total flow into WTP	OP	See Section 5.2: *Simulated Operating Logic*
Q_{se}	Spill at Exeter Reservoir	Natural	Net inflow in excess of storage capacity is spilled
Q_{le}	Leakage at Exeter Res. Spillway	Natural	Meas. at 0.066 mgd with stoplogs (0.007 when below)
Q_{supply}	Available flow for water supply	OP	Equal to Q_{wtp}

**See Figure 5-1*

** Natural flows are flows that occur without human intervention. "OP" flows refer to operational flows that require human intervention.

Figure 5-1: System Model Schematic



CDM

5.2 Simulated Operating Logic

5.2.1 Simulated Logic for Operational Flows

To evaluate the yield of the system using continuous simulation, it is important to simulate not only the hydrology and storage characteristics of the system, but also the decision logic that governs when water is transferred from one source to another, and how much is transferred. Applying the decision logic in the model facilitates the evaluation of yield under current operating rules, and the evaluation of the sensitivity of the yield to the rules.

Operating rules for the Exeter water supply system were identified with the assistance of personnel from the Exeter Water Treatment Plant and other water users. The rules were translated into the system simulation model for all of the operational flows as listed below. Each description includes a general description of the primary logic followed by a detailed description of logic for all contingencies, if necessary. The detailed descriptions are shown in italics:

Q_{pwtp} Flow from the river pump station directly to the treatment plant: The Exeter River is the primary source of supply from April through October. If water is available for withdrawal in the river, demand will be satisfied solely from the river.

Detailed Logic: If the date is between April and October, Q_{pwtp} is the lesser of the demand (target yield multiplied by monthly demand factor) or the remaining active storage behind Great Dam. The river is also used to augment supply from the Exeter Reservoir if the Reservoir fails to provide enough water during the months that it is the primary source (November through March). If the date is between November and March, Q_{pwtp} is equal to the deficit between demand and the water pumped from the reservoir to the WTP, if such a deficit exists. The program allows users to change the months that distinguish between primary supply sources.

Q_{pres} Flow from the river pump station into the Exeter Reservoir: No water is pumped from the river to the reservoir between April and October. From November through March, water is pumped from the river to the reservoir in order to keep the reservoir full.

Detailed Logic: Between April and October (inclusive – the period during which the river is the primary source of supply and its water is pumped directly to the treatment plant), no water is pumped into the Reservoir. From November through March, water is pumped into the reservoir to keep it full, and Q_{pres} is the lesser of the active storage deficit (below capacity) at the reservoir or the available active storage in the river that can be transferred.

Q_{rwtp} Flow from the Exeter Reservoir into the Treatment Plant: From November through March, the reservoir is the primary source of supply. During other months, the reservoir is only used to augment supply if the storage in the river is depleted.

Detailed Logic: If the river pump station is pumping directly to the treatment plant (from April through October, when Qpwtp > 0), then Q_{rwtp} *is 0 unless the storage in the river is too low to satisfy demand, in which case the deficit is pumped in from the reservoir (*Q_{rwtp}*) as the lesser of the full deficit or the remaining active storage in the reservoir. From November through March, the reservoir is the primary source of supply and* Q_{rwtp} *is the lesser of the daily demand (target yield multiplied by monthly demand factor) or the remaining active storage in the reservoir.*

Q_{wtp} Total flow into the Treatment Plant: Q_{wtp} is the sum of flows for any given day into the treatment plant (Q_{pwtp} + Q_{rwtp}). During normal conditions, simulated flow comes to the treatment plant each day either from the river or the reservoir, but not both. Only when a secondary source is used to augment a failing primary source would both sources be drawn from on the same day in the simulation.

Q_{fp}, Q_{fg} Fish Ladder Flows: According to the New Hampshire Department of Environmental Services, flows in the fish ladders are not strictly regulated. Average flows at both dams are estimated by NHDES at 20 cfs from mid-April through mid-June. However, during low flow periods, no flow is required to pass through the fish ladders. At Pickpocket Dam, fish ladder flow is simulated as the lesser of 20 cfs (13 mgd) or the net daily inflow for each day between April 15 and June 15. The same logic prevails at Great Dam, except that if the water surface elevation drops more than 2 feet below the dam crest, flow into the fish ladder is considered to be hydraulically infeasible, and no flow is simulated.

Q_{well} Well Withdrawals: Water withdrawn from wells located within the Exeter River watershed are is assumed to directly (linearly) reduce flow in the river, since the ground water is no longer available to recharge the river. Although well withdrawals would normally cause a delayed response in instream flow, all daily well withdrawals are simulated as linear withdrawals from the surface storage behind Great Dam. An average daily withdrawal from the Lary Lane well (estimated from recent records at 0.11 mgd) can be extracted, and 0.13 mgd is extracted to simulate the groundwater withdrawals from the nearby mobile home park. This approach is conservative, in that the groundwater withdrawals are not likely to cause immediate reduction of flow or storage in the river/reservoir system, but the simulation model accounts for the water reduction immediately. In order to report system yield as a single value (instead of a surface yield and a groundwater yield), withdrawals from the Lary Lane Well were not included in the simulation analysis, and all system withdrawals were simply modeled as linear extractions from the surface reservoir through the treatment plant.

Q_{ac} Water withdrawn by Phillips Exeter Academy: The academy withdraws 1.5 mgd from the Exeter River but returns all of this water to the Little River (tributary to the Exeter River near the Great Dam Impoundment). The academy also withdraws and consumes approximately 0.084 mgd during the summer for irrigation (simulated as May 15 - Sept 15), both from the river and from wells, but the simulation model aggregates this into a single linear withdrawal from the surface water. The academy also withdraws approximately 0.004 mgd from the river year-round for boiler make-up water.

Q_{apt} Water withdrawn by Exeter Mills Apartment Complex: Water is withdrawn from the Great Dam Impoundment for cooling from May - October at approximately 1 mgd, although this flow can be throttled down to 0.5 mgd with a variable speed pump. Water may either be returned to the storage impoundment or discharged downstream into the Squamscott River, where it is lost from the system. The model can simulate either condition. Additional water is withdrawn from the impoundment for irrigation from May through October at approximately 0.025 mgd, but this usage is eliminated if water is not flowing over Great Dam.

Q_{rp} Release of water from the Pickpocket Impoundment: The Town of Exeter does not normally operate the release gates at Pickpocket Dam, but the model includes the option of releasing water to augment storage behind Great Dam. This only occurs if the dam is "activated" prior to simulation, and only when the Great Dam impoundment is nearly empty.

Detailed Logic: If user input specifies that the Pickpocket Impoundment is a viable source of emergency water (see Q3 below), then if active storage is depleted at Great Dam (drawdown to less than 3 MG), water is released from Pickpocket at a rate commensurate with the lesser of total daily demand, or the remaining active storage behind Pickpocket Dam.

Q3 Total flow past Pickpocket Dam: While the model allows Pickpocket Dam to be simulated as an active (or "operable") structure, operation of Pickpocket Dam is normally simulated as "run-of-the-river," which means that the effects of storage are not considered. This logic is compatible with current operating protocol for the Town of Exeter. However, the model can simulate the effects of storage and releases at the Pickpocket Dam if the dam is "activated" prior to the simulation.

Detailed Logic: The model allows simulation of Pickpocket Dam in either of two modes: (1) Active Mode, or (2) Inactive Mode. If the Active Mode is simulated, Q3 is computed as the sum of the four other outflows from the dam: [$Q_{fp} + Q_{sp} + Q_{lp} + Q_{rp}$]. The effects of this mode are that flow may be impounded during low flow periods, but that dam operations can be simulated to augment storage at Great Dam if needed. If the Inactive Mode is simulated, then the dam is simulated as a "run-of-the-river" dam, *all computations for the individual outflows are superceded, and Q3 is simply equal to the net inflow (Q2 +* P_{pick} *–* E_{pick}*).*

Spills Since the safe yield estimates are insensitive to responses of the impoundments when they are at or above spillway levels, all excess water above the spillway capacity for each timestep (if any) is simulated as a spill. Therefore, the simulation model does not consider additional storage capacity above spillway elevations. Accordingly, the active storage capacity at each impoundment is fixed.

5.2.2 Simulated System Constraints

The safe yield estimates presented in this report are indicative of how much water Exeter could withdraw for water supply purposes, regardless of current hydraulic limitations at the treatment plant, pump station, or transmission facilities.

The primary constraints in the system simulation model are the limits of active storage in the impoundments. The active storage in each reservoir, including the variability in active storage based on intake flow rates and head loss at Exeter Reservoir, are simulated using the data presented in Section 2.

While a new intake structure may be constructed at the Exeter Reservoir in the future as part of the proposed construction of a new water treatment plant, the existing conditions (more conservative) were used in this analysis. Correspondingly, the intake level at the Exeter River Pump Station is not expected to change in the future.

5.2.3 Simulation of Operational Flexibility

The model is equipped with "ON-OFF" switches (input values) that control certain rules and constraints so that the sensitivity of yield to alternative operating conditions could be evaluated (see Section 6.3). The options include:

- Removing the hydraulic intake constraints at Exeter Reservoir
- Recycling of water used by the Exeter Mills Apartments for cooling
- Changing the lowest allowable water surface elevation behind Great Dam
- Changing the months that distinguish between the Exeter River and Exeter Reservoir as primary storage
- Removing the leak at Great Dam
- Removing the withdrawal at Lary Lane Well
- Applying Active or Inactive Mode for Pickpocket Dam (discussed above – dam is simulated as "run-of-river" dam or as an operational dam).

5.3 Demand Simulation

The ability of the system to satisfy demand is measured by the simulation model as the yield of the system to the treatment plant. For each simulation, a target yield is input as an average annual value for daily yield. To compute daily demand for each daily timestep, this annual average target value is multiplied by the monthly demand factors discussed in Section 3. Water is drawn from the primary and secondary source (either the River or the Reservoir, depending on the time of year) until the daily demand is satisfied or the active storage is depleted. The model graphically depicts the depletion of total active storage as a system failure.

5.4 System Model Verification

Very little data were available with which to verify the logical statements and mass balance computations used in the system simulation model. Using available data and knowledge of system operating rules, the model was verified in two ways:

- The model was verified to ensure that the simulated response characteristics matched expected characteristics

- The model was verified against observed drawdown data from 2002.

Each verification procedure is discussed below, and results are presented. In order to understand the verification procedure, it will be useful to understand how model output is interpreted.

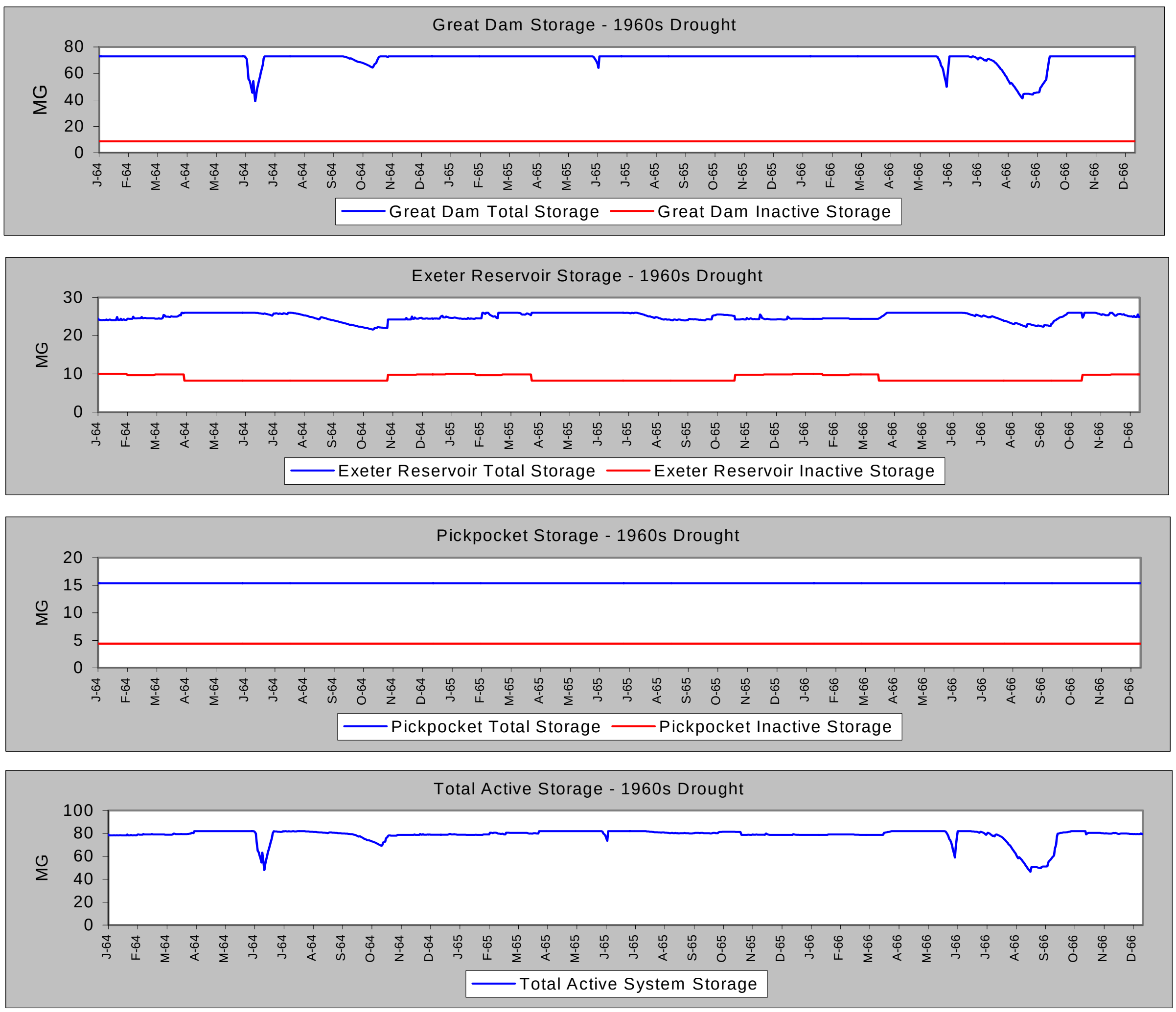
5.4.1 Explanation of Model Output

The model displays output in the form of time series of daily storage levels at each reservoir, and a time series of total active storage in the system. Storage levels are displayed for each reservoir through the primary droughts of record (1964-1966, 1980, and 2002) as well as through a year with representative normal precipitation (1998). A sample of this output (for the 1960s drought) is shown in Figure 5-2. In this example, 2 mgd is simulated as the annual average withdrawal (multiplied by monthly demand factors). This withdrawal rate is used here for illustrative purposes only, and does not necessarily represent the safe yield of the system (see Section 6 for safe yield estimates). Pickpocket Dam is simulated as INACTIVE for this example. The model suggests that the Great Dam Impoundment would be drawn down to approximately 50% of its active storage capacity (drawdown of approximately 34 million gallons), and the Exeter Reservoir would be drawn down to approximately 75% of its active storage capacity (drawdown of approximately 4.4 million gallons) under normal operating rules. This translates into a 40% depletion of total active storage (drawdown of total active storage to 60% of capacity).

Figure 5-3 illustrates the model output in the form of total active storage for the entire period of simulation (1964 – 2002). The conditions described above for Figure 5-2 also apply in this example. The different colors represent years at various statistical thresholds of annual precipitation, as noted. The output can be interpreted to suggest that the total active storage would be depleted only once during the period of study, in 1980. Significant drawdowns (or depletion of active storage reserves) would also occur during other years, and the output offers insight into the likely frequency of potentially severe system drawdown under sustained withdrawal rates. This type of output was used to evaluate the reliability of the water supply system over a wide range of withdrawal rates (see Section 6.2).

Figure 5-2: Sample Model Output for Drought of 1960s*

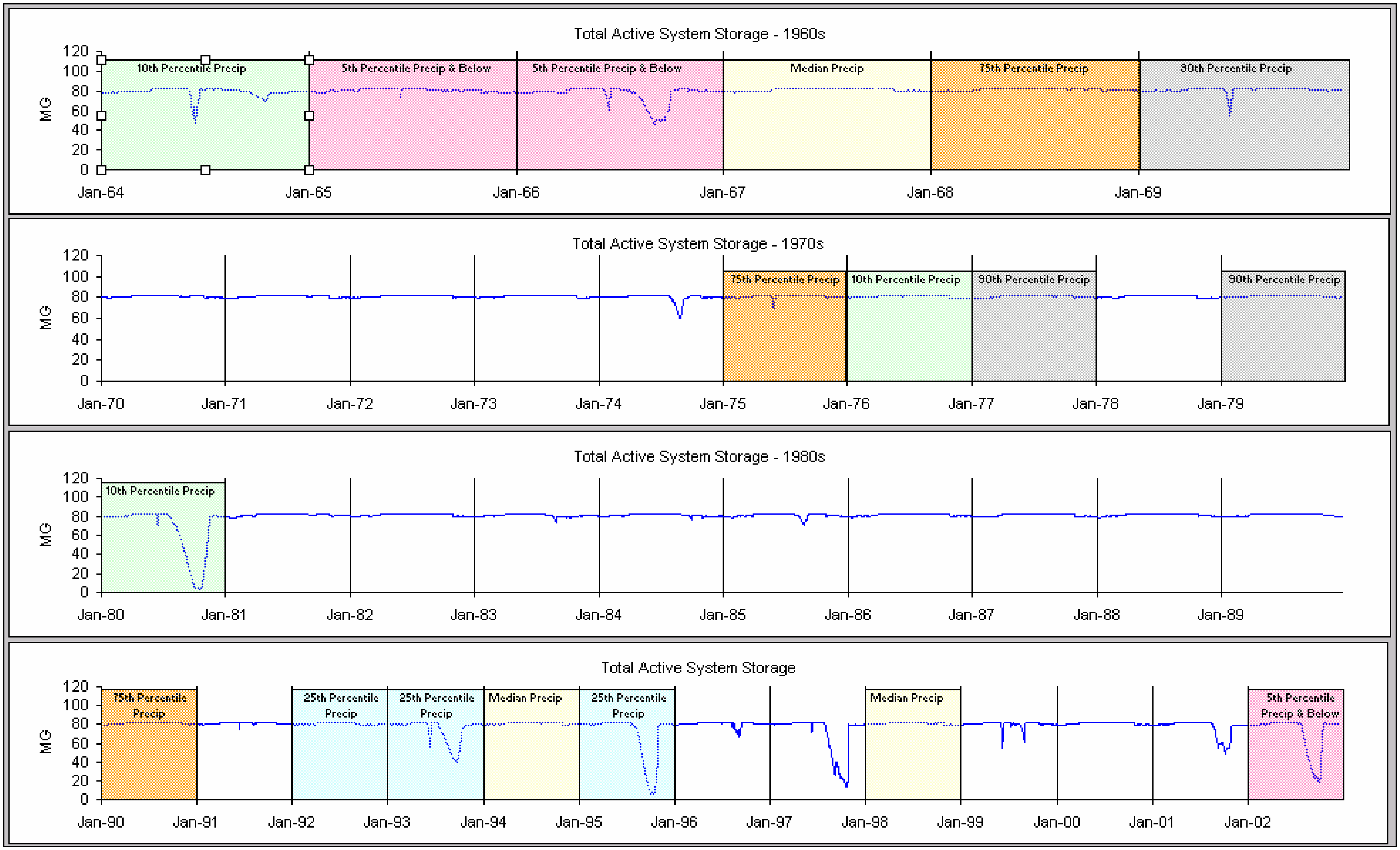
**Average Daily Withdrawal = 2 mgd (for sample purposes only – See Section 6 for safe yield estimates)*



**Note that the model simulates the variability of inactive storage in the Exeter Reservoir based on intake flow rates and head loss.*

*** The total active storage is the combined active storage at Great Dam and Exeter Reservoir. Inactive storage is not included in the final graph, nor is any storage at Pickpocket Dam.*

Figure 5-3: Sample Model Output – Total System Storage



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Despite the fact that this is an example scenario, all of the hydrologic input and operational logic was applied as presented in preceding sections. We can draw a very significant inference from the sample output in Figure 5-3. The droughts of 1980 and 2002, among others, appear to have had a more severe impact on the system than that of the 1960s. This matches our expectation (as discussed in Section 4) that the prolonged gradual drought of the 1960s would be less severe on a system with small storage impoundments (that is, systems with less than a year's supply in storage) than the more rapid and severe reduction in precipitation and streamflow that occurred in 1980 and 2002.

The results also suggest that total annual precipitation is not the only indicator of likely drawdown levels, and that the *distribution* of precipitation throughout the year is as important as the *amount* of precipitation. For example, if we compare the system response during 1968 and 1969, we discover that the model predicts a drawdown during the year with more precipitation (1969), and no drawdown during the year with less precipitation. For systems with small storage reservoir, such as the Exeter system, such responses are entirely expected, since the storage levels will respond noticeably to within-year (weekly and monthly) variations in climate.

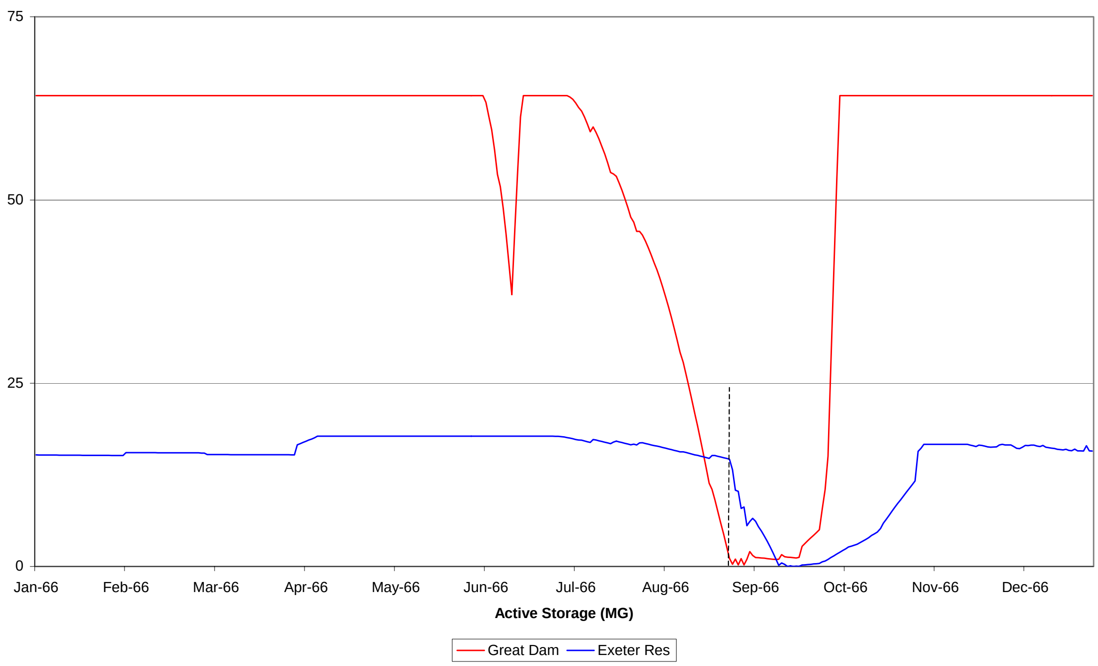
Recall that the yield estimates presented in this study comply with all applicable regulations. The system draws water only from <u>active</u> storage reserves, that is, only water above the intakes to the river pump station and the treatment plant is simulated as being available for withdrawal in this study. Hence, even when active storage is depleted in the impoundments, there is still water below the intakes; nearly 10 million gallons in the Exeter River impoundment, and nearly 9 million gallons in the Exeter Reservoir. Hence, neither impoundment would be physically emptied as a result of the sustainable yield rates presented in this report. Water would continue to flow into the impoundments (river flow would be unaffected upstream of the pump station), although water levels would decrease and flow would not pass through Great Dam.

5.4.2 Verification of Operating Logic

To verify that the model logic was functioning properly, a timeseries of storage levels was evaluated qualitatively for the year 1966 (the first year in the simulation during which significant drawdown could be simulated). The daily demand was increased incrementally until the active storage in the Great Dam Impoundment and the Exeter Reservoir was depleted. Figure 5-4 illustrates the simulated drawdown traces for the two storage reservoirs (storage in the Pickpocket Impoundment was not included in this assessment, and was reserved for the sensitivity analysis described in Section 6.3). These active storage traces were evaluated to determine if the model was simulating withdrawals from the appropriate impoundment, as dictated by the operating logic presented in Section 5.2.

As expected, since the Exeter River is the primary source from April through October, the drawdown occurs first in the River, beginning in early July. The Exeter Reservoir also exhibits a very gradual drawdown beginning at roughly the same time, although this is to be due to reduced inflow and not operational withdrawals. Once the active storage in the River is depleted (near the end of August, as marked with a vertical dashed line in the figure), the storage in the Exeter Reservoir is rapidly drawn down. This indicates that the model successfully switched the primary source of supply to the Exeter Reservoir once the active storage in the river had been depleted, even though the river would normally remain the primary source through October. Once the river begins to recover in the simulation (late September), withdrawals from active storage in the reservoir cease and withdrawals from the river resume. The reservoir begins to recover shortly after withdrawals cease. All of these responses match expected behavior based on the logic programmed into the model. The model draws water from the primary source first, and only resorts to secondary sources when active storage in a primary source is depleted.

Figure 5-4: Verification of Anticipated Operating Response*
This is a sample drawdown scenario, and is not necessarily representative of any particular value of safe yield.



5.4.3 Simulation of 2002 Drawdown

Reservoir system models are normally verified by comparing predicted fluctuations in water surface elevation or storage levels to operating records of water levels. For the Exeter System, no data were available for water surface level or storage at the Exeter Reservoir, and only two data points were available for water surface elevation at Great Dam. Hence, these two points were used to help verify that the model was accurately reproducing system response.

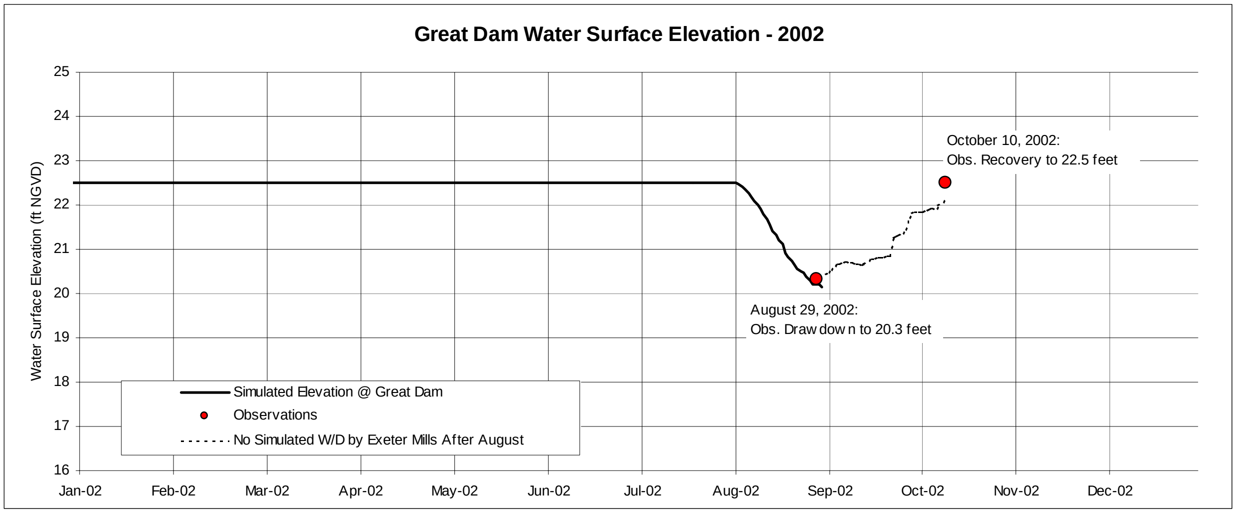
On August 29, 2002, the water level behind Great Dam had dropped 2-feet 2-inches below the dam crest. This was the lowest observed water level during the year, and the only level that was recorded by town personnel. On October 10, 2002, during field inspections, CDM observed that the water had returned to the elevation of the dam crest.

To simulate the 2002 drawdown, actual withdrawal records were input to the model. The objective of this verification test was to assess the accuracy of the simulated response of the Exeter River to known inflows and withdrawals. The results of the verification test are shown in Figure 5-5.

USGS gage data were used to estimate streamflow into the Great Dam Impoundment. The effects of Pickpocket Dam were not simulated during this test in order to help evaluate the adequacy of the assumption of "run-of-the-river" conditions at that dam. The USGS data for 2002 was still provisional at the time of this writing, and has not been through the quality assurance process, but the USGS has indicated that data from the Exeter River gage has historically been very reliable.

Operating logs for the river pump station were used as input to simulate withdrawals from the river to the treatment plant. Through August of 2002, the normal operating logic was used for the other withdrawals (Phillips Exeter Academy, Exeter Mills Apartments, Fish Ladder, Lary Lane Well, which is used in this simulation to reproduce actual withdrawals from the system, and the Mobile Home Park). Beyond August, the withdrawals by the Exeter Mills Apartments are uncertain. Management personnel at the apartments indicated that normal operations prevailed through the summer, but with cooler temperatures in September, use of the cooling system (and corresponding use of the Exeter River) was significantly reduced by reducing the speed of the variable speed pump drive. Since no records are available for actual withdrawals by the Apartment complex, the model trace in Figure 5-5 is shown as a dashed line between September 1 and October 10, and is based on an assumption of no withdrawals by the apartment complex.

Figure 5-5: Verification of 2002 Drawdown



From Figure 5-5, we can see that the model accurately predicted the water surface elevation as measured on August 29. Simulation of the recovery is less certain because of the uncertain operations of the Exeter Mills Apartments cooling system during this time period, but the model predicts a near recovery if no withdrawals by the apartment complex are simulated. <u>The most important aspect of this verification test, however, is the simulation of the magnitude and timing of the drawdown, since it is drawdown rates that affect system yield estimates most directly. Recovery rates factor only into the reliability analysis. The model simulated the magnitude and timing of the observed 2002 drawdown with very reasonable accuracy.</u>

Therefore, since the model logic seems to be functioning adequately (as discussed in Section 5.4.2), and since the model accurately reproduced the observed drawdown during the 2002 drought, we can have confidence that it is an accurate tool for predicting sustainable yield from the system.

Section 6
Results Summary

The system simulation model, as described in Section 5, was used to estimate the safe yield of the Exeter water supply system. The safe yield is not presented in this section as a single value, but rather, as sustainable average annual withdrawals rates through various historic drought periods and based on assumptions of different operating protocols and constraints.

This analysis also produced estimates of the frequency of system failure for withdrawal rates in excess of fully sustainable rates. These results are included to assist planners and decision makers in understanding the reliability of the system under various levels of withdrawal rates.

Values of sustainable yield were determined for each scenario by incrementally increasing the annual average daily withdrawal rate until the total active storage in the system was just depleted (all inactive storage below the intakes remained in the impoundments in every simulation – roughly 10 million gallons in the river, and 9 million gallons in the reservoir). In practically every case, the simulated system failures (depletion of active storage) occurred during the summer months when daily demand is simulated as nearly 120% of the average annual value. In general, sustainable yield rates are reported as the average annual daily withdrawals rates, which account for the higher monthly demands during the summer.

Each value of estimated safe yield will be qualified with several assumptions about operating rules and system constraints. The sensitivity to these assumptions is evaluated in Section 6.3.

6.1 Estimate Safe Yield Without Failure

The results in this section are presented as the sustainable withdrawal rates that would not cause a system failure during the droughts of record. The droughts of record are defined as the periods from 1964 – 1966, 1980, and 2002. The analysis indicated that the 1980 drought had a more severe impact on the Exeter system than the climate patterns of any other year (or combination of years) throughout the entire period of record, which extends from 1963 through 2002. The total annual precipitation during 1980 was not the lowest accumulation in the record, but the distribution of precipitation throughout the year resulted in the rapid simulated drawdown of the system during the dry summer months. The drought of 2002 is representative of many of the low-flow periods that occurred throughout the 1990s.

The following assumptions were applied to this analysis (the analysis was repeated without these assumptions to test for sensitivity, and these results are included in Section 6.3):

- Normal dam operating protocols and withdrawal patterns for the River and Reservoir
- Run of River operations at Pickpocket Dam, with no utilization of upstream storage
- Exeter Mills Apartments withdrawing 1 mgd during all summer days with no water returned to storage
- Water behind Great Dam can be drawn down 6.5 feet to hydraulic limit of 16 feet NGVD (1 foot above the intake to the pump station)
- Existing intake structure at the Reservoir is utilized (this may be replaced in the future in coordination with Exeter's new treatment plant)
- All of Exeter's demands are supplied from the treatment plant

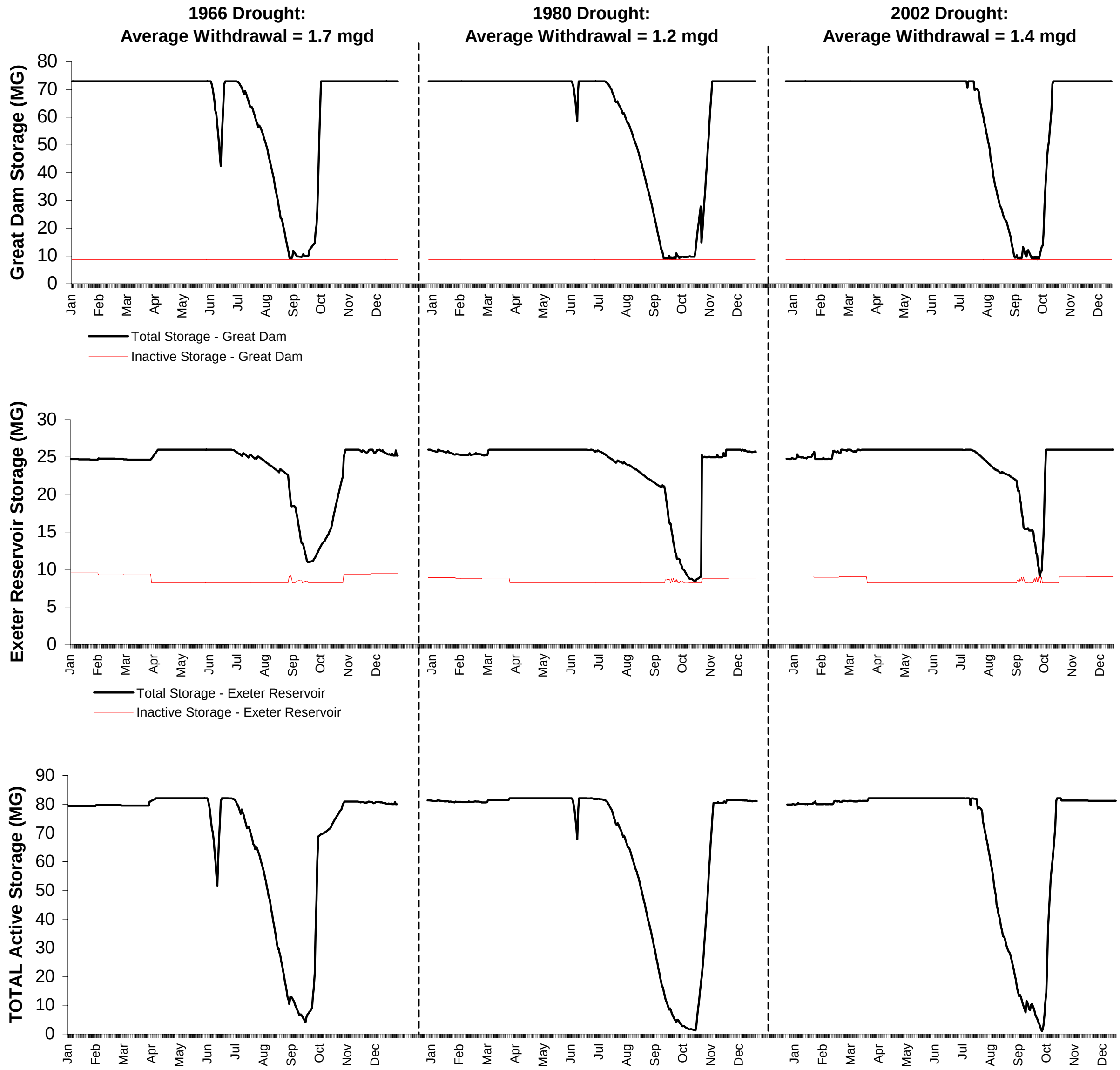
The safe yield estimates for these assumptions are tabulated in Table 6-1 and depicted graphically in Figure 6-1. Estimated sustainable yield for the three most significant droughts of record are tabulated, as well as for a year with normal precipitation (1998). Note that the safe yield reported is an average annual value, and includes variability in monthly demand in accordance with Table 3-2 (that is, an annual safe yield of 1.7 mgd corresponds to a maximum monthly demand of 2.0 mgd in late summer months).

Table 6-1: Safe Yield Estimates for Droughts of Record*

	1966	**1980**	**2002**	**1998**
Total Precipitation (in)	30.85	31.86	42.14	43.38
Percentile of Annual Precipitation (1963-2002)	< 5th	8th	44th	51st
Safe Yield with no recycling from apartment cooling system (annual average – mgd)	1.7	1.2	1.4	4.3
Peak monthly withdrawal in summer (corresponds with annual average numbers immediately above - mgd)	2.0 *(July-Aug)*	1.4 *(July-Aug)*	1.7 *(July-Aug)*	5.1 *(July-Aug)*
Safe Yield with recycling from apartment cooling system (annual average – mgd)**	2.7	2.2	2.4	5.3

**These values are based on the assumptions stated above, which include 1 mgd withdrawals made by Exeter Mills Apartments with no return.*
***Safe yield with recycled water from the apartment cooling system is presented as an additional 1 mgd, but careful operational control (blending, for example) would be required to capture all of this water, since the reservoir intake structure could not keep up with the associated higher withdrawal rates once active storage in the river is depleted. This is discussed in Section 6.3.3.*

Figure 6-1: Safe Yield Estimates for Droughts of Record*



**These values are based on the assumptions stated above, which include 1 mgd withdrawals made by Exeter Mills Apartments with no return.*

The top two series of graphs in Figure 6-1 illustrate active and inactive storage in the river and reservoir impoundments, and show that active storage is first depleted in the river, and then in the reservoir, as we would expect, since during the drawdown period, the river is the primary source of supply. The lower series of graphs is the sum of active storage in the above two sources. The annual average safe yield values presented at the top of the figure represent the highest value (to the nearest one-tenth mgd) that can be sustained without depleting the active storage in the system.

6.2 Failure Frequency Analysis

6.2.1 Failure Frequency for Normal Operating Rules

For planning purposes, the reliability of the system is also analyzed in the context of withdrawal rates that may exceed the sustainable rate but that result in depletion of active storage on an infrequent basis (once every ten years, for example). Continuous daily simulations were conducted over the period of 1964 through 2002 for incremental rates of withdrawal. Results were evaluated for three characteristics:

- Number of years from 1964 – 2002 during which a failure occurred during the simulation
- Average number of days during the failure years that the system could not meet demand
- Total number of days during the simulation period that the system could not meet demand

The following assumptions were applied for this analysis:

- Normal dam operating protocols and withdrawal patterns for the River and Reservoir
- Run of River operations at Pickpocket Dam, with no utilization of upstream storage
- *Exeter Mills Apartments recycles all water withdrawn for cooling (different assumption from previous analysis)*
- Water behind Great Dam can be drawn down 6.5 feet to hydraulic limit of 16 feet NGVD (1 foot above the intake to the pump station)
- Existing intake structure at the Reservoir is utilized
- All of Exeter's demands are supplied from the treatment plant

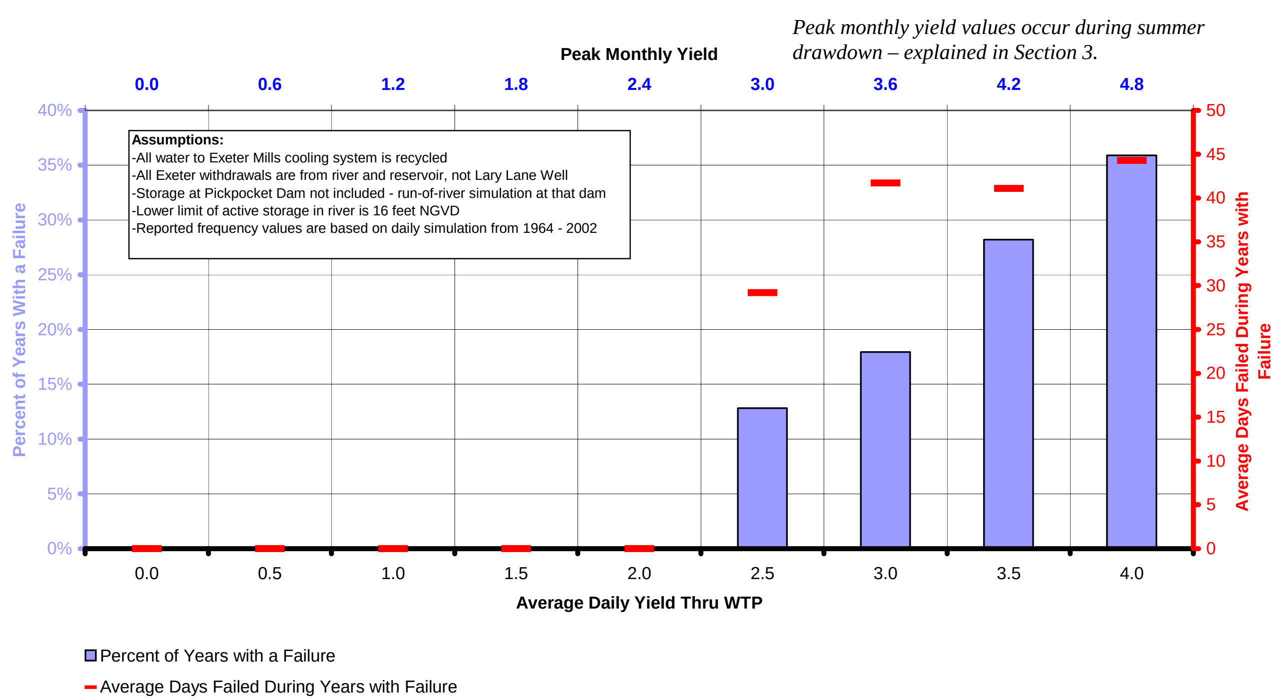
The results are summarized in Table 6-2 and Figure 6-2.

Table 6-2: Results of Failure Frequency Analysis for Normal Operations (1964-2002)*

Annual Avg. Yield (mgd)	Peak Monthly Yield (mgd)	# of Years with a failure	% of Years with a failure	Total # of days failed from 1964 - 2002	Average days failed during each failure year	% of total days with failure
0.0	0.00	0	0%	0	0	0.0%
0.5	0.60	0	0%	0	0	0.0%
1.0	1.19	0	0%	0	0	0.0%
1.5	1.79	0	0%	0	0	0.0%
2.0	2.38	0	0%	0	0	0.0%
2.5	2.98	5	13%	146	29	1.0%
3.0	3.57	7	18%	292	42	2.1%
3.5	4.17	11	28%	452	41	3.2%
4.0	4.76	14	36%	620	44	4.4%

**Based on the assumptions stated in this section – including recycling of water at Exeter Mills Apartments*

Figure 6-2: Results of Failure Frequency Analysis for Normal Operations (1964-2002)*



**Based on the assumptions stated in this section – including recycling of water at Exeter Mills Apartments*

6.2.2 Failure Frequency for Prospective Operating Conditions

The above results are indicative of the frequency of failure that can be expected during normal operations, based on the period of record. The analysis was continued to simulate actual prospective operational protocols that may assist in the planning and decision process. Specifically, failure frequency was analyzed for:

- Full Buildout Demand Projections: Projected demand in 2020 under full buildout conditions in Exeter (annual average demand of 1.92 mgd)
- Prospective Transfer to Hampton: Potential transfer of 0.5 mgd to Hampton in addition to projected 2020 Exeter demand of 1.92 mgd
- Consumption Restrictions: Implementation of demand restrictions during droughts (simulated as 10% reduction in daily demand whenever the water behind Great Dam is drawn down more than one foot below the dam crest). Note that the 10% reductions were applied to both Exeter withdrawals and the potential Hampton transfer of 0.5 mgd.

These scenarios were simulated for the entire period of record, and in more detail for the simulated climates of 1980 and 2002, which represent worst case conditions for this system. The results of the analysis are tabulated in Tables 6-3 and Table 6-4 and Figure 6-3. Aside from the projected operating regimes listed above, the same assumptions that were applied to the previous failure frequency analysis (as presented in Table 6-2 and Figure 6-2) were applied to this analysis.

KEY FINDING: The results in Table 6-3 suggest that Exeter's projected demand of 1.92 mgd in 2020 is within the safe yield of the system. If an additional 0.5 mgd is transferred to Hampton, the analysis suggests that the system would still be nearly 100% reliable, but that full demand may not be satisfied for roughly 25 days once in a ten year period (approximately). This corresponds to less than 1% of the time that full demand would not be satisfied, and the failures most frequently occurred in the simulation during the months of September and October (as shown in Table 6-4) - periods in which demand in Hampton is normally reduced due to lower seasonal tourist populations (although the demand of 0.5 mgd was not reduced in the simulation). The analysis also suggests that if demand restrictions are invoked (as described in the text), the failure rate drops to less than 0.5%.

Table 6-3: Failure Frequency Analysis for Projected Conditions: 1964-2002

Avg. Exeter Demand (mgd)*	Hampton Transfer (mgd)	Total Avg. Withdrawal (mgd)	Implement Demand Restrictions?	#/% of Years with a failure	Average days failed during failure years	% of Total days with failure
1.92	0	1.92	No	0Y / 0%	0	0%
1.92	0.5	2.42	No	5Y / 13%	25	0.9%
1.92	0	1.92	Yes	0Y / 0%	0	0%
1.92	0.5	2.42	Yes	4Y / 10%	16	0.4%

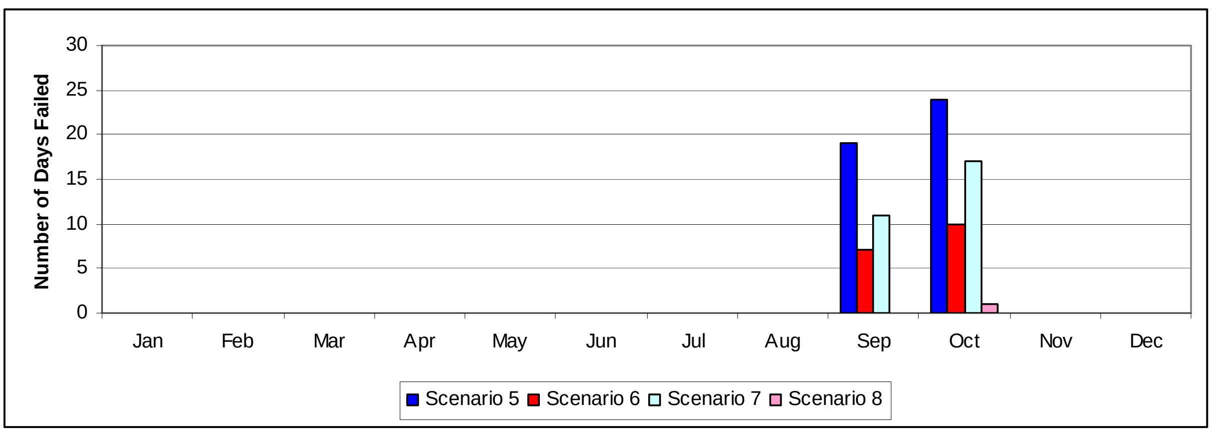
**Average Exeter Demand is estimated for full buildout conditions in 2020, and is multiplied by the same monthly peaking factors applied to previous analyses.*

Table 6-4: Failure Frequency Analysis for Projected Conditions: 1980 and 2002

Scenario ID *(for use with Figure 6-3)*	Time Period	Avg. Exeter Demand (mgd)*	Hampton Transfer (mgd)	Total Avg. Withdrawal (mgd)	Implement Demand Restrictions?	# of days failed in September	# of days failed in October	# of days failed in other months
5	1980	1.92	0.5	2.42	No	19	24	0
6	2002	1.92	0.5	2.42	No	7	10	0
7	1980	1.92	0.5	2.42	Yes	11	17	0
8	2002	1.92	0.5	2.42	Yes	0	1	0

**Average Exeter Demand is estimated for full buildout conditions in 2020, and is multiplied by the same monthly peaking factors applied to previous analyses.*

Figure 6-3: Failure Frequency Analysis for Projected Conditions*: 1980 – 2002
(Based on Table 6-4)



** Exeter demand = 1.92 mgd*
Hampton demand = 0.5 mgd
Total demand = 2.42 mgd

Two important results from this analysis are summarized again below:

a) These results suggest that even under full buildout conditions and the implementation of a prospective transfer of water to Hampton (0.5 mgd), **the system could sustain demand with a failure rate of less than 1%** (based on the number of days failed).

b) The results also suggest that the system would be most likely to experience failures during the months of September and October. For planning purposes, these are not expected to be months during which peak demand is experienced in Hampton due to the historic drop in tourism in these months.

6.3 Sensitivity Analysis

The results presented in Section 6.1 and 6.2 are based on the assumptions stated at the beginning of each section. The results in this section can be used to evaluate how sensitive the yield estimates are to several of these key assumptions. In other words, the following results present yield estimates based on the removal or alterations of some of these assumptions.

The following four conditions are analyzed with respect to their effect on yield estimates:

- Normal operating protocols and withdrawal patterns are altered so that different months are used to trigger the switch between the River and the Reservoir as primary source
- The contribution of the storage behind Pickpocket Dam is included
- The cooling water at Exeter Mills Apartments is recycled
- The storage thresholds (allowable drawdown) are altered

6.3.1 Effects of Primary Source Changeover Timing

As specified in Section 5.2.1, under normal operating rules, the Exeter River is utilized as the primary source between April and October, and the Exeter Reservoir is utilized as the primary source between November and March.

The simulation model logic was altered so that the months that trigger each changeover were varied incrementally. However, since the model logic is developed so that the secondary source is utilized as soon as the primary source is exhausted, there appeared to no appreciable benefit to altering the timing of the changeover.

6.3.2 Effects of Pickpocket Storage

The analyses presented thus far have not accounted for the stored water behind Pickpocket Dam. This approach was selected both for conservatism and to be representative of normal operations (the Town does not normally open the release gates at Pickpocket Dam). However, since the active storage behind Pickpocket Dam is estimated in Section 2.2 to be 11 million gallons (or roughly 12% of the total active storage in the system), a simulation analysis was conducted to estimate the impact of including water behind Pickpocket Dam as available for utilization. The alternate model logic is defined in Section 5.2.1 (see details for flows Q3 and Q_{rp}).

Table 6-5 illustrates the estimated increase in sustainable yield if Pickpocket storage is considered to be available for utilization. Figure 6-4 presents the results of simulation of the 1980 drought using all three storage impoundments. Note that the Pickpocket storage is not utilized until the Great Dam storage is nearly depleted. The Pickpocket storage is used to augment supplies in the river for a period of approximately 1.5 months during the critical drawdown in September and October. All of the other assumptions stated in Section 6.1 are held constant.

Table 6-5: Effects of Pickpocket Dam on Safe Yield*

	1966	1980	2002	1998
Safe Yield WITHOUT Pickpocket Dam (annual average – mgd)	1.7	1.2	1.4	4.3
Safe Yield WITH Pickpocket Dam (annual average – mgd)	1.9	1.3	1.5	4.3

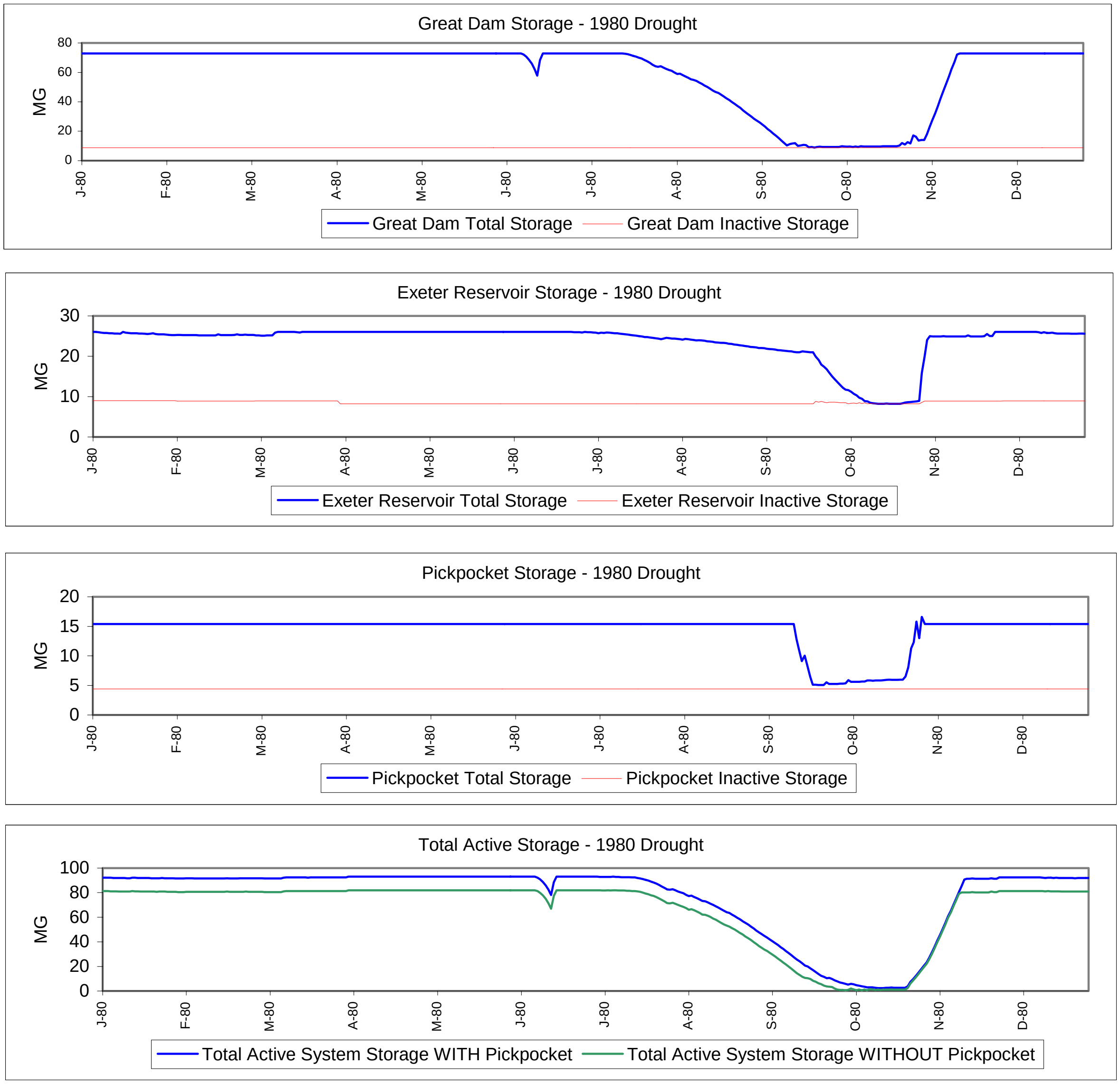
**recycling of 1 mgd at Exeter Mills Apartments not included*

As illustrated by the results in Table 6-5, utilization of the storage behind Pickpocket Dam would result in a very limited increase in the sustainable yield of the system.

The estimate can be confirmed with the following logic: Figure 6-4 indicates that the Pickpocket storage is utilized for approximately 1.5 months during the simulation of the 1980 drought. Dividing the total active storage behind Pickpocket Dam of 11 million gallons by 45 days, the estimated contribution from this impoundment is 0.24 mgd. This is roughly equivalent to the estimated increase in safe yield of 0.2 mgd (an increase from 1.7 mgd to 1.9 mgd).

Therefore, the safe yield estimates for the Exeter water supply system are not appreciably sensitive to the storage behind Pickpocket Dam. For conservatism, all other estimates of safe yield in this report have been computed without considering the availability of water at Pickpocket Dam or the operational activities necessary to extract it effectively.

Figure 6-4: Storage Traces For 1980 Drought When Pickpocket Dam is Utilized*



**Average daily withdrawal is 1.3 mgd*

6.3.3 Effects of Recycling Water at Exeter Mills Apartments

During the summer months, the Exeter Mills Apartment complex withdrawals approximately 1 mgd for use in the cooling system for the facility. This water may be discharged downstream into the Squamscott River (lost from the water supply system) or recycled back into the supply system. However, because the existing piping for recycling returns water to the point of intake, heated water is drawn back into the cooling system before equalizing with the surrounding water temperature ("short-circuiting"), limiting the cooling benefit. Hence, the facility operators have historically discharged water downstream into the Squamscott River.

Discharging water downstream results in water that is unavailable for Exeter's water supply purposes, on the order of 1 mgd during the summer months. This practice effectively reduces the sustainable yield of the system for water supply by roughly 1 mgd.

The simulation model was run during the severe drought years, with all assumptions listed in Section 6.1 held constant except for the fate of the water withdrawn for the cooling system. All cooling water was assumed to be recycled back into the supply system. Since the model extracts 1 mgd for cooling during the summer months, sustainable yield values would be expected to increase by 1 mgd. However, at higher withdrawal rates, the active storage at Exeter Reservoir decreases due to higher head losses (as discussed in Section 2), and hence the total active storage in the system decreases. Careful operational control may mitigate these effects so that the full 1 mgd may be reclaimed by the supply system. Additionally, the new reservoir intake, planned in coordination with Exeter's new water treatment plant, will have substantially lower head losses that will also help mitigate these effects. Table 6-6 tabulates the estimated effects of full recycling on sustainable yield, as simulated with normal operating rules and constraints.

Table 6-6: Effects of Recycling Cooling Water at Exeter Mills Apartments

	1966	1980	2002	1998
Safe Yield WITHOUT Recycling (annual average – mgd)	1.7	1.2	1.4	4.3
Safe Yield WITH Recycling – existing conditions (annual average – mgd)	2.6	2.0	2.2	5.2
Safe Yield WITH Recycling – effects of reservoir head loss eliminated (annual average – mgd)	2.7	2.2	2.4	5.3

Based on assumptions of Section 6.1, except for Exeter Mills cooling water

As listed in the table, the effective increase in yield is approximately 0.8 – 0.9 mgd (not the full 1 mgd which is recycled due to the reduced active storage capacity in the system associated with higher head loss at the reservoir). However, careful operational management and the new planned reservoir intake may result in a full increase of 1 mgd in sustainable yield.

6.3.4 Effects of Various Elevation Thresholds

The previous analyses have assumed that the water behind Great Dam may be drawn down to 6.5 feet below the dam crest. This corresponds to a water surface elevation of 16 feet (NGVD), which is one foot above the invert of the intake pipe to the river pump station. It is estimated that one foot of head is necessary to maintain a level of flow into the pump station commensurate with yield values discussed in this report.

While this threshold represents a physical limit, there may be other reasons for the Town to limit the drawdown behind Great Dam. This analysis estimates the reduction in sustainable yield if the physical threshold of 16 feet NGVD is raised to accommodate aesthetic or environmental needs. Recall that even if the river is drawn down to 16 feet NGVD, there is still 10 million gallons of stored water below this level, and flow levels upstream of the river pump station would remain unchanged.

The previous analyses have also assumed that the intake facilities at the Exeter Reservoir remain unchanged. For planning purposes, since the Town is considering the development of a new treatment plant, the analysis was repeated with the assumption that active storage at Exeter Reservoir increases so that all water above the lowest intake pipe (approximately 10 feet NGVD) is available for withdrawal. This effectively increases the active storage in the reservoir from 18 MG to 24 MG.

The assumptions in this analysis are the same as those presented in Section 6.2 (same as Section 6.1 with the exception that all cooling water at Exeter Mills Apartments is recycled).

Table 6-7 and Figure 6-5 illustrates the effects of various water elevation thresholds on the estimated safe yield of the system. As shown, for each foot that the river threshold is raised, the safe yield is reduced by 0.1 – 0.2 mgd. Also, by lowering the Reservoir intake, an additional 0.1 mgd of yield could be realized.

Table 6-7: Effects of Elevation Thresholds on Safe Yield*

Lowest allowable River Elev (ft NGVD) **	Minimum Reservoir intake Elev (ft NGVD) ***	System Active Storage (MG) ****	Safe Yield: 1964-1966 (mgd)	Safe Yield: 1980 (mgd)	Safe Yield: 2002 (mgd)	Safe Yield: 1998 (mgd) *****
16 -baseline	**17.6 (existing)**	**81.3**	**2.6**	**2.0**	**2.2**	**5.2**
17	17.6 (existing)	76.8	2.5	1.9	2.1	5.0
18	17.6 (existing)	70.3	2.4	1.9	2.0	4.9
19	17.6 (existing)	62.0	2.3	1.8	1.9	4.7
20	17.6 (existing)	52.3	2.2	1.7	1.8	4.5
21	17.6 (existing)	38.2	1.9	1.5	1.6	4.2
22	17.6 (existing)	25.0	1.7	1.4	1.5	4.0
16	10 (new)	87.3	2.7	2.1	2.3	5.3
17	10 (new)	82.8	2.6	2.0	2.2	5.1
18	10 (new)	76.3	2.5	2.0	2.1	5.0
19	10 (new)	68.0	2.4	1.9	2.0	4.8
20	10 (new)	58.3	2.3	1.8	1.9	4.6
21	10 (new)	44.2	2.0	1.6	1.7	4.3
22	10 (new)	31.0	1.8	1.5	1.6	4.1

* *All cooling water at Exeter Mills Apartments is simulated as fully recycled*

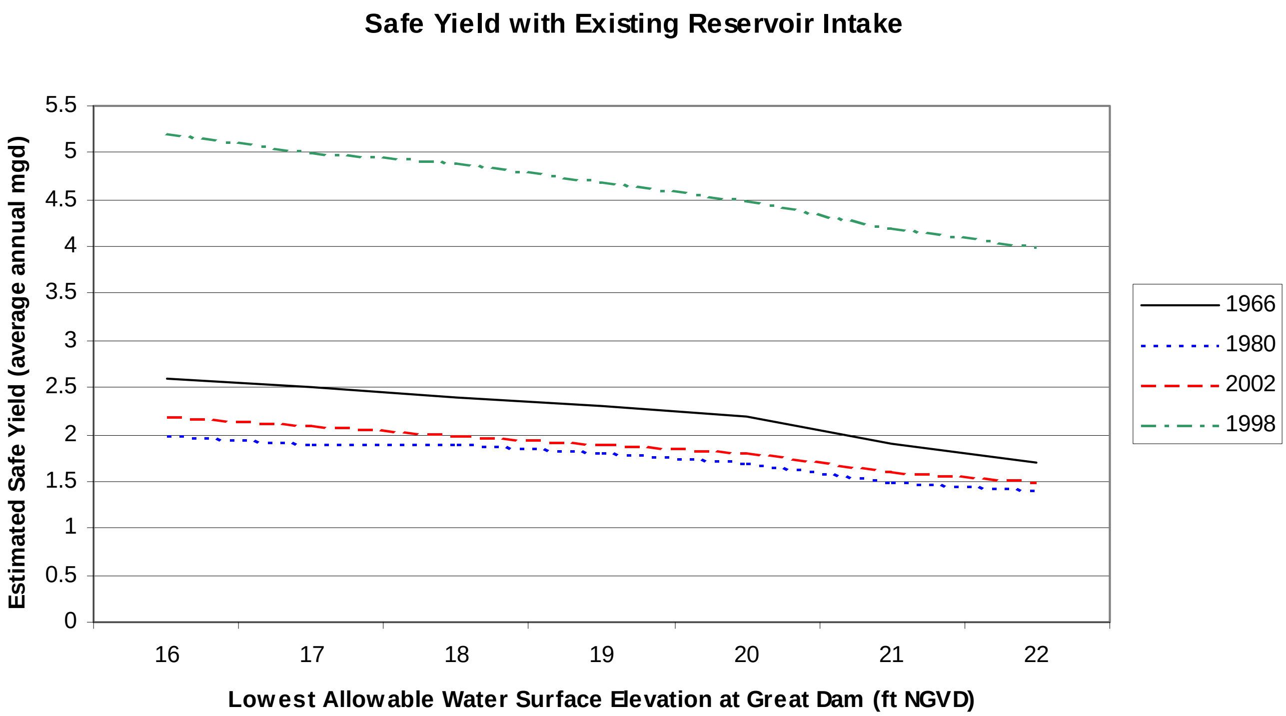
** *The crest of Great Dam is at 22.5 NGVD*

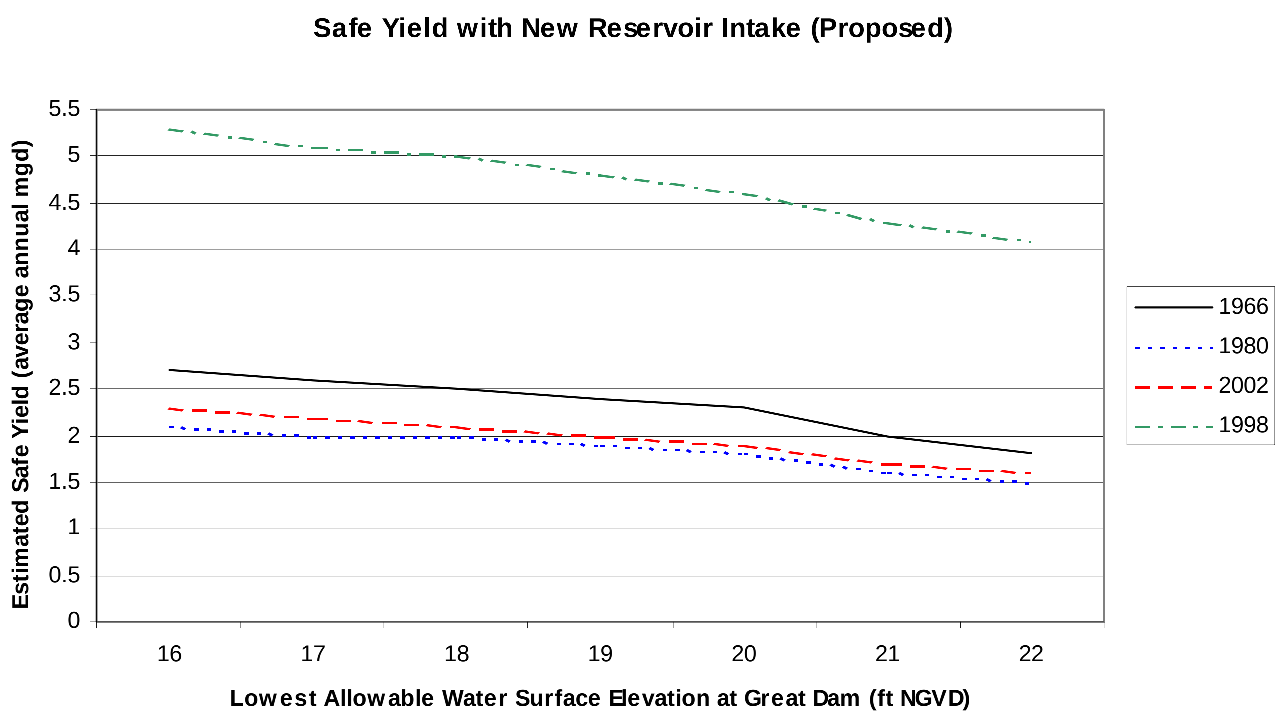
*** *17.6 feet is the existing weir elevation at the treatment plant that limits the active storage in the reservoir. 10 feet is the minimum invert of pipes leading from the reservoir, that could serve as a hydraulic constraint for a new intake system.*

*** *System storage does not include Pickpocket Dam and includes all water above intakes regardless of head loss*

***** *1998 represents a year with 50th percentile total annual precipitation*

Figure 6-5: Effects of Elevation Thresholds on Safe Yield
(per Table 6-7)



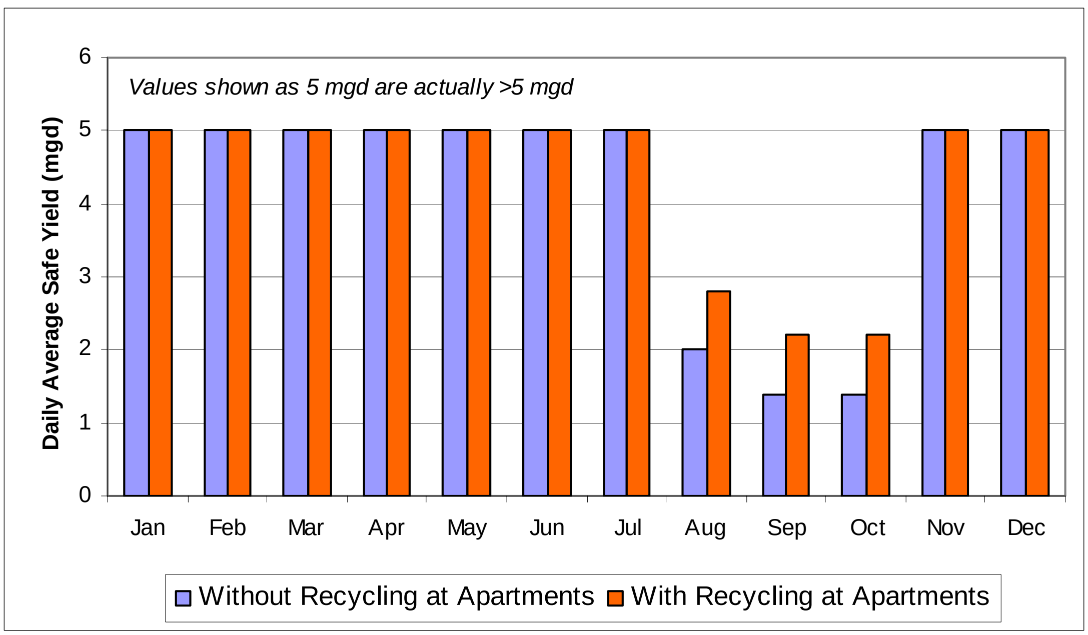


These results suggest that the safe yield estimate is practically insensitive to the active storage in the reservoir. The six million gallons of additional active storage that could become available with a lower intake would only increase the system yield by approximately 0.1 mgd. The results also suggest that the yield results are sensitive to the water elevation threshold in the River that the Town deems appropriate. As an example, if the Town decides to limit the drawdown to just six inches below the dam crest (22 feet elevation threshold), the safe yield for the 1980 drought would decrease from 2.0 mgd to 1.4 mgd.

6.4 Safe Yield Rates Through 2002 Drought

In Section 6.1, the safe yield for 2002 is reported as 1.4 mgd (or 2.4 mgd if the water from the apartment complex is recycled). However, this value represents a simulated sustained annual average rate that only resulted in system drawdown during the late summer months. Repeated simulation suggests that a great deal more water could have been safely withdrawn during other months of the year. Figure 6-6 illustrates the monthly sustainable withdrawal rates that could have been safely taken from the system during 2002. *Exeter could have safely withdrawn more than 5 mgd in all months except August, September, and October.*

Figure 6-6: Monthly Sustainable Yield through 2002



Section 7
Conclusions and Recommendations

This study evaluated the safe yield of Exeter's water supply system (the Exeter River and the Exeter Reservoir). This report provides guidance on the flows that can be reliably withdrawn from the system without causing failure, defined as the depletion of active storage. Additionally, information is provided on the duration and frequency of failures when the safe yield withdrawal rates are exceeded. The conclusions from this study are summarized below:

- During years with average precipitation accumulations (1967, 1994, 1998), the safe yield of the Exeter system is approximately 4.3 mgd (with the continued 1 mgd withdrawal by Exeter Mills).

- The droughts of record for Exeter occurred in 1964 – 1966, 1980, and 2002. The 1980 drought had the most severe impact on the Exeter system because, while the total precipitation was not the lowest accumulation in the record, the distribution of precipitation throughout the year resulted in the rapid simulated drawdown of the system during the dry summer months. Table 7-1 summarizes the safe yield during the droughts of record, with and without the 1 mgd withdrawal by Exeter Mills.

Table 7-1: Summary of Safe Yield During Droughts

	1966	1980	2002
Safe Yield (annual average – mgd) with Exeter Mills withdrawal	**1.7**	**1.2**	**1.4**
Safe Yield (annual average – mgd) without Exeter Mills withdrawal	**2.6**	**2.0**	**2.2**

- As shown in Table 7-1, the safe yield results are very sensitive to the 1 mgd withdrawal by Exeter Mills. The Town of Exeter should work with the Mills to re-capture the flow that is currently being discharged to the Squamscott River. A possible solution would be to extend the current recycle line from the end of the penstock approximately 350 feet to the Great Dam impoundment.

- The safe yield results are also sensitive to the restriction imposed by the Brentwood Hydro Dam under low flow conditions. As shown in Figure 1-1, the Brentwood Hydro Dam controls flow from approximately 60% of the watershed. Accordingly, when the water elevations are below the dam crest, flow past the dam is reduced (calibration of the hydrologic model suggested that the dam can effectively reduce the entire drainage area considered in this analysis by 20% during low flow periods). The removal of this dam would increase the available yield.

- Exeter's projected 2020 buildout demands are approximately 1.92 mgd. Assuming that 0.5 mgd is transferred to Aquarion, the system will be able to meet demands over 99% of the time, as summarized in Table 7-2.

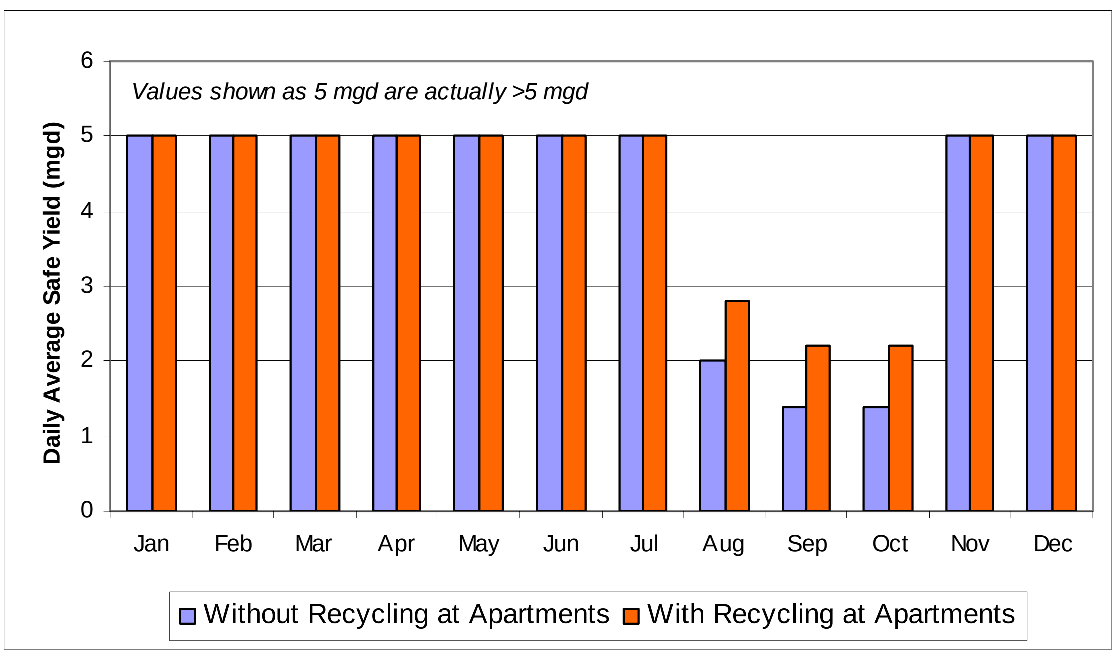
Table 7-2: Failure Frequency for Future Conditions

Based on climate records from 1964-2002 and the assumption that cooling water from the Exeter Mills Apartments is recycled into the impoundment:

Avg. Exeter Demand (mgd)*	Hampton Transfer (mgd)	Total Avg. Withdrawal (mgd)	Implement Demand Restrictions?	#/% of Years with a failure (1964 – 2002)	Average days failed during failure years	% of Total days with failure
1.92	0.5	2.42	No	5Y / 13%	25	0.9%
1.92	0.5	2.42	Yes	4Y / 10%	16	0.4%

- The safe yield for 2002 is reported as 1.4 mgd (or 2.4 mgd if the water from the apartment complex is recycled). However, this value represents a simulated sustained annual average rate that only resulted in system drawdown during the late summer months. Repeated simulation suggests that a great deal more water could have been safely withdrawn during other months of the year. Figure 7-1 illustrates the monthly sustainable withdrawal rates that could have been safely taken from the system during 2002. Exeter could have safely withdrawn more than 5 mgd in all months except August, September, and October. In the summer of 2002, Exeter would have been able to transfer 0.5 mgd of flow during every month except September and October.

Figure 7-1: Monthly Sustainable Yield through 2002



- An interconnection would benefit both communities. It would provide additional supply to Aquarion during emergency conditions and peak summer demands. The additional supply would also allow Aquarion to 'rest' their groundwater wells during off-peak times. For Exeter, an interconnection would provide improved fire flows in the eastern part of Town and would provide emergency supply in the event of a failure at the WTP. Additionally, there is the potential for Exeter to generate additional revenue through water sales or cost sharing of the new water treatment plant.

Section 8
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APPENDIX A

General Description of Hydrologic Model

Appendix A: General Description of Hydrologic Model

This appendix describes the structure and mathematics of the hydrologic model developed to simulate low flows in the Exeter River. The calibration and verification results are included in Section 4 of this report.

A.1 Selection of a Hydrologic Model

Many hydrologic models have been presented in the literature and used to simulate surface and sub-surface flow patterns in drainage basins. The selection of a model for the Exeter River Basin was based on the following criteria:

- Model parameters were to be representative of physical basin characteristics. While non-physically-based parameters might reproduce observed data reasonably well, we would not be able to confidently apply a non-physical model outside its period of calibration. Conversely, when model parameters are based on physical basin characteristics that do not change, we can more confidently apply the model to other situations for predictive purposes.

- The number of parameters was to be no greater than 6. Jakeman and Hornberger (1993) studied the complexity of rainfall-runoff models as measured by the number of parameters. Their report includes the findings of Hornberger et al (1985), who claim that four parameters are adequate to explain basin hydrology based on rainfall. Beven (1989), reported that three- to five parameters were usually adequate to simulate basin hydrology based on rainfall. The inference from these papers is that models with more than six parameters may be over-parameterized, and may be less reliable in reproducing the general flow patterns within the basin.

- The model was to be capable of simulating a daily hydrologic record in order to reproduce the daily variations observed in the recorded streamflow data.

- The model was not to require input other than daily precipitation and daily temperature extremes, all of which are readily available.

- The model was to have a structure that accounted for state variables within the watershed (that is, variations in soil moisture and groundwater storage).

- The model was to account for direct runoff, baseflow, basin-wide evapotranspiration and surface evaporation.

With some minor modifications to account for snow and surface evaporation, the *abcd* model, first introduced by Thomas (1981) satisfied all of these criteria. The mathematical structure of the model is described in Section A-2. It is also explained by Fernandez *et al* (2000), who used it to study regionalized calibration of watershed models based on physical watershed characteristics.

The model is reviewed by Alley (1984), who demonstrated that it was the best of five models in his investigation at reproducing annual flows, and at least as good as the others in reproducing monthly flow variations. His study also showed that the model could simulate variations in groundwater storage that were similar to observations obtained from monitoring wells. Westphal (2001) showed that the *abcd* model was superior to two similar physically-based models, and used it to predict flows in the Swift River, Stillwater & Quinepoxet Rivers, Ware River, and Connecticut River in an integrated decision support model for the MWRA's Quabbin and Wachusett reservoir system. As part of this study, model tests revealed that the *abcd* model was superior to two additional physically-based models in predicting low-flow hydrology. In 2001, CDM used the *abcd* model to predict the daily hydrologic response of the Spot Pond reservoir in Massachusetts as part of a study for MWRA on the management of emergency supply reservoirs.

Because the model satisfies the selection criteria, because it has been successfully employed in the past, and because it performed better than other similar models in several comparative studies, it was selected for the Exeter Safe Yield study.

A.2 Model Description

The following sections describe the mathematics of the model, including the modifications noted above. Sections A.2.1 and A.2.2 are paraphrased from Westphal (2001).

A.2.1 The Basic *abcd* Model

The *abcd* model predicts daily flow from climatic inputs of daily precipitation, daily minimum temperature, and daily maximum temperature. In terms of basic fluid mechanics, the model establishes the entire basin as a control volume, and by the principle of continuity (conservation of mass), balances the water coming into and moving out of the basin.

The model computes the values of two storage variables for each time step; soil moisture and groundwater storage. Precipitation is directed into the soil, and soil infiltration is divided between evapotranspiration, runoff , groundwater recharge, and remaining soil moisture. Groundwater is then depleted by discharging to the river at rates proportional to aquifer storage. The flows are computed at a daily level using calibrated parameters and climate input. Total flow into the river is the sum of runoff and groundwater flow (baseflow).

Table A-1 describes each of the major variables employed in the model. Table A-2 defines the model parameters and explains the physical significance of each. The relationships between the parameters and the primary storage variables are illustrated in Figure A-2. Note that the parameters do not equate to the value of the flow, but rather are used to compute the flows shown in the figure. The mathematical formulation of the model follows the figure.

Table A-1
abcd Model Variables

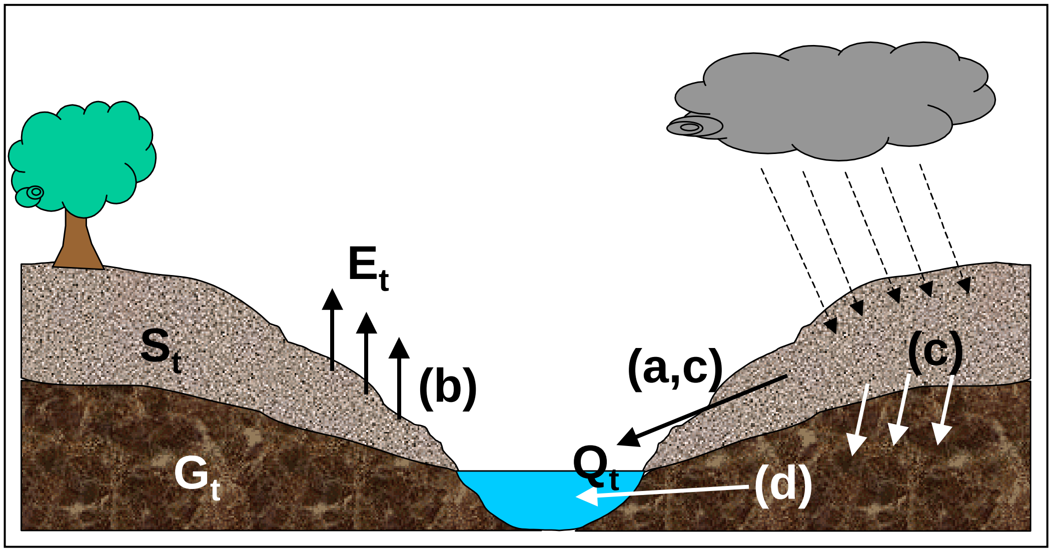
Relationship to Water Balance	Variable Name	Variable Symbol and Description
Climatic Inputs	Precipitation	$P_t =$ Daily precipitation
	Max Temperature	T_{max} = Maximum daily temperature
	Min Temperature	T_{min} = Minimum daily temperature
	Average Temperature	T_{av} = Average daily temperature [$T_{av} = (T_{max} + T_{min})/2$]
	Potential Evapotranspiration	PE_t = Theoretical amount of water which could evaporate or transpire in a given day due to the available energy (solar radiation and temperature)
Hydrologic Variables	Available Water	W_t = Amount of water equal to daily precipitation and the water stored in the soil at the end of the previous day
	Evapotranspiration Opportunity	Y_t = Amount of water which will eventually leave the basin through evapotranspiration
	Soil Moisture Storage	S_t = Amount of water stored in the unsaturated soil zone (not groundwater)
	Groundwater Storage	G_t = Amount of water stored in the groundwater aquifers
	Actual Evapotranspiration	E_t = Amount of water leaving through evapotranspiration on a given day
Basin Outflow (model output)	Predicted Flow	Q_t = Predicted daily flow into the reservoir.

The model consists of four governing parameters: *a, b, c,* and *d.* The parameters are used mathematically as coefficients or limits, but can be better understood as representing various physical characteristics of the river basin. Table A-2 describes the physical interpretation of each parameter:

Table A-2
Physical Interpretations of abcd Model Parameters

Param	Physical Significance
a	Though this parameter has relatively little direct correlation to the landscape, it reflects the propensity for water to either runoff before the soil is saturated, or to continue infiltrating the soil. In relatively flat basins, "a" usually approaches a value of 1.
b	This parameter reflects the ability of the unsaturated soil to hold moisture. It also acts as an upper bound on the sum of the soil moisture and actual evapotranspiration. For a basin with very flat relief, soil moisture may be very high since runoff is expected to be relatively low, and "b" could approach the annual amount of precipitation.
c	This parameter is an allocation ratio. It represents the percentage of the available water minus the evapotranspiration opportunity (W_t - Y_t) that will be directed into groundwater as groundwater recharge. (1-c) represents the percentage of (W_t - Y_t) that will be allocated to direct runoff into the reservoir.
d	This parameter represents the percentage of groundwater that flows into the reservoir during each time period.

Figure A-3
Primary Relationships between Parameters and Flow



To estimate each daily value of inflow, the model uses the climatic inputs for the day as well as information from preceding time periods. The primary equations used to determine the hydrologic variables are listed below. The equations make physical sense in that they allocate water into various hydrologic regimes (direct runoff, groundwater, evapotranspiration) based on climatic inputs, geographic characteristics of the basin, and the principle of mass conservation.

Available Water: $$W_t = P_t + S_{t-1} \qquad \text{(A.1)}$$

Evapotranspiration Opportunity: $$Y_t = \left[\frac{W_t + b}{2a} - \sqrt{\left(\frac{W_t + b}{2a}\right)^2 - \frac{bW_t}{a}} \right] \qquad \text{(A.2)}$$

Soil Moisture Storage: $$S_t = Y_t \exp\left(\frac{-PE_t}{b}\right) \qquad \text{(A.3)}$$

Groundwater Storage: $$G_t = \frac{c(W_t - Y_t) + G_{t-1}}{1+d} \qquad \text{(A.4)}$$

Actual Evapotranspiration: $$E_t = Y_t - S_t \qquad \text{(A.5)}$$

Flow $$Q_t = \left[(1-c)(W_t - Y_t) + dG_t\right] \qquad \text{(A.6)}$$

Each variable is expressed in units of equivalent water depth. Q_t is converted to a daily volumetric flow rate by multiplying the two terms in the equation by their respective contributory drainage areas. That is, the first term, [(1-c)(W_t – Y_t)], represents the runoff, and the second term, [dG_t] represents net groundwater inflow. Both are multiplied by the drainage area to yield a volumetric flow.

Potential evapotranspiration was estimated using the Hargreaves method (Shuttleworth, 1993):

$$PE_t = 0.0023 S_o \overline{\delta}_t (T_{av} + 17.8) \quad \text{mm/day} \tag{A.7}$$

where $\overline{\delta}_t$ is the square root of the difference between the minimum and maximum temperatures. S_o represents the solar radiation available to evaporate water, and it is expressed as a function of the relative positions of the basin and the sun:

$$S_o = 15.392 d_r (\omega_s \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_s) \quad \text{mm/day} \tag{A.8}$$

where

$$d_r = 1 + 0.033 \cos\left(\frac{2\pi J}{365}\right) \tag{A.9}$$

$$\omega_s = \arccos(-\tan\phi \tan\delta) \tag{A.10}$$

$$\delta = 0.4093 \sin\left(\frac{2\pi J}{365} - 1.405\right) \tag{A.11}$$

where J is the Julian Day (1 – 365) and Φ represents the latitude of the basin, in radians.

The model structure indicates that as temperature increases, potential evapotranspiration also increases (eqn. A.7). As potential evapotranspiration increases, soil moisture is depleted (eqn. A.3), since soil moisture is the "reservoir" from which water leaves the basin via evapotranspiration. Thus, the primary sensitivity of the model to temperature is that as temperature increases, evaporative losses increase and soil moisture is depleted more quickly. The model accounts for these variations on a daily basis.

A.2.2 Modification for Snow Accumulation and Melting

Because snow is common during New England winters, the model accommodates snow accumulation and melting. This can improve the modeling accuracy, since the timing of runoff and infiltration can be better approximated. This modification requires the addition of two final parameters; T_b and *e*. The model bases water phase on a calibrated temperature, T_b, above which precipitation falls as liquid water, and below which it falls as snow. For days when $T_{av} \leq T_b$, the model allows snow to accumulate, and precipitation is not added into the available water. When $T_{av} > T_b$, the model allows the snow to melt, and adds the meltwater, as well as any new precipitation, to the available water. The parameter *e* is termed the "melt factor," and determines the rate at which accumulated snow will melt at a particular temperature.

Table A-3 supplements Table A-1, and explains the additional variables associated with the snow model. The model equations for snow accumulation and melting are listed below the table.

Table A-3
Snow Accumulation and Melting Variables

Relationship to Water Balance	Variable Name	Variable Symbol and Description
Snow Model	Snow Accumulation	A_t = Amount of snow accumulation (when $T_{av} < T_b$)
	Snow Melt	m_t = Amount of snow melt when $T_{av} > T_b$ (becomes available water)
	Effective Precipitation	P_{eff-t} = Effective precipitation: includes daily precipitation and snowmelt

Ultimately, the *abcd* model was used only to simulate low flows in the Exeter River, which typically occur during the late summer months. Hence, the accuracy of the snow accumulation and melting simulation was not an important consideration for this study, but the simulation was included anyway because as the model was being developed, the range of its utility had not been determined.

Snow Accumulation: $A_t = A_{t-1} + P_t - m_{t-1}$ (*for* $T_{av} \leq T_b$) (A.12a)

$A_t = A_{t-1} - m_{t-1}$ (*for* $T_{av} > T_b$) (A.12b)

Snow Melt: $m_t = MIN[\, e(T_{av} - T_b),\ A_t\,]$ (*e = melt factor*) (A.13)

Effective Precipitation: $P_{eff-t} = P_t + m_t$ (*for* $T_{av} > T_b$) (A.14a)

$P_{eff-t} = 0$ (*for* $T_{av} \leq Tb$) (A.14b)

The inclusion of a temperature value that distinguishes between rain or snow also allows us to apply further temperature constraints on the model to increase the hydrologic realism. If the precipitation is frozen, the water in the upper soil is also likely frozen, and the model was constrained so that evapotranspiration does not occur when the minimum daily temperature drops below the calibrated freezing point (T_b).

A.2.3 Modifications for the Brentwood Hydropower Impoundment

The hydropower dam in Brentwood is no longer operated. For high flows, the model assumes that the dam has no impact on streamflow, and that all flow is passed through the dam. During low flow periods, however, the dam may impound some flow and prevent immediate passage downstream, despite high observed leakage rates. To simulate the reduction of flow in the river caused by the Brentwood Dam during low flow periods, a calibrated parameter was added to the model that effectively reduces the contributing drainage area upstream of the USGS gage by 38% when simulated flow in the previous timestep drops below 6 cfs. Note that this does not represent a true ratio of drainage areas. The area upstream of the dam is approximately 59.1 square miles, while the area upstream of the gaging station is 63.5 square miles. However, because of the high rates of observed leakage through the dam, the complete removal of the hydrologic contribution from upstream of the dam would have been unrealistic.

The model was also modified to account for surface evaporation from the impoundment upstream of the Brentwood Dam. The surface area of the impoundment was estimated to be approximately 19 acres.

A.3 Model Calibration and Verification

The *abcd* model was calibrated by constraining the parameters within physically plausible bounds and tuning them until the model best matched the observed data over a selected period. The calibrated model was then tested over the period of remaining data to ensure that the calibrated parameters could indeed reproduce observed daily streamflow values.

Prior to calibration, a decision was made to use the empirical relationship between the Lamprey River and the Exeter River to estimate flow in the Exeter River when flow exceeded 20 cfs. Hence, the primary focus of the calibration of the *abcd* model was to produce reasonable low-flow simulation. While not included directly in the calibration, the high-flow model performance was inspected to ensure that the annual water budgets were reasonable.

A.3.2 Calibration Technique

The model was linked to an optimization routine in order to find the optimum combination of parameters within the physical constraints applicable to this watershed. The objective was to minimize the sum of absolute model errors for the calibration period. Johnston and Pilgrim (1976) suggest that the first six time periods (days, in this case) be excluded from the sum of errors. They term this period the "warm-up" period; it allows the model to adjust for any inaccuracies in estimating the initial conditions of soil moisture and groundwater storage. For the Exeter River, the model was calibrated from June 26, 1996 through December 31, 1999, and verified from January 1, 2000 through July 31, 2002. The model was allowed to stabilize for one month, which was actually longer than the recommended 6 days.

The groundwater storage trace of the calibrated model was also compared to elevation levels of a nearby well to ensure that the simulated water table fluctuation followed observed patterns.

Model calibration and verification results are included in Section 4 of this report.

A.3.4 Assessment of Calibrated Model

Because the parameters of the model are related to physical basin characteristics, it is useful to evaluate the calibrated values with respect to expected ranges. The calibrated parameters are listed in Table A-4, and an assessment of the values follows the table.

Table A-4
Calibrated Model Parameters

Parameter	Primary Relationship to Flows	Typical Values for Northeast US	Calibrated Value for Spot Pond
a	Propensity to runoff before soil is saturated (1 is low, 0.95 is high)	0.97 – 1.00*	0.99988
b	Upper limit on annual soil moisture influx plus annual evapotranspiration (in equivalent inches)	8 – 23* (may approach annual precipitation for basins with high holding capacity)	17.32
c	Percentage of soil moisture, after evapotranspiration, that recharges groundwater instead of running off.	0.15 – 0.59* (must be <1)	0.449
d	Percentage of groundwater that flows into reservoir each day	0.16 – 0.33* (must be <1)	0.110
e	Snow melt rate	0.4 – 2.1* (1.82 recommended for northeast Canadian forests**)	0.066
T_b	Temperature below which precipitation falls as snow	-2°C …-3°C* (could reasonably be any value near 0°C)	0°C

**compiled from four calibrated abcd models for Massachusetts rivers (Westphal, 2001)*
***typical values from literature, as close as possible to New England*

Parameter *a:*
For basins with relatively flat relief, such as the Exeter River Basin, the value of *a* usually falls between 0.97 and 1.00. This means that precipitation is more likely to infiltrate into the upper soil layer than to runoff immediately. The calibrated value for the Exeter River of 0.99988 is extremely close to 1 (the model performance is very sensitive to this parameter, and five

decimal places is not an unrealistic level of precision). A high infiltration rate is compatible with the dominant land uses within the mostly rural watershed.

Parameter *b:*
The parameter *b* reflects the ability of the soil to hold moisture. The high value of parameter *a* suggests that the soil has a high holding capacity, since precipitation is very likely to infiltrate the soil rather than run off immediately. Basins with high infiltration rates may actually have a holding capacity in the soil that is roughly equivalent to the annual precipitation. This does not mean that moisture is stored in the soil for one year, nor does it mean that no flow occurs until the soil is fully saturated. Rather, the high infiltration rate suggests that a lot of water is required to saturate the upper soil layer. For the Exeter River, the calibrated value of parameter *b* is toward the high end of the range of this parameter for other calibrated models in New England, and it is compatible with the high value of parameter *a.*

Parameter *c:*
The parameter *c* divides the soil moisture, after evapotranspiration, between groundwater recharge and runoff. There are no geologic or topographic characteristics of the basin with which to assess the validity of the calibrated value of 0.449, but by definition, the value must be between 0 and 1. However, assuming that groundwater plays an important role in providing water to the stream (based on the calibrated values of *a* and *b* that suggest high infiltration rates and low rates of immediate runoff), it is not unreasonable to suggest that a high percentage of the soil moisture is routed into the simulated groundwater storage variable, which is what the calibrated value of 0.449 does. Phrased another way, this suggests that much of the water stored in the soil infiltrates to the groundwater storage below, eventually to flow into the reservoir. The value of parameter *c* for the Exeter River is compatible with the range observed in four other calibrated *abcd* models from Massachusetts.

Parameter *d*:
The parameter *d* is the net fraction of groundwater storage that flows into the reservoir on a daily basis (it must be between 0 and 1). The value of 0.11 signifies that flow passes into the river slowly after infiltrating through the soil into the groundwater aquifer. The calibrated value is slightly below the range of values collected from calibrated models in Massachusetts.

Parameter *e*:
The parameter *e* is the "melt factor," and governs the rate at which snow will melt based on the daily temperature. The calibrated value of 0.066 is actually not realistic, but in inconsequential to the development of the Exeter River model because this model focuses only on low flows, which occur long after the snow has melted.

Parameter T_b:
The parameter T_b is the average daily temperature below which precipitation will fall as snow. Again, this value has no impact on the Exeter Safe Yield study, but was calibrated at the expected value of 0 degrees Celsius.

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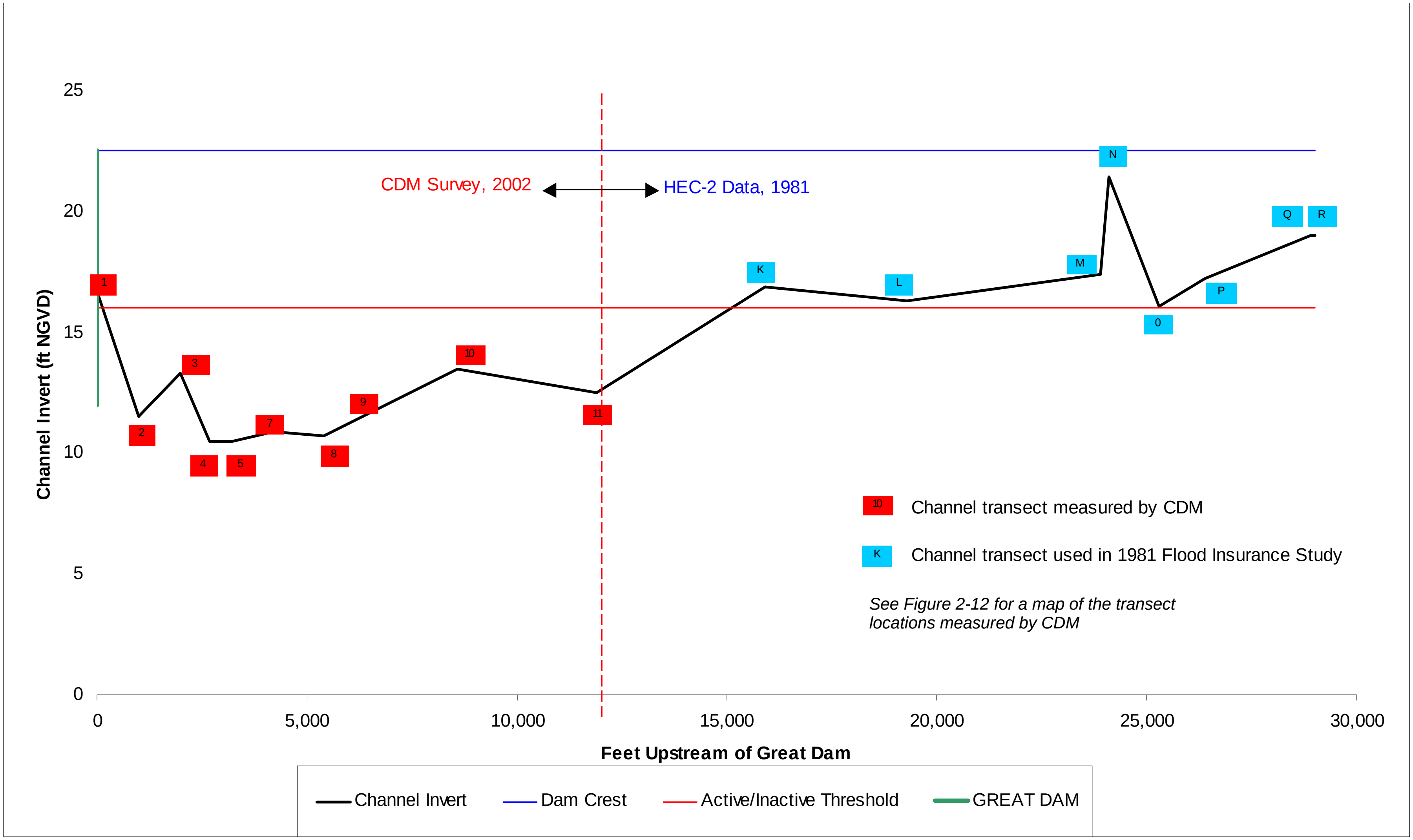
APPENDIX B

Bathymetric Data for Exeter River

This data was collected by CDM as part of this study. Data from FEMA Flood Insurance Studies were used to augment this field data.

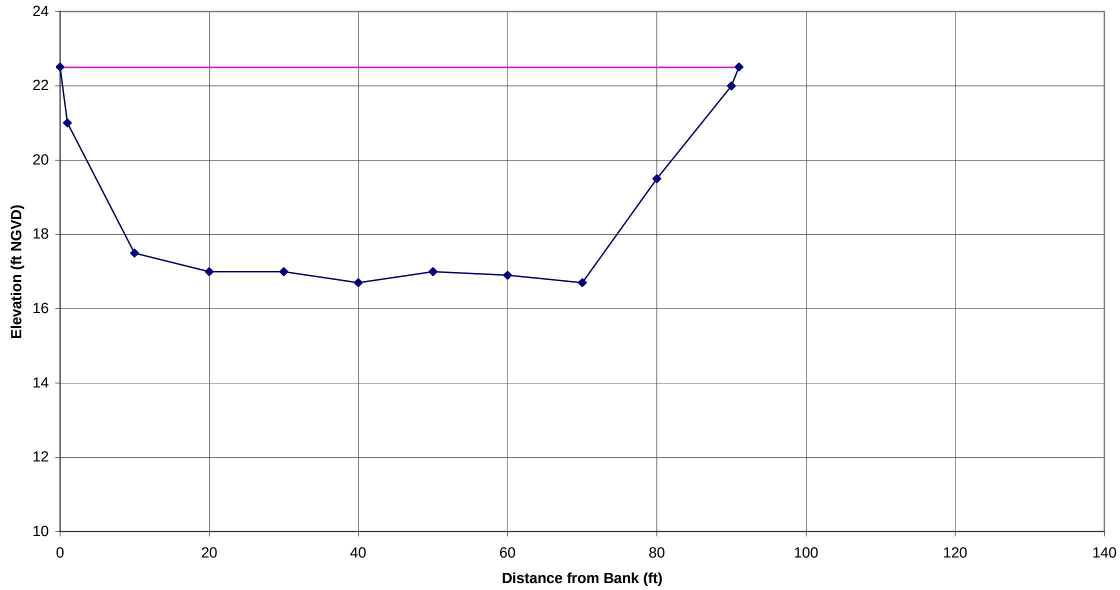
Water surface elevations are shown at the level of the Great Dam Crest (22.5 feet).



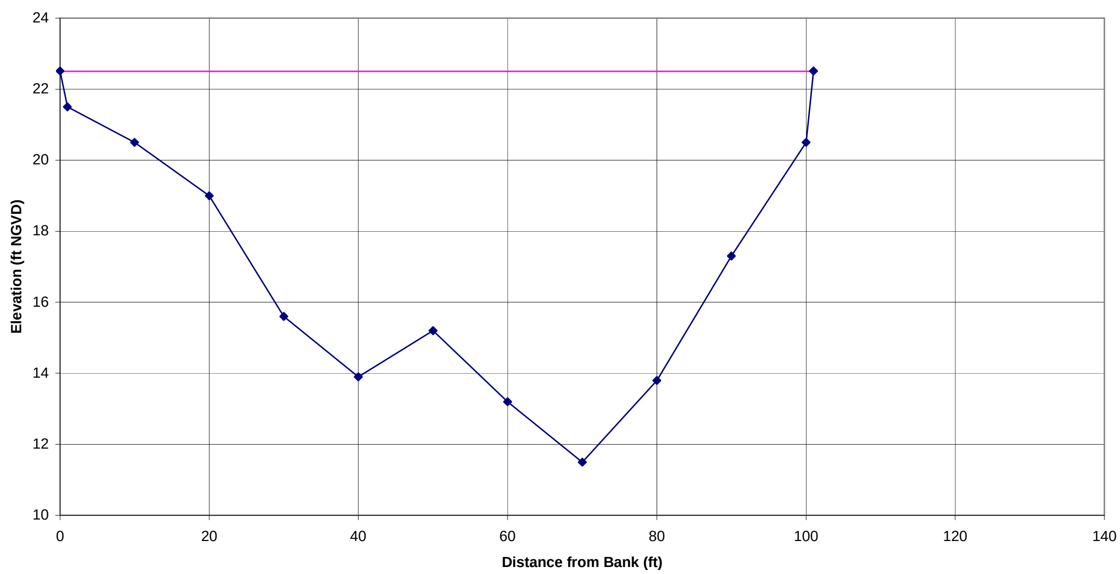
Channel Invert Profile for Great Dam Impoundment

Cross Sectional Graphs are shown for Sections 1-11 on the following pages

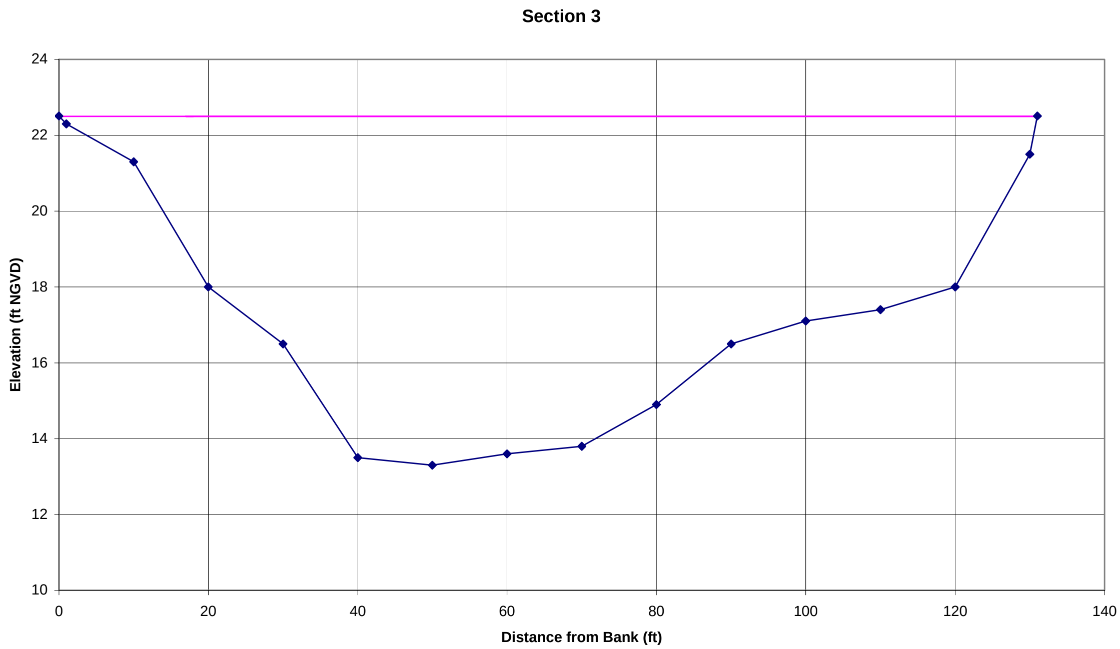
Section 1



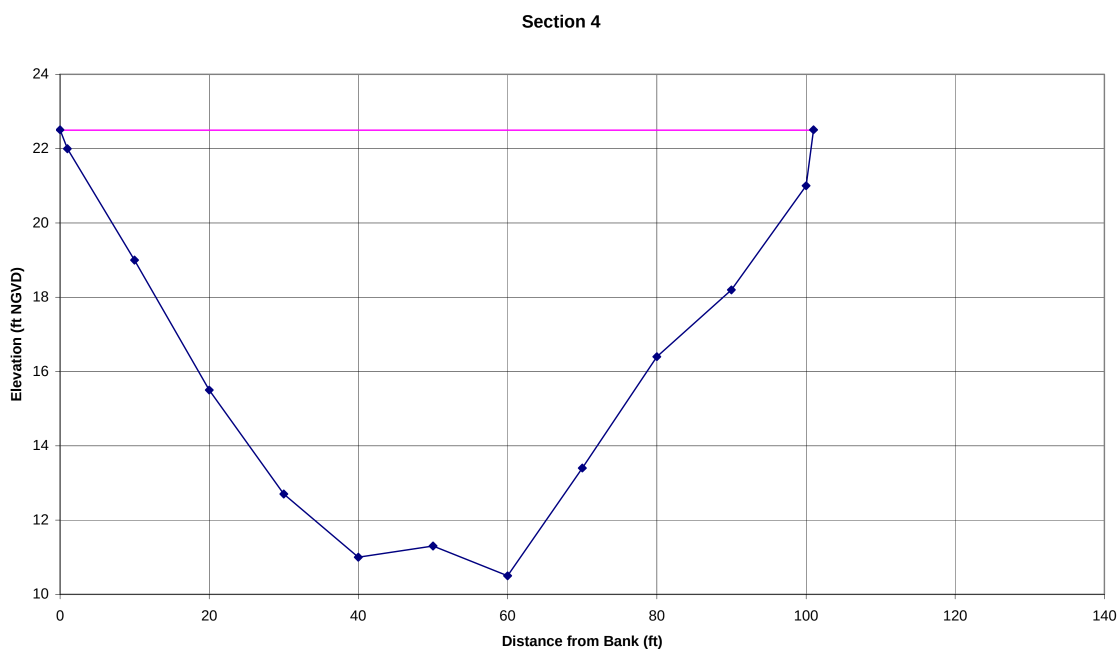
Section 2



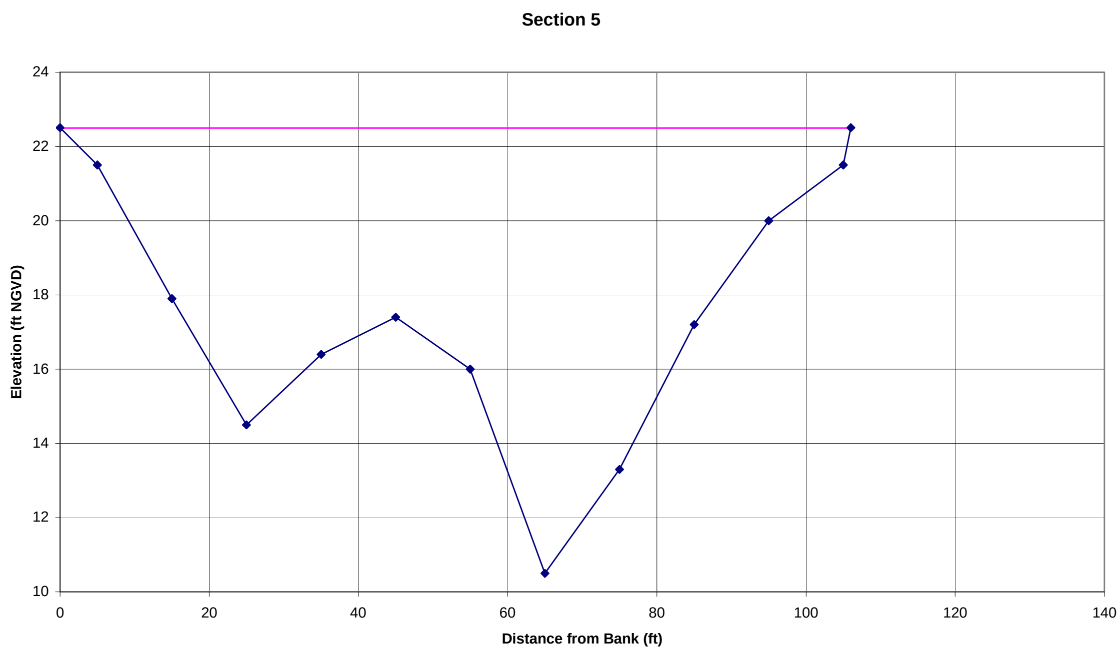
Views are shown looking upstream.



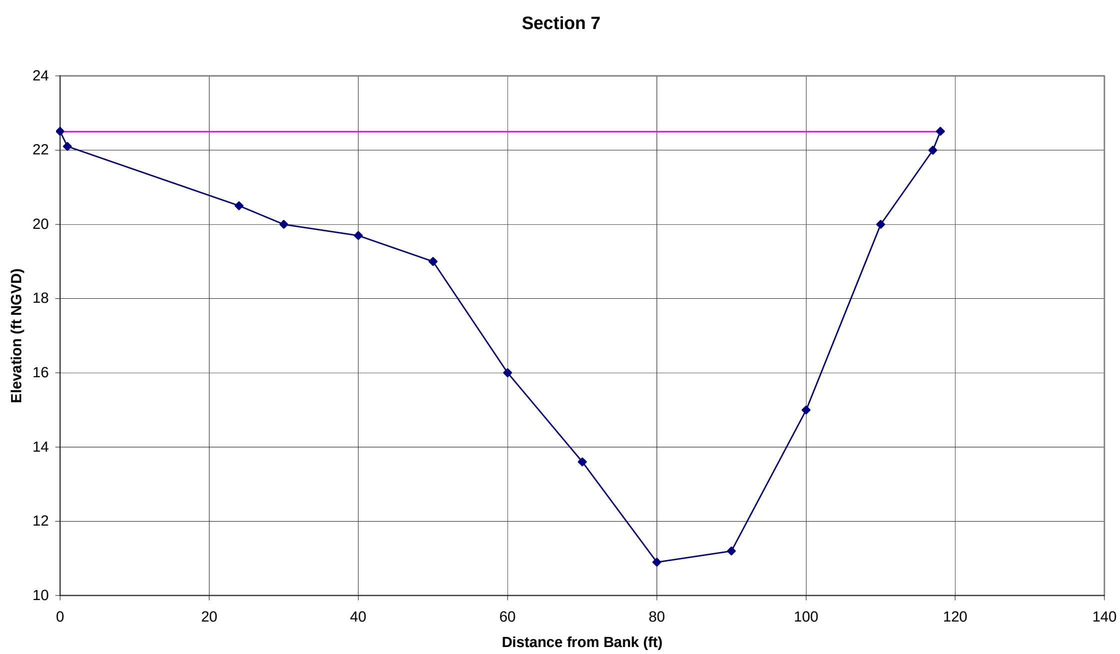
Section 3
Elevation (ft NGVD)
Distance from Bank (ft)
24
22
20
18
16
14
12
10
0
20
40
60
80
100
120
140



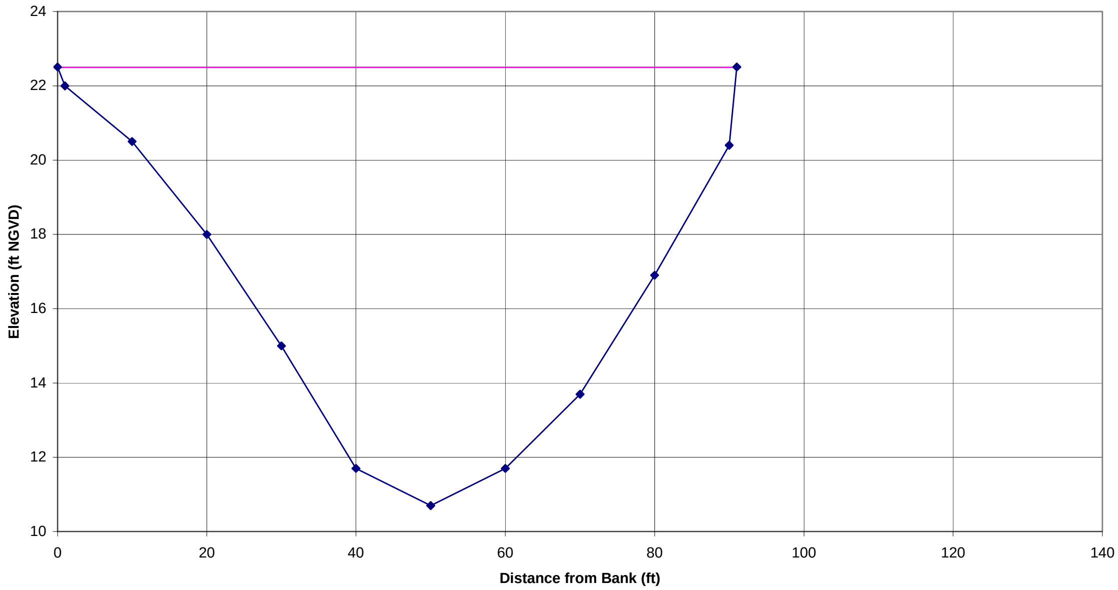
Section 4
Elevation (ft NGVD)
Distance from Bank (ft)
24
22
20
18
16
14
12
10
0
20
40
60
80
100
120
140



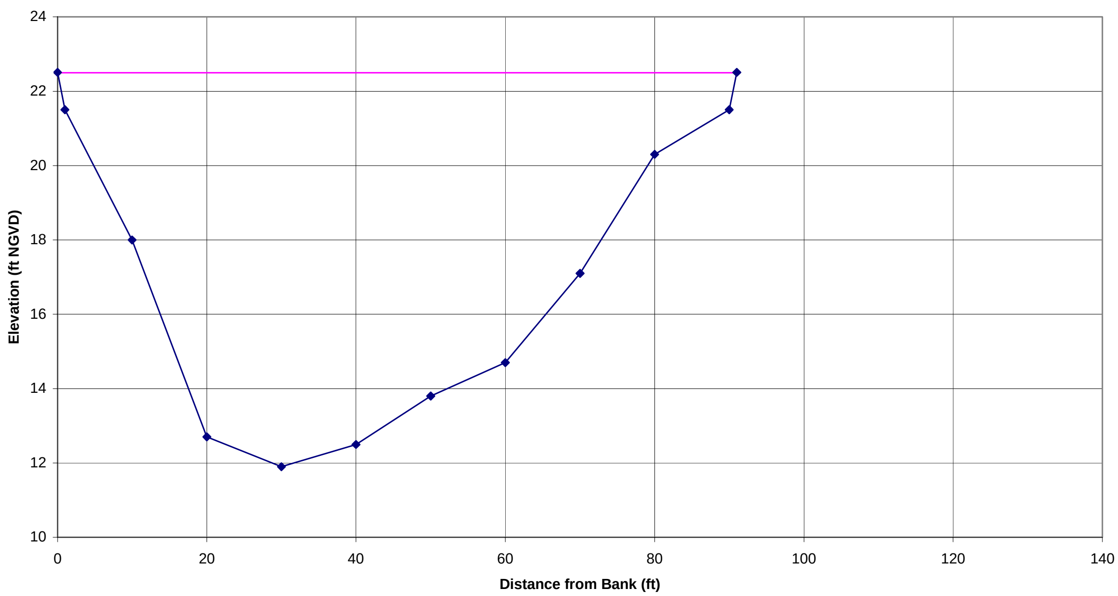
(The section identified as "6" is on a tributary)

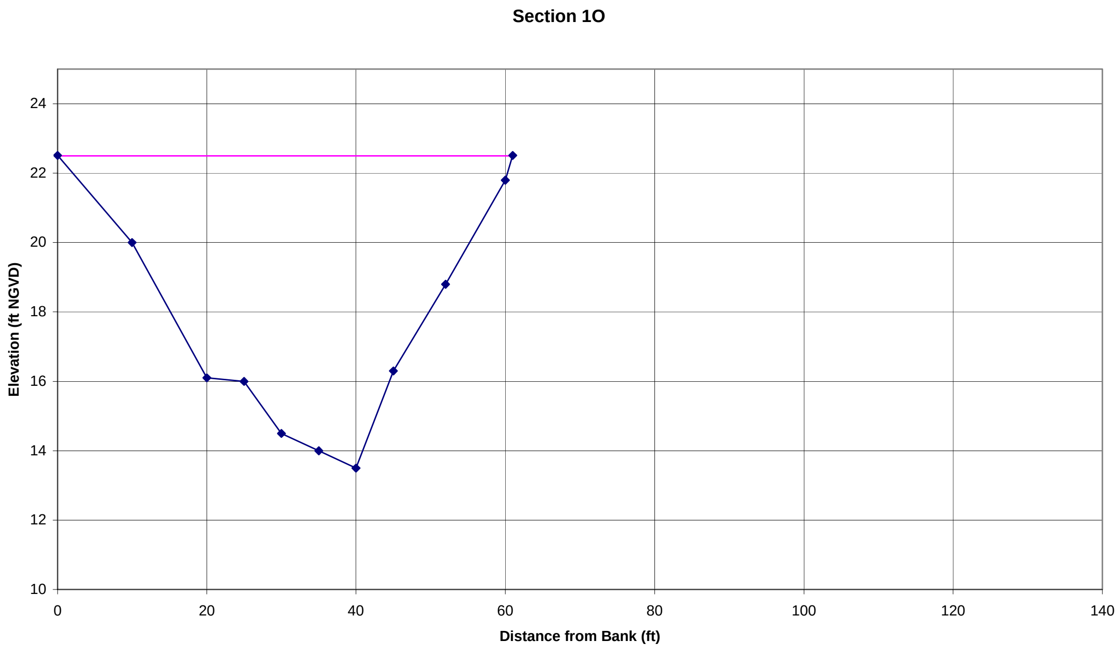


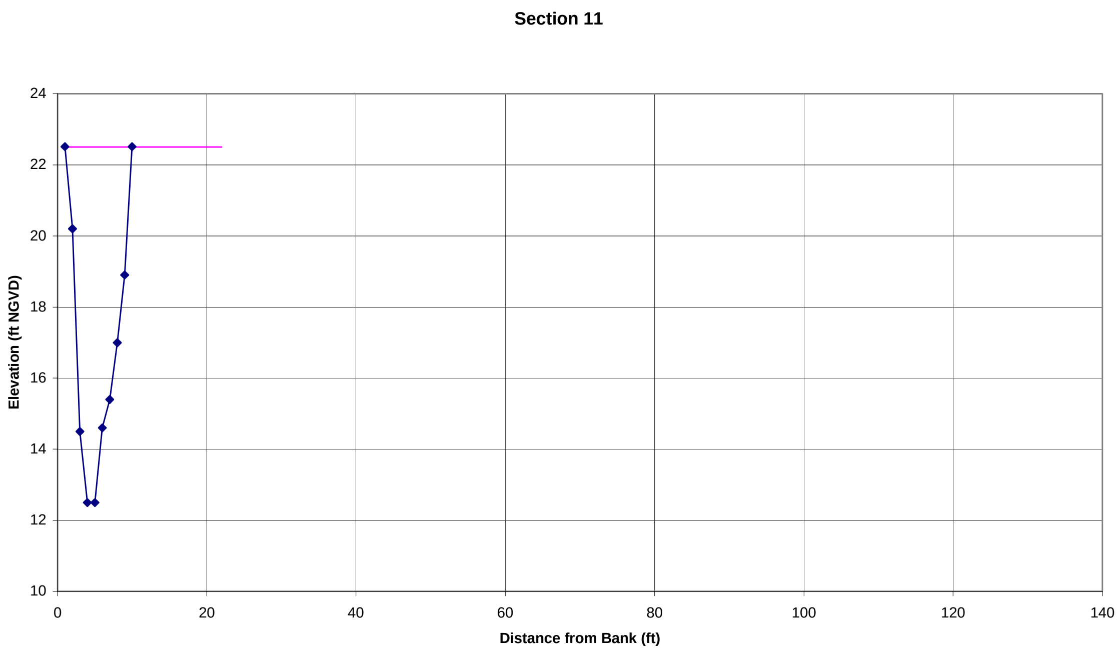
Section 8



Section 9




Section 1O
Elevation (ft NGVD)
Distance from Bank (ft)
10
12
14
16
18
20
22
24
0
20
40
60
80
100
120
140


Section 11
Elevation (ft NGVD)
Distance from Bank (ft)
10
12
14
16
18
20
22
24
0
20
40
60
80
100
120
140

APPENDIX C

Calculations of Head Loss at Exeter Reservoir Intake

Exeter Reservoir Intake Works Kirk Westphal, 12/2/02
Head Loss Computation

See attached sketches for system description.

The friction factors and loss coefficients are based on CDM calculations by Al LeBlanc, dated 12/15/00. The values are based on a flow of 3.4 MGD through the WTP. Although Reynolds numbers will vary with different flow rates, the friction factors are assumed to be reasonably constant for this analysis.

Notation begins at reservoir, and ends at the WTP intake chamber weir.

Specify Flows for Head Loss Analysis:

$$Q := \begin{pmatrix} 1 \\ 2 \\ 3 \\ 3.4 \\ 4 \\ 5 \end{pmatrix} \quad \text{mgd}$$

Pipe Diameters (feet, in series):

$$D_1 := \frac{16.3}{12} \qquad D_2 := \frac{24.56}{12} \qquad D_3 := \frac{12.14}{12} \qquad D_4 := \frac{24.56}{12} \qquad D_5 := \frac{20.44}{12}$$

Pipe Lengths (linear feet, in series):

$$L_1 := 30 \qquad L_2 := 26 + 11 \qquad L_3 := 30 \qquad L_4 := 6 + 8 + 14 + 4 + 6 \qquad L_5 := 6 + 5$$

(Note: L1 is the same for 2 inlet pipes of D1 in parallel - assume flow thru one pipe only.)

Pipe Areas (sq ft)

$$A_1 := \pi \cdot \left(\frac{D_1}{2}\right)^2 \qquad A_2 := \pi \cdot \left(\frac{D_2}{2}\right)^2 \qquad A_3 := \pi \cdot \left(\frac{D_3}{2}\right)^2 \qquad A_4 := \pi \cdot \left(\frac{D_4}{2}\right)^2 \qquad A_5 := \pi \cdot \left(\frac{D_5}{2}\right)^2$$

Pipe Velocities (fps)

$$V_1 := \frac{1}{1} \cdot \frac{Q}{0.646} \cdot \frac{1}{A_1} \qquad V_2 := \frac{Q}{0.646} \cdot \frac{1}{A_2} \qquad V_3 := \frac{Q}{0.646} \cdot \frac{1}{A_3} \qquad V_4 := \frac{Q}{0.646} \cdot \frac{1}{A_4} \qquad V_5 := \frac{Q}{0.646} \cdot \frac{1}{A_5}$$

Velocity Summary (fps):

$$V_1 = \begin{pmatrix} 1.068 \\ 2.136 \\ 3.205 \\ 3.632 \\ 4.273 \\ 5.341 \end{pmatrix} \quad V_2 = \begin{pmatrix} 0.471 \\ 0.941 \\ 1.412 \\ 1.6 \\ 1.882 \\ 2.353 \end{pmatrix} \quad V_3 = \begin{pmatrix} 1.926 \\ 3.852 \\ 5.777 \\ 6.548 \\ 7.703 \\ 9.629 \end{pmatrix} \quad V_4 = \begin{pmatrix} 0.471 \\ 0.941 \\ 1.412 \\ 1.6 \\ 1.882 \\ 2.353 \end{pmatrix} \quad V_5 = \begin{pmatrix} 0.679 \\ 1.359 \\ 2.038 \\ 2.31 \\ 2.717 \\ 3.397 \end{pmatrix}$$

Friction Factors (assume relatively constant for all flows):

$f_1 := 0.020 \quad f_2 := 0.019 \quad f_3 := 0.021 \quad f_4 := 0.019 \quad f_5 := 0.019$

Miner Losses:

Pipe 1 (16"):

$K_{1ent} := 0.78 \quad K_{1valve} := 0.35 \quad K_{1exit} := 1.0$

$K_1 := K_{1ent} + K_{1valve} + K_{1exit}$

$K_1 = 2.13$

Pipe 2 (24"):

$K_{2ent} := 0.78 \quad K_{2.90bend} := 0.36 \quad K_{2.45bend} := 4 \cdot 0.36$

$K_2 := K_{2ent} + K_{2.90bend} + K_{2.45bend}$

$K_2 = 2.58$

Pipe 3 (12"):

$K_{3red} := 0.29 \quad K_{3valve} := 0.35 \quad K_{3exp} := 0.43$

$K_3 := K_{3red} + K_{3valve} + K_{3exp}$

$K_3 = 1.07$

Pipe 4 (24"):

$K_{4.90bend} := 2 \cdot 0.36 \quad K_{4valve} := 0.10 \quad K_{4tee} := 0.72$

$K_4 := K_{4.90bend} + K_{4valve} + K_{4tee}$

$K_4 = 1.54$

Pipe 5 (20"):

$K_{5red} := 0.1 \quad K_{5.90bend} := 0.36 \quad K_{5exit} := 1.0$

$K_5 := K_{5red} + K_{5.90bend} + K_{5exit}$

$K_5 = 1.46$

Gravitational Constant: $g := 32.2$

TOTAL HEAD LOSS CALCULATIONS:

Frictional Losses:

$$h_{Lf} := \left(f_1 \cdot \frac{L_1}{D_1} \cdot \frac{V_1^{\,2}}{2 \cdot g}\right) + \left(f_2 \cdot \frac{L_2}{D_2} \cdot \frac{V_2^{\,2}}{2 \cdot g}\right) + \left(f_3 \cdot \frac{L_3}{D_3} \cdot \frac{V_3^{\,2}}{2 \cdot g}\right) + \left(f_4 \cdot \frac{L_4}{D_4} \cdot \frac{V_4^{\,2}}{2 \cdot g}\right) + \left(f_5 \cdot \frac{L_5}{D_5} \cdot \frac{V_5^{\,2}}{2 \cdot g}\right)$$

Miner Losses:

$$h_{Lm} := K_1 \cdot \frac{V_1^{\,2}}{2 \cdot g} + K_2 \cdot \frac{V_2^{\,2}}{2 \cdot g} + K_3 \cdot \frac{V_3^{\,2}}{2 \cdot g} + K_4 \cdot \frac{V_4^{\,2}}{2 \cdot g} + K_5 \cdot \frac{V_5^{\,2}}{2 \cdot g}$$

Venturi Head Loss:

$Q_{design} := 4.3$ mgd $\qquad h_{L.vent.design} := \frac{7.8}{12}$

$$h_{Lvent} := \left(\frac{Q}{Q_{design}}\right)^2 \cdot \left(h_{L.vent.design}\right)$$

Total Head Loss:

$$h_{Lt} := h_{Lf} + h_{Lm} + h_{Lvent}$$

For Q in mgd:

$$Q = \begin{pmatrix} 1 \\ 2 \\ 3 \\ 3.4 \\ 4 \\ 5 \end{pmatrix} \quad h_{Lf} = \begin{pmatrix} 0.047 \\ 0.188 \\ 0.423 \\ 0.543 \\ 0.751 \\ 1.174 \end{pmatrix} \quad h_{Lm} = \begin{pmatrix} 0.124 \\ 0.496 \\ 1.116 \\ 1.433 \\ 1.984 \\ 3.1 \end{pmatrix} \quad h_{Lvent} = \begin{pmatrix} 0.035 \\ 0.141 \\ 0.316 \\ 0.406 \\ 0.562 \\ 0.879 \end{pmatrix} \quad h_{Lt} = \begin{pmatrix} 0.206 \\ 0.824 \\ 1.855 \\ 2.383 \\ 3.298 \\ 5.153 \end{pmatrix}$$

Computation of Required Reservoir Elevation :

Head on Intake Chamber Weir: (sharp-crested)

Weir Length (ft): $L := 8$

Initialize Head: $H := 1$

For flow (Q) in mgd:

$$H_{weir} := \left(\frac{Q}{2.152 \cdot L}\right)^{.667}$$

$$Q = \begin{pmatrix} 1 \\ 2 \\ 3 \\ 3.4 \\ 4 \\ 5 \end{pmatrix} \qquad H_{weir} = \begin{pmatrix} 0.15 \\ 0.238 \\ 0.312 \\ 0.339 \\ 0.378 \\ 0.438 \end{pmatrix}$$

$Crest_{weir} := 17.55$ feet

Reservoir Elevation

$$ELEV := Crest_{weir} + H_{weir} + h_{Lt}$$

$$Q = \begin{pmatrix} 1 \\ 2 \\ 3 \\ 3.4 \\ 4 \\ 5 \end{pmatrix} \qquad ELEV = \begin{pmatrix} 17.906 \\ 18.612 \\ 19.717 \\ 20.271 \\ 21.225 \\ 23.141 \end{pmatrix}$$