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## Doing More with What You Have –
## *Using Custom Daily Flow Models for Source Water Investigations*

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## ABSTRACT

Water supply providers are facing increasing difficulty expanding their water supply systems to satisfy growing population and industry demands. Developing a new or expanding an existing water supply source to satisfy growing demands is often an arduous process met with opposition. Many water supply managers are simply directed to "*do more with what you have*". In some cases, water suppliers find themselves operating beyond the safe yield of their system and must rely on conservation measures to satisfy demands during severe droughts. Operating a water supply system this close to the edge of its reliable limits requires accurate knowledge of the safe yield and a thorough understanding of how the system performs during drought events.

The authors have performed detailed water supply studies for over forty systems that vary in complexity from multiple reservoirs, river intakes, and wells working in conjunction, to simple single reservoir systems. The safe yield analyses involved developing a custom computer model of the system and simulating daily operation for a lengthy period of historical hydrologic record, often exceeding 80 years. These site-specific computer models are capable of simulating a variety of operating assumptions, variations in demand, conservation measures, complex regulatory restrictions, water quality parameters, and many other factors.

In addition to estimating safe yield, daily flow models can:

- Identify current and future supply surplus or deficit,
- Guide and optimize day-to-day operations,
- Perform statistical and economic analyses of system operation,
- Develop drought probability relationships to evaluate system reliability and resiliency,
- Test conservation plans, and
- Facilitate risk-based decision making.

This paper summarizes the process of creating a daily flow model and demonstrates how such models can help water supply managers "*do more with what they have*." It also discusses lessons learned from case studies and the need to present safe yield in the context of probability rather than as a single value.

**INTRODUCTION: WHAT IS A DAILY FLOW MODEL?**

A daily flow model is a custom computer model that is programmed to simulate the daily operation of a specific raw water system. In most cases, the primary purpose of the model is to simulate the existing operation of the system, including site specific conditions and operating procedures, for a lengthy period of record to determine the safe yield. The definition of safe yield (as noted in Title 27 of the Pennsylvania General Assembly) is *"the amount of water that can be withdrawn from a water resource over a period of time without impairing the long-term utility of a water resource… Safe yield of a particular water source is primarily determined based upon the predictable rate of natural and artificial replenishment of the water source over a reasonable period of time."* Industry practice is to evaluate operation of a water system for as long a period of record for which reliable streamflow data is available. Evaluating a longer "period of time" provides greater confidence in the safe yield estimation. For practical purposes, the drought of record for the mid-Atlantic region of the country is commonly found to occur in the 1930s, 1960s or early 2000s.

Secondary benefits of such models include the ability to compute the safe yield for different assumptions, simulate conservation and drought contingency measures, evaluate expansion alternatives, and explore variations of the operating criteria to maximize existing supply sources. Such models also allow safe yield to be understood in terms of probability rather than as a single, absolute value. This is important because droughts that are more severe than the drought of record will invariably occur. Understanding the frequency of droughts and the corresponding safe yield values can help water suppliers plan for the future and maximize beneficial use.

Many water supply systems are very complex and have variable low-flow release requirements, exhibit significant predictable variations in monthly demand, involve conjunctive use with river intakes, reservoirs, and wells, and have transmission limitations and water quality issues that must be considered in the analyses. By using custom code, any infrastructure constraints, operating rules, or other unique features can be modeled for even extremely complex systems involving multiple storage facilities, intakes, interconnections, and points of supply. See Figure 1 for an example of the level of system complexity that can be simulated. For these systems, the computer simulation must be performed on a daily basis to accurately represent all of the operating decisions, and the temporal variations in the hydrologic inputs. Other time-dependent variables such as reservoir evaporation, available withdrawal at an intake, spillway losses, and the point at which all of the useable storage is depleted can also be more accurately computed.

Hydrologic input for a daily model includes the daily inflows into the reservoir(s), the river flows at the intake(s), and net evaporation rates for the entire period of historical record. The determination of safe yield and other water supply system statistics requires extensive hydrological and climatological data to accurately identify critical drought periods and to determine the availability of water at each source. Developing a reliable hydrologic database for the study or understanding the possible uncertainty in the database is critical as the accuracy of the analyses will only be as good as the hydrologic data used in the model.

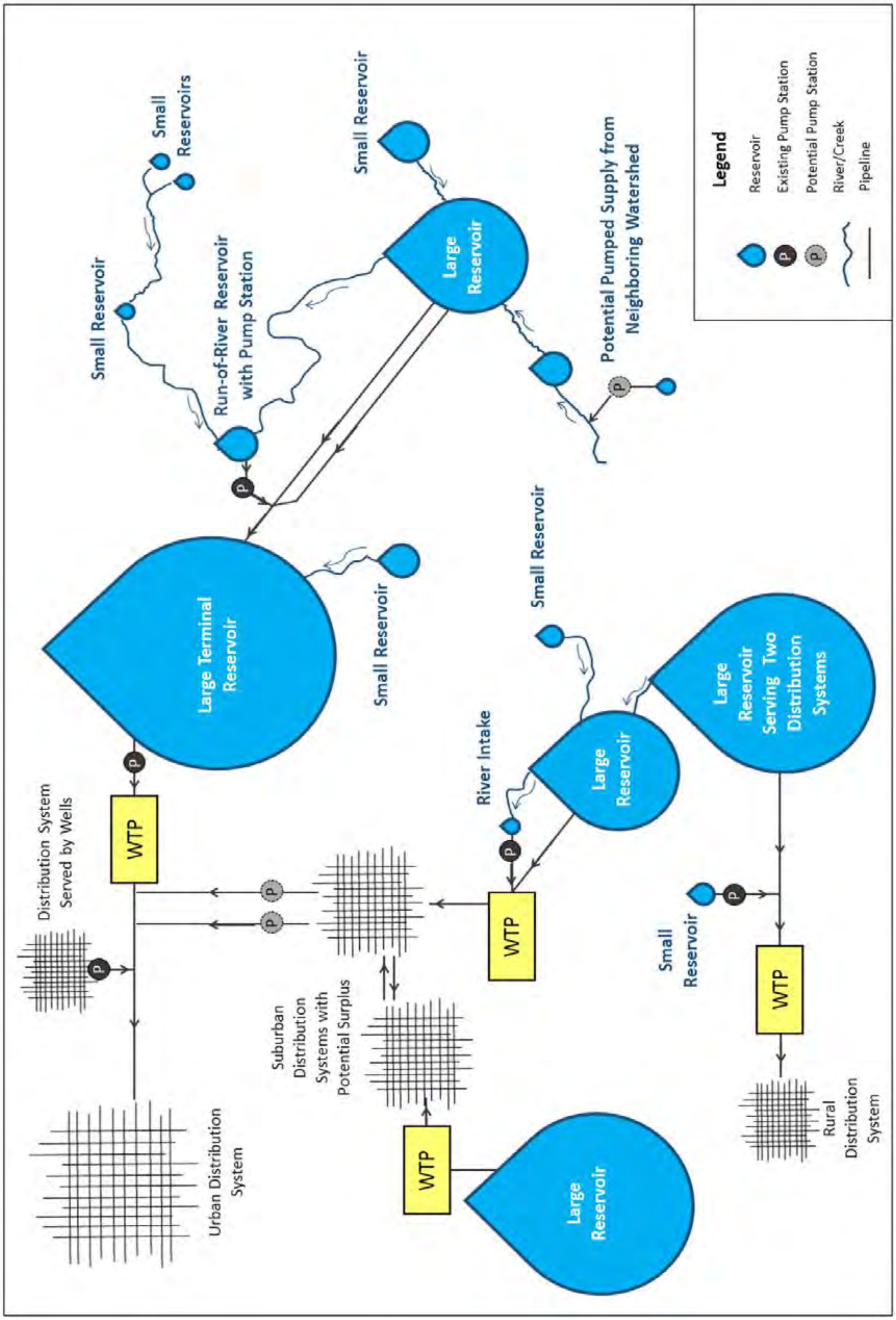


**Figure 1 – Sample System Complexities That Can Be Included in a Custom Daily Flow Model**

In a typical analysis, a custom daily model will calculate millions of data points as it integrates both the system data and operating rules and the hydrologic data over the selected period of record. The daily output from the simulations can be plotted and presented graphically to evaluate the long-term performance of the system, including the frequency of occurrence and duration of various conditions, and the effectiveness of operating practices such as the implementation of conservation measures during severe drought events. An example of the graphical output that can be derived from a typical daily flow model is included in Figure 2.

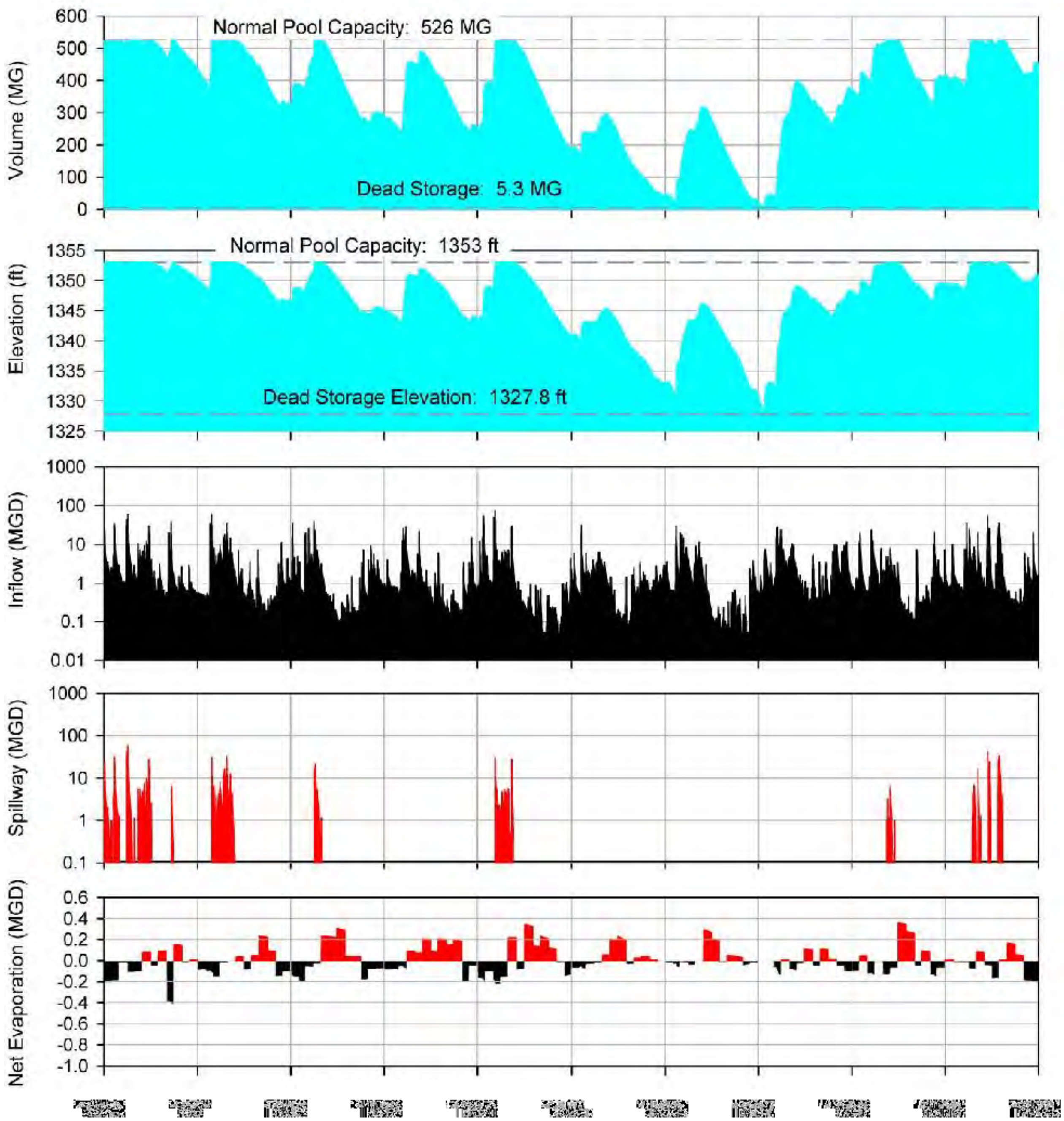


**Figure 2 – Typical Graphical Output Generated from a Custom Flow Model**

## IMPORTANT MODEL COMPONENTS AND ASSUMPTIONS

The accuracy of an analysis is dependent on representative inputs and sound assumptions. Hydrologic data such as stream flows at river intakes, reservoir inflows, and net evaporation from reservoirs provide the basis for natural supply limitations. Additional system-specific data including stage-storage-surface area relationships of storage facilities and pump intake capacities are used to define the physical or operational limitations of the supply system. System operating rules including permitted withdrawal limitations or flowby requirements are applied within the model code to reflect how the system would respond to any scenario ranging from a wet year to the drought of record. The following section discusses several components and assumptions relating to model development that are critical to the accuracy of the model.

***Daily Time Step.*** Due to the computational constraints and data limitations at the time, past safe yield analyses may have been based on coarse monthly data; however, the use of a monthly time increment in a flow model compromises the accuracy and reliability of the analysis. Not only does a monthly time step not account for the obvious temporal variation in the variables, but may actually result in the overestimation of the system safe yield. As the duration of the time step used in the analysis increases, the magnitude of the inflow data tends toward the mean and attenuates short duration high- and low-flow events. The end result is the inability to accurately pinpoint the beginning and ending of the drought of record, and the underestimation of the severity of the drought. In addition, source water systems with complex operating criteria cannot be accurately modeled with monthly time steps.

For example, a complex system comprised of a dam and a river intake that has a minimum flowby requirement based on river discharges at the intake and reservoir stages cannot be accurately modeled using a monthly time step. As a drought intensifies, the daily river discharges within a given month may fall below the trigger point requiring low-flow augmentation through reservoir releases. With a monthly time step, the average monthly flow may remain above the trigger point, completely neglecting the required releases from storage and erroneously reporting an inflated system safe yield. Similarly, at the river intake, intense runoff events of short duration during a drought period can create conditions where the flow at the river intake exceeds the flowby requirement and the draft rate at the intake, and the excess flow is lost from the system. Using a monthly time step, the river flows are averaged, and the flow that is lost from the system can be erroneously computed to be available for supply. Figure 3 illustrates this condition and the importance of a daily time step.

***Net Evaporation.*** Evaporation can play a significant role, especially in systems with shallow reservoirs that store more than a year's supply of water. In one case, the authors observed that the average monthly gross evaporation from a network of supply reservoirs was as high as 15 MGD. Accounting for seasonal variations in evaporation rates is important since maximum evaporative losses frequently coincide with periods of greatest demand and drought. One common oversight in accounting for evaporation losses is the use of gross evaporation rather than net evaporation. Net evaporation is the difference between the gross evaporation from the reservoir and the direct precipitation onto the reservoir. Using gross evaporation alone ignores the direct precipitation over the reservoir, overestimates the net evaporative losses, and underestimates the safe yield of the system.

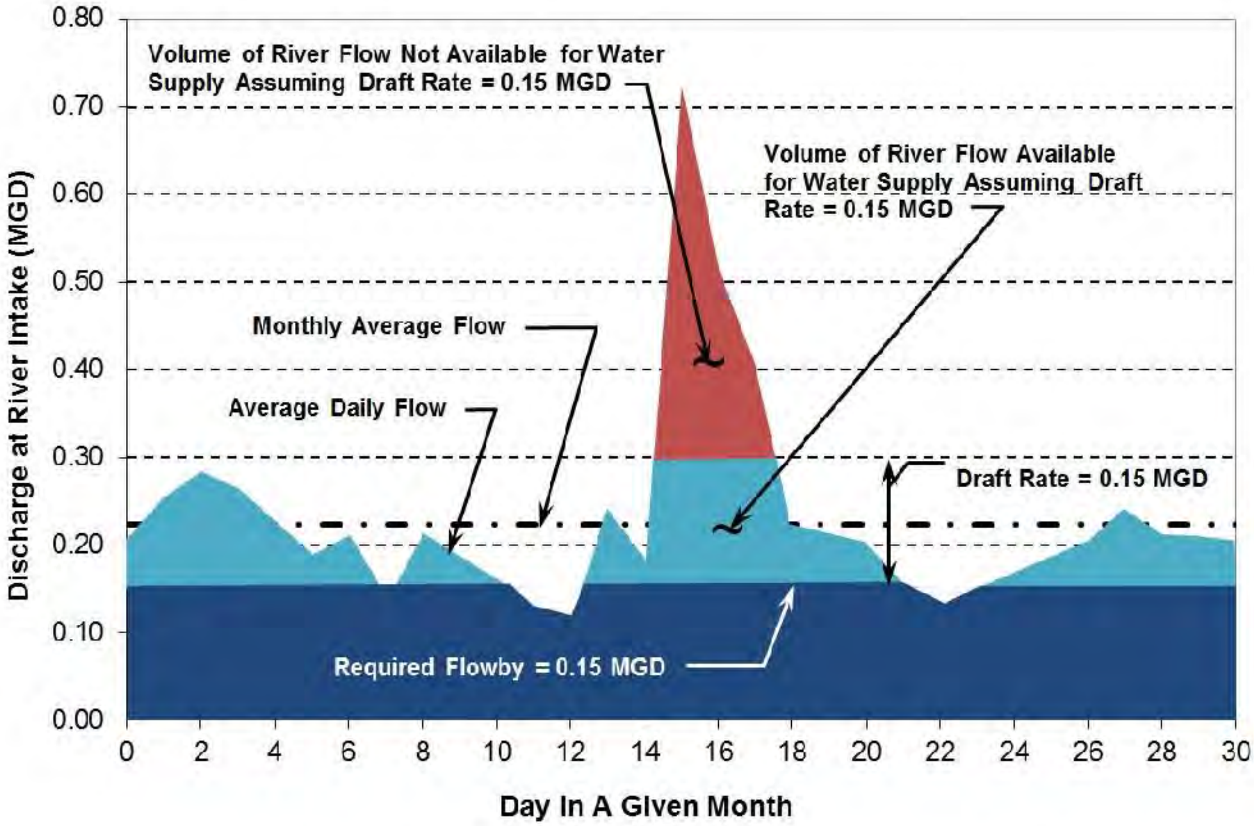


**Figure 3 – Example of Potential Overestimation of Available Source Water from a Combined River Intake and Reservoir System by Using a Monthly Time Step Instead of a Daily Time Step**

***Inflow Data.*** Developing the inflow data for the model is the most important part of a safe yield study. The inflow data should be continuous throughout a long period of historical record, and should be extensively scrutinized to make sure that it is as accurate as possible. A long-term continuous record is important because in both simple and complex systems the "drought of record" is a function of the usable reservoir storage of the system. For some systems, the usable storage is so large relative to the contributing drainage area that the reservoir(s) can store more than a year's flow, and the worst drought may last several years. For systems with relatively small reservoir storage, the worst drought may last only several months. Without a continuous long-term flow record, it is difficult to identify the drought of record, especially if the safe yield is being computed for a variety of reservoir storage conditions. For studies where increasing the storage capacity of an existing reservoir is being analyzed, the period corresponding to the "worst drought" may actually change based on the expansion alternative. Having a model with a continuous long-term record eliminates the need to independently analyze individual drought events and make assumptions concerning antecedent reservoir storage conditions.

Ideally, unregulated streamflow data can be obtained from stream gages within the watershed of interest. Completeness of the inflow data over the entire period of record (usually extending back to at least 1930) is also essential. Any data that is missing or of poor or questionable quality should be checked or reconstituted using the best, most representative statistical method. To supplement the data available from the selected gages or in the case where there are no stream flow gages in the immediate vicinity of the system under study, statistical analyses can be completed with other nearby long-term stream gages. A common practice in water supply investigations is to simply transpose the streamflows from the closest gaging station with the longest record to the study watershed. However, when sufficient system data exists, it is prudent to use this data to verify the applicability of making a simple linear transposition of the streamflow data, or to develop a more accurate correlation through statistical analyses. This may include developing special statistical relationships for low-flow conditions that are different than the flow relationships for average or above average flow conditions. Graphical plots of streamflow data in the form of scatter graphs are recommended to determine the need for developing special low-flow relationships (See example correlation plot in Figure 4). It is important that the low-flow values be truly representative of the actual flow conditions because these are the flows that will determine the safe yield of the system.

Rather than just selecting the nearest gage or using engineering judgment to select the most representative gage, it can also be beneficial to develop multiple streamflow datasets based on several nearby gages. This is especially important in ungaged watersheds where no runoff records are available. By developing and analyzing multiple datasets, a range of safe yield estimates can be obtained. This provides some level of confidence in the analysis and an understanding of the level of uncertainty of the safe yield estimate for the ungaged watershed. Ultimately, the most appropriate stream gage for a given reservoir or stream can be selected based on a broad range of watershed characteristics and low flow statistics. In the authors' experience, some of the factors which have the best correlation to safe yield, and therefore should have the highest weight in this selection process, include mean annual precipitation, mean watershed elevation, percent of forested area within the watershed, and the minimum average flow for 90 consecutive days, expected to occur once every ten years (or "Q90,10" as estimated using the regression method summarized in *USGS Scientific Investigations Report 2006-5130*).

***System Interconnections and Synergism.*** When the two independent sources of supply are combined or connected, the hydrologic conditions that determine the safe yield of each system become moderated and produce a combined effect where the total system safe yield is greater than the sum of the safe yields of the individual systems. Because the duration and timing of the worst drought of record for the individual systems is somewhat different, the synergy of the two systems operating in tandem provides opportunity for the moderation and mitigation of these events.

A system behaves synergistically when the safe yield obtained by operating all the system components together is greater than the sum of the safe yields determined for the individual parts of the system. This synergistic effect can have a substantial impact on safe yield, and can be directly impacted by system operation. Because of the potential for synergy, it is important that all system components and operating rules be analyzed as a whole and not as individual entities.

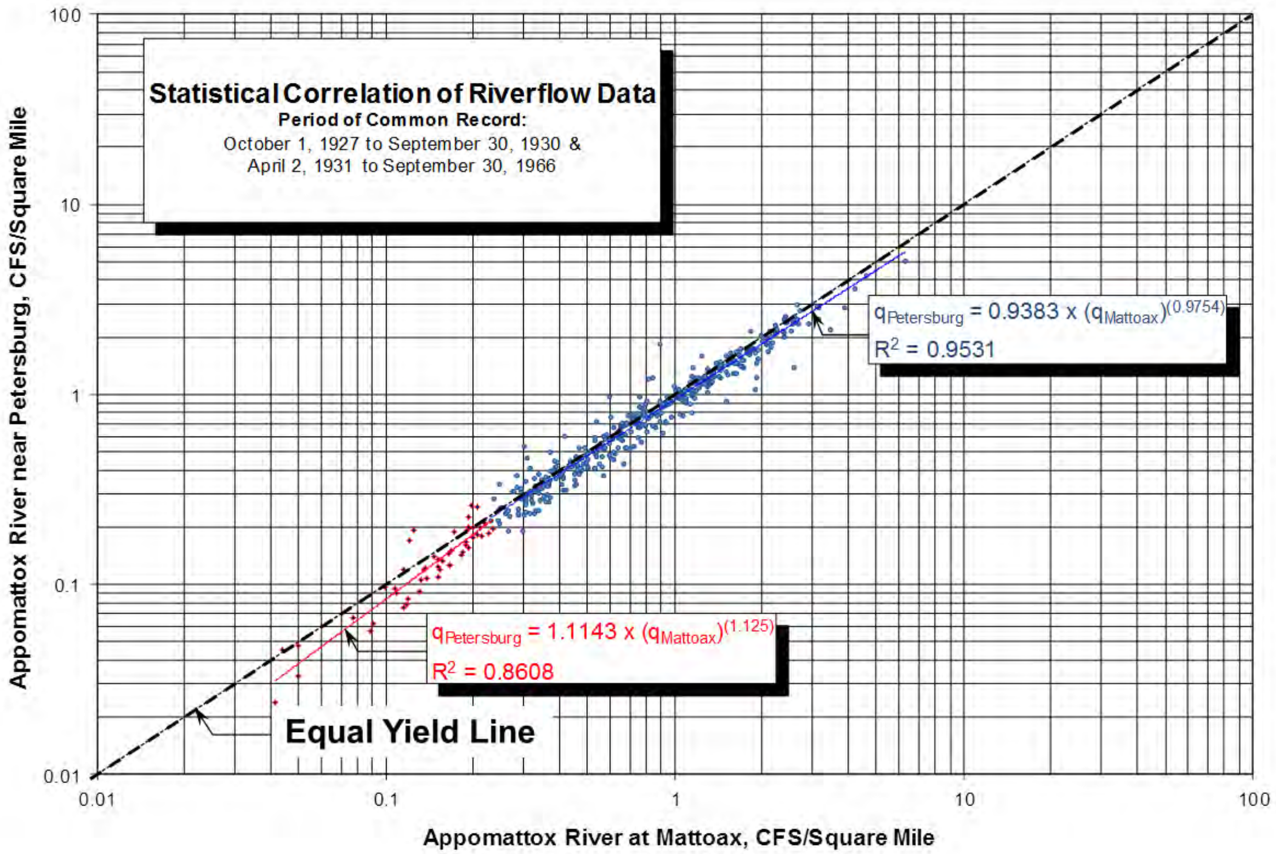


**Figure 4 – Scatter Graph Showing Correlation of Monthly Streamflow Data for Two Gaging Stations**

***Physical Limitations of the System.*** For some systems, the theoretical safe yield computed using available source water may be greater than the yield that can be physically obtained from the system. That is, the safe yield of an existing system may be limited by the capacity of existing intake facilities (especially if dependent on gravity flow), pumping stations, transmission lines, and the ability of the water treatment plant to process the water under different conditions. The safe yield of the system should be compared with potential transmission limitations to determine if there is a physical condition that limits the yield from the system.

In addition to the conveyance capacity of the system components, water quality may also be a constraint. As reservoir storage is depleted, the turbidity and other water quality parameters of the stored water may deteriorate and exceed the ability of the water treatment plant to process the water. In some cases involving conjunctive use of surface water and well water, the well water requires dilution before use, and the depleted reservoir storage could limit the use of well water. There can also be environmental restrictions on the minimum amount of reservoir storage required to sustain fish and other aquatic species. Accounting for the physical limitations in a particular raw water system is critical to accurately estimate the existing safe yield of a system.

***Reservoir Siltation.*** Reservoir siltation or sedimentation is a dynamic, time dependent process that is typically difficult to quantify. This process results in a loss of reservoir storage over time that needs to be considered, especially for systems with small reservoirs relative to their respective drainage areas, since loss of reservoir capacity due to silting is proportional to drainage area. Reservoir siltation reduces the useable storage volume and decreases the safe yield of the system. If reservoir siltation is determined to be a significant factor, reservoir silting rates can be estimated and the safe yield of the system should be estimated and reported as a function of time. Figure 5 illustrates the impact that siltation can have on safe yield.

***Other Factors.*** Many other factors, in addition to those previously mentioned, can have an influence on the safe yield of a source water system, and should be considered in the analysis. For example, water demands vary considerably from day to day as well as season to season. Demands tend to peak during the summer when droughts typically occur. Failure to consider variation in demand at least on a monthly basis could result in overestimating the safe yield of the system. Other factors that should also be considered in developing a custom daily flow model include seepage losses from the reservoir(s) and transmission pipeline(s), land use changes within the watershed, special system operating procedures, intake flowby requirements, and reservoir release requirements to comply with regulatory and institutional agreements.

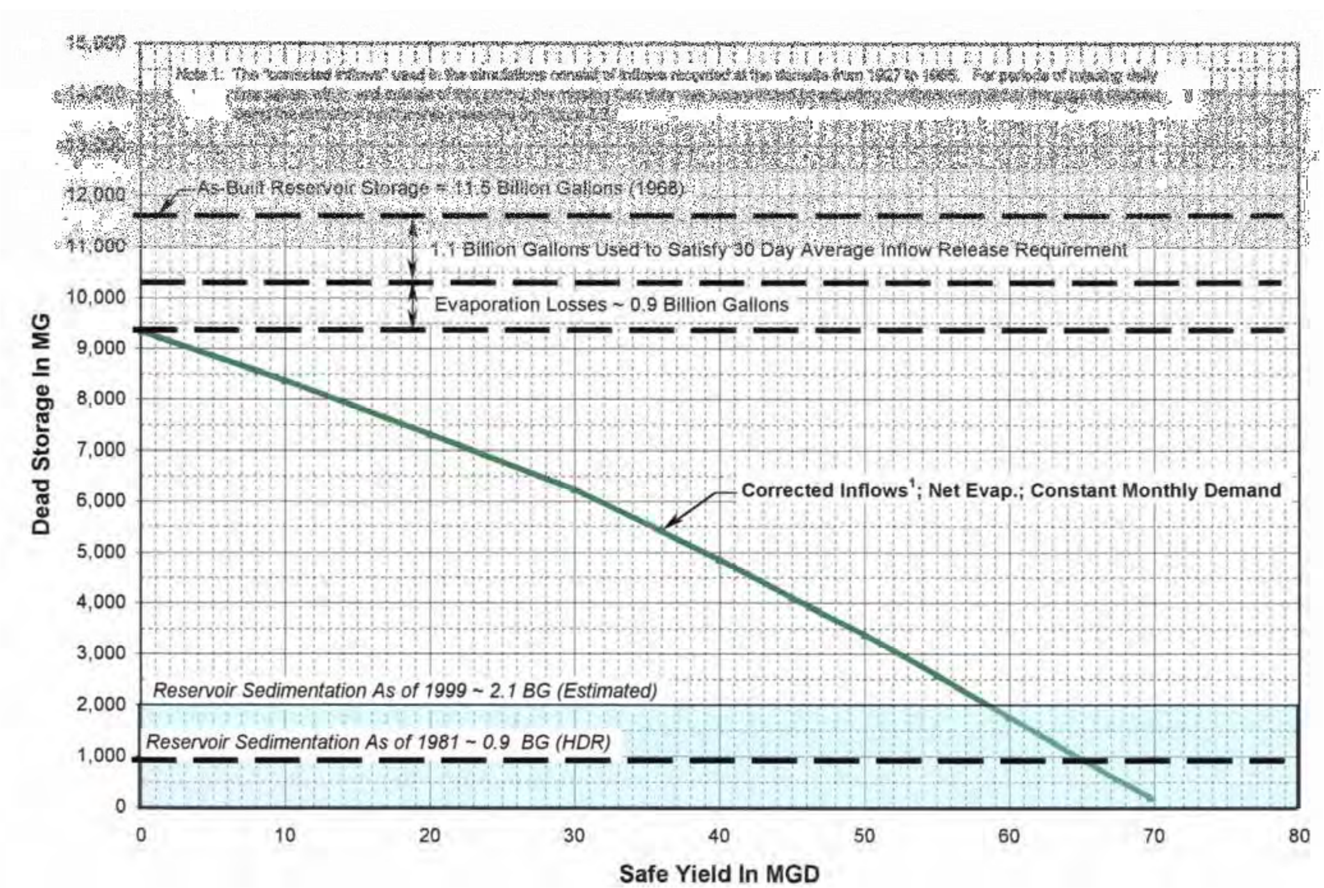


**Figure 5 – Example of Relationship between Reservoir Siltation and Safe Yield**

## USES OF A DAILY FLOW MODEL

A typical model run simulates the daily operation of a water supply system for a given scenario and operating mode through the entire period of hydrologic record (typically about 80 years). For each day, the model computes and records the movement and availability of water as well as other important system information, including unsatisfied demand if it occurs. These site specific computer models are capable of simulating a variety of operating assumptions, variations in demand, conservation measures, complex regulatory restrictions, water quality parameters, and many other factors and provide vast amounts of data for statistical, economic, and optimization analyses. Given the custom nature of these models, there are limitless possibilities for analyzing various aspects of both existing and planned water supply systems. The following section summarizes a few of these potential model uses.

***Estimating Safe Yield.*** In most cases, the primary objective of creating a custom daily flow model is to estimate the safe yield of a water supply system. Iterative routines are created within the model to estimate the safe yield of each operating scenario. Safe yield is estimated by identifying the maximum withdrawal rate that can be sustained during the worst drought of record for a given raw water supply source or system. A safe yield value for the system is reached when storage is all but depleted and unsatisfied demand would occur if the demand were increased.

Historically, safe yield has been incorrectly viewed by many as an absolute and unchanging measure of the amount of water a system can safely supply. This misrepresentation has caused many water suppliers to be dismayed or even doubtful when new analyses estimate a safe yield that is less than the previous estimate. As discussed in the previous section, the accuracy of an analysis is dependent on representative inputs and sound assumptions, and any change in inputs or assumptions can result in a change in the estimated safe yield. However, it is equally important to understand that safe yield is estimated using a limited period of record (usually less than 100 years), and that droughts that are more severe than the current "drought of record" will inevitably occur. In fact, many recent water supply studies performed in Mid-Atlantic States have found that recent regional droughts in 2002 and 2008 were more severe than the previous drought of record in the 1930s or 1960s. In short, safe yield will always be a moving target as system characteristics evolve, climate changes, and more severe droughts occur.

Rather than viewing safe yield as an absolute value, it is better to view it in terms of probability and risk-based decision making. The use of a daily flow model facilitates this understanding by providing not just a singular value corresponding to safe yield, but substantial amounts of simulated operational data for statistical and other risk-related analyses. For example, a daily flow model can be configured to analyze each water year of the period of record individually and estimate a safe yield corresponding to each year. These data points can then be ranked and plotted; thereby illustrating the recurrence interval associated with not just the drought of record, but also other more common drought events (See example plot in Figure 6). Similar techniques can also be used to identify drought events that are statistical outliers, or assign exceedance probabilities to desired water supply targets that are in excess of the safe yield. These types of statistical analyses can help water suppliers make risk-informed decisions as they manage current use and plan for the future.

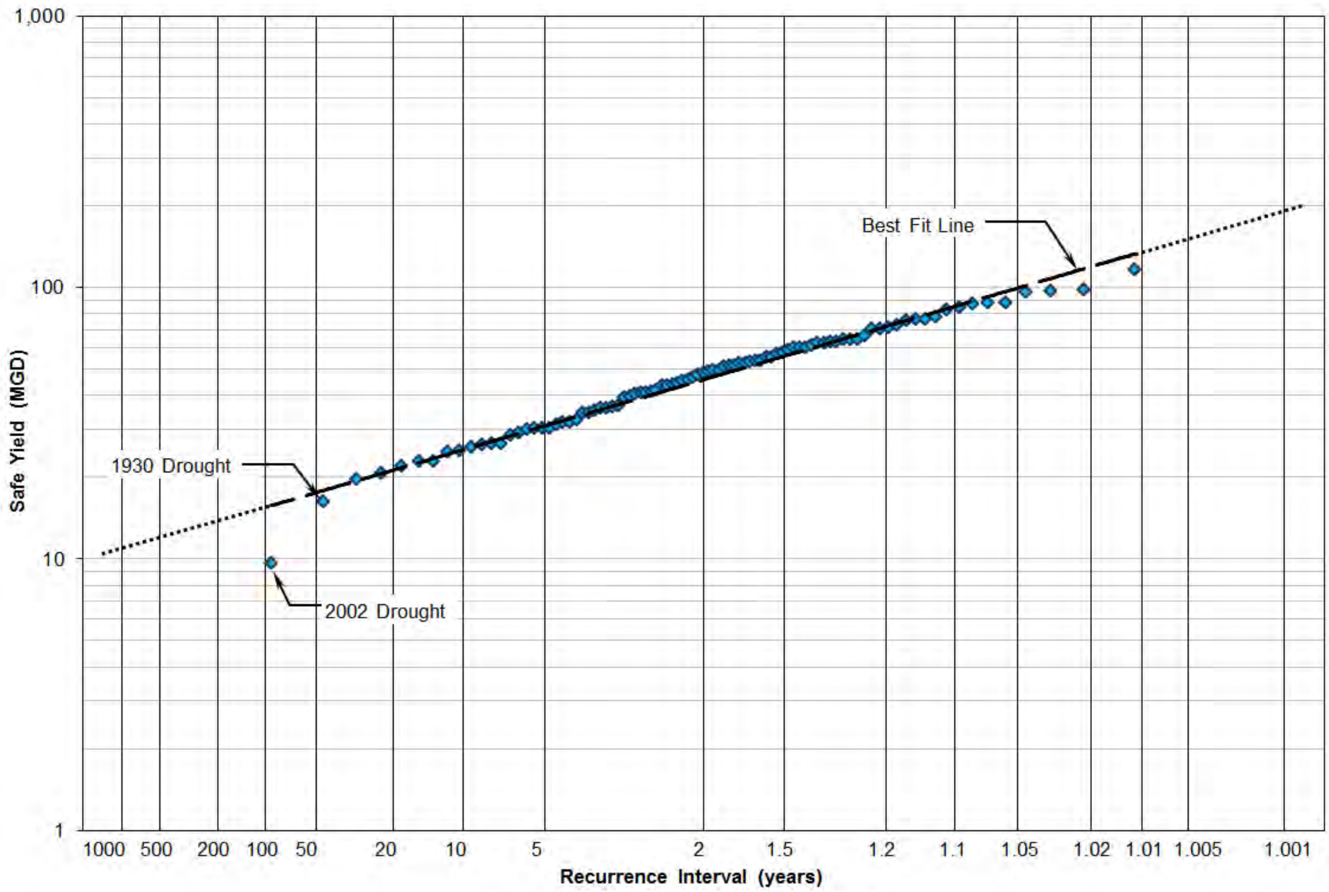


**Figure 6 – Example of Probability Plot Illustrating the Recurrence Interval of Safe Yield Values for the Entire Period of Record**

***Evaluating/Designing Drought Contingency Plans & Conservation Measures.*** Some water utilities use reservoir condition curves to help ensure adequate water supply during periods of severe drought. The drought condition curves define normal, drought water, drought warning, and drought emergency conditions during the year based on the total remaining reservoir storage (see example reservoir storage condition curves in Figure 7). These drought conditions correspond to drought stages defined in a drought contingency plan. Each drought stage defines specific conservation objectives.

The general shape of the reservoir storage condition curves can be determined and evaluated using a daily flow model. The shapes of these curves generally reflect the normal wet and dry seasons of the year. The computer simulation of the raw water system for the long-term period of record can be performed to verify and modify the reservoir storage condition curves to ensure proper definition of drought stages. It is important that the stages are not triggered frequently or prematurely, causing the public to become complacent and not respond, or too late, risking emptying the reservoirs. The daily model can also be used to verify the storage condition curves by simulating reductions in demand resulting from implementing conservation measures as defined by the curves. This enables testing and confirmation of the selected reservoir condition curves to see how the system would have performed.

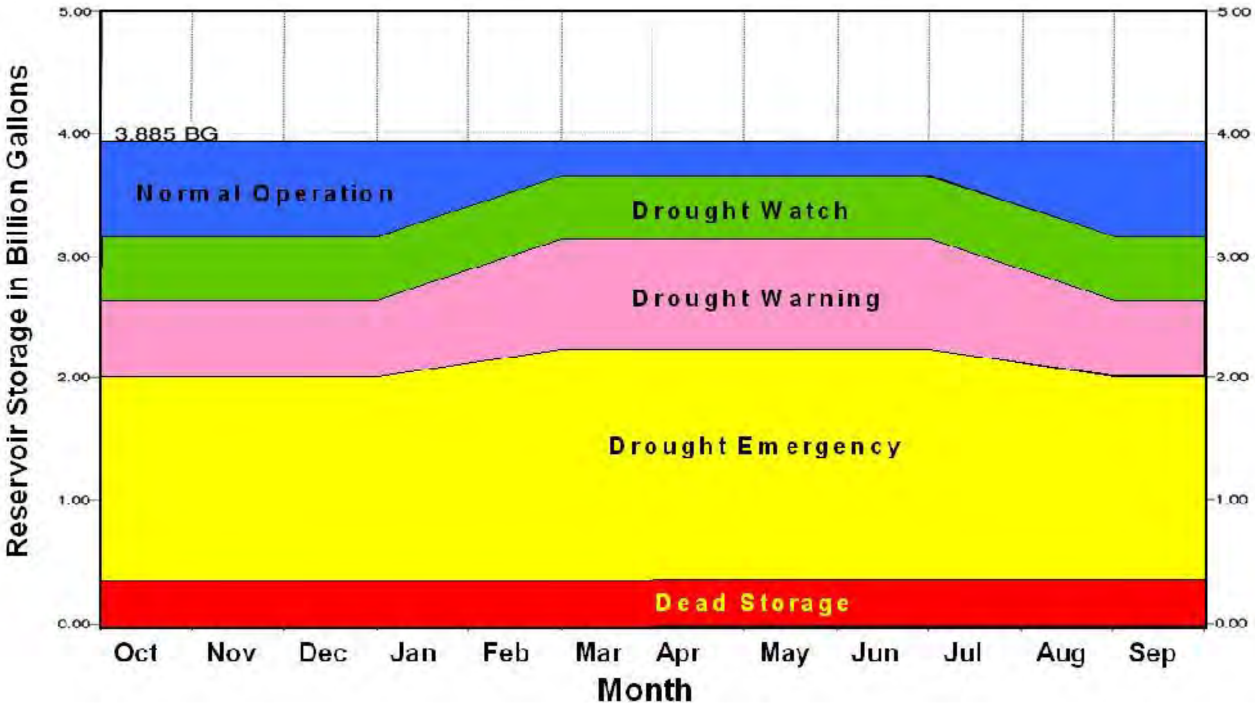


**Figure 7 – Example of Reservoir Storage Condition Curves Typically Used as Part of a Drought Contingency Plan**

***Surplus Water Analyses.*** Surplus water availability investigations involve determining how much and for what durations or percent of the time additional source water can be supplied to a potential system customer(s) without reducing the safe yield of the existing system. Implicit in these investigations is the realization that during normal and above average flow conditions there is an abundance of source water. This is often evidenced by source water flowing over the spillway of the water supply reservoir or past the river intake and leaving the system. The questions that need to be answered when evaluating surplus water availability are: (1) how much and how frequently can surplus water be provided, (2) what would be the frequency and duration of interruptions in the supply of surplus water, (3) what is the seasonal variability in providing surplus water, and (4) how should the system be operated to minimize interruptions without significantly impacting the safe yield of the existing supply. These questions can be answered with confidence by simulating the daily operation of the system using a daily flow model. Detailed water supply statistics can be obtained by analyzing the model output (See Figure 8).

***Optimizing System Operating Procedures or Potential System Improvements.*** The operation of complex water systems requires operating procedures to define when to begin pumping from river intakes and wells, and when to use reservoir storage for water supply. These decisions can have significant economic consequences and require a careful balance to minimize pumping and water treatment costs, while at the same time maximizing the safe yield of the system. Source water from a reservoir on a small watershed is often preferred over source water from a river intake as it usually requires less treatment and involves less pumping. On the other hand, pumping the water available at the river intake whenever possible maximizes the safe yield of the system. Here, the daily flow model can be used to evaluate the safe yield and operating costs for a variety of operating scenarios, and provide the necessary information to evaluate and optimize the operating procedures. Similarly, the daily flow model can be used as a planning tool to analyze the benefit of potential system improvements and estimate their operational costs prior to design and construction. Figure 9 illustrates the pumping frequency that would be expected for three pumps of varying capacities, and the increase in safe yield associated with the larger pumps. This type of information can be used to estimate both capital and operational costs associated with proposed infrastructure.

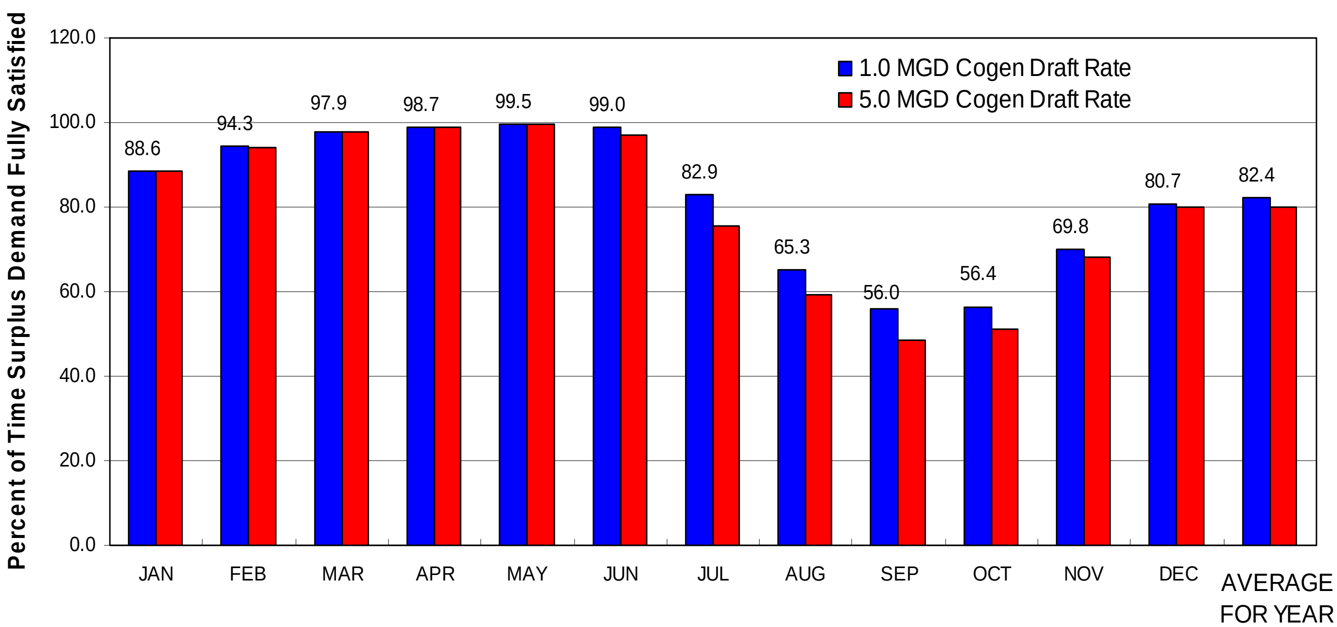


**Figure 8 – Example of Surplus Water Supply Statistics Developed from a Custom Daily Flow Model**

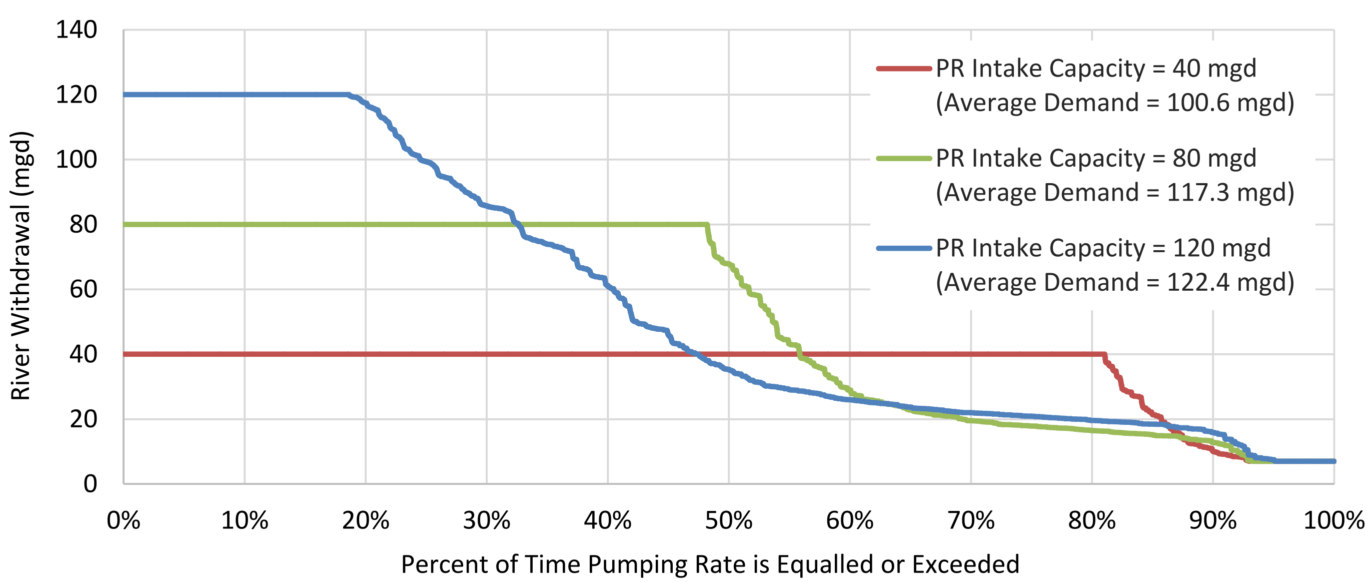


**Figure 9 – Exceedance Plot of Total Withdrawals Assuming Three Varying Pump Sizes**

***Tools to Assist with Real-time Operating Decisions.*** The concept of refill curves was first developed and used by the City of New York in the mid-1950s as a tool for balancing reservoirs to optimize their utilization. The refill curves are based on the historical record and show the storage necessary on any date to ensure that the reservoirs will be full by the succeeding June 1, assuming various percentage years and draft rates. A "percentage year" refers to the ratio between the number of years a given yield has been equaled or exceeded and the total number of years of record. For example, a "90 percent year" is one for which the yield has been reached or exceeded 90 out of 100 years.

Whereas reservoir refill curves provide insight into the probability that the reservoirs will refill, reservoir drawdown curves provide insight into the probability that the reservoirs will empty. Drawdown curves are a useful tool in providing insight into determining when a reservoir or reservoir system is in danger of total depletion. Drawdown curves can also help determine the shape of the reservoir condition curves that are used to determine when to curtail water use during critical drought periods. The development of reservoir drawdown curves is very similar to the procedure used to develop refill curves. The same basic data and equations are used in each. The main difference is the point of reference. Refill curves assess the probability of recovering from various levels of drawdown throughout the year to a full pool at the end of the season (May 31). Drawdown curves, on the other hand, assess the probability of depletion throughout the year beginning from a given storage level on June 1. (DRBC, 1979). Using a similar approach, daily flow models can be used to develop interactive tools that allow operators to make real-time, informed decisions based on refill targets and historical data. Figure 10 illustrates one such application derived from a custom daily flow model that provides statistical-based information to help guide pumping decisions.

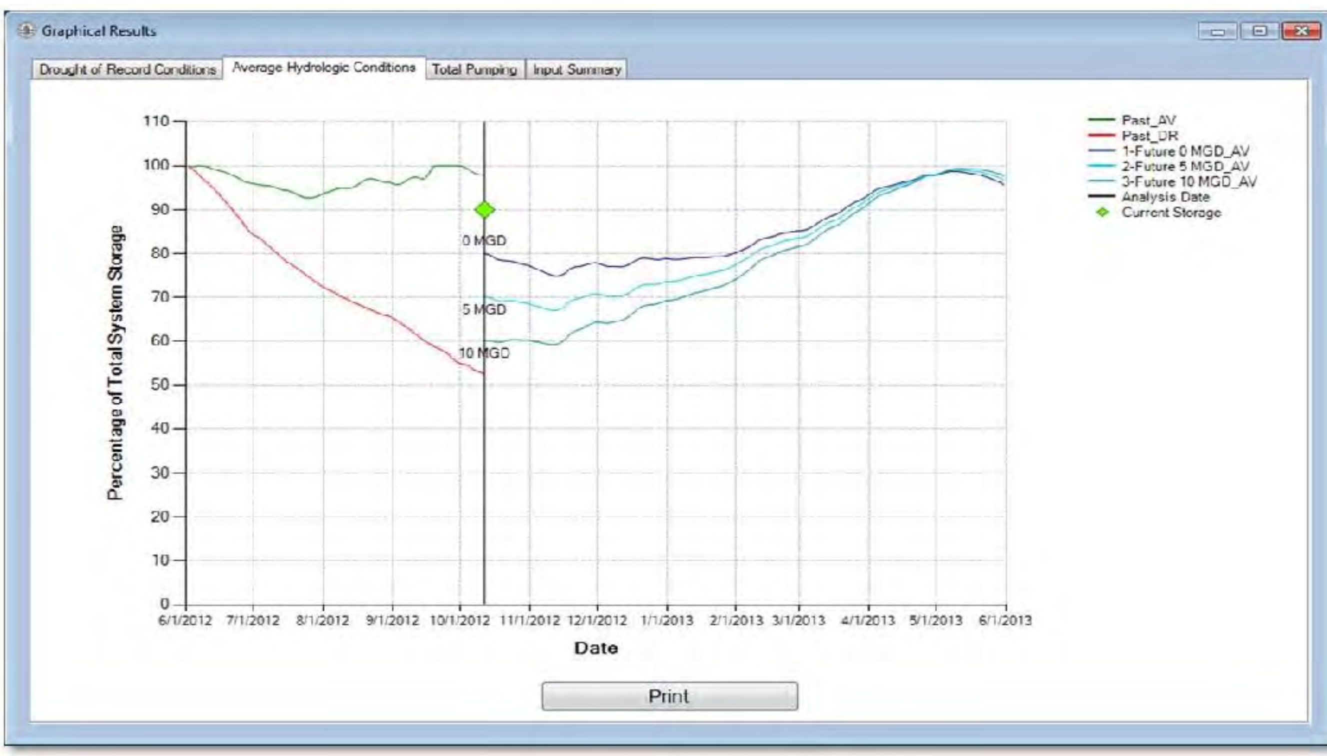


**Figure 10 – Sample Application to Assist with Operating Decisions Based on Reservoir Refill Curves**

***Assessment and Negotiation of Regulatory Permit Conditions.*** Permit conditions specifying a regulatory flowby requirement for a pump intake structure or a conservation release from a reservoir often have a significant impact on the safe yield of a water system. When seeking a new permit, or if an existing or grandfathered permit has the potential to be revisited based on updated regulatory guidance, it can be beneficial to understand the implications of potential permit requirements prior to sitting down at the negotiating table with regulators. A custom daily flow model can be used to analyze a range of potential permit conditions to understand their impact to the system.

For example, the Susquehanna River Basin Commission (SRBC) recently adopted a *Low Flow Protection Policy* specifying a new methodology for determining conservation releases. In order to determine the necessary level of protection downstream of a reservoir, these guidelines require that streams and rivers be placed in one of six Aquatic Resources Classes (ARCs) according to the total upstream watershed area from the point of withdrawal. Based on the ARC, a required monthly conservation release is specified as a percent exceedance of historical monthly flow. Therefore, conservation releases will vary on a monthly basis, with highest flows occurring during the wet seasons of the year. See Figure 11 for an illustration of this approach.

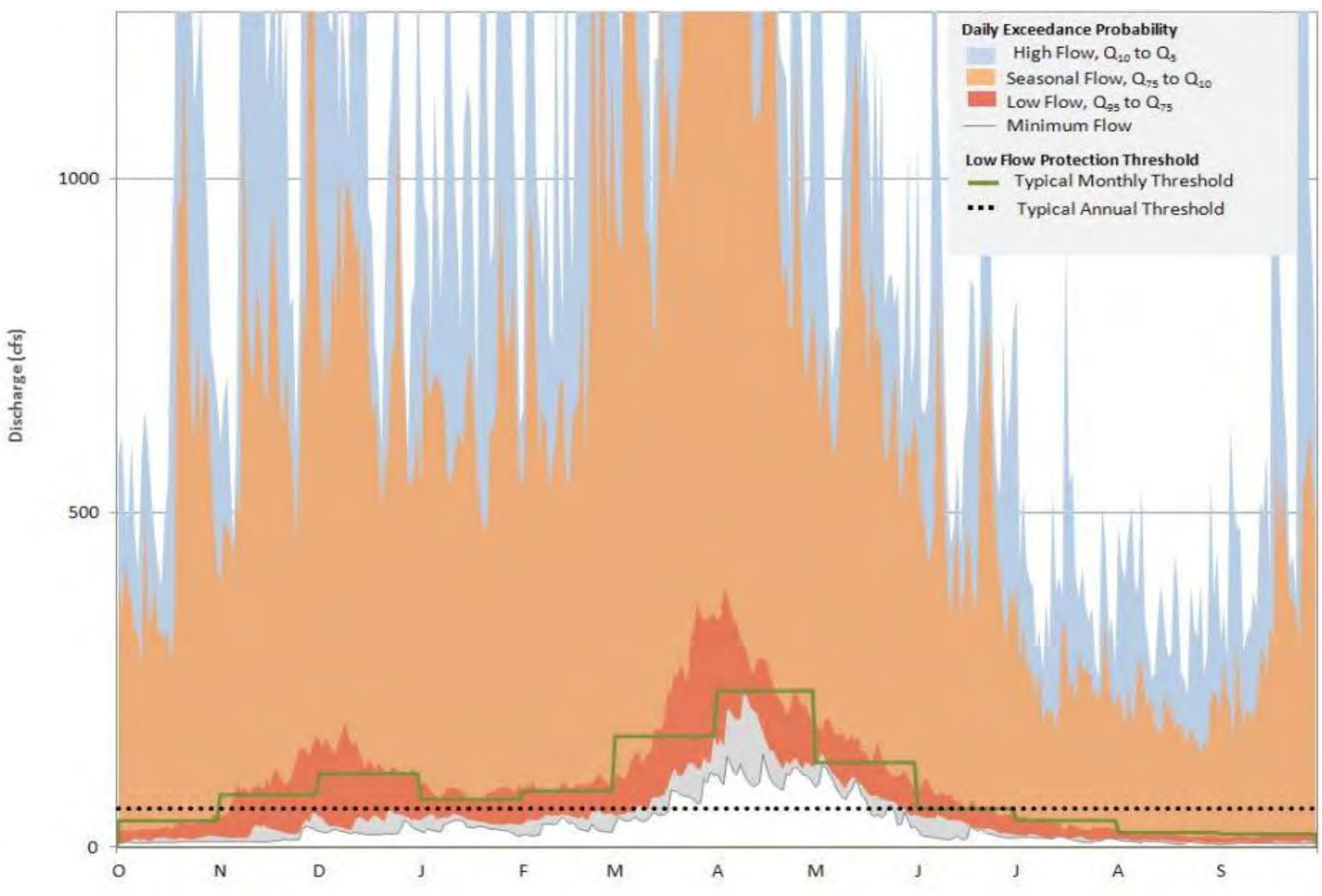


**Figure 11 – SRBC Constant Annual Vs. Variable Monthly Low Flow Protection Thresholds (SRBC, 2012)**

In light of this recent change by the SRBC, the authors have analyzed several water systems to estimate the impact of this new approach on estimated safe yield. In some cases, varying conservation releases based on historical monthly flow is beneficial to a system since smaller conservation releases are required during the driest months of the year when droughts occur and demands are typically the highest. In most cases, however, it has been found that the new SRBC policy results in an overall increase in annual average conservation release and a corresponding reduction of available safe yield.

## CONCLUSION

A custom computer model of a source water supply system is a valuable tool that can be used to simulate the theoretical operation of the system for numerous operating conditions and procedures, and to perform "what if" analyses for forecasting and planning. The application of a daily flow model requires extensive hydrologic data and system-specific operating information as input. The results obtained through such an analysis are only as reliable as the input data. Furthermore, it is important to view safe yield in terms of probability and risk-based decision making rather than as an absolute, unchanging value. The use of a daily flow model facilitates this type of analysis and thinking.

Site specific computer models are capable of simulating a variety of operating assumptions, variations in demand, conservation measures, complex regulatory restrictions, water quality parameters, and many other factors and provide vast amounts of data for statistical, economic, and optimization analyses. Given the custom nature of these models, there are limitless possibilities for analyzing various aspects of both existing and planned water supply systems. Application of the tools discussed in this paper should help water supply managers operate their systems with more confidence and ultimately "do more with what they have".

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