# Ecological, Environmental and Hydrological Integrity in Sustainable Water Resource Management for River Basins

by

Robert Louis Oxley

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Graduate Supervisory Committee:

Larry Mays, Chair
Peter Fox
Paul Johnson
Alan Murray

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# ABSTRACT

This dissertation presents a new methodology for the sustainable and optimal allocation of water for a river basin management area that maximizes sustainable net economic benefit over the long-term planning horizon. The model distinguishes between short and long-term planning horizons and goals using a short-term modeling component (STM) and a long term modeling component (LTM) respectively. An STM optimizes a monthly allocation schedule on an annual basis in terms of maximum net economic benefit. A cost of depletion based upon Hotelling's exhaustible resource theory is included in the STM net benefit calculation to address the non-use value of groundwater. An LTM consists of an STM for every year of the long-term planning horizon. Net economic benefits for both use and non-use values are generated by the series of STMs. In addition output from the STMs is measured in terms of sustainability which is quantified using a sustainability index (SI) with two groups of performance criteria. The first group measures risk to supply and is based on demand-supply deficits. The second group measures deviations from a target flow regime and uses a modified Hydrologic Alteration (HA) factor in the Range of Variability Approach (RVA). The STM is a linear programming (LP) model formulated in the General Algebraic Modeling System (GAMS) and the LTM is a nonlinear programming problem (NLP) solved using a genetic algorithm. The model is applied to the Prescott Active Management Area in north-central Arizona. Results suggest that the maximum sustainable net benefit is realized with a residential population and consumption rate increase in some areas, and a reduction in others.

# DEDICATION

To my wife Rachel, and my sons, Joshua, Nicholas, Micah and Zachary.

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# 1 Introduction

This research addresses questions of sustainability for river basin management areas experiencing rapid population growth. A water resources management model is developed that is the first to integrate and combine several sustainability concepts: a sustainability index, a flow regime comparison metric and a cost of depletion for aquifers. The developed model distinguishes between short-term and long-term goals and planning horizons. A monthly water allocation is determined annually and optimized for maximum net economic benefit by a short term model. Demands competing in the short term model include a river's flow regime, which is fundamental to a river's ecological, environmental and hydrological integrity. The allocations generated by a series of short term models are in turn measured for sustainability by a long-term model, using the concept of a sustainability index. The series of short-term models are optimized to determine the series with the most sustainable net economic benefits. The developed model is applied to the Prescott Active Management Area in north-central Arizona using 4 scenarios to illustrate potential applications.

This introduction continues with the problem statement, followed by research objectives and limitations, background and approach, and an overview of the developed model and summary of the presented research.

## 1.1 Problem Statement

Water managers are tasked with the efficient allocation and distribution of a shared and closed system resource under increasing demands. Water stress is a reality for a large portion of the world's population (Alcamo et al. 2007; Rijsberman 2006; Rosegrant et al. 2002; Vorosmarty 2000). Relatively recently, the dependency of riverine ecological systems on flow regimes has been recognized (Arthington et al. 2006; Poff 2009; Poff et al. 1997) and concern over ecosystem degradation adds to the challenges of river basin management. The questions at hand are: how do managers meet immediate water demands while ensuring water availability for future needs? And, how are established societal needs balanced against the increasing awareness that human society is reliant upon a water dependent ecological system?

The concept of sustainability gained traction after the Brundtland Report (World Commission on Environment and Development 1987) and discussion on definition and application followed. In general terms, sustainability is often associated with environmental concerns, long term availability and use patterns. In this context, the principals of sustainability would seem to be especially suited to answer the water management questions raised in the preceding paragraph. Despite the prominence and appeal of the idea of sustainability, translating the current definitions and principals into practical application remains problematic (Gleick 2000; Kuhlman and Farrington 2010; Lant 2007; Loucks 1997; Loucks et al. 1999; Solow 1993; Unver 2007). As Solow (1993) suggests: *'…the less you know about it* [sustainability], *the better it sounds"*.

As an introduction to the principals of water resource sustainability addressed in this research, Mays (2007) offers the following definition:

> *"Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life and to protect humans from the dangers brought about by natural and human-caused disasters that affect sustaining life."*

Specific objectives are discussed next, followed by background and approach.

## 1.2 Research Objectives

This research addresses the application of sustainability to the water management problem at the river basin level, with special attention to riverine ecological concerns. The objective was accomplished by creating a river basin management model. Specifically:

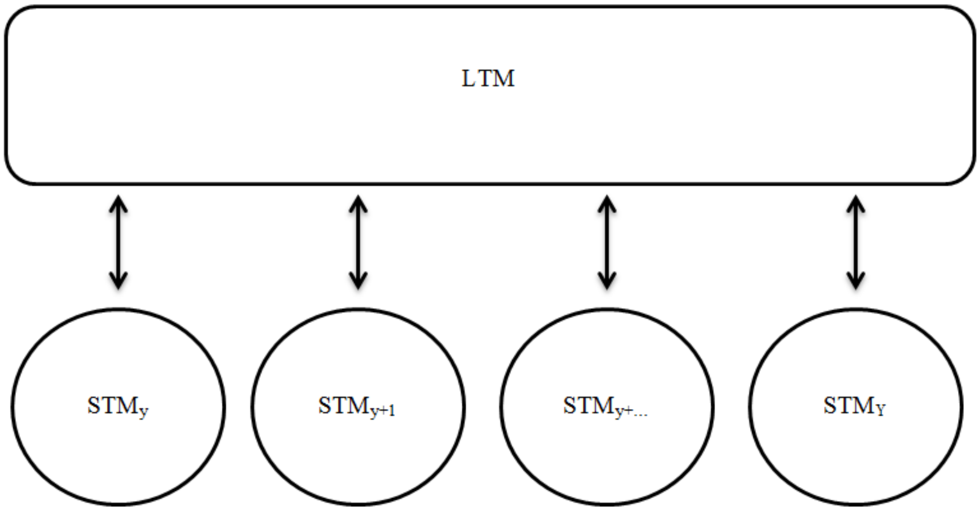
1) *The development of a short-term model component.*

The short-term model component (STM) addresses the monthly water allocation on an annual basis, optimizing the allocation in terms of the maximum net economic benefit. The STM is a linear programming model solved using the General Algebraic Modeling System (GAMS). A cost of depletion (Rothman and Mays 2013) associated with aquifer drawdown is included in the net benefit calculation and the management area is represented using the node-link concept.

### 2) *The development of a long-term model component*

The long-term model component (LTM) is concerned with long-term management goals and planning horizons and consists of an STM for every year ($y$) of the long-term time horizon (see Figure 1.1). The LTM suggests population growth and consumption rates for each STM, and evaluates the output from the series of STMs in terms of sustainability and the sum of net economic benefits. The LTM is developed in PHP: Hyper-text Processor (PHP) (version 5.4.9) and optimized using a genetic algorithm.

**Figure 1.1. Schematic depicting the relationship between the LTM and STM.**



### 3) *Integration of a sustainability index*

Sustainability in the LTM is measured using the concept of a sustainability index (SI) (Sandoval-Solis et al. 2011). The SI uses two groups of performance criteria. The first group uses demand-supply deficit based performance criteria and measures the risk to supply for each demand. The second group is only applied to river demands and compares a river's allocation to a target flow regime using the Range of Variability Approach (RVA). The performance criteria for both groups are dependent upon the allocations generated by the series of STMs. A combined sustainability metric for the system (SS) is also determined. The SI is developed in PHP.

### 4) *Integration of the Range of Variability Approach*

The RVA (Richter et al. 1996) is used to compare the flow regime resulting from the allocation projected by the series of short-term models to a target or ecologically sound flow regime. Difference in flow regimes is typically measured by the RVA using a hydrologic alteration factor. A modified hydrologic alteration factor is developed for use in this application and is available to the SI as a performance criterion. Existing water resource management models address ecological concerns by using a fixed minimum volume allocation. The adopted approach is based on a target flow regime which is more ecologically relevant. The relationship between the STM, LTM, RVA, SI and SS is indicated in Figure 1.2.

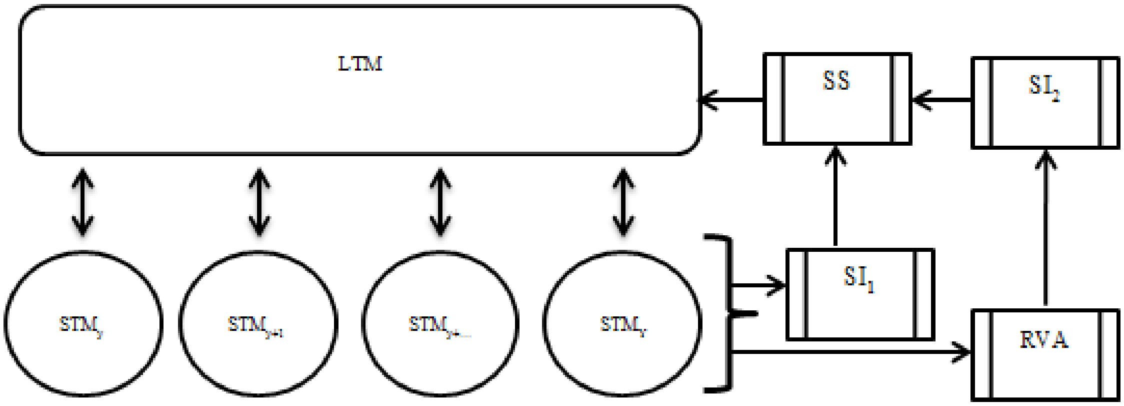
### 5) *Integration of a genetic algorithm*

As formulated, the LTM is a non-linear programming problem (NLP). Metaheuristic approaches such as evolutionary algorithms have successfully been used to solve NLPs. A genetic algorithm is developed in PHP and used to determine the LTM with the most sustainable net benefit.

### 6) *Implementation of MySQL database*

Communication between the model components and results analysis are facilitated with the integration of a MySQL database. MySQL is an open source Structured Query Language (SQL) database management system developed, supported and distributed by the Oracle Corporation. The MySQL database is fast, reliable, scalable and simple to use, making it the most popular SQL database management system in use at the time of this research. The MySQL database is a relational database and consists of separate tables for data storage. The tables are used to organize and manage the model data, including tables for the physical parameters of the modeled system, tables for STM input and output and tables for LTM input and output.

**Figure 1.2. Schematic depicting the relationship between the STM, LTM, RVA, SI and SS.**



### 7) *Prescott Active Management Area application*

The model is applied to the Prescott Active Management Area (Prescott AMA), a management area in north-central Arizona experiencing rapid population growth (see

Figure 1.3). Population growth in the Prescott AMA has stressed available water resources and a plan has been proposed to pump and transport ground-water from a remote location. Studies have suggested that pumping water at the proposed location will impact flows on the Verde River. The Prescott AMA configuration is based in large part on Rothman (2007) and depicted in Figure 1.4. Four scenarios are developed for the model application and results are evaluated. The first scenario uses historical flows as the basis for a target flow. The second scenario uses 15% of the historical average Julian day flows as the basis for the target regime. The third and fourth scenarios are based on the historical flow regime target and require that 90% of initial storage volumes be maintained in the aquifers. Scenario 4 also allows 7.5% drawdown on the Big Chino aquifer to occur without impacting flows on the Verde River.

**Figure 1.3. Verde watershed and relative location of the Prescott AMA.**

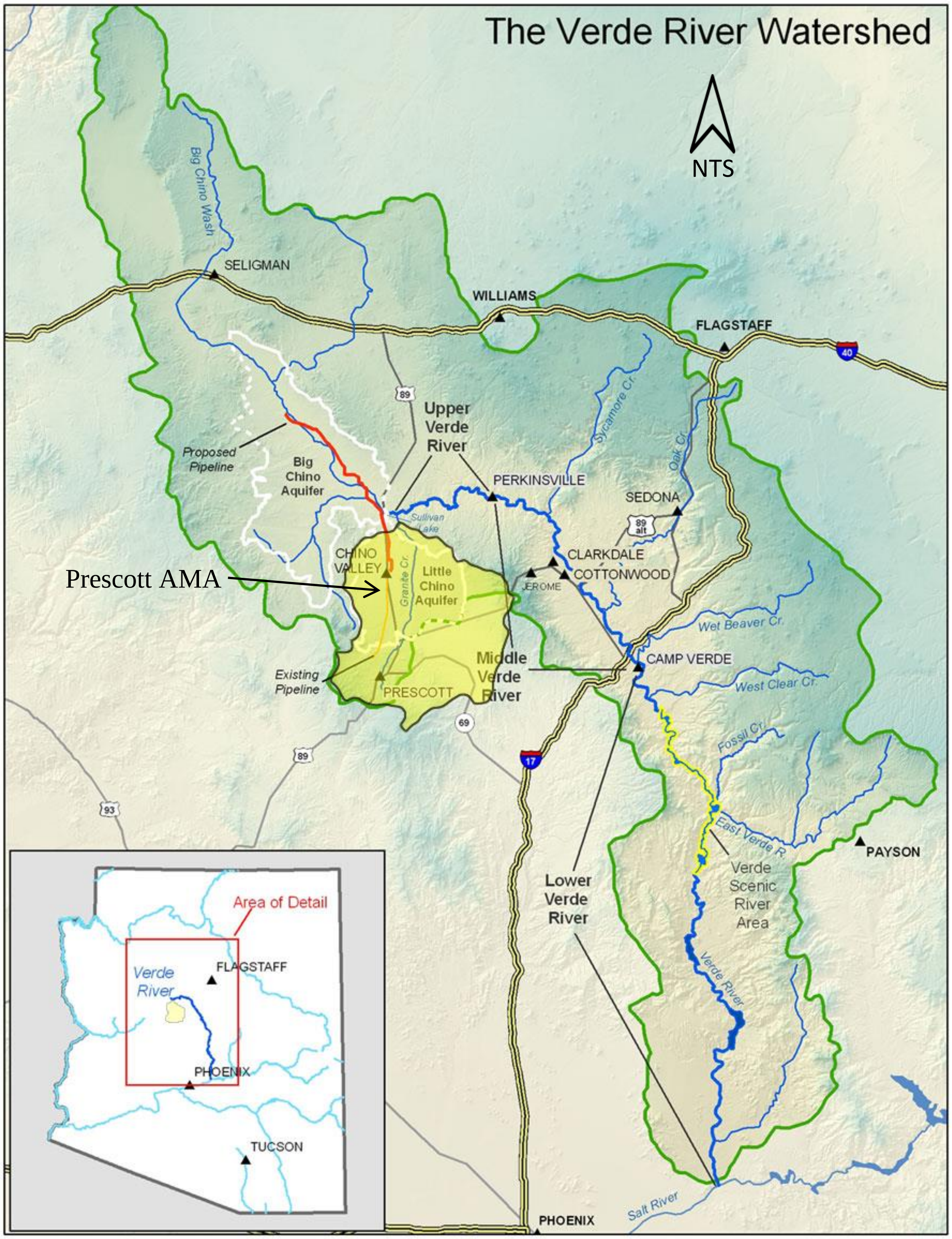
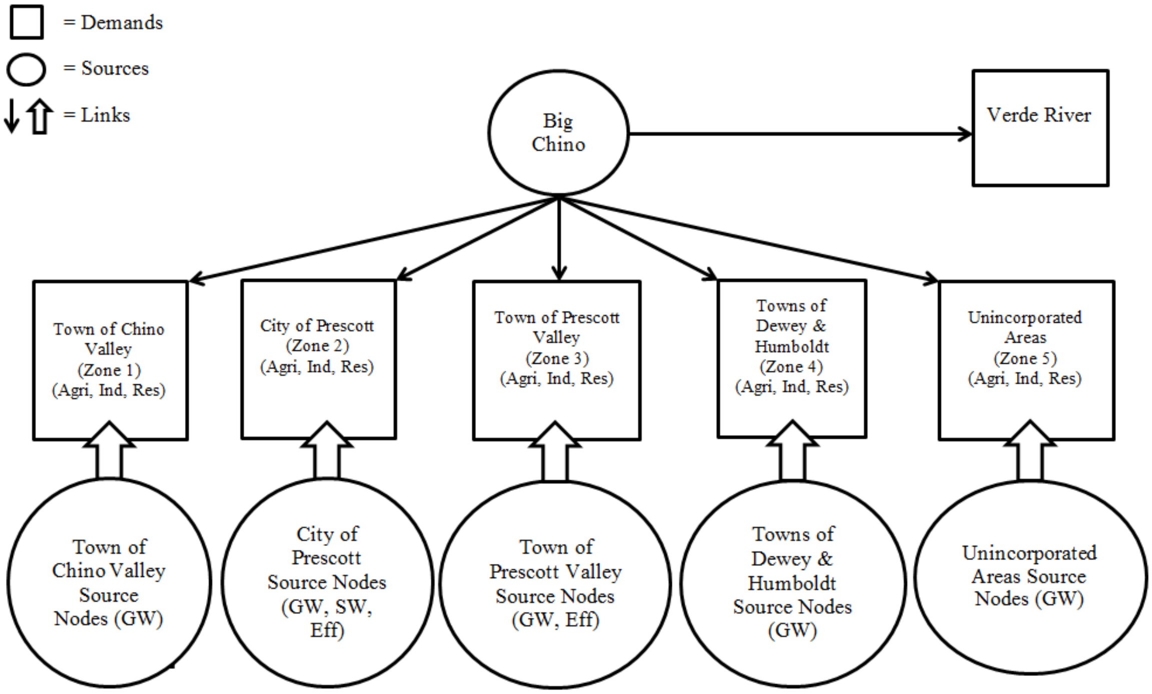


**Figure 1.4. Schematic of the Prescott AMA. The adaption of the Prescott AMA is largely based on Rothman (Rothman 2007).**



## 1.3 Overview of the Developed Model: Background and Approach

It can be said that water resource planning and management activities are motivated by the realization that there is a supply problem or that there is an opportunity to increase the benefits associated with water use. Water management is a cross-discipline effort (Loucks et al. 2005) and reaching an agreement on a solution requires tools for the modeling, analysis and comparison of multiple scenarios. Computational models are often employed in this capacity and are especially suited to this task with their ability to rapidly and efficiently assess multiple scenarios. There are recognized methods for computational water management model development (Mays and Tung 1992).

Ecological science readily acknowledges the importance of the flow regime to riverine ecological response. Despite this importance, water management models have yet to fully integrate the flow regime into the allocation scenario (Poff 2009). Challenges include defining and adapting an acceptable metric, the intensity and complexity involved in describing an acceptable degree of regime change, and given that flow regimes are described in units of daily flow values - computational tractability.

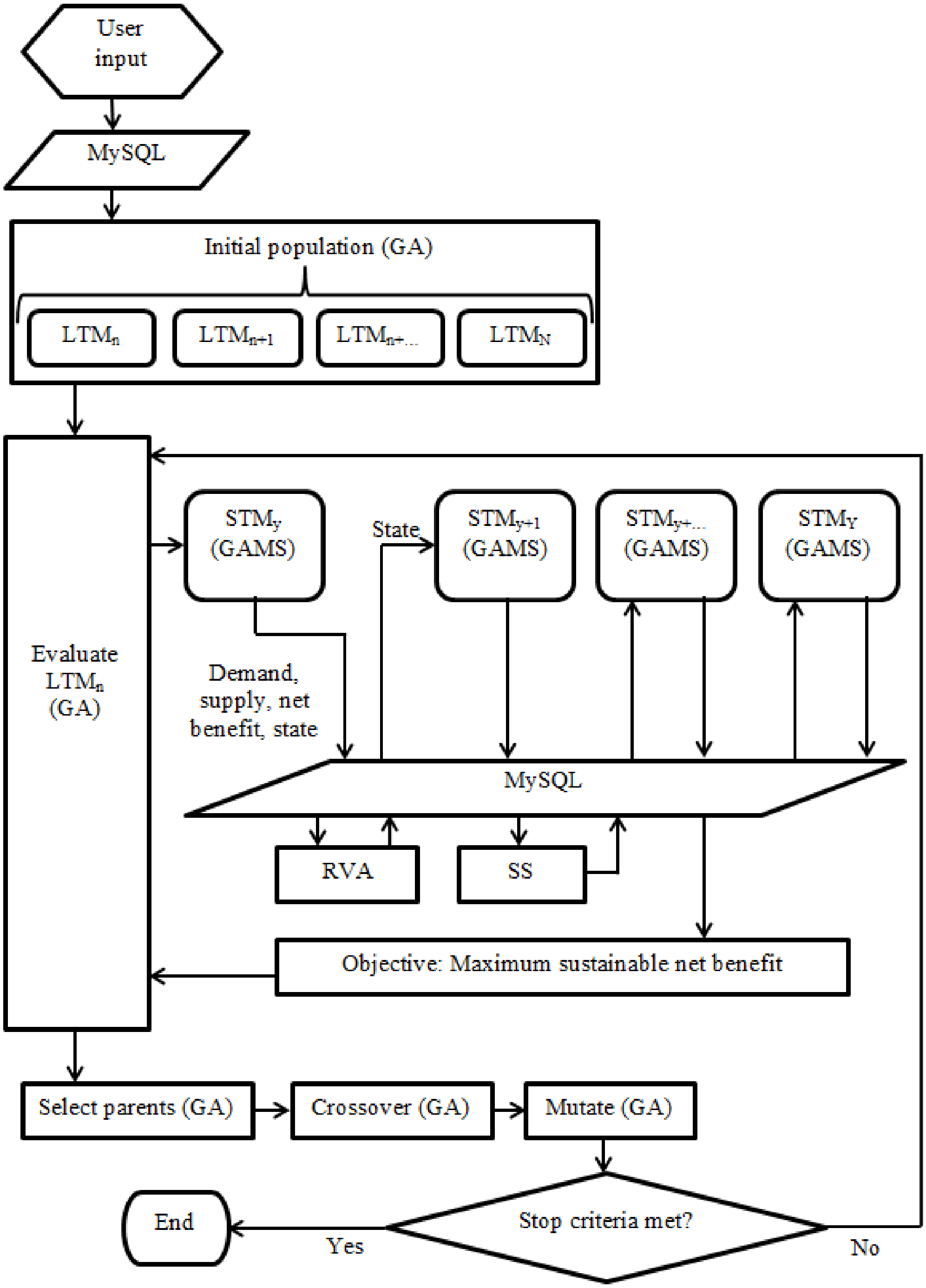
The model developed and presented in this research addresses these challenges. The adopted approach is briefly presented here as a model overview with detailed discussion in subsequent chapters.

The developed methodology distinguishes between short and long term management goals in the STM and LTM respectively. The STM allocates water supply to maximize net economic benefit on an annual basis using a linear programming model implemented in GAMS (GAMS Development Corporation n.d.). Economic benefit is associated with use at a demand while costs are related to developing and transporting supply to a demand. The overall model schematic and flowchart are depicted in Figure 1.5.

An LTM consists of $Y$ number of STMs over the long term time horizon, and proposes a population growth rate and a change in consumption rate for each STM in the series. A GA is used to determine the best LTM in terms of maximum net economic benefit and sustainability. A MySQL database is used to facilitate storage and communication between the modelling components.

As indicated in Figure 1.5, the overall model includes several sustainability concepts. The first is a sustainability index for the system (SS). Sandoval-Solis et al (2011) proposes an SI for water resource demand-supply scenarios using the geometric average of several deficit-based performance criteria. Reliability, resilience, vulnerability, standard deviation and maximum deficits are defined in terms of demand and supply and combined as a measure of supply scenario sustainability. As defined by Sandoval-Slois et al, the SI is not dependent upon specific performance criteria. In this research a second set of performance criteria is defined and used to measure the sustainability of a river's flow regime. The flow regime is the annual pattern of daily flows for a river, and is recognized as fundamental to a river's ecological system (Poff et al. 1997). Differences between a target or ecologically sound flow regime and the projected flow regime are measured by the RVA in this research. Richter et al. (1996) proposes the RVA as a tool for measuring the differences between pre- and post-impact flow regimes and to aid in ecological remediation. Differences between flow regimes are expressed using a degree of hydrologic alteration (HA), which measures the change to one of thirty-three Indicators of Hydrologic Alteration (IHA). The IHAs can be thought of in terms of flow regime characteristics and are derived from daily flow values. This research uses a modified version of the HA metric. Both the SI and flow regime comparison metric are discussed with more detail in subsequent chapters.

**Figure 1.5. Model components and flowchart. LTM refers to long term model, STM refers to short term model, GAMS refers to General Algebraic Model System, GA refers to genetic algorithm, RVA refers to range of variability approach, SS refers to the sustainability index for the system and MySQL is representative of the database.**



Another sustainability concept adopted in this model relates to net economic benefit. There are two principal components in determining the total economic value of water: 1) ‘use’ values, and 2) ‘non-use’ values. Non-use values are often associated with sustainability and are summarized as the value that an individual assigns to a resource to ensure its availability for others both now and in the future. Rothman and Mays (2013) applies Hotelling’s ‘exhaustible resource’ theory (Hotelling 1931) using a ‘cost of depletion’ function to assign a non-use value to groundwater resources. A linear approximation of this function is used in this research.

## 1.4 Contributions and Limitations

Water management is a very active area of research and numerous models have been developed to facilitate the decision making process. Water management optimization models are fewer in number and water management models that explicitly identify ecological concerns and allow them to compete directly with human demands are even fewer. This research is the first effort to develop a comprehensive model for sustainable river basin area management utilizing the concept of a sustainability index, flow regime metric and net economic benefits.

One of the contributions of the presented research is the consideration of riverine ecological demands in the water allocation management decision and in the long term viability of the allocation schedule. Prior work has been limited to satisfying time dependent minimum flow volumes. Some of this is due to the lack of an applicable unit of comparison. Human demands are often described and evaluated in terms of economic units, and the idea of a monetary basis for ecological concerns is highly controversial and open ended (see Appendix C for additional background). However, associating a monetary value with environmental services derived from river flows is not unheard of (Engel et al. 2008; Millennium Ecosystem Assessment (Program) 2005). This allows the ecological demands to compete for short term allocation, but is perhaps not entirely representative.

The concept of ecological, environmental and hydrological integrity comes up often in water resource sustainability literature. The concept is addressed in this research via the RVA. The RVA measures differences in flow regimes and is used in this application to compare a projected flow regime to a target flow regime. To the author's knowledge, this is the first time that the RVA has been integrated into a long term water resource management optimization model. The HA metric used in the RVA had to be modified for use in the SI performance criteria.

Additionally, this research is the first to integrate the SI concept into the objective function of an optimization model. To date, the SI has not been utilized in any peer-reviewed optimal water resource allocation research. Prior application of the SI has been limited to the comparison of static demand schedules: an annual demand schedule is projected over the long term time horizon (Sandoval-Solis et al. 2011). Application to a changing annual demand schedule required the definition of accommodating performance criteria.

One of the challenges in implementing the RVA in an optimal water management strategy is that daily flow patterns are deemed critical to riverine flow regimes, and the daily time unit for large space scale management systems and multi-decadal time horizons is perhaps too fine a resolution; both in terms of computational difficulty and solution tractability, and practicality: the applicability of forecast daily allocation decisions for a large space scale management area over a multi-decadal time horizon are questionable at best. This research compromises by using the difference between the monthly demand and supply to determine a median change for each daily flow value. IHA values and subsequently the regime characterization for the projected flow are based upon the adjusted daily values.

A final limitation is that the RVA is meant to be used as part of an adaptive management strategy, whereby a cross-discipline team studies the historical flow regime patterns and the riverine ecological system, and establishes critical ecological flow criteria suited to the locale. After appropriate ecological indicators are identified and a monitoring system is setup, river flow is managed to meet the developed criteria. Feedback from the ecological system is used to gage the ecological response to the managed flow regime and adjustments for unintended or unforeseen consequences are made where necessary. This model is not intended to address this aspect of the management process and any meaningful practical application requires the development of an ecologically sound flow to be used as the basis of comparison against projected flows.

## 1.5 Organization of the Research

This dissertation may be organized into four parts. The first part serves as background, introducing the concepts presented in this research and reviewing available research. This begins with Chapter 2 and the topic of water management models. In Chapter 3 research on sustainability and flow regimes is reviewed to establish working definitions and applicable methodologies.

The second portion of the research addresses the development of the model including the approach, methodology and an explanation of the programming logic in the primary algorithms. This includes the adaptation and application of the sustainability and flow regime definitions and metrics and is presented in Chapter 4.

Application, results analysis and discussion, and suggestions for additional research are presented in the third part of the research. Chapter 5 details the model's application to the Prescott AMA and includes a discussion of the results. Chapter 6 follows with a conclusion and suggestions for further research.

The final section provides background and supporting information for several key concepts discussed in this research. As mentioned earlier, software for the RVA was created as part of this research. The pseudo code for the implemented algorithms and the Modified HA is available in Appendix A. An introduction to the Prescott AMA is provided in Chapter 5 and covered more extensively in Appendix B, including a brief summary of the Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona (RGFM) (Pool et al. 2011), which is used for determining the aquifer response function. Appendix C discusses the topic of economic valuation of streamflow. The objective function for the LTM evolved during the course of this research from focusing solely on sustainability to considering sustainability and net economic benefits. Appendix D discusses this evolution and includes results from previous forms of the LTM objective function. The GAMS code used in the STM is provided in Appendix E. Several PHP classes and files were developed while pursuing this research. These are listed in alphabetical order in Appendix F along with a short description.

# 2 Water Management Models

## 2.1 Introduction

This chapter begins with a brief background on water management models, followed by a summarization of the conclusions and recommendations that have been suggested for water management models in general and holistic modeling applications specifically. Applications across varying domains are examined, with special attention to how sustainability and ecological concerns were addressed. This is used to conceptualize the framework for the model developed in this dissertation and is followed by discussion on best practices for water management models. The chapter ends with discussion on the developed model basis, methodology and optimization.

## 2.2 Background

McKinney et al traces the origin of basin scale management models to the design and application of computational models used to predict hydro-meteorological processes during the first quarter of the 20th century. More complex hydrologic processes began to be simulated in the 1950s and 1960s with the advent of computers. The increased computing power realized with the introduction of the personal computer brought with it a plethora of water management modeling resources.

Water resource modeling takes many forms. Resources can be modeled and managed at the sub-system (e.g., reservoirs, groundwater, irrigation and drainage) or basin levels; modeled and analyzed via simulation, optimization or a combination of the two; and examined via a hydrologic approach or an integrated hydrological-economic approach. The latter often take two forms, compartment modeling approaches and holistic modeling approaches (Daene C McKinney and System-Wide Initiative for Water Management 1999).

Compartment modeling has been described as the integration of two separate and existing models: economic models and hydrologic models (Van der Ploeg et al. 1987). A compartment modeling approach establishes and maintains a relatively loose connection between the economic and hydrologic models. This maintains the integrity and complexity of the models and offers a 'more realistic' simulation. The primary concern for this approach is the integration of the models and what information technology standards are available to communicate information between the components (Heinz et al. 2007). However, the lack of dynamic connection is also a drawback to the approach (Daene C McKinney and System-Wide Initiative for Water Management 1999).

In contrast, the holistic modeling approach uses economic and hydrologic sub-models, which are combined into a single consistent model and typically solved in the entirety. Holistic models are better at depicting the coupled human-natural inter-relationships and mimicking the impact of driving forces in feedbacks from the environment (Daene C McKinney and System-Wide Initiative for Water Management 1999). Holistic water resources-economics models are particularly useful for regions where competition for water use is intense, economic water uses dominate, economic and operational impacts of proposed management alternatives are of interest, and data are available to calibrate supporting economic models (Cai 2008a). The next section discusses sustainability and ecological concerns in holistic modeling applications.

## 2.3 Sustainability and Ecological Concerns in Water Management Models

### *2.3.1 Groundwater and Commonality*

Commonality refers to the concept of common goods in economics: whereby a good is rivalrous and non-excludable. A holistic approach is used to understand the problem of commonality in groundwater use in Worthington et al. (1985). Early groundwater management strategies attempted to minimize commonality by employing the concept of safe yield: total use is limited to volume of water flowing into the aquifer over some regular time period. In contrast, Worthington et al recognizes interdependencies between pumpers and use a dynamic programming approach to solve for the optimal rate of inter-seasonal withdrawals on a confined aquifer in southwestern Montana. The authors found that the magnitude of economic consequences from ignoring interdependencies between pumpers and the stock value of the resource depend upon several factors, including: 1) the rate at which future returns from a basin are reduced to present value terms; 2) assumptions about land productivity and the resulting shape of the gross returns function from groundwater use; and 3) relative pumping costs.

### *2.3.2 Sustainability in Hydrologic-Agronomic-Economic-Institutional Relationships*

Cai proposes a holistic basin management model that is applied to the Syr Darya River basin in Central Asia (Cai 1999; Cai et al. 2001). Sustainability is defined as ensuring a long-term, stable and flexible water supply capacity to meet demands, as well as the maintenance of environmental consequences associated with irrigation practices. Metrics are proposed for sustainability criteria including reliability, reversibility, and vulnerability of the water supply system, environmental system integrity through consideration of water quantity and quality, spatial and temporal equity, and 'socio-economic acceptability'. The concept of socio-economic acceptability is a measure of weak sustainability, directly pertaining to the comparison of marginal costs associated with natural capital depletion and the marginal benefits: when the environmental costs exceed the marginal benefits associated with the use of the resource (or depletion), the system becomes unsustainable. Ecological and environmental concerns are addressed via minimum volume and quality constraints.

The modeling framework consists of an intra-year short-term optimization model examining essential hydrological, agronomic, economic and institutional relationships, and an inter-year dynamic long-term model which includes long term changes and uncertainties in supply and demand. The intra-year model is simplified by identifying a set of complicating variables which are fixed such that the remaining variables are linear. The inter-year model varies the complicating variables and the solution is determined using a genetic algorithm-linear programming approach. Aspects of this work are adopted for use in this research.

### *2.3.3 Maximum Net Benefit and Economic-Hydrologic Relationships*

Rapid agricultural and economic development in mainland Southeast Asia during the 1990's increased demand on the Mekong River Basin. Ringler (2001) examines the tradeoffs and complementarities in water usage and the efficient allocation of water resources in the basin using an integrated economic-hydrologic model. Water benefit functions are developed for competing demands and minimum flows are used as constraints for environmental, ecological and navigation concerns as well as water quality criterion. Maximum net benefit is used to explore allocation scenarios across complex economic, political, and environmental interests.

### *2.3.4 Non-use Value of Groundwater*

A holistic modeling approach is developed and used in Rothman (2007) to consider the issue of water supply sustainability. The model is applied to the Prescott Active Management Area and utilizes a cost function for the non-use of groundwater which was developed using Hotelling's exhaustible resource theory. The cost function associated an 'existence' or 'bequest' value with the groundwater, in an attempt to make it available for future users (sustainable). The model successfully allowed the quantification and comparison of assumed groundwater cost factors and factors to consider in resource protection.

### *2.3.5 Environmental Concerns in Conjunctive Use*

Conjunctive use of surface water and groundwater at the basin scale is examined via a holistic approach in Pulido-Velázquez et al. (2006). Optimization is used to find an ideal operation and allocation schedule and maximize economic benefit for the Adra River system in Spain. Hydrologic simulation in the model is accomplished via a distributed-parameter groundwater simulation and dynamic stream-aquifer interaction. Stream-aquifer interaction is modeled using the embedded multi-reservoir method with the aquifer response simulated using an eigenvalue technique. Environmental constraints are imposed via minimum stream flows.

### *2.3.6 Riparian Basin Concerns*

Ringler and Cai (2006) analyzes alternative water–using strategies for a riparian basin by incorporating water values for fisheries and wetlands into an integrated economic-hydrologic river basin model. Optimal allocation across water using sectors in the Mekong Basin is determined on the basis of the economic value of water in alternative uses, considering both sectoral structure (agriculture, industry, hydropower, households, and the environment) and spatial distribution. Fish harvest is modeled as an increasing function of water availability, taking into account extractions and return flows. Net wetland benefits are described as a function of wetland area and yield and decline with increasing deviation from normal monthly flows. In addition, minimum flow requirements were specified for all source flow, along with navigation and monthly outflow to the sea constraints.

### *2.3.7 Conclusion*

In general, research on water resource management models is an active field and numerous models are available for nearly every concern in water resource management: quality, quantity, distribution, collection, storage and drainage. Recent research has seen increasing interest in managing and modeling for ecological and sustainability concerns (Alley and Leake 2004; Carlisle et al. 2009; Hedelin 2006; Homa et al. 2005; Daniel P Loucks et al. 1999, among others).

A review of the available literature on water management models provides a foundation for additional research and a basis for the developed model. Guidelines and best practices are well established and management models have been employed in a diverse cross-section of problem areas. Management models are often holistic, but not always and optimization methods are generally employed when questions of allocation are asked.

Given the critical nature of the resource, the optimal allocation of water resources has received much attention. What is in relatively short supply is the explicit consideration of ecological requirements and sustainability. Homa et al. (2005) reports that out of hundreds of optimization-oriented reservoir operations reviewed, only three were identified as focusing on the optimal tradeoff among ecological and human flow needs. The vast majority of the reviewed research considers stream flow needs as a fixed constraint assuring some minimum level of flow or level of quality. As discussed in Chapter 3, this is not adequate for ecological concerns, and the need for a model that does adequately address ecological integrity is apparent. This discussion is followed by an examination of best practices for water management models.

## 2.4 Best Practices

As expressed in Jakeman et al. (2006), the use of models can bring dangers, especially for non-modelers. With every model there are limitations, uncertainties, omissions and subjective choices. The risk is that too much is read in the outputs and/or predictions, or that the model be used for purposes for other than it was intended. Parker et al. (2002) presents essential questions in the evaluation of a model:

- Has the model been constructed of approved materials i.e., approved constituent hypotheses (in scientific terms)?
- Does its behavior approximate well that observed in respect of the real thing?
- Does it work i.e., does it fulfill its designated task or serve its intended purpose?

King and Brown (2006) lists three informational requirements for water resource decision makers: 1) a range of options of what the future could be like, using scenarios or potential river changes and social impact; 2) simple summaries of each scenario of river change in a context that the decision makers can relate to; and 3) expressing the financial implications of each scenario in terms of both impacts and costs for compensation or mitigation purposes and benefits, e.g., increased hydroelectric power generation or crop production.

Loucks et al. (2005) offers several suggestions for water management and planning best practices. As applied to modeling and analysis tools, best practice mandates that these tools should:

- Be accommodating of both short and long term issues
- Integrate the biotic and abiotic parts of the basin
- Take into account the allocation of water for all needs including those of natural systems
- Be accommodating of multiple objectives

McKinney et al. assesses the potential of coupled economic-hydrologic models to address critical issues related to increasing water demand and resulting inter-sectoral competition. The authors suggest that the fundamental dilemma facing water policy managers is that water demand in developing countries is increasing rapidly across all demand categories, while watersheds, irrigated land base and the quality of water being delivered are all deteriorating and propose research objectives for future river basin modeling. They identify a set of recommended characteristics for water management models (Daene C McKinney and System-Wide Initiative for Water Management 1999):

- Integration of hydrologic, agronomic and economic relationships in an endogenous system that will adapt to environmental, ecological, and socioeconomic statuses related to the river basin domain
- Specification of an integrated river basin network, on which mathematical models are built, that includes the water supply system (surface water and groundwater), the delivery system (canal network), the water users system (agricultural and nonagricultural), the drainage collection system (surface and subsurface drainage), and the waste water disposal and treatment system, as well as the connections between these subsystems
- Representation of the spatial and temporal distribution of water flow and pollutant transport and mass balance through the river basin
- Representation of water demands from all water-using sectors for analysis of inter-sectoral water allocation policies
- Evaluation of the economic benefits from each of these demands, including crop acreage and crop production functions incorporating both water application and quality
- Incorporation of economic incentives for salinity and pollution control, water conservation and irrigation system improvement as policy levers within the model

McKinney et al also suggests that basin-scale water resources management:

> *"…needs the development and use of a systems approach, which is built upon the integrity of a river basin system."*

This systems approach should be able to:

- Represent the geographic information of the basin
- Combine water quantity and quality management
- Integrate economic and hydrologic components
- Dynamically connect short- and long-term models.

Cai (2008a) reflects on the development and application of holistic water resources-economic models and suggests that they are particularly useful for highly competitive water use scenarios: ones in which economic uses dominate, economic and operational impacts of proposed management alternatives are of interest, and data are available for economic model calibration. Cai also identifies several challenges with respect to holistic models, including appropriately identifying the modeling problem and objectives, balancing disciplinary perspectives, selecting appropriate spatial and temporal scales, and developing trust with stakeholder groups. With respect to spatial scales, the model should attempt to take into consideration that the spatial aggregation of the water resources modeling needs to facilitate economic analysis and the economic modeling needs to be effective in simulating impacts on the hydrologic system operation and water allocation. With respect to model structure and matching spatial scales – the questions to ask are:

- What hydrologic relationships will be needed for reasonable economic analysis and effective decision making?
- Will the coupled hydrologic and economic structure make the model too difficult to solve?

The goal in the creation of the holistic management model is to capture the important interactions of hydrologic and economic variables, while understanding that this needs to be implemented in a feasible and effective way: too complex and convergence becomes a problem; too simplistic and the physical basis fails to characterize the management problem. With respect to time scales, the time interval should be small enough to reflect real-world processes and capture the transition change of physical systems, which will affect economic costs and benefits. The time horizon should be long enough to reflect the regional hydro-climatic cycle and economic and environmental. Lastly, Cai recommends modelers work with water managers in studying the basin and constructing the model.

## 2.5 Conclusion

This chapter summarizes a portion of the available research with special attention to holistic applications that addressed aspects of sustainability. Best practices for the developed model were established.

Holistic water management models have seen widespread development and application and research into the topic continues to see considerable attention, providing a sound basis for the developed model. Sustainability is a growing concern, but formal application has been limited. Water managers have nearly always been concerned with the minimizing risk to future supplies, but only relatively recently has this been formalized under the auspices of sustainability; and traditionally fails to acknowledge a more comprehensive set of sustainability metrics:  both society's objectives, and ecological, environmental, and hydrological integrity. This chapter concludes with a basis and methodology for the developed model.

## 2.6 Model Basis

A water management model typically contains two models: the simulation model and the optimization model (see Figure 2.1). The simulation model addresses hydrologic relationships sufficient to characterize the management problem. The optimization model uses the output from the simulation model to construct the objective function and feasible solution space with the ultimate objective of reducing the total number of simulations. The roles of each model are complimentary, neither really sufficient in and of itself (McKinney et al. 1999):

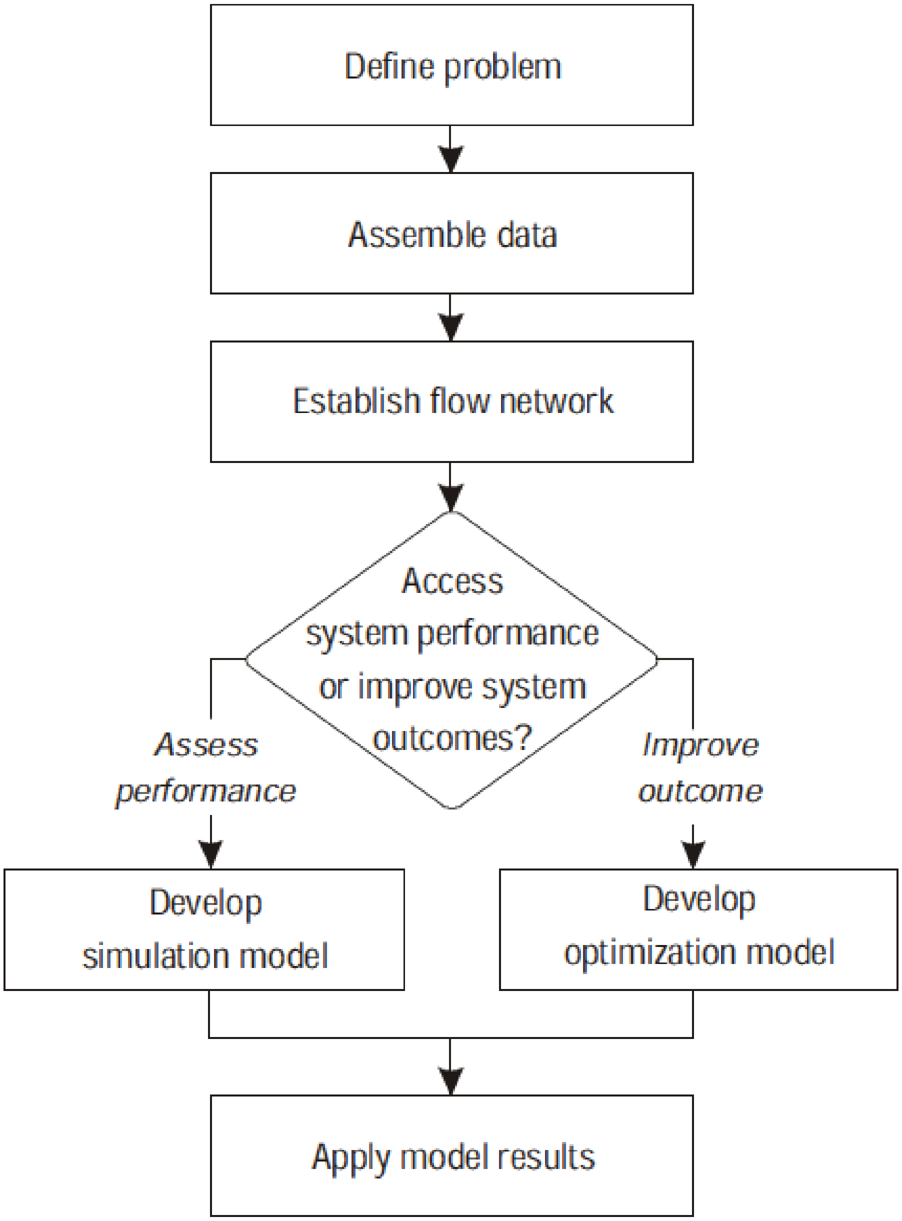
> *"Simulation by itself begs the question: 'What to simulate?' Optimization by itself begs the question: 'Is the solution really the best?'"*

Both types of models require same basic data types and an understanding of system operations. Models in general consist of algebraic equations with known and unknown variables. Known variables are generally called parameters and though assumed to be known, may be associated with some degree of uncertainty. Unknown variables are considered decision variables and are comprised of both design and operating policy variables. The system being analyzed has conditions or constraints that must be satisfied and ‘solving the model’ becomes the practical task of finding values of its unknown decision variables.

Simulation models require that decision variable values be assigned before being performed, and are intended to provide a solution to the ‘what if’ question: what happens when a particular decision variable configuration is used. For example, decision variables values may affect operation of the model entities and the timing and magnitude of flows. It is not uncommon to find water management simulation models with thousands of decision variables and exponentially more possible management scenarios. This by necessity limits the best use of simulation models to the consideration of a select few scenarios.

Optimization models utilize the same relationships paired with an objective function to effectively reduce the number of ‘good’ decision variable configurations and provide planners with policy and management options. However, optimization models are limited in their depiction of the physical relationships: the highly complex and nonlinear relationships available to simulation models often pose convergence problems for optimization models.

**Figure 2.1. Complimentary optimization and simulation model application (From Daene C McKinney and System-Wide Initiative for Water Management 1999).**



Two different approaches are typically used in the application of simulation and optimization models to water resource management: the compartmental approach and the holistic approach. The compartmental approach keeps the simulation and optimization models distinct with what has been described as “a loose connection between compartments” (Cai 1999). This approach is primarily used in large complex systems as it is relatively easy to solve individual compartments. Limitations to this approach include data translation and compatibility concerns and concerns over the effect of errors and uncertainty in separated compartments (Cai 2008b). The holistic approach essentially simulates the hydrologic systems in the process of satisfying values requested by the optimization constraint sets and objective functions. This tightly couples the simulation and optimization components (e.g., the hydrologic and economic components) eliminating the need for information translation/transfer and allowing for more comprehensive sensitivity and error analysis. However, tractability necessitates a reduction in complexity. The question in holistic models becomes one of how much complexity is required to adequately address the management problems. The holistic modeling approach is utilized in this research.

## 2.7 Methodology

Water resource management can be sub-divided into three broad categories: 1) water supply-management, 2) water-excess management, and 3) environmental restoration (Mays 2011). This research is concerned with the first category, specifically (from the introduction):

> *"The application of sustainability to the water management problem at the river basin level, with special attention to riverine ecological concerns."*

Addressing this problem requires the definition of the terms and scope, a review and summary of prior research, the development of a methodology and its application, and an analysis and summary of the results.

### *2.7.1 Model Scope*

Mays and Tung (1992) develops the concept of a system as

> *"... a set of interactive elements that perform independently of each other."*

A system is characterized by: 1) a system boundary or a rule that determines whether an element is to be considered as a part of the system or the surrounding environment; 2) statements of input and output interactions within the system and surrounding environment; and 3) statements of inter-relationships between the system elements and the inputs and outputs. Simply stated, the primary task of the water resource manager is to modify the inputs to a system so that the desirable outputs are maximized while undesirable outputs are minimized. Water within a management area can be described in terms of quantity and quality as functions of time (**t**) and location (**x**). Volume (**V**) and quality (**Q**) may be expressed as dependent variables of **t** and **x**, which are in turn used to define the state (**S**) of the system:

$$S = [V(t,x), Q(t,x)] \tag{2.1}$$

The development and management of water resources is concerned with the transformation of the current state into the desired state ($\mathbf{S}^*$), which in turn is dependent upon the desired volume ($\mathbf{V}^*$) and quality ($\mathbf{Q}^*$) and desired time ($\mathbf{t}^*$) and location ($\mathbf{x}^*$):

$$S^* = [V^*(t^*,x^*), Q^*(t^*,x^*)] \tag{2.2}$$

The transformation from **S** to $\mathbf{S}^*$ is the primary objective of water resource management and with the aid of a transfer function (**W**) and a waste or by-product function (**E**) may be expressed via the transformation equation:

$$S^* = WS + E \tag{2.3}$$

Additionally, the transfer function may be considered in terms of physical components or hardware ($\mathbf{W_1}$) and the operational aspects or software ($\mathbf{W_2}$), that is to say:

$$W = (W_1, W_2) \tag{2.4}$$

Recognized techniques used to describe the transformation process are simulation, optimization and a combination of the two. This research is limited to questions of quantity and utilizes a holistic simulation-optimization framework to determine sustainable growth and consumption patterns and the most efficient allocation among competing demands (Mays and Tung 1992).

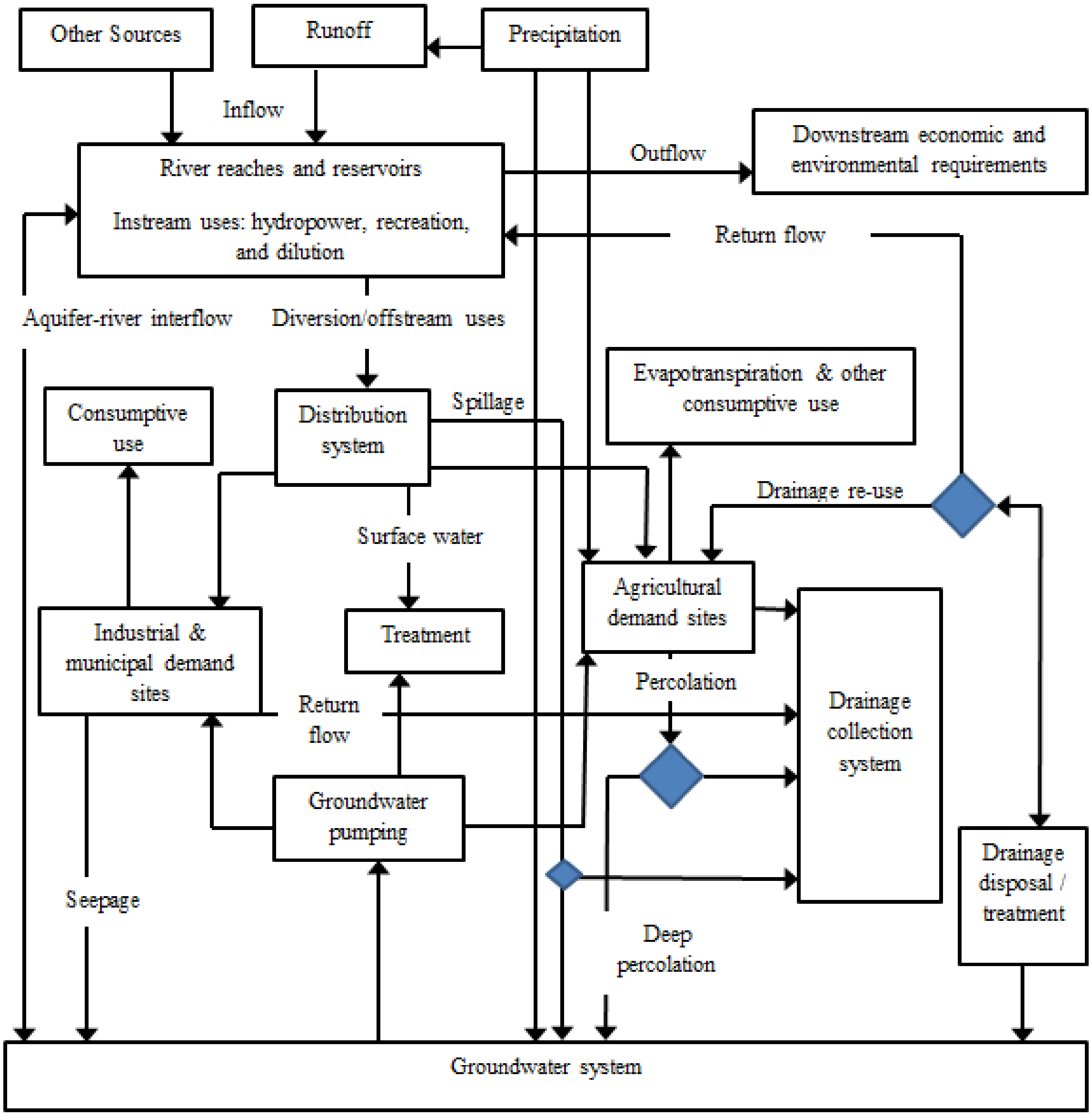
### *System Boundary*

In the conventional use of the term, water resource management involves the distribution, use and care of a water resource. This requires the definition of a management area and the identification of supply, water users and the associated demands on the supply. Water resource management areas can be defined with one of several criteria or some combination: geological and/or topological boundaries, political boundaries, and/or legal boundaries. River basins and watersheds are often the logical choice for management area boundary (Cai 1999; Loucks et al. 2005). However, the natural river basin boundaries are often in conflict with aquifer boundaries and/or politically established boundaries. Ideally, management areas should encompass the entire physical, socio-economic and administrative water resource system or the 'problem-shed' (Loucks et al. 2005). The base management unit utilized in this research is referred to as the river basin, but the scope is defined in terms of the problem-shed.

### *River Basins*

The river basin unit is a natural choice for water planning and management purposes: topographical boundaries facilitate water budget calculations, and water flow has a large influence on the extent of other natural components such as soil, vegetation, and wildlife (Cai et al. 2003). River basins can be divided into three components, (1) source components such as rivers, canals, reservoirs, and aquifers, (2) demand components such as irrigation fields, industrial plants, and cities, and (3) intermediate components such as treatment plants and water reuse and recycling facilities (Cai 1999). An organizational schematic of these component and their relationships is presented in Figure 2.2. The river basin system is characterized by the atmospheric conditions which drive the basin hydrology and generally determines the volume of water required and available to the system.

**Figure 2.2. River basin management simulation schematic (after Ximing Cai 1999; Daza and Peralta 1993).**



## *Time Scale*

Water planning is a ‘continuing sequential process’ dependent upon forecasts, updated forecasts, current information and management objectives (Loucks et al. 2005). Resource management strategy requires looking into the future; one of the goals in resource management is to ensure that a resource will be available when it is most needed. In practical, every day application, water managers are attempting to satisfy the immediate demands on the system while trying to understand what impact decisions made today will have on future decisions. This suggests two management time horizons and objectives, the short term concerned with an immediate objective, and the long term horizon concerned with the long term objective. Good management practice dictates that short term decisions always be made with long term consequences in mind.

One of the goals of this research is to provide a framework that accommodates both human and ecological demands. Flow regimes are defined in terms of the annual schedule of daily flows. This suggests that the short term time horizon be expressed on an annual basis, which works out for human consumption patterns as well. In terms of ecological impact, a daily unit of time for the short term time horizon would seem to be in order. However, given the computational load that a daily unit of time implies, not to mention the applicability of a daily allocation decision for a long term management model, the unit of time selected for the short term time horizon is a month.

Cai (1999) suggests several items for consideration when considering appropriate long term time horizons for basin management models:

- The time horizon should be long enough to reflect climate changes in the hydrologic record. Forecasting this is complicated due to global climate change trends.

- The long term horizon should be long enough that effects from short term decisions can be identified. For example, consistent surface water diversions and reliance upon river flows will eventually affect river ecology.
- The time horizon should allow the identification of sustainable to non-sustainable system shifts, if they exist.

Longer time horizons involve more uncertainty in the forecasts resulting in a more complex solution space or less applicable real-world results. Modeling capacity and data availability are often the constraint on long term planning horizons (Cai 1999).

### *2.7.2 Statements of Input and Output*

The inputs for a water management system consist of water supplies and demands while outputs for a system are expressed as an optimization model's objective functions. In general terms, an objective may be expressed as:

$$Max\ f(x) \tag{2.5}$$

Such that:

$$x \in X \subseteq \mathbb{R}^n \tag{2.6}$$

Where *x* denotes the decision variables in the mathematical model, *f(x)* is the objective function measuring the quality of the solution, and *X* is the set of feasible solutions (Pardalos 2002).

The problem statement establishes two objectives for water allocation in the system: *maximum sustainability* and *net benefits*. This type of problem is a multi-objective optimization problem, but the objectives are combined as a single objective in the developed model. Net benefit is readily measured in monetary terms, except for cases in which the entire value of the service is not fully understood or known, such as environmental services. Degree of sustainability is measured under a longer term analysis using an index that takes into consideration reliability, resilience, maximum vulnerability, maximum deficit, and a specified flow regime. The next chapter discusses the sustainability index and flow regime concepts.

# 3 Sustainability and Flow Regime

Beginning with the Brundtland Report in 1987, interest in sustainability and its application has seen widespread attention and discussion. The concept of sustainability was originally used in connection with forestry science and the long term management and availability of the forest resource in the 18th century; however, the definition of sustainability is vague, especially in the water resources field. Lant (2007) points out that:

> *"...sustainability is both a vague and politicized term, yet it is precisely because the world community has rallied around sustainability and sustainable development as normative goals of ecological-economic performance that the stakes are high for defining the concept in a manner that is true to its spirit"*

Sustainable development is a concept still in the making (Unver 2007).

This chapter discusses the origins and evolution of the sustainability concept, its application in water resource management and formalizes a definition and the approach selected for this research. Two themes are identified in water resource sustainability definitions. The first is the concept of equitable distribution, the second is integrity. These are addressed under the demand-supply deficit performance criteria and flow regime criteria discussions respectively.

## 3.1 Sustainability

### *3.1.1 Introduction*

The concept of sustainability is concerned with the present and future use of a limited resource. In its simplest terms, the idea is not new or complicated and the predominant issue of interest in nearly every resource decision: how do we use available resources while considering both current and future needs? This resource allocation - or ‘temporal equity’ is a daily decision everyone is faced with. The issue becomes more complicated as the basic premise is applied to the wide array of demands competing for the resources; demands that are not so readily identified and understood.

Evidence suggests that society’s present resource use and management practices may significantly impact the welfare of those living in the future (Kates et al. 2001; Loucks et al. 2005). Science and society are recognizing that the true impact of our collective decisions are not so easily understood, mitigated and adapted to by our home environment; the results of our decisions have implications for both immediate and long-term time horizons.  Above all else, the science of sustainability acknowledges the reality of the implications and is an effort to ensure the competency of resource allocation decisions. The difficulty is in recognizing the true impact of our decisions, or perhaps better said, the true nature of the demands for the resource in question.

### *3.1.2 Background*

The concept of sustainability was reportedly first formally used in conjunction with forestry science, where it was defined as never harvesting more than what the forest yields in new growth. The German term for sustainability *nachhaltigkeit* was used in relation to forestry as early as 1713. In 1804 the German forestry lecturer Hartig described the concept in terms of sustained forest yield (Wiersum 1995):

> *"Every wise forest director has to have evaluated the forest stands without losing time, to utilize to the greatest possible extent, but still in a way that future generations will have at least as much benefit as the living generation."*

As the concept evolved, Wiersum (1995) reports that the focus of the sustainability question expanded. Sustainable yield began to be considered in terms of the maintenance of a dominant product or product mix, the sustenance of production capacity, the conservation of total forest ecosystems rather than specific components of such ecosystems and the maintenance of human systems that are forestry-dependent. The simplistic notion of 're-planting what is harvested' is currently overshadowed by the true nature of the problem with cross-disciplinary questions and competing philosophies and values. Wiersum concludes that despite 200 years of efforts to operationalize the concepts of sustainability in forestry, the application remains troublesome (Wiersum 1995). This is the true nature of the sustainability question.

Contemporary interest in sustainability is generally recognized as beginning with the publication of the World Commission on Environment and Development (also known as the Brundtland Report). This report adopted the idea of sustainable development as a response to predictions of the depletion of critical resources and offered a way out of the 'impending doom' (Kuhlman and Farrington 2010). The Brundtland report defined sustainable development as (World Commission on Environment and Development 1987):

> *"Sustainable development is development that meets the needs of the present without compromising the ability of the future generations to meet their own needs."*

The strength and relevance of the Bruntland definition lie in the juxtaposition and means of reconciling two goals that are often in tension: sustainability and development. Yet the definition has been criticized in that broadness of the definition left application open to interpretation and thus potential misunderstanding (Dixon and Fallon 1989).

Kuhlman and Farrington (2010) reports that since the Brundtland Report there have been two major developments in the concept of sustainability: one, its interpretation in terms of three dimensions (social, economic, and environmental), and two, the distinction between 'strong' and 'weak' sustainability. The three dimensional approach to sustainability stemmed from the Triple Bottom Line concept in management science, which was intended as a means of operationalizing corporate social responsibility: to the conventional bottom line of profit (economic dimension) should be added the bottom line of 'being good to people' (social dimension) and the bottom line of caring for the environment (environmental dimension). Kuhlman and Farrington (2010) argues that the social and economic dimensions are not so easily distinguished in policy decisions and suggest that both should be considered under a single policy goal of ‘well-being’ which must in turn be balanced against another policy goal: that of sustainability. Sustainability is then defined as ‘maintaining well-being over a long time’. Practically speaking, this is expressed as the decision of what resources to bequeath to future generations.

This is exemplified in Loucks (1997) and Goodland et al. (1991) where it is reported that sustainable development is a relationship between changing human economic systems and larger and slower changing, ecological systems, with the suggestion that sustainable development is concerned with progression. That is to say, sustainable development is development which continually seeks improvement in the quality of life without necessarily causing an increase in the quantity of resources consumed.

The ‘what’ of the sustainability question centers around the issue of substitutability – can one resource be substituted for another? ‘Weak sustainability’ is based on the belief that “*what matters for future generations is only the total aggregate stock of man-made and natural capital (and possibly other capital)*”; that is to say that the resources produced in the consumption of natural capital (e.g., infrastructure, technology, research, etc.) may be substituted for the natural capital that was consumed. ‘Strong sustainability’ dictates that natural capital is regarded as non-substitutable (Neumayer 2010). Kuhlman and Farrington (2010) suggests that the two schools of thought are not mutually exclusive and that both should be considered in sustainability.

Strong sustainability can be thought of in terms of thresholds which cannot be crossed and within which the outcomes of policy decisions are measured by weak sustainability.

Sustainability as applied to water resource system models has by necessity always been weak sustainability; as Kuhlman and Farrington (2010) notes, "*Strong sustainability puts* [modelers] *out of work*". As discussed however, constraints on a model are often substitutability thresholds or a strong sustainability 'boundary'. Recognizing the role of both weak and strong sustainability allows resources to be put to 'reasonable' beneficial use; thus rendering a resource to manage and a system to model. The burden rests upon science, society and policy makers to describe the thresholds.

### *3.1.3 Sustainable Development of Water Resources*

As it concerns the question of temporal equity and resource allocation, water resource management has in general terms always been about sustainability. Though initially more concerned with questions of human consumption and health, the focus of water resource management has expanded to include environmental concerns as well (Loucks et al. 2005).

One of the first in depth research studies into sustainable water resource development is the *Sustainable Criteria for Water Resource Systems*, which was produced in a joint effort of the International Hydrological Programme of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the Task Committee of the Division of Water Resources Planning and Management of the

American Society of Civil Engineers (ASCE) (Loucks et al. 1999). Sustainable water resource systems are defined by the authors as:

> *"Sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity."*

The authors review sustainability guidelines and the extent to which they had been applied in water resource management and go on to present approaches for measuring and modeling sustainability. They suggest that sustainability should not require that every component of every system never fail and note that anticipation of change is the most essential aspect in the planning, design and management of sustainable systems. Particularly, sustainable water resource systems are systems that are:

> *"…those designed and operated in ways that make them more adaptive, robust, and resilient to these uncertain changes."*

As it concerns weak and strong sustainability, the authors suggest that sustainability should not be equated with the preservation of non-renewable resources, but rather the question for stakeholders is using non-renewable resources when it is the most beneficial (Loucks et al. 1999).

In a review of contemporary and historical water resources sustainability applications, Mays (2007) offers a definition:

> *"Water resources sustainability is the ability to use water in sufficient quantities and quality from the local to the global scale to meet the needs of humans and ecosystems for the present and the future to sustain life, and to protect humans from the dangers brought about by natural and human-caused disasters that affect sustaining life."*

Mays also summarizes the water planning aspects that must be considered in successful application of sustainability:

- Water resources sustainability includes the *availability of freshwater supplies* throughout periods of climatic change, extended droughts, population growth, and to leave the needed supplies for the future generations
- Water resources sustainability includes having the *infrastructure* to provide water supply for human consumption and food security, and to provide protection from water excess such as floods and other natural disasters.
- Water resources sustainability includes having the *infrastructure* for clean water and for treating water after it has been used by humans before being returned to water bodies.
- Water sustainability must have adequate *institutions* to provide for both the water supply management and water excess management.
- Water sustainability can be defined on a local, regional, national and international basis.

In the course of pursuing a sustainable water plan for California, Gleick et al. (1995) presents a definition for sustainable water use:

> *"The use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it."*

This definition is meant to provide an over-arching qualitative framework, while the following seven sustainability criteria are intended to guide planning and management decisions (Gleick et al. 1995):

- A basic water requirement will be guaranteed to all humans to maintain human health
- A basic water requirement will be guaranteed to restore and maintain the health of ecosystems
- Water quality will be maintained to meet certain minimum standards. These standards will vary depending on location and how the water is to be used.
- Human actions will not impair the long-term renewability of freshwater stocks and flows.
- Data on water resources availability, use, and quality will be collected and made accessible to all parties.
- Institutional mechanisms will be set up to prevent and resolve conflicts over water.
- Water planning and decision making will be democratic, ensuring representation of all affected parties and fostering direct participation of affected interests.

Gleick (1998) stresses that these guidelines by themselves are not recommendations for actions as much as they are endpoints for policy, offering a "*basis for alternative 'visions' for future water management and can offer some guidance for legislative and nongovernmental actions in the future*". The lack of such criteria is certain to result in unsustainable policy.

### *3.1.4 Conclusion*

The definitions of sustainability are by necessity vague, but this does not make them useless (Solow 1993). Common themes in the presented definitions include the protection and pursuit of societal objectives and ecosystem integrity. This is perhaps most succinctly presented in Loucks et al. (1999):

> *"Sustainable water resource systems are those designed and managed to fully contribute to the objectives of society, now and in the future, while maintaining their ecological, environmental, and hydrological integrity."*

This definition nominates two standards of measure: societal objectives and ecological, environmental and hydrological integrity of the resource. To integrate these, a sustainable management plan must first identify society's objectives and ascertain some sense of integrity. Assuming an efficient market, societal objectives can be at least partially expressed as demand patterns – where is the water used? The definition also implies that the needs and values of a future generation be anticipated. Together these suggest the idea of equitable distribution in space and time. Integrity implies the identification and protection of the characteristic nature of the resource.

Loucks et al. (1999) suggests that the guiding principal of sustainable water resource management is to provide options for future generations rather than attempt to anticipate needs. The best way to accomplish this is to attempt to identify all of the beneficial and adverse ecological, economic, environmental and social effects associated with long term projects (Loucks et al. 2005). This is a daunting task, and if one is to avoid being completely overwhelmed, it must be acknowledged that the task is continuous in nature – implementation must start with the available information and managers should continually seek to improve upon that knowledge and be prepared for things to change. The goal however remains clear – sustainability must be measured with respect to how equitable distribution and integrity are maintained. The following section discusses application of integrity for riverine systems.

## 3.2 Flow Regime

Historically, the management and protection of riverine ecosystems has concentrated upon two aspects of a river: water quality and minimum flow. However, these approaches fail to recognize the understanding that ecological health and balance depends upon the naturally dynamic characteristics of river flow. Poff et al. (1997) describes these dynamic characteristics as the ‘natural flow regime’. This section introduces the topic of flow regime and discusses its application in water management models.

### *3.2.1 Background*

It can be said that all river flow is dependent upon precipitation and the time it takes for the precipitation to reach the river. The process by which this occurs is what is known as the rainfall-runoff process. This process is deterministic, which is to say that it is governed by definite physical laws that are widely known and understood (Nash and Sutcliffe 1970).

The path from rainfall to river flow is diverse. Water falls with very little of it contributing directly to river flow. The majority of rainfall becomes runoff, which is drawn by gravity towards the river and hindered along the way by vegetation, geological structure and climate. The various delays in timing combined with seasonal rainfall patterns combine to form a river's distinctive flow characteristics or *flow regime*. The riverine ecological system is highly dependent upon the flow regime, so much so that the flow regime is referred to as the 'maestro' (Walker et al. 1995) and 'master variable' (Power et al. 1995) when referenced with respect to riverine ecological response.

The natural flow regime refers specifically to the range and variation of flows over recent historical time (Poff et al. 1997; Richter et al. 1996). Poff et al. suggests five components as descriptors of flow regimes: magnitude, frequency, duration, timing and rate of change. *Magnitude* is defined as the volume of water moving past a fixed point for a certain time period. *Frequency* refers to the occurrence of a specific magnitude of flow for some time interval. *Duration* is the period of time over which particular flow conditions take place. *Timing* is the measure of predictability with which flows of a defined magnitude occur. *Rate of change* describes how rapidly flow changes from one magnitude to another. In addition to describing a flow regime, each of these is deemed to independently fulfill ecological roles as well. (Poff et al. 1997).

Managing flow regimes for environmental concerns is not a new idea, however, Poff (2009) suggests that the dominant water resource management paradigm has been to avoid violating water quality standards and meeting some minimum hydraulic habitat flow criteria. Such practice is still the norm (Cai 1999, 2008a; Jager and Smith 2008; Rosegrant et al. 2000; Sandoval-Solis and McKinney 2009). This may be attributed in part to the inherent complexity of the ecological relationships and challenges associated with modeling these relationships for management purposes.

### *Flow Regimes and Ecological Systems*

Understanding, predicting, and measuring the ecological outcomes and derived social and economic benefits from environmental flow allocations is crucial to best water resource management practices (Arthington et al. 2010). However, determining cause-effect relationships in natural systems is a challenging task (Lloyd and Cooperative Research Centre for Freshwater Ecology (Australia) 2004; Poff and Zimmerman 2010). Difficulties include limits to random allocation of treatments due to scale (Webb et al. 2011), insufficient replication associated with natural variability, data describing the experiment location prior to development, and difficulty in allocating control or reference locations (Norris et al. 2012). Despite these difficulties, some relationships between flow regimes and ecological response have been established.

Poff and Zimmerman (2010) presents a comprehensive review of historical studies linking change in flow regime to ecological impact and found that larger changes in flow alteration are associated with greater risk of ecological change. Their review categorized qualitative relationships and attempted to establish quantifiable relationships between flow alteration and ecological impact. The majority of the studies reviewed examined flow alteration in terms of changes to flow magnitude; however the authors were unable to extract robust statistical relationships between the magnitude of the change in flow alteration and ecological impacts among taxonomic groups. Flow alteration is only one environmental factor in ecologic riverine response (Bunn and Arthington 2002), but a qualitative summary of the reported results documented strong and variable ecological responses to all types of flow alteration.

In an effort to overcome the challenges expressed in Poff and Zimmerman (2010), Webb et al. (2011) introduces 'causal criteria analysis' as a means of standardizing the approach to synthesizing evidence found in environmental science literature, especially as it concerns ecological responses to flow alteration. Causal criteria analysis is a method developed by epidemiologists in the 1960s, for purposes of inferring causality when strong experimental evidence is lacking (Webb et al. 2011). Thus, relationships supported by sufficient evidence can inform both transparent and robust environmental flow recommendations.

Several studies have used causal criteria analysis to prove or disprove ecological response hypotheses, primarily in Australia's Murray-Darling Basin (Webb et al. 2011).

Benthic macroinvertebrates (animals without backbones that live on a riverbed) are recognized as a good barometer of riverine ecological assessment due to their abundance, importance to the food chain, and sensitivity to changes in habitat and water quality (Rosenberg and Resh 1993). An early adoption of the causal criteria analysis method determined that macroinvertebrate assemblages were affected by flow regulation (Australian Stream Management Conference et al. 2005). Harrison (2010) reviews the impact of fine sediment addition in streams to macroinvertebrate assemblages and found strong evidence for a decrease in diversity and both a decrease and increase along finer taxonomic scales. Greet et al. (2011) conducts a systematic review of the available literature and find support for a causal relationship between seasonal flow timing and a number of riparian plant processes, suggesting that changes in the timing of peak flow patterns affect the riparian vegetation of regulated rivers. Webb et al. (2010) investigates flow regulation and the response of native fish using the causal criteria analysis method and found strong support for the hypotheses that both the diversity and abundance of native fish are positively related to flow magnitude.

### *Conclusion*

In review, research supports a relationship between the flow regime and ecological changes within the riverine environment. Though the relationship is not completely understood, it can be argued that integrating the flow regime metric into a water management model is an important step in sustainable water use and maintaining ecological, environmental and hydrological integrity. One of the goals of this research is to present a method for the inclusion of the flow regime in a water management model.

### *3.2.2 Flow Regime Assessment*

Tharme (2003) reports that there have been more than 200 methods developed to describe and measure change in natural flows. These are generally grouped in four categories: hydrological rules, hydraulic rating methods, habitat simulation models, and holistic rating methods. A description of each of the categories is presented in Table 3.1. The remainder of this section presents a synopsis of the most common methodologies and recommendations reported in Tharme (2003) along with a summary of more recent research.

#### *Hydrological*

#### Tennant Method

The Tennant method was developed by Tennant and the U.S. Fish and Wildlife Service using data collected from a series of field studies conducted over 10 years and 3 different states. The studies revealed that the condition of aquatic habitat '…*is remarkably similar on most streams carrying the same portion of the average flow*'. Based on this similarity, Tennant (1976) makes recommendations for base flow regimes dependent upon the time of year, giving each a narrative description pertaining to ecological and recreational use.

**Table 3.1. Summary of environmental flow methodologies (Pyrce 2004; Tharme 2003).**

| Category | Description |
|---|---|
| 1. Hydrological | •Environmental flow recommendations are made using simple desktop methods primarily using hydrological data (daily or monthly flow records)<br>•Typically a rapid, non-resource intensive method, providing low-resolution environmental flow estimates<br>•Considered appropriate at the planning level of water resource development, or in low controversy situations where used as a primary flow target |
| 2. Hydraulic Rating | •Uses changes in hydraulic variables (such as wetted perimeter or maximum depth) as a surrogate for habitat factors known or assumed to be limiting to target biota; this assumes a threshold value of the selected hydraulic parameter will sustain biota/ecosystem integrity |
| 3. Habitat Rating | •Uses detailed analysis of the quantity and suitability of instream physical habitat under different flow regimes based on integrated hydrological, hydraulic and biological response data<br>•Flow related changes in microhabitat are modeled using one or more hydraulic variables (e.g., depth, velocity, substratum composition, etc.) and optimum flow is linked to preferred microhabitat conditions for target species |
| 4. Holistic Rating | •The requirements of the complete ecosystem are integrated and considered (including the river channel, source areas, riparian zone, floodplain, etc.)<br>•The natural regime of the river is the fundamental guide, and must be incorporated into the flow regimes<br>•Critical flow criteria are identified for some or all major components of the riverine ecosystem<br>•The basis for most approaches is a systematic construction of a modified flow regime on a month-by-month and element-element basis which defines features of the flow regime to achieve particular ecological, geomorphological, water quality, social or other objectives of the modified system |

### Flow Duration Curves

Flow duration curves (FDC) relate discharge volume to the percentage of time that it is equaled or exceeded (Auble et al. 1994). Using an FDC, an exceedence percentile can be described and subsequently used as a minimum flow requirement, often in terms of seasonal levels, or indices. Examples include $Q_{95}$ (that flow which is met or exceeded 95 percent of the time) and 7Q10 (consecutive 7-day low flow event with a 1:10 year return period) (Tharme 2003). The FDC ranks flows by exceedence of probability and has a rich history in the field of hydrology (Vogel and Fennessey 1994), however, the metric loses seasonal daily variation which would suggest that it is not the best predictor of ecological response. A flood in the spring serves a different ecological purpose than a flood in the fall (Poff et al. 1997), but the FDC loses this distinction.

### Ecological Stream Classification

Arthington et al. (2006) proposes an adaptive approach to the identification of environmental flow guidelines, incorporating essential aspects of natural flow variability among classes of rivers. Using an ecological stream classification, class reference streams are identified within a basin, and distinction between classes is defined using natural flow regime flow metrics and a weighting scheme. Frequency distributions for each flow metric are derived from the historical flow records of each reference river and establish temporal and spatial variability limits. Flow impaired streams are then assigned to one of the regional classes using pre-disturbance flow metrics and flow response relationships are indicated from ecological health data comparisons between reference streams and flow impaired streams.

### Geospatial Predictors

Central to hydrological assessment is a specification of the hydrological attributes prior to possible human modification. Carlisle et al. (2009) proposes a method using geospatial data such as climate, topography, soils and geology for hydrological assessment on a national scale. The research successfully predicted average attributes of the natural flow regime at undisturbed sites and across diverse environmental settings.

### Range of Variability Approach and Environmental Flow Components

Using 33 Indicators of Hydrologic Alteration (IHA) indices derived from long-term, daily flow records, the Range of Variability Approach (RVA) was developed to describe flow regime changes. Pre- and post-impact time frames are defined and statistical differences between the pre- and post-impact IHAs are determined to describe the change in pre- and post-impact flows. The RVA was developed to aid in the determination of how much flow alteration was too much and is intended for application in situations in which very little or no ecological information is available to support environmental flow determination (Mathews and Richter 2007). The RVA is available in a software package developed by The Nature Conservancy and called the Indicators of Hydrologic Alteration software (The Nature Conservancy 2009). The RVA is the method selected for this research and a more comprehensive summary is presented later in this chapter.

Practical challenges in RVA implementation led to the development of the environmental flow components (EFC) concept which is also included in the IHA software package. Mathews and Richter (2007) reports that there are five major components of flow that have consistently been considered as being ecologically important in a broad spectrum of hydro-climatic regions: extreme low flows, low flows, high flow pulses, small floods, and large floods. Daily flows or series of daily flows are analyzed by the software and then categorized as one of the five flow components using 33 parameters, and the RVA is then used to suggest limits to the variability in the EFCs. It should be noted that the RVA does not provide an answer to how much hydrologic alteration of any one or combination of EFCs is too much, rather it is meant to provide the basis for statistical correlations between EFCs and ecological indicators which are further refined in an adaptive management plan.

The five components of the EFC are 1) low flows; 2) extreme low flows; 3) high flow pulses; 4) small floods; and 5) large floods. Table 3.2 presents a summary of the EFC types and parameters. The EFCs are intended to aid in developing environmental flow recommendations and are suited to real time management decisions, but are not an environmental flow prescription.

**Table 3.2. Summary of the EFC types and parameters (The Nature Conservancy 2009).**

| EFC Type | Hydrologic Parameters |
|---|---|
| 1. Monthly low flows | •Mean or median value for each calendar month<br>(12 parameters) |
| 2. Extreme low flows | Frequency of extreme low flows during each water year or season<br>Mean or median values of extreme low flow event:<br>•Duration (days)<br>•Peak flow (minimum flow during event)<br>•Timing (Julian date of peak flow)<br>(4 parameters) |
| 3. High flow pulses | Frequency of high flow pulses during each water year or season<br>Mean or median values of high flow pulse events:<br>•Duration (days)<br>•Peak flow (maximum flow during event)<br>•Timing (Julian date of peak flow)<br>•Rise and fall rates<br>(5 parameters) |
| 4. Small floods | Frequency of small floods during each water year or season<br>Mean or median values of small flood event:<br>•Duration (days)<br>•Peak flow (maximum flow during event)<br>•Timing (Julian date of peak flow)<br>•Rise and fall rates<br>(6 parameters) |
| 5. Large floods | Frequency of large floods during each water year or season<br>Mean or median values of large flood event:<br>•Duration (days)<br>•Peak flow (maximum flow during event)<br>•Timing (Julian date of peak flow)<br>•Rise and fall rates<br>(6 parameters) |

### *Habitat Rating*

#### Instream Flow Incremental Methodology

Of the habitat simulation methods, Reiser et al. (1989). reports that the in-stream flow incremental methodology (IFIM) is the most popular in the United States The IFIM has been considered by some environmental flow practitioners (Tharme 2003):

> *"…as the most scientifically and legally defensible methodology available for assessing EFRs [environmental flow requirements]".*

IFIM attempts to integrate the planning concepts of water supply, analytical models from hydraulic and water quality engineering, and empirically derived habitat versus flow functions (Stalnaker et al. 1995). The goal is to produce simulations of potential habitat quantity and quality as a result of water development projects, illustrated through a series of alternative flow regimes. Study implementation involves the collection of data, model calibration, and verification of model input and output. Alternatives are meant to be examined by an interdisciplinary team and judged in terms of effectiveness, physical feasibility, risk of failure, and economic considerations. A final solution is reached through iterative problem-solving and negotiation (Bovee et al. 1998).

#### Building Block Method

As described by King and Louw (1998), the Building Block Method (BBM) embraces the idea that some flows within a flow regime are more important than others for maintaining the river's ecosystem. Moreover, these flows can be identified and described in terms of the timing, duration, and magnitude, and combined to define a recommended modified flow regime. Identifying and incorporating the most important components of the natural flow regime is assumed to facilitate maintenance of the natural biota and functioning of the river. The BBM depends on available knowledge and the expert opinion and consensus of a multi-disciplinary structured workshop process.

### *Holistic Rating*

#### <u>Environmental Flow Assessment</u>

King and Brown (2006) summarizes the challenges of managing riverine systems for both human and ecological needs and the methods that have been adopted to overcome these challenges in South Africa. This includes the development of the *environmental flow assessment* (EFA) concept. EFAs are an attempt to create a structured understanding of a river system's flow-ecosystem relationship. The first step involves the identification of flow regime components important to ecosystem health and which are defined as flow categories. Daily flows are then assessed and assigned to a flow category using a minimum of 20 years of historical or simulated flow data. Multi-disciplinary teams utilizing a structured scientific process work together in an attempt to predict the ecological dependency and response to changes in each flow category.

### *Conclusion*

Research suggests that ecological, environmental and hydrological demands are best understood and expressed using the concept of the flow regime. The methods available for flow regime assessment are varied, with the most popular being the hydrologic rating methods, likely due to comparatively accessible data. The model developed in this research uses the RVA to compare a projected flow regime to a target or ecologically sound flow regime. The next section reviews the application of the flow regime concept in water management models followed by a discussion on the RVA implementation in this research.

### *3.2.3 Water Management Models and Flow Regime*

As discussed, ecological science suggests that flow regime is a critical component of the riverine ecological system and an important consideration in management decisions. The majority of water management models adopt a minimum volume or quality threshold in lieu of a flow regime (Poff 2009). The following reviews available water resource management research that considers some form of the flow regime (minimum of intra-year flow change and an ecological metric) in the decision structure.

#### *Reservoir Management*

The concept of an *ecodeficit* is presented in Homa et al. (2005). An ecodeficit is defined as the difference between an average or pre-development FDC and a managed or post-development FDC. A reservoir management policy is optimized for water supply in terms of reliability, and optimized for instream flow requirements by minimizing the ecodeficit. The goal was to provide the basis for a negotiation support system and the identification of a Pareto-optimal water allocation agreement.

Suen and Eheart (2006) adopts the flow regime paradigm to establish a comprehensive and complex management reservoir operation target. Both ecological and human needs are considered using a multi-objective methodology to optimize reservoir reservations. Human demands include domestic, agricultural, and power while ecological demands are identified using the intermediate disturbance hypothesis and subset of the Taiwan Eco-hydrology Indicator System (TEIS). TEIS was developed in Suen et al. (2004) and is similar in concept to EFCs. The objective of the optimization model is to determine a reservoir release schedule that is as similar as possible to the natural flow regime, as measured by the TEIS, while still providing a reliable water source for human consumption

### *Water Shortages*

Cardwell et al. (1996) examines trade-offs between water shortages and fish population capacity in a west-slope Nevada stream using a habitat capacity metric and a multi-objective optimization model. The habitat capacity metric serves as a surrogate for fish populations and considers monthly minimum flows against fish life stage.

Ripo et al. (2003) proposes an annual flow duration curve (AFDC) framework to aggregate flow conditions and define control points. This aids in identifying the volume and timing of water available for human consumption while maintaining ecological integrity. An AFDC is based on a series of flow duration curves (FDCs) which are constructed using rank-ordered streamflow versus exceedence of probability data, which is representative of the number of times a particular streamflow magnitude is realized over the time horizon. The ADFC is then based on an N-series of annual FDCs. Control points provide the link between annual flow variation and the ecological system, and require both hydrologic flow measures and allowable flow modifications in the definition. Allowable modifications in the example problem are based on state permitting requirements but could theoretically be determined using any scientifically sound methodology. The modification to the control point and shift in annual streamflow regime is accomplished by linear interpolation within the FDC. The research is applied to the lower Suwannee River basin in Florida to determine an estimate of the available average annual basin yield.

### *Diversions*

Some research has utilized the RVA to optimize post-development flows. A feasible combination of diversions and instream flow requirements using the RVA is discussed in Shiau and Wu (2004). Focus is on the tradeoffs between hydrological indicator changes and human water needs in an attempt to restore natural flow variability. Low flow characteristics were found to be most easily influenced by flow diversions with correspondingly higher degrees of hydrologic alteration associated with increases in flow diversion. Building on their prior research, Shaiu and Wu develops a method to integrate the 33 IHA into a single index representing the overall degree of hydrologic alteration between the pre- and post-impact flow regimes. This is used as a basis for a RVA assessment framework which the authors use to optimize weir operation via compromise programming in Shiau and Wu (2007).

### *Conclusion*

Riverine ecological system research is no stranger to contemporary concerns. Given the ecological importance of river systems and the increasing concern over anthropogenic impacts on the environment, much research has focused on ecological responses to changes in river flow. Despite the importance of the flow regime to changes in riverine ecological systems, relatively little research has been conducted on the integration of water management models and flow regimes, opting to address questions of quality or minimum flow as surrogates (Poff 2009). Homa et al. (2005) reports that out of the hundreds of optimization-oriented reservoir operations reviewed, only three were identified as focusing on the optimal tradeoff among ecological and human flow needs Jager and Smith (2008) reviews optimal reservoir operations as well, reporting that though some studies considered natural flow variability as an objective, concerns over natural flow variability are primarily a tautological argument working under the assumption that '…*evolution has perfected the adaptation of the extant community to historical conditions and that any future change is undesirable and harmful to the ecosystem*'. Whether this paradigm reflects the mainstream opinion and contributes to the lack of integrated flow regime and water management research or not, a majority of the literature reviewed considers stream flow needs as a fixed constraint assuring some minimum level of flow or level of quality. Research suggests that this is inadequate - variability in river flow (or the *flow regime*) is the primary factor in understanding and protecting ecological diversity (Poff et al. 1997). Introducing the flow regime as a competing demand on the water system directly addresses ecological concerns.

Of the reviewed flow regime metrics and applications, the RVA is the most comprehensive, most widely applied in riverine ecological studies, and adaptable to a water management model. It is also the method selected for this research. The following section examines the approach more in-depth and presents the basis for the developed application.

### *3.2.4 Range of Variability Approach*

Of the approaches developed for assessing flow regimes, the RVA is by far the most prevalent and widely used in the science of environmental flow assessment (Tharme 2003). The RVA was developed in Richter et al. (1997) in response to the need to determine how much flow alteration was ‘too much’ and attempts to provide a comprehensive statistical characterization of ecologically relevant flow regime features.

The RVA uses the pre-impact natural variation of 33 IHA parameter values derived from long-term daily flow records as a basis for measuring and defining the extent to which a flow regime has changed post-development. The IHA parameters were selected based upon two primary criteria: ecological relevance (particularly their use in published ecological studies) and an ability to reflect a broad range of human induced changes. The IHAs are grouped in one of 5 parameter groups and are presented in Table 3.3.

**Table 3.3. Summary of IHA Parameters (The Nature Conservancy 2009).**

| IHA Parameter Group | Hydrologic Parameters |
|---|---|
| 1. Magnitude of monthly water conditions | •Mean or median value for each calendar month |
| 2. Magnitude and duration of annual extreme water conditions | •Annual minima, 1-day mean<br>•Annual minima, 3-day means<br>•Annual minima, 7-day means<br>•Annual minima, 30-day means<br>•Annual maxima, 1-day mean<br>•Annual maxima, 3-day means<br>•Annual maxima, 7-day means<br>•Annual maxima, 30-day means<br>•Annual maxima, 90-day means<br>•Number of zero-flow days<br>•Base flow index: 7-day minimum flow/mean flow for year |
| 3. Timing of annual extreme water conditions | •Julian date of each annual 1-day maximum<br>•Julian date of each annual 1-day minimum |
| 4. Frequency and duration of high and low pulses | •Number of low pulses within each water year<br>•Mean or median duration of low pulses (days)<br>•Number of high pulses within each water year<br>•Mean or median duration of high pulses (days) |
| 5. Rate and frequency of water condition changes | •Rise rates: Mean or median of all positive differences between consecutive daily values<br>•Fall rates: Mean or median of all negative differences between consecutive daily values<br>•Number of hydrologic reversals |

To perform the RVA, flow data is separated into pre- and post-impact respective to the ‘time of impact’ (generally corresponding with some man-made change to the river). IHAs are then independently calculated for each data set. The IHAs are further divided into three equal bins based upon either percentile values (for non-parametric analysis) or some number of standard deviations from the mean (parametric analysis), making for a total of 99 IHA parameter values. The *observed* IHA occurrences from the pre-impact period become the *expected* occurrences for the post-impact period with:

$$Expected = Observed * \left(\frac{Years^{Post}}{Years^{Pre}}\right) \tag{3.1}$$

Where $Years^{Post}$ and $Years^{Pre}$ are the number of years in the post- and pre-impact datasets respectively. This process is depicted graphically in Figures 3.1 and 3.2. The change to the flow regime is expressed in terms of a series of Hydrologic Alteration (HA) factors which are calculated as:

$$HA = \frac{(Observed - Expected)}{Expected} \tag{3.2}$$

A positive HA value indicates an increase in the frequency of the IHA values in the category from the pre- to post-impact years (maximum value of infinity), while a negative value indicates a decrease in the relative occurrences (minimum value of negative one). An HA value of zero signifies no change. A modified HA is developed and used in this research.

Figure 3.1.  Example of non-parametric bin delineation on the pre-impact time period and expected values.

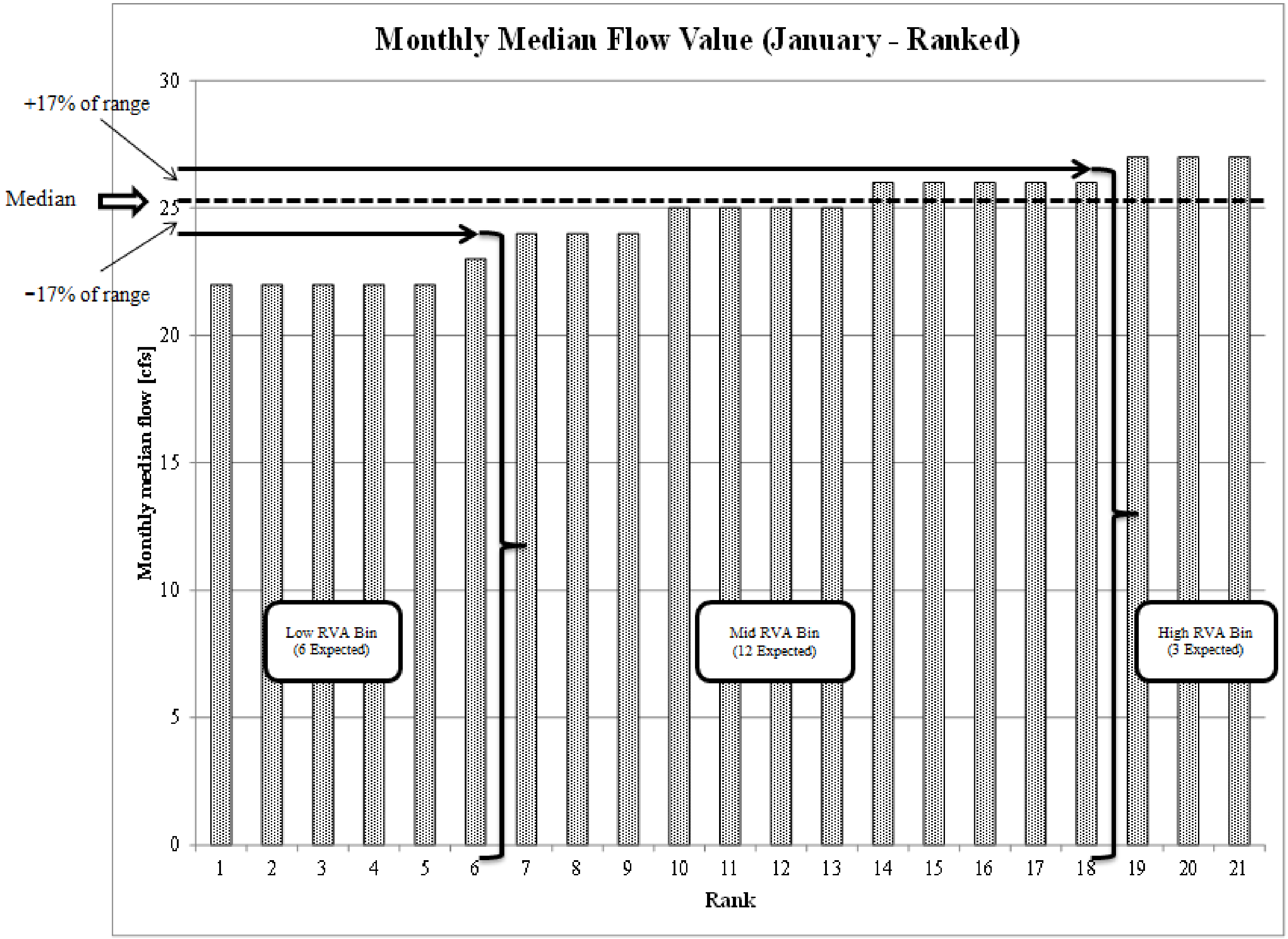
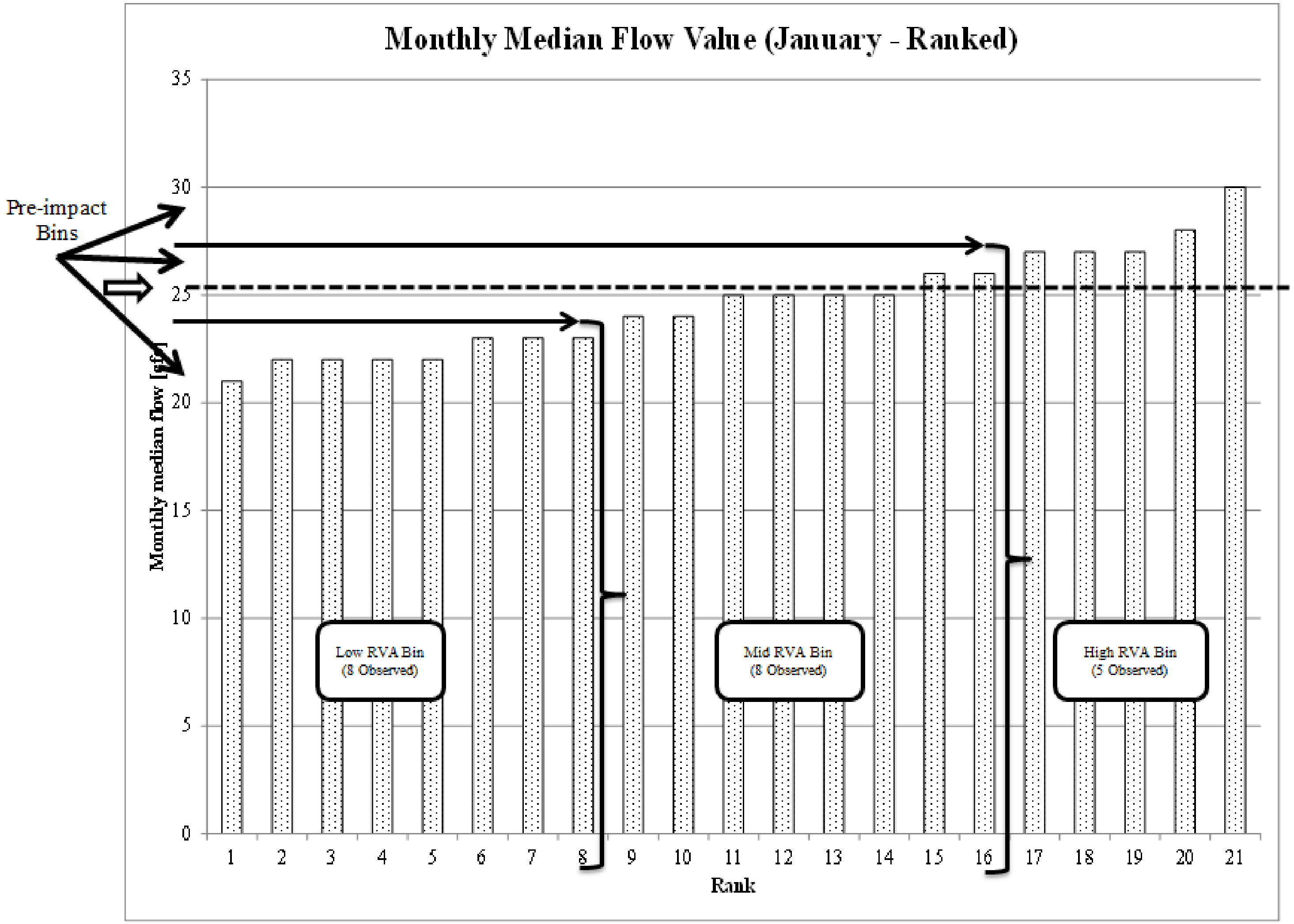


Figure 3.2. Example of non-parametric bin assignments for the post-impact time period and observed values.



### *3.2.5 Conclusion*

It should be noted that the underlying assumption in environmental flow analysis is that the local ecosystem has evolved and adapted to the ‘natural’ flow regime. This suggests that any deviation from the natural flow regime is likely to be detrimental to the established ecosystem. Whether or not this is true and how much change to the natural flow regime the local ecological system can sustain can only be determined via a clear ecological objective and real-time adaptive management approach. This is an intensive cross-discipline process and beyond the scope of this research application. There are however general principles for managing river flows (Postel and Richter 2003):

1. A modified flow regime should mimic the natural one, so that the natural timing of different kinds of flows is preserved.
2. A river’s natural perenniality or non-perenniality should be retained.
3. Most water should be harvested from a river during wet months; little should be taken during the dry months.
4. The seasonal pattern of higher base-flows in wet seasons should be retained.
5. Floods should be present during the natural wet season.
6. The duration of floods could be shortened, but within limits.
7. It is better to retain certain floods at full magnitude and to eliminate others entirely than to preserve all or most floods at diminished levels.
8. The first flood (or one of the first) of the wet season should be fully retained.

It has been established that maintaining riverine ecological, environmental and hydrological integrity of the riverine system is a requirement for sustainable development. The RVA helps fulfill this requirement by providing a means of measuring the differences between a projected and target flow regime. The next section discusses the methods used to measure sustainability in the developed model.

## 3.3 Measuring Sustainability

Sandoval-Solis et al. (2011) proposes a variation on a sustainability index (SI) developed in Loucks (1997). Following is a brief summary of the various components of the SI. The reader is directed to Sandoval-Solis et al. for additional material.

The sustainability index for the *j*th water user belonging to sustainability group $g$ is defined as the geometric average of $M$ performance criteria ($C_{g,m,j}$):

$$SI_{g,j} = \left[\prod_{m=1}^{M} C_{g,m,j}\right]^{1/M} \tag{3.3}$$

The SI has the following properties: 1) its values vary from 0 to 1; 2) if one of the performance criteria is zero, the SI will be zero; and 3) an implicit weighting. Sandoval-Solis et al. points out that the definition allows the inclusion of multiple criteria of interest, a scaling of the various criteria, and the flexibility of allowing varying sustainability structures and approaches. The sustainability of a system ($SS$) is calculated as the sum of the weighted sustainability indexes:

$$SS = \sum_{g} \sum_{j} v_{g,j} * SI_{g,j} \tag{3.4}$$

Where $v_{g,j}$ is the relative weight for the $j$th water user in sustainability group $g$ and ranges from zero to one and sums to one. As described by Sandoval-Solis et al., the potential weighting options include 1) a weighting based on water demand; 2) and arithmetic average or equal-attribute-based weighting system; 3) explicit weights based on a) utility theory analysis, principal components analysis, or hedonic model according to regression coefficients; or b) based on expert and professional opinion. Determining which of these is case dependent and subjective. Principal component analysis determines weighting based on the variance of the SI, this invokes the normality assumption of theoretical statistics and utilizes the overall variance of the data matrix. The hedonic approach regresses variables against selected instrumental variable(s) and weights the variables per the regression coefficients (Slottje 1991).

### *3.3.1 Performance Criteria*

Performance criteria provide a means of evaluating water management policies and enable the comparison of alternative polices. Examples of performance criteria for water resource systems includes simple averages (system storage, water supply, evaporation, municipal shortfalls, and outflow), probability based criteria (time-based and volumetric reliability), and resilience. The sustainability groups in this application are distinguished by performance criteria. The first group of performance criteria addresses the sustainability concept of equitable distribution in space and time using demand-supply deficits. The second is concerned with the integrity of the riverine system using a modified version of the HA.

*Demand-Supply Deficits*

The following performance criteria are based upon the concept of a demand-supply deficit after Sandoval-Solis et al. (2011) and are intended to address the equitable distribution of the resource. The deficit ($Def_{j,t}$) is expressed as the difference between a target demand ($d_{j,t}$), and the amount supplied ($x_{j,t}$) for some time period (*t*):

$$Def_{j,t} = d_{j,t} - x_{j,t} \tag{3.5}$$

Deficits are positive when a target is not fully realized for the $i^{th}$ water user and equal to zero when the water supplied is equal to the demand target ($d_{j,t} = x_{j,t}$) during time period *t*.

Reliability

As it concerns water resource systems, reliability can be expressed as the number of times that a particular criteria are met (Sandoval-Solis et al. 2011) or not met (Moy et al. 1986) during the period of evaluation. For reliability measured in terms of criteria being met, the larger value may be considered more desirable, as opposed to the criteria not being met and larger values being less desirable. As defined, the SI requires that criteria be expressed in scales favoring larger values. In terms of water demand, this would equate to the number of times that a water demand is met for a particular user:

$$Rel_j = \frac{Number\ of\ times\ Def_{j,t} > 0}{T} \tag{3.6}$$

This amounts to a measure of frequency and hence probability of successfully meeting demand.

Resilience

Hashimoto et al. (1982) expresses resilience as a measure of the probability of being in a period of no failure this period given that there was a failure in the last period. After Sandoval-Solis et al. (2011), resilience is a statistic that assesses the flexibility of water management policies to adapt to changing conditions. Mathematically, resilience $Res^i$ is the probability that a successful period ($D^i_t$ = 0) follows a failure period ($D^i_t$ > 0), for all failure period:

$$Res_j = \frac{Number\ of\ times\ Def_{j,t} = 0\ follows\ Def_{j,t} > 0}{Number\ of\ times\ Def_{j,t}\ not = 0\ occurred} \tag{3.7}$$

Vulnerability

Not all failures to meet demand are equal. Vulnerability attempts to measure the significance or severity of failure. Solis et al. report several options for mathematical expression: 1) the average of failure; 2) the average of maximum shortfalls over all continuous failure periods; and 3) the probability of exceeding a certain deficit threshold. The first approach is used in this research and is calculated as:

$$Vul_j = \frac{\left(\sum_{t=0}^{t=n} Def_{j,t}\right) / Number\ of\ times\ Def_{j,t} > 0}{\sum_t d_{j,t}} \tag{3.8}$$

Where $\sum_t d_{j,t}$ is the total water demand for the period of interest. The idea of a maximum vulnerability over a specific time period is used in this research to accommodate the changing inter-annual water demand (see Chapter 4 for additional information).

### Maximum Deficit

Another indicator of performance is the value of the maximum shortfall that occurs during the year (Moy et al. 1986) - the higher the maximum deficit, the less desirable the management policy. Maximum deficit is the value of the greatest annual deficit $Max\left(Def_{j,t}\right)$ with respect to water demand for the *j*th user.

$$MaxD_j = Max\left(\frac{Def_{j,t}}{\sum_t d_{j,t}}\right) \tag{3.9}$$

### Conclusion

The first group of performance criteria is used to address the sustainability concept of equitable distribution in space and time using a demand-supply deficit. These are combined in the definition of the SI for sustainability group 1 as:

$$SI_{1,j} = \left[Rel_j * Res_j * \left(1 - MaxVul_j\right) * \left(1 - MaxD_j\right)\right]^{1/4} \tag{3.10}$$

### *Modified HA*

The RVA is being used in this application to compare a 'projected flow regime', which is the flow regime projected by the model, to a 'target' or ecologically sound flow regime. This concept is introduced here as performance criteria for the SI with applicable nomenclature.

In review, the 'observed' IHA values from the target flow regime become the 'expected' IHA values in the projected flow regime dependent upon the number of years being used as the basis for each regime:

$$Expected_{Bin,IHA}^{Projected} = Observed_{Bin,IHA}^{Target} * \left( \frac{Years^{Projected}}{Years^{Target}} \right) \tag{3.11}$$

Where $Expected_{Bin,IHA}^{Projected}$ refers to the IHA values for the projected flow regime, $Observed_{Bin,IHA}^{Target}$ refers to the IHA values for the target flow regime, $Bin$ is the bin index (1 through 3) (see Figures 3.1 and 3.2), $IHA$ is the IHA index (1 through 33) and $Years^{Projected}$ and $Years^{Target}$are the number of years being used as the basis for the projected and target flow regimes respectively. The IHA index values are available in Table 3.4.

**Table 3.4. IHA Index values used in the developed model.**

| IHA Index | IHA |
|---|---|
| 1 | Median flow for month 1 |
| 2 | Median Flow for month 2 |
| 3 | Median flow for month 3 |
| 4 | Median flow for month 4 |
| 5 | Median flow for month 5 |
| 6 | Median flow for month 6 |
| 7 | Median flow for month 7 |
| 8 | Median flow for month 8 |
| 9 | Median flow for month 9 |
| 10 | Median flow for month 10 |
| 11 | Median flow for month 11 |
| 12 | Median flow for month 12 |
| 13 | 1-day minimum |
| 14 | 3-day minimum |
| 15 | 7-day minimum |
| 16 | 30-day minimum |
| 17 | 90-day minimum |
| 18 | 1-day maximum |
| 19 | 3-day maximum |
| 20 | 7-day maximum |
| 21 | 30-day maximum |
| 22 | 90-day maximum |
| 23 | Number of zero days |
| 24 | Base flow index |
| 25 | Date of minimum |
| 26 | Date of maximum |
| 27 | Low pulse count |
| 28 | Low pulse duration |
| 29 | High pulse count |
| 30 | High pulse duration |
| 31 | Rise rate |
| 32 | Fall rate |
| 33 | Number of reversals |

The IHA values for each regime are typically compared using a degree of Hydrologic Alteration (HA):

$$HA_{Bin,IHA} = \frac{\left(Observed_{Bin,IHA}^{Projected} - Expected_{Bin,IHA}^{Projected}\right)}{Expected_{Bin,IHA}^{Projected}} \tag{3.12}$$

Where $HA_{Bin,IHA}$ is the HA value, $Observed_{Bin,IHA}^{Projected}$ is the IHA occurrence in the projected flow regime and $Expected_{Bin,IHA}^{Projected}$ is the expected IHA occurrence for bin $Bin$ and IHA index $IHA$. Values for the HA range from -1 to infinity, with 0 representing no difference between the target and projected flow regimes. It is noted that positive values signify more observed values than expected values, and for this application, it is assumed that values greater than 1 do not necessarily require more attention than the most negative value. Under this assumption, the HA has been modified ($HA_{Bin,IHA}^{Mod}$) for this research as:

$$HA_{Bin,IHA}^{Mod} = \begin{cases} \frac{\left(Observed_{Bin,IHA}^{Projected} - Expected_{Bin,IHA}^{Projected}\right)}{Observed_{Bin,IHA}^{Projected}} & \text{(if } Expected_{Bin,IHA}^{Projected} < Observed_{Bin,IHA}^{Projected}\text{)} \\ \frac{\left(Observed_{Bin,IHA}^{Projected} - Expected_{Bin,IHA}^{Projected}\right)}{Expected_{Bin,IHA}^{Projected}} & \text{(if } Expected_{Bin,IHA}^{Projected} > Observed_{Bin,IHA}^{Projected}\text{)} \end{cases} \tag{3.13}$$

Where $HA_{Bin,IHA}^{Mod}$ is the Modified HA value, $Observed_{Bin,IHA}^{Projected}$ is the IHA value in the projected flow regime and $Expected_{Bin,IHA}^{Projected}$ is the IHA value in the projected flow regime for bin $Bin$ and IHA index $IHA$. $HA^{Mod}_{Bin,IHA}$ ranges in value from -1 to 1, with 0 still representative of no differences between the target and projected flow regimes.

Conclusion

A modified version of the HA is proposed to address the sustainability concept of integrity for riverine systems. The modified HAs are based on 99 IHA metric values divided over 3 bins and are combined in the SI for the second sustainability group as:

$$SI_{2,j} = \begin{cases} \prod_{IHA}\prod_{Bin}\left[\left(1 - HA^{Mod}_{j,IHA,Bin}\right)\right]^{1/99} & HA^{Mod}_{j,IHA,Bin} \geq 0 \\ \prod_{IHA}\prod_{Bin}\left[\left(1 + HA^{Mod}_{j,IHA,Bin}\right)\right]^{1/99} & HA^{Mod}_{j,IHA,Bin} < 0 \end{cases} \tag{3.14}$$

## 3.4 Conclusion

Per the adopted definition, sustainability requires the identification and pursuit and protection of societal objectives and ecosystem integrity. Though by no means comprehensive, societal objectives can be examined and then expressed as demands. Likewise, ecological, environmental and hydrological integrity can be expressed as demands within the system if a means of determining the demand and measuring the adequacy of both the demand and supply are available. Ecological research suggests that this is best addressed using the concept of the flow regime. By allowing the ecological demand to compete with societal demands for the available supplies, the allocation schedule may be determined on some common basis. A series of annual allocations becomes the projected flow regime which can then be compared to an ecologically sound target flow regime using the RVA. The SI uses the discussed performance criteria to characterize the equitable distribution of supply and the integrity of a river resource. These concepts are combined and implemented in the developed model which is discussed next.

# 4 Model Development

This research develops a modeling framework for the determination of an optimal allocation schedule for a river basin management area in terms of the maximum sustainable net economic benefit. The presented model is comprised of three basic components: the short term model component (STM), the long term model component (LTM) and the MySQL database. Distinguishing between the STM and LTM provides a means of compartmentalizing the solution process, addresses the typical management paradigm and facilitates tractability (Cai 1999). Optimal monthly allocation schedules are determined on an annual basis using the STM under the sustainable growth and consumption variables proposed and measured by the LTM. Communication between the two models and reporting is facilitated with the MySQL database.

This chapter discusses the model framework and development, including the implementation of the sustainability concepts and formulation.

## 4.1 Model Components

There are three components to the developed model: the STM, the LTM and the MySQL database (see Figure 1.5). STMs maximize the net benefit associated with the monthly water allocation for a one year period using the General Algebraic Modeling System (GAMS) and there is one STM for each year of the long-term time horizon. The series of STMs associated with a long term time horizon are created and managed by an LTM which determines total net benefit, degree of hydrologic alteration (HA), risk associated with supply and system sustainability (SS) for the allocations generated by the

STMs. A genetic algorithm (GA) is used to discover the most sustainable net benefit for a population of LTMs. All of the data including physical parameters (consumption rates, sources, demands, links, etc.), STM configuration and allocation schedules and LTM configuration and results are stored in the MySQL database.

### *4.1.1 MySQL Database*

MySQL is an open source Structured Query Language (SQL) database management system developed, supported and distributed by the Oracle Corporation. The MySQL database is fast, reliable, scalable and simple to use, making it the most popular SQL database management system in use at the time of this research ("MySQL :: MySQL 5.6 Reference Manual :: 1.3.1 What is MySQL?" n.d.). The MySQL database is a relational database and consists of separate tables for data storage. The tables are used to organize and manage the model data, including tables for the physical parameters of the modeled system, tables for STM input and output and tables for LTM input and output.

A database table consists of columns and rows, with a single 'field' represented as a single column-row combination. A 'record' may contain a single field or multiple fields on the same row. Each table must have at least one column with unique values. This column is generally referred to as the 'id' column and serves as an identifying field for each record. Table 4.1 lists the database tables utilized in the model in this research and provides a brief description of each.

**Table 4.1. MySQL database tables**

| Table name | Description |
|---|---|
| daily_river_demand | Daily river demand schedule |
| daily_river_supply | Daily river supply schedule |
| demand_delta | Delta decision variables for the current STM |
| demand_nodes | Physical parameters for the demand nodes |
| demand_rate | Rate decision variables for the current STM |
| links | Physical parameters for the links |
| model_config | Meta data and optimal results for the model scenario associated with this database |
| model_results | Results as determined by the GA for the most recent generation |
| model_stats | Status of the GAMS model, used to track feasibility and errors |
| monthly_river_demand | Monthly demand for the river, generated at run time based on daily river demand |
| monthly_river_supply | Monthly supply for the river, generated at run time based on daily river supply |
| parents | All the decision variables for each LTM in the current model |
| parents_existing | Decision variables for a single generation of LTMs, used if the model needs to be re-started or continued from a specific generation. |
| results_demand | Output from the STM related to demand nodes |
| results_si | Output from the LTM related to the demand SI |
| results_supply | Output from the STM related to source nodes |
| results_temp | Stores temporary model_results, cleared between generations to expidite read/write times |
| rva | Output from the LTM related to RVA |
| si_components | Output from the LTM related to the SS calculation |
| source_input | Monthly source node inputs for the STM |
| source_nodes | Physical parameters for the source nodes |
| sustainable_net_benefit | Output from the LTM related to net benefits and SI |

The majority of tables used in the model requires no input from a user and are managed by the software at model run time. The exceptions are the tables related to the daily river supply and demand and those related to the physical parameters for the modeled system. River supply and demand tables are generally unique to a management area and are specified using daily flow values. A management area is characterized using the physical parameters associated with the sources, demands and links and is discussed in the following section.

### *Representation of the Physical System*

A common framework for basin-scale water resource management is the node-link network (Cai et al. 2003; Letcher et al. 2007; Rosegrant et al. 2000; Wang et al. 2008). In a node-link network, sources and demands in the management area are represented using nodes and movement of water between the sources and demands is accomplished via links. The node-link network serves to describe the behavior of the physical system.

#### Source Nodes

Source nodes are used to represent sources of water within the management area. This may include reservoirs, aquifers, rivers, storage tanks or treatment facilities. Each source node has a state variable which is representative of the volume of water currently available at the source. Behavior is governed by parameters for the source node, such as minimum and maximum state variable values. The source node parameters are stored in the fields for a source node record. Each source node record contains 9 fields (see Table 4.2) and is stored in the *source_nodes* table of the database. The data type listed in Table 4.2 refers to the type of data required by the field.

**Table 4.2. Source node parameters with data type and descriptions.**

| Table | Field | Data type | Description |
|---|---|---|---|
| *source_nodes* | *id* | Integer | Identifier |
| | *label* | Text | Name of source node |
| | *type* | Integer | Used for cost function assignment |
| | *output_max* | Double | Maximum output |
| | *state_min* | Double | Minimum value of state variable |
| | *state_max* | Double | Maximum value of sate variable |
| | *initial_state* | Double | Initial value of state variable |
| | *dev_cost* | Double | Development cost coefficient |
| | *state_temp* | Double | Source state between STMs |

### Demand Nodes

Demand nodes represent the demands for water on the network and may be used to describe any point of consumptive use. A demand node is governed by parameters such as minimum fill rates, consumer populations, and rate of consumption. The complete set of fields available for a demand node record is listed in Table 4.3. Each demand node record consists of 20 fields and is stored in the *demand_nodes* table of the database.

**Table 4.3. Demand node data with data type and descriptions.**

| Table | Field | Data type | Description |
|---|---|---|---|
| *demand_nodes* | *id* | Integer | Index |
| | *label* | Text | Name of demand node |
| | *initial_consumer_units* | Double | Initial number of consumer units |
| | *initial_delta* | Double | Initial delta value |
| | *delta_min* | Double | Minimum delta value |
| | *delta_max* | Double | Maximum delta value |
| | *delta_rounder* | Integer | Decimal places for Delta |
| | *initial_rate* | Double | Initial rate of consumption |
| | *rate_min* | Double | Minimum rate of consumption |
| | *rate_max* | Double | Maximum rate of consumption |
| | *initial_rate_change* | Double | Initial rate of consumption rate change |
| | *rate_change_min* | Double | Minimum rate of consumption rate change |
| | *rate_change_max* | Double | Maximum rate of consumption rate change |
| | *rate_rounder* | Integer | Decimal places for rate |
| | *theta* | Double | Minimum fill rate |
| | *benefit* | Double | Benefit coefficient |
| | *si_weight* | Double | SI weighting factor |
| | *rva* | Integer | RVA analysis flag |
| | *consumer_units_temp* | Double | Consumer units between STMs |
| | *consumption_rate_temp* | Double | Consumption rate between STMs |

### Links

Links convey water between source nodes and demand nodes and are described positionally in terms of a start node (source), end node (demand) and change in elevation. Link records are maintained in the *links* database table and use the fields listed in Table 4.4.

**Table 4.4. Link data table with data types and descriptions.**

| Table | Field | Data type | Description |
|---|---|---|---|
| *links* | *id* | Integer | Index |
| | *label* | Text | Name of link |
| | *input_max* | Double | Maximum input |
| | *s_node* | Integer | Start node id |
| | *e_node* | Integer | End node id |
| | *elevation_head* | Double | Change in elevation |

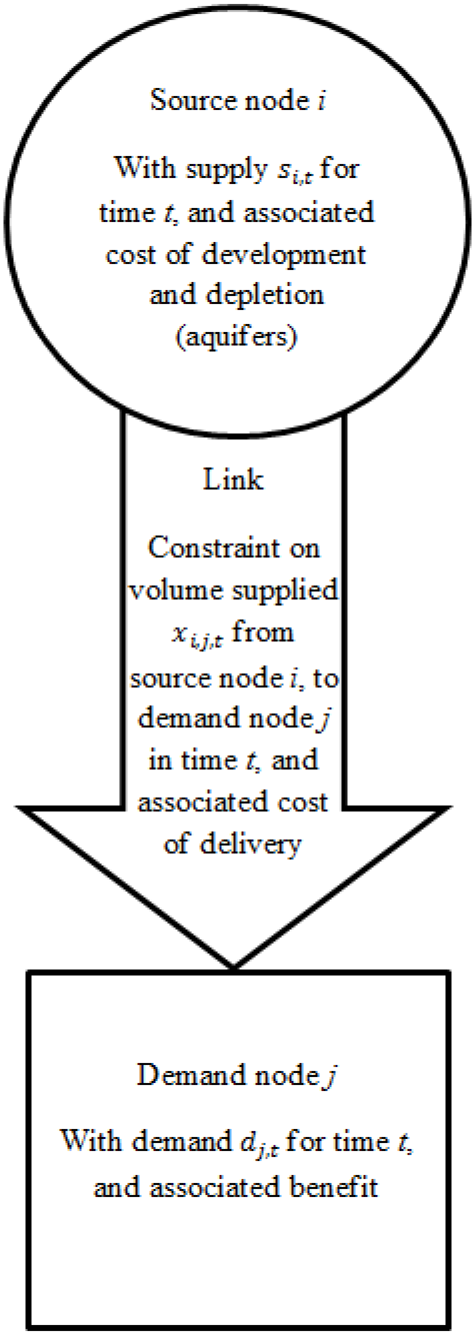
The physical parameters for the river basin system are used to generate the STM which in turn optimizes the water allocated to a demand from an available source. This is described in the next section.

## 4.2 Short-term Model Component (STM)

The STM optimizes the available water supply allocation over the short term time horizon by maximizing net economic benefit. The STM addresses the typical short term management paradigm and serves two purposes: the optimization of short term management objectives and a reduction in the computational intensity of the overall model. It is implemented and solved using GAMS.

The STM is described using a set of source nodes ($i$), each with an available supply $s_{i,t}$, and demand node ($j$), each with a demand $d_{j,t}$ during a time period ($t$). This is depicted in Figure 4.1. Links are used to define a capacity or upper limit for a volume supply $x_{i,j,t}$ from source node $i$ to demand node $j$ in time $t$ and do not require an index.

**Figure 4.1. Depiction of the source node, demand node and link relationships and associated parameters and variables in the STM.**



The STM determines the amount supplied $x_{i,j,t}$ from source node $i$ to demand node $j$ during time period $t$. Each demand in the management area is assumed to have an associated economic benefit. A supply allocation has an associated economic cost, including the cost of development (ground water pumping, infrastructure, treatment, etc.) and cost of delivery for the supply. Groundwater sources have an additional cost related to aquifer drawdown and called a ‘cost of depletion’.

### *4.2.1 Cost of Depletion*

One of the sustainability concepts adopted in this model relates to net economic benefit. There are two principal components in determining the total economic value of water: 1) ‘use’ values, and 2) ‘non-use’ values. Non-use values are often associated with sustainability and are summarized as the value that an individual assigns to a resource to ensure its availability for others both now and in the future. Rothman and Mays (2013) addresses this concern using a ‘cost of depletion’.

The cost of depletion is based on Hotelling’s ‘exhaustible resource’ theory (Hotelling 1931). Hotelling’s theorem states that, ignoring the cost of extraction, the optimal price $(P)$ of an exhaustible resource at any time $(t)$ is equal to the initial price $(P_0)$ compounded at a rate $(r)$, the discount rate:

$$P_t = P_0 e^{rt} \tag{4.1}$$

The price path is described as increasing until a ‘backstop price’ (the price of a backstop technology or alternative resource) is reached (Pearce and Turner 1990). These concepts are used as the basis for a cost of depletion function based on aquifer drawdown (Rothman 2007; Rothman and Mays 2013):

$$CostDep_{i,t} = Backstop_i \, {}^{\left(e^{\rho\mu_{i,t}} - 1\right)}\!\Big/\!_{\left(e^{\rho\mu'_i} - 1\right)} \tag{4.2}$$

Where $Backstop$ is the backstop price, $\rho$ is the price path factor, $\mu$ the aquifer drawdown fraction and $\mu'$ the allowable aquifer drawdown fraction at source $i$ and time $t$. The aquifer drawdown fraction $\mu_{i,t}$ is calculated as:

$$\mu_{i,t} = \frac{S_{i,Initial} - S_{i,t}}{S_{i,Initial}} \tag{4.3}$$

Where $S_{i,Initial}$ is the initial or target aquifer storage and $S_{i,t}$ is the available storage for source $i$ and time $t$.

The depletion cost increases non-linearly as aquifer drawdown increases, reaching at some point ($\mu'$) a steady state ($Backstop$). For purposes of this application, it is assumed that this occurs when the resource is fully depleted. The depletion cost function (4.2) is estimated via a linear piecewise approximation which is discussed in the formulation of the STM.

### *4.2.2 STM Formulation*

The STM maximizes net benefit for a one-year monthly water allocation. The objective function of the STM is expressed as:

$$Maximize\text{: } wZ_1 - (1-w)Z_2 \tag{4.4}$$

Where $w$ is a preferential weighting ($w \leq 1$) of the respective objectives $Z_1$ and $Z_2$:

$$Z_1 = \sum_i \sum_j \sum_t Benefit_j\, x_{i,j,t} \tag{4.5}$$

$$Z_2 = \sum_i \sum_j \sum_t \left[CostDev_i x_{i,j,t} + CostDel_{i,j} x_{i,j,t} + CostDep_{i,t}\right] \tag{4.6}$$

Where $Benefit_j$ is the economic benefit coefficient associated with demand $j$, $x_{i,j,t}$ is a decision variable and is the volume of water supplied from source $i$ to demand $j$ in time $t$, $CostDev_i$ is the development cost coefficient associated with source $i$, $CostDel_{i,j}$ is the delivery cost coefficient associated with delivering water from source $i$ to demand $j$ and $CostDep_{i,t}$ is the cost of depletion for source $i$ and time $t$.

$CostDep_{i,t}$ is only applied to aquifers and is a decision variable constrained by a piece-wise approximation of (4.2):

$$CostDep_{i,t} \;\geq\; f_k(\mu_{i,t}) \tag{4.7}$$

where $f_k(\mu_{i,t})$ is a set of linear equations in the form of:

$$f_k(\mu_{i,t}) = a_k + b_k \mu_{i,t} \;\; for\; \mu_{i,t} \in [d_{k-1}, d_k], k \in \{1, \dots, K\} \tag{4.8}$$

Where $\mu_{i,t}$ is the drawdown ratio of the aquifer and $a_k$ and $b_k$ are coefficients as determined by the piecewise approximation. The piecewise approximation is constructed by allowing $d_0$ = -∞ and $d_N$ = ∞ and imposing the following conditions (Rubin, P. 2010):

$$d_{k-1} < d_k \; \forall k \; \in \{1, \dots, K\} \tag{4.9}$$

$$b_{k-1} < b_k \; \forall k \; \in \{2, \dots, K\} \tag{4.10}$$

$$a_{k-1} + b_{k-1}d_{k-1} = \; a_k + b_k d_{k-1} \quad \forall k \; \in \{2, \dots, K\} \tag{4.11}$$

There are also constraints on the allocated supply. The delivered supply must be positive:

$$x_{i,j,t} \geq 0 \tag{4.12}$$

And within the capacity of the delivering infrastructure:

$$x_{i,j,t} \leq Capacity_{i,j} \tag{4.13}$$

Where $Capacity_{i,j}$ is the capacity of the infrastructure between source $i$ and demand $j$. The supply delivered from a source must be less than the total supply available at a source:

$$\sum_j \sum_t x_{i,j,t} \leq S_i \tag{4.14}$$

Where $S_i$ is the supply available at source $i$. The allocated supply must also be less than or equal to the demand:

$$\sum_{i} x_{i,j,t} \leq d_{j,t} \tag{4.15}$$

Where $d_{j,t}$ is the demand at demand node $j$ and time $t$. Depending upon management priorities, a demand may or may not need to be completely satisfied. To address this, a minimum fill ratio $\theta_j$ is specified:

$$\sum_{i} x_{i,j,t} \geq \theta_j d_{j,t} \tag{4.16}$$

Where $\theta_j$ is between 0 and 1. Remaining constraints pertain to the maximum and minimum supply available at a source node.

### *4.2.3 STM Solution Procedure*

As described, the STM is a linear programming (LP) model. LP problems refer to the maximization or minimization of a linear function. The domain is defined by a set of linear constraints. LP problems have a wide range of application with basically two classes of solution algorithms: simplex-type methods and interior-point methods (Pillo and Palagi 2002). The STM is formulated and solved using GAMS which includes a library of solution methods for LPs.

#### *Introduction to GAMS*

The early 1980s saw a focus on the development of modeling systems created for the analysis and solution of large mathematical programming problems. One of the first of these was GAMS. The design of GAMS merges concepts from mathematical programming and relational database theory and is meant to address the needs of strategic modelers. Specifically it was created to (McCarl et al. 2012; Rosenthal 2012) :

- Provide a high-level language for the compact representation of large and complex models.
- Allow changes to be made in model specifications simply and safely.
- Allow the unambiguous statement of algebraic relationships.
- Provide an environment where model development is facilitated by subscript based expandability allowing the modeler to begin with a small data set, then after verifying correctness expand to a much broader context.
- Be inherently self-documenting, allowing the use of longer variable, equation and index names as well as comments, data definitions etc. GAMS is designed so that the model structure, assumptions, and any calculation procedures used in the report writing are documented as a byproduct of the modeling exercise in a self-contained file.
- Be an open system, facilitating interface to the newest and best solvers while being solver independent allowing different solvers to be used on any given problem.
- Automate the modeling process, including:
    - Permitting data calculation;
    - Verifying the correctness of the algebraic model statements;
    - Checking the formulation for obvious flaws;

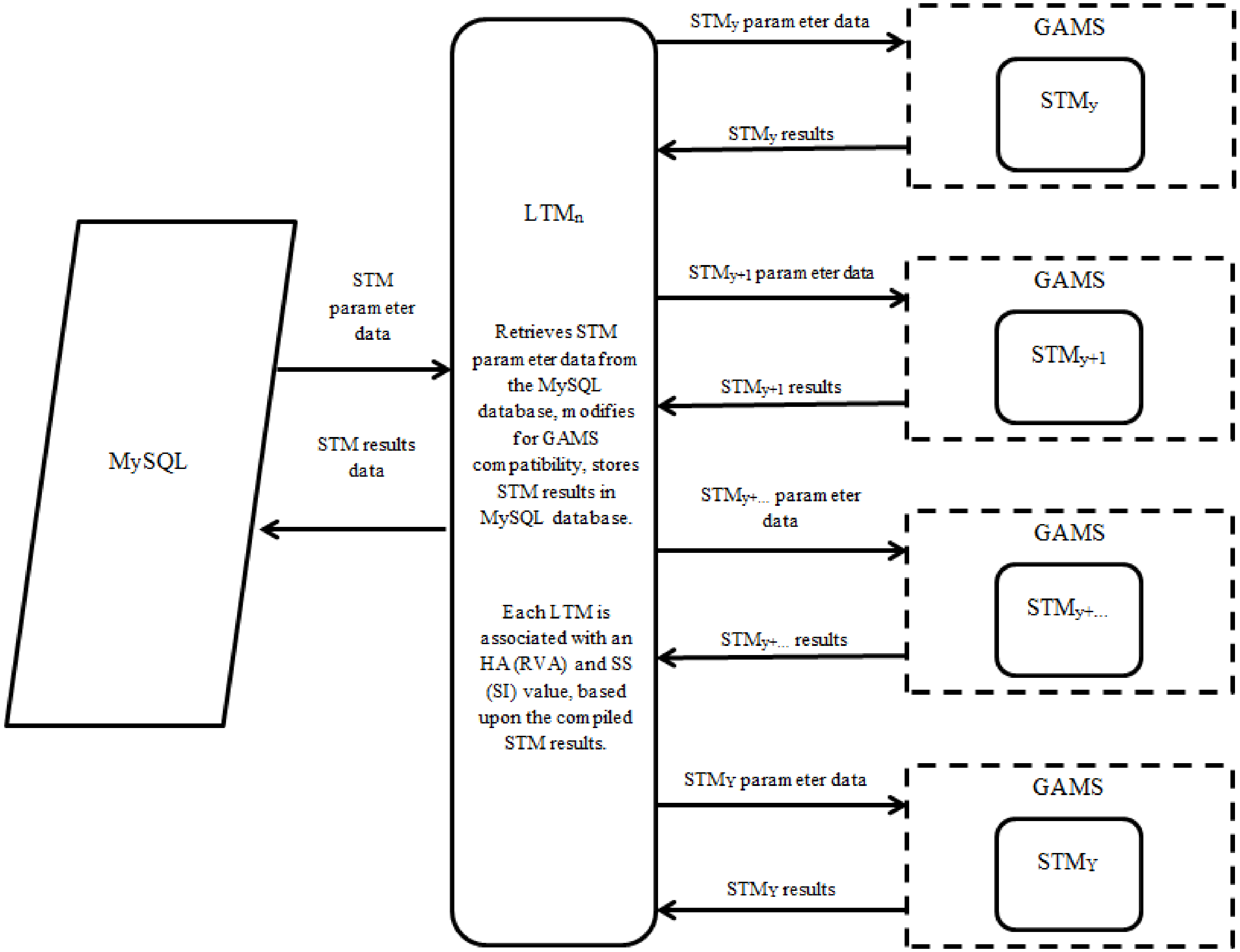
    - Interfacing with a solver;
    - Saving and submitting an advanced basis when doing related solutions;
    - Permitting usages of the solution for report writing.
- Permitting portability of a model formulation between computer systems allowing usage on a variety of computers ranging from PCs to workstations to super computers.
- Facilitate a simple change in solution methodology (solver selection).
- Facilitating import and export of data to and from other computer packages.
- Allow use by groups of varying expertise.
- Provide example models that may assist modelers through provision of a model library.
- Permit model descriptions that are independent of solution algorithms.

GAMS is used for the STM development and solution. Recall that each STM is maximizing the net benefit associated with a one-year monthly water allocation schedule. To accomplish this, the STM requires a set of parameters describing the physical system and metadata (see Table 4.5). The required parameter set is generated using the data in the MySQL database and passed to GAMS by the LTM. This data flow process is depicted in Figure 4.2 and discussed in detail in the following section.

**Table 4.5. Sets and parameters required by the STM.**

| Set/Parameter | Description |
|---|---|
| generationID | Current generation, as controlled by the GA |
| parentID | Current LTM, as specified by the GA |
| y | Current year, as specified by the LTM |
| w | Weighting coefficient for the objective function, hard coded in GAMs |
| EnergyPrice | Cost of energy, hard coded in GAMS |
| i | Source node index, set is scenario specific, hard coded in GAMS |
| j | Demand node index, set is scenario specific, hard coded in GAMS |
| t | Time index, set is constant at 12, hard coded in GAMS |
| k | Linear cost of depletion constraint index, set is scenario specific, hard coded in GAMS |
| Lcost (k,*) | Linear cost of depletion constraint coefficient table, scenario specific, hard coded in GAMS |
| d (j,t) | Demand at a demand node, generated by LTM, text file |
| s (i) | Supply available at a source node, generated by LTM, text file |
| s_input (i,t) | Monthly input at a source node, generated by LTM, text file |
| benefit (j) | Benefit coefficient at a demand node, generated by LTM, text file |
| theta (j) | Minimum fill percentage at a demand node, generated by LTM, text file |
| Capacity (i,j) | Maximum volume of water available from a source node to a demand node, generated by LTM, text file |
| DevCostCoefficient (i) | Development cost coefficient at a source node, generated by LTM, text file |
| HeadEle (i,j) | Elevation head between a source node and demand node, generated by LTM, text file |
| TypeOfSource (i) | Type of source node (checking for aquifer), generated by LTM, text file |
| InitialStorage (i) | The supply available at a source node at t=1, generated by LTM, text file |
| MaxStorage (i) | Maximum storage at a source node, generated by LTM, text file |
| MinStorage (i) | Minimum storage at a source node, generated by the LTM, text file |
| MaxStorageOutput (i) | Maximum output from a source node (combined), generated by LTM, text file |
| ConsumerUnits (j,t) | Consumer units at a demand node at t=1, generated by LTM, text file |
| ConsumptionRate (j,t) | Consumption rate at a demand node at t=1, generated by LTM, text file |

**Figure 4.2. Schematic of the STM data flow between the LTM and MYSQL database.**



## 4.3 Long-term Modeling Component (LTM)

As discussed previously, an LTM uses the output from a series of STM's corresponding with the long-term time horizon to determine a measure of sustainability for a management area. Maximum sustainability in this application has been defined practically in terms of maintaining the ecological, environmental and hydrological integrity of a river resource and minimizing the long-term risks associated with management decisions. This is accomplished using the RVA and SI concepts introduced in Chapter 3. Specific application of the concepts in the LTM is presented next, followed by discussion on the LTM formulation and solution procedure.

### *4.3.1 RVA Application in the LTM*

As discussed in Chapter 3, the RVA uses the natural variation of 33 Indicators of Hydrologic Alteration (IHA) derived from long-term daily flow records as a basis for measuring and defining the extent to which flow regimes differ (see Table 4.6). To aid in preserving critical extreme values, IHAs are categorized as low, mid or high in value and assigned to one of three corresponding bins based upon percentiles (33%) of the total range for a total of 99 IHA values (see Figures 3.1 and 3.2). In practice, the RVA is used to measure how the current flow regime differs from a historical regime, with the historical regime being defined as prior to some point in time, or 'pre-impact'. The RVA is being used in this application to compare a 'projected flow regime' to a 'target' or ecologically sound flow regime. In review, the 'observed' IHA values from the target flow regime become the ‘expected’ IHA values in the projected flow regime dependent upon the number of years being used as the basis for each regime:

$$Expected_{Bin,IHA}^{Projected} = Observed_{Bin,IHA}^{Target} * \left(\frac{Years^{Projected}}{Years^{Target}}\right) \tag{4.17}$$

Where $Expected_{Bin,IHA}^{Projected}$ refers to the ‘expected’ IHA values for the projected flow regime, $Observed_{Bin,IHA}^{Target}$ refers to the ‘observed’ IHA values for the target flow regime, $Bin$ is the bin index (1 through 3), $IHA$ is the IHA index (1 through 33) and $Years^{Projected}$ and $Years^{Target}$are the number of years being used as the basis for the projected and target flow regimes respectively. The IHA values for each regime are typically compared using a degree of Hydrologic Alteration (HA) (Richter et al. 1996). The HA has been modified ($HA_{Bin,IHA}^{Mod}$) for this research as:

$$HA_{Bin,IHA}^{Mod} = \begin{cases} \dfrac{\left(Observed_{Bin,IHA}^{Projected} - Expected_{Bin,IHA}^{Projected}\right)}{Observed_{Bin,IHA}^{Projected}} & \text{(if } Expected_{Bin,IHA}^{Projected} < Observed_{Bin,IHA}^{Projected}\text{)} \\ \dfrac{\left(Observed_{Bin,IHA}^{Projected} - Expected_{Bin,IHA}^{Projected}\right)}{Expected_{Bin,IHA}^{Projected}} & \text{(if } Expected_{Bin,IHA}^{Projected} > Observed_{Bin,IHA}^{Projected}\text{)} \end{cases} \tag{4.18}$$

Where $HA_{Bin,IHA}^{Mod}$ is the Modified HA value, $Observed_{Bin,IHA}^{Projected}$ is the IHA value in the projected flow regime and $Expected_{Bin,IHA}^{Projected}$ is the IHA value in the projected flow regime for bin $Bin$ and IHA index $IHA$. $HA^{Mod}_{Bin,IHA}$ ranges in value from -1 to 1, with 0 still representative of no differences between the target and projected flow regimes.

There are two sets of data required by the RVA as applied in the LTM. The first is the target flow regime. Recall that a flow regime is described using a record of daily flows. The target flow regime is supplied by the user and is an ecologically sound daily flow record spanning one or more years. The LTM creates a monthly flow demand for an STM by summing the daily flow values in the target regime for each respective month:

$$d_{y,j,t} = \sum_{day}^{Day} DailyFlow^{Target}_{y,j,t,day} \tag{4.19}$$

Where $d_{y,i,t}$ is the monthly demand and $DailyFlow^{Target}_{y,j,t,day}$ is the daily flow value for STM $y$, demand node $j$, and day $day$, belonging to month $t$.

The second set of data required by the RVA is the projected flow regime, which is derived from the allocations determined by the series of STMs associated with an LTM. An STM allocates a monthly flow supply to meet a monthly flow demand. The allocated monthly flow supply is based upon an available monthly flow supply as determined by the LTM. To generate an available monthly flow supply, the LTM requires an available daily flow supply, also supplied by the user, which is summed for each respective month. This becomes the monthly input for a source node in the STM:

$$source\_input_{y,i,t} = \sum_{day}^{Day} DailyFlow_{y,i,t,day}^{Available} \tag{4.20}$$

Where $source\_input_{y,i,t}$ is the monthly input and $DailyFlow_{y,i,t,day}^{Available}$ is the daily flow value for STM $y$, source node $i$, and day $day$, belonging to month $t$. The $source\_input_{y,i,t}$ is available for monthly allocation to a river by an STM.

After the monthly flow supply is allocated, the LTM determines the projected flow regime by first determining the daily flow value for the projected flow regime by calculating the difference between the monthly demand and monthly supply:

$$MonthlyDifference_{y,j,t} = d_{y,j,t} - \sum_{i}^{I} x_{y,i,j,t} \tag{4.21}$$

Where $MonthlyDifference_{y,i,t}$ is the difference between the demand and allocated supply, $d_{y,j,t}$ is the monthly demand and $x_{i,j,t}$ is the supply, for STM $y$, source node $i$, demand node $j$, during month $t$. $MonthlyDifference_{y,i,t}$ is in turn used as the basis for determining the projected daily flows:

$$AveDailyDif_{y,j,t} = \frac{MonthlyDifference_{y,j,t}}{30.42} \tag{4.22}$$

Where $AveDailyDif_{y,j,t,day}$ is the average flow difference per day for STM $y$, demand node $j$, and month $t$. The denominator is in units of [days per year]/[months per year].

(4.22) will typically require a unit conversion for flow values as well. Finally, the projected daily flow is calculated as:

$$DailyFlow_{y,j,t,d}^{Projected} = DailyFlow_{y,j,t,day}^{Target} - AveDailyDif_{y,j,t} \tag{4.23}$$

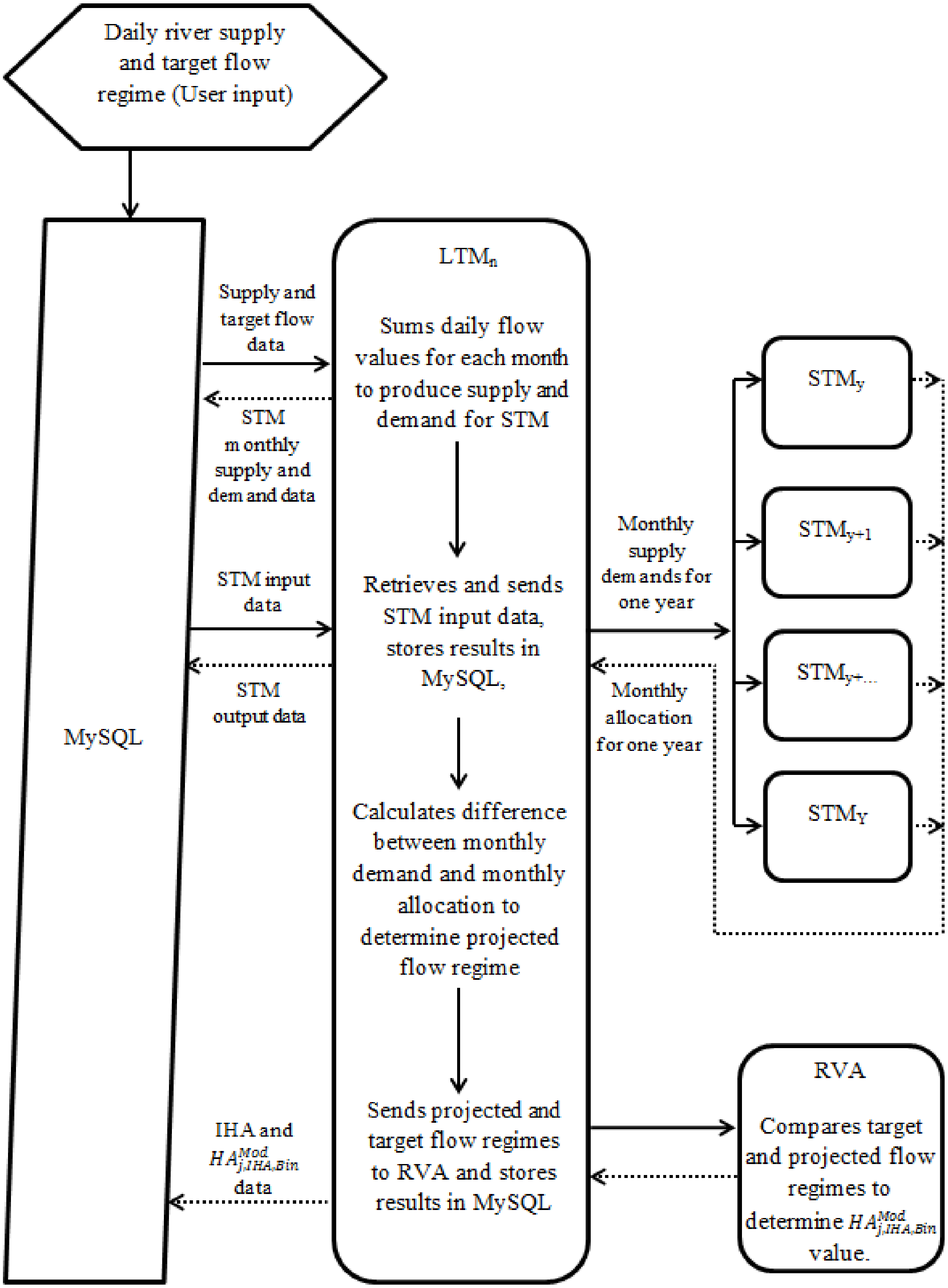
Where $DailyFlow_{y,j,t,d}^{Projected}$ is the daily projected flow for STM $y$, demand node $j$, and day $day$, belonging to month $t$. Conceptually, this is similar to a decrease in base flow for a river. Figure 4.3 depicts the RVA processes and data flow in the developed model.

Given the limited command line capabilities of the IHA software (The Nature Conservancy 2009), a separate PHP application was developed for the RVA. Psuedo code for the developed PHP application may be found in Appendix A. The next section provides guidelines for practical interpretation of the Modified HA.

**Table 4.6. IHA Index values used in the developed model.**

| IHA Index | IHA |
|---|---|
| 1 | Median flow for month 1 |
| 2 | Median Flow for month 2 |
| 3 | Median flow for month 3 |
| 4 | Median flow for month 4 |
| 5 | Median flow for month 5 |
| 6 | Median flow for month 6 |
| 7 | Median flow for month 7 |
| 8 | Median flow for month 8 |
| 9 | Median flow for month 9 |
| 10 | Median flow for month 10 |
| 11 | Median flow for month 11 |
| 12 | Median flow for month 12 |
| 13 | 1-day minimum |
| 14 | 3-day minimum |
| 15 | 7-day minimum |
| 16 | 30-day minimum |
| 17 | 90-day minimum |
| 18 | 1-day maximum |
| 19 | 3-day maximum |
| 20 | 7-day maximum |
| 21 | 30-day maximum |
| 22 | 90-day maximum |
| 23 | Number of zero days |
| 24 | Base flow index |
| 25 | Date of minimum |
| 26 | Date of maximum |
| 27 | Low pulse count |
| 28 | Low pulse duration |
| 29 | High pulse count |
| 30 | High pulse duration |
| 31 | Rise rate |
| 32 | Fall rate |
| 33 | Number of reversals |

Figure 4.3. Dataflow and processes utilized in the LTM's implementation of the RVA.



### *4.3.2 Interpretation of the Modified HA*

The following summarizes how the Modified HA is calculated and how the output may be interpreted. Recall that the Modified HA is measuring the observed occurrences of an IHA value (projected flow) against the expected occurrences of an IHA value (target flow) and that zero is the optimal value (no difference between projected flow and target flow, see (4.18)).

Recalling the adopted terminology, the target flow regime refers to the river's demand, or the ecologically sound (assumed) flow regime; while the projected flow regime refers to the flow regime that is a result of the model's attempt to meet the river's demand. A negative value indicates that the occurrences in the target flow (*Expected*) are more than the occurrences in the projected flow (*Observed*). A positive value indicates that the occurrences for the target flow (*Expected*) are fewer than the occurrences in the projected flow (*Observed*).

Recall that in order to preserve extreme values, the IHA values are broken up into 3 bins. The bins are defined using the range of IHA values discovered in the target flow, the range is divided equally into three bins, and each of the discovered IHA occurrences are assigned accordingly.

For example, consider the Median Flow in April IHA. Assume that the Median Flow in April ranges from 18 CFS to 41 CFS in the target flow. The bin thresholds would be established as:

$$Thresholds = 29.5\ [cfs] \pm 23\ [cfs] * 0.17 \tag{4.24}$$

Where 29.5 is the median value, 23 CFS is the range, and 17% is one-half of 33%. The assignments are as:

$$\begin{gathered} Median\ Flow\ in\ April < 25.6\ [cfs] = Bin\ 1 \\ 25.6\ [cfs] \leq Median\ Flow\ in\ April \leq 33.4\ [cfs] = Bin\ 2 \\ Median\ Flow\ in\ April > 33.4\ [cfs] = Bin\ 3 \end{gathered} \tag{4.25}$$

Each occurrence of the Median Flow in April in the target flow is assigned to a bin, which then become the *Expected* value of occurrences. After the model produces a projected flow, each value of the Median Flow in April discovered in the projected flow is assigned to a bin (using the same thresholds), and becomes one of the *Observed* occurrences. When *Expected* occurrences are more than the *Observed* occurrences, the $HA_{Bin,IHA}^{Mod}$ will be negative. When *Observed* occurrences are more than *Expected* occurrences, the value of $HA_{Bin,IHA}^{Mod}$ will be positive. General characterizations of the modeled flow are listed in Table 4.7.

**Table 4.7. General characterizations of the modeled flow using the modified HA.**

| Bin | Value | Cause | Observation | Practical Interpretation |
|---|---|---|---|---|
| 1 | Positive | Observed > Expected | The projected flow has more IHAs with lower values | IHAs in projected flow tend to be lower than target flow IHAs |
|  | Negative | Observed < Expected | The projected flow has fewer IHAs with lower values | IHAs in the projected flow tend to be higher than target flow IHAs |
| 2 | Positive | Observed > Expected | The projected flow has more IHAs with median values | - |
|  | Negative | Observed < Expected | The projected flow has fewer IHAs with median values | - |
| 3 | Positive | Observed > Expected | The projected flow has more IHAs with higher values | IHAs in projected flow tend to be higher than target flow IHAs |
|  | Negative | Observed < Expected | The projected flow has fewer IHAs with higher values | IHAs in the projected flow tend to be lower than target flow IHAs |

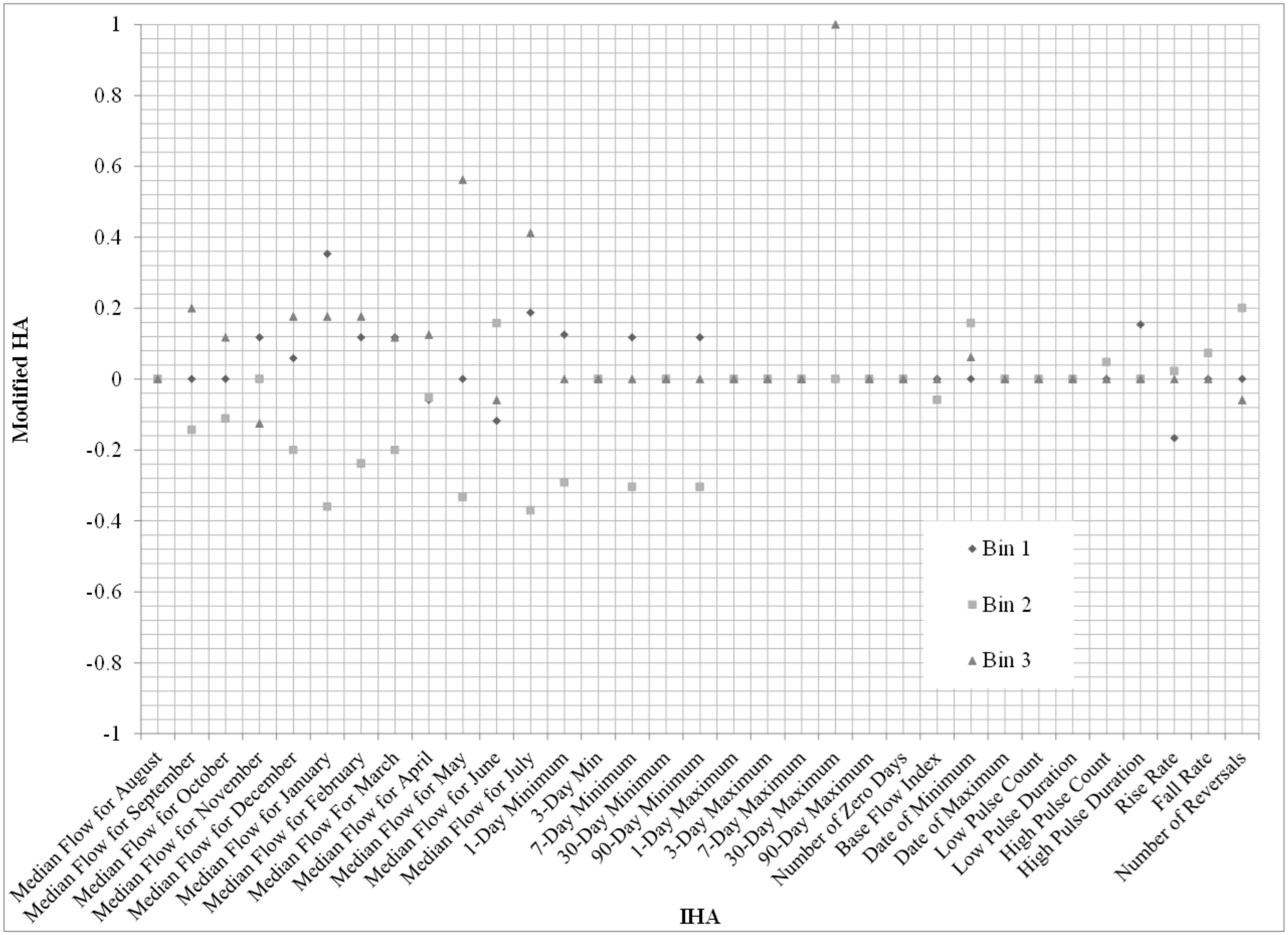
One of the applications in this research uses an annual daily schedule of flows for the target flow. A single year of daily flows produces only one value for each of the IHA metrics. In this case, the Bins have a threshold of the discovered value ± 0.Understanding this permits an interpretation of the sample Modified HA data presented in Figure 4.4.

For example, the Median Flow in January has a Modified HA value of -0.4 in Bin 2. This suggests that the Median Flow in January in the modeled flow was not the Median Flow in January value discovered in the target flow. It does not however suggest that the Median Flow in January is smaller in magnitude in the modeled value than in the target flow. To discover this, the Modified HA value in Bins 1 and 3 are referred to: Bin 1 has a Median Flow in January of approximately 0.35 while Bin 3 has a value of approximately 0.17. This indicates that the Median Flow in January value occurs more frequently in Bin 1 than it does in Bin 3. As the denominator remains the same (*Observed > Expected*), it can be said that the frequency of occurrence in Bin1 is twice that of Bin 3; or that the Median Flow In January for the modeled flow is less than the value in the target flow twice as often as it is higher; suggesting a deficit in January for most of the modeled flow regime. The same method may be applied to the remaining IHAs for a general characterization of the deficiencies in the modeled flow regime.

The prior discussion is unique to the one-year target regime. In practical application, a target regime encompassing several years of daily flows would allow more variance in the projected flows by widening the bin delineations.

The LTM uses the $HA^{Mod}_{Bin,IHA}$ as a set of performance criteria in the SI. The application of the SI in the LTM is discussed in the following section.

Figure 4.4.  Example modified HA values.



### *4.3.3 SI Application in the LTM*

As discussed previously, the LTM proposes consumer growth and consumption rate patterns for a series of STMs over the long-term time horizon, to find the most beneficial and sustainable series. Maximum sustainability in this application has been defined in terms of minimizing the long-term risks to supply and maintaining the ecological, environmental and hydrological integrity of available river resources. The sustainability of each LTM is quantified using the SI described in Chapter 3. The SI as implemented in the developed model is described in more detail here.

The total sustainability for a system is defined as:

$$SS = \sum_{g} \sum_{j} v_{g,j} * SI_{g,j} \tag{4.26}$$

Where $SS$ is the system sustainability, $v_{g,j}$ is a weighting coefficient and $SI_{g,j}$ is the sustainability index associated with sustainability group $g$ and demand $j$. The weighting coefficient is subject to:

$$\sum_{g} \sum_{j} v_{g,j} = 1 \tag{4.27}$$

And $SI_{g,j}$ is defined as:

$$SI_{g,j} = \left[ \prod_{m}^{M} C_{g,m,j} \right]^{1/M} \tag{4.28}$$

Where $C_{g,m,j}$ is performance criterion $m$ belonging to sustainability group $g$ and demand $j$. As described, the SS ranges from 0 to 1 with a value of 1 being the most sustainable scenario.

The performance criteria in this application are divided into two groups. The first group measures the risk associated with a demand's supply and is based on demand-supply deficits. The second group measures the integrity of a river's regime and uses the modified HA ($HA_{Bin,IHA}^{Mod}$). Each demand is assigned to a sustainability group ($g$) based upon performance criteria applicability. For example, flow regime criteria are not applicable to non-river flow demands.

Demands in sustainability group 1 ($g = 1$) are assessed with the demand-supply deficit based criteria:

$$Def_{y,j,t} = d_{y,j,t} - \sum_{i}^{I} x_{y,\mathrm{i},j,t} \tag{4.29}$$

Where $Def_{y,j,t}$ is the deficit and $d_{y,j,t}$ is the demand for STM $y$, demand $j$ in month $t$; and $x_{y,\mathrm{i},j,t}$ is the volume water supplied demand for STM $y$, source $i$, demand $j$ in month $t$. Deficits are positive when a demand is not fully realized for the $j^{th}$ demand and equal to zero when the water supplied is equal to the demand ($\sum_i^I x_{y,\mathrm{i},j,t} = d_{y,j,t}$). The deficit based performance criteria are calculated over the length of the long term time horizon for each demand and include reliability, resilience, maximum vulnerability, and maximum deficit.

The first performance criterion for sustainability group 1 is reliability, which is concerned with the number of times a demand has been fully supplied. Reliability for demand $j$ is defined as:

$$C_{1,1,j} = Rel_j = \frac{\#\, of\ times\ Def_{y,j,t} = 0}{Y * T} \tag{4.30}$$

Where $Y$ is the number of STMs and $T$ is the number of months in each STM.

Resilience is a measure of system recovery after a failure to meet demand:

$$C_{1,2,j} = Res_j = \frac{\#\, of\ times\ Def_{y,j,t} = 0\ follows\ Def_{y,j,t} > 0}{No.of\ times\ Def_{y,j,t} > 0\ occurred} \tag{4.31}$$

Maximum vulnerability is defined as the most severe of the system's failures to meet annual demand:

$$C_{1,3,j} = MaxVul_j = Max_{y,j}\left(\frac{\left(\sum_t Def_{y,j,t}\right)/\#\, of\ times\ Def_{y,j,t} > 0\ occurred}{\sum_t x_{y,j,t}}\right) \tag{4.32}$$

The last performance criterion is concerned with the maximum deficit, which is defined as the most severe case of failure to meet demand over the long term time horizon:

$$C_{1,4,j} = MaxD_j = Max_{y,j}\left(\frac{\sum_t Def_{y,j,t}}{\sum_t d_{y,j,t}}\right) \tag{4.33}$$

For demands in the system that are susceptible to demand-supply deficits ($g = 1$), the SI is expressed as:

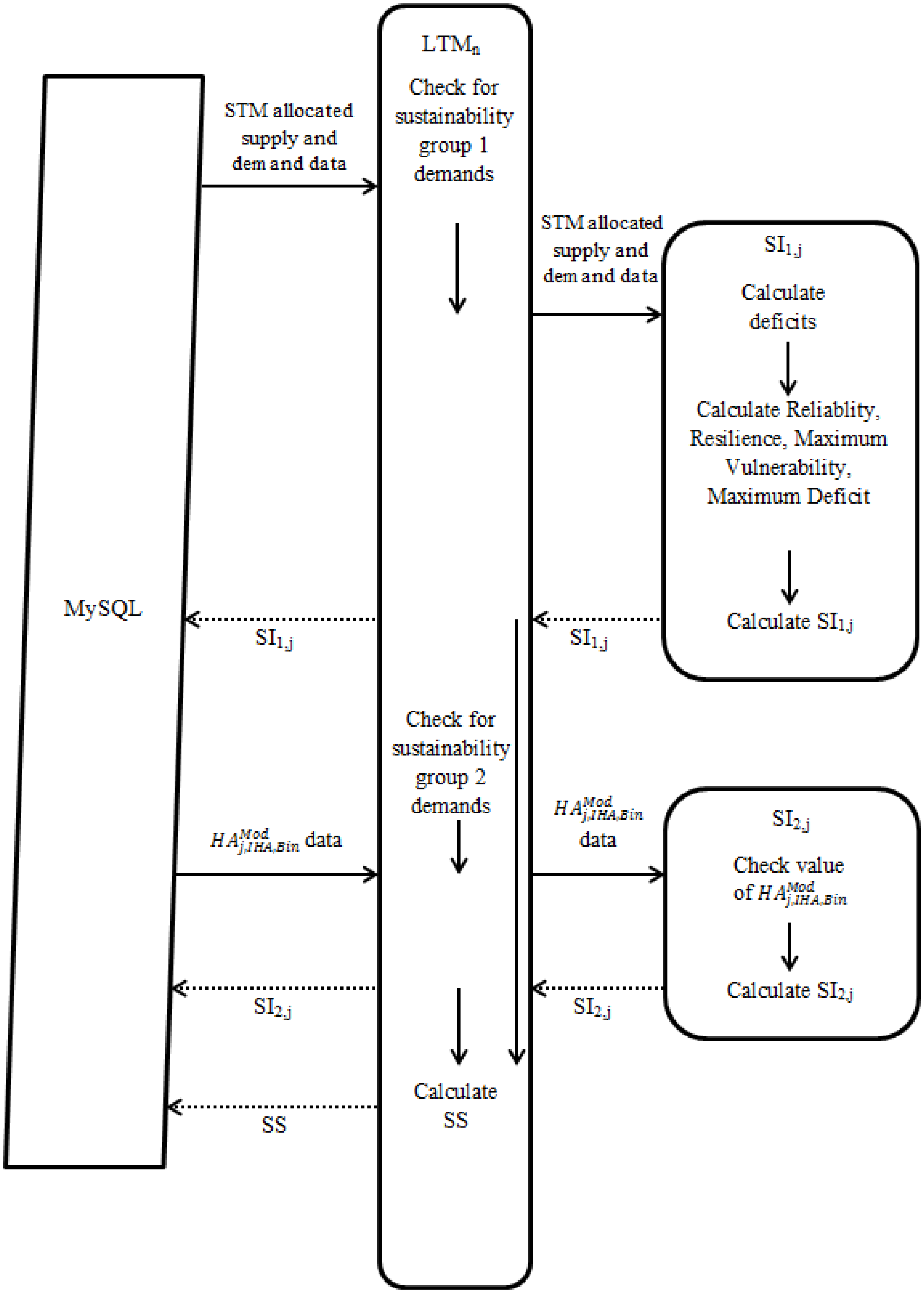
$$SI_{1,j} = \left[Rel_j * Res_j * \left(1 - MaxVul_j\right) * \left(1 - MaxD_j\right)\right]^{1/4} \tag{4.34}$$

The second set of performance criteria ($g = 2$) is based upon the differences between a target and projected flow regime as measured by the modified HA (4.18).The SI calculation associated with these criteria is conditional based upon the value of the modified HA:

$$SI_{2,j} = \begin{cases} \prod_{IHA} \prod_{Bin} \left[\left(1 - HA_{j,IHA,Bin}^{Mod}\right)\right]^{1/99} & HA_{j,IHA,Bin}^{Mod} \geq 0 \\ \prod_{IHA} \prod_{Bin} \left[\left(1 + HA_{j,IHA,Bin}^{Mod}\right)\right]^{1/99} & HA_{j,IHA,Bin}^{Mod} < 0 \end{cases} \tag{4.35}$$

The processes and data flow for the LTM’s implementation of the SI is depicted in Figure 4.5.

**Figure 4.5. Dataflow and processes utilized in the LTM's implementation of the SI.**



### *4.3.4 LTM Formulation*

The objective for the LTM is expressed as:

$$Max\text{: } Sustainable\ Net\ Benefit = \sum_{g}^{G}\sum_{j}^{J} v_{g,j} * NetBenefit_j * \left(2 - \frac{1}{{SI_{g,j}}^2}\right) \tag{4.36}$$

Where $NetBenefit_j$ are the net benefits associated with demand $j$ and STM $y$:

$$NetBenefit_j = \sum\nolimits_{y}^{Y} (wZ_1 - (1-w)Z_2)_{y,j} \tag{4.37}$$

Where $w$ is a weighting coefficient, $Z_1$ are the benefits and $Z_2$ are the costs for demand $j$ and STM $y$.

The net benefits for an STM are a function of the supply ($x_{i,j,t}$) consumed at a demand node (see (4.4), (4.5) and (4.6)). An STM allocates supply to meet the demand which is defined in the LTM as:

$$d_{y,j,t} = rate_{y,j} * consumer_{y,j,t} \tag{4.38}$$

Where $d_{y,j,t}$ is the demand, $rate_{y,j}$ is the consumption rate and $consumer_{y,j,t}$ is the number of consumer units for STM $y$, demand $j$ and time $t$.

The LTM specifies the rate of consumption ( $rate_{y,j}$) and number of consumer units ($consumer_{y,j,t}$) by specifying growth rates. The consumption rate changes annually:

$$rate_{y,j} = rate_{y-1,j}\left(1 + roc_{y,j}\right) \tag{4.39}$$

Where $roc_{y,j}$ is the rate of change in percent (decimal) for STM $y$, demand $j$ and month $t$. The change in consumer units is expressed as an exponential function (population growth):

$$consumer_{y,j,t} = consumer_{y,j,0} * \left(1 + \frac{\delta_{y,j}}{12}\right)^{t} \tag{4.40}$$

Where $\delta_{y,j}$is the annual growth rate for STM $y$, demand $j$ and month $t$. Constraints on the variables are user-specified minimums and maximums:

$$\delta\_min_j \leq \delta_{y,j} \leq \ \delta\_max_j \tag{4.41}$$

$$roc\_min_j \leq roc_{y,j} \leq \ roc\_max_j \tag{4.42}$$

The LTM is non-linear in terms of the consumer unit growth (4.40) which affects the demand values used in the deficit calculation (4.29) and related performance criteria. The SI definitions ((4.34) and (4.35)) are also nonlinear and surjective, and the objective function introduces additional non-linearity. A maximum solution for (4.36) is determined using a genetic algorithm.

### *4.3.5 LTM Solution Procedure*

As described, the LTM is a nonlinear programming (NLP) model. Metaheuristic approaches have been successfully used to solve NLP problems. The following section offers a brief background to optimization problems, followed by a survey of metaheuristic solution methodologies which is used as the basis for the genetic algorithm developed in this application.

### *4.3.6 NLP Optimization*

Metaheuristic approaches have been successfully used to solve NLP problems. This section offers a brief background to NLP optimization problems, followed by a survey of metaheuristic solution methodologies and concludes with the basis for the selected method.

#### *Background*

NLP problems are part of a much larger scope of problems known as combinatorial optimization problems, where the feasible domain is finite, but the problem is often of exponential size. Combinatorial optimization has been described by Lawler (Lawler 2001) as:

> *"Combinatorial optimization is the mathematical study of finding an optimal arrangement, grouping, ordering, or selection of discrete objects usually finite in numbers."*

Most practical problems which have finite or countable infinite number of alternative solutions can be formulated as combinatorial optimization problems (Osman and Kelly 1996). Despite significant increases in computing power and advanced solution algorithms (cutting plane methods, branch and bound, branch and cut, column generation, decomposition techniques and polyhedral combinatorics), many combinatorial optimization problems remain too difficult for exact solutions. Difficulty is largely determined by the 'size' or number of variables in the problem, linearity, convexity, and continuity of the solution space. Metaheuristic methods present a means of determining an approximate solution for these difficult problems within a reasonable computation time. A survey of popular metaheuristic optimization methods follows and is used as the selection basis for the integrated approach.

### *Metaheuristics*

The term metaheuristics was originally used with reference to a solution method (specifically, tabu search) superimposed on another heuristic (Glover 1986). Metaheuristics are also set apart from more traditional heuristics in that they allow uphill as well as downhill intermediate moves (in minimization problems). They may also allow infeasible intermediate moves. The following offers a brief introduction to popular solution methods in metaheuristics and relies heavily upon Golden and Wasil (2002).

#### Simulated Annealing

Simulated annealing relies upon a stochastically based algorithm analogous to the physical annealing process realized when highly heated metal or glass is allowed to cool in a controlled fashion. This method was introduced in Kirkpatrick (1984). Assuming a minimization problem, the simulated annealing procedure beings with a current solution $X$, with $N(X)$ pertaining to the neighborhood of $X$ that contains alternative solutions in the vicinity of $X$. $X'$ is randomly selected and the difference $D$ between the objective functions $f(X)$ and $f(X')$ is calculated. If $D < 0$ (downhill move), then $X'$ is selected. If $D>0$ (uphill move), and $e^{-D/T} > q$ (where $q$ is a uniformly distributed random value between 0 and 1), then $X'$ is selected. $T$ is known as the *temperature* and operates as a control parameter, with the value decreasing as the solution progresses. The procedure continues until a stopping condition is satisfied.

### Deterministic Annealing

Simulated annealing suggested new ways of thinking about heuristic search. This ushered in several methods that fall under the label of deterministic annealing. These include threshold accepting, record-to-record travel, great deluge algorithm, and the demon algorithm and variants.

The demon algorithm was first proposed in Wood and Downs (1998) and is based upon the concept of a 'creditor', or demon. A new solution $X'$ is selected and the change in length is credited or debited against the demon. Assuming a minimization problem, uphill solutions are only accepted if the demon has enough credit to 'pay' for the increase in length. Minimization is encouraged by imposing an upper bound on the demon value or annealing the value as the solution progresses.

### Smoothing Algorithms

Smoothing algorithms were introduced in Gu and Huang (1994) and have been applied to traveling salesman problems. Intercity distances ($d$) are smoothed using a specified function, such as:

$$d_{ij}(\propto) = \begin{cases} \bar{d} + \left(d_{ij} - \bar{d}\right)^{\propto}, d_{ij} \geq \bar{d} \\ \bar{d} - \left(\bar{d} - d_{ij}\right)^{\propto}, d_{ij} < \bar{d} \end{cases} \tag{4.43}$$

Where $d_{ij}$ is the distance between city *i* and city *j*, $\bar{d}$ is the average intercity distance, and ∝ is the 'smoothing' factor. A local search heuristic is then applied to generate a locally optimal solution. A schedule is then applied to the smoothing schedule and the distances are smoothed once again to a lesser extent. Using the previous solution as the starting tour, the local heuristic is applied once again to generate a new solution. This process is continued until the heuristic is applied to the original intercity distances ($\propto = 1$). Variants on the original smoothing algorithm have been proposed with sequential smoothing proving the most efficient as applied to the classic traveling salesman problem.

### Tabu Search

Tabu search utilizes a memory to direct intelligent search as opposed to probability. Intermediate solutions are recorded and the search progression is prohibited from selecting the same location for a prespecified number of iterations. Tabu search was first proposed by Glover (1986) and several variations of the method have been proposed since. Tabu search has been successfully applied to problems resembling the classical vehicle routing problem, but have not been effective at solving traveling salesman type problems.

## Genetic Algorithms

Genetic algorithms (GA) were originally developed in the 1960s and 1970s with application to combinatorial optimization problems beginning in the 1980s (Holland 1992). GAs mimic the process of natural evolution with each model solution representing an individual in a population set or generation. The individual is comprised of a set of decision variable values for a model and has a fitness value that corresponds with the model's objective function value. Individuals with the best fitness values are assigned a higher probability of becoming 'parents' for the next generation of individuals, with the resulting 'child' sharing the combined 'traits' of each parent. Generations progress until an optimal solution is realized. The basic algorithm is as follows (Golden and Wasil 2002):

1. Initialization – construct an initial population of solutions.
2. Crossover – augment the population by adding offspring solutions.
3. Mutation – randomly perform small modifications to the offspring.
4. Evaluation – obtain fitness values for the offspring.
5. Selection – reduce the population size by selecting the appropriate number of survivors (with the largest fitness values) from the current population.
6. Evolution – repeat steps 2 to 5 until a stopping criterion is satisfied.

GAs are readily adapted to combinatorial optimization problems, and have seen numerous applications.

### Guided Local Search

In guided local search, the objective function is augmented with a set of penalty terms. The augmented function is subject to a local search procedure, which is restricted by the penalty terms. When a local optima is attained, the penalty terms are altered and the cost function is minimized using a second local search procedure in an attempt to escape the locality. The guided local search method was developed by Voudouris and Tsang (1996) and has been used in a wide application of problems with a degree of success.

### Greedy Randomized Adaptive Search Procedure

Greedy randomized adaptive search procedure is a two phase method that has been adapted for use in a wide variety of optimization problems. It was first applied by Feo and Resende (1995). The construction phase produces a feasible solution and is followed by a local search phase that attempts to improve upon the construction phase. In typical applications, this two-step process is repeated several times. Several improvements to the original method have been proposed including the use of path relinking and long-term memory.

### Scatter Search

The origins of scatter search hale back to the 1960s and job shop scheduling literature. It is considered an evolutionary algorithm and consists of five steps:

1. Generate a starting set of diverse solutions. Apply a heuristic procedure to improve the starting solutions. Extract the best solutions and designate them as reference solutions.
2. Construct new solutions by combining subsets of the current reference solutions.
3. Apply a heuristic procedure to improve the new solutions.
4. Extract the best solutions from the improved new solutions and add them to the set of reference solutions.
5. Repeat steps 2, 3 and 4 until the set of reference solutions does not change.

Additional information is available in Glover et al. (2000).

### Ant Colony Optimization

Ants establish shortest routes between feeding sources and a colony using pheromones left along the trail. When another ant crosses a pheromone trail, it decides with a high probability to follow the trail, leaving its own trail of pheromones. The probability of following the trail increases with the level of pheromones, providing a positive feedback loop in the foraging process. Ants are quite efficient at finding the shortest route: this is explained in part by the fact that ants using the shortest route get to the food faster and return to the nest within a shorter period of time, increasing the amount of pheromone on the shortest route. This efficiency inspired the optimization algorithm proposed in Dorigo et al. (1996). Artificial ants build solutions and share a common memory, which is updated each time a new solution is constructed. The ant system and extensions have realized competitive solutions in symmetric and asymmetric traveling salesman problems, the quadratic assignment problem, vehicle routing and communication network routing problems.

### Variable Neighborhood Search

The variable neighborhood search algorithm systematically changes the neighborhood for a local search heuristic in a simple approach to improving a local solution. The algorithm consists of two steps:

1. Initialization – let $N_x(x)$ be the set of solutions in the $k^{th}$ neighborhood of $x$. Select a finite set of neighborhood structures $N_k$, $k=1,2,\ldots,k_{max}$ to use in the search. Find an initial solution $x$.
2. Main step – set $k = 1$. Repeat the following steps until $k=k_{max}$. Randomly generate $x'$ from $N_x(x)$. Apply the local search heuristic using $x'$ as the initial solution. If the local optimum obtained (say $x''$) is better, move from $x$ to $x''$ and continue the search with $N_1$. Otherwise, $k=k+1$.

The variable neighborhood search ends upon reaching stopping criteria, usually a maximum number of iterations or computation time.

### Conclusion

A wide range of metaheuristics have been developed and applied to many types of optimization problems with some degree of success. The drawbacks of metaheuristics include the fine tuning of parameters, uncertainty regarding the optimality of the solution, and computation time: models may have to run for hours and sometimes days to reach an optimal solution.

Genetic algorithms fall into a larger classification of methods known as population heuristics. These are marked by the initial construction of multiple solutions, or population, which are combined as the solution progresses to form a more desirable ‘child’ solution. The population approach may often result in more time consuming solutions, yet it is believed that population heuristics are capable of producing better solutions than single solution heuristics (Beasley 2002). Genetic algorithms are adapted to a wide range of NLPs and relatively simple to implement. A genetic algorithm is utilized in this research to solve the LTM and is discussed next.

### *4.3.7 Genetic Algorithm application*

As discussed previously, genetic algorithms utilize a 6-step process to generate a solution. There are various methods available for the 6-steps and it is recognized that performance is sensitive to both the parameters values selected and the adopted methods. The following discusses the steps as they are applied in this model. The steps are presented in order and are depicted in Figure 4.6.

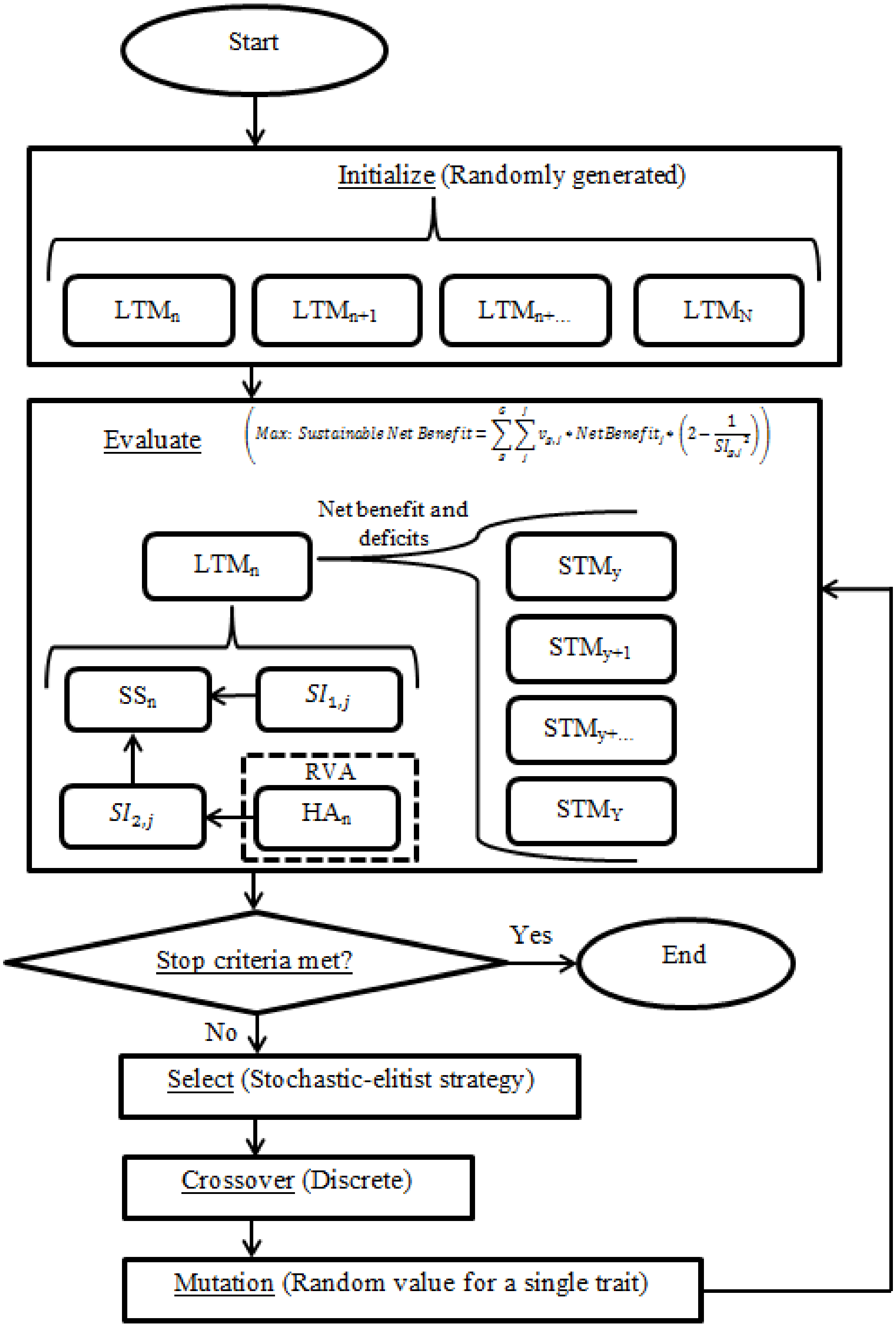
#### Initialization

Each individual in the GA consists of the set of decision variables required to generate a trial solution. For the LTM this is the annual consumer growth rate ($\delta_{y,j}$) and the rate of change in consumption rate ($roc_{y,j}$), which are specified for each demand in the STMs. An initial population is generated randomly within the user specified minimum and maximum values, and rounded to the number of decimal places specified under *delta_rounder* and *rate_rounder* respectively in the *demand_node* table.

### Evaluation

Evaluation associates a fitness value with the individual and corresponds with the value of the objective function. For the LTM this is (4.36). In addition, solutions that do not have enough supply to meet demands for the length of the long term time horizon (infeasible) are ranked based on the number of years that the solution remained feasible. This allows the model to progress towards a feasible solution even when all individuals in the current generation are infeasible.

**Figure 4.6. Steps utilized in the LTM's genetic algorithm solution procedure.**



### Selection

The purpose of the selection operator is to select individuals from the current generation to be parents for the subsequent generation. The selection operator can be deterministic or stochastic and is based on the fitness value. Deterministic selection follows specific rules which may or may not incorporate probability in the actual selection. Stochastic selection bases probability of selection directly on the fitness value. Elitist strategies may be implemented in both and serve to preserve the integrity across generations by allowing a fixed number or percentage of the best solutions to pass directly to the next generation. This application uses a stochastic elitist strategy: the user specifies the number of elites to pass directly through to the next generation. Couples are determined using a rank based system. Individuals are ranked based on fitness value and the top 50% of individuals are selected as a parent with an 80% probability. Individuals in the bottom 50% have a 40% probability of being selected.

### Crossover

The crossover is utilized to generate the next generation. This is accomplished using the concept of selected individuals acting as parents and mating to produce children. Parents pass forward their traits (decision variable values) to the child such that the child shares traits from both parents. This can be accomplished via a variety of methods. Yao (1999) describes two broad classes of real parameter crossover operators, discrete and intermediate. Discrete crossover operation maintains the value of parent’s trait using:

$$Trait_l^{Child} = \begin{cases} Trait_l^{Parent\ 1} & (with\ some\ probabiliy\ p) \\ Trait_l^{Parent\ 2} & (otherwise) \end{cases} \tag{4.44}$$

Where $Trait_l^{Child}$ is the inherited trait $l$. Using the same terminology, intermediate crossover operation combines the parent traits:

$$Trait_l^{Child} = Trait_l^{Parent\ 1} + \alpha(Trait_l^{Parent\ 2} - Trait_l^{Parent\ 1}) \tag{4.45}$$

Where $\alpha$ is generally between 0 and 1. This application uses the discrete crossover operation.

### Mutation

Mutation serves to explore new areas of the search space by maintaining a level of population diversity. Most applications generate mutations with some level of probability and utilize some form of random re-assignment of the individual's trait or traits independent of the parent's values. Application of the mutation process is considered problem specific (Reeves 2010), but probability of mutation is generally low. This research generates a new random value for a single trait per the probability indicated by the user.

### Stopping Criteria

Stochastic metaheuristics do not ever produce a conclusive optimal solution. A number of different stopping criteria are used to halt the algorithm, including model run time, maximum number of generations, minimum population diversity and minimum rate of improvement. This model is setup to run a user specified maximum number of generations.

## 4.4 Summary

The developed model consists of 3 modeling components: the STM, the LTM and the MySQL database, and utilizes GAMS and a genetic algorithm to generate a solution. The STM maximizes net benefit for system demands over the short term time horizon (annual schedule on a monthly basis), while the LTM determines the most sustainable net benefit for the long term time horizon using the SI and RVA. The MySQL database stores model parameters and results and facilitates communication between the STM and LTM. The developed model is applied to the Prescott AMA in the following chapter.

# 5 Application to Prescott AMA

Rapidly growing populations and scarcity of water is not a new problem and research into finding solutions is ongoing. (See (Gleick 2000), (Rosegrant et al. 2002), (Seckler et al. 1999), (Rijsberman 2006), (Shiklomanov and Rodda 2003) among others.) One of the objectives of this research is the development of a tool to aid in sustainable basin management and planning, scenario modeling, and decision making, while maintaining ecological, environmental and hydrological integrity. A practical application is made to the Prescott Active Management Area (Prescott AMA) to gage the viability of the model and guide future research. This area was selected due to its proximity, the nature of the problem, and readily available information. A brief introduction to the area is presented followed by a structuring of the problem for model application, computational results and analysis.

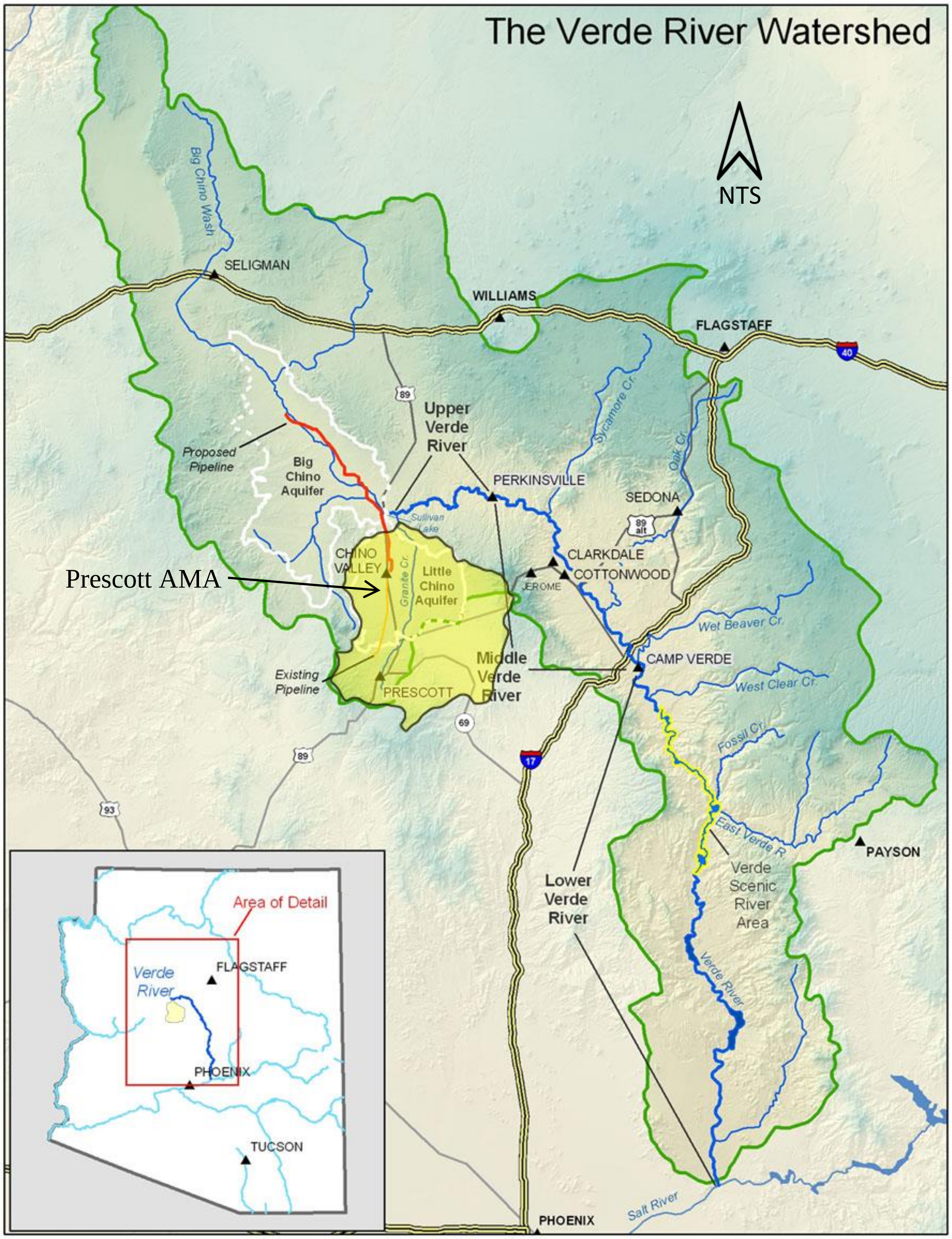
## 5.1 Introduction

The developed model is applied to an area surrounding the Prescott Active Management Area (AMA) in Arizona (see Figure 5.1). The Arizona AMAs are a management concept pursuant to the 1980 Arizona Groundwater Management Code, created to address severe ground water overdraft within the state. Five AMAs were established in Arizona, covering the areas of most severe overdraft with boundaries generally determined by groundwater basins and sub-basins ("Overview of the Arizona Groundwater Management Code" n.d.).

The largest municipality in the Prescott AMA is the Town of Prescott, which is located in central Arizona and home to approximately forty-thousand people (U.S. Census Bureau 2010). The populations of Prescott and the surrounding area have enjoyed rapid growth over the last several years as more people become aware of the many benefits of residing in the area. As is often the case, rapid growth has placed undue pressure on the surrounding ecosystem and available natural resources that support the population, most notably, on the very limited water supply. In response to declining aquifer levels and regulatory compliance deadlines, the Town of Prescott has developed a plan to pump and transport water from the Big Chino aquifer, a location outside of the Prescott AMA (see Figure 5.1) and AMA regulation. This plan has generated a lot of controversy as the ecological and economic impacts of the pumping are beginning to be understood. A recent study completed by the United States Geological Survey (USGS) (Pool et al. 2011) suggests that pumping in the proposed location would significantly impact the flows of the Verde River, a primary source of water for the City of Phoenix.

Additional information regarding the study area may be found in Appendix B. What follows is the adaptation of the problem-shed to the developed model, with the identification of available supplies and competing demands, physical representation of the problem-shed, and the basis for value and cost assignment.

**Figure 5.1. Verde watershed and relative location of the Prescott AMA.**



## 5.2 Application

The developed model is applied to the Prescott AMA and the proposed remote pumping location. A schematic of the physical system and adaptation for the model is presented in Figure 5.2. The representation of the physical system is after Rothman (2007). Each of the sources for the zones are described as independent source nodes with independent links for each source to the demand within the model but are pictured as composites in the schematic. The long term time horizon is 50 years. Extensive tests suggested an initial population of 100, 10 elites, a mutation rate of 5 percent and a maximum of 150 generations as parameters for the GA.

Four scenarios are examined in this application. The first uses historical daily flows on the Verde River for the target river demand. The second scenario uses 15% of the Julian day flow average for a target flow regime. Scenarios 3 and 4 also use the historical flows as the basis for the target regime, but impose a minimum storage volume on the aquifers in the Prescott AMA. Scenario 4 allows drawdown on the Big Chino aquifer to decrease 7.5% prior to impacting flows on the Verde River. Table 5.1 provides a summary of the differences between the Prescott AMA scenarios.

The model parameters are discussed next, including a discussion on the relationship between the Big Chino aquifer and Verde River and the basis for the river supply data.

### *5.2.1 Model Parameters*

Model parameters where applicable are based on the data found in Rothman (2007). This includes initial states, consumer unit growth rates and tolerances, consumption rates and tolerances, available supplies and delivery limitations, and some costs and benefits. These are listed in Tables 5.2 through 5.9.

#### *Beneficial Use and Cost Basis*

Beneficial use (residential, industrial and agricultural) within the problem-shed was calculated per the City of Prescott water rates. The rate schedule utilizes a sliding scale depending upon volume and use ("City of Prescott, Arizona Water Rates" 2013). For single family residential use this equates to \$14.49 per 1000 gallons for use above 20,000 gallons. Using this as a basis suggests a benefit of approximately \$4700 per acre foot. Non-residential use costs \$13.21 per 1000 gallons for uses exceeding 4,800,000 gallons, which equates to \$4306 per acre foot. Since the primary use in the management area is residential, a value of \$4700 per acre foot was adopted for non-residential use as well. Determining benefits associated with eco-services is a challenging task (see Appendix C for additional discussion), but assuming a value equal to residential use is reasonable for this application.

**Figure 5.2. Physical model schematic of the Prescott AMA model application.**

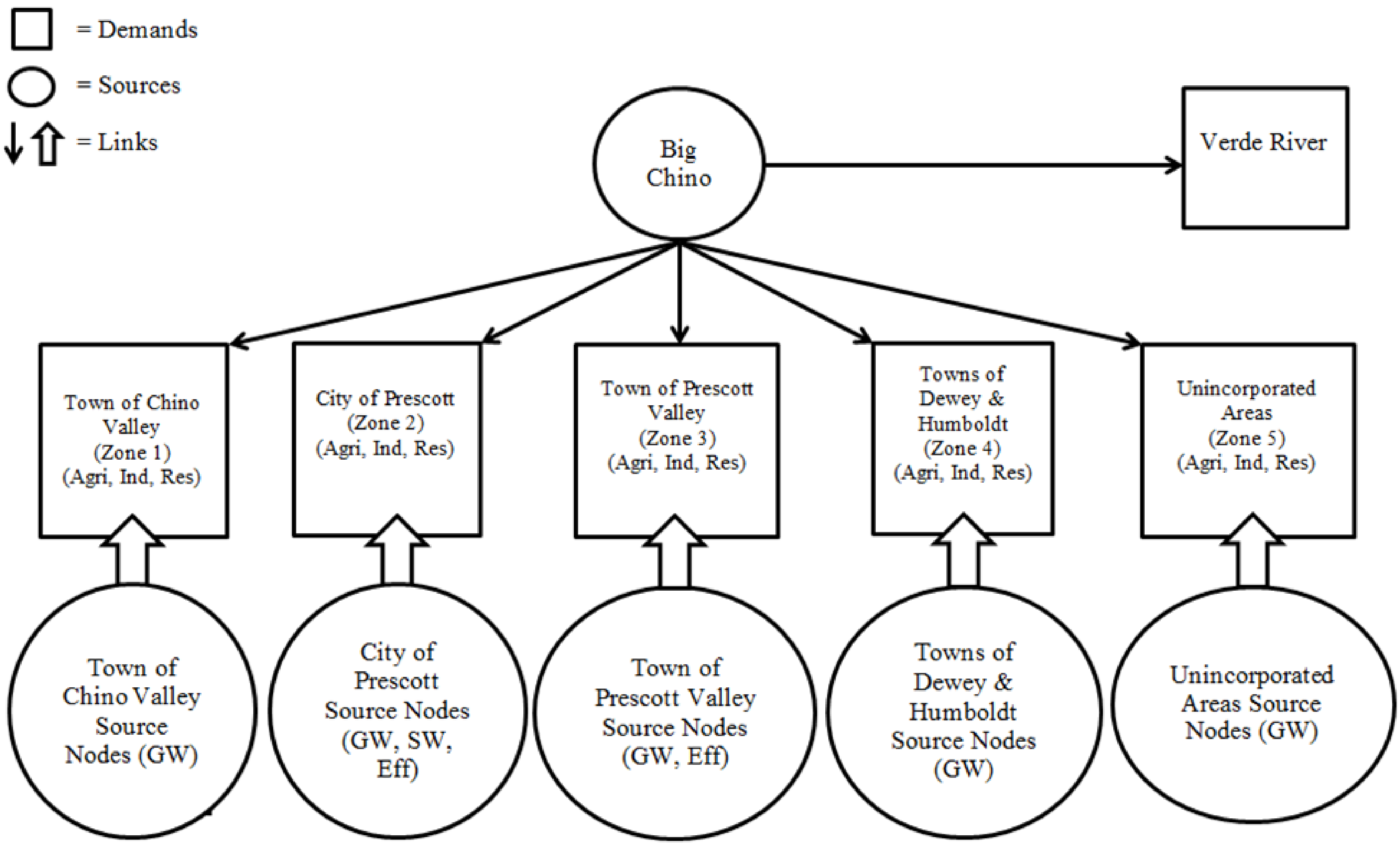


**Table 5.1. Description of scenarios for the Prescott AMA application.**

| Scenario | Description |
|---|---|
| 1 | Historical river flows used as the target flows. Examines the sustainability and benefit for the current conditions. |
| 2 | 15% of average Julian day flows are used as the target flows. Examines the sustainability and benefits of additional water availability for population growth. |
| 3 | Historical river flows used as the target flows. Drawdown for aquifers in the Prescott AMA limited to 90% of initial storage volumes. |
| 4 | Historical river flows used as the target flows. Drawdown for aquifers in the Prescott AMA limited to 90% of initial storage volumes. Impact to flows on the Verde River begin at 7.5% drawdown on the Big Chino aquifer. |

## Table 5.3. Parameter basis for the Prescott AMA application.

Rothman's Data

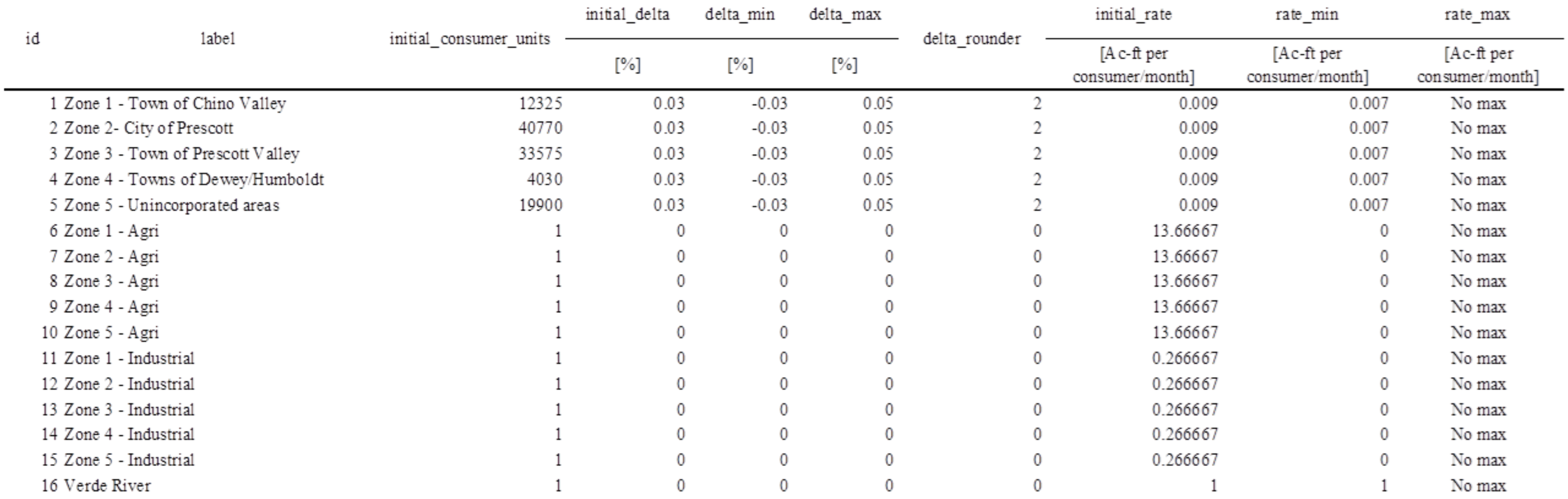
| | Supply | | | | | | Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Groundwater | Surface water | Effluent Min & Max | | Recharge | Import | Residential | | | Industrial | Agricultural |
| Zone | [Ac-ft] | [Ac-ft/year] | [Ac-ft/year] | [Ac-ft/year] | [Ac-ft/year] | [Ac-ft/year] | Population | Rate [gpcpd] | Consumption [Ac-ft/yr] | [Ac-ft/yr] | [Ac-ft/yr] |
| 1 | 870000 | 0 | 0 | | 520 | | 12325 | 180 | 0.201759 | 3.2 | 164 |
| 2 | 150000 | 900 | 1200 | 2200 | 320 | | 40770 | 180 | 0.201759 | 3.2 | 164 |
| 3 | 720000 | 0 | 800 | 1800 | 320 | 18600 | 33575 | 180 | 0.201759 | 3.2 | 164 |
| 4 | 290000 | 0 | 0 | | 160 | | 4030 | 180 | 0.201759 | 3.2 | 164 |
| 5 | 870000 | 0 | 0 | | 2680 | | 19900 | 180 | 0.201759 | 3.2 | 164 |

## Table 5.2. Converted parameters for the Prescott AMA application.

Conversion to Monthly Units

| | Supply | | | | | | Demand | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Groundwater | Surface water | Effluent Min & Max | | Recharge | Import | Residential | | | Industrial | Agricultural |
| Zone | [Ac-ft] | [Ac-ft/mo] | [Ac-ft/mo] | [Ac-ft/mo] | [Ac-ft/mo] | [Ac-ft/mo] | Population | Rate [gpcpd] | Consumption [Ac-ft/mo] | [Ac-ft/mo] | [Ac-ft/mo] |
| 1 | 870000 | 0 | 0 | 0 | 43.3333333 | | 12325 | 180 | 0.016813 | 0.26667 | 13.6667 |
| 2 | 150000 | 75 | 100 | 183.3333333 | 26.6666667 | | 40770 | 180 | 0.016813 | 0.26667 | 13.6667 |
| 3 | 720000 | 0 | 66.66666667 | 150 | 26.6666667 | 1550 | 33575 | 180 | 0.016813 | 0.26667 | 13.6667 |
| 4 | 290000 | 0 | 0 | 0 | 13.3333333 | | 4030 | 180 | 0.016813 | 0.26667 | 13.6667 |
| 5 | 870000 | 0 | 0 | 0 | 223.333333 | | 19900 | 180 | 0.016813 | 0.26667 | 13.6667 |

Table 5.4.  Demand node parameters for the Prescott AMA application.

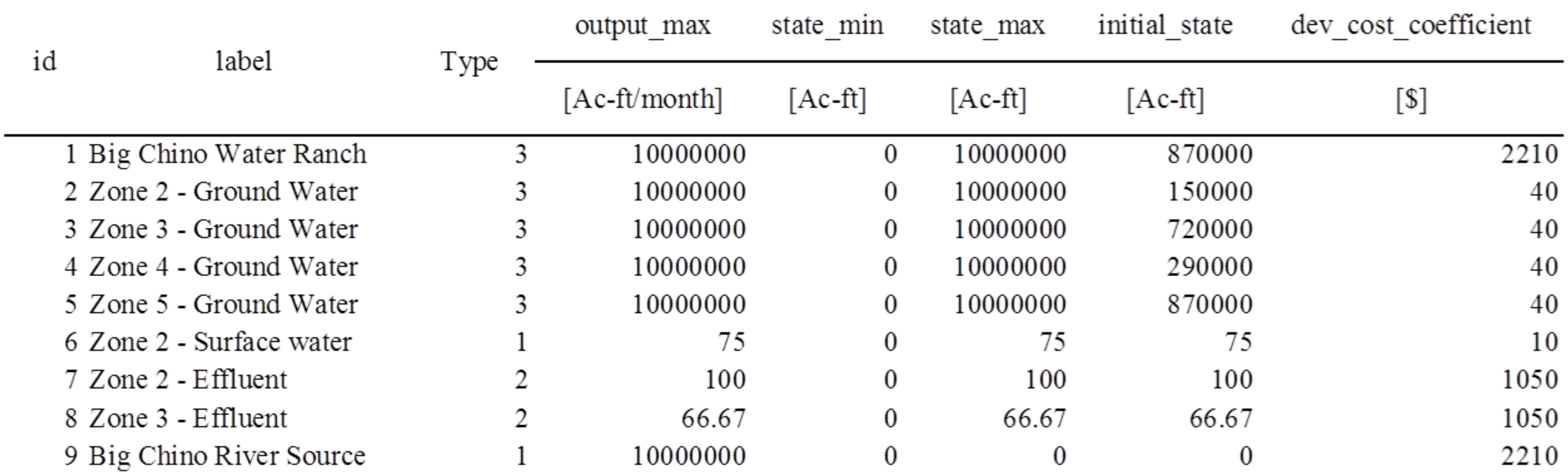


| id | label | initial_consumer_units | initial_delta | delta_min | delta_max | delta_rounder | initial_rate | rate_min | rate_max |
|---|---|---|---|---|---|---|---|---|---|
| | | | [%] | [%] | [%] | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] |
| 1 | Zone 1 - Town of Chino Valley | 12325 | 0.03 | -0.03 | 0.05 | 2 | 0.009 | 0.007 | No max |
| 2 | Zone 2- City of Prescott | 40770 | 0.03 | -0.03 | 0.05 | 2 | 0.009 | 0.007 | No max |
| 3 | Zone 3 - Town of Prescott Valley | 33575 | 0.03 | -0.03 | 0.05 | 2 | 0.009 | 0.007 | No max |
| 4 | Zone 4 - Towns of Dewey/Humboldt | 4030 | 0.03 | -0.03 | 0.05 | 2 | 0.009 | 0.007 | No max |
| 5 | Zone 5 - Unincorporated areas | 19900 | 0.03 | -0.03 | 0.05 | 2 | 0.009 | 0.007 | No max |
| 6 | Zone 1 - Agri | 1 | 0 | 0 | 0 | 0 | 13.66667 | 0 | No max |
| 7 | Zone 2 - Agri | 1 | 0 | 0 | 0 | 0 | 13.66667 | 0 | No max |
| 8 | Zone 3 - Agri | 1 | 0 | 0 | 0 | 0 | 13.66667 | 0 | No max |
| 9 | Zone 4 - Agri | 1 | 0 | 0 | 0 | 0 | 13.66667 | 0 | No max |
| 10 | Zone 5 - Agri | 1 | 0 | 0 | 0 | 0 | 13.66667 | 0 | No max |
| 11 | Zone 1 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.266667 | 0 | No max |
| 12 | Zone 2 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.266667 | 0 | No max |
| 13 | Zone 3 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.266667 | 0 | No max |
| 14 | Zone 4 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.266667 | 0 | No max |
| 15 | Zone 5 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.266667 | 0 | No max |
| 16 | Verde River | 1 | 0 | 0 | 0 | 0 | 1 | 1 | No max |

Table 5.5.  Demand node parameters for the Prescott AMA application (cont.).

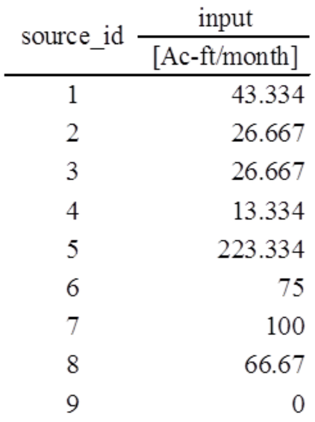
| id | label | initial_consumer_units | initial_rate_change | rate_change_min | rate_change_max | rate_rounder | theta | benefit | si_weight | rva |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | | [%] | [$] | | |
| 1 | Zone 1 - Town of Chino Valley | 12325 | 0 | -0.02 | 0.02 | 4 | 1 | 4700 | 0.058824 | 0 |
| 2 | Zone 2- City of Prescott | 40770 | 0 | -0.02 | 0.02 | 4 | 1 | 4700 | 0.058824 | 0 |
| 3 | Zone 3 - Town of Prescott Valley | 33575 | 0 | -0.02 | 0.02 | 4 | 1 | 4700 | 0.058824 | 0 |
| 4 | Zone 4 - Towns of Dewey/Humboldt | 4030 | 0 | -0.02 | 0.02 | 4 | 1 | 4700 | 0.058824 | 0 |
| 5 | Zone 5 - Unincorporated areas | 19900 | 0 | -0.02 | 0.02 | 4 | 1 | 4700 | 0.058824 | 0 |
| 6 | Zone 1 - Agri | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.058824 | 0 |
| 7 | Zone 2 - Agri | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.058824 | 0 |
| 8 | Zone 3 - Agri | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.058824 | 0 |
| 9 | Zone 4 - Agri | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.058824 | 0 |
| 10 | Zone 5 - Agri | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.058824 | 0 |
| 11 | Zone 1 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.75 | 4700 | 0.058824 | 0 |
| 12 | Zone 2 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.75 | 4700 | 0.058824 | 0 |
| 13 | Zone 3 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.75 | 4700 | 0.058824 | 0 |
| 14 | Zone 4 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.75 | 4700 | 0.058824 | 0 |
| 15 | Zone 5 - Industrial | 1 | 0 | 0 | 0 | 0 | 0.75 | 4700 | 0.058824 | 0 |
| 16 | Verde River | 1 | 0 | 0 | 0 | 0 | -100000 | 4700 | 0.058824 | 1 |

Table 5.7. Source node parameters for the Prescott AMA application for Scenarios 1 and 2.



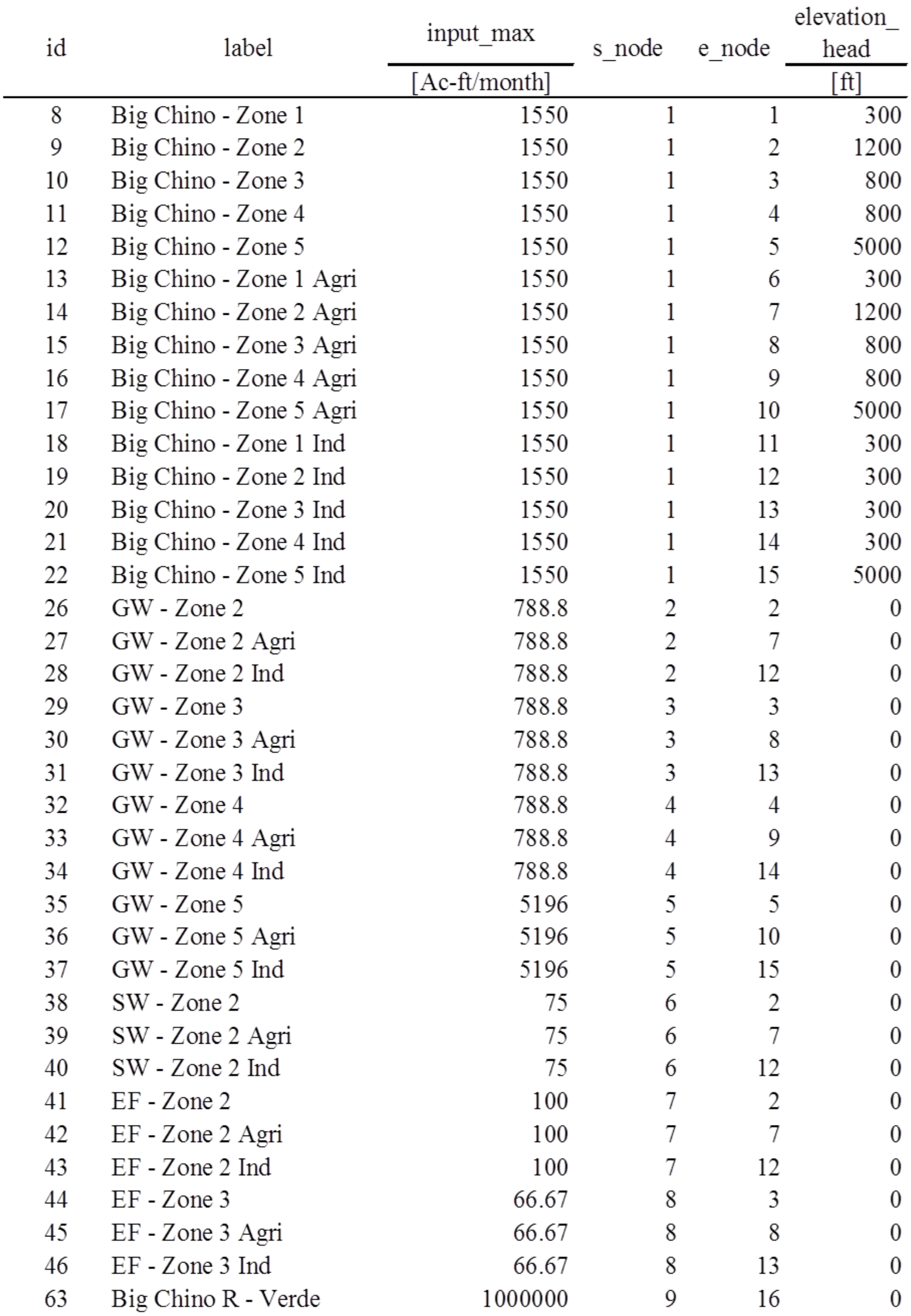
| id | label | Type | output_max | state_min | state_max | initial_state | dev_cost_coefficient |
|---|---|---|---|---|---|---|---|
| | | | [Ac-ft/month] | [Ac-ft] | [Ac-ft] | [Ac-ft] | [$] |
| 1 | Big Chino Water Ranch | 3 | 10000000 | 0 | 10000000 | 870000 | 2210 |
| 2 | Zone 2 - Ground Water | 3 | 10000000 | 0 | 10000000 | 150000 | 40 |
| 3 | Zone 3 - Ground Water | 3 | 10000000 | 0 | 10000000 | 720000 | 40 |
| 4 | Zone 4 - Ground Water | 3 | 10000000 | 0 | 10000000 | 290000 | 40 |
| 5 | Zone 5 - Ground Water | 3 | 10000000 | 0 | 10000000 | 870000 | 40 |
| 6 | Zone 2 - Surface water | 1 | 75 | 0 | 75 | 75 | 10 |
| 7 | Zone 2 - Effluent | 2 | 100 | 0 | 100 | 100 | 1050 |
| 8 | Zone 3 - Effluent | 2 | 66.67 | 0 | 66.67 | 66.67 | 1050 |
| 9 | Big Chino River Source | 1 | 10000000 | 0 | 0 | 0 | 2210 |

Table 5.6. Source input for the Prescott AMA application.



| source_id | input |
|---|---|
| | [Ac-ft/month] |
| 1 | 43.334 |
| 2 | 26.667 |
| 3 | 26.667 |
| 4 | 13.334 |
| 5 | 223.334 |
| 6 | 75 |
| 7 | 100 |
| 8 | 66.67 |
| 9 | 0 |

**Table 5.8. Link parameters for the Prescott AMA application.**



| id | label | input_max<br>[Ac-ft/month] | s_node | e_node | elevation_head<br>[ft] |
|---|---|---|---|---|---|
| 8 | Big Chino - Zone 1 | 1550 | 1 | 1 | 300 |
| 9 | Big Chino - Zone 2 | 1550 | 1 | 2 | 1200 |
| 10 | Big Chino - Zone 3 | 1550 | 1 | 3 | 800 |
| 11 | Big Chino - Zone 4 | 1550 | 1 | 4 | 800 |
| 12 | Big Chino - Zone 5 | 1550 | 1 | 5 | 5000 |
| 13 | Big Chino - Zone 1 Agri | 1550 | 1 | 6 | 300 |
| 14 | Big Chino - Zone 2 Agri | 1550 | 1 | 7 | 1200 |
| 15 | Big Chino - Zone 3 Agri | 1550 | 1 | 8 | 800 |
| 16 | Big Chino - Zone 4 Agri | 1550 | 1 | 9 | 800 |
| 17 | Big Chino - Zone 5 Agri | 1550 | 1 | 10 | 5000 |
| 18 | Big Chino - Zone 1 Ind | 1550 | 1 | 11 | 300 |
| 19 | Big Chino - Zone 2 Ind | 1550 | 1 | 12 | 300 |
| 20 | Big Chino - Zone 3 Ind | 1550 | 1 | 13 | 300 |
| 21 | Big Chino - Zone 4 Ind | 1550 | 1 | 14 | 300 |
| 22 | Big Chino - Zone 5 Ind | 1550 | 1 | 15 | 5000 |
| 26 | GW - Zone 2 | 788.8 | 2 | 2 | 0 |
| 27 | GW - Zone 2 Agri | 788.8 | 2 | 7 | 0 |
| 28 | GW - Zone 2 Ind | 788.8 | 2 | 12 | 0 |
| 29 | GW - Zone 3 | 788.8 | 3 | 3 | 0 |
| 30 | GW - Zone 3 Agri | 788.8 | 3 | 8 | 0 |
| 31 | GW - Zone 3 Ind | 788.8 | 3 | 13 | 0 |
| 32 | GW - Zone 4 | 788.8 | 4 | 4 | 0 |
| 33 | GW - Zone 4 Agri | 788.8 | 4 | 9 | 0 |
| 34 | GW - Zone 4 Ind | 788.8 | 4 | 14 | 0 |
| 35 | GW - Zone 5 | 5196 | 5 | 5 | 0 |
| 36 | GW - Zone 5 Agri | 5196 | 5 | 10 | 0 |
| 37 | GW - Zone 5 Ind | 5196 | 5 | 15 | 0 |
| 38 | SW - Zone 2 | 75 | 6 | 2 | 0 |
| 39 | SW - Zone 2 Agri | 75 | 6 | 7 | 0 |
| 40 | SW - Zone 2 Ind | 75 | 6 | 12 | 0 |
| 41 | EF - Zone 2 | 100 | 7 | 2 | 0 |
| 42 | EF - Zone 2 Agri | 100 | 7 | 7 | 0 |
| 43 | EF - Zone 2 Ind | 100 | 7 | 12 | 0 |
| 44 | EF - Zone 3 | 66.67 | 8 | 3 | 0 |
| 45 | EF - Zone 3 Agri | 66.67 | 8 | 8 | 0 |
| 46 | EF - Zone 3 Ind | 66.67 | 8 | 13 | 0 |
| 63 | Big Chino R - Verde | 1000000 | 9 | 16 | 0 |

**Table 5.9. Source node parameter changes for Scenarios 3 and 4.**

| id | label | state_min [Ac-ft] |
|---|---|---|
| 1 | Big Chino Water Ranch | 783000 |
| 2 | Zone 2 - Ground Water | 135000 |
| 3 | Zone 3 - Ground Water | 648000 |
| 4 | Zone 4 - Ground Water | 261000 |
| 5 | Zone 5 - Ground Water | 783000 |

### *River Flow*

Two target flows are examined in this application. The first assumes projected demand is the same as historical daily flow. The second uses 15% of the average Julian day flow. Flow data was collected from the USGS gage data for the Verde River (*USGS 09503700 Verde River Near Paulden, AZ* n.d.). It should be noted that the decision to use 15% of the average Julian day flow has no ecological basis. The determination of an ecologically sound flow regime is a complex task and beyond the scope of this research.

Verde River supply is also based on the historical flow data, modified by an aquifer response function. A relationship between drawdown in the Big Chino aquifer and historical flows on the Verde river has been derived from the Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona (RGFM) (Pool et al. 2011). Additional information on the RGFM is included in Appendix B. A graph of the data used and the derived equation is indicated in Figure 5.3. The relationship is applied as a constraint on the decision variable in the STM:

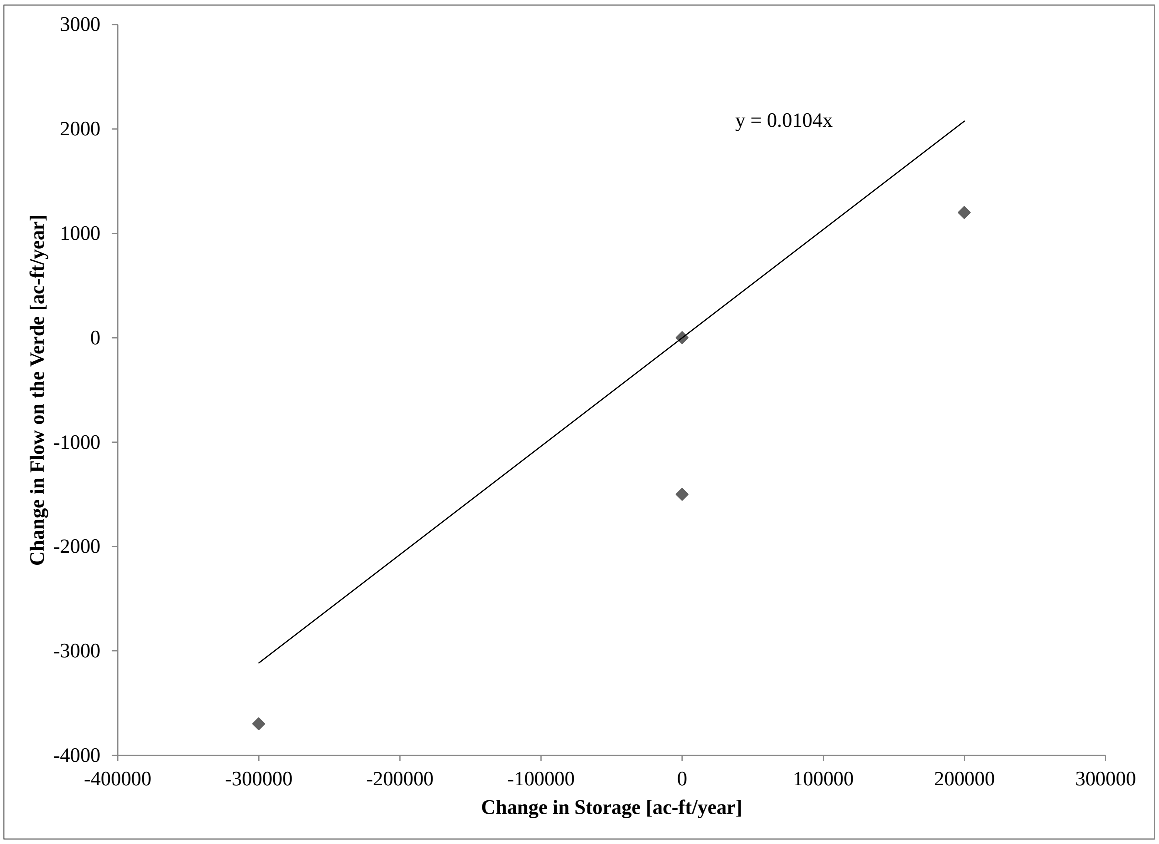
$$x_{y,9,16,t} \leq source_{input_{y,9,t}} - 0.0104 * \Delta s_{y,1,t} \tag{5.1}$$

Where $x_{y,9,16,t}$ is the allocated supply from source node 9 (Verde River source), demand node 16 (Verde River), $source_{input_{y,9,t}}$ is the monthly input at source node 9 (Verde River source) and $\Delta s_{y,1,t}$ is the change in storage at source node 1 (Big Chino), for STM $y$ and month $t$. Historical daily flows are used as the basis for monthly input at source node 9. The change in storage at source node 1 (Big Chino) is defined as:

$$\Delta s_{y,1,t} = s_{0,1,0} - s_{y,1,t} \tag{5.2}$$

Where $s_{0,1,0}$ is the initial storage volume and $s_{y,1,t}$ is the storage volume for STM $y$, source node 1 (Big Chino) and month $t$. For Scenario 4, 92.5% of the initial storage volume on the Big Chino is used in lieu of the initial storage volume. This allows a 7.5% drawdown on the aquifer prior to the change in storage volume impacting flows on the Verde River.

**Figure 5.3. Change in flow on the Verde River as a response to change in aquifer storage.**



## 5.3 Results and Discussion

A summary of results from the four scenarios is indicated in Table 5.10. The run times ranged from between 23 seconds and 30 seconds per individual, with total run times between 100 and 120 hours per scenario. Three computers were used to run the scenarios. Processor details, available memory and average run time per individual are listed in Table 5.11. All of the computers were running a 64-bit version of Windows 7 OS.

Table 5.10. Summary of results for the Prescott AMA application.

| Scenario | Net Benefits [$] | SS | Population | Objective | Best Generation | Best Individual |
|---|---|---|---|---|---|---|
| 1 - Historical | 6.82E+09 | 0.840293 | 201514 | -3.2E+10 | 145 | 74 |
| 2 - 15% Average Julian day | 5.32E+09 | 0.932986 | 264869 | -2.72E+09 | 135 | 50 |
| 3 - 90% Min Aquifer | 5.23E+09 | 0.840253 | 116016 | -3.15E+10 | 141 | 81 |
| 4 - 90% Min Aquifer, 7.5% Big Chino drawdown | 6.22E+09 | 1.000000 | 135245 | 5.82E+08 | 132 | 61 |

Table 5.11. Computer configurations and average run times per individual.

| CPU | RAM | Windows Experience Index | Average run time per individual |
|---|---|---|---|
| Intel Core i7-4600U CPU@2.10 GHz 2.70GHz | 8 GB | 6.9 | 24.7 Seconds |
| Intel Core i7-2600U CPU@3.40 GHz 3.40GHz | 12 GB | 5.8 | 23.1 Seconds |
| Intel Core i7-2670U CPU@2.20 GHz 2.20GHz | 8 GB | 6.9 | 29.7 Seconds |

Referring to Table 5.10, Scenario 1 resulted in the highest net benefits, with Scenario 3 seeing the lowest. In terms of sustainability, Scenario 4 reached maximum sustainability, and Scenario 3 saw the lowest sustainability. Population was highest for Scenario 2 and lowest for Scenario 3. Population growth, population per zone, percent change in population per zone, average consumption rate, net benefits per unit consumer, volume supplied over time, total volume supplied, change in groundwater storage per zone, percent drawdown per zone, and percent fill for the Verde’s demands are compared for each scenario in Figures 5.4 through 5.13.

As indicated in Figure 5.4, all scenarios realized a net increase in ending population. Comparing this to Figure 5.6, Zone 1 saw a decrease in population for nearly every scenario, with a negligible increase in Scenario 4. Zones 2 and 3 saw increases for Scenarios 1 and 2 and Zones 4 and 5 realized increases for every scenario. Average consumption rates decreased in Scenarios 3 and 4, with a slight increase evident in Scenario 1 (see Figure 5.7). Total net benefits per unit consumer are marked by the steep decline towards the end of all the scenarios. Percent drawdown is referenced with respect to percent of initial aquifer storage volumes per each zone in Figure 5.12. Scenarios 3 and 4 both reached the minimum storage volumes in Zones 2, 3 and 4; with minimum realized in Zone 5 for Scenario 4 as well. Fill on the Verde was 100% only for Scenario 4. Scenarios 3 and 4 saw deficits from the first year of the simulation while Scenario 2 realized deficits beginning in year 26 (see Figure 5.13).

Figure 5.4.  Population over time across the entire Prescott AMA for each scenario.

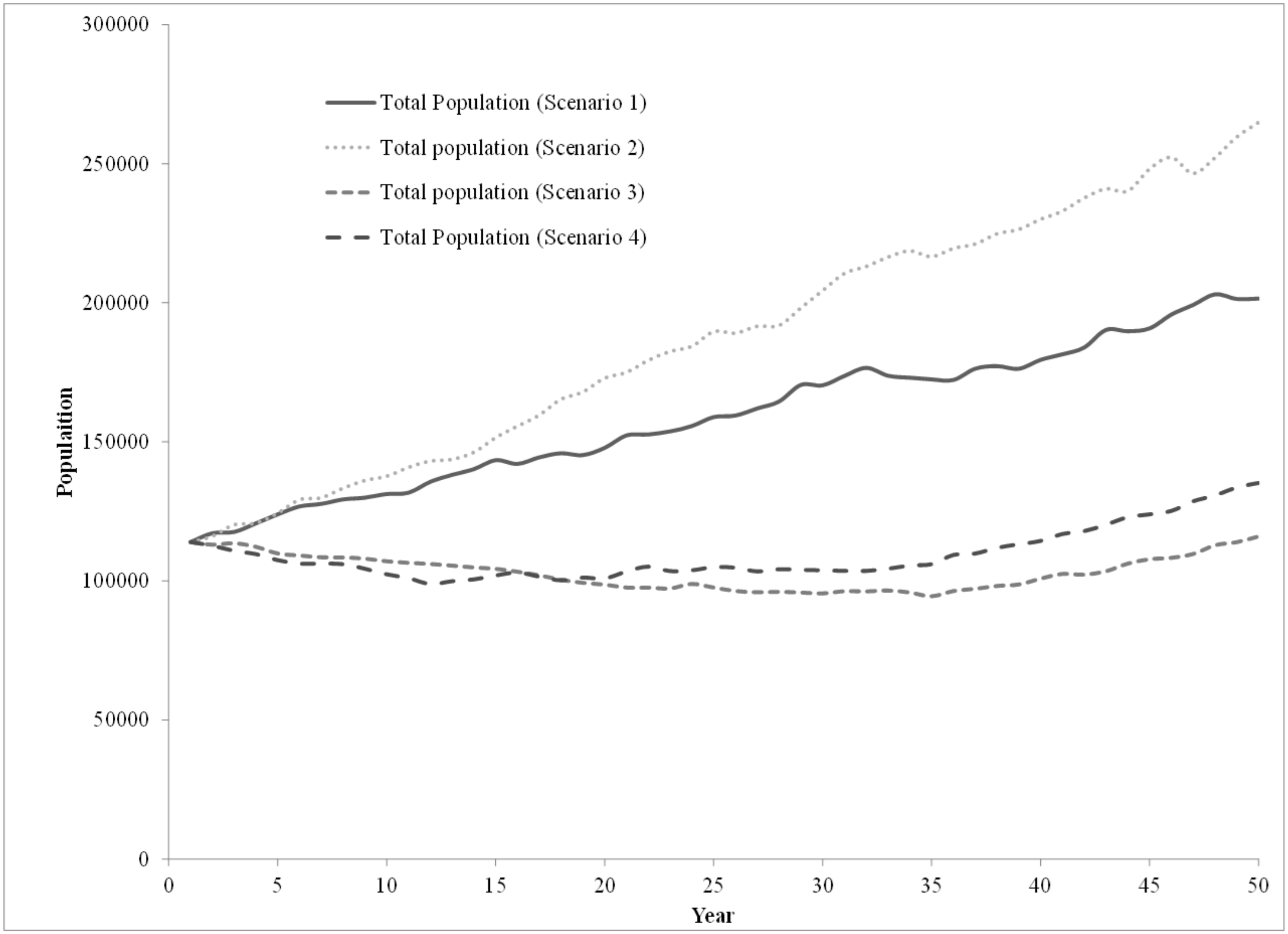


Figure 5.5.  Final population in each zone for each scenario.

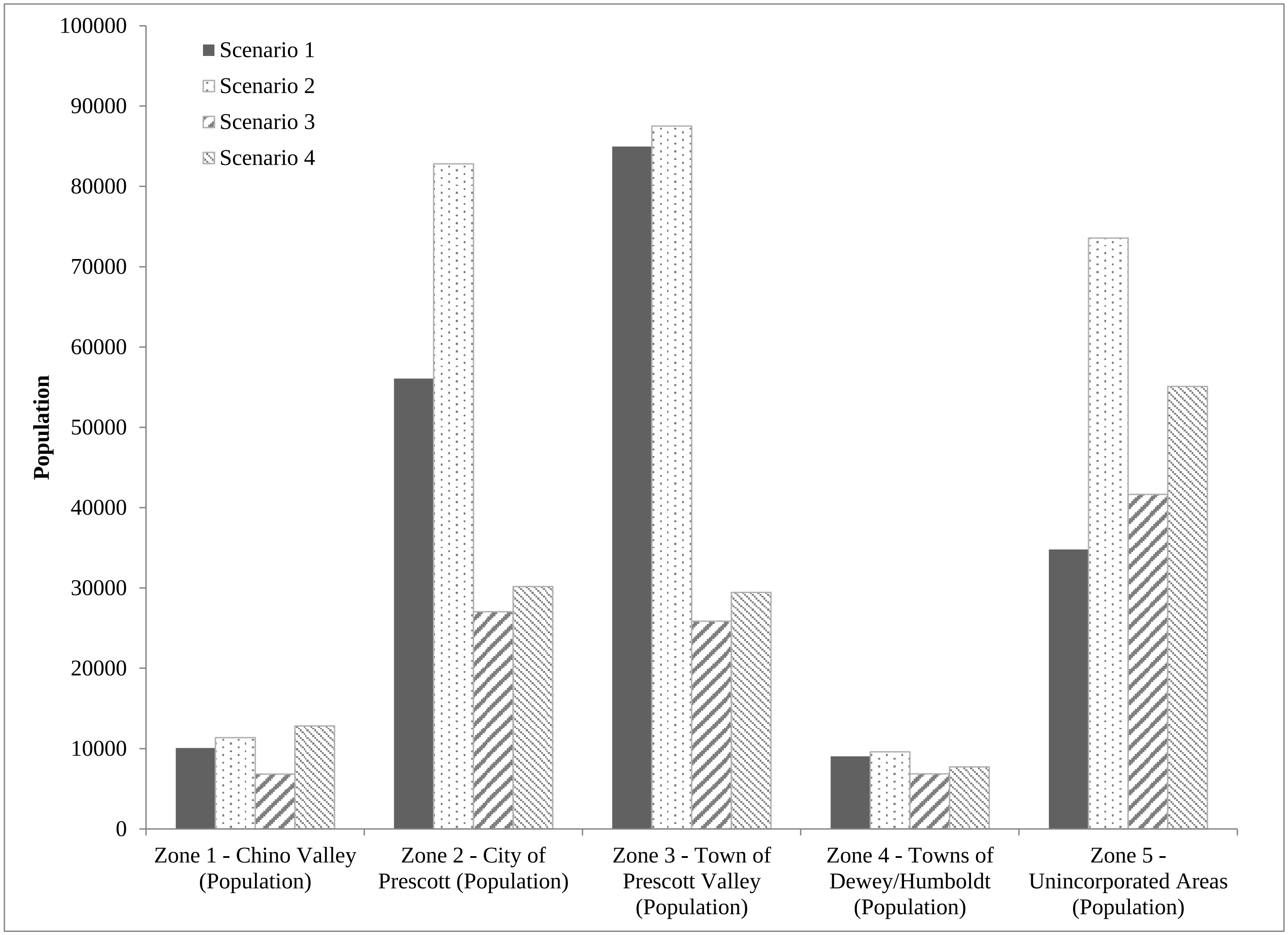


**Figure 5.6. Percent change in population in each zone for each scenario.**

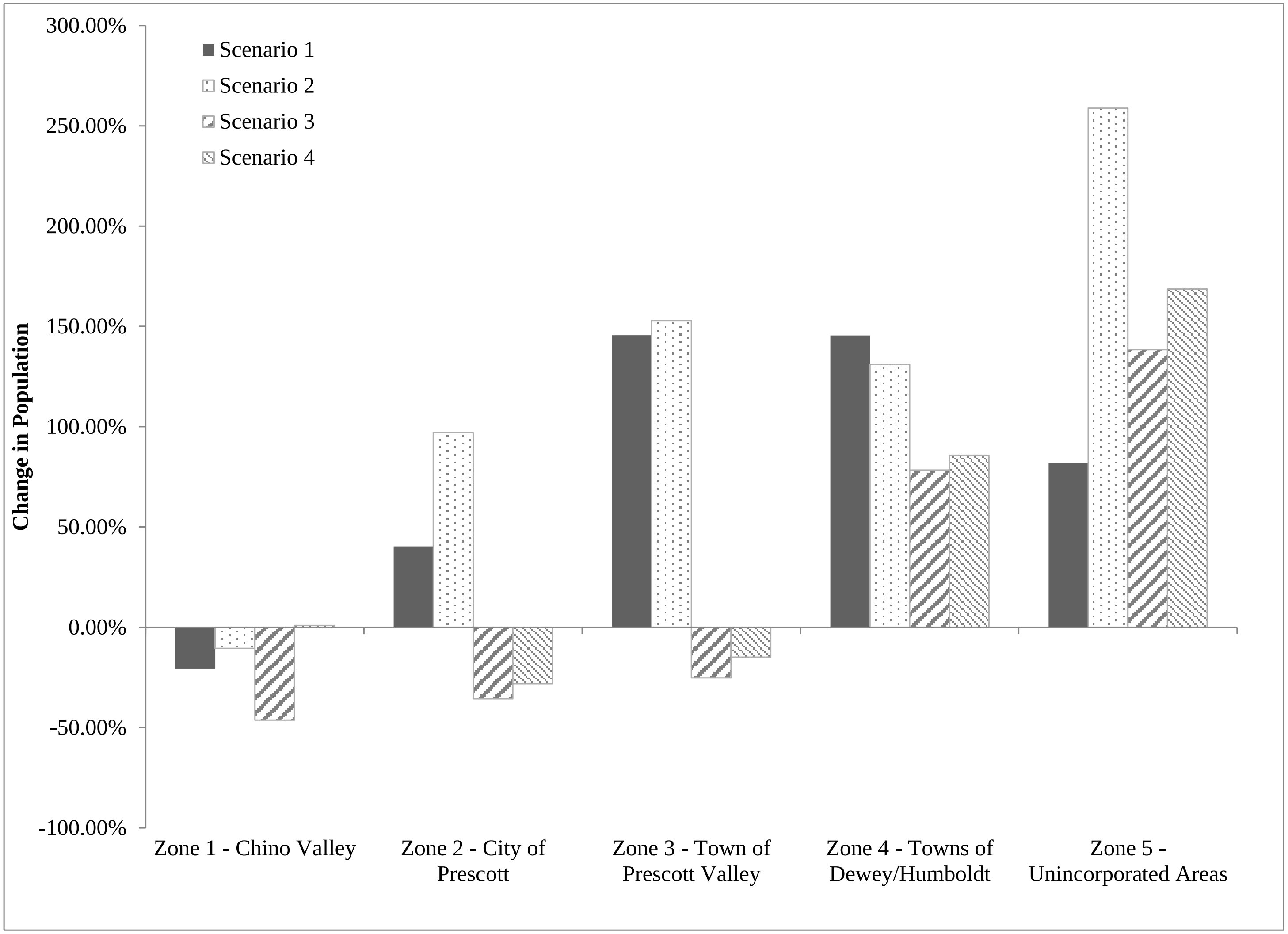


Figure 5.7.  Average consumption rate over time across the entire Prescott AMA for each scenario.

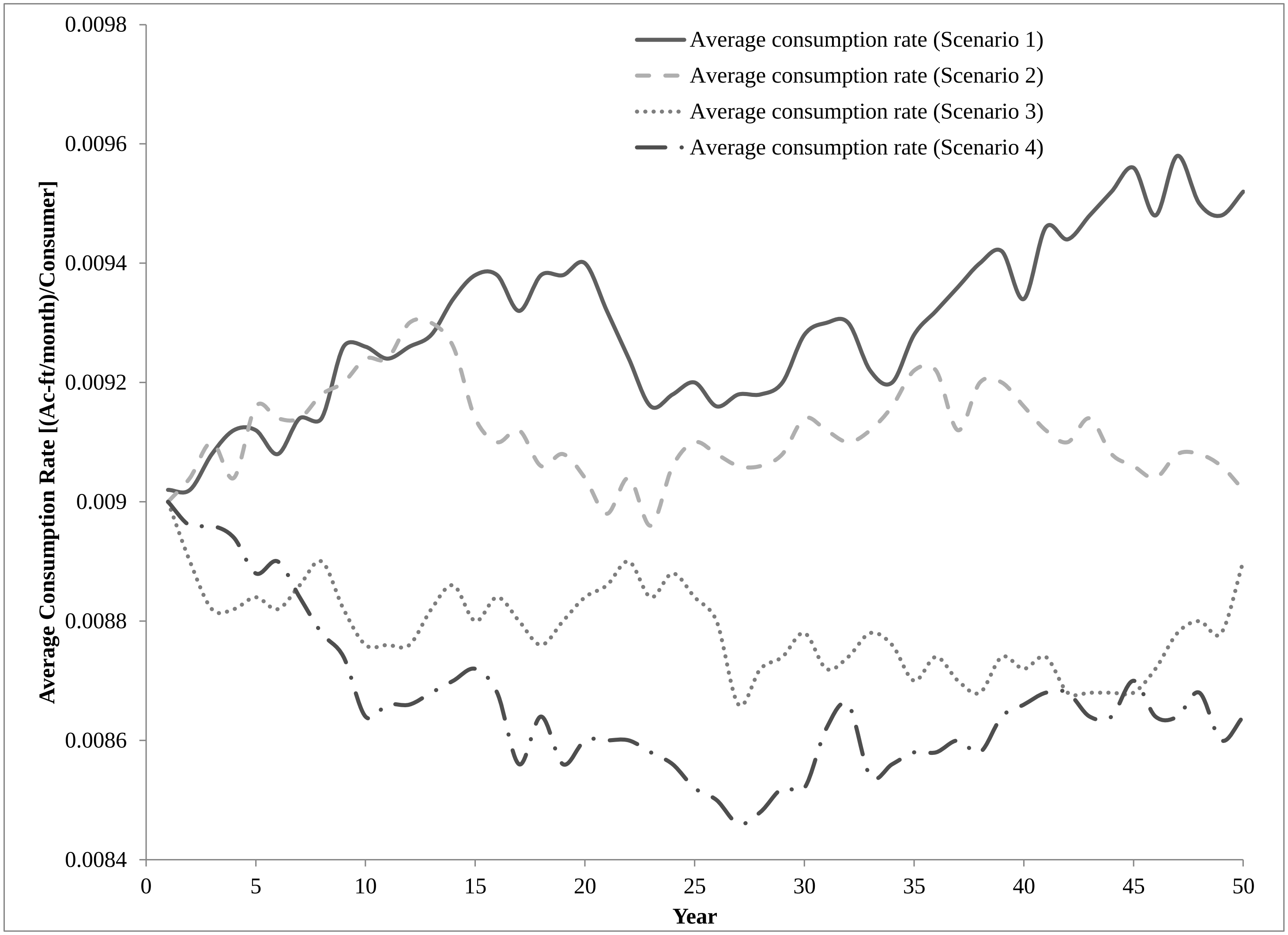


**Figure 5.8. Net benefits per unit consumer over time across the entire Prescott AMA for each scenario.**

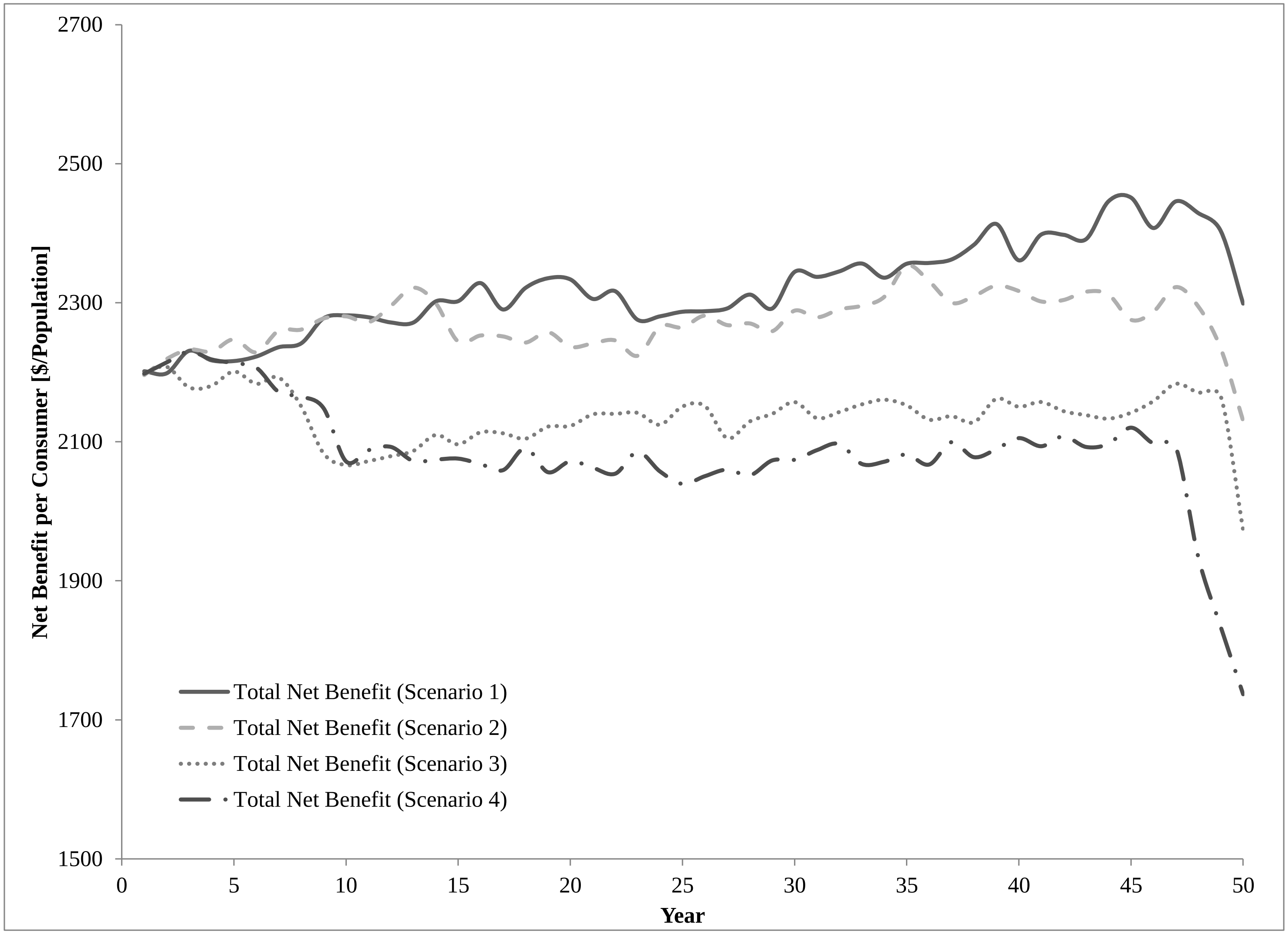


Figure 5.9.  Volume supplied over time across the entire Prescott AMA for each scenario.

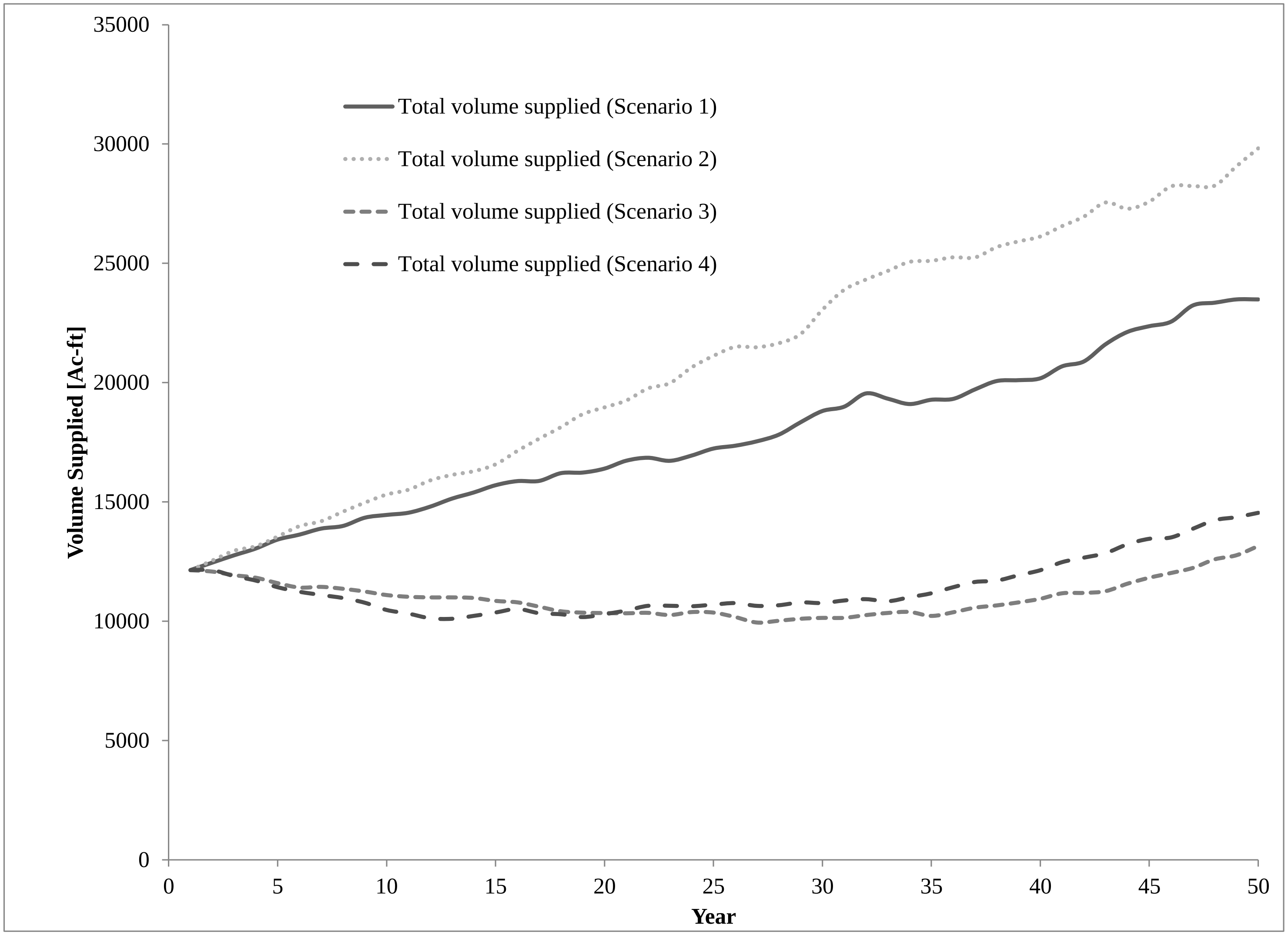


**Figure 5.10. Total volume supplied in each zone for each scenario.**

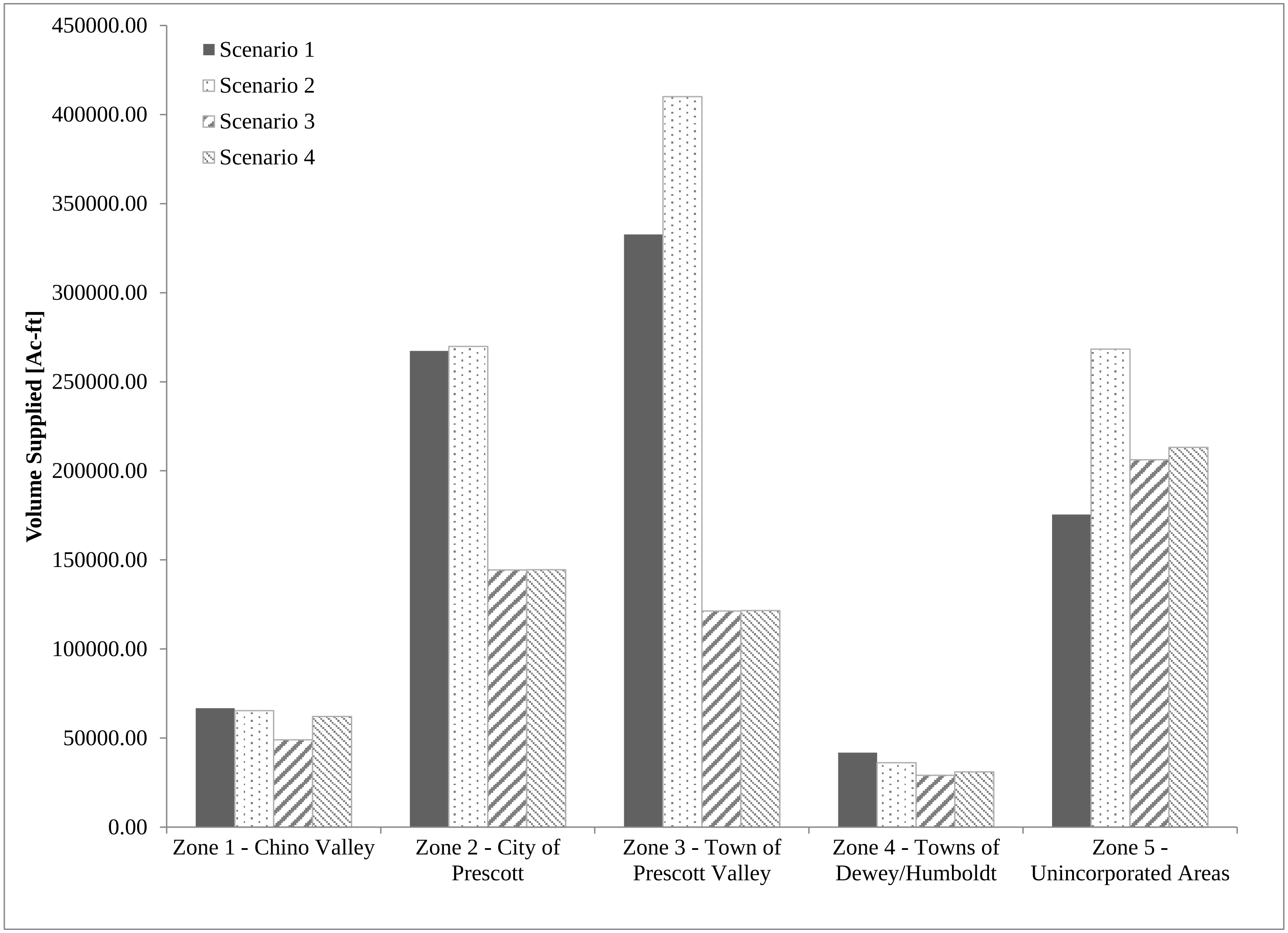


**Figure 5.11. Change in storage in each zone for each scenario.**

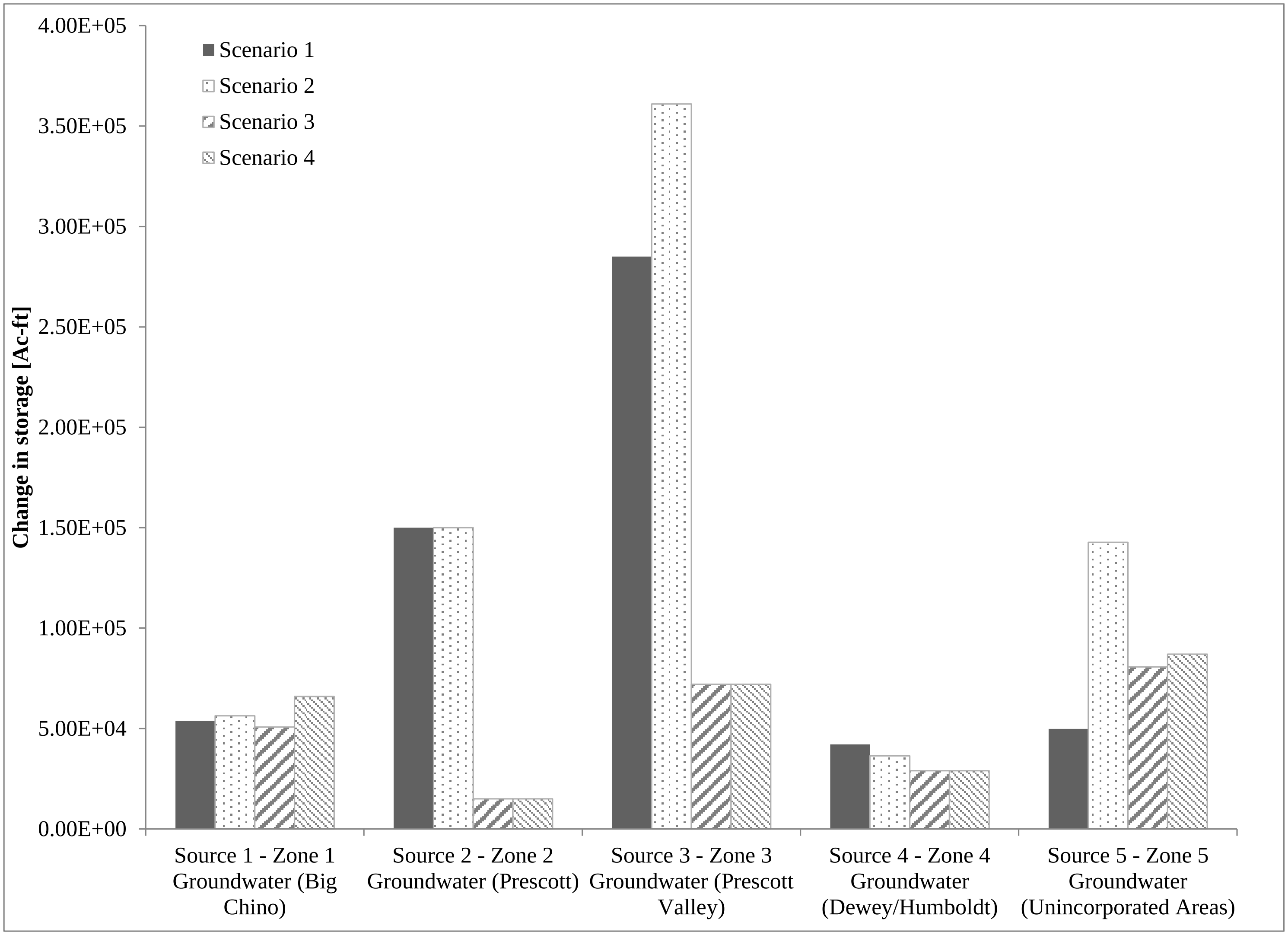


**Figure 5.12. Percent drawdown in aquifer storage in each zone for each scenario.**

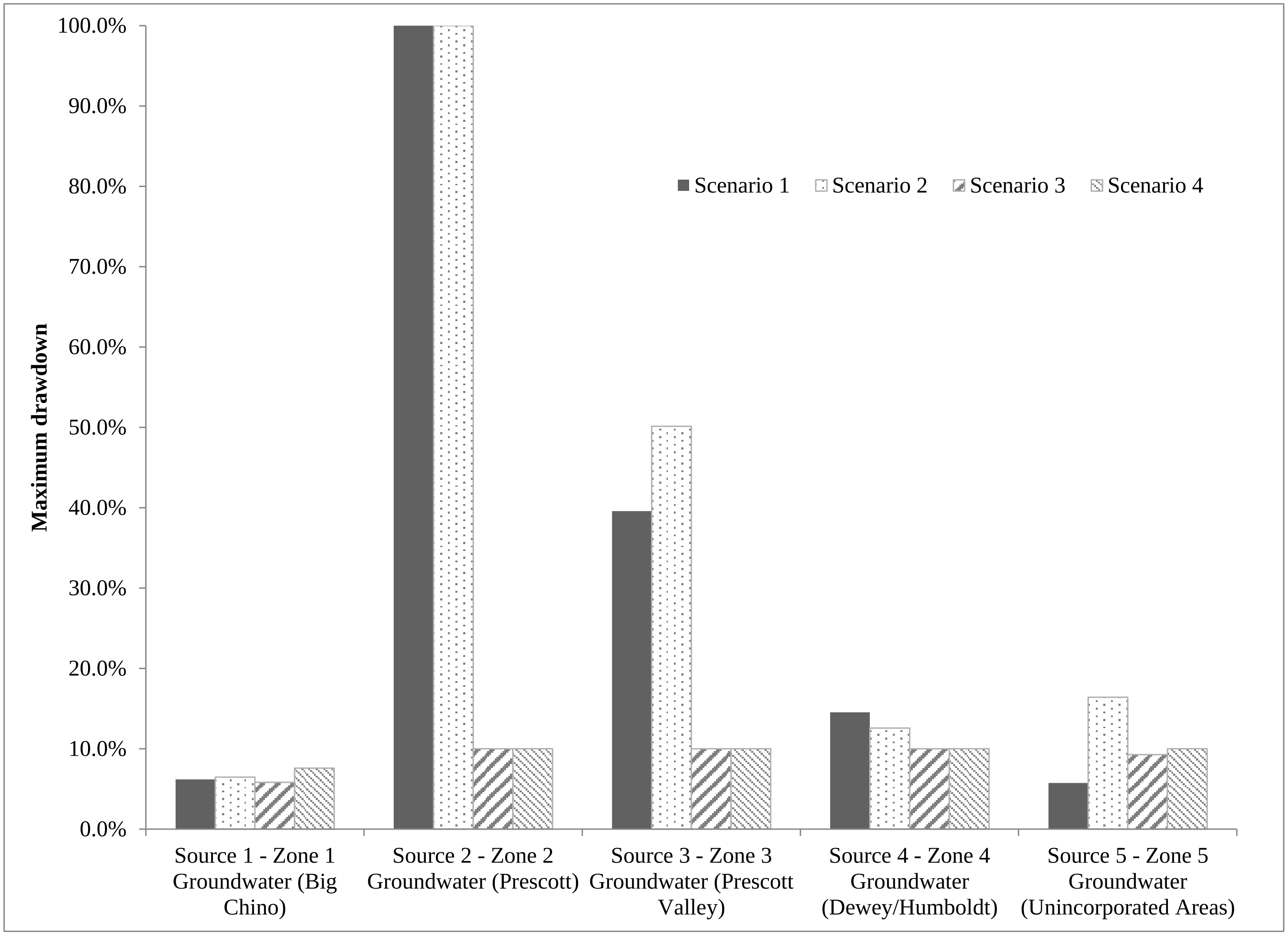


Figure 5.13.  Percent fill on the Verde River for each scenario.

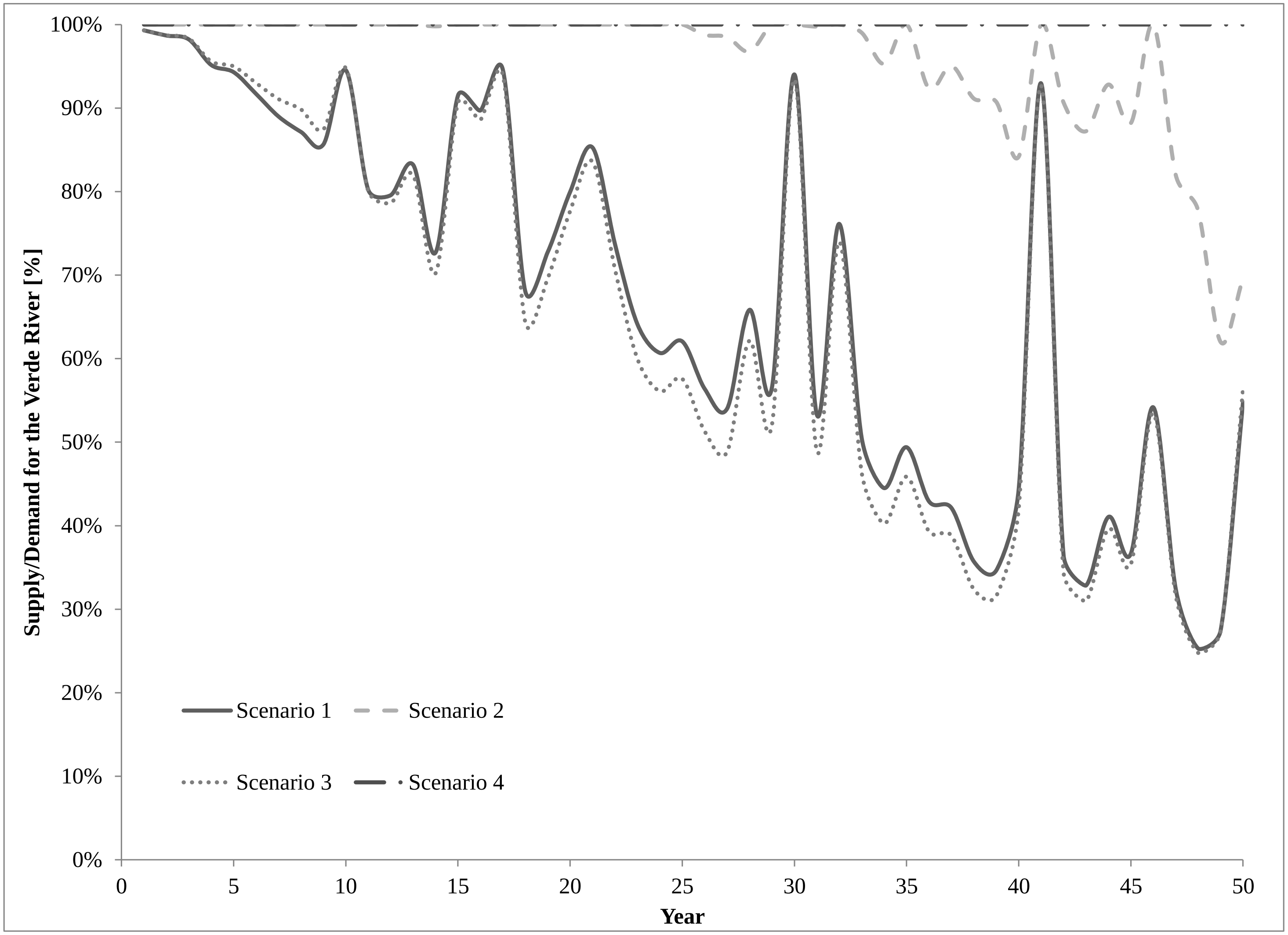
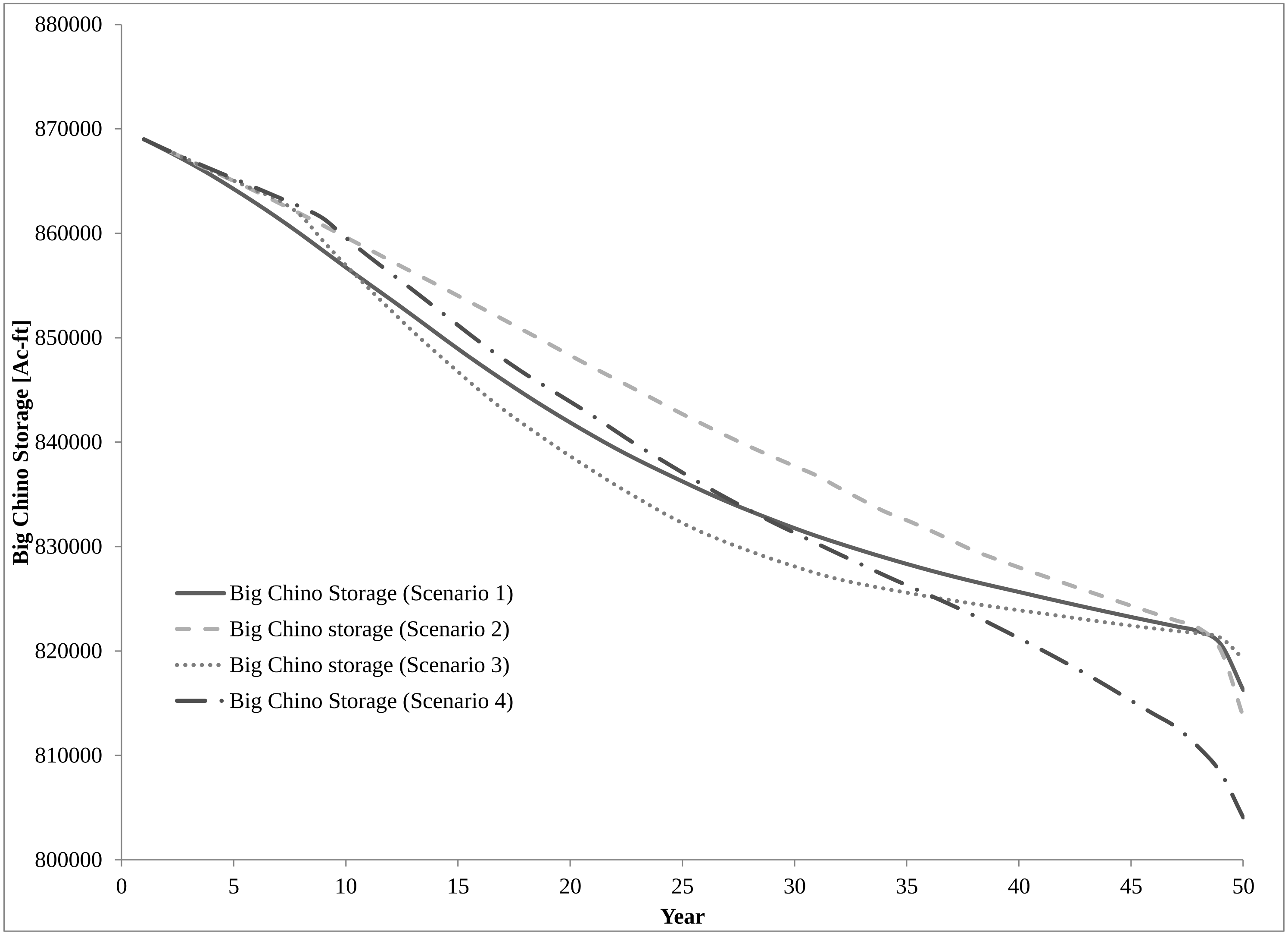


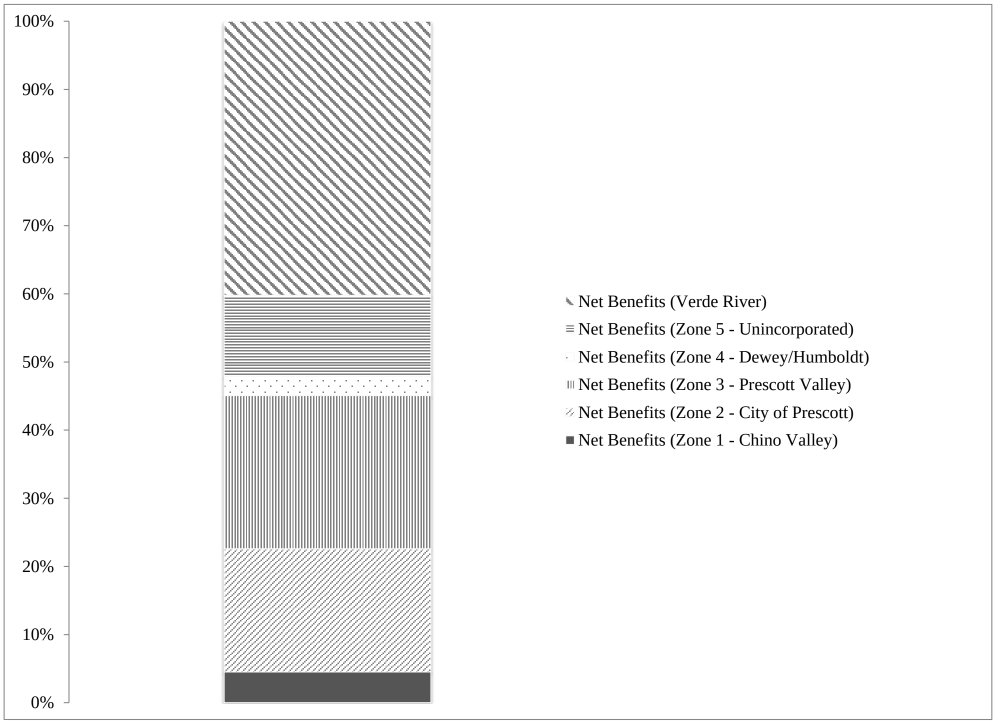
Figure 5.14.  Change in storage on the Big Chino aquifer over time for each scenario.



The distribution of the net benefits for each scenario is illustrated in Figures 5.15 through 5.18. The majority of net benefit in Scenario 1 is attributed to the Verde River flows. The same is true for all the scenarios with the historical flow regime target, higher demands permits higher consumption. Scenario 3, which uses 15% of the Julian Day average flow as a target regime finishes with the third highest net benefits, slightly higher than Scenario 3.

The net benefits per unit residential population over time is indicated in Figures 5.19 through 5.22. There are several observations. Zone 1 (Chino Valley) consistently sees a comparatively lower net benefit per unit population due to the reliance on the Big Chino supply and associated development costs. Zone 2 (City of Prescott) is either at or near to the next lowest net benefits per unit consumer for all four scenarios as well due to the availability of effluent. Zone 5 sees an increase in net benefits per consumer unit over time for every scenario.

### Figure 5.15. Net benefit distribution for Scenario 1.



### Figure 5.16. Net benefit distribution for Scenario 2.

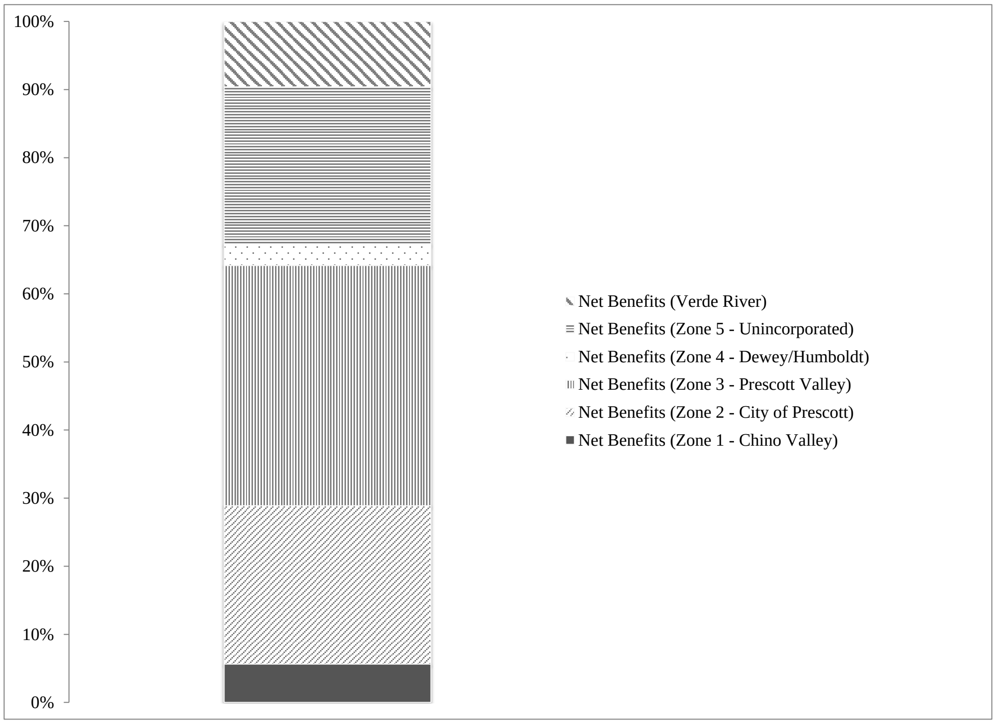


**Figure 5.17. Net benefit distribution for Scenario 3.**

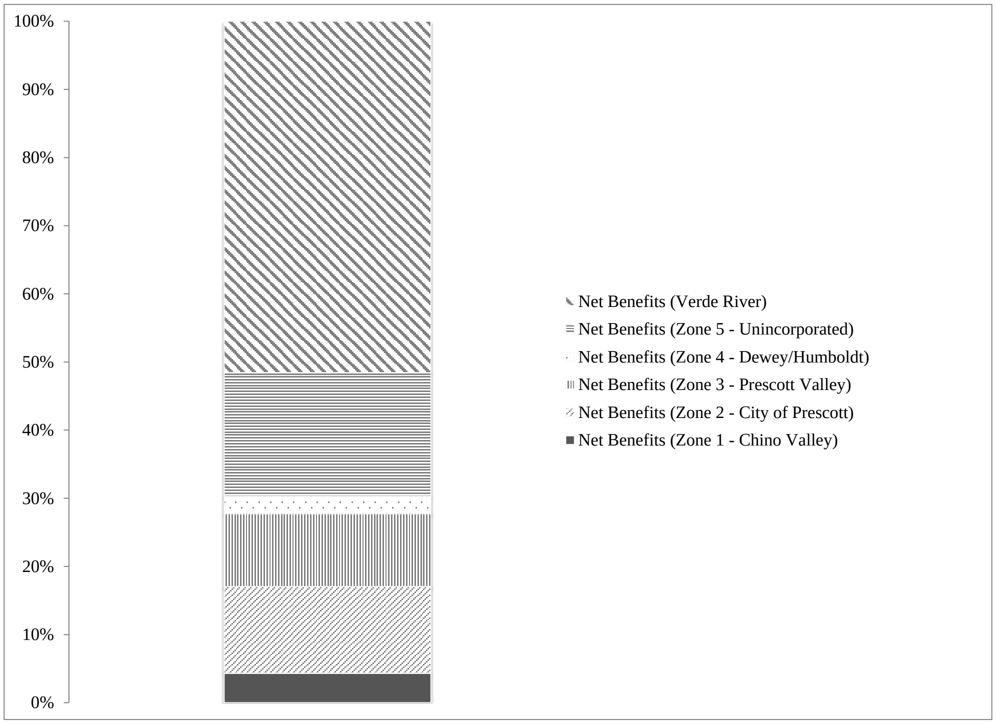


**Figure 5.18. Net benefit distribution for Scenario 4.**

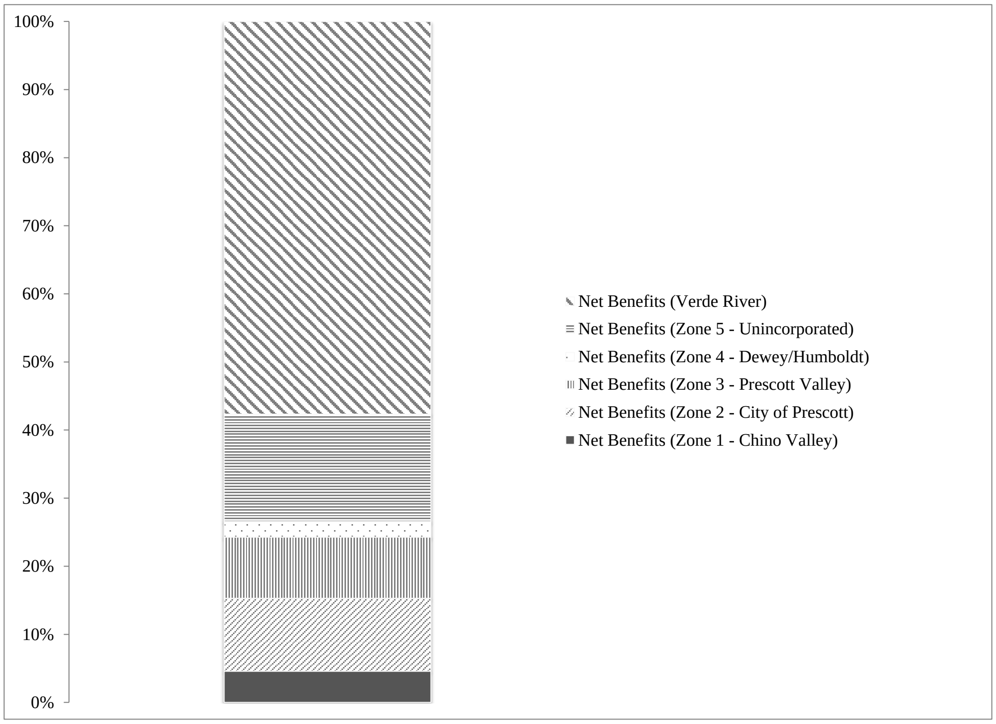


Figure 5.19. Net benefits per unit consumer for Scenario 1.

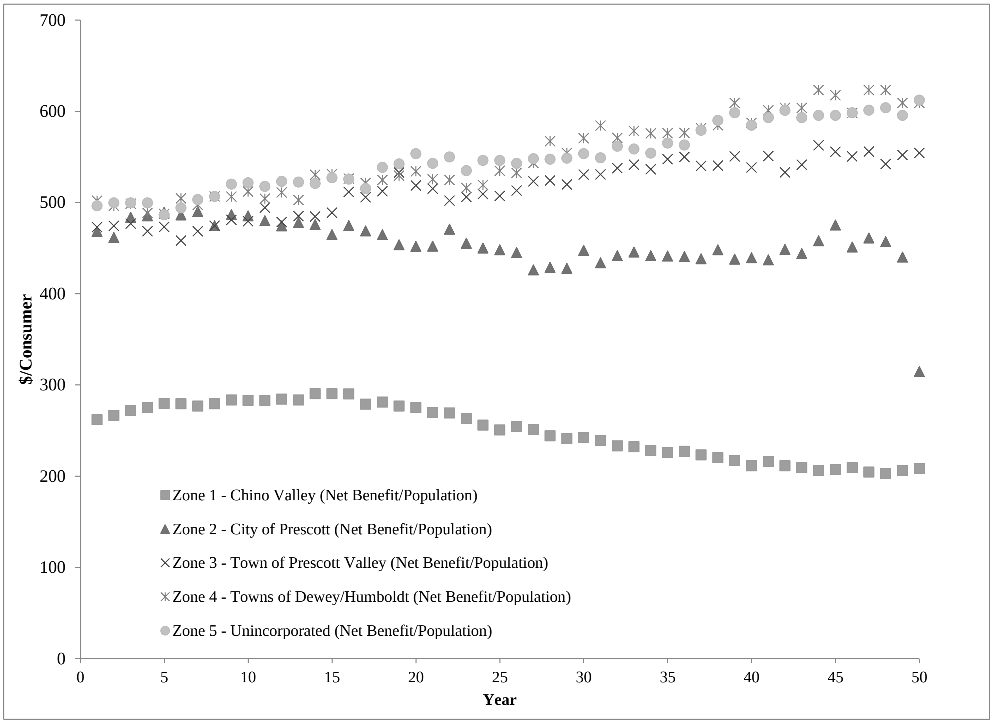


Figure 5.20. Net benefits per unit consumer for Scenario 2.

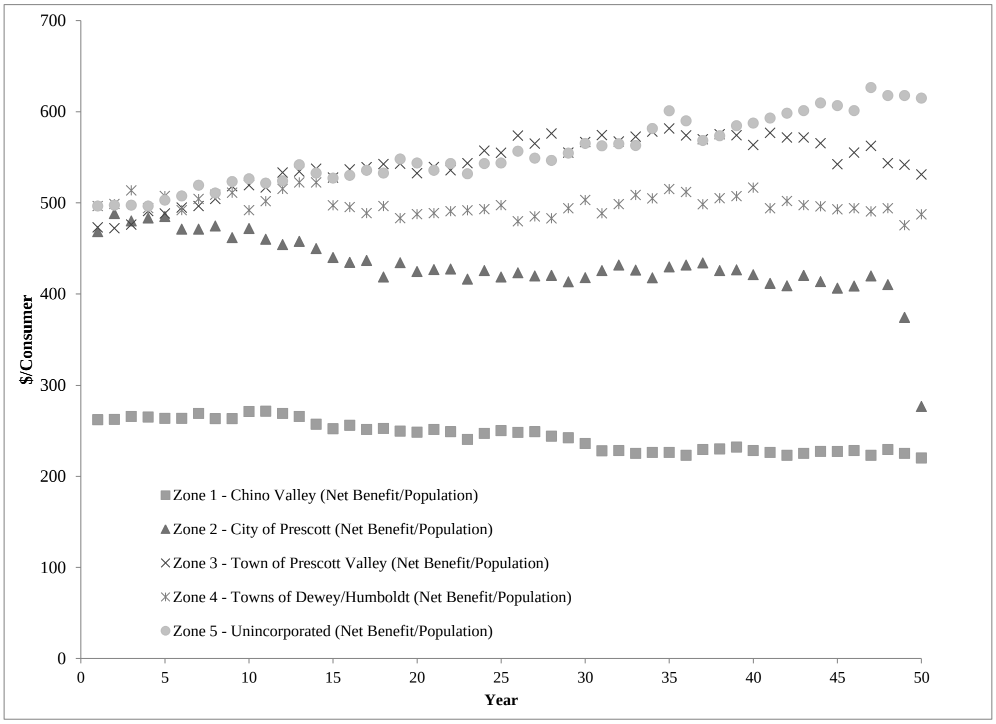


**Figure 5.21. Net benefits per unit consumer for Scenario 3.**

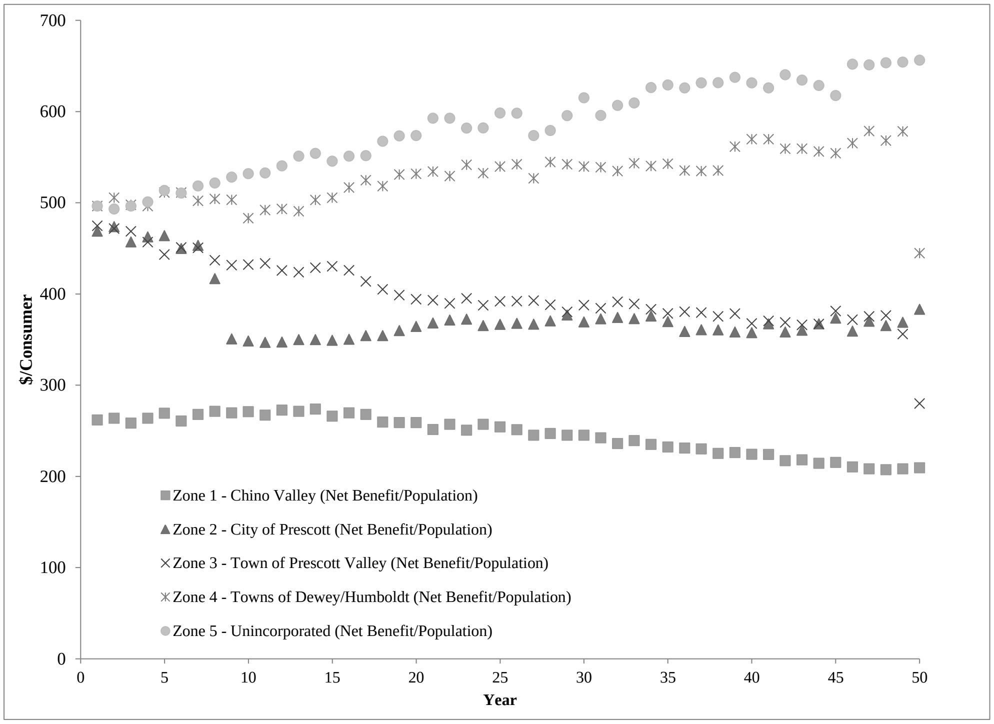
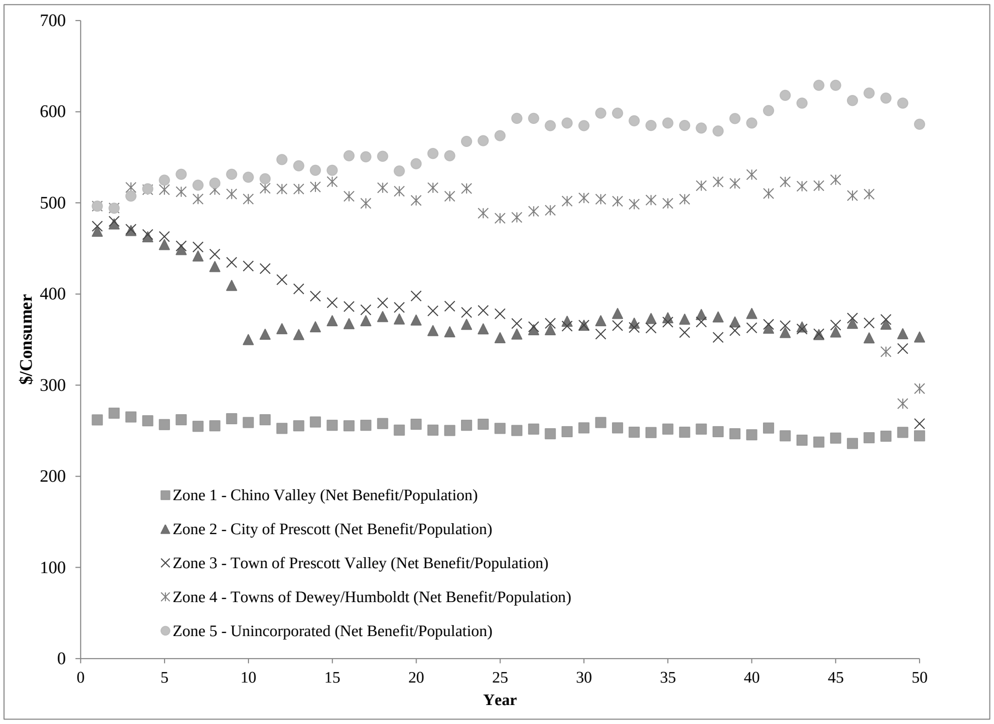


**Figure 5.22. Net benefits per unit consumer for Scenario 4.**



Rates of consumption for each zone over time are indicated in Figures 5.23 through 5.27 for each scenario. The consumption rate for Zone 5 tends to remain high and increase in every scenario. Zone 1 sees a decline in the first three scenarios and remains relatively constant in Scenario 4.

Population growth for each of the scenarios is illustrated in Figures 5.28 through 5.31. Zone 4 consistently experiences population growth in each scenario. With the exception of Scenario 4, Zone 1 sees a decline. Zones 2 and 3 realize an increase in the first two scenarios, and a decrease in the latter two. This is attributed to the minimum aquifer storage levels.  This is consistent with the volume supplied over time for each demand depicted in Figures 5.32 through 5.35. Figure 5.35 indicates consumption rate over population for each of the scenarios. Casual inspection indicates the widest range of consumption rates are evidenced in Scenarios 1 and 4. Scenario 1 and 2 show the same pattern with Scenario 1 increasing for populations greater than approximately 175,000 and Scenario 2 remaining relatively constant. No discernible patterns are evident for Scenarios 3 and 4.

Figure 5.23. Rates of consumption for Scenario 1.

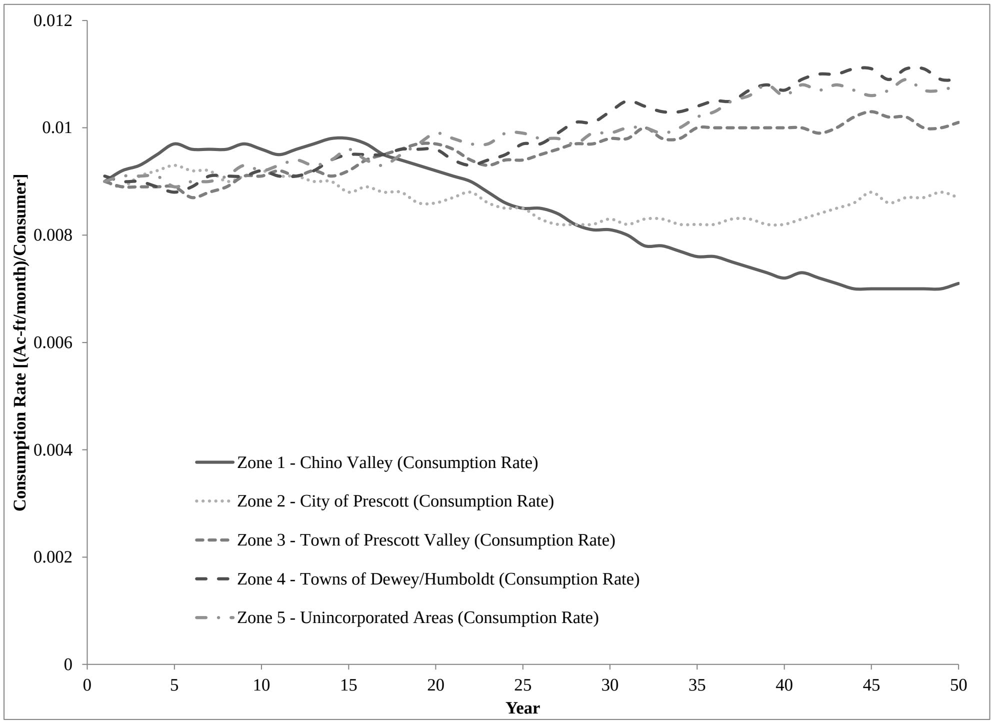


Figure 5.24. Rates of consumption for Scenario 2.

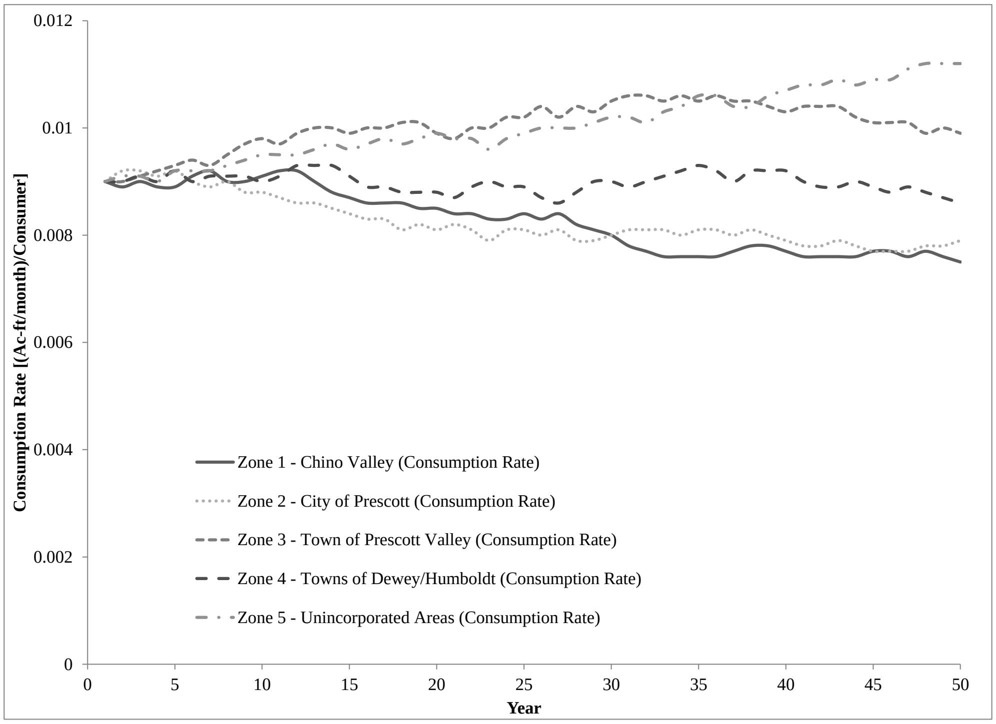


**Figure 5.25. Rates of consumption for Scenario 3.**

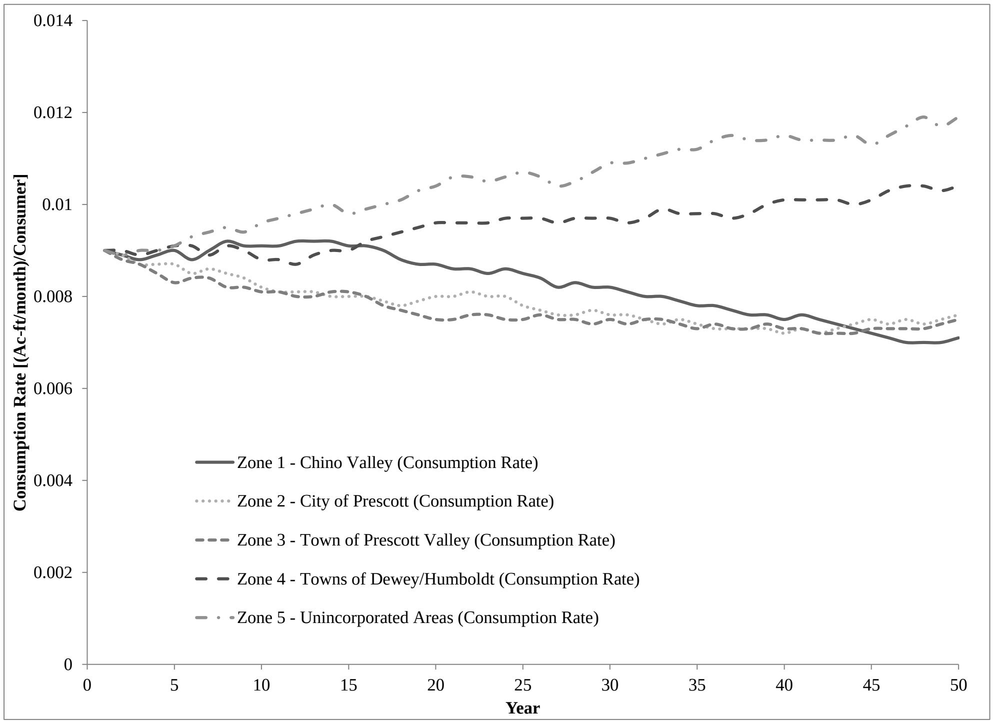


**Figure 5.26. Rates of consumption for Scenario 4.**

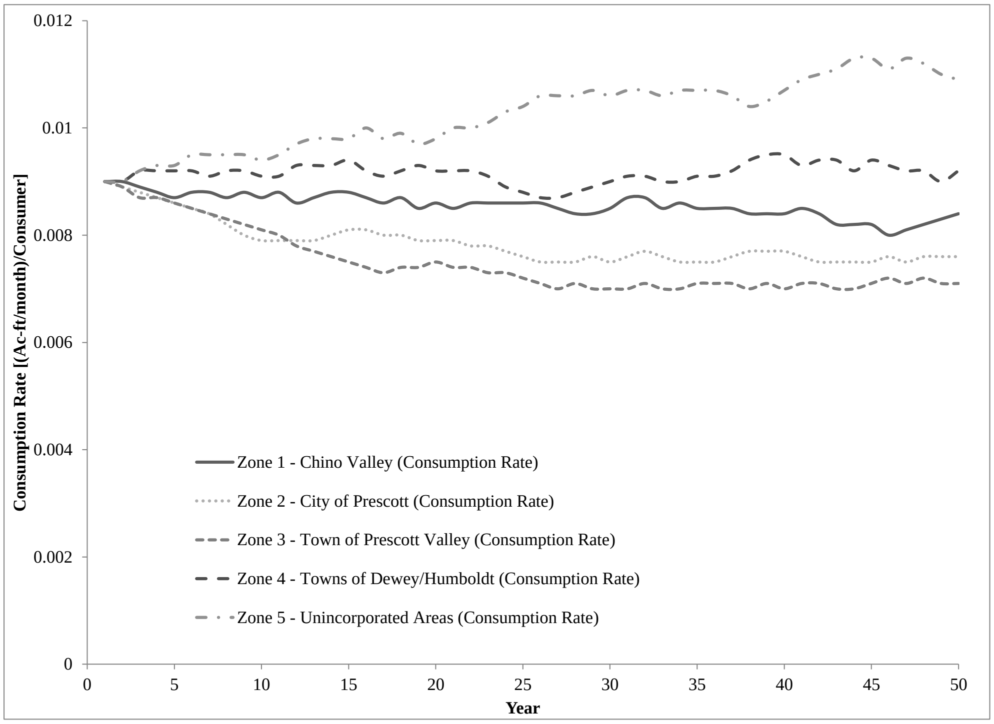


**Figure 5.27. Residential population growth for Scenario 1.**

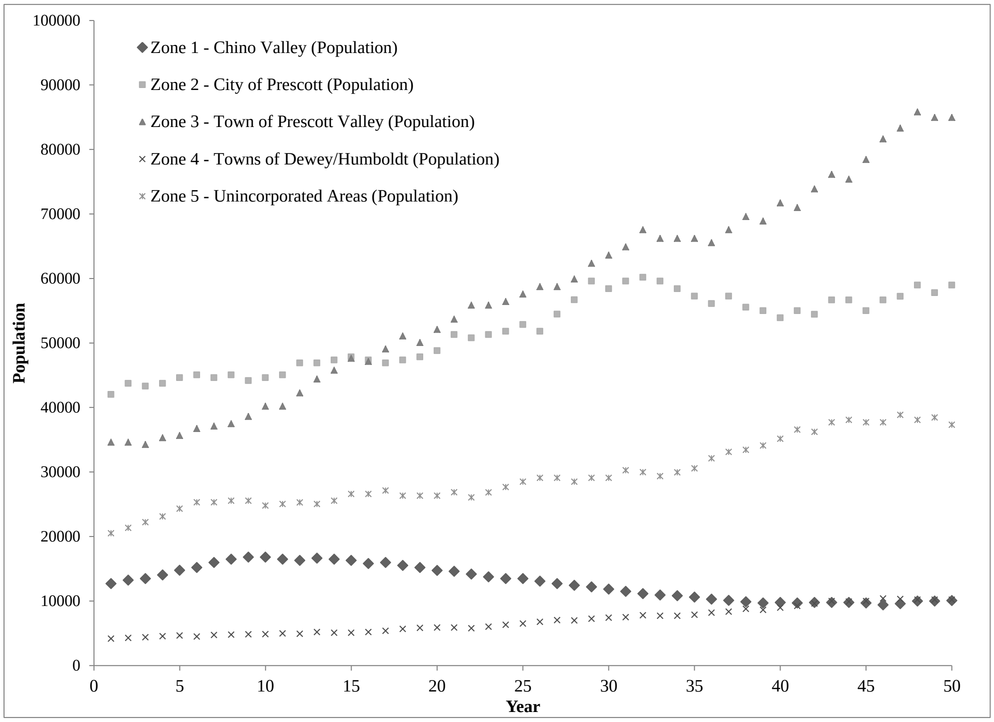
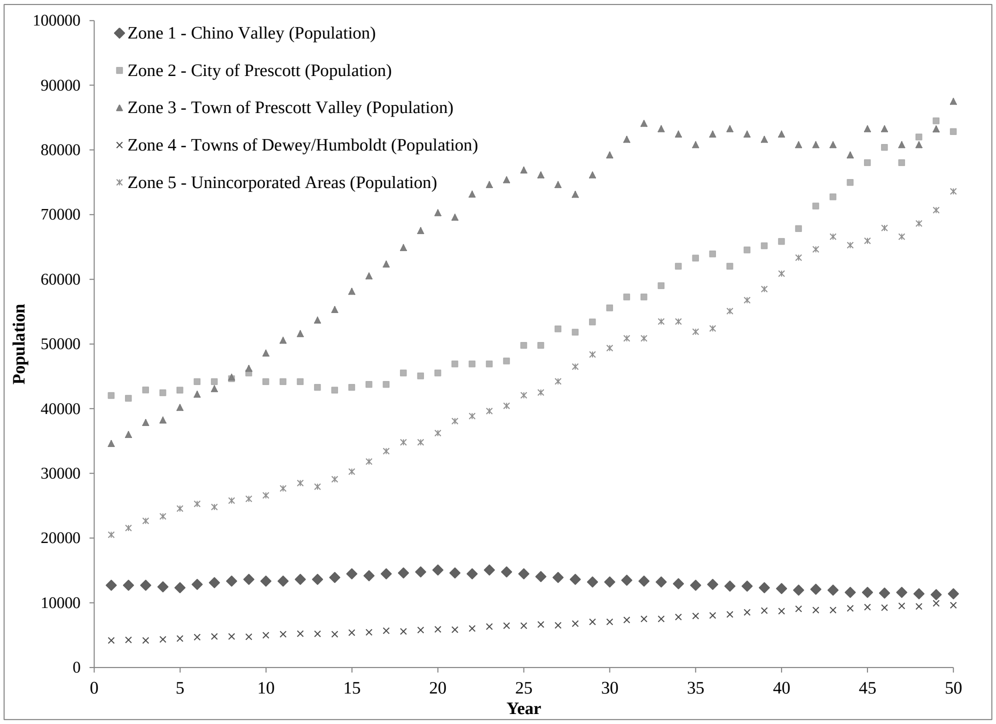
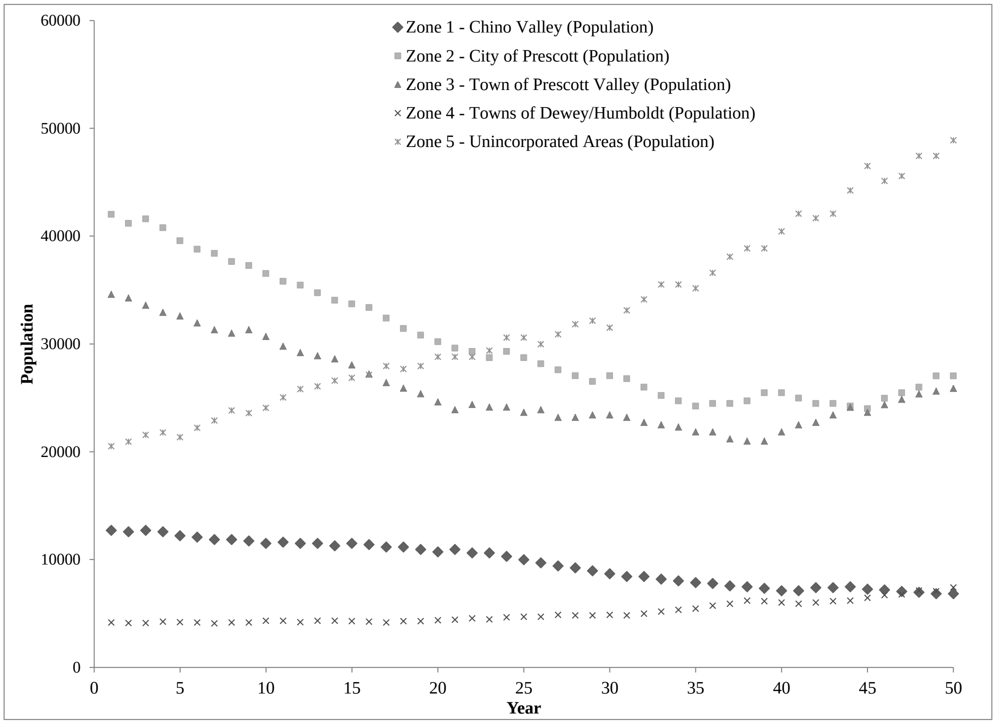


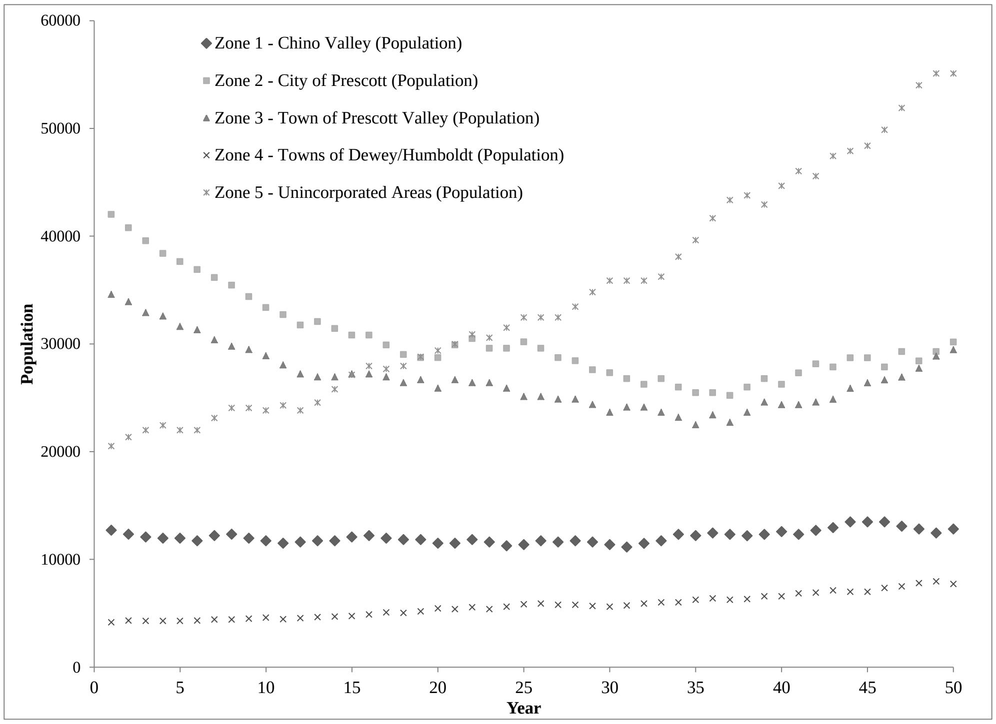
**Figure 5.28. Residential population growth for Scenario 2.**



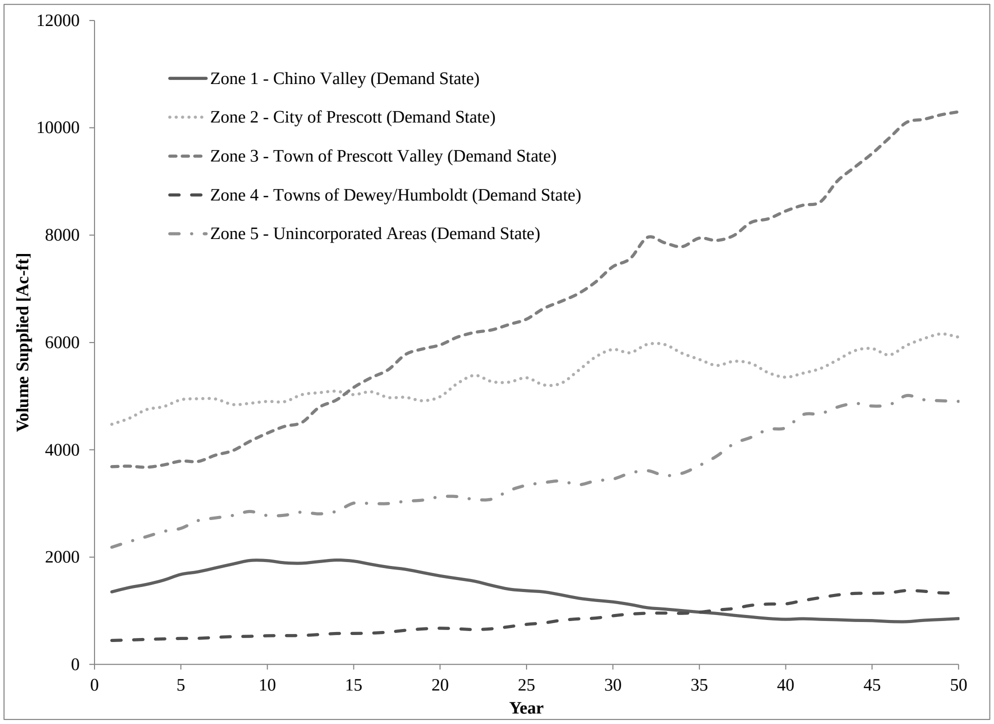
## Figure 5.29. Residential population growth for Scenario 3.



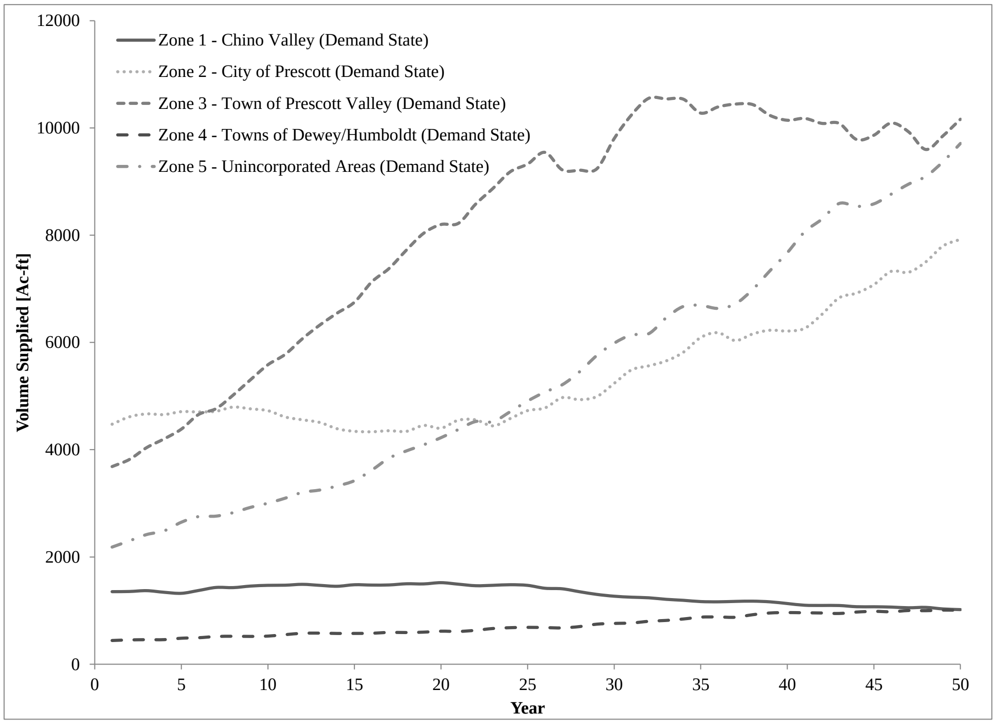
## Figure 5.30. Residential population growth for Scenario 4.



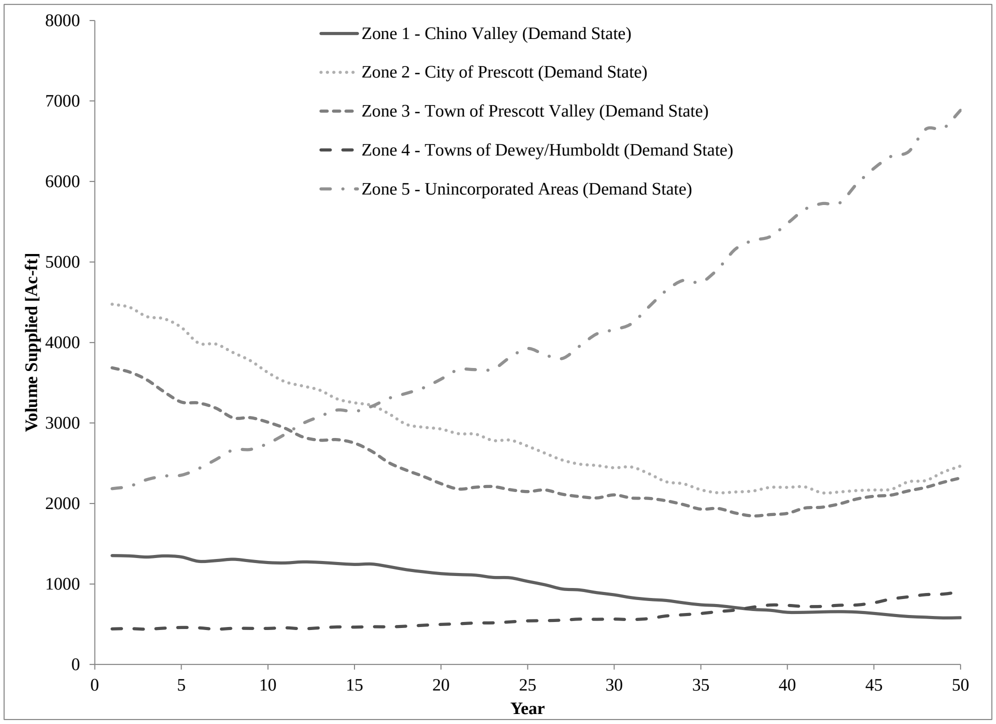
## Figure 5.31. Volume supplied in Scenario 1.



## Figure 5.32. Volume supplied in Scenario 2.



## Figure 5.33. Volume supplied in Scenario 3.



## Figure 5.34. Volume supplied in Scenario 4.

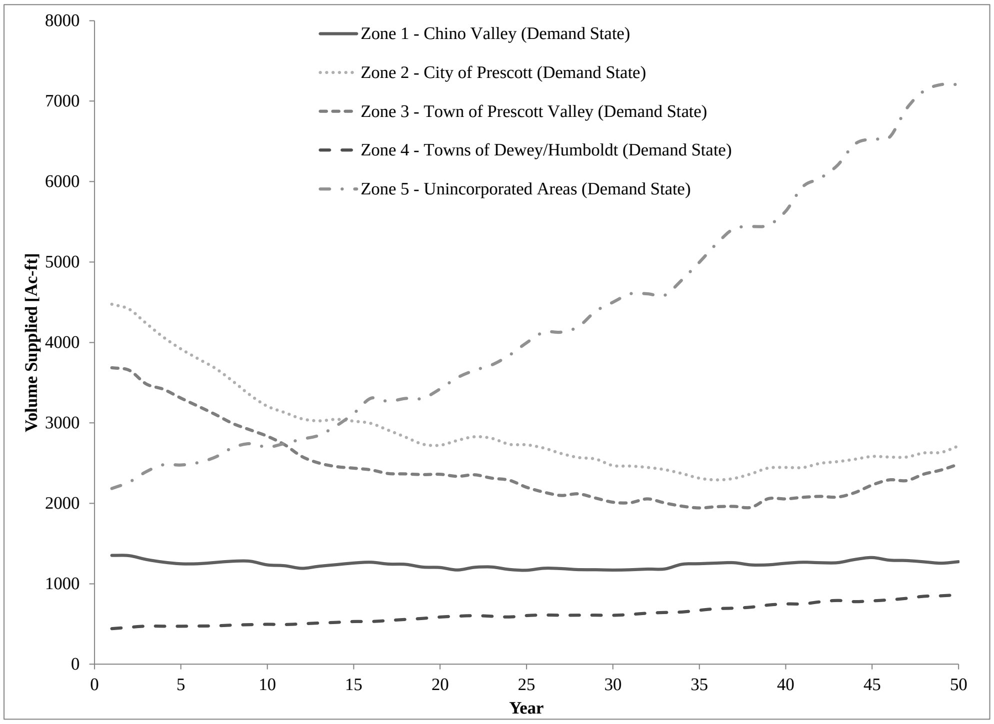
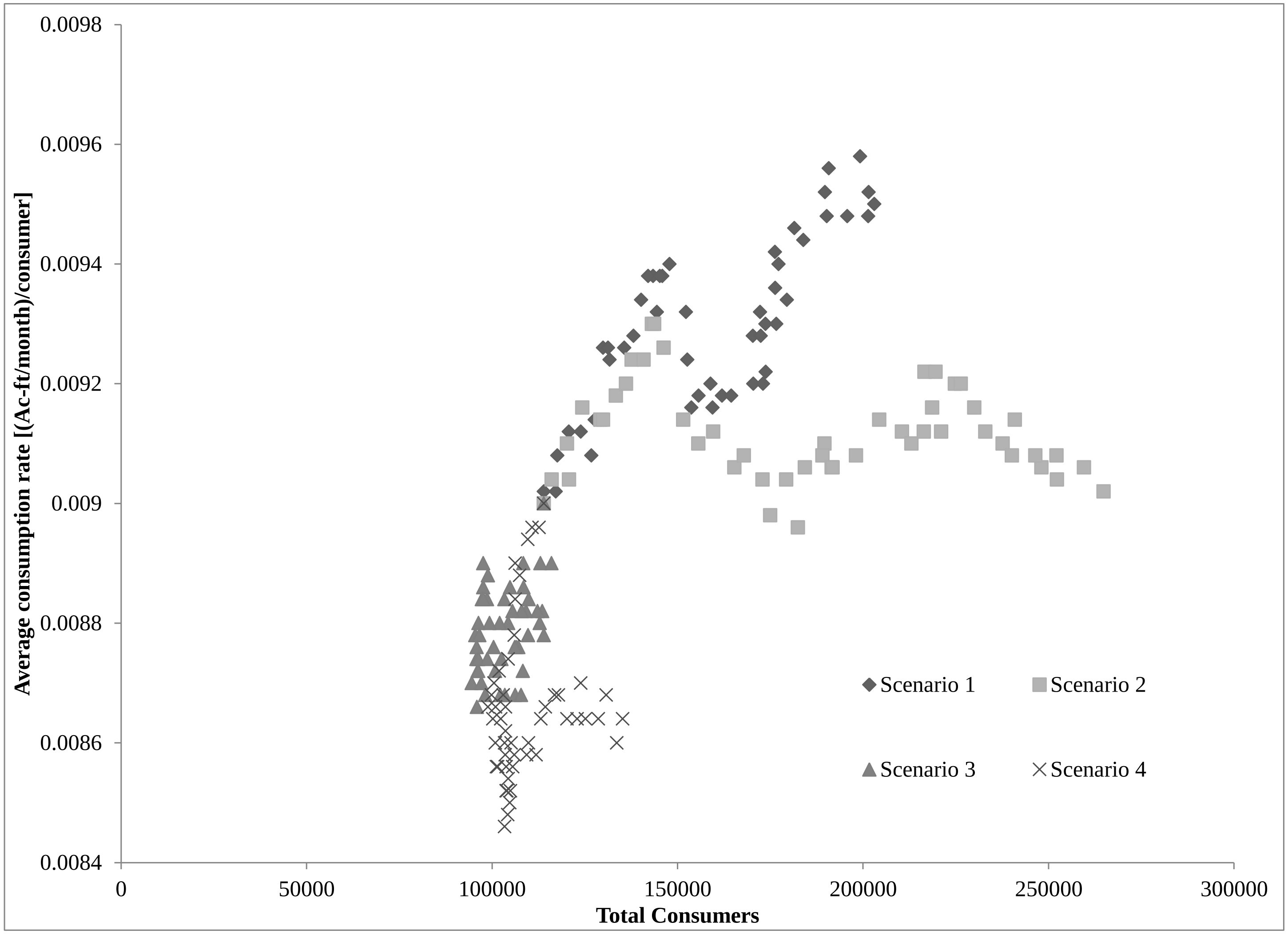


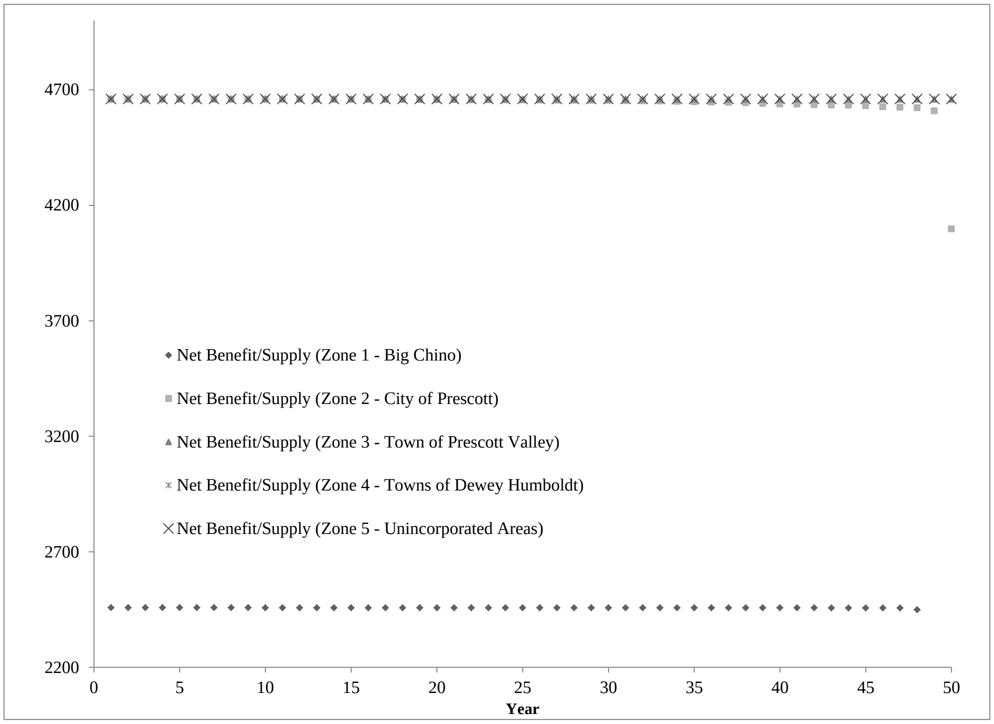
Figure 5.35. Consumption rates over population for each scenario.



Net benefit per unit volume supplied from each aquifer is available in Figures 5.36 through 5.39. Very little change is evident, with the most change occurring in Scenario 4 on the Big Chino aquifer (Zone 1). Scenarios 1 and 2 reflect a steep decline in Zone 2 at the very end of the long-term time horizon. This is associated with the depletion of the Zone 2 aquifer as evidenced in the groundwater storage charts in Figures 5.40 and 5.41. Figures 5.42 and 5.43 present the groundwater storage over time for Scenarios 3 and 4.

Deficit-based SI performance criteria are indicated in Table 5.12. Figures 5.44 through 5.46 reflect the Modified HA based performance criteria values for Scenarios 1,2 and 3 respectively. All of the Modified HA values for Scenario 4 were 0. Table 5.12 and Figure 5.13 suggest that reliability and resilience performance criteria are the most sensitive to supply deficits. Figure 5.44 indicates that the 1-day, 7-day, 90-day minimums and the 3-day and 30-day maximums are the most susceptible ($HA_{j,IHA,Bin}^{Mod} = 1$) to the annual deficit patterns exhibited in Figure 5.13. With 15% of Julian Day averages as the target regime basis (Scenario 2), more values are at the extreme ($HA_{j,IHA,Bin}^{Mod} = 1$), but there are fewer deviations in total (see Figure 5.45). Scenario 3 exhibits an $HA_{j,IHA,Bin}^{Mod}$ pattern similar to Scenario 1 in Figure 5.46.

## Figure 5.36. Net benefit per unit volume supplied in Scenario 1.



## Figure 5.37. Net benefit per unit volume supplied in Scenario 2.

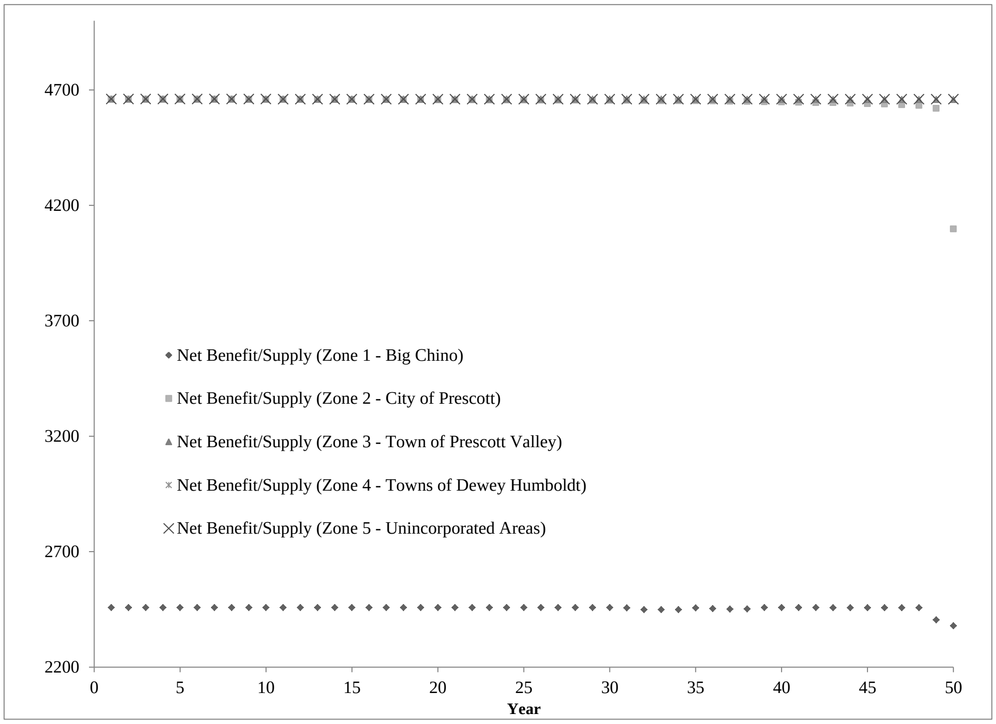


Figure 5.38. Net benefit per unit volume supplied in Scenario 3.

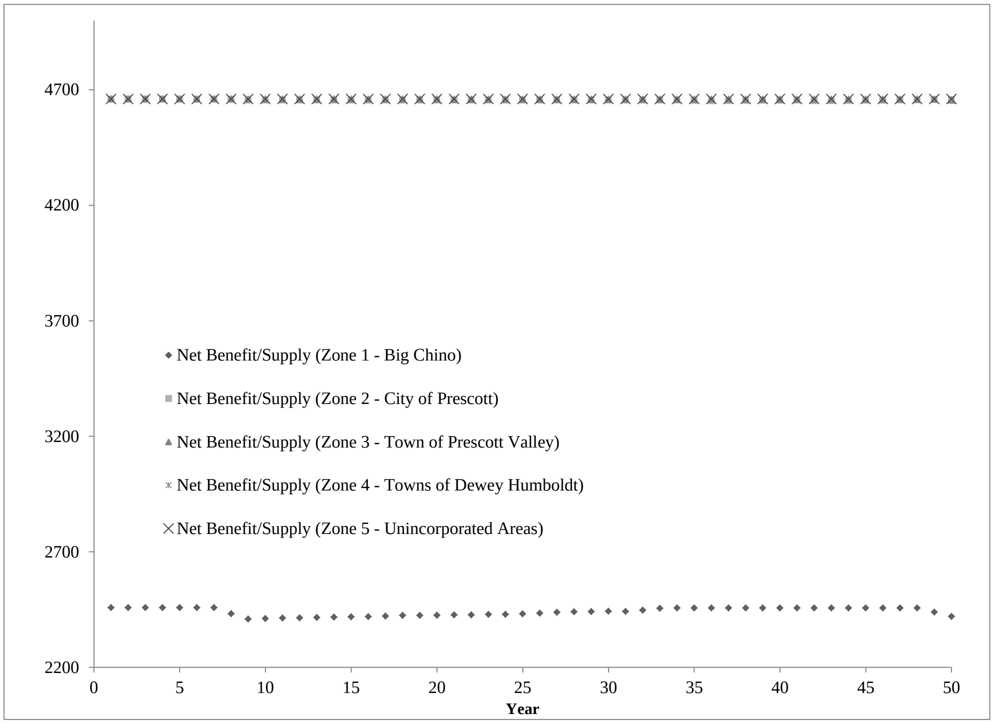


Figure 5.39. Net benefit per unit volume supplied in Scenario 4.

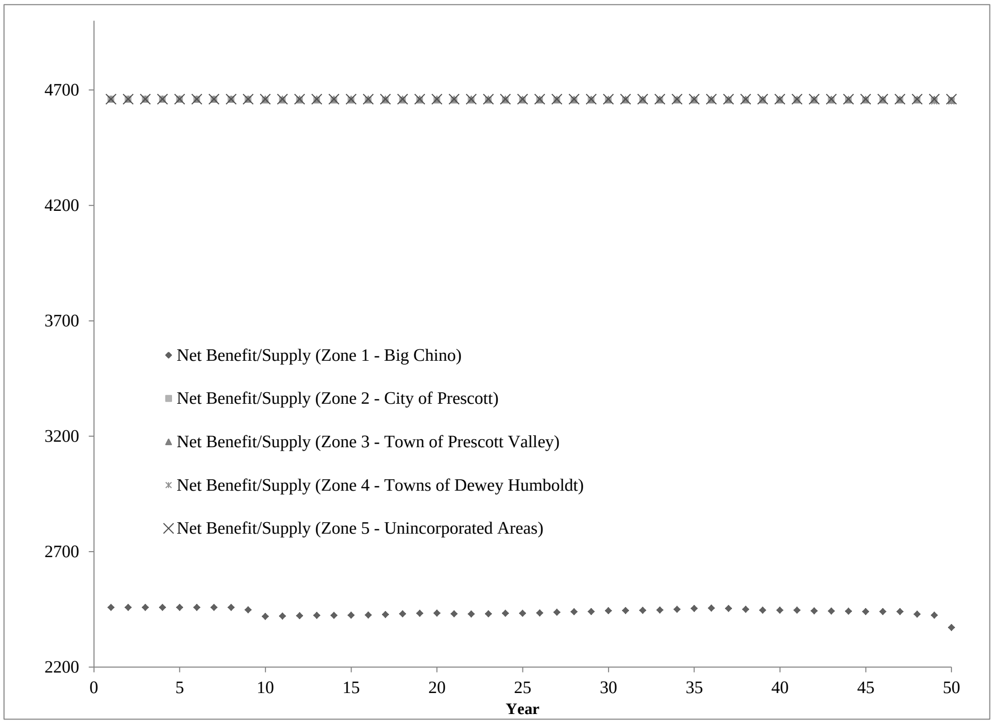


**Figure 5.40. Change in groundwater storage in Scenario 1.**

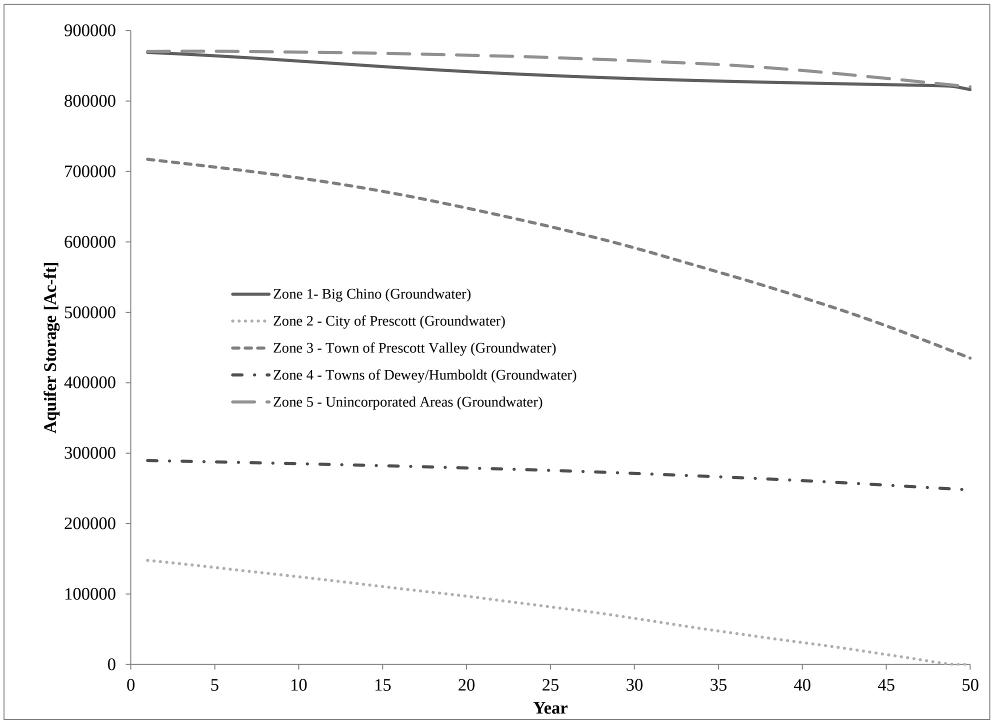


**Figure 5.41. Change in groundwater storage in Scenario 2.**

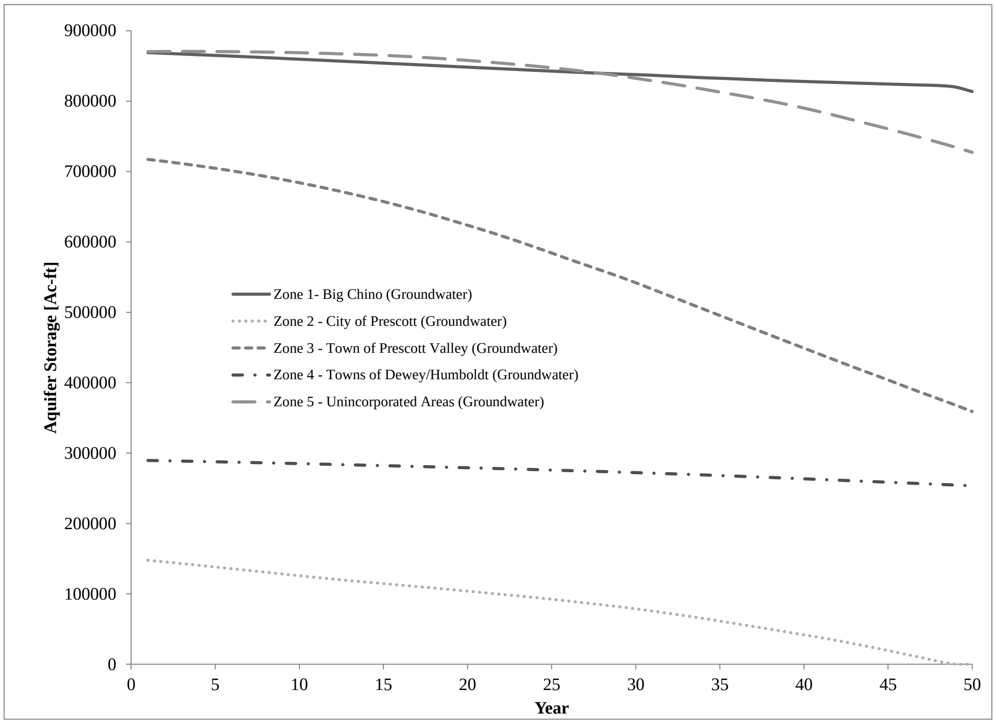


Figure 5.42.  Change in groundwater storage in Scenario 3.

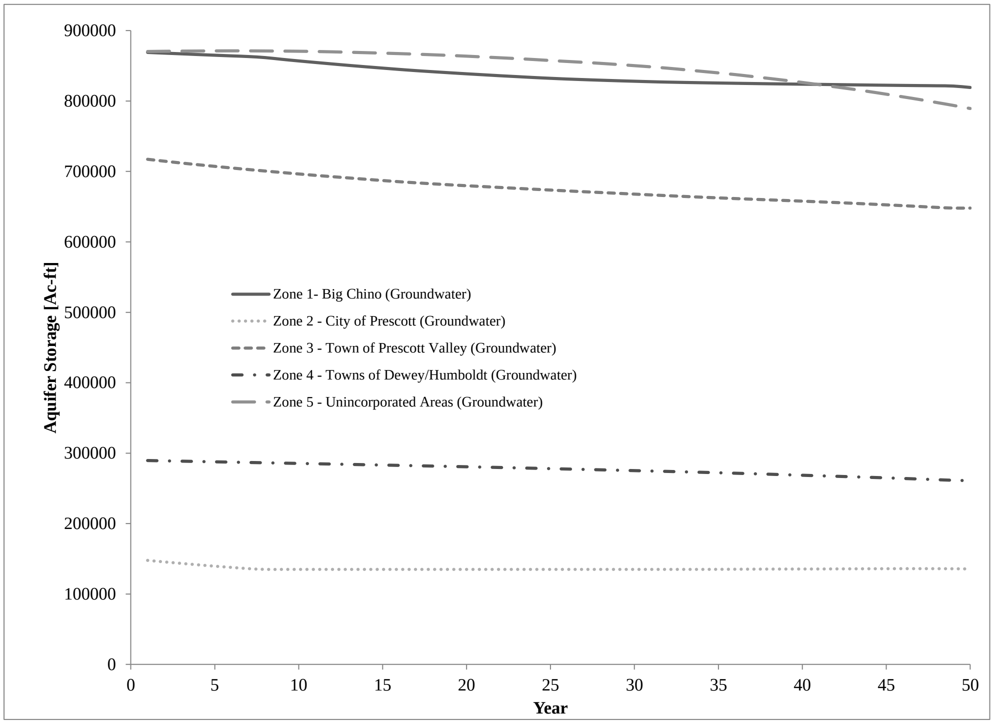


Figure 5.43.  Change in groundwater storage in Scenario 4.

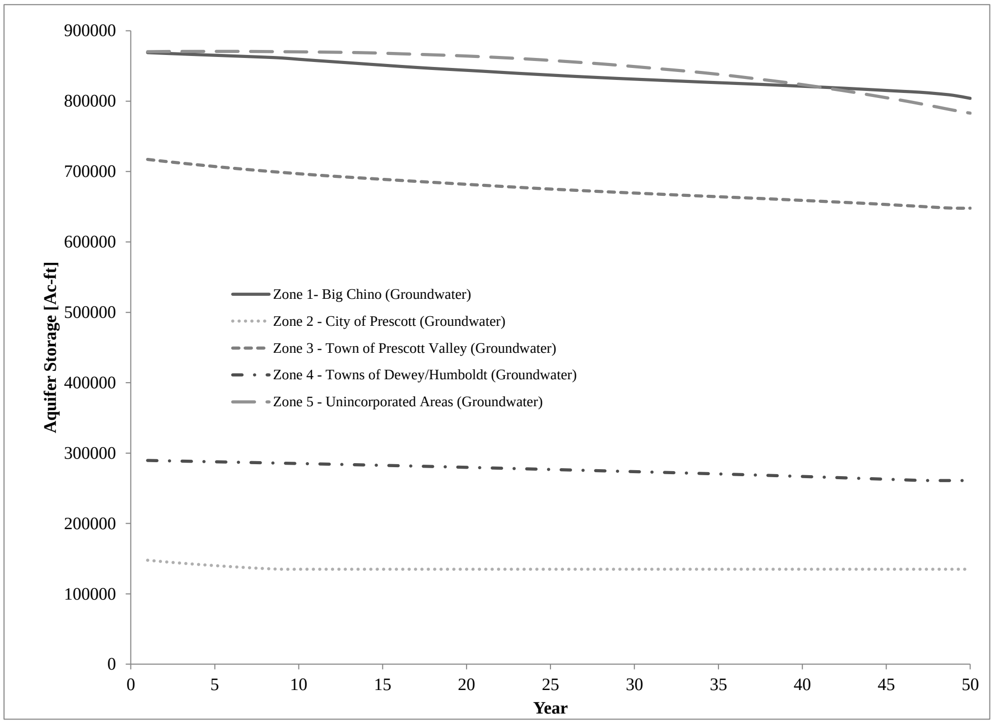


**Table 5.12. Deficit-based performance criteria (group 1) for the Verde River SI value.**

| Scenario | Reliability | Resilience | Vulnerability | Max Deficit | SI |
|---|---|---|---|---|---|
| 1 - Historical (Verde River) | 0 | 0 | 0.972 | 0.664023 | 0 |
| 2 - 15% Average Julian day (Verde River) | 0.9267 | 0.5909 | 0.9196 | 0.941354 | 0.861313 |
| 3 - 90% Min Aquifer (Verde River) | 0 | 0 | 0.9702 | 0.642712 | 0 |
| 4 - 90% Min Aquifer, 7.5% Big Chino drawdown (Verde River) | 1 | 1 | 1 | 1 | 1 |

Figure 5.44. Modified HA based performance criteria for Verde River SI (Group 2) on Scenario 1.

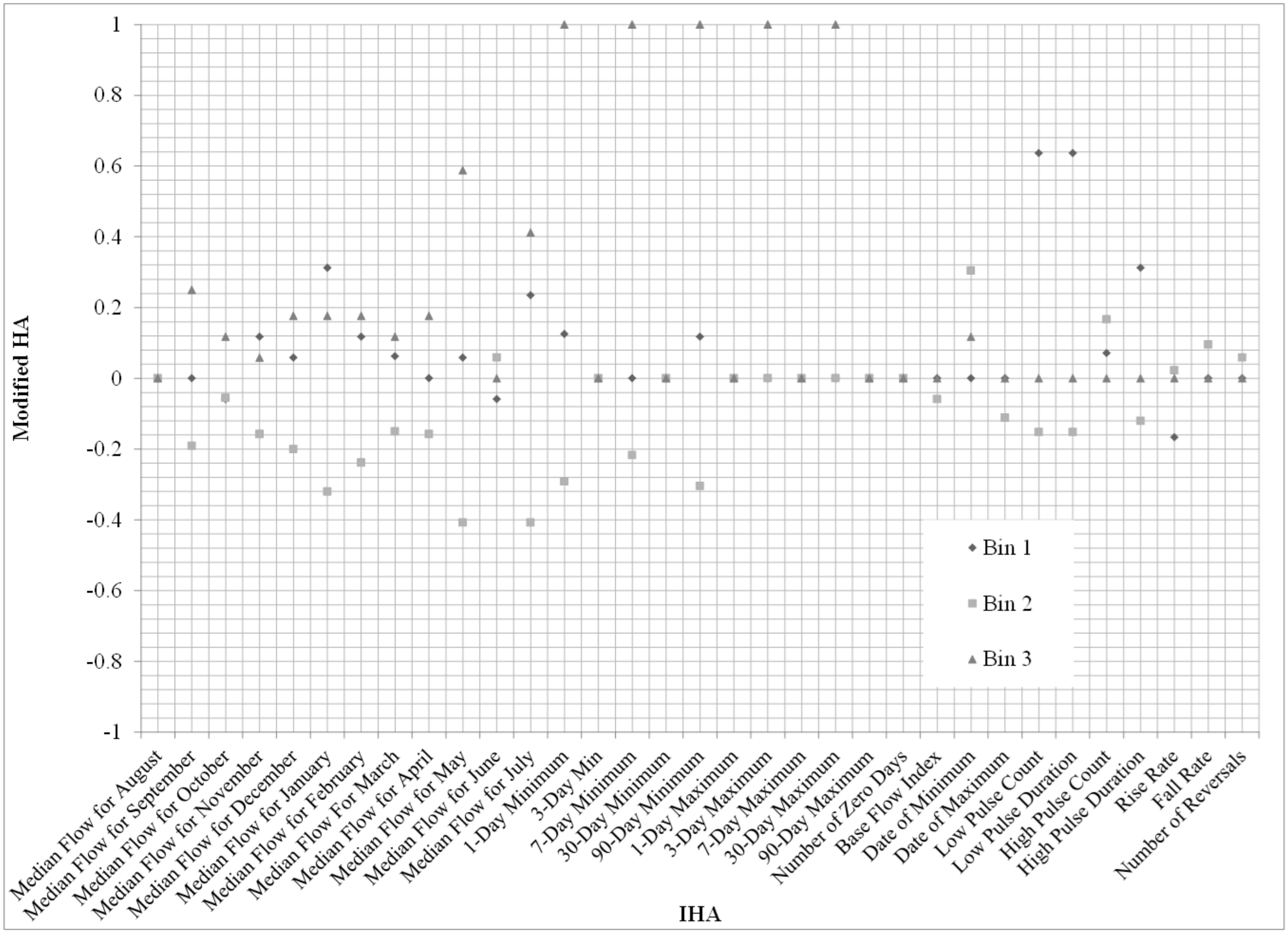


Figure 5.45. Modified HA based performance criteria for Verde River SI (Group 2) on Scenario 2.

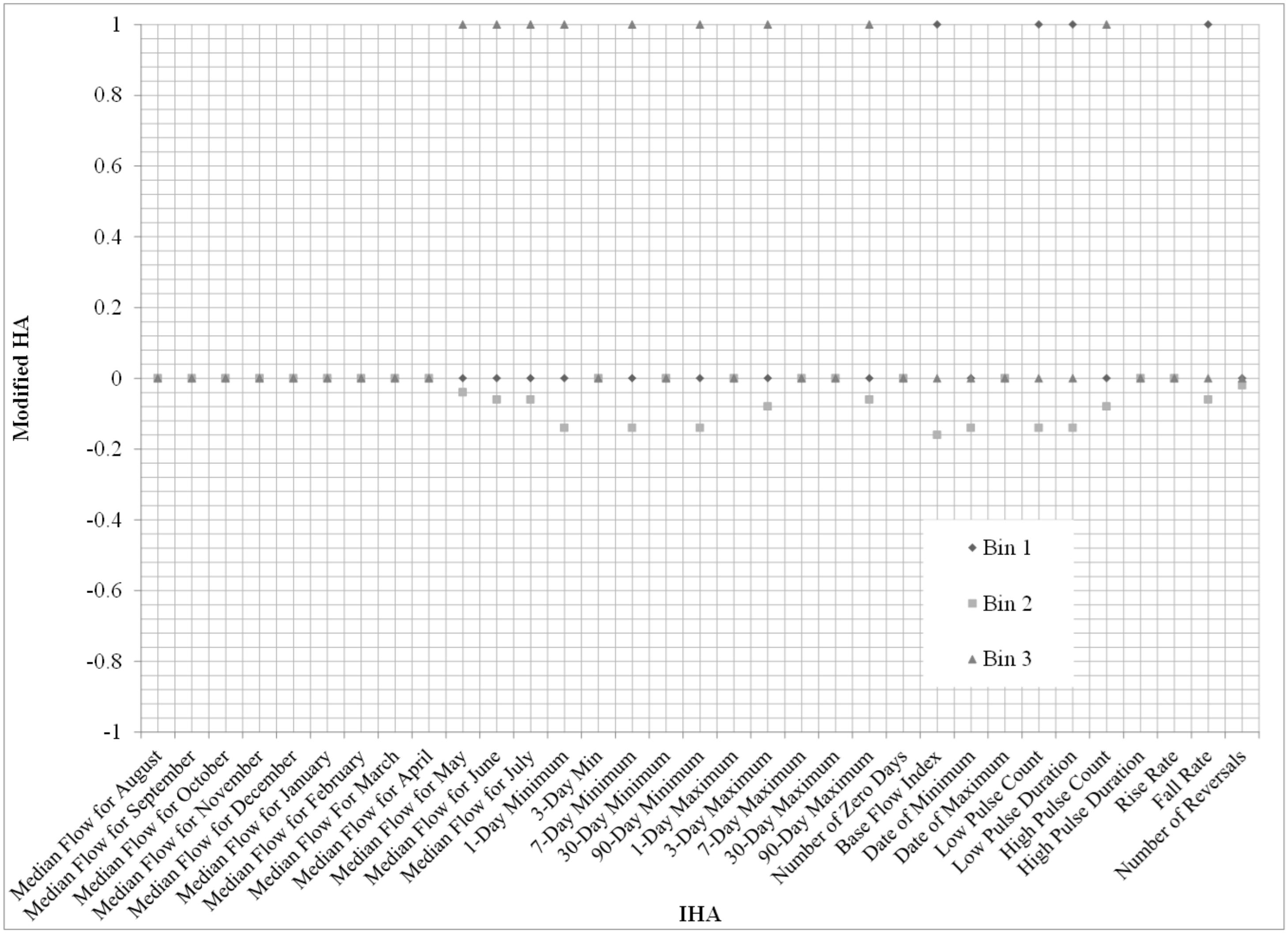
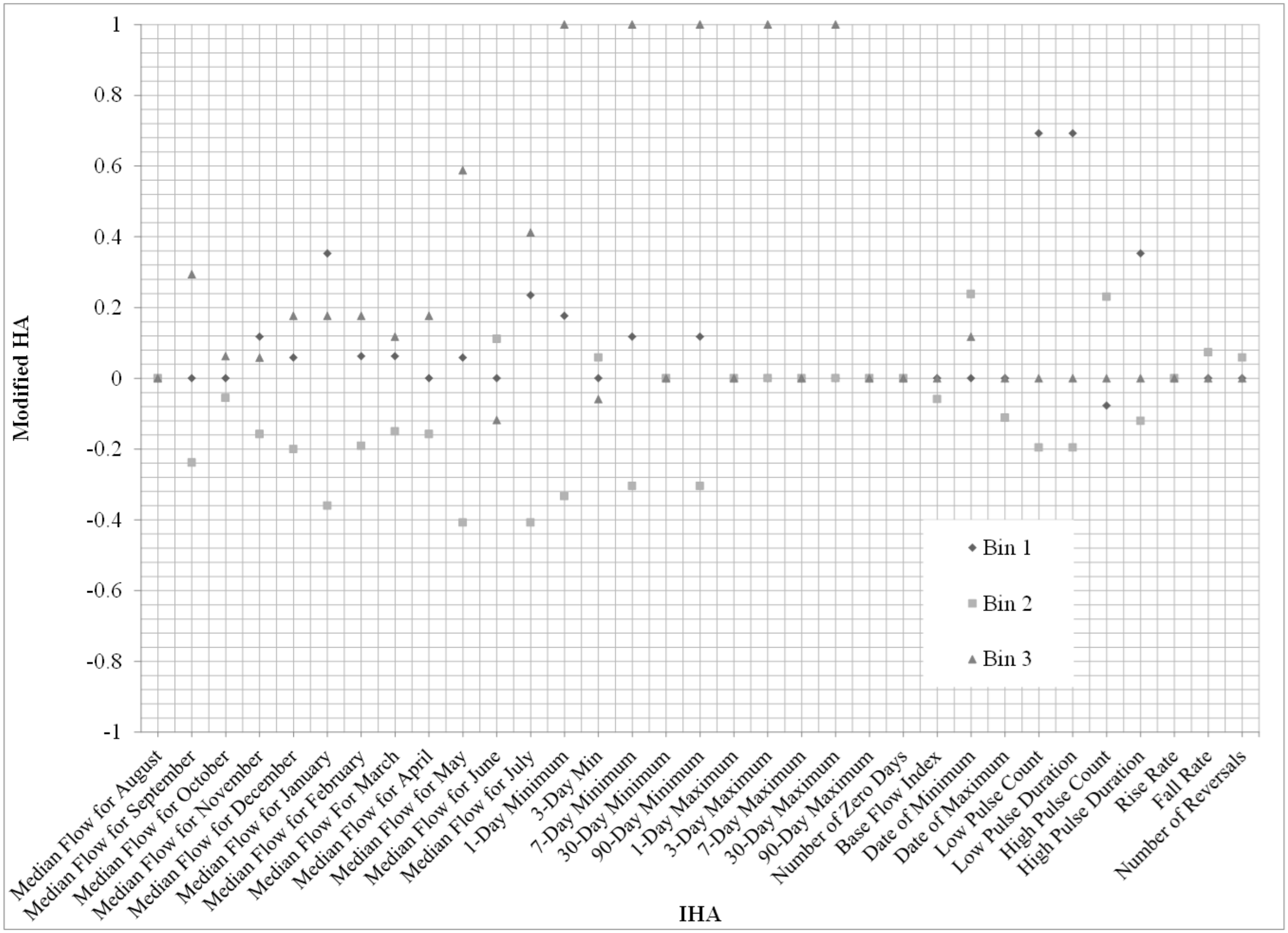


Figure 5.46. Modified HA based performance criteria for Verde River SI (Group 2) on Scenario 3.



## 5.4 Conclusion

Four scenarios are applied to the Prescott AMA. Scenario 1 serves as a baseline of comparison, assuming unlimited access to the local aquifers and availability of the Big Chino pumping and transport facility. This scenario resulted in the highest net benefits and second most highest ending population, but was the third most sustainable. Scenario 2 examined a hypothetical target regime based on 15% of the Julian day averages, seeing the second most sustainable allocation schedule and the largest increase in population. Given that the flows on the Verde River are fully allocated for downstream users, this scenario is the least applicable to the management area, but serves to illustrate a potential application of the developed model.

Scenario 3 places a minimum storage volume on aquifers within the Prescott AMA, meant to represent regulatory compliance deadlines (safe-yield by 2025). All of the aquifers remained above this minimum with the exception of Zone 2 (City of Prescott) which reached the minimum storage volume in year 8. This scenario resulted in the least net benefits and the lowest sustainability index and smallest change in population: the population finished at 116,002, an increase of approximately 2% from the initial study area population of 113,964. It also resulted in the greatest deficits to flows on the Verde River, impacting downstream users as well as the integrity of the river system.

Allowing the Big Chino aquifer storage volumes to decrease by 7.5% prior to impacting flows on the Verde River resulted in the most sustainable solution and the second highest net benefits. The population increased approximately 19% to nearly

136,000. It should be noted that 7.5% drawdown on the aquifer is completely arbitrary. Scenarios at 1%, 2%, 5% and 10% drawdown were conducted, but only the 7.5% and 10% scenarios resulted in maximum sustainability. The results from the 7.5% scenario are reported in this research as it is the lowest allowable drawdown value to discover a solution with maximum sustainability.

In terms of population change, Zone 1 (Chino Valley) saw a decline more frequently than the other zones (see Figure 5.6). Zones 4 (Dewey/Humboldt) and 5 (Unincorporated Areas) realized an increase for all 4 scenarios. Zones 2 (City of Prescott) and 3 (Prescott Valley) were evenly split with increases in Scenarios 1 and 2 and decreases in Scenarios 3 and 4, suggesting that the minimum allowable aquifer storage levels of 90% influenced the population growth in these zones. This is confirmed in Figures 5.49 and 5.50 which reflect net benefits per unit consumer per unit consumption rate for Scenarios 3 and 4 respectively. In both of these Zone 2 (City of Prescott) reaches the minimum allowable storage in years 8 and 9, reducing the benefits in Zone 2. Maximum sustainable net benefit is realized by keeping the net benefit per consumer rate as high as possible for as long as possible, which can only be accomplished by reducing population growth and consumption rates. This also serves to illustrate a limitation of the model: the results are only sustainable within the declared scope.

As noted earlier, net benefits per unit volume supplied (see Figures 5.36 through 5.39) indicate little change. This suggests that the cost of depletion ($CostDep_{i,t}$) has little impact as the storage volumes decline in each of the aquifers. Increasing the value of the price path factor ($\rho$) will increase the costs associated with depletion. For purposes of this application, the price path factor value recommended by Rothman was used (Rothman 2007).

Though the scenarios were primarily designed to validate the developed model and to provide examples of potential application, Scenario 3 is somewhat representative of the realities that the Prescott AMA is facing. The results from Scenario 3 suggests that in order to achieve the maximum sustainable net benefits, residential populations in the Prescott AMA should be reduced for Zones 1 (Chino Valley), 2 (City of Prescott), 3 (Town of Prescott Valley), with moderate growth allowed in Zones 4 (Dewey/Humboldt) and 5 (Unincorporated Areas) (see Figure 5.29). Likewise, consumption rates in Zones 1, 2 and 3 should decrease, and increase in Zones 4 and 5 (see Figure 5.25). However, any meaningful application will require a re-evaluation with more recent data, a prioritization of demands, and a better estimate of the minimum allowable aquifer storage volumes.

Figure 5.47. Net benefit per unit consumer per unit consumption rate over time for Scenario 1.

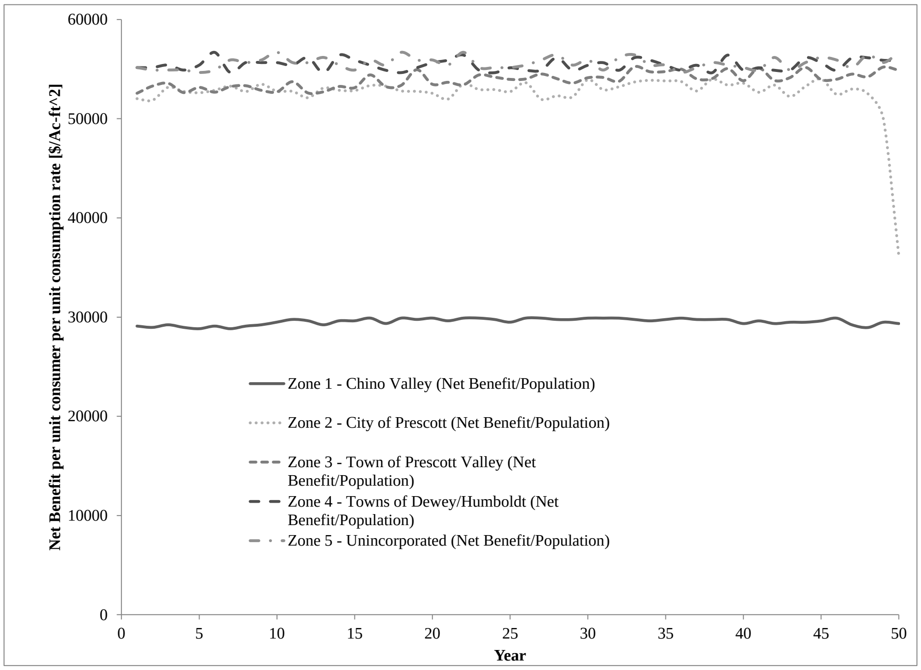


Figure 5.48. Net benefit per unit consumer per unit consumption rate over time for Scenario 2.

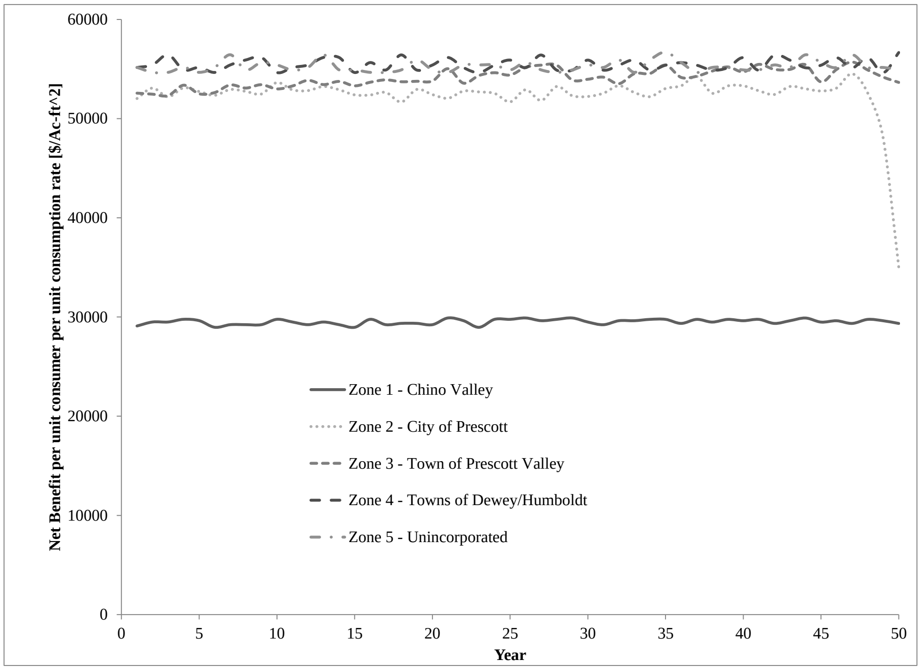


**Figure 5.49. Net benefit per unit consumer per unit consumption rate over time for Scenario 3.**

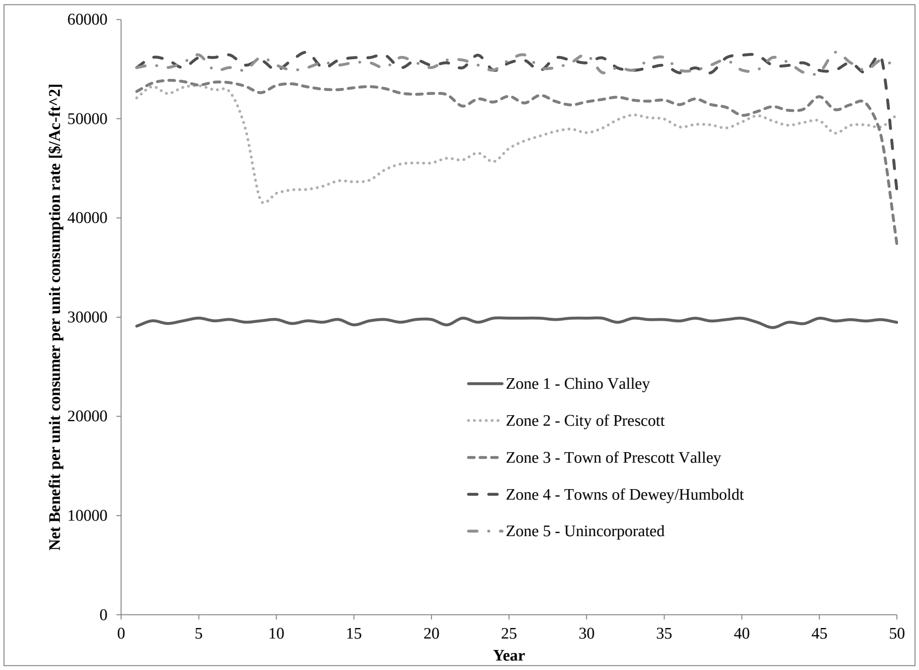
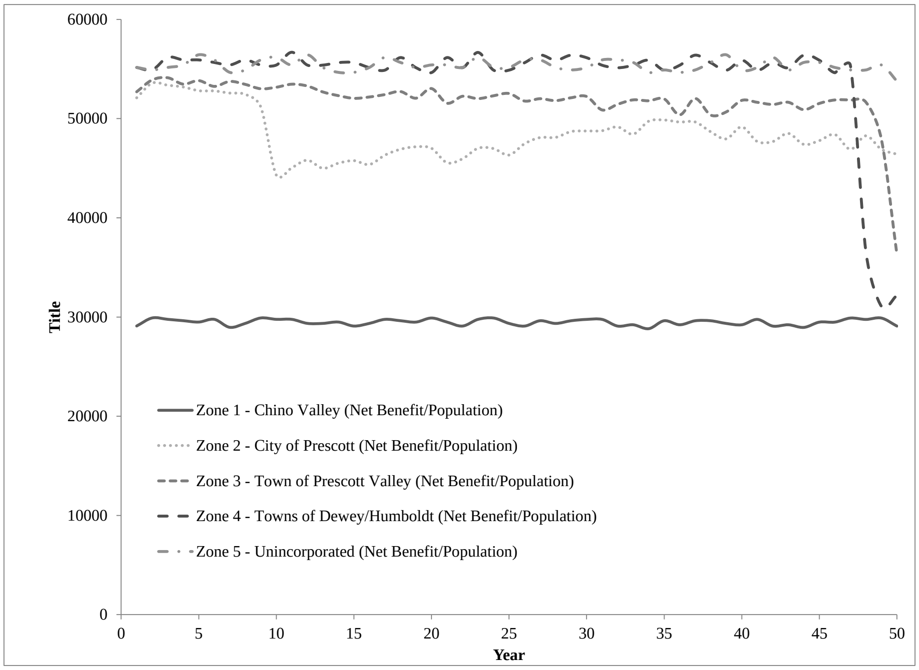


**Figure 5.50. Net benefit per unit consumer per unit consumption rate over time for Scenario 4.**



# 6 Conclusions and Recommendations

This chapter concludes this research by summarizing the tasks involved in the fulfillment of the overall research objective and follows with recommendations for future research.

## 6.1 Research Objective

The results of this research must be measured against the overall objective expressed in Chapter 1:

> *"The objective of this research is the application of sustainability to the water management problem at the river basin level, with special attention to riverine ecological concerns."*

This objective was accomplished by creating a river basin management model. The following describes the specific tasks that were involved.

### *6.1.1 The Development of a Short-Term Model Component*

The STM addresses the monthly water allocation on an annual basis, optimizing the allocation in terms of the maximum net economic benefit. The STM was created for several purposes. First it reduces the complexity of the overall model by separating the linear and non-linear problems and improves tractability and potentially run times (Cai 1999). Short-term decisions are made in the STM under short-term goals – namely how to most efficiently allocate the available water to meet immediate demands. Short-term management goals are generally in conflict with long-term goals and serve to create tension in the model.

Net economic benefit in the STM is described using both use and non-use values. Use values are related to the ‘consumption’ of the water, while non-use values are associated with sustainability and are summarized as the value that an individual assigns to a resource to ensure its availability for others both now and in the future. Non-use values are addressed through the use of the ‘cost of depletion’ concept described by Rothman and Mays (Rothman and Mays 2013). The ‘cost of depletion’ concept is included in the STM using a piece-wise approximation, maintaining linearity. River demand is based on the ecological, environmental and hydrological integrity of a river’s flow regime and competes against other demands for the available water supply on an economic basis.

The STM also serves as the framework for the physical representation of the management area. Management areas are described using a node-link system, whereby demands and sources are represented using nodes and water is conveyed between sources and demands using links. Source and demand nodes have different attributes which are used to describe the availability and response of the node. Each STM represents one year of the long-term time horizon and the ending ‘state’ of an STM is passed to the subsequent STM via the LTM. The allocations described by the series of STMs are used to determine sustainability metrics for the LTM. The STM is developed and implemented in GAMS as an LP.

### 6.1.2 *The Development of a Long-Term Model Component*

The allocation projected by a series of STMs is measured for sustainability over the long-term by the LTM. The LTM is an optimization model and consists of an STM for every year ($y$) of the long-term time horizon. The objective of the LTM is to maximize the sustainable net benefits associated with the allocations generated by the series of STMs. The LTM accomplishes this by providing population growth and consumption rates for the STMs.

The LTM addresses the non-linear aspects of the management model. This includes the sustainability performance criteria and the population growth rates. The sustainability performance criteria are combined to determine an SI for the individual demands and the system as a whole and are divided into two groups. The first group is based on the demand-supply deficits and measures the risk associated with a water supply. The second group is based on a river's HA, which is the comparison of a projected flow regime to a target flow regime. The HA performance criteria are generated using the RVA and the two groups of performance criteria are combined using the SI concept. The LTM is developed in PHP and solved using a genetic algorithm.

### 6.1.3 *Integration of a Sustainability Index*

Research suggests that the concept of sustainability has proven difficult to define and apply in water resource management models. Common themes in the reviewed definitions include the pursuit and protection of societal objectives and resource integrity. To integrate these, a sustainable management approach must first identify society's objectives and ascertain some sense of integrity. This research assumes societies' objectives are at least partially expressed in current demand patterns and ecosystem integrity is rooted in the identification and protection of the characteristic nature of a resource. Research suggests that for a river, this characteristic is the river's flow regime.

The sustainability of static annual demand patterns has been measured using the concept of an SI (Sandoval-Solis et al. 2011). The concept is adopted in this research to measure sustainability for dynamic demand schedules. Applicable deficit-based performance criteria are defined in terms of the dynamic demands and include the concepts of reliance, resilience, maximum vulnerability and maximum deficit. A second group of performance criteria are based on a modified HA value as measured by the RVA. The modified HA value is a measure of how much a river's projected flow regime differs from a target flow regime. Assuming the target flow regime is ecologically sound, the modified HA serves as a measure of integrity. The SI is measured for each demand in the management area. The SIs for each demand are combined for an indicator of the sustainability of the system. The SI is developed as a separate class in PHP.

### *6.1.4 Integration of the Range of Variability Approach*

The flow regime is considered the 'master variable' when referenced with respect to riverine ecological response (Power et al. 1995). The most prevalent and widely method used in flow regime assessment is the RVA (Tharme 2003). The RVA (Richter et al. 1996) is used by the LTM to compare the flow regime resulting from the allocation projected by the series of short-term models to a target or ecologically sound flow regime. This addresses the ecological, environmental and hydrological integrity of the riverine system.

Difference in flow regimes is typically measured by the RVA using an HA factor. The HA factor consists of 33 IHAs, each originally selected based upon two primary criteria: ecological relevance (particularly their use in published ecological studies) and an ability to reflect a broad range of human induced changes. A modified hydrologic alteration factor is developed for use in the developed and comprises the second group of performance criteria for the SI. Existing water resource management models typically address ecological concerns by using a fixed minimum volume allocation, often imposed as a system constraint. The advantages of the adopted approach are that the river's allocation is permitted to vary and the demand for the allocation is based on a target flow regime making it more ecologically relevant.

Given the limited command line capabilities of the IHA software (The Nature Conservancy 2009), a separate PHP class was developed for the RVA implementation in this research.

### *6.1.5 Integration of a Genetic Algorithm*

As described, the LTM is an NLP. Metaheuristic approaches have been successfully used to solve NLP problems. The GA method is selected for use in this research with each individual in the GA consisting of a single LTM. GAs utilize a 6-step process to generate a solution. The PHP application developed for this research implements the steps as follows:

### Initialization

Each individual in a GA consists of the set of decision variables required to generate a trial solution. For the LTM this is the annual consumer growth rate ($\delta_{y,j}$) and the rate of change in consumption rate ($roc_{y,j}$), which are specified for each demand in the STMs. An initial population is generated randomly within the user specified minimum and maximum values, and rounded to a user specified number of decimal places.

### Evaluation

During evaluation, each individual is assigned a fitness value. The fitness value of the LTM is the value of the objective function. In addition, solutions that do not have enough supply to meet demands for the length of the long term time horizon (infeasible) are ranked based on the number of years that the solution remained feasible. This allows the model to progress towards a feasible solution even when all individuals in the current generation are infeasible.

### Selection

The developed application uses a stochastic elitist strategy for selection: the user specifies the number of elites to pass directly through to the next generation. Couples are determined using a rank based system. Individuals are ranked based on fitness value and the top 50% of individuals are selected as a parent with an 80% probability. Individuals in the bottom 50% have a 40% probability of being selected.

Crossover

This application uses the discrete crossover operation whereby the child maintains the value of the parent's trait based on some probability.

Mutation

Mutation in this application generates a new random value for a single trait per the probability indicated by the user.

Stopping Criteria

This model is setup to run a user specified maximum number of generations.

### *6.1.6 Integration of MySQL Database*

Running the developed model generates significant amounts of data and requires an efficient storage and retrieval framework. MySQL database was selected for this purpose, due its speed, reliability, scalability and simplicity. The MySQL database is a relational database consisting of separate tables for data storage. The tables are used to organize and manage the model data, including tables for the physical parameters of the modeled system, tables for STM input and output and tables for LTM input and output. Integration of the MySQL required the definition and organization of data tables and the development of queries for storing and retrieving the data.

### *6.1.7 Prescott Active Management Area Application*

The final step in pursuing the stated objective was to apply the model to the Prescott AMA in north-central Arizona. Population growth in the Prescott AMA has stressed available water resources and a plan has been proposed to pump and transport ground-water from a remote location for use within the basin. Studies have suggested that pumping water at the proposed location will impact flows on the Verde River. Four scenarios are evaluated for purposes of validating the developed model and to provide examples of potential application.

The first scenario assumes no restrictions on groundwater pumping and uses the historical flow regime as the basis for the target flow regime. The only check on residential population growth in the management area is the system sustainability. Scenario 2 also assumes no regulatory limits on groundwater pumping, but uses 15% of the average Julian Day flow as the basis for the target flow regime. This target flow has no ecological basis, but serves to illustrate the impact that additional water availability has on net benefits and sustainability for the management area. The third scenario also uses the historical flows as the target flow basis, but water withdrawn from the aquifers is limited to 90% of the initial aquifer storage volumes. This scenario is the most relevant to the Prescott AMA and results suggest that the residential population needs to decrease for the maximum sustainable net benefit to be realized. Scenario 4 is similar to Scenario 3, but flows on the Verde are not affected until storage on the Big Chino aquifer decreases by 7.5%. This last scenario is the only scenario that achieved maximum sustainability for the system.

### *6.1.8 Conclusion*

The overall objective of this research was accomplished through the development of a river basin management model. The development of the model was broken down into several actionable tasks and culminated with the application of the model to the Prescott AMA. There are three key components of this research that have been identified:

1) *Sustainability is defined practically for this research in terms of maintaining the ecological, environmental and hydrological integrity of a river resource and minimizing the long-term risks associated with management decisions*

Sustainability is defined in the available research using broad somewhat vague language and with noble intent. This can lead to challenges for practical application and compiling workable definitions and actionable metrics was a daunting task. Common themes in the reviewed definitions include the protection and pursuit of societal objectives and ecosystem integrity. In theory these are not in conflict, but practically they often are. Setting up a model that balances these two goals was considered essential to making the accomplishment of this research objective's relevant.

2) *Measuring and maintaining riverine system integrity requires consideration of the river's flow regime*

Riverine ecological system research is no stranger to contemporary concerns. Given the ecological importance of river systems and the increasing concern over anthropogenic impacts on the environment, much research has focused on ecological responses to changes in river flow. Despite the importance of the flow regime to changes in riverine ecological systems, relatively little research has been conducted on the integration of water management models and flow regimes. Consideration of the flow regime was deemed critical to the objectives of this research. Though complicated by the fact that flow regimes are measured in terms of daily flow units, a method was devised that provides actionable data for the LTM objective function.

3) *Measuring sustainability for a system requires the definition of a system scope.*

Ensuring equitable distribution of resources across space and time requires a scope. As it pertains to time, the scope for the developed application is the long-term time horizon. This by necessity will be a factor in any attempt to measure and determine the sustainability for a system: measurement and application require scope. This serves to illustrate the complexities and limitations of all attempts to define and apply sustainability principals. Long-term time horizons can be increased, but with the increase comes additional uncertainty. Any sustainability metric will be limited by the

## 6.2 Recommendations for Future Research

As is often the case, pursuing the accomplishment of this research generated more questions than answers. Several of these questions were instrumental in formalizing the objective and narrowing the focus. This chapter concludes with the remainder of these questions expressed as recommendations for future research.

### *6.2.1 Multiple Objectives*

The initial objective for the LTM only examined sustainability. This was changed as it became apparent that maximum system sustainability was achievable for a wide range of net benefits. Net benefits were examined in several forms of the LTM objective (see Appendix G), but always as a single objective. The LTM could be formulated as a multiple objective problem, considering for example, maximum net benefits and maximum values for each of the sustainability performance criteria groups.

### *6.2.2 Questions of Sustainability Beyond Model Scope*

As evidenced by the drawdown in the Big Chino aquifer (see Figure 5.14) in the Prescott AMA application, the sustainability of the solution is only relevant for the length of the long-term time horizon. The optimized solution will use as many resources as possible with no consideration for demand requirements beyond the examined time period, and there may be no resources available immediately after. At the least, this suggests that the long-term planning horizon be carefully considered in the interpretation of the model’s results. Non-use values are one method of considering demands beyond the model's scope, but as implemented in this research, increasing cost of depletion amounts to a change in the preferred source. However, there may be additional methods to utilize.

### *6.2.3 Short-Term Application*

Sustainability is inherently associated with long-term planning horizons. However, the model may be modified to examine daily flows rather than monthly if the length of the long-term time horizon is shortened. With small changes, the STM can be setup to determine daily allocations for LTMs spanning several months or years. This would be beneficial for scenarios involving controlled river releases and assist in short-term planning management plans. The primary constraint to this application is model run time and potentially hardware limitations.

### *6.2.4 Long-Term Application*

As evidenced in the Prescott AMA application, maximum sustainable net benefits were only defined within the model scope. Practically speaking, the model cannot consider the state of the problemshed at $Y + 1$; this was reflected in the rapid decline in net benefits per unit consumer per unit consumption rate at the end of the long-term time horizon: $Y + 1$ has no impact. It is assumed that the model would still reflect this type of behavior with longer timer horizons, but confirmation is in order.

### *6.2.5 Platform Optimization*

In terms of run times, much progress was made between the first version and the final version of the model. Individual run times went from averaging more than 300 seconds to averaging less than 30 seconds. This was accomplished primarily by re-structuring the database and discarding un-necessary data between LTM solutions. Some changes were made to code structure, but there are likely additional changes that may be made, including the re-structuring of MySQL queries. Also, the model was setup to run on Windows machines using an Apache server (ver. 2.2). Setting up the server on a Linux machine gives access to additional performance enhancing services, such as Memcached (which did not exist for Windows at the time of this research).

### *6.2.6 Additional Performance Criteria*

Additional sustainability performance criteria could be implemented to examine the integrity of other water resources. For example, surface water (lake or spring ecosystems) or groundwater (landscape or subsidence) could perhaps be measured and protected from the perspective of system integrity.

### *6.2.7 Definitions for the Sustainability Index*

Per the SI definition in this application, there are no system sustainability contributions from a demand in an SI performance group when one or more of the performance criteria for that demand are zero. It is unclear whether this impacts the model’s progress towards a solution or the solution itself, but with the group 1 performance criteria all using the demand-supply deficits as a basis, it is reasonable to assume so. Exploring alternative definitions for the SI and their impact on the solution would provide additional insight.

### *6.2.8 Application to the Prescott AMA*

The scenarios for the Prescott AMA were developed primarily to gage the model viability. More relevant results are in order prior to any application. This includes more data with respect to the connection between the drawdown in the Big Chino and flows on the Verde, updated cost, benefit and population data, prioritization of the demands, minimum allowable aquifer levels and longer-term time horizons.

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# APPENDIX A.

# PSEUDO CODE FOR THE RVA AND IHA

The Range of Variability Approach as outlined by Mathews and Richter is available as a software application maintained by The Nature Conservancy (Mathews and Richter 2007; The Nature Conservancy 2009). For more discussion on the methods used the reader should refer to Chapter 3 of this research and the listed references.

The application developed and maintained by the Nature Conservancy is entitled IHA. The most recent version of the IHA (which at the time of this research was Version 7) offered limited command-line options and proved impossible to integrate into this research. In order to use the RVA methodology in this research, a separate PHP class was developed. The pseudo code for the developed class is included here for reference.

(Note: This was the initial pseudo code, which was not updated if a problem or discrepancy was identified in the course of building the application. Refer to the actual PHP code for discrepancy resolution.)

## A.1 Big Picture

- There are two things going on, 1) the calculation of the IHAs, and 2) the RVA analysis

- There will be a baseline dataset that will need IHAs calculated numerous times – this should be stored in the database to reduce computational demand.

- The comparison data will be generated numerous times and will need IHAs calculated every time.

- The RVA will always use the baseline dataset IHAs and one of the comparison dataset IHAs

- Overall flow of the model and general requirements:

    - There is a short term model (STM) and a long term model (LTM). The STM encompasses 1 year of data and is optimized to maximum net benefit. There are some number of years (Y) of STM in one LTM. The LTM uses the output from Y STMs to calculate a sustainability value and attempts to optimize the STM variables to maximize sustainability (as defined by the Sustainability Index or SI).

    - One of the components of the SI is the output from the RVA.

    - The LTM will run thousands and perhaps millions of times to find an optimal configuration of STMs. This suggests that each set of IHAs and RVA output be stored with an ID associated with the LTM.

    - The model requires the RVA output (Hydrologic Alteration (HA) Factor for each IHA and Bin) which will be modified and brought into the SI calculation. The IHAs should be stored in the database for verification and troubleshooting.

        - This suggests a 4 column table for the RVA: LTM ID, IHA Parameter, Low RVA Category HA value, Mid RVA Category HA value, High RVA Category value

## A.2 Pseudo Code

```
1. Calculate Julian date for all flows
2. Calculate IHA parameters
    a. Group 1
        i. Calculate median flow for each month
            1. Sort flow values for each month from low to high
            2. Median flow value for each month = center value
    b. Group 2
        i. For each year of data:
            1. Calculate Annual minima and maxima
                a. Annual 1-day minima mean
                    i. Find lowest flow value in each year
                    ii. Annual 1-day minima mean = Sum of
                        lowest flow for each year/number of years
                b. Annual 1-day maxima mean
                    i. Find highest flow value in each year
```

    ii. Annual 1-day maxima mean = Sum of highest flow value for each year/number of years

c. Annual 3-day minima mean

    i. Sum of flows on: (day n + day n+1 + day n+2)/3 for all of n (n = 1 to N; N = last day in year) in one year

    ii. Find lowest value for each year (=3 day minima)

    iii. Annual 3-day minima mean = Sum of 3-day minima for each year/number of years

d. Annual 3-day maxima mean

    i. Sum of flows on: (day n + day n+1 + day n+2)/3 for all of n in one year

    ii. Find highest value for each year (=3 day minima)

    iii. Annual 3-day maxima mean = Sum of 3-day maxima for each year/number of years

        e. Same for 7-day, 30-day, and 90-day maxima/minima means
        f. The period must be completely in the water year. For example, N – 90 is the last possible 90-day maxima/minima
    2. Calculate number of zero-flow days
        a. Where flow = 0
    3. Calculate Base flow index
        a. Base flow index = 7-day minimum/(sum of flow for year/days in year)

c. Group 3
    i. Julian date of each annual 1-day maximum/minimum
        1. Find respective lowest and highest flow values for each year.
        2. Date of highest/lowest flow is Julian date
        3. If multiple days have the same highest/lowest value, only earliest date is reported

d. Group 4

        i. Frequency and duration of high and low pulses

            1. High pulse = any flow value > median + (0.25 * median)

            2. Low pulse = any flow value < median – (0.25 * median)

            3. Consecutive days of high/low pulse = duration

                a. Pulse belongs in year of beginning, but duration can extend beyond year of start

            4. Number of high/low pulses = periods of flow > or < median + or – (0.25 * median)

            5. Median of duration

                a. Sort duration values low to high

                b. Median = center value

    e. Group 5

        i. Calculate rate of change for each day:

            1. Flow $\text{day}_n$ – flow $\text{day}_{n-1}$

        ii. Number of hydrologic reversals = count number of times – changes to + and + changes to –

        iii. Group by positive rate of change and negative rate of change

        iv. Median of rise rates
            1. Sort positive rate of changes
                a. Median of positive differences = center value
            2. Sort negative rate of changes
                a. Median of negative differences = center value

3. Perform RVA
    a. Using the Baseline data, classify each IHA parameter as either low, mid, or high RVA Bin
        i. Calculate median for the IHA parameter value
            1. Sort IHA parameter values in order of value from low to high
            2. Median = center value
        ii. Values > Median +17% = High RVA
        iii. Values <Median – 17% = Low RVA
        iv. All other values = Mid RVA
        v. Values that fall on a category boundary are considered Mid RVA
    b. Using baseline data (needs to be calculated only one time)

        i. Count number of times each parameter appears in each category
            1. This equals the *Expected Frequency*
    c. Using the comparison data (this is calculated multiple times)
        i. Count the number of times each parameter appears in each category
            1. This equals the *Observed Frequency*
    d. Calculate the Hydrologic Alteration Factor for each IHA and category:
        i. This is the original HA calculation (use for testing developed app against IHA software):
            1. (*Observed Frequency - Expected Frequency*)/*Expected Frequency*
        ii. Use this for the Modified HA:

*(Observed Frequency - Expected Frequency)*/*(If Expected Frequency > Observed Frequency then Expected Frequency; otherwise Observed Frequency)*

# APPENDIX B.

## PRESCOTT AMA (STUDY AREA)

## B.1 Introduction

The developed model is applied to an area surrounding the Prescott Active Management Area (AMA) in Arizona. The Arizona AMAs are a management concept pursuant to the 1980 Arizona Groundwater Management Code, created to address severe ground water overdraft within the state. Five AMAs were established in Arizona (see Figure B.1), covering the areas of most severe overdraft with boundaries generally determined by groundwater basins and sub-basins ("Overview of the Arizona Groundwater Management Code" n.d.). Rapid growth has been experienced in the Prescott AMA, stressing available water supplies and water managers. In response, an 'out of basin' withdrawal and transfer have been proposed as solutions to the long term problem.

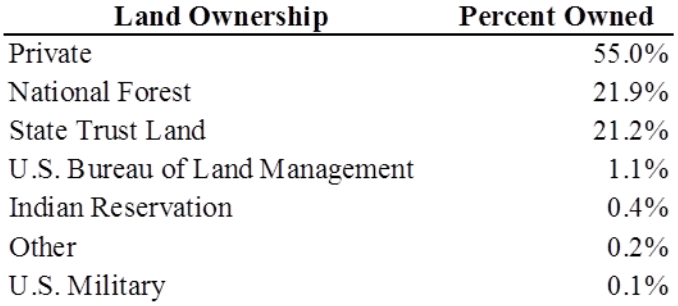
The Prescott AMA area was briefly described in Chapter 5, along with a detailed explanation of model adaptation. What follows in this section is a more in-depth discussion of the study area, including legal background and regulatory issues, a brief description of the Verde River, and an introduction to the Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona (RGFM) (Pool et al. 2011). Interested readers are directed to the listed references for additional information.

**Figure B.1. Arizona planning areas and groundwater basins (ADWR 2010b).**

## B.2 Description of Study Area

The Prescott AMA is situated in north central Arizona and at 485 square miles, it is the smallest of the Arizona AMAs. The area is characterized by rolling hills and broad valleys, with elevations ranging from 4,400 feet in the valleys to 7,800 feet in the mountain ranges. Streamflows are primarily ephemeral or intermittent with recent average annual temperatures of 56˚ Fahrenheit and an average annual precipitation of 18.7 inches. Highest average annual rainfall occurs between the months of July and September. This area is within what has been described as the Highlands basins, and geologically it is comprised of basin fill and alluvium deposits, with plains and Great Basin grassland, southwestern chaparral, Great Basin conifer woodland and petran montane conifer forest comprising the dominant biotic communities (ADWR 2010a). Geographical features of interest include the Agua Fria River running southeast from the center of the AMA and the Chino Valley in the north central art of the AMA. The land ownership distribution is listed in Table B.1.

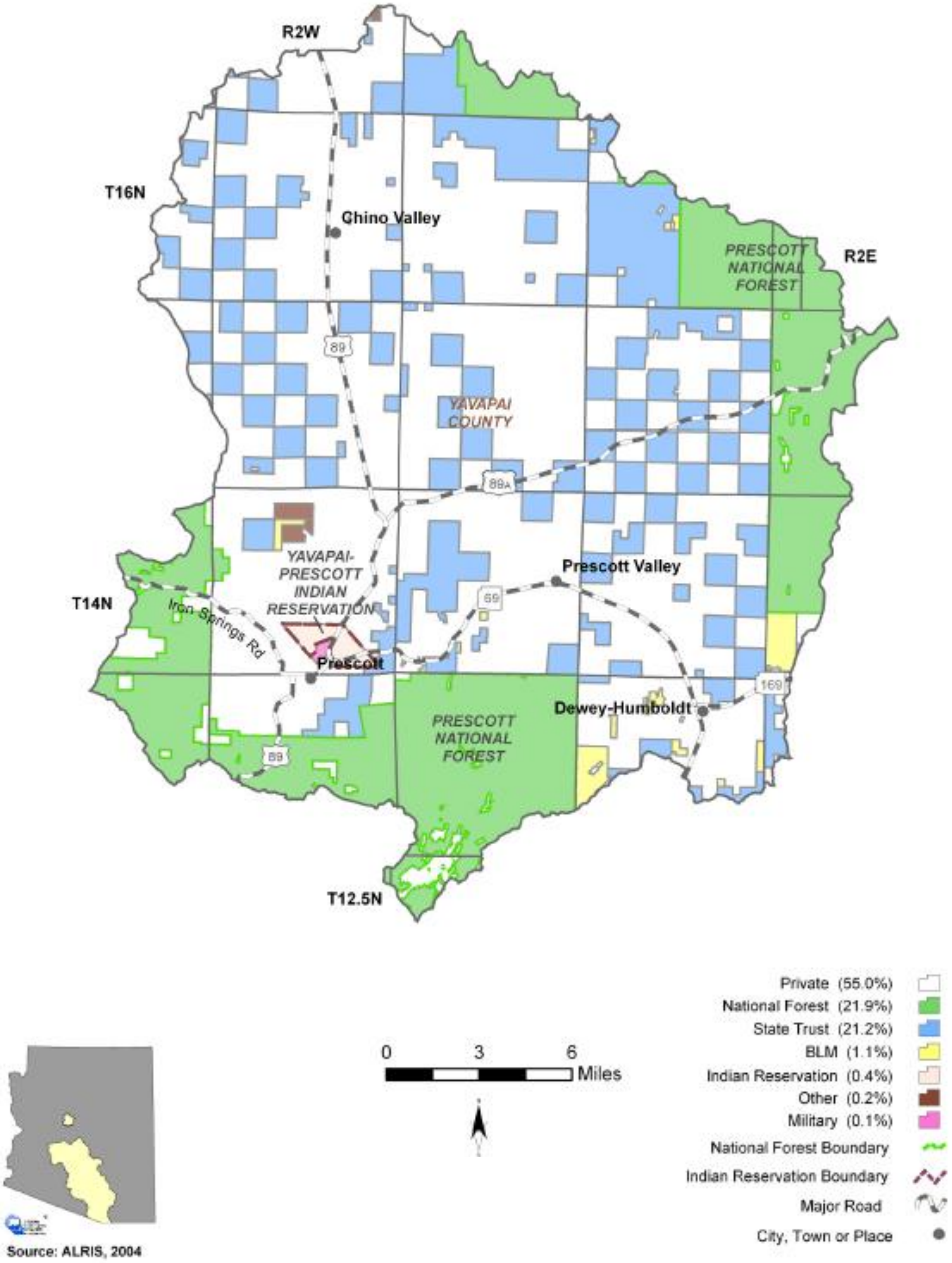
**Table B.1. Land ownership distribution in the Prescott AMA (ADWR 2010a).**



| Land Ownership | Percent Owned |
|---|---|
| Private | 55.0% |
| National Forest | 21.9% |
| State Trust Land | 21.2% |
| U.S. Bureau of Land Management | 1.1% |
| Indian Reservation | 0.4% |
| Other | 0.2% |
| U.S. Military | 0.1% |

The Prescott AMA encompasses an area of rapid population growth, including the City of Prescott, Towns of Prescott Valley and Chino Valley, and the communities of Dewey-Humboldt (see Figure B.2). The area as a whole has seen a decline in agricultural since 1985, a trend which is expected to continue into the future, and attributed to the higher land prices associated with residential land use and facilitated by the Arizona regulatory structure (ADWR 2010a).

**Figure B.2. Land ownership in the Prescott AMA (ADWR 2010b).**



### *B.2.1 Water Availability in the Prescott AMA*

Characteristic of the area, the Prescott AMA is marked by a lack of water availability. Perennial streams are limited to a portion of the Agua Fria River, with intermittent streams found on the eastern AMA boundary and the south central area. The Del Rio spring is the one major spring in the AMA with a discharge of 874 gallons per minute. The area also has 10 minor springs, with discharges over 10 gallons per minute. All of the flows are typically higher between January and March.

Major aquifers in the area are comprised of Basin Fill and Igneous and Metamorphic Rock, with an estimated natural recharge of 7,000 acre-feet per year. The time between 1993 and 2004 noted water level declines in the area of over 30 feet in the most stressed areas, with the largest number of index wells listing declines between 15 and 30 feet. There are three active recharge sites with a total permitted storage capacity of almost 13,000 acre-feet per year. The primary source of recharge is effluent with currently over 6,800 acre-feet treated per year (ADWR 2010a).

There are over 11,000 wells registered in the area and groundwater provides the majority of water for use in the AMA. Over 700 of these have a capacity great than 35 gallons per minute, with the remaining with a capacity under 35 gallons per minute.

Table B.2 lists the historical and projected demand patterns and the potential shortfall. It is clear that the Prescott AMA's reliance on local groundwater is not a long term solution nor in compliance with the regulatory 'safe-yield' goal established by Arizona's Groundwater Management Act of 1980. The following section briefly introduces this topic and some of the legal and regulatory issues that pertain to water use in the AMAs.

**Table B.2. Historical and projected water use distribution and shortfall (ADWR 2010a; Rothman 2007).**

| Year | Population | Municipal/Residential Water Use | Agricultural Water Use | Industrial Water Use | Total Water Use | Natural and Artifical Recharge | Shortfall |
|---|---|---|---|---|---|---|---|
| | | [Ac-ft] | [Ac-ft] | [Ac-ft] | [Ac-ft] | [Ac-ft] | [Ac-ft] |
| 1985 | 43,000 | 7,200 | 14,000 | 300 | 21,500 | - | |
| 2005 | 111,000 | 18,600 | 5,000 | 300 | 23,900 | 14,000 | (9,900) |
| 2025 | 182,000 | 30,600 | - | 300 | 30,900 | 14,000 | (16,900) |

### *B.2.2 Legal and Regulatory Issues*

Arizona state law makes a distinction between the right to use surface water and the right to use ground water. As is common throughout the western United States, the right to use surface water is established under the doctrine of prior appropriation – "first in time, first in right." Prior appropriation is established thru an approval and permitting process overseen by either the Arizona Department of Water Resources (ADWR) or a court sponsored adjudications. Most if not all of the surface water within the state of Arizona has been appropriated (Rothman 2007). The right to use groundwater within the state of Arizona on the other hand is established thru beneficial use doctrine. Outside of state defined Irrigation Non-Expansion Areas (INAs) and Active Management Areas (AMAs), there is essentially no restriction placed on withdrawing groundwater as long as it is put to reasonable and beneficial use (ADWR 2010b).

Arizona state officials have known since the early 1930's that action was required to control groundwater overdraft and protect groundwater basins. The Arizona Groundwater Management Act (AGMA) was adopted in 1980, pursuant to federal funding requirements for the Central Arizona Project (CAP) and to facilitate dispute settlement and the mitigation of severe groundwater table declines. The AGMA established a state water use regulatory code and the ADWR, which was charged with water planning and regulation responsibility (Arizona Department of Water Resources, Public Information Officer 2014). The AGMA also established management goals for each of the AMAs, a data reporting system, mandatory conservation requirements, and 100-year assured water supply requirements for new sub-divisions in the AMAs (ADWR 2010b).

The AMAs were designated as areas requiring (ADWR 2010a p. 8):

> *"...specific, mandatory management practices to preserve and protect groundwater supplies for the future."*

The AGMA originally established 4 AMAs, with the 5th , the Santa Cruz AMA, established in 1994, after it was recognized that the area required a coordinated surface and groundwater management approach. The AMAs include most of Arizona's largest urbanized areas and are required to reach 'safe yield' by the year 2025. Safe yield is defined as (A.R.S.§ 5-562 (A)) :

> *"...a groundwater management goal which attempts to achieve and thereafter maintain a long-term balance between the annual amount of groundwater withdrawn in an active management area and the annual amount of natural and artificial groundwater recharge in the active management area."*

ADWR has determined that the Prescott AMA is not in safe yield and that even with maximum use of effluent, demand would outstrip supply through the year 2025 (Arizona Department of Water Resources 1999, 2014). The largest source of alternative water for the Prescott AMA is the Big Chino sub-basin, which lies outside of the Prescott AMA, but is allowed to be transferred under state statute (A.R.S. §45-555 (E)). A plan to import up to 19,400 acre-feet of water per year from the Big Chino has been proposed by municipalities in the AMA (Black and Veatch 2006). However, concern over how the Verde River and Big Chino sub-basin are connected has generated significant resistance to the plan (Citizens Water Advocacy Group n.d.). Most recently, the City of Prescott has entered into agreement with the Salt River Project and the Town of Prescott Valley to implement an enhanced groundwater and surface water monitoring system for purposes of collecting data for a more refined groundwater model of the area (City of Prescott 2014). This model would conceivably be utilized to facilitate the development of a mitigation plan prior to the construction of the pipeline (Citizens Water Advocacy Group n.d.)..

### B.3 Verde River

The Verde River flows nearly 200 miles south through central and northern Arizona, supplying multiple communities with irrigation and drinking water and attracting numerous recreational and outdoor sport enthusiasts (see Figure 5.1). The river also supports a variety of fish and aquatic habitat and in 1984, a portion of the river was designated as Arizona’s only Wild and Scenic River by the Wild and Scenic Rivers Act (U.S. Forest Service n.d.).

As with most surface water in the arid southwest, rights to use the water in the Verde River have long been appropriated. However, Verde River baseflow is threatened due to groundwater pumping in the Upper and Middle Verde watersheds, and in 2006, the Verde River was listed as one of the Nation's most endangered rivers by the American Rivers organization (Newell 2007). Concern regarding supply to the Verde River has been expressed in connection with the proposed Big Chino import plan discussed in the prior section. Though not comprehensive, the RGFM suggests a definitive link between well levels in the upper reaches of the river shed and river flows. This study is introduced next.

### B.4 The RGFM

The RGFM was produced by the Arizona Water Science Center (AZWSC) of the U.S. Geological Survey (USGS) in cooperation with the Arizona Department of Water Resources (ADWR) as part of the Rural Watershed Initiative (RWI). The RWI is a program that addresses water-supply issues in rural areas of Arizona, with an emphasis on regional watershed studies and encourages cooperation between local stakeholders and resource agencies. These areas are experiencing increasing growth and associated stress on scarce natural water supplies (Pool et al. 2011).

The RGFM was developed to assist in the assessment of regional groundwater supplies and to provide guidance towards the potential effects of increased groundwater use on water levels, streamflow, and riparian vegetation. The numerical model simulates groundwater flow in the primary aquifers of the region and has two primary uses: (1)

evaluation of the hydrologic effects of groundwater use on the groundwater-flow system and (2) identification of major hydrogeologic parameters that need improved definition. Per the authors, the certainty of projected changes is dependent on future validation of the hydrologic assumptions, but the model was intended to be used to estimate changes in water levels, discharge to streams, springs, and riparian evapotranspiration that could result from anticipated future groundwater use (Pool et al. 2011).

Change in flow on the Verde River is derived using a response function for the aquifer. The response function was developed using the simulated change in flow on the Verde in response to the simulated change in the aquifer storage. It should be noted that the response function is subject to the same assumptions and limitations inherent in the RGFM, including the scarcity of streamflow and water-level records before the mid-1960s, potentially inaccurate estimates of the spatial and temporal distribution of recharge and groundwater withdrawals, and the spatial discretization of the model domain. Precise simulation of the storage, discharge and recharge cannot be expected from the RGFM, but general trends in observations should be possible (Pool et al. 2011).

Using the simulated results, change in flow is plotted against change in storage and a linear estimation of the response is presented in Figure 5.3. The linear estimation is used in this research to gage the response of the Verde River to that change in storage in the aquifer. For more information on the simulated data use for the response function see the RGFM (Pool et al. 2011).

# APPENDIX C.

# ECONOMIC VALUATION OF STREAMFLOW

How to ascribe value to the water flowing in a river? For that matter, what exactly is value? Value may be thought of in terms of '*the contribution of an action or object to user-specified goals, objectives or conditions'*, while valuation is the process whereby value is expressed or assigned to an action or object (Farber et al. 2002). By necessity, all value and the process of valuation depends upon 'a beholder', a perspective, and some means of communicating a beholder's perspective; broadly speaking, value can only be described in terms of recognized benefits.

The following discussion relates this author's investigation into economic valuation for stream flows. Examination is made into the concepts and historical basis and different methods of evaluation, with the goal of discovering methods for use in this research. The topic of economic valuation for stream flows is a very active and evidently controversial.

## C.1 Introduction

When it comes to ecosystem valuation, distinction is made between *intrinsic value* (per (Leopold and Aldo 1949) and *instrumental value* (anthropocentric and corresponding with the satisfaction of human preferences) (Farber et al. 2002). The follows is a brief discussion of concepts in ecosystem valuation, its history and an introduction to the proposed methodology and relies heavily on Farber et al (Farber et al. 2002).

## C.2 Concepts

### *C.2.1 Economic Value*

Economic value is a measure of benefit and relies upon the idea that the concepts of value and benefit can be exchanged, most often in units of currency. The concept of economic value – what it is and how it is measured – has a long and varied history (Farber et al. 2002).

Aristotle was the first to distinguish between use and exchange value, the ideas that something may have value in use which may not necessarily equate to a market or exchange value. This is most aptly portrayed by the diamond-water paradox: water, being required for life, is considered infinite or indefinite in use value; but in terms of exchange value, water has little to no value. Diamonds on the other hand have little to no use in terms of being necessary for life, but are recognized as having large market or exchange values.

The process of valuation and trade-off is problematic when wants and desires are not readily reducible to a tradable means (e.g. money). Ekins and Manfred suggested the universality of several basic human needs: subsistence, affection, protection, understanding, leisure, identity, and freedom (Ekins and Manfred 1992). Affection and identity are not readily translated into a tradable or purchasable form. The same follows for environmental goods and services, making trade-offs ambiguous at best.

There are several considerations in understanding the concept of economic value as it pertains to ecological systems; these include the ideas of *diminishing marginal utility, lexicographic preferences* and *total utility*.

### *Diminishing Marginal Utility*

The idea that value depends upon *scarcity* and *utility* was first proposed by Ferdinado Galiani in the 18th century (Schumpeter 1978). Carl Menger's theory of marginality proposed different categories of wants or desires, ordered in terms of their subjective importance.  Within each category, wants or desires for one additional unit declines with successive units of the good – the principle of *diminishing marginal utility* (Farber et al. 2002). All else being equal, natural waterways are likely to be valued less in locals with numerous unhindered river flow and valued much higher than in areas with few riverways.

### *Lexicographic Preferences*

The concept of diminishing marginal utility introduces the possibility of *lexicographic preferences* and whether or not *trade-offs* exist between categories of goods. Assuming an ordered or lexicographic preference, one level of wants and desires must be satisfied before a lower level is relevant to the valuation process. The possibility of trade-offs addresses how specific the fulfillment of a desire must be. For example, consider the desire to fish in a river and the desire to drink water from a river. An ordered lexicographic preference would suggest that the desire to drink water be fulfilled before the desire to fish is considered. It is evident that no trade-offs exist for drinking water while the desire to fish could be acknowledged as a desire for recreation and be resolved through some other means. Individuals are still able to state how much of a resource they are willing to commit to a desire under this model, but will always use available resources to first fulfill higher order desires if they are at risk (Farber et al. 2002).

### *Total Utility*

The concept of consumption technology was introduced by Kelvin Lancaster (Lancaster 1971). In consumption technology, the consumer considers the characteristics of goods while ascribing value (Farber et al. 2002). As an illustration, consider recreational fishing areas. The characteristics of recreational fishing areas may be evaluated in terms of the size, species and quantity of fish available in a stream. Recreational fishing areas may be substitutable depending upon the respective comparison characteristics. Consumers in turn allocate budgets across an efficiency of characteristics. This is formalized in the multi-attribute utility theory whereby total utility is a function of the characteristics of goods or services. Using a simple linear example, total utility ($U$) from a recreational fishing area may be expressed in terms of size ($Si$), species ($Sp$), and quantity ($Qu$) characteristics, and their respective weighting factors:

$$U = a * Si + b * Sp + c * Qu \tag{C.1}$$

When utility is measured in monetary willingness to pay (WTP) or willingness to accept (WTA) compensation, the weighting factors represent the marginal monetary value of each characteristic (Farber et al. 2002). This concept forms the basis for hedonic pricing model valuations, e.g., the price of a house depends upon the characteristics of the house:

style of architecture, its location, access to amenities, etc. Hermann Heinrich Gossen built on this concept saying that maximum satisfaction of a good is realized when valuation takes into consideration incremental utility across varying uses of the good (Blaug 1985). Per Farber et. al's example, '…treating commodities such as iron, cement, fertilizer, natural agent and labor as incomplete consumable goods, the marginal utility of the goods they produce can be used to explain their exchange value' (Farber et al. 2002). They go on to suggest that this logic established a 'full theory' of value and demonstrated that exchange values can be based on use values.

### *C.2.2 Ecological Value*

Anthropological activity and its impact on nature have been long recorded. Notable examples include Plato's descriptions on the effects of deforestation on soil erosion and the drying of springs in 400 BC. In the first century AD, Pliny the Elder observed the links between deforestation, rainfall, and the occurrence of torrents (Gómez-Baggethun et al. 2010). There are several paradigms for ecological value and valuation (Farber et al. 2002), but only the concept of *ecosystem services* is discussed here. Again, this discussion is primarily this author's personal summary of Farber et al (Farber et al. 2002).

Using the definition of value provided earlier, it is presumed that eco-systems and non-human species are not pursuing conscious goals, and therefore do not have a value-system. While evolution is not a conscious, goal-directed behavior, the end is readily acknowledged to be the survival of a species. This concept is the basis for natural selection models which happen to bear close similarities to economic utility maximization models (Low 2000). Hence, when speaking of particular traits in an organism, value is often spoken of in terms of ‘survival value’ (Farber et al. 2002). Expanding the concept of value ‘to the degree to which an item contributes to an objective or condition in a system’, value may also be expressed in terms of eco-system functions, e.g., the value that a particular tree species has in controlling soil erosion. Along the same lines, the idea of co-evolution allows for the concept of one species being valuable to another species, e.g., the value that a particular tree species in providing habitat for another species. This is the basis for *ecosystem services*.

### *C.2.3 Ecosystem Services*

The concept of ecosystem services was introduced in 1981 (Gómez-Baggethun et al. 2010). For a more comprehensive understanding of the topic, Gómez-Baggethun et al. 2010 examine three stages in the evolution of economic theory and the role of the environment. Following is a brief summary of their findings and interpretation.

#### *Classical Economics*

The thought that nature’s benefits were of no value in exchange appears to be a common theme as evidenced in the writings of prominent economists of the time (Gómez-Baggethun et al. 2010). Over this period economists started to emphasize labor as the major production of wealth, most notably in Adam Smith. Smith referred to the timber of the woods, the pastures from rangelands, and the yield of the soil as ‘natural production’. However, Smith did not consider the value as derived from nature; rather value was derived from the ‘rent associated with appropriation’ (Gómez-Baggethun et al. 2010).

The authors quote Naredo (Naredo 1987) in suggesting that by the fall of the Classical economics period (around 1870), economic theory was marked by three shifts in thought: a change in focus away from labor and land and towards labor and capital as the primary factors; second a move from physical analysis to monetary analysis; and third, a change in focus from use value to exchange value (Gómez-Baggethun et al. 2010). This set the stage for the Neo-Classical period of thought and the conceptual decoupling of economics from the physical world.

### *Neo-Classical Economics*

In general terms, the Neo-Classical period of economics saw the expansion of monetary analysis beyond the limits of the markets as a way to tackle economic externalities. The early part of the twentieth century saw some economists raising concerns with respect to environmental resource depletion and the effect on future generations – ‘…and elaborated on the ethical and technical aspects involved in the application of discount rates.’ This same period saw the genesis of the idea of technological innovation as allowing for increased substitutability between production inputs such as land and capital, putting concerns with respect to physical scarcity to rest (Gómez-Baggethun et al. 2010).

### *Environmental and Ecological Economics*

With the increase in environmental awareness during the second half of the 20th century, specialized sub-disciplines within economics arose in an attempt to address shortcomings in environmental economic theory.

One of these shortcomings was the systematic undervaluation of ecological concerns stemming from the Neo-Classical orthodoxy. The Society of Environmental and Resource Economics attempted to develop a range of methods with the purpose of extending the scope of environmental cost-benefit analysis. For example, Krutilla's rule defines a high economic present value to the loss of landscape amenities in the context of a cost-benefit analysis of dams (Krutila 1967).

A series of theoretical divergences within the society of Environmental and Resource Economics led to a split in the late 1980s, resulting in the founding of a second school of thought, what came to be known as Ecological Economics (Gómez-Baggethun et al. 2010). Ecological Economics attempts to account for physical and social costs in the valuation process using biophysical accounting as well as other non-monetary valuation concepts in addition to monetary (Gómez-Baggethun et al. 2010).

Gomez-Baggethun et al. (2010) discusses two primary areas of controversy between the two schools of thought. The first has to do with the substitutability of natural capital and is often referred to as the 'Strong versus weak sustainability debate'. 'Weak sustainability' assumes substitutability between natural and manufactured capital and is espoused by the Environmental Economists. 'Strong sustainability' on the other hand maintains that natural capital and manufactured capital are complimentary rather than substitutionary; which is to say, capital cannot be produced without inputs from natural resources.

The second area of controversy relates to ecosystem services valuation. Some ecological economists argue that environmental decision making consists of conflicting valuation concepts that may not be commensurable in monetary terms. Seen from this perspective, environmental decision making tools that utilize a single measuring rod (e.g., environmental economics) tend to be critically appraised (Gómez-Baggethun et al. 2010).

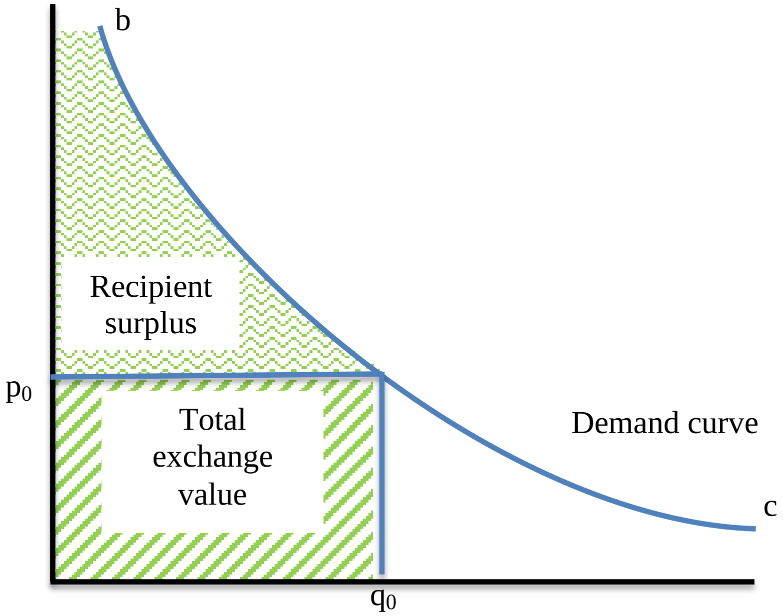
These topics are still being debated and it is beyond the scope of this research to attempt to resolve the issues. Rather, as noted earlier, this research assumes that the weak/strong sustainability positions are not mutually exclusive; strong sustainability is manifest via constraints on the optimization model and without assuming some substitutability, questions of optimal resource allocation and modeling don’t exist.

### *Concept*

Ecosystem goods and services represent the benefits humans derive, directly or indirectly, from ecosystem functions (Costanza et al. 1997). The goods and services provided by ecosystem functions can be divided into two categories: (1) the provision of direct market goods or services such as drinking water, recreation, transportation, electricity generation, pollution disposal, and irrigation; and (2) the provision of nonmarket goods or services, including things like biodiversity, support for terrestrial and estuarine ecosystems, habitat for plant and animal life and the satisfaction people derive from knowing that an ecosystem exists (e.g., a river, lake, etc.) (Wilson and Carpenter 1999).

As it applies to ecosystem service valuation, the marginal utility value theory allows for the definition of use value in monetary terms (as opposed to simply exchange value). Adopting the lexicographic preference model and assuming that individuals are best suited to determine the possibility and potential value of any tradeoffs, value can be expressed in two empirical measures:  (1) the willingness to pay for a particular service (WTP) and (2) the willingness to accept compensation for the loss of a service (WTA). For example, if an ecosystem service provides an additional $100 in timber productivity, the recipients of the benefit should be willing to pay up to $100 for this service. On the opposite side of the transaction, if the implementation of the same ecosystem service causes a net $100 loss in recreational opportunities, then the donors would accept no less than $100 as compensation.  The price of any transaction will be any point between a recipient's WTP and the donor's WTA. This concept is illustrated in Figure C.1.

**Figure C.1. Demand curve and price point**



Line *bc* represents the marginal benefit (i.e., *demand curve*) generally associated with ecosystem services. Given the non-substitutionary aspects of eco-system services, the price will tend towards infinity as the available quantity reaches some minimum level of required service. For some quantity ($q_0$) an efficient market will reach some price ($p_0$) (corresponding to a recipient's WTP and a donor's WTA) which will clear the market. Total exchange value is $p_0$ times $q_0$. The area above $p_0$ and below the demand curve represents total benefits minus the cost of attainment, or recipient surplus.

### *Valuation Methods*

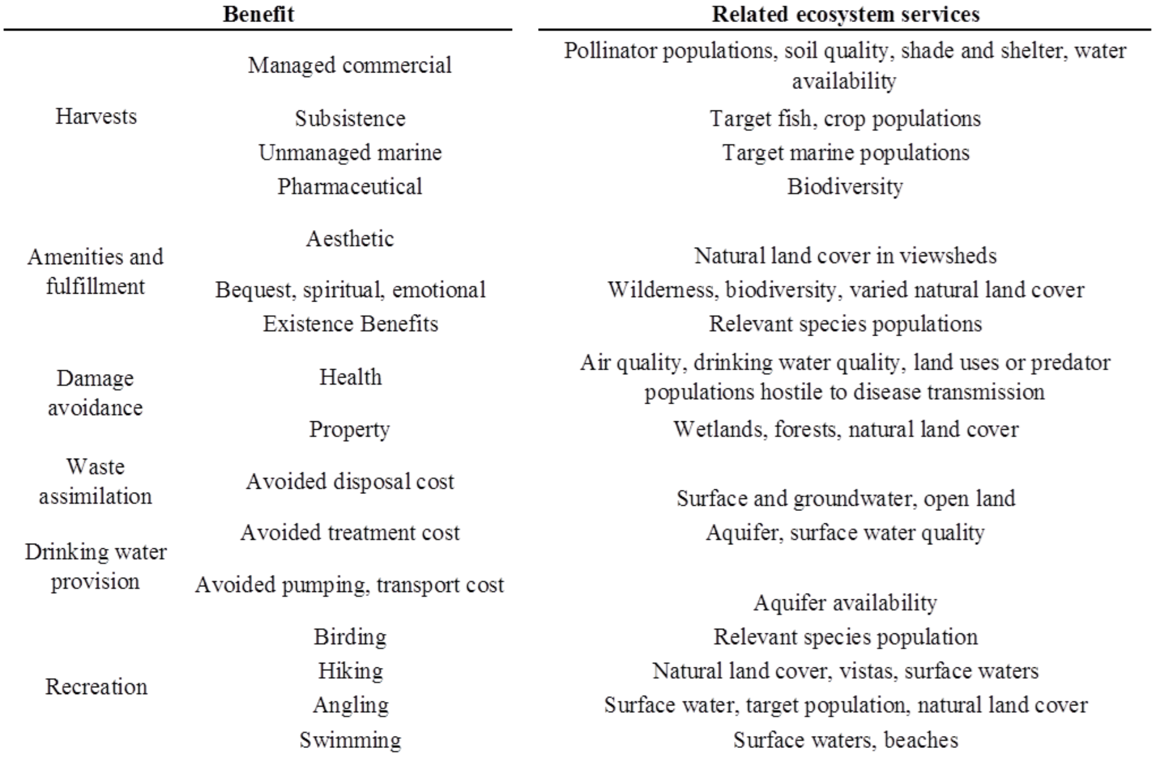
Boyd and Banzhaf propose a standardized unit of measure for ecosystem services and suggest a definition:

> *"Final ecosystem services are components of nature, directly enjoyed, consumed, or used to yield human well-being."*

This definition does three things. First, it specifies that final services are end-products of nature, making an important distinction between intermediate and end goods. Second, it proposes that in addition to being directly used, ecosystem services are components, implying that services are ecological characteristics or things (surface water, vegetation types, species populations), and not functions or processes (biological, chemical and physical interactions between components). Third, the definition facilitates a distinction between quantity or physical measure of a service, and the value of the service (Boyd and Banzhaf 2007).

Adopting this definition, the first step in the procedure for identifying ecosystem services is to list sources of well-being related to nature. Boyd and Banzhaf list illustrative examples, which are replicated here in Table C.1.

**Table C.1. Ecosystem services.**



| Benefit | | Related ecosystem services |
|---|---|---|
| Harvests | Managed commercial | Pollinator populations, soil quality, shade and shelter, water availability |
| | Subsistence | Target fish, crop populations |
| | Unmanaged marine | Target marine populations |
| | Pharmaceutical | Biodiversity |
| Amenities and fulfillment | Aesthetic | Natural land cover in viewsheds |
| | Bequest, spiritual, emotional | Wilderness, biodiversity, varied natural land cover |
| | Existence Benefits | Relevant species populations |
| Damage avoidance | Health | Air quality, drinking water quality, land uses or predator populations hostile to disease transmission |
| | Property | Wetlands, forests, natural land cover |
| Waste assimilation | Avoided disposal cost | Surface and groundwater, open land |
| Drinking water provision | Avoided treatment cost | Aquifer, surface water quality |
| | Avoided pumping, transport cost | Aquifer availability |
| Recreation | Birding | Relevant species population |
| | Hiking | Natural land cover, vistas, surface waters |
| | Angling | Surface water, target population, natural land cover |
| | Swimming | Surface waters, beaches |

See (Brauman et al. 2007; Loomis et al. 2000), (Millennium Ecosystem Assessment (Program) 2005)(Raudsepp-Hearne et al. 2010) for more reading.

### *The Emergence of Ecosystem Services*

The last three decades have seen the adoption of a utilitarian argument towards the environment, one that stresses societal dependence on natural ecosystems. Traditionally, operational ecosystem processes have been labeled as ecosystem functions, regardless of the value to human society. In the 1970s and 1980s, authors began framing ecological concerns in economic terms, stressing a societal dependence on natural ecosystems. The term *ecosystem services* came to be associated with ecosystem functions critical to human well-being, specifically the impact of biodiversity degradation (Gómez-Baggethun et al. 2010).

Gómez-Baggethun et al. (2010) mark several milestones in the adoption of the ecosystem services to the mainstream and policy arena. Increasing research on the monetary value of ecosystem services resulted in increased interest in the creation of economic incentives for conservation and market exchange systems. This has brought into existence several commodified ecosystem services, including emission trading of greenhouse gases, sulphur dioxide emission trading, wetland mitigation, watershed protection, carbon sequestration, habitat conservation/wildlife services, bio prospecting, and agro environmental measures. The first international market is probably the EU emission trading system launched in 2005 (Gómez-Baggethun et al. 2010).

# APPENDIX D.

# EVOLUTION OF THE LTM OBJECTIVE FUNCTION

## D.1 Introduction

The objective function used for the LTM (4.36) was not derived in a straightforward manner. The model concept initially examined only the SS value in the LTM objective until it was realized that for any particular SS values, there were numerous possible values for net benefit. This prompted the introduction of the net benefit into the LTM objective:

$$Max\ Sustainable\ Net\ Benefit = \sum_{y}^{Y} NetBenefits_y * SS \tag{D.1}$$

Where $NetBenefits_y$ is the net benefits associated with STM $y$:

$$NetBenefits_y = \left(wZ_1 - (1 - w)Z_2\right)_y \tag{D.2}$$

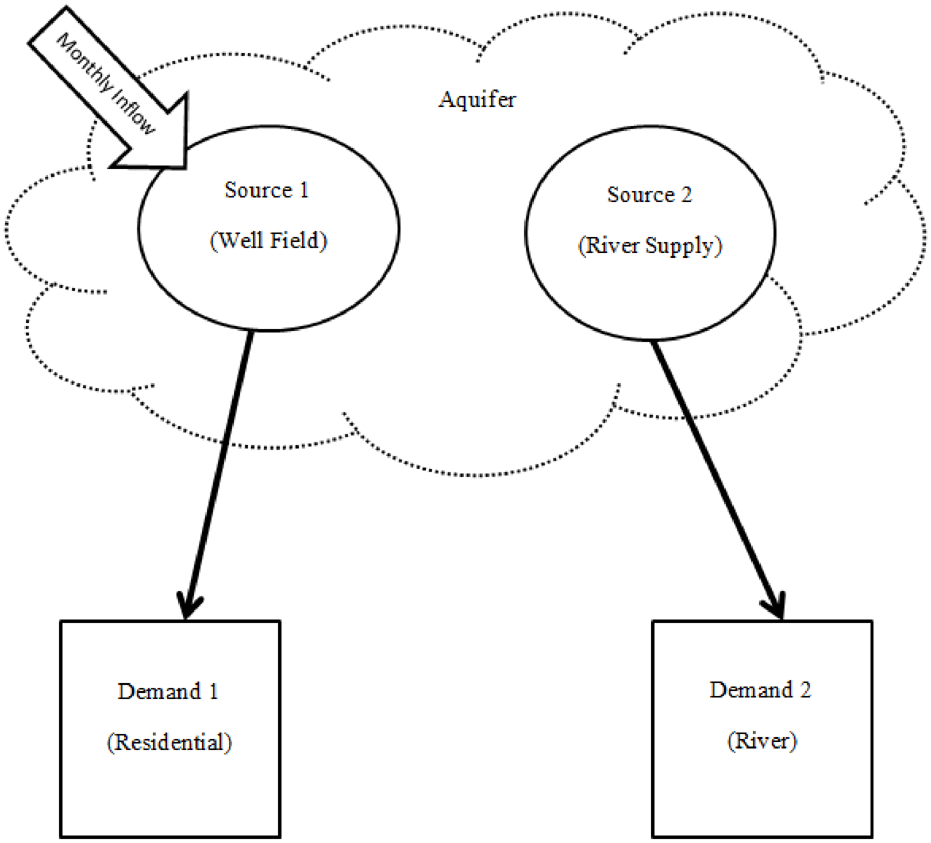
This was effective for the hypothetical water management area used to validate the model, but proved lacking for the Prescott application.

This following presents the hypothetical application and the results from the Prescott application that led to the objective function used in the LTM in Chapter 4.

## D.2 Hypothetical Application (Linear LTM objective)

A hypothetical river basin management area is used to test and validate the developed model. The hypothetical management area consists of a simplified and relatively predictable physical system comprised of a residential demand, a river demand and two groundwater sources (see Figure D.1). The hypothetical management area is used as the basis for 8 scenarios. The physical basis for the hypothetical management area is described next, along with the parameters for the first scenario. The parameters are modified in subsequent scenarios. Each of the scenarios is described and then results are presented and discussed in the final portion of this chapter.

Figure D.1. Depiction of the simple hypothetical river management area.



### *D.2.1 Physical Basis for the Hypothetical River Basin Management Area*

The hypothetical river basin management area is a simple physical system consisting of one residential demand and one river demand, with both demands relying upon the same aquifer (see Figure D.1). The aquifer is represented by two sources, Source 1 is a well field supplying the residential demand, and Source 2 represents the supply for the river. The supply at Source 2 is dependent upon the aquifer storage levels. The aquifer re-supply is assumed to be partially understood and represented by a monthly inflow schedule for Source 1.

Physical parameters for the scenarios include initial residential population, population growth and consumption rates, aquifer storage levels, historical river flow data, a linear aquifer response function, infrastructure capacities, costs of development, delivery and depletion, and beneficial use values. The aquifer response function links aquifer storage levels to the supply available for the river:

$$x_{y,2,2,t} \leq source_{input_{y,2,t}} - 0.0104 * \Delta s_{y,2,t} \tag{D.3}$$

Where $x_{y,2,2,t}$ is the allocated supply, $source\_input_{y,2,t}$ is the monthly input at the source and $\Delta s_{y,2,t}$ is the change in storage at the source, for STM $y$, source node 2, demand node 2 and month $t$. The change in storage at source 2 is defined as:

$$\Delta s_{y,2,t} = s_{0,2,0} - s_{y,2,t} \tag{D.4}$$

Where $s_{0,2,0}$ is the initial storage volume and $s_{y,2,t}$ is the storage volume for STM $y$, source node 2 and month $t$.

Population growth (-8% to 8%) and consumption ( 0.0112 [ac-ft/month]/capita to 0.0224 [ac-ft/month/]capita) rate constraints are assumed to be typical for a fast growing residential population in Arizona, as are the costs of development ($2210/ac-ft), delivery ($0.05/kwh), price path factor ($\rho$ =0.01), and beneficial use ($4200/ac-ft) values. USGS river gage data is used for historical flows and for projected river supplies (*USGS 09503700 Verde River Near Paulden, AZ* n.d.). The remaining parameters are scenario dependent and are addressed in the scenario descriptions.

### *D.2.2 Description of the Hypothetical Scenarios*

#### *Hypothetical Scenario 1 – Historical Flow Target*

Scenario 1 uses the un-modified historical flow regime as the target flow regime. This examines the response of the system to population growth and provides guidance for how much population growth can occur while maintaining sustainability and maximum net benefit. The entire parameter set for Scenario 1 is presented in Tables D.1 through D.5. The same parameters are used in the subsequent hypothetical scenarios, except as noted in the scenario description.

**Table D.1. Source node parameters for Hypothetical Scenario 1. These are used for subsequent scenarios, except where noted.**

| id | label | Type | output_max | state_min | state_max | initial_state | dev_cost_coefficient |
|---|---|---|---|---|---|---|---|
| | | | [Ac-ft/month] | [Ac-ft] | [Ac-ft] | [Ac-ft] | [$] |
| 1 | Source 1 - Well field | 3 | 40000 | 0 | 5000000 | 150000 | 2210 |
| 2 | Source 2 - River supply | 1 | 10000000 | 0 | 0 | 0 | 0 |

**Table D.2. Demand node parameters for Hypothetical Scenario 1. These are used for subsequent scenarios, except where noted.**

| id | label | initial_consumer_units | initial_delta | delta_min | delta_max | delta_rounder | initial_rate | rate_min | rate_max |
|---|---|---|---|---|---|---|---|---|---|
| | | | [%] | [%] | [%] | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] |
| 1 | Residential | 10000 | 0.08 | -0.08 | 0.08 | 2 | 0.0168 | 0.0112 | 0.0224 |
| 2 | River | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

**Table D.3. Demand node parameters (cont.) for Hypothetical Scenario 1. These are used for subsequent scenarios, except where noted.**

| id | label | initial_consumer_units | initial_rate_change | rate_change_min | rate_change_max | rate_rounder | theta | benefit | si_weight | rva |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | | [%] | [$] | | |
| 1 | Residential | 10000 | 0 | -0.02 | 0.02 | 2 | 1 | 4700 | 0.333333 | 0 |
| 2 | River | 1 | 0 | 0 | 0 | 0 | 0 | 4700 | 0.333333 | 1 |

**Table D.4. Link parameters for Hypothetical Scenario 1. These are used for subsequent scenarios, except where noted.**

| id | label | input_max | s_node | e_node | elevation_ head |
|---|---|---|---|---|---|
| | | [Ac-ft/month] | | | [ft] |
| 1 | Well field to Residential | 1000000 | 1 | 1 | 800 |
| 2 | River supply to River | 1000000 | 2 | 2 | 0 |

**Table D.5. Source node input for Hypothetical Scenario 1. These are used for subsequent scenarios, except where noted.**

| source_id | month | input |
|---|---|---|
| | | [Ac-ft/month] |
| 1 | 1 | 250 |
| 1 | 2 | 250 |
| 1 | 3 | 250 |
| 1 | 4 | 250 |
| 1 | 5 | 250 |
| 1 | 6 | 250 |
| 1 | 7 | 500 |
| 1 | 8 | 500 |
| 1 | 9 | 500 |
| 1 | 10 | 500 |
| 1 | 11 | 500 |
| 1 | 12 | 500 |
| 2 | All | Historical (modified by aquifer response function) |

### *Hypothetical Scenario 2 – Daily Average Flow Target*

15% of the average flow for each Julian day is calculated from the historical flow data and used as the target flow regime in Hypothetical Scenario 2. This scenario evaluates the population growth and consumption patterns available using water not required by the environmental flow regime. It should be noted that 15% of the average flow for each Julian day has no ecological basis.

### *Hypothetical Scenario 3 – Daily Average Flow Target and Reservoir*

Hypothetical Scenario 3 also uses 15% of the average flow for each Julian day as the target flow regime. In addition, storage at Source 2 is permitted so that water not required for immediate river demand is available for future river demands. This effectively behaves as a reservoir placed at the headwaters of the river and de-couples the dependency of the immediate river demand on the aquifer storage levels. A cost of development for Source 2 is also imposed. The changes to the parameter values are listed in Table D.6.

### *Hypothetical Scenario 4 – Daily Average Flow Target and Reservoir Available to All Demands*

The storage at Source 2 is made available to all demands for Hypothetical Scenario 4. This requires the specification of a new link for delivering the supply to the residential demand (see Table D.9). Hypothetical Scenario 4 evaluates the response of the residential population growth and consumption patterns with access to all of the water not used for the assumed environmental requirements.

*Hypothetical Scenario 5 – Daily Average Flow Target, Reservoir to all Demands, Increased Cost of Delivery*

Scenario 5 changes the elevation head difference between Source 2 and Demand 1, effectively increasing the cost of delivery to meet residential demand from the reservoir. This change is noted in Table D.10.

*Hypothetical Scenario 6 – Daily Average Flow Target, Reservoir to all Demands, Overdraft*

The model's response to an overdraft is evaluated in Scenario 6 by increasing the starting residential population for Demand 1 such that the available source will be completely depleted within 18 months if initial consumption rates are maintained (see Table D.7).

*Hypothetical Scenario 7 – Historical Daily Flow Target, Overdraft*

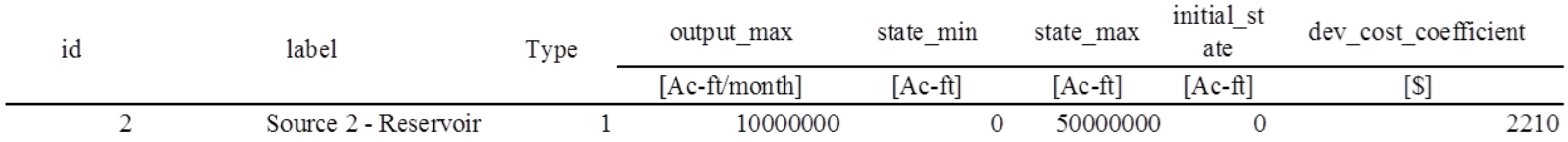
Overdraft conditions are evaluated under the historical daily flow target by increasing the initial population for Demand 1 such that the available source will be completely depleted within 18 months if initial consumption rates are maintained (see Table D.7).

*Hypothetical Scenario 8 – Historical Daily Flow Target, Overdraft*

Overdraft conditions are evaluated under the historical daily flow target by increasing the initial population for Demand 1 such that the available source will be completely depleted within 36 months if initial consumption rates are maintained (see Table D.8). The population is increased to one half the amount of Scenarios 6 and 7.

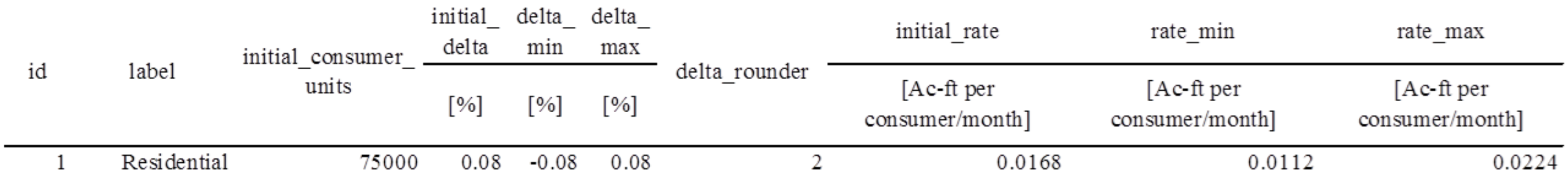
For reference, a verbal summary of the hypothetical scenarios is presented in Table D.12.

**Table D.6. Source node parameter changes for Hypothetical Scenarios 3, 4, 5 and 6. All parameters not listed maintain Hypothetical Scenario 1 values.**



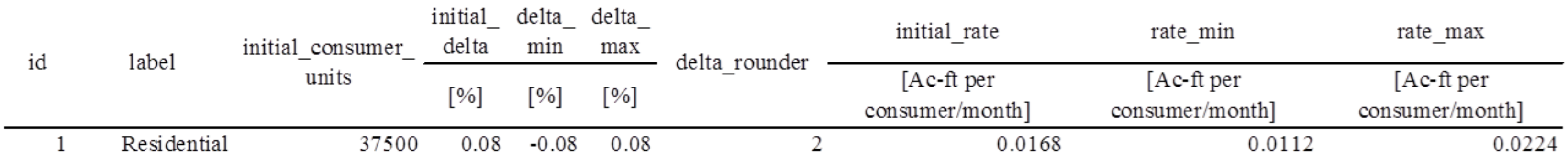
| id | label | Type | output_max | state_min | state_max | initial_state | dev_cost_coefficient |
|---|---|---|---|---|---|---|---|
| | | | [Ac-ft/month] | [Ac-ft] | [Ac-ft] | [Ac-ft] | [$] |
| 2 | Source 2 - Reservoir | 1 | 10000000 | 0 | 50000000 | 0 | 2210 |

**Table D.7. Demand node parameter changes for Hypothetical Scenarios 6 and 7. All parameters not listed maintain Hypothetical Scenario 1 values.**



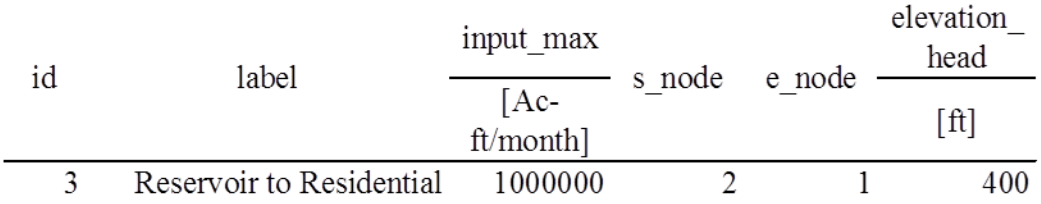
| id | label | initial_consumer_units | initial_delta | delta_min | delta_max | delta_rounder | initial_rate | rate_min | rate_max |
|---|---|---|---|---|---|---|---|---|---|
| | | | [%] | [%] | [%] | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] |
| 1 | Residential | 75000 | 0.08 | -0.08 | 0.08 | 2 | 0.0168 | 0.0112 | 0.0224 |

**Table D.8. Demand node parameter changes for Hypothetical Scenario 8. All parameters not listed maintain Hypothetical Scenario 1 values.**



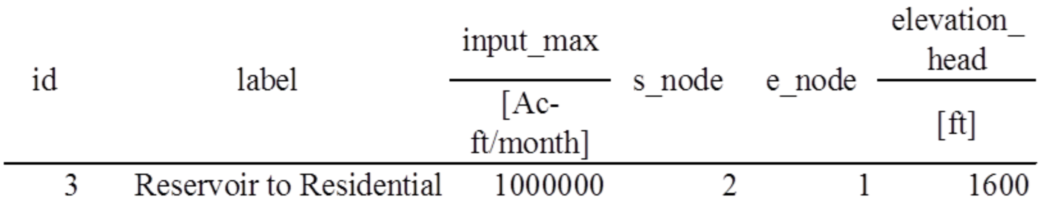
| id | label | initial_consumer_units | initial_delta | delta_min | delta_max | delta_rounder | initial_rate | rate_min | rate_max |
|---|---|---|---|---|---|---|---|---|---|
| | | | [%] | [%] | [%] | | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] | [Ac-ft per consumer/month] |
| 1 | Residential | 37500 | 0.08 | -0.08 | 0.08 | 2 | 0.0168 | 0.0112 | 0.0224 |

**Table D.9. Link parameters changes for Hypothetical Scenarios 4 and 6. All parameters not listed maintain Hypothetical Scenario 1 parameters.**



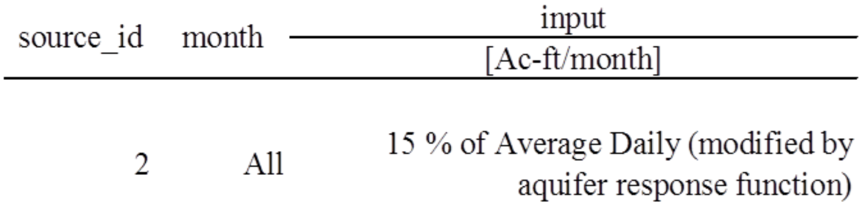
| id | label | input_max | s_node | e_node | elevation_head |
|---|---|---|---|---|---|
| | | [Ac-ft/month] | | | [ft] |
| 3 | Reservoir to Residential | 1000000 | 2 | 1 | 400 |

**Table D.10. Link parameters changes for Hypothetical Scenario 5. All parameters not listed maintain Hypothetical Scenario 1 parameters.**



| id | label | input_max | s_node | e_node | elevation_head |
|---|---|---|---|---|---|
| | | [Ac-ft/month] | | | [ft] |
| 3 | Reservoir to Residential | 1000000 | 2 | 1 | 1600 |

**Table D.11. Source node input parameters changes for Hypothetical Scenarios 3, 4, 5 and 6. All parameters not listed maintain Hypothetical Scenario 1 parameters.**



| source_id | month | input |
|---|---|---|
| | | [Ac-ft/month] |
| 2 | All | 15 % of Average Daily (modified by aquifer response function) |

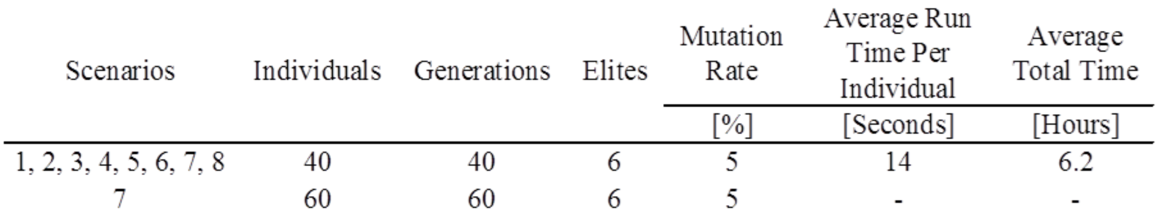
**Table D.12. Verbal summary of differences in the Hypothetical scenarios.**

| Scenario | Description |
|---|---|
| 1 | Historical river flows used as the target flows. Examines the sustainability and benefit for the current conditions. |
| 2 | 15% of average Julian day flows are used as the target flows. Examines the sustainability and benefits of additional water availability for population growth. |
| 3 | 15% of average Julian day flows are used as the target flows with reservoir storage available for river demands. Examines the impact of eliminating the aquifer dependency of the river supply. |
| 4 | 15% of average Julian day flows are used as the target flows with reservoir storage available for all demands. Examines the sustainability and benefits associated with the availability of all water not required for river environmental concerns. |
| 5 | 15% of average Julian day flows are used as the target flows with reservoir storage available for all demands, increased delivery costs. Examines the impact of increased delivery costs to the residential population. |
| 6 | 15% of average Julian day flows are used as the target flows with reservoir storage available for all demands. Overdraft - examines the model's response to an increased starting population (75,000). |
| 7 | Historical river flows used as the target flows. Overdraft - examines the model's response to an increased starting population (75,000). |
| 8 | Historical river flows used as the target flows. Overdraft - examines the model's response to an increased starting population (37,500). |

### *D.2.3 Results and Discussion*

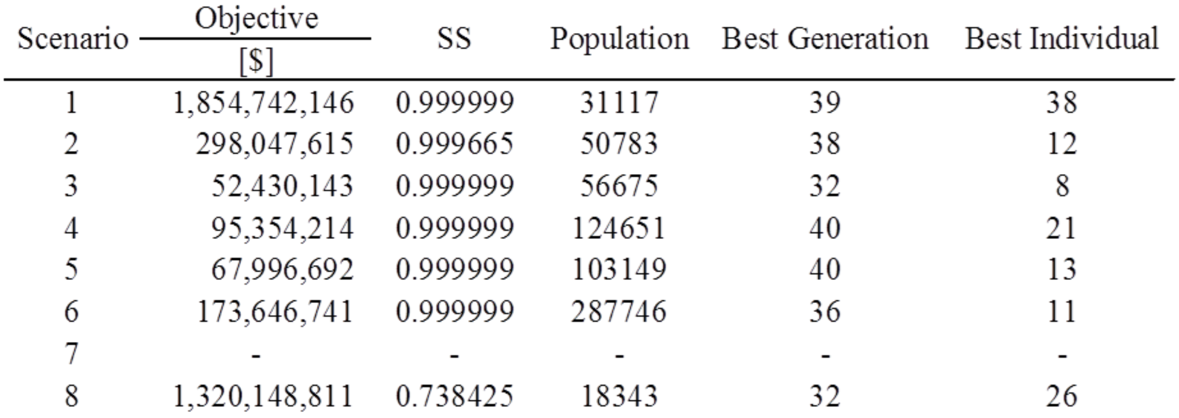
GA parameters were the same for each scenario and are presented with the average run time in Table D.13. Scenario 7 was run twice, the second time with an increased population and number of generations. No solution was found for Scenario 7 in both runs. GA parameters were selected after numerous Hypotheticals and run-time performance tweaks. Run-time was highly dependent upon hardware, with an order of magnitude decrease using solid-state drives (data storage). The scenarios were run on an i7 processor with 8 GB of RAM under a Windows 7 install of Apache 2.2, MySQL 5.6 and PHP 5.4 using the Google Chrome browser. Scenario results are reflected in Table D.14.

**Table D.13. GA parameters for the hypothetical scenarios and average run times.**



| Scenarios | Individuals | Generations | Elites | Mutation Rate | Average Run Time Per Individual | Average Total Time |
|---|---|---|---|---|---|---|
| | | | | [%] | [Seconds] | [Hours] |
| 1, 2, 3, 4, 5, 6, 7, 8 | 40 | 40 | 6 | 5 | 14 | 6.2 |
| 7 | 60 | 60 | 6 | 5 | - | - |

**Table D.14. Hypothetical Scenario results**



| Scenario | Objective | SS | Population | Best Generation | Best Individual |
|---|---|---|---|---|---|
| | [$] | | | | |
| 1 | 1,854,742,146 | 0.999999 | 31117 | 39 | 38 |
| 2 | 298,047,615 | 0.999665 | 50783 | 38 | 12 |
| 3 | 52,430,143 | 0.999999 | 56675 | 32 | 8 |
| 4 | 95,354,214 | 0.999999 | 124651 | 40 | 21 |
| 5 | 67,996,692 | 0.999999 | 103149 | 40 | 13 |
| 6 | 173,646,741 | 0.999999 | 287746 | 36 | 11 |
| 7 | - | - | - | - | - |
| 8 | 1,320,148,811 | 0.738425 | 18343 | 32 | 26 |

The highest objective value was achieved in Hypothetical Scenario1 due to the historical flow basis for the river demand: the entire volume of water is ‘consumed’ and of beneficial value. The lowest objective value is realized in Hypothetical Scenario 3 which used 15% of the average Julian day flow (hereafter referred to as 15%) for the river demand and introduced the availability of reservoir storage for river demands. This significantly reduced water consumption and introduced a cost for water delivered to the river, representative of the associated infrastructure. Maximum SS values were realized across all scenarios except Hypothetical Scenario 2 and Hypothetical Scenario 8. Hypothetical Scenario 2 is slightly below optimal due to unmet river demand in years 48, 49 and 50 of the LTM. Hypothetical Scenario 8 started in an overdraft condition and river demand was not met a majority of the time, affecting the SI for river demand and the RVA. Note that the maximum SS value is not 1 for the scenarios due to the SS being weighted equally among 3 sustainability groups (Demand 1, Demand 2 and RVA).

Population levels vary greatly across the scenarios. Growth in Hypothetical Scenario 1 is limited due the sensitivity of the river supply to the aquifer storage levels: the historical flows were the highest river demand basis. The highest ending population is achieved in Hypothetical Scenario 6 and the lowest in Hypothetical Scenario 8. Hypothetical Scenario 6 starts with a higher initial population value, which is the basis for future growth. The starting population in Hypothetical Scenario 8 is much higher than Hypothetical Scenarios 1, 2, 3, 4 and 5, but finishes lowest as water consumption is reduced to compensate to achieve maximum sustainable net benefit.

A graph of the scenario population growth is shown in Figure D.2. All scenarios with the exception of Hypothetical Scenarios 6 and 8 are nearly identical for approximately the first 5 years. There is a slight difference between Hypothetical Scenarios 1 and 2 (historical and 15% target flows respectively) from years 5 to 37, with Hypothetical Scenario 2 seeing a lower population over this time and then increasing for the remainder of the simulation. This difference is attributed to the higher consumption rates realized in Hypothetical Scenario 2 as reflected in Figure D.3. Population growth rates are expected to be higher for Hypothetical Scenarios 3, 4 and 5 due to introduction of the reservoir storage and de-coupling of the aquifer storage level and immediate supply available to the river demand. Hypothetical Scenario 3 is the lowest of the three with reservoir storage only available to the river demand, with a final population only slightly higher than Hypothetical Scenario 2. Hypothetical Scenario 4 finishes highest of the three with the reservoir storage being available for residential growth and the lower cost of delivery from the reservoir. Hypothetical Scenario 6 starts in overdraft conditions and sees an initial decline in population as the model reduces residential consumption to meet river demands. Hypothetical Scenario 8 starts in overdraft conditions with one half of Hypothetical Scenario 6's initial population, but stays low for the entire long-term time horizon as the river's demand is much higher and sensitive to the storage levels in Source 1.

Figure D.2. Hypothetical scenario population growth.

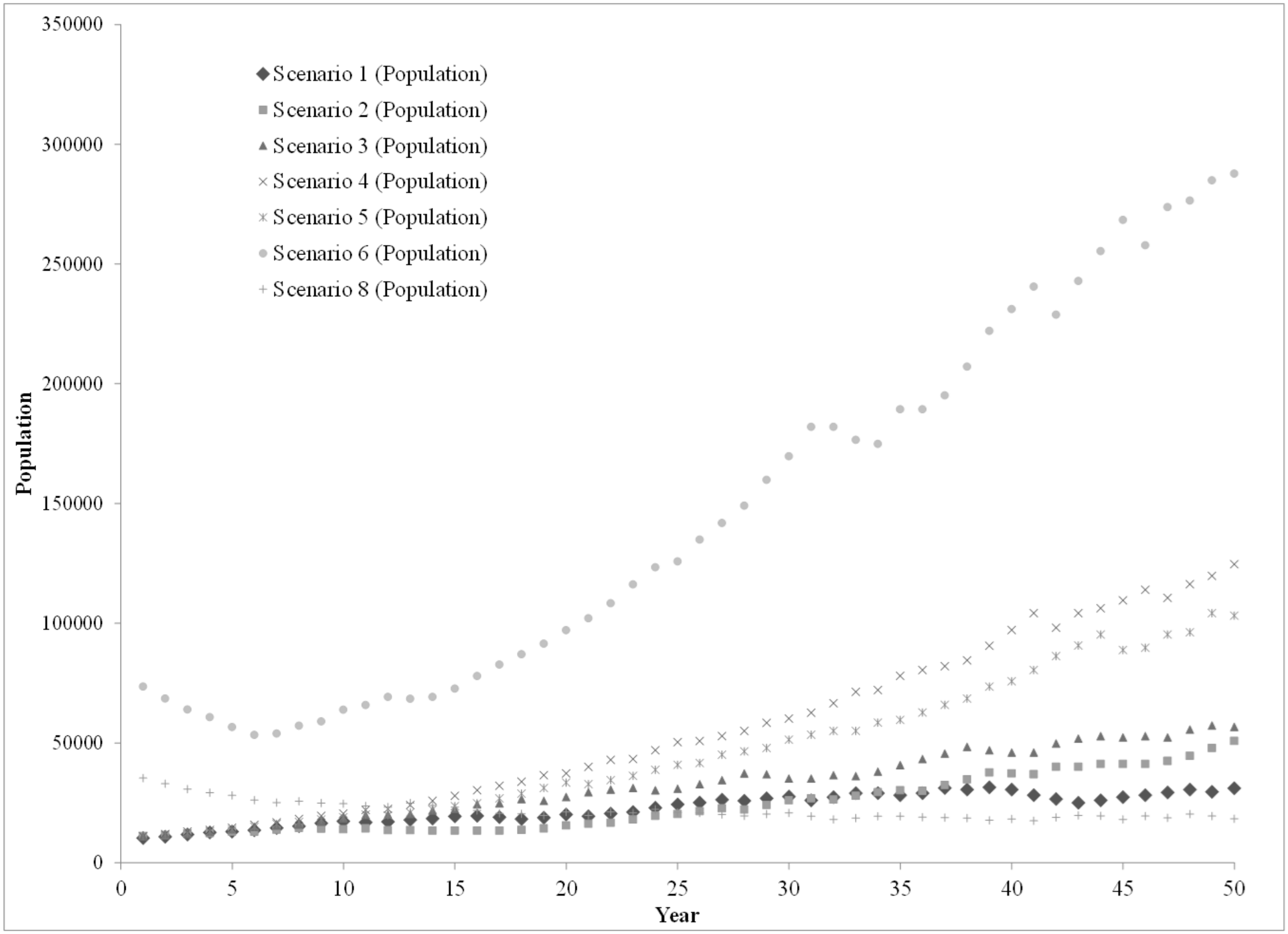
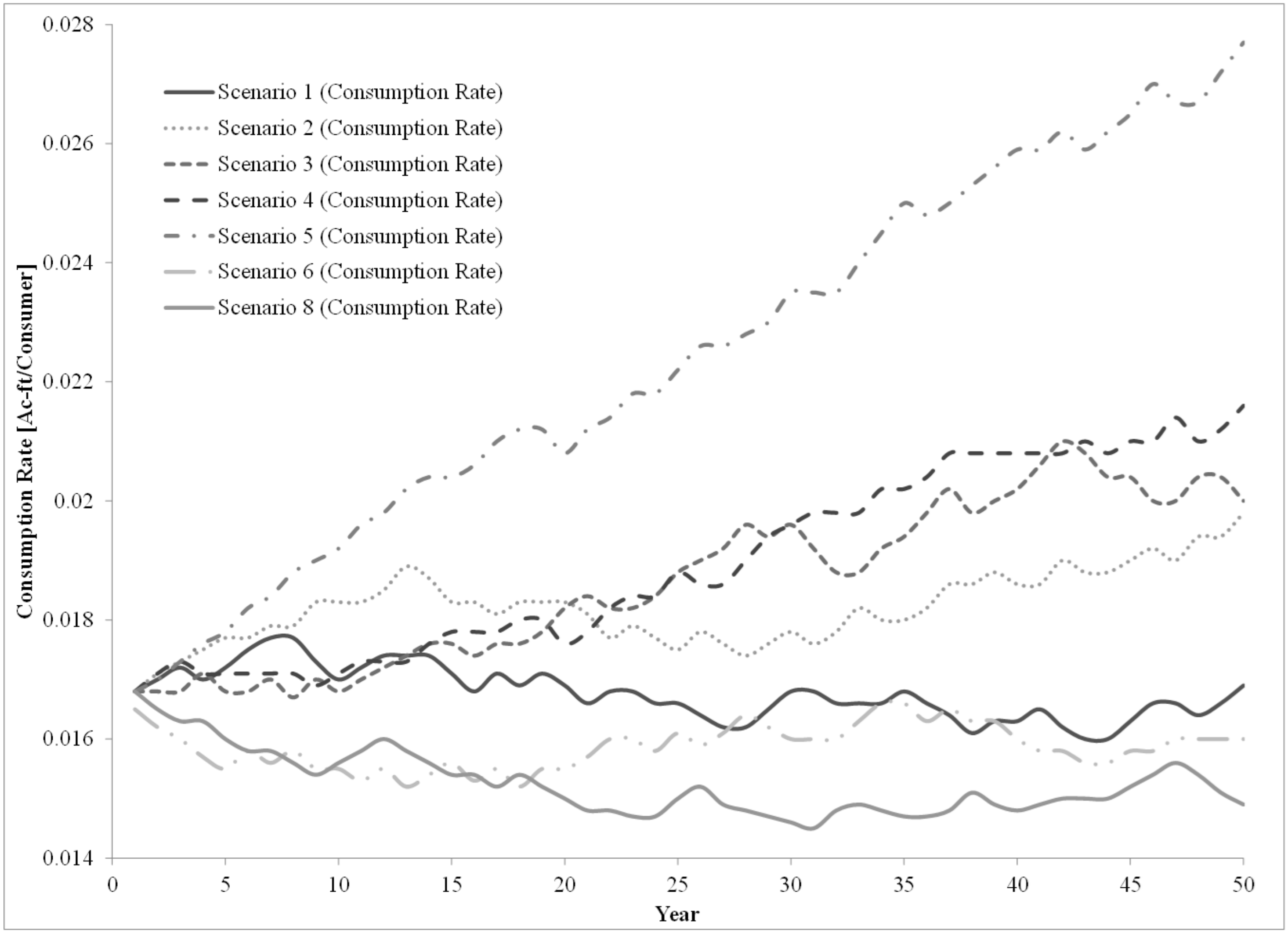


Figure D.3. Hypothetical scenario consumption rates.



As net benefit is based upon unit of water consumed, population can decrease with no detriment to net benefit if consumption rate increases (or vice-versa) for all the Hypothetical scenarios. As mentioned previously, this is reflected in the population growth and consumption rates for Hypothetical Scenarios 1 and 2, as indicated in Figure D.2 and D.3. Hypothetical Scenarios 3 and 4 demonstrate no significant differences in consumption rate, both trending upwards across the long-term time horizon. Hypothetical Scenarios 6 and 8 both decline initially, which is attributed to the higher initial population and overdraft. Hypothetical Scenario 8 continues the decline until approximately year 40, but never reaches the minimum (0.0112). Hypothetical Scenario 5 has by far the largest increase in consumption rate (approximately 60%), as the model is attempting to maximize net benefit for the given population, and a surplus of water is available from the reservoir. This is compensating for the lower population growth as compared to Hypothetical Scenario 4, similar to the differences between Hypothetical Scenarios 1 and 2. This is also reflected in the total volume supplied to Demand 1 shown in Figure D.4.

Change in Source 1 (Well Field) for all the scenarios is presented in Figure D.5. With the exception of Hypothetical Scenarios 6 and 8 (both in overdraft), all of the scenarios realize an initial increase in the available storage volume. Storage in Hypothetical Scenario 6 begins to increase after approximately the second year as reservoir storage becomes available. It continues to increase until year 39, when reservoir storage is insufficient to meet demands (see Figure D.6). Hypothetical Scenario 8 sees a decline until year 14, after which it increases for the duration of the long-term time horizon. Source 1 storage for Hypothetical Scenario 6 experiences the most rapid decline, beginning in approximately year 44, due to the reliance of the river on the reservoir, and inadequate storage in the reservoir to meet residential demands. Hypothetical Scenarios 4 and 5 both completely deplete the aquifer storage levels, with Hypothetical Scenario 5 experiencing a more rapid decrease due to the increased cost of delivering from the reservoir.

Figure D.6 depicts the change in storage for Source 2 (Reservoir). Storage in Scenarios 3, 4 and 5 are nearly identical until approximately year 20, when storage in Hypothetical Scenario 5 begins to deviate, and in year 30 when Hypothetical Scenario 3 sees a reduction in the rate of accumulation. The reduction in accumulation rate for Hypothetical Scenario 3 is attributed to the declining storage in Source 1 and the reduced river supply (see Figure D.5), which also explains the departure for Hypothetical Scenario 5. As storage decreases below the initial value, river supply is impacted. Hypothetical Scenario 4 remains high as the lower delivery costs result in a preference to supply residential demands from Source 2.

Figure D.4. Hypothetical scenario volume supplied.

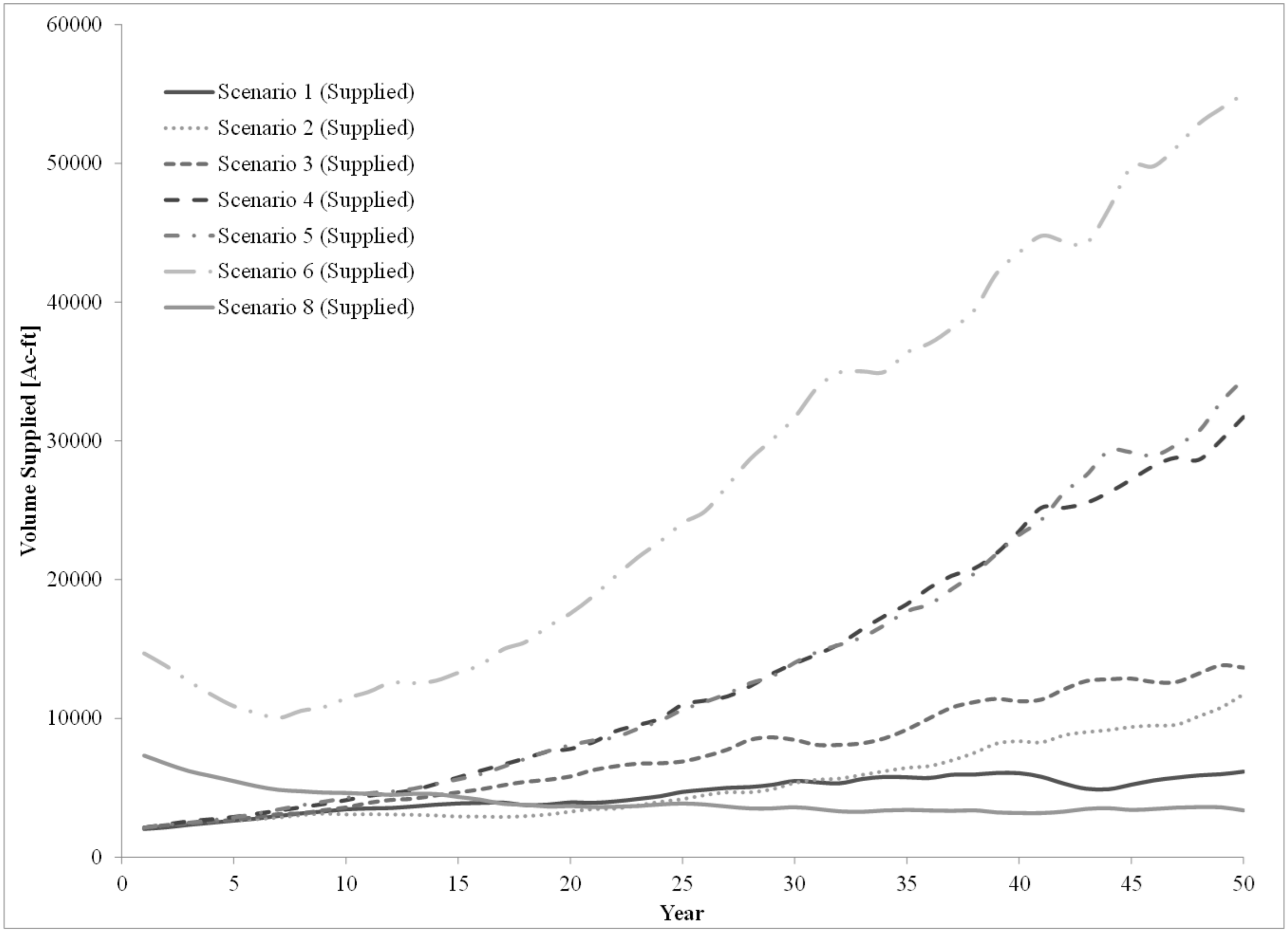


Figure D.5.  Hypothetical scenario changes in Source 1 storage.

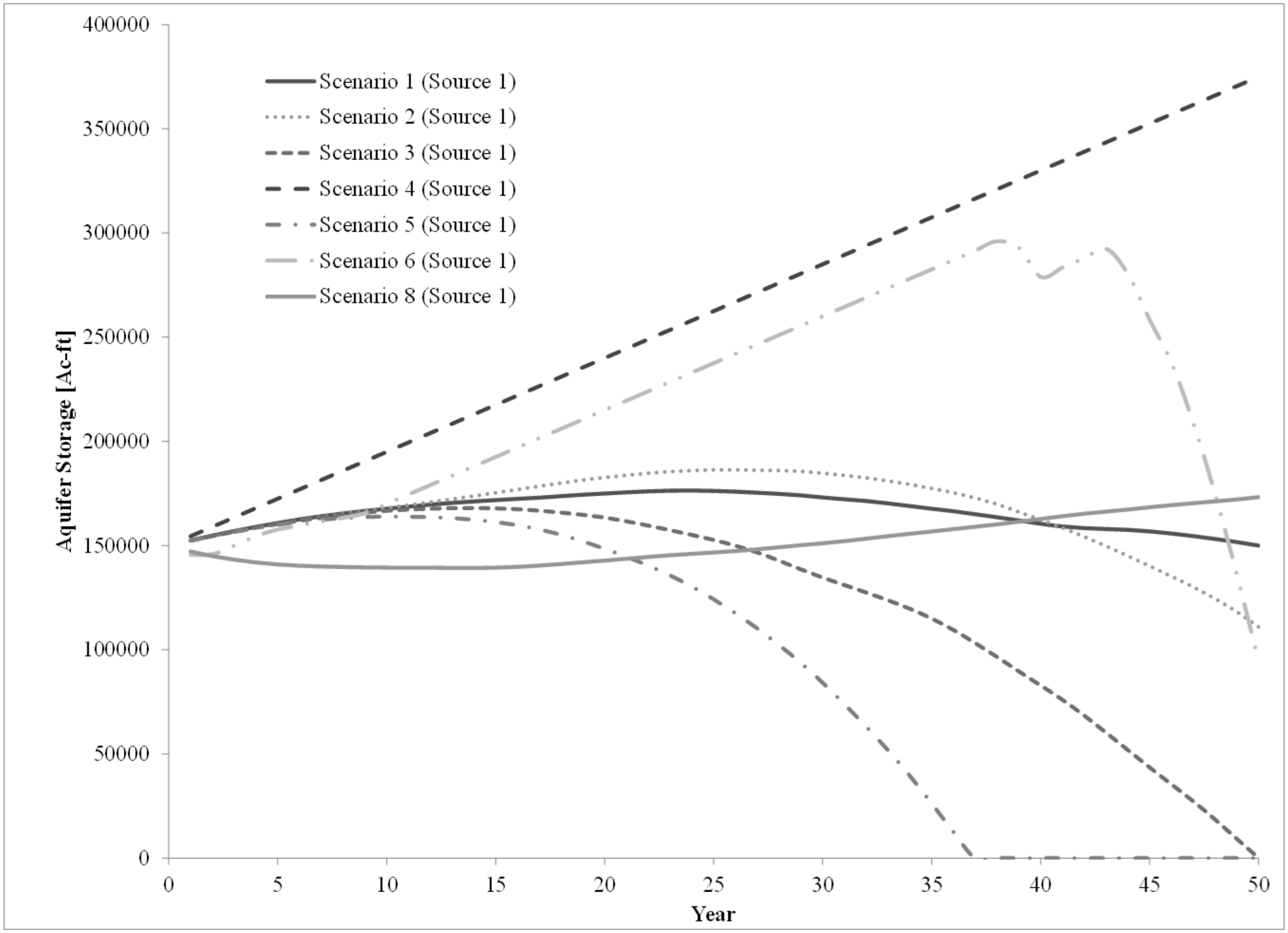
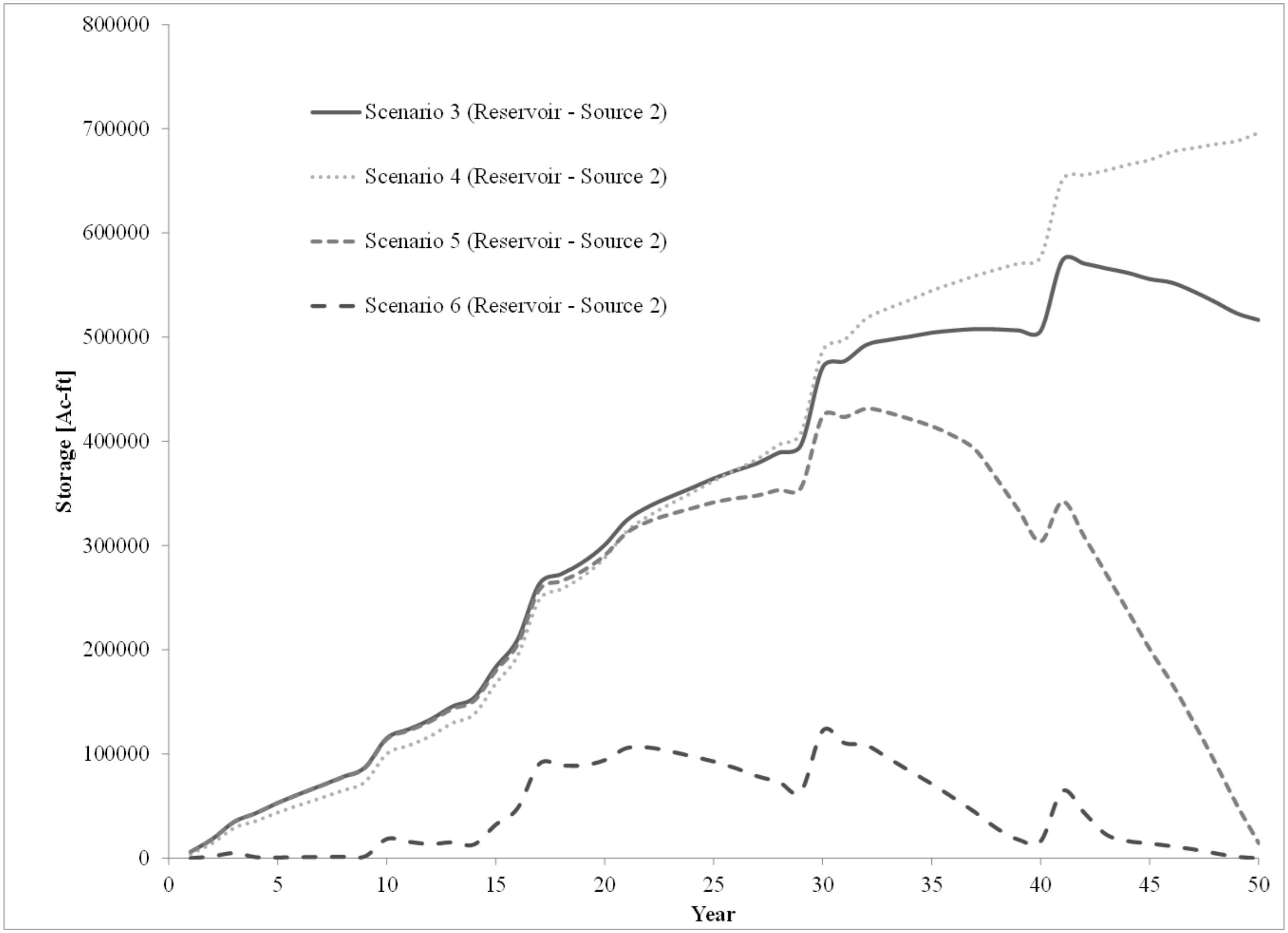
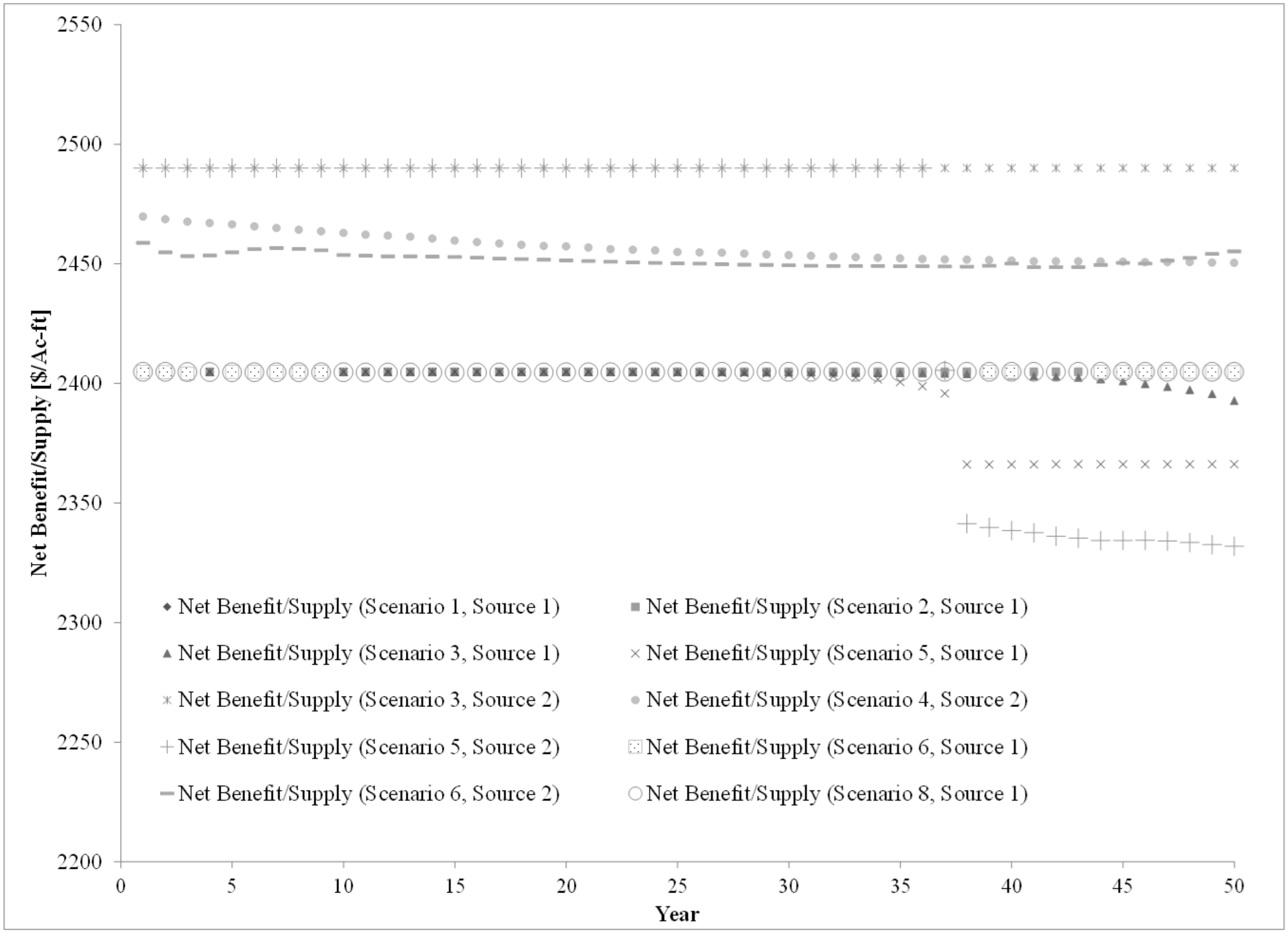


**Figure D.6. Hypothetical scenario changes in Source 2 reservoir storage.**



Net benefit per unit supplied from each of the sources for all scenarios is shown in Figure D.7. Source 2 (Reservoir) for Hypothetical Scenarios 3 and 5 sees the highest net benefit per unit supplied, with Hypothetical Scenario 5 seeing a sharp decline on its way to the lowest net benefit per unit starting in year 36 and continuing the decline at a reduced rate in year 38. Referring to Figure D.5, Source 1 (Well Field) is emptied in year 36, which forces residential demand to be supplied from Source 2 (Reservoir) despite the higher cost of delivery. The sharp decline in net benefits from Source 2 in Hypothetical Scenario 5 is attributed to the cost of delivery to Demand 1 (Residential). The cost of depletion ($CostDep_{i,t}$) is evidenced as the decline in net benefits for Source 1 in Hypothetical Scenarios 3 and 5, in approximately year 38 and year 30 respectively. Hypothetical Scenario 5 reaches a steady state as the Well Field storage is fully depleted and supply is limited to the inflow for the source in year 38. Hypothetical Scenario 3 continues to decline for the remainder of the long-term time horizon. Source 2 (Reservoir) for Hypothetical Scenario 6 is the only source that realizes an increase over time in net benefit per unit supply which is attributed to how much supply the source is contributing to Demand 1 (Residential): supply to Demand 1 has a cost of delivery. The net benefit per unit supply remains relatively constant in Hypothetical Scenario 8.

Figure D.7.  Hypothetical scenario net benefit over volume supplied.



SS versus Net Benefit for Hypothetical Scenarios 1 and 8 are examined in Figure D.8. No relationship is apparent with the same SS value realized for multiple values of Net Benefit. At smaller values there is a tendency for the SS values to gap as the SI has a value of zero if one of the performance criteria is zero. The tendency to gap decreases as the SS approaches 1 (sustainability) and demands are being satisfied more often.

Recall that the SS is comprised of 3 SI groups: Demand 1(Residential), Demand 2 (River) and the SI for the RVA (which is only performed on Demand 2). The Demand 1 SI values for every individual in Generation 40 of Hypothetical Scenarios 1 and 8 are all equal to 1. Figure D.9 shows the values of the SI performance criteria for Demand 2. Resilience appears to be the most sensitive to un-met demands in this generation with a higher frequency of zero values. This same information for Hypothetical Scenario 8 is presented in Figure D.10. In this case both Reliance and Resilience are impacting the SI, with Resilience essentially zero for every individual.

Figure D.8.  SS versus net benefit for Hypothetical Scenarios 1 and 8.

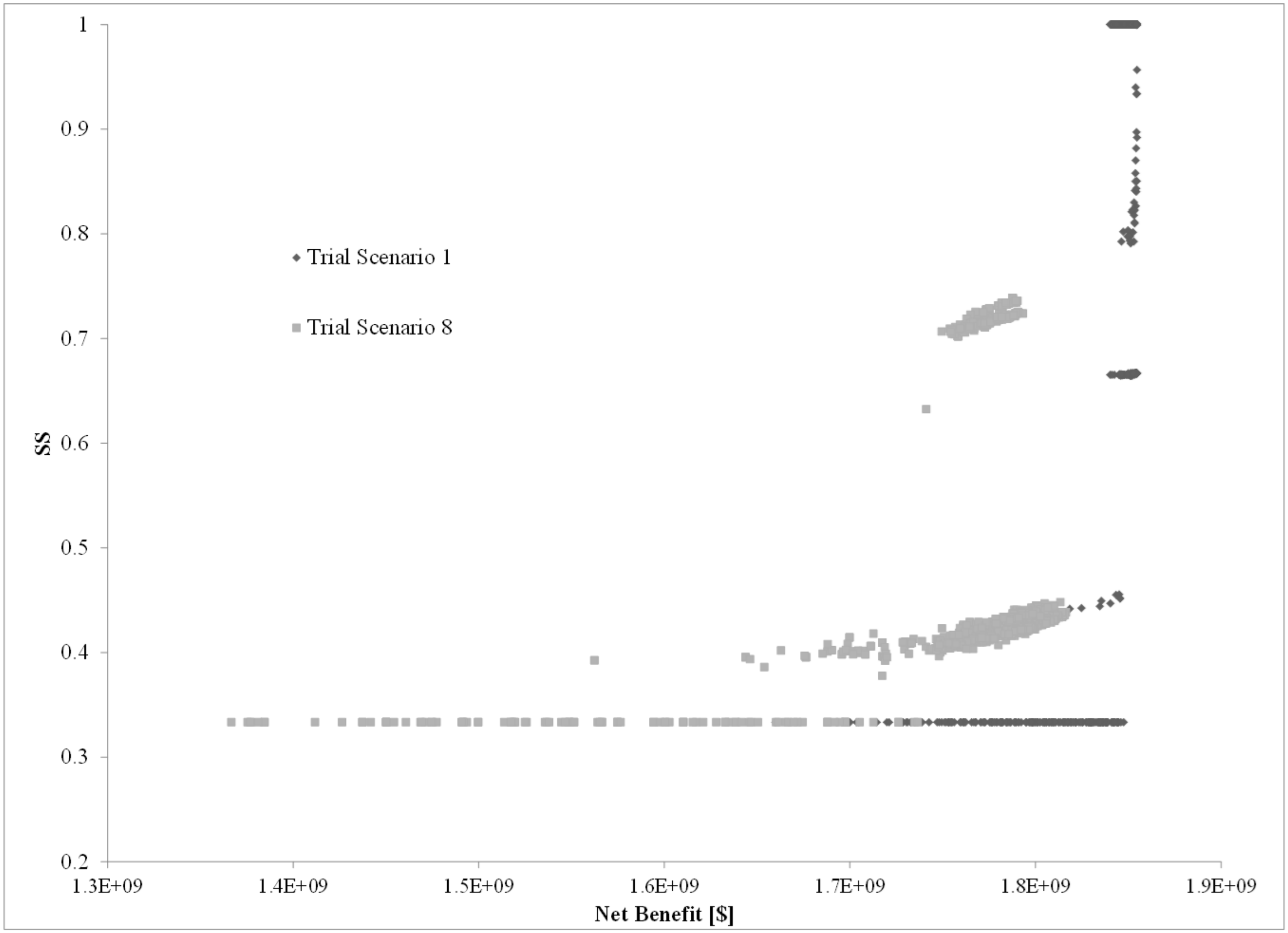


**Figure D.9. Demand 2 Group 1 SI performance criteria for Hypothetical Scenario 1, Generation 40.**

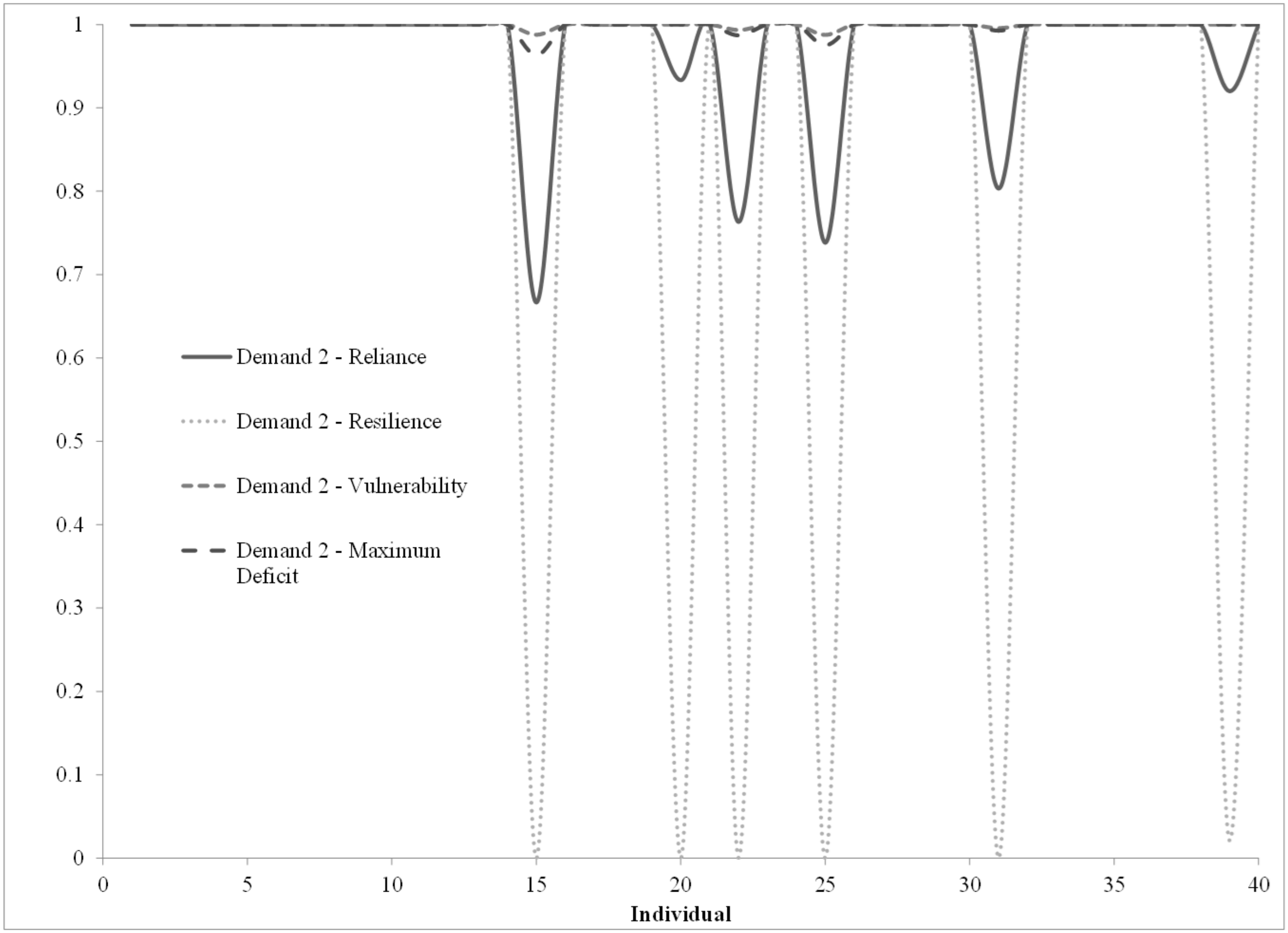
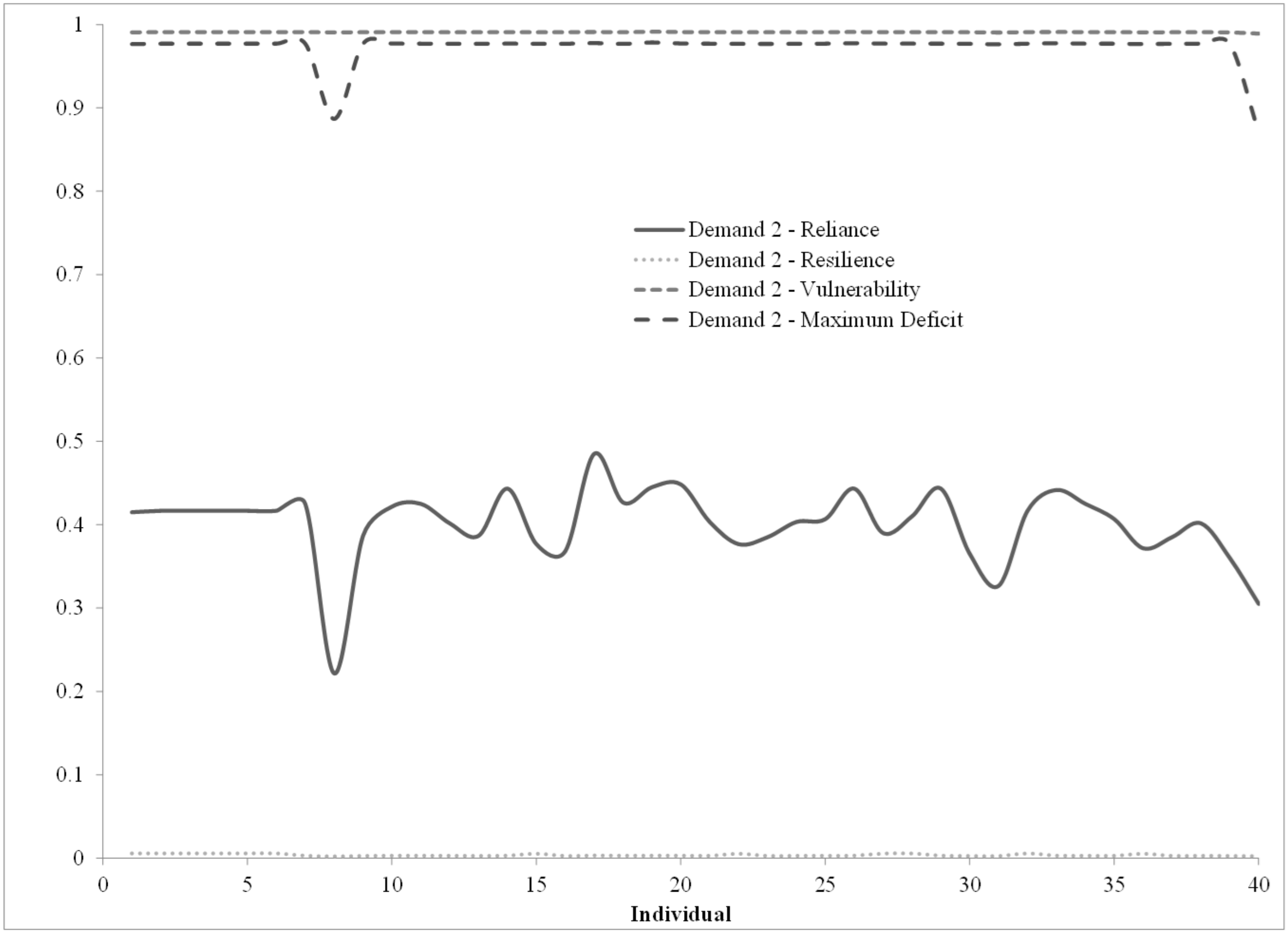


Figure D.10. Demand 2 Group 1 SI performance criteria for Hypothetical Scenario 8, Generation 40.



The SI for the RVA on Demand 2 is plotted against the SI for Demand 2 in Figure D.11. No relationship is apparent with multiple corresponding values of each SI. The RVA SI for Hypothetical Scenario 1 reaches sustainability at a value of 1, Scenario 8 reaches a high of approximately 0.30. The composition of these values is examined in Figures D.12 and D.13 respectively. These figures display all of the RVA performance criteria ( $HA_{j,IHA,Bin}^{Mod}$) with non-zero (non-optimal) values for Generation 40 in Hypothetical Scenarios 1 and 8. The IHAs for both scenarios are broken down for Bins 1, 2 and 3 in Figures D.14 through D.19. These plots give an indication of which IHAs were most frequently impacted for the last generation of each scenario. Recall that the modified HA is measuring the observed frequency of an IHA value (modeled flow) against the expected frequency of an IHA value (target flow) and that zero is the optimal value (no difference between modeled flow and target flow, see Chapter 3). A negative value indicates that the frequency of an IHA value for the modeled flow is less than the frequency of an IHA value for the target flow. A positive value indicates that the frequency of an IHA value for the modeled flow is more than the frequency of an IHA value for the target flow. Bins 1, 2 and 3 represent the lower, middle and top third (magnitude) of the expected values respectively. For additional discussion, refer to Chapter 4.

General observations can be made for both scenarios. Bin 1 (Figures D.14 and D.17) is the lower third value of the IHAs for each scenario. Hypothetical Scenario 1 shows some non-optimal values for the Base Flow Index and the Low Pulse Counts, but for the most part, Observed values are equal to Expected values for each IHA.

Hypothetical Scenario 8 realizes a much broader range of non-optimal IHA values, with the largest displacements seen in the Rise Rate and the High Pulse Duration. The Rise Rate is negative, suggesting that lower (in magnitude) (Bin 1) Observed values of the Rise Rate occur less frequently than Expected values of the Rise Rate. High Pulse Duration is greater than 0, suggesting that the High Pulse Durations are lower overall for modeled flow. These generalizations can be made for all of the Bin data to give some indication of how the modeled flow is failing to meet the target flow. It is also noted that the SI for the RVA in Scenario 1 has negligible impact on the SS for the scenario.

Figure D.11.  SI for the RVA versus SI for Demand 2 for Hypothetical Scenarios 1 and 8.

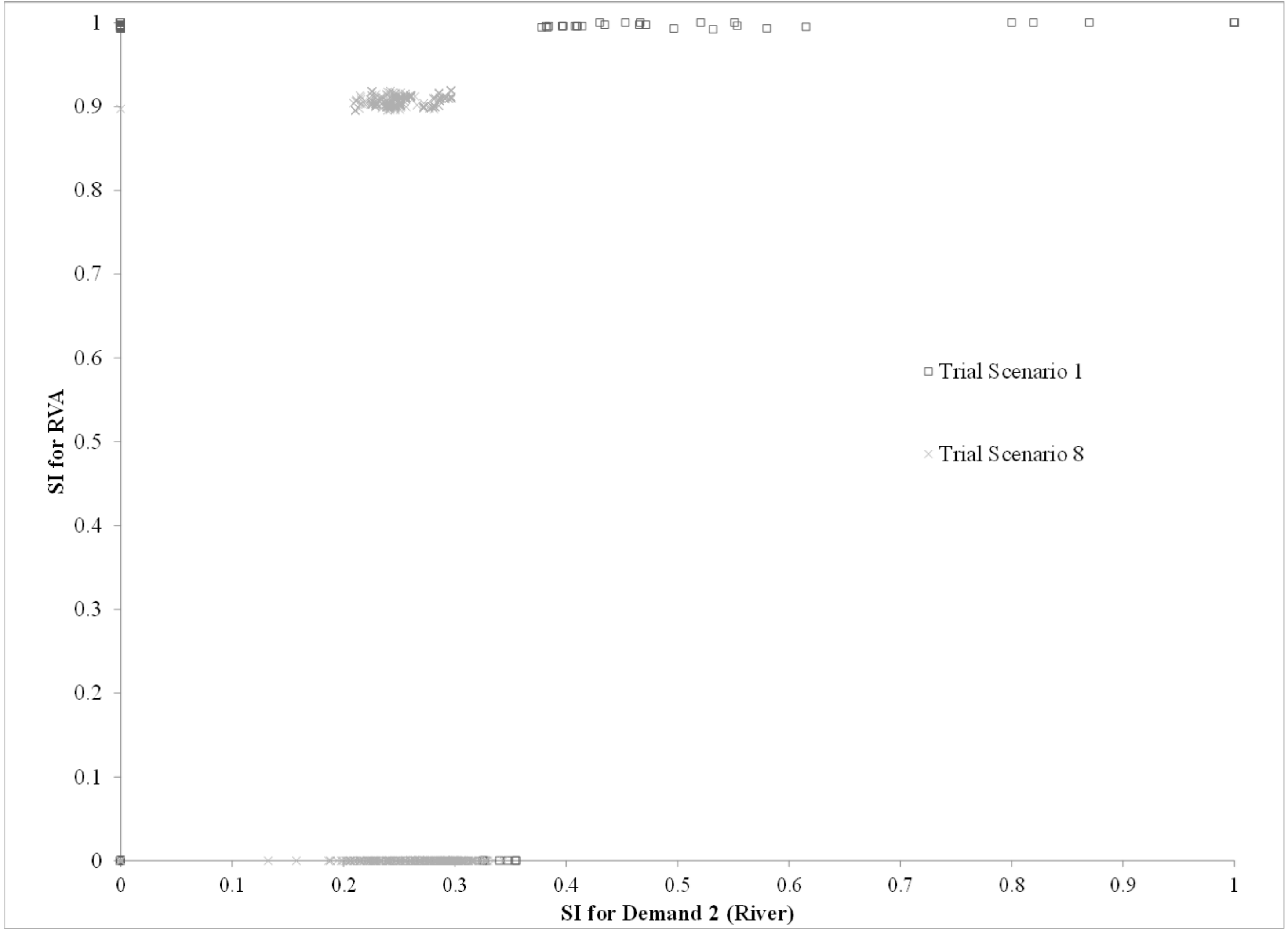


**Figure D.12. RVA SI performance criteria that have non-zero values (zero is optimal) for Hypothetical Scenario 1, Generation 40. The displayed data is for all three bins.**

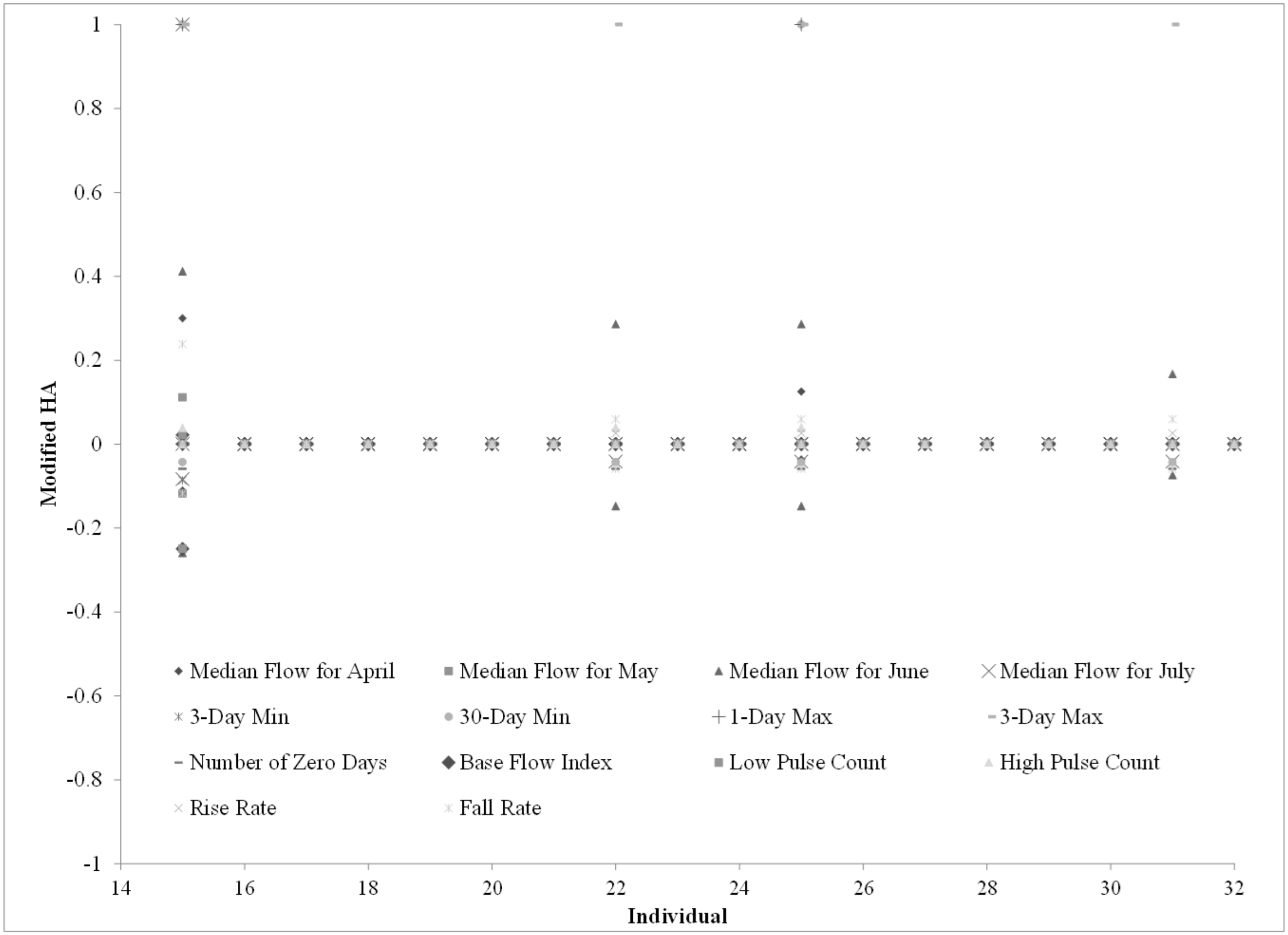


**Figure D.13. RVA SI performance criteria that have non-zero values (zero is optimal) for Hypothetical Scenario 8, Generation 40. The displayed data is for all three bins.**

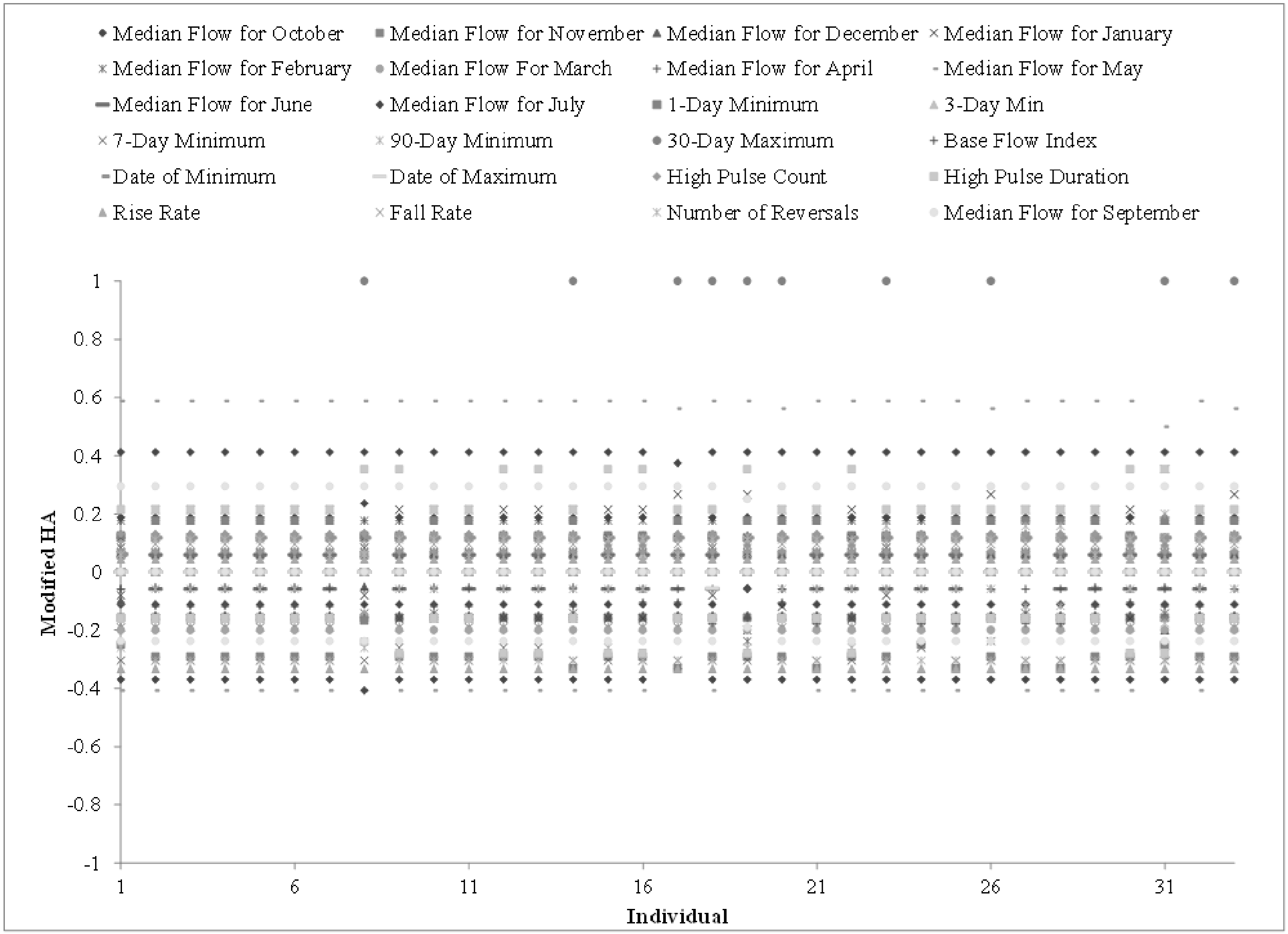


Figure D.14.  Non-zero Bin 1 RVA performance criteria for Hypothetical Scenario 1 Generation 40.

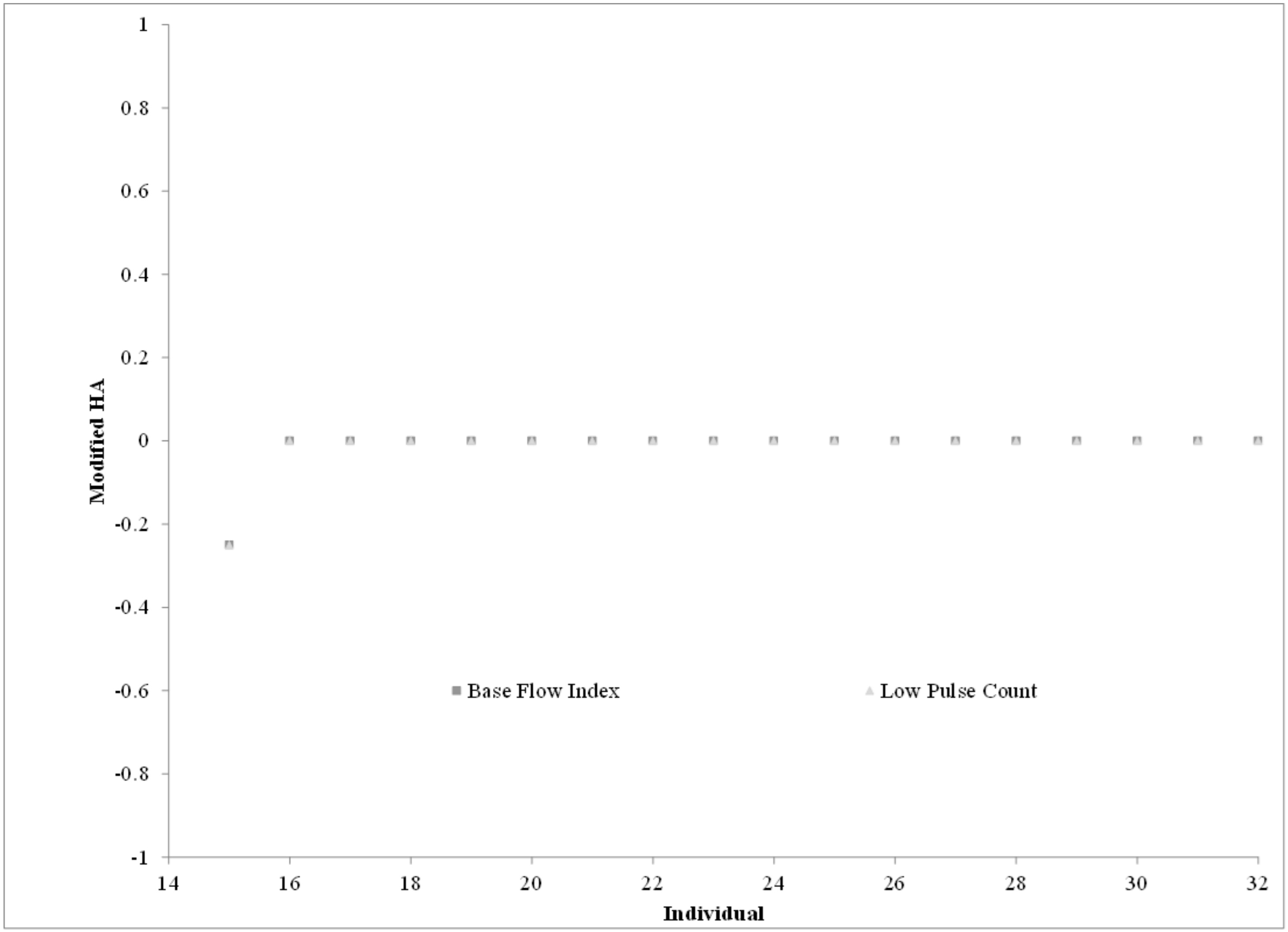


**Figure D.15. Non-zero Bin 2 RVA performance criteria for Hypothetical Scenario 1 Generation 40.**

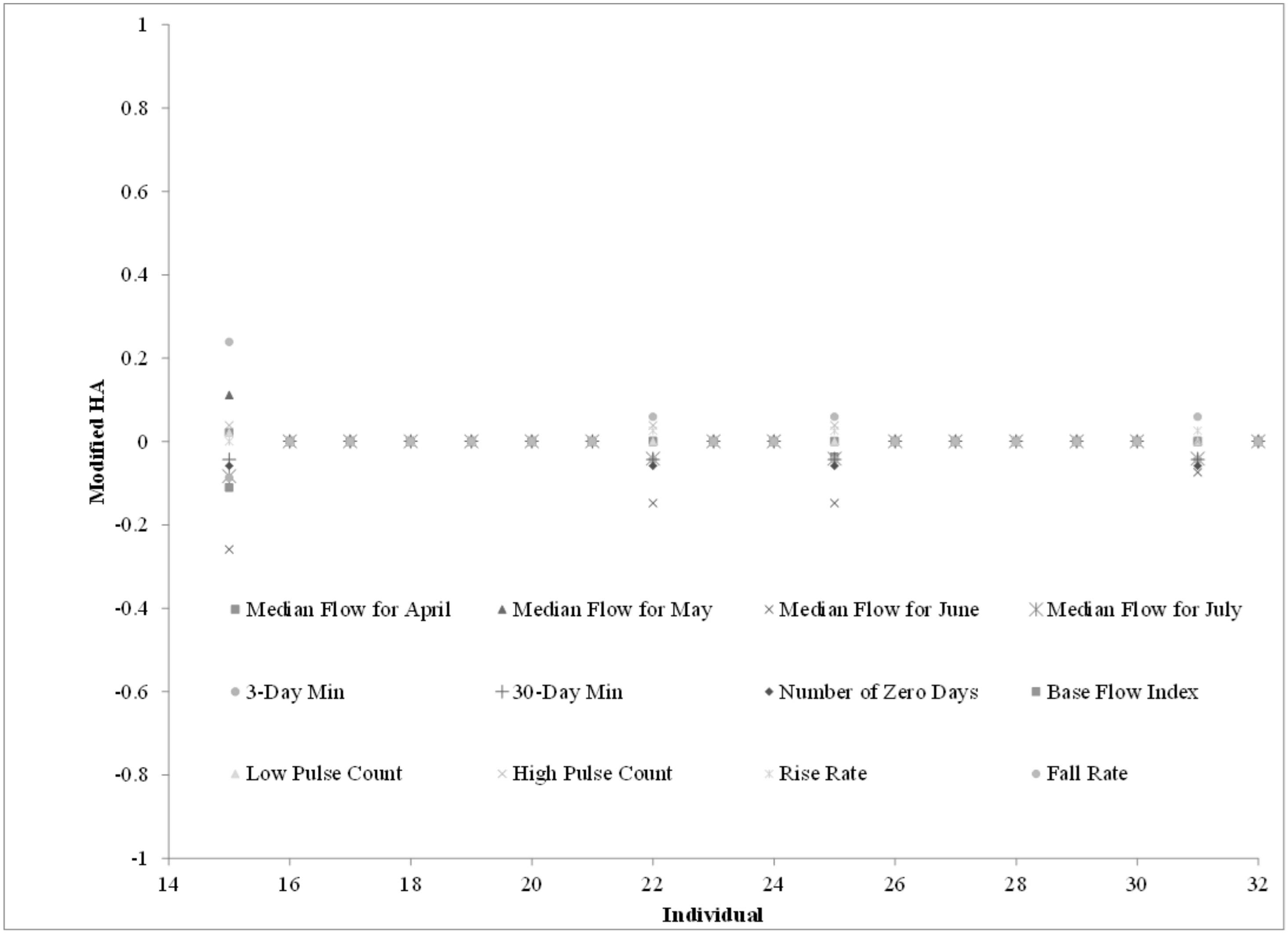


Figure D.16.  Non-zero Bin 3 RVA performance criteria for Hypothetical Scenario 1 Generation 40.

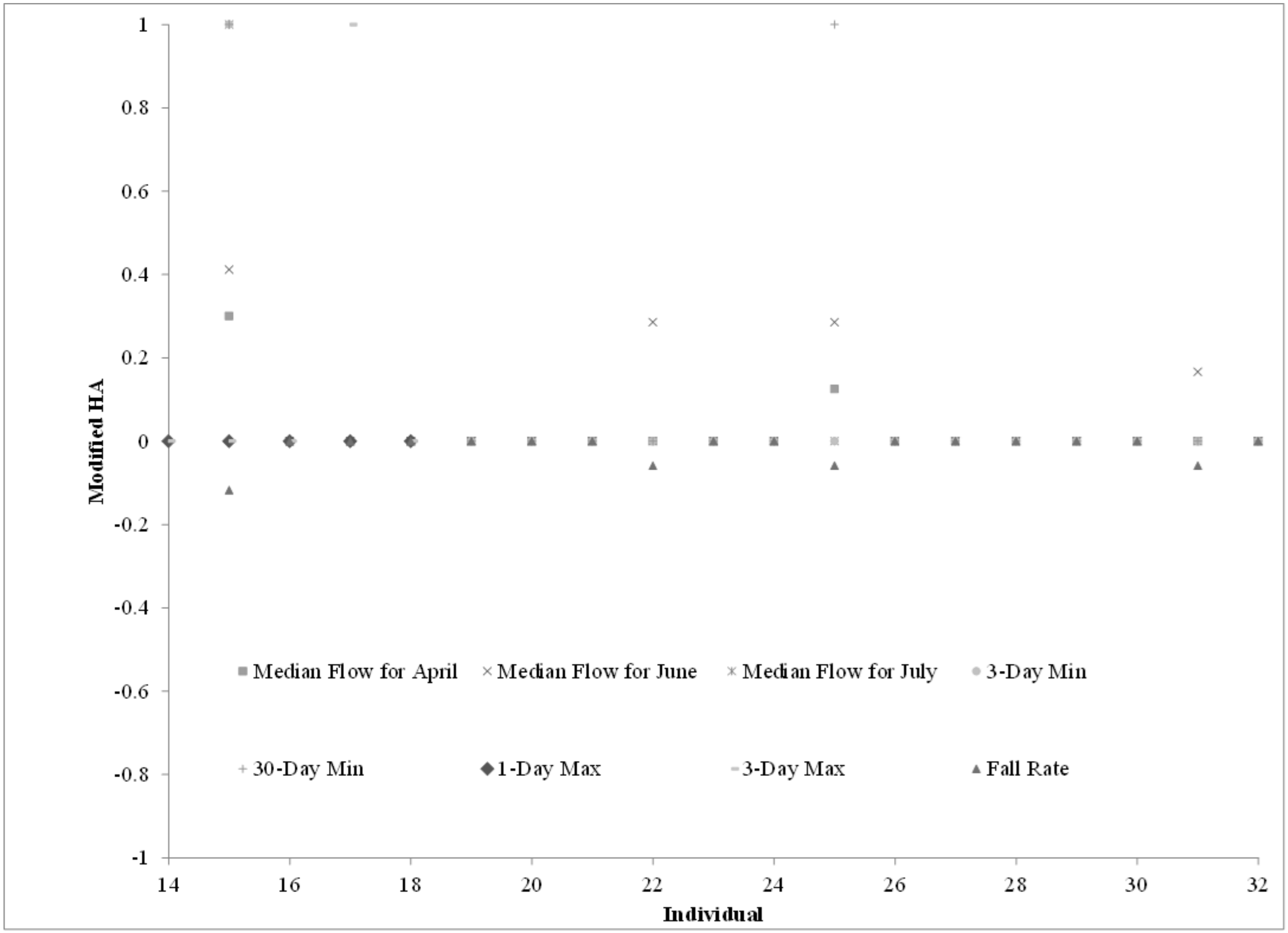
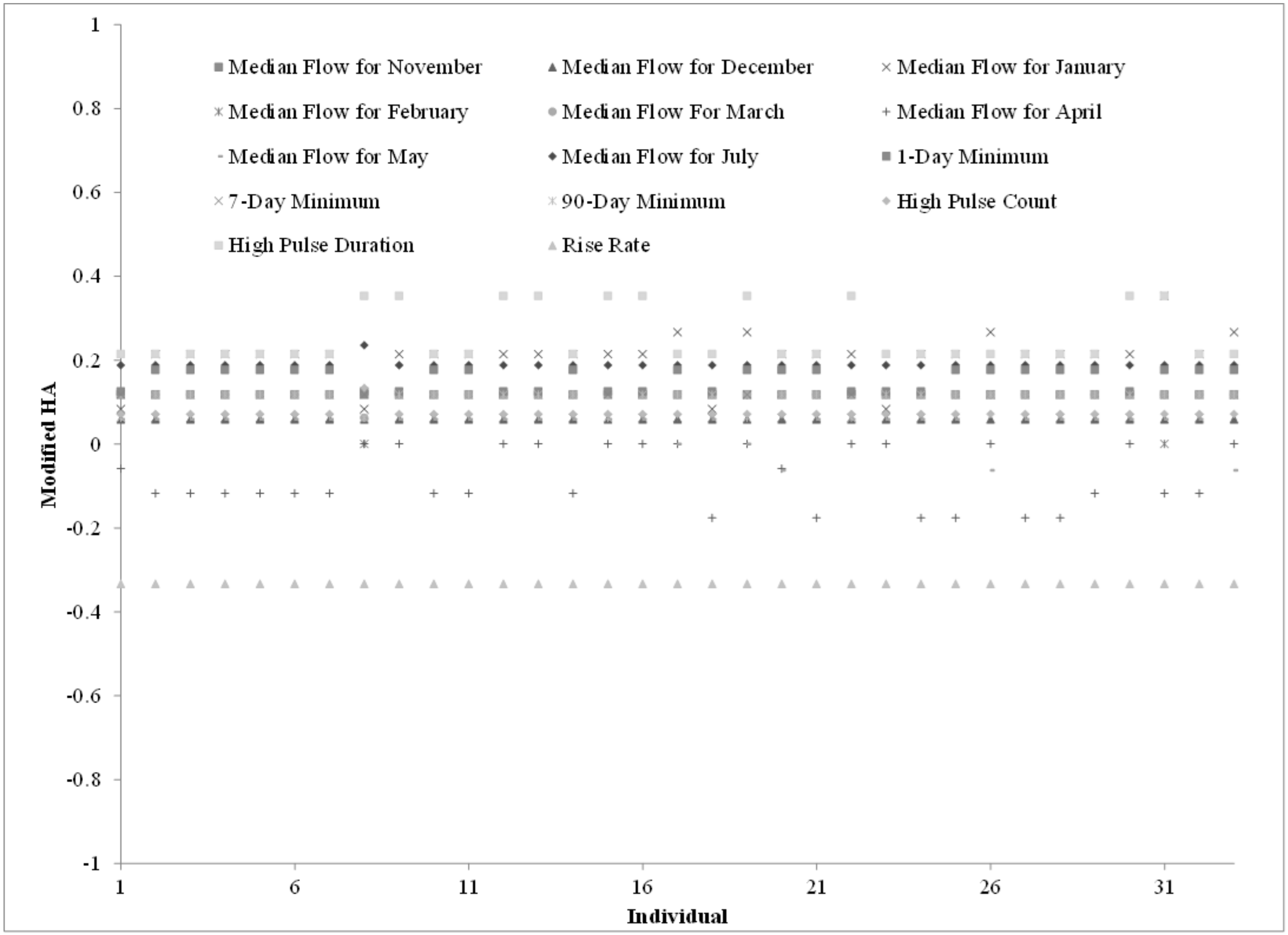


Figure D.17.  Non-zero Bin 1 RVA performance criteria for Hypothetical Scenario 8 Generation 40.



## Figure D.18. Non-zero Bin 2 RVA performance criteria for Hypothetical Scenario 8 Generation 40.

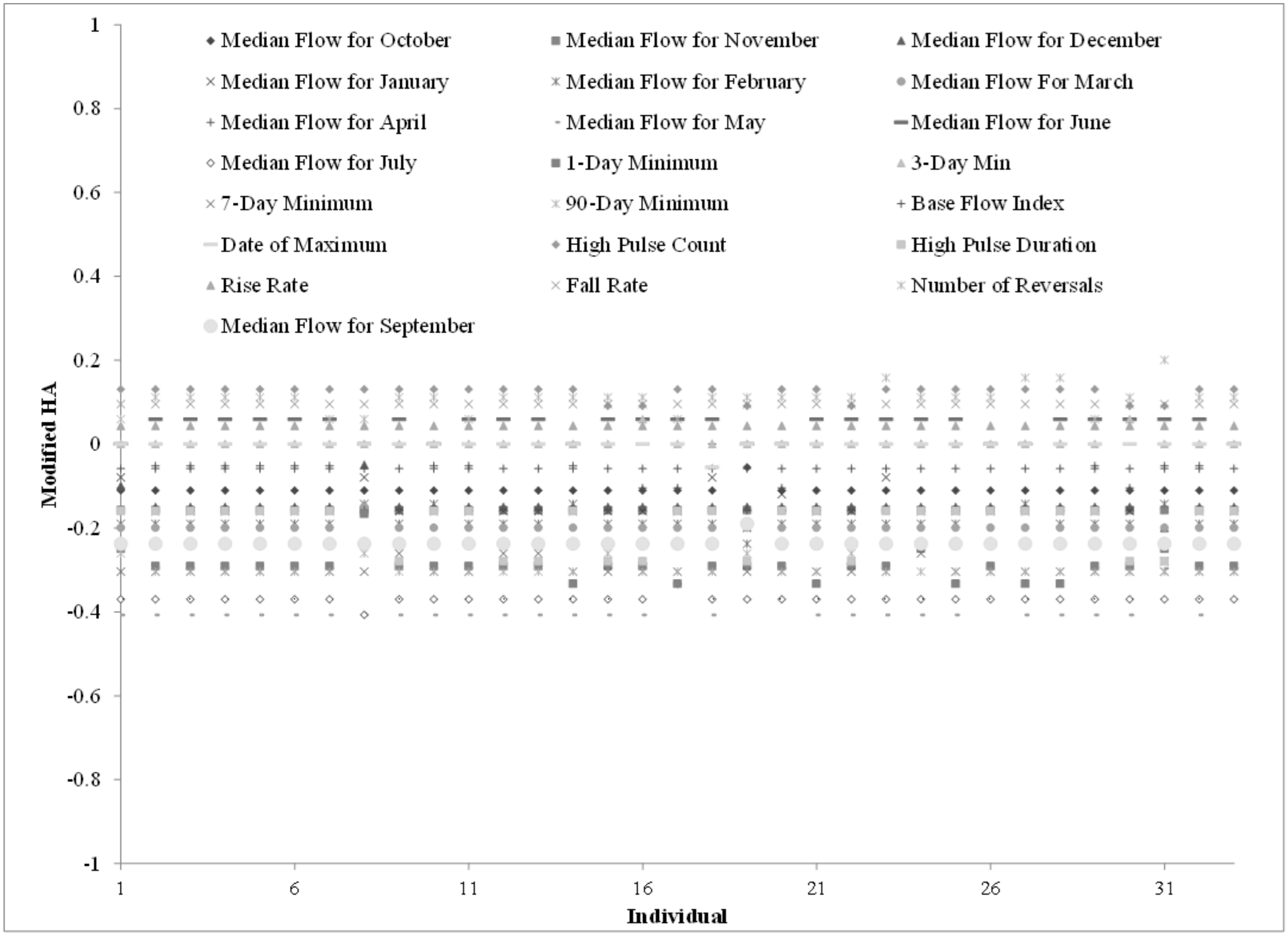
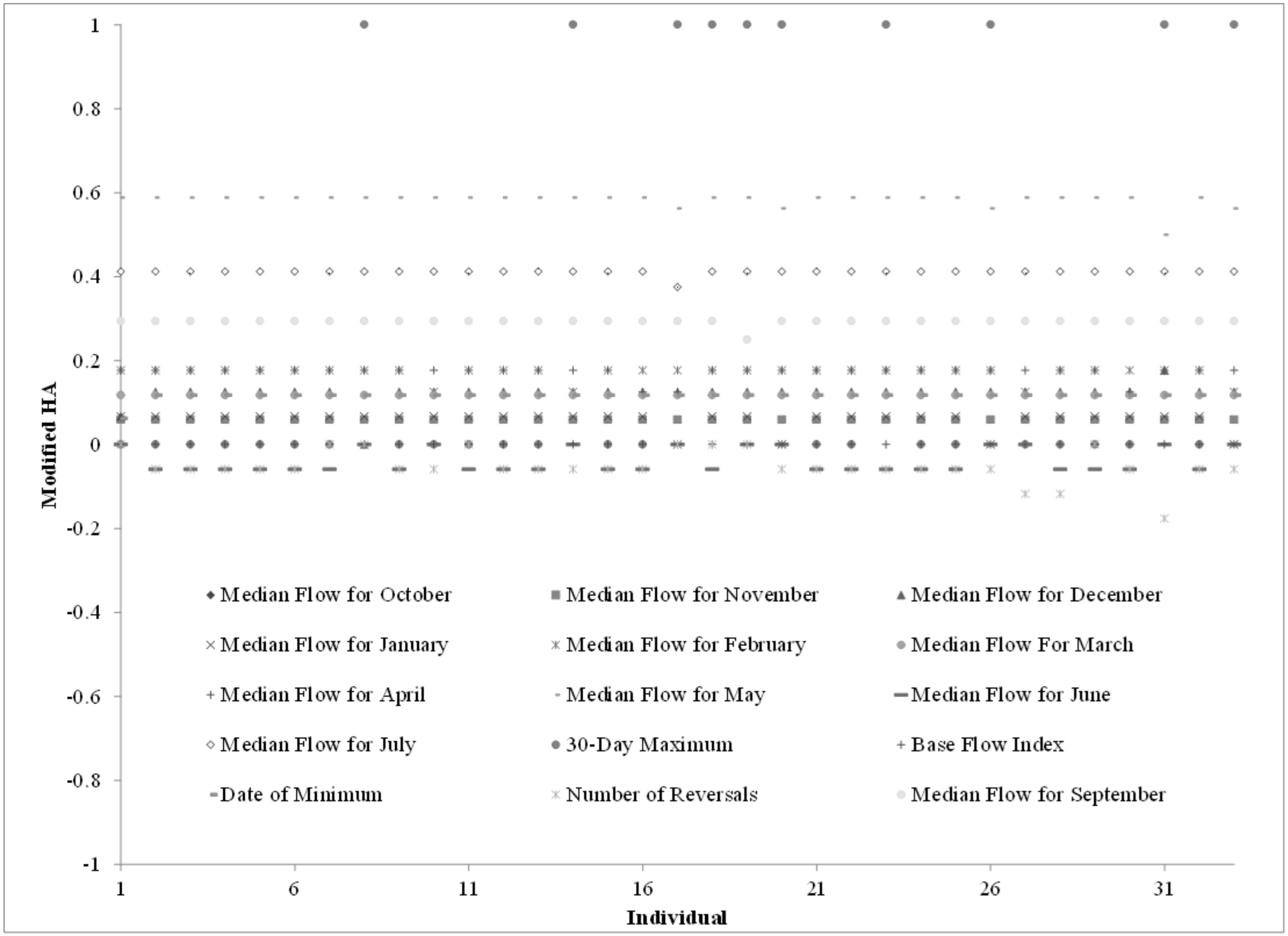


**Figure D.19. Non-zero Bin 3 RVA performance criteria for Hypothetical Scenario 1 Generation 40.**



### *D.2.4 Conclusion*

The model was successfully applied to simplified hypothetical management area and several hypothetical scenarios. Solutions were obtained for each scenario with the exception of Scenario 7 which imposed overdraft conditions on the historical daily flow target. The model failed to find any solutions that extended for the length of the long term time horizon, despite running a second time with an increased number of generations and a larger population. The longest time frame that the model remained feasible for Hypothetical Scenario 7 was 21 years. It is assumed this is due to the imposed overdraft conditions.

Given the nature of the problem and the GA solution procedure, it is impossible to know for certain if an optimal solution was found in each scenario. However, a casual survey of all the results would suggest that the solutions are at least near optimal: optimal solutions should result in similar responses, with deviations readily attributable to changes in scenario parameters. This is most clearly illustrated in the volume supplied (Figure D.6). Recall that Hypothetical Scenarios 1and 8 use the historical daily flows as the target flows, while Hypothetical Scenarios 2, 3, 4, 5 and 6 use 15% of the Julian day average daily flows. River demand is most sensitive to changes in aquifer storage in Hypothetical Scenarios 1 and 8. Hypothetical Scenario 8 begins with a higher volume supplied due to the higher initial population, but then dips below Hypothetical Scenario 1 in approximately year 20, continuing the trend for the remainder of the long-term time horizon. Examining the change in Source 1 storage (Figure D.4), the Hypothetical

Scenario 8 aquifer storage volume no longer impacts the river beginning in year 29 (storage > initial storage), at which point the volume supplied by Source 1would be permitted to increase without affecting the river's SI. However, this is not the case, suggesting that some benefit is not being realized in Hypothetical Scenario 8. Examining the respective objective values indicates a 3.6% difference in net benefits:

$$\frac{Objective^{Trial\ Scenario\ 8}}{SS^{Trial\ Scenario\ 8}} = \frac{1{,}320{,}148{,}811}{0.738425} = 1{,}787{,}789{,}973 \tag{D.5}$$

$$\begin{gathered} Objective^{Trial\ Scenario\ 1} - 1{,}787{,}789{,}973 \\ 1{,}854{,}742{,}146 - 1{,}787{,}789{,}973 = 66952173 \\ \frac{66952173}{1{,}854{,}742{,}146} * 100 = 3.6\% \end{gathered} \tag{D.6}$$

Hypothetical Scenario 2 uses 15% of the Julian Day average for the daily target flow which should allow the volume supplied to be greater than it is in Hypothetical Scenario 1 (not including the water volume supplied to river). It does finish higher, however it is below that of Hypothetical Scenario 1 from approximately year 10 to year 30, suggesting that an increase in net benefits could be realized. Also, too much volume was being supplied towards the end of the long-term time horizon, impacting the SS value. Given the lower attainable net benefits associated with the lower demand on the river, comparing the Hypothetical Scenario 2 objective value to that of Hypothetical Scenario 1 offers no additional insight.

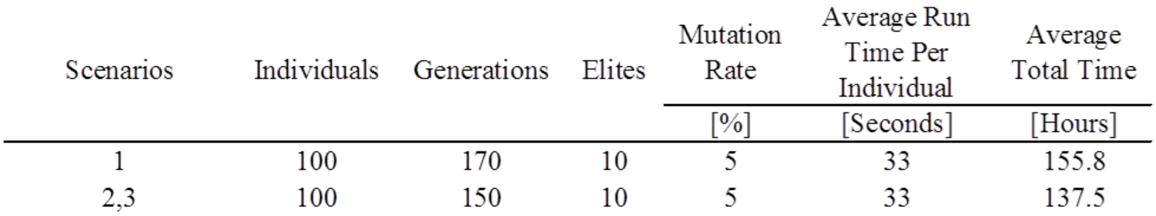
The connection between the storage volume in the aquifer and the supply available to the river is disrupted with the introduction of the reservoir on Source 2 in Hypothetical Scenario 3. This coupled with the 15% target flows allows the volume supplied to Demand 1to be much greater than in Hypothetical Scenario 2. This is also expected in Hypothetical Scenarios 4 and 5 and confirmed in Figure D.6. The change in volume supplied in Hypothetical Scenarios 4 and 5 is nearly identical with more rapid rates of increase than in Hypothetical Scenario 3. The rate of increase is not as great as it is on Hypothetical Scenario 6, which has the benefit of a higher starting population. Hypothetical Scenario 6 set up conditions such that all of the available water could be used by the system, and as indicated in Figures D.4 and D.6, steep declines in the aquifer storage and the exhaustion of the reservoir storage suggest that the solution is at least near optimal for Hypothetical Scenario 6. This is also suggested by an average growth rate of 6.5% ($\delta_{y,j}$) which is near the maximum allowed.

Though perhaps not optimal for all scenarios, the results of the hypothetical scenarios are an indicator of near optimality. The least optimal solution is perhaps Hypothetical Scenario 8, at 97.4% of the net benefit realized in Hypothetical Scenario 1 and no significant increases in consumers or consumption rate after the aquifer storage volume theoretically permits an increase in volumes supplied.

## D.3 Prescott Application (Linear Form of the LTM Objective)

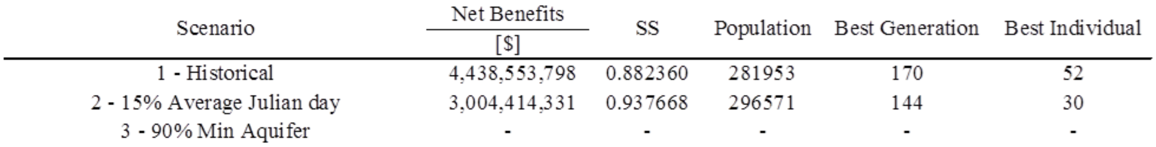
The first application to the Prescott AMA was made using the linear LTM objective function. The results from this model run are presented beginning with Tables D.15 and D.16 with the GA parameters and results respectively.

**Table D.15. GA parameters for the Prescott AMA application**



| Scenarios | Individuals | Generations | Elites | Mutation Rate [%] | Average Run Time Per Individual [Seconds] | Average Total Time [Hours] |
|---|---|---|---|---|---|---|
| 1 | 100 | 170 | 10 | 5 | 33 | 155.8 |
| 2,3 | 100 | 150 | 10 | 5 | 33 | 137.5 |

**Table D.16. Results from Prescott AMA scenarios.**



| Scenario | Net Benefits [$] | SS | Population | Best Generation | Best Individual |
|---|---|---|---|---|---|
| 1 - Historical | 4,438,553,798 | 0.882360 | 281953 | 170 | 52 |
| 2 - 15% Average Julian day | 3,004,414,331 | 0.937668 | 296571 | 144 | 30 |
| 3 - 90% Min Aquifer | - | - | - | - | - |

Referring to Table D.16, Scenario 1 sees the largest net benefits, with Scenario 4 a distant second and Scenario 2 a distant third. Scenario 3 failed to find an allocation schedule that ran for the entire long-term time horizon. None of the scenarios reached optimal sustainability, with Scenario 2 seeing the most sustainable solution at 0.937668. Scenarios 1 and 4 were equally sustainable. Scenario 2 realized the largest population at just under 300,000. Comparing the SS values, it is evident that sustainability values (SI) for each demand are likely the limiting factor for the net benefits. The SI values for each demand in the scenarios are all equal to 1 except for the SI associated with the river demand and the river's flow regime. Both of these are equal to 0 for Scenario 1, and

0.9413 and 0 for Scenario 2 respectively. For Scenario 1 the SI value of 0 is attributed to the reliance and resilience, which are both 0 suggesting that supply for the river is never sufficient to meet demand. The SI composition for the Verde River's demands are presented in Table D.17. The RVA based performance criteria are indicated in Figure D.20. Resilience contributes the most to the lack of sustainability for the deficit criteria at 0.79. The RVA based criteria see the largest lack of sustainability associated with the Maximum 90-day flow (Bin 1), the pulse count metrics (Bin 1) and the fall rate (Bin 1). This corresponds with a shortfall in supply for the river (see Chapter 4).

**Table D.17. SI values for the deficit-based criteria on the Verde River's demands.**

| Scenario | Reliance | Resilience | Max Vulnearability | Max Deficit | SI (Deficits on River Demand) |
|---|---|---|---|---|---|
| 2 - 15% Average Julian day | 0.968300 | 0.789500 | 0.981900 | 0.984511 | 0.941304 |

The Verde River is dependent upon the storage levels in the Big Chino aquifer (Source 1). Change in storage for each of the applicable scenarios is indicated in Figure D.21. Examining the change in storage on the Big Chino, Scenario 2 allows for an earlier drawdown on the aquifer, which is attributed to the decreased demand on the river. However, the increased availability fails to result in significant differences in the ending storage on the aquifer, with Scenarios 1 and 2 ending at nearly identical drawdowns on the aquifer. This serves to illustrate one of the shortfalls with the proposed objective function (D.1): after the river has an SI of 0, the model is 'free' to use as much water as necessary to support non-river uses. Given the costs for the Prescott application, residential demands will draw from local aquifers until depleted, at which point, residential demand is allowed to utilize the Big Chino supply with no impact to the Verde

River’s SI value. Equation (D.1) requires that the net benefits associated with residential demand’s use of the Big Chino supply be greater than the loss of net benefits associated with the Verde River’s consumption over the same time frame. For both scenarios, the beginning of the steep drop in storage on the Big Chino corresponds with zero supply available in Zone 2’s aquifer (see Figure D.22 and D.23). Net benefits associated with the various ground-water supplies over time is indicated in Figures D.24. and D.25.

**Figure D.20. RVA based performance criteria for Scenario 2 and the Verde River (linear form of the LM objective).**

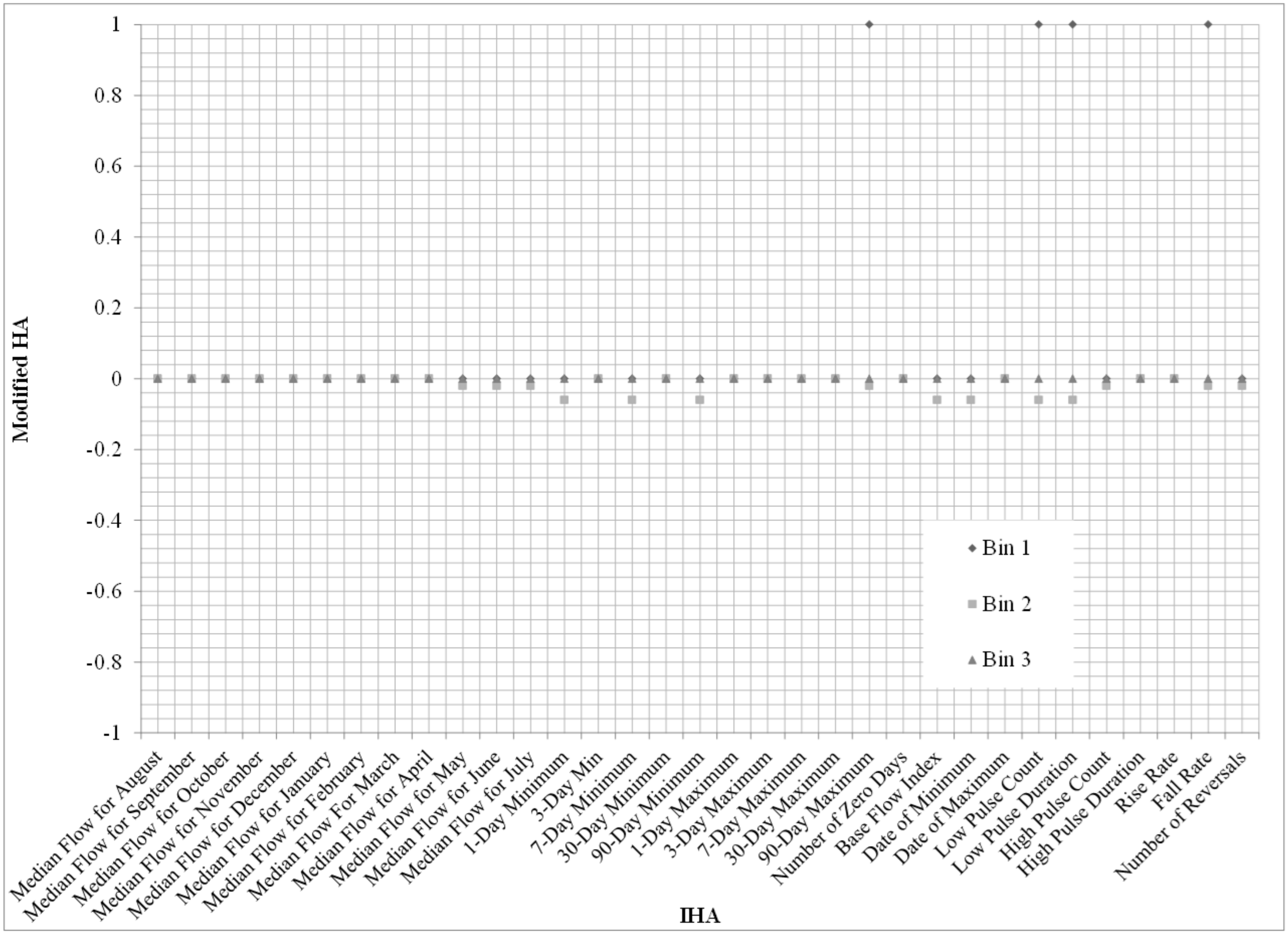


Figure D.21.  Change in storage on the Big Chino (Source 1) for Scenarios 1 and 2 (linear form of the LM objective).

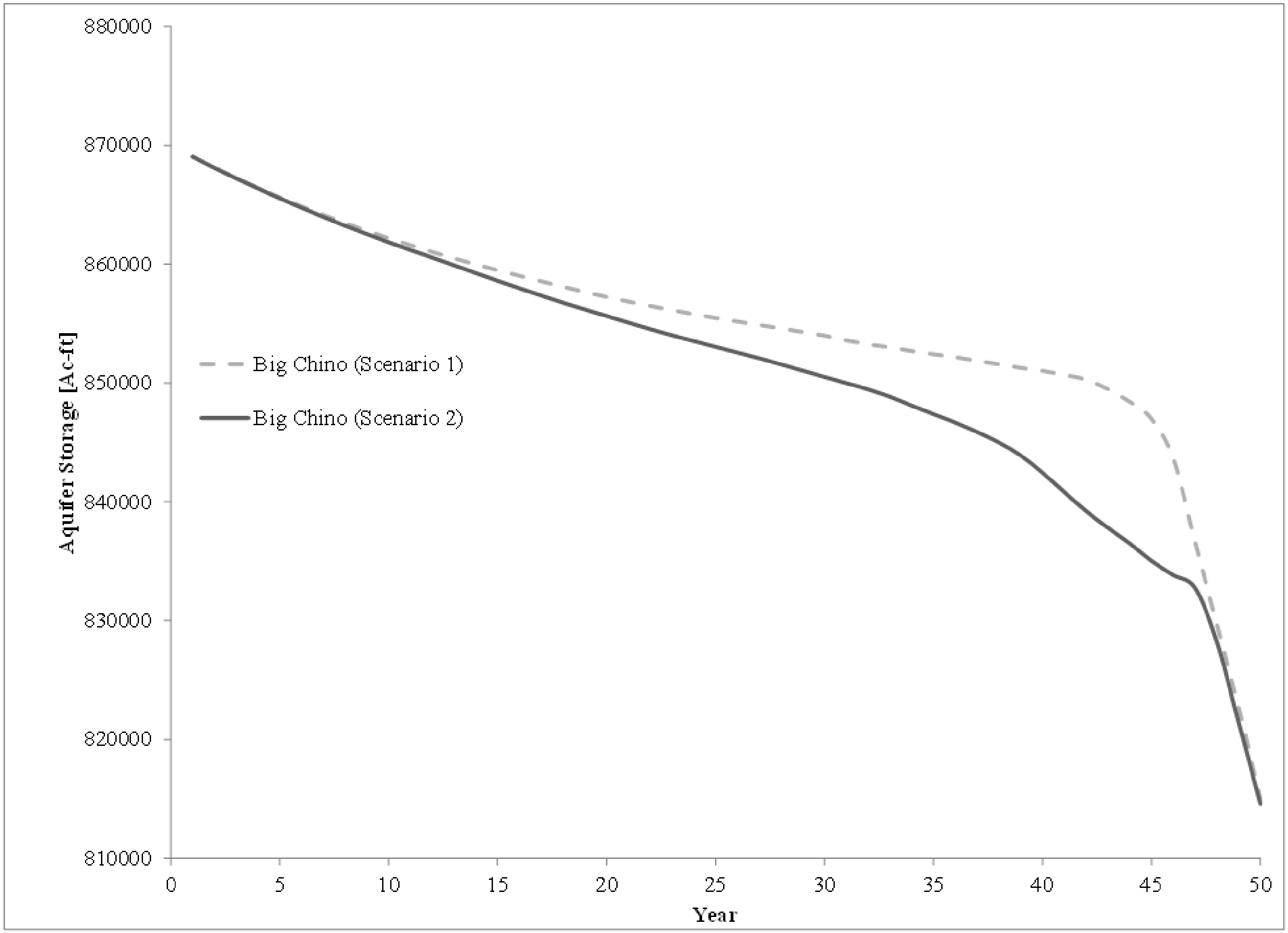


Figure D.22.  Change in storage for ground-water sources in Scenario 1 (linear form of the LTM objective).

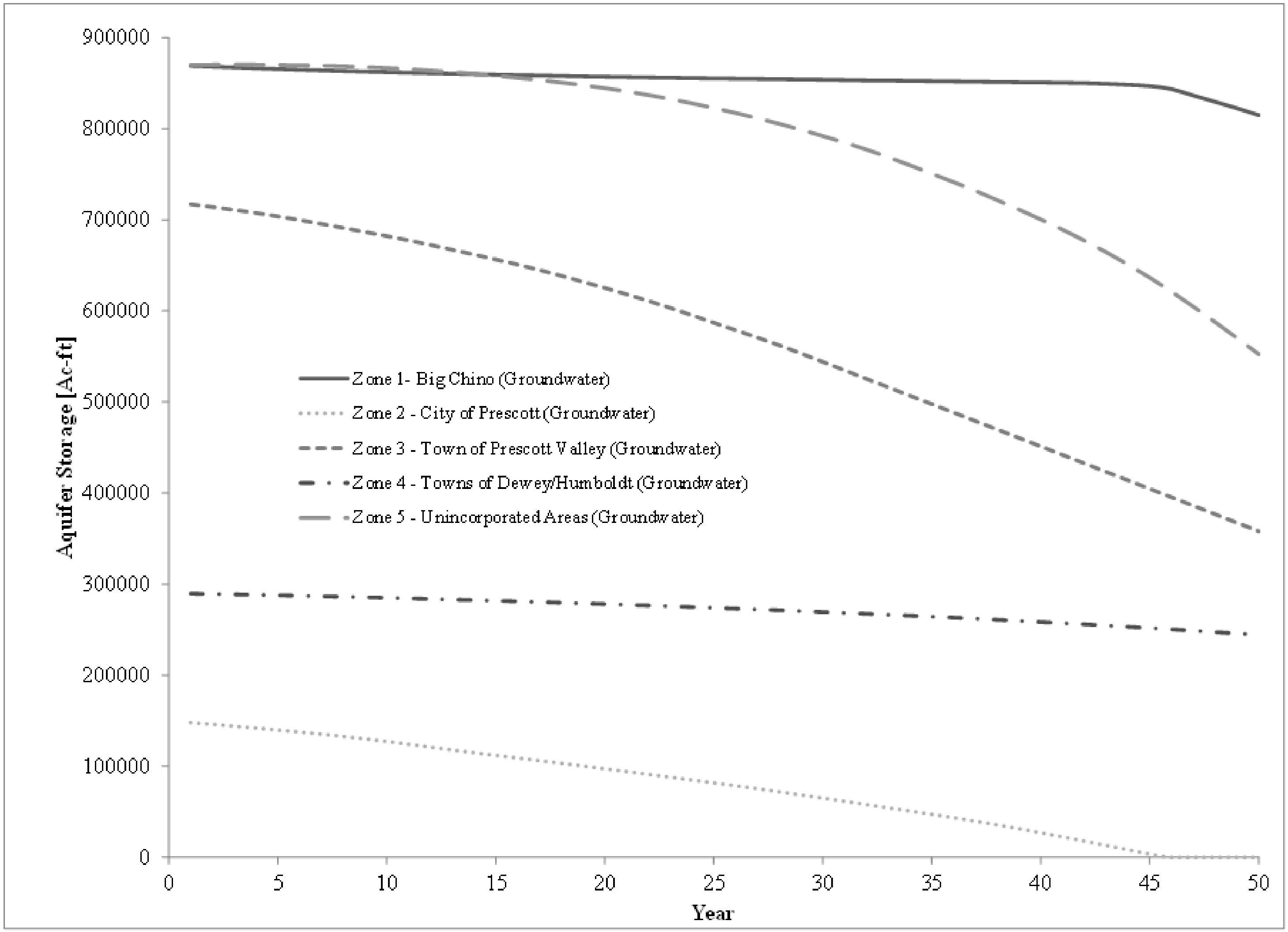


Figure D.22.  Change in storage for ground-water sources in Scenario 2 (linear form of the LTM objective).

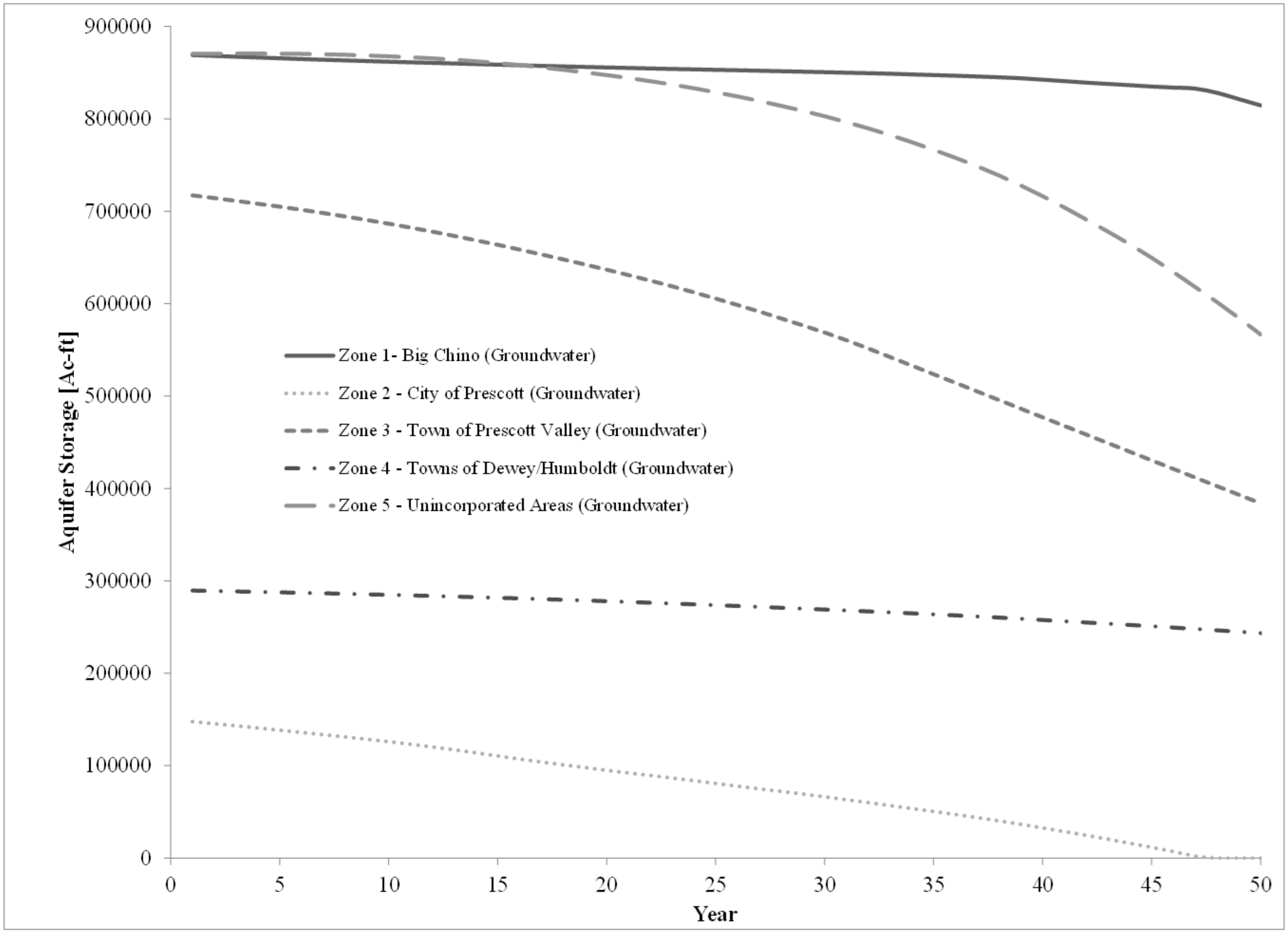


Figure D.23.  Net benefits over supply for Scenario 1 (linear form of the LTM objective).

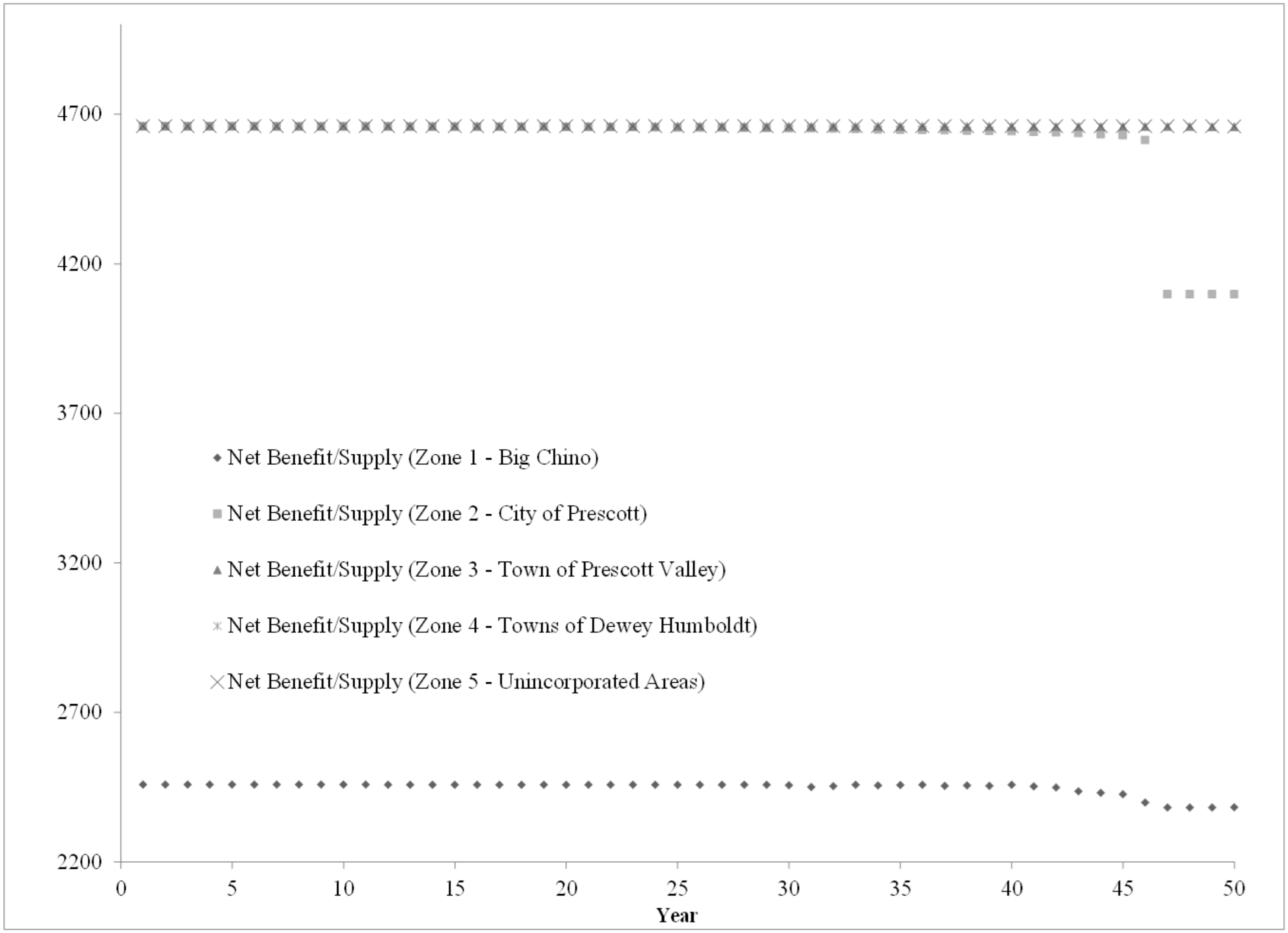
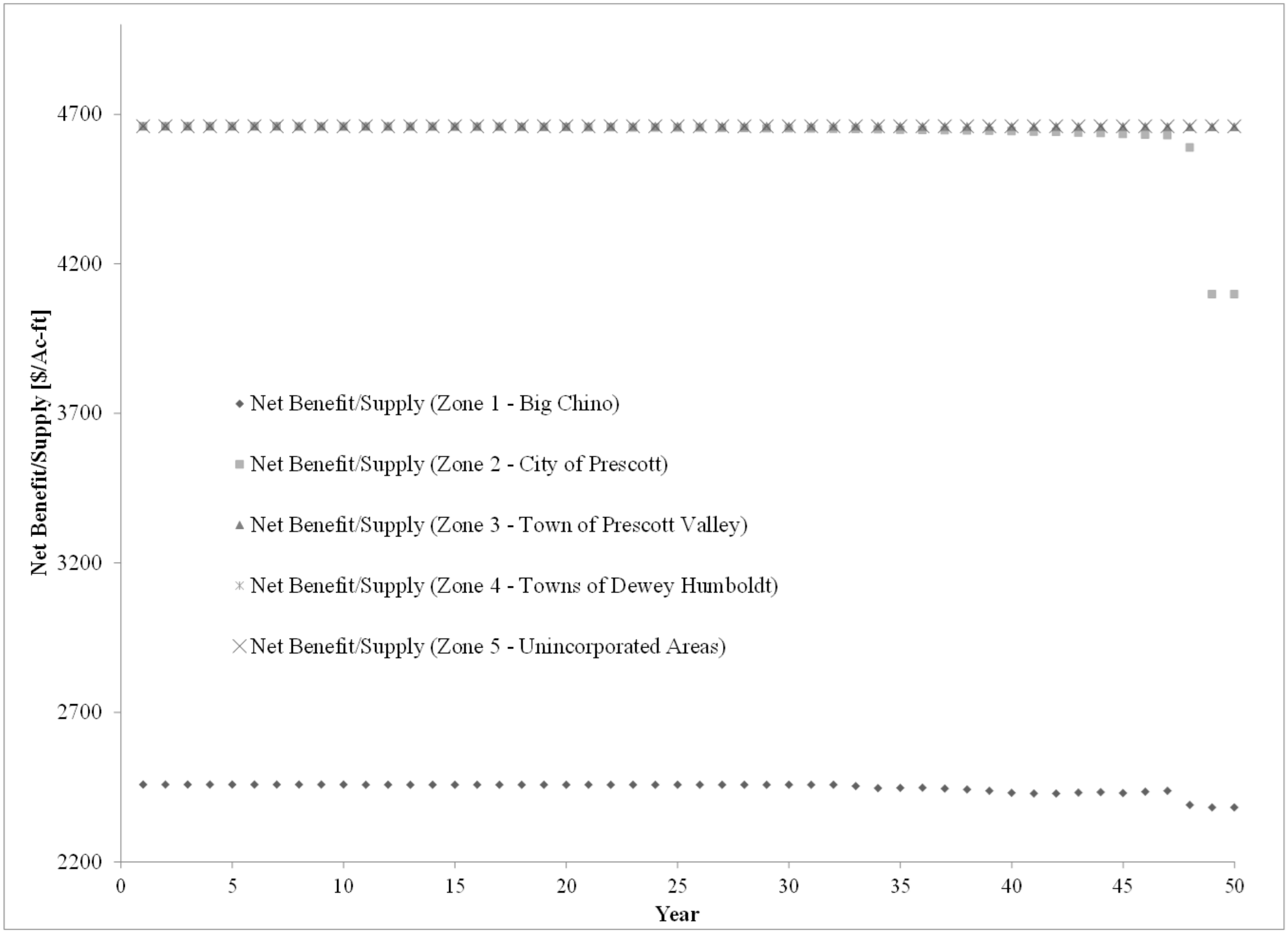


Figure D.24.  Net benefits over supply for Scenario 2 (linear form of the LTM objective).



## D.4 Prescott Application (Non-linear Form of the LTM Objective)

The linear form of the objective function proved inadequate for ensuring sustainability for demands that were most susceptible to having SI values of zero. To overcome these deficiencies, a non-linear form of the LTM objective was determined as:

$$Max\ Sustainable\ Net\ Benefit = \sum_{y}^{Y} NetBenefits_y * \left(1 - \frac{1}{SS^2}\right) \qquad \text{(D.7)}$$

Equation (D.7) has a maximum of 0 and emphasizes change in the SS. Applying this version of the objective to the Prescott AMA resulted in decreasing volumes supplied (see Figure D.25). Upon investigation, it was recognized that when SS < 1 and constant, this form of the objective resulted in net benefits decreasing until a value of 0 was achieved. Theoretically, net benefits could be decreased until the value of SS achieved a value of 1, but this objective also fails to recognize contributions from the respective demands. For example, in the Prescott AMA application, the supply for the river is most susceptible to not realizing sustainability. The Verde River supply is dependent upon storage volumes in the Big Chino aquifer, suggesting that the largest impacts to the objective is realized in decreasing residential demands impacting the Big Chino aquifer (Zone 1 in the Prescott AMA application). However, as indicated in Figure D.26, the model was decreasing residential demands dependent upon Zone 3 groundwater. All of this resulted in the objective function presented in Chapter 4:

$$Max\colon\ Sustainable\ Net\ Benefit = \sum_{g}^{G}\sum_{j}^{J} v_{g,j} * NetBenefits_{j} * \left(2 - \frac{1}{{SI_{g,j}}^{2}}\right) \qquad \text{(D.8)}$$

Equation D.8 sums the net benefits for each demand and associates the net benefit contribution to the objective with the sustainability ($SI_{g,j}$) for the demand. It should be noted that net benefits associated with demands in multiple sustainability groups ($g$) contribute to the objective function value for each sustainability group. Practically speaking, for the Prescott AMA application, this results in the net benefits associated with flow on the Verde River being counted once for the deficit-based criteria and once for the RVA based criteria, with each contribution dependent upon the SI for the respective criteria.

Figure D.25. Volume supplied for Scenario 1 (non-linear form of the LTM objective).

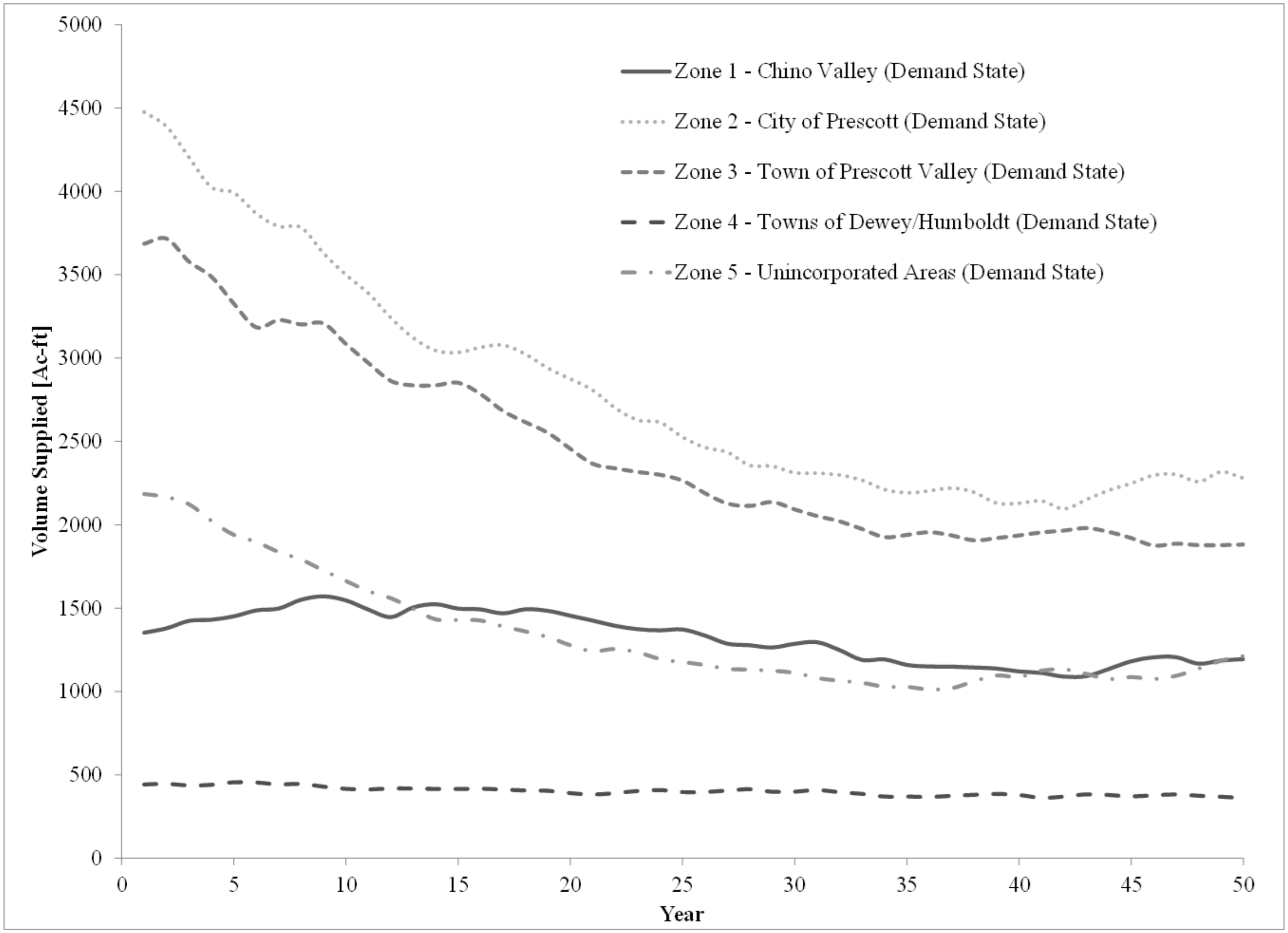
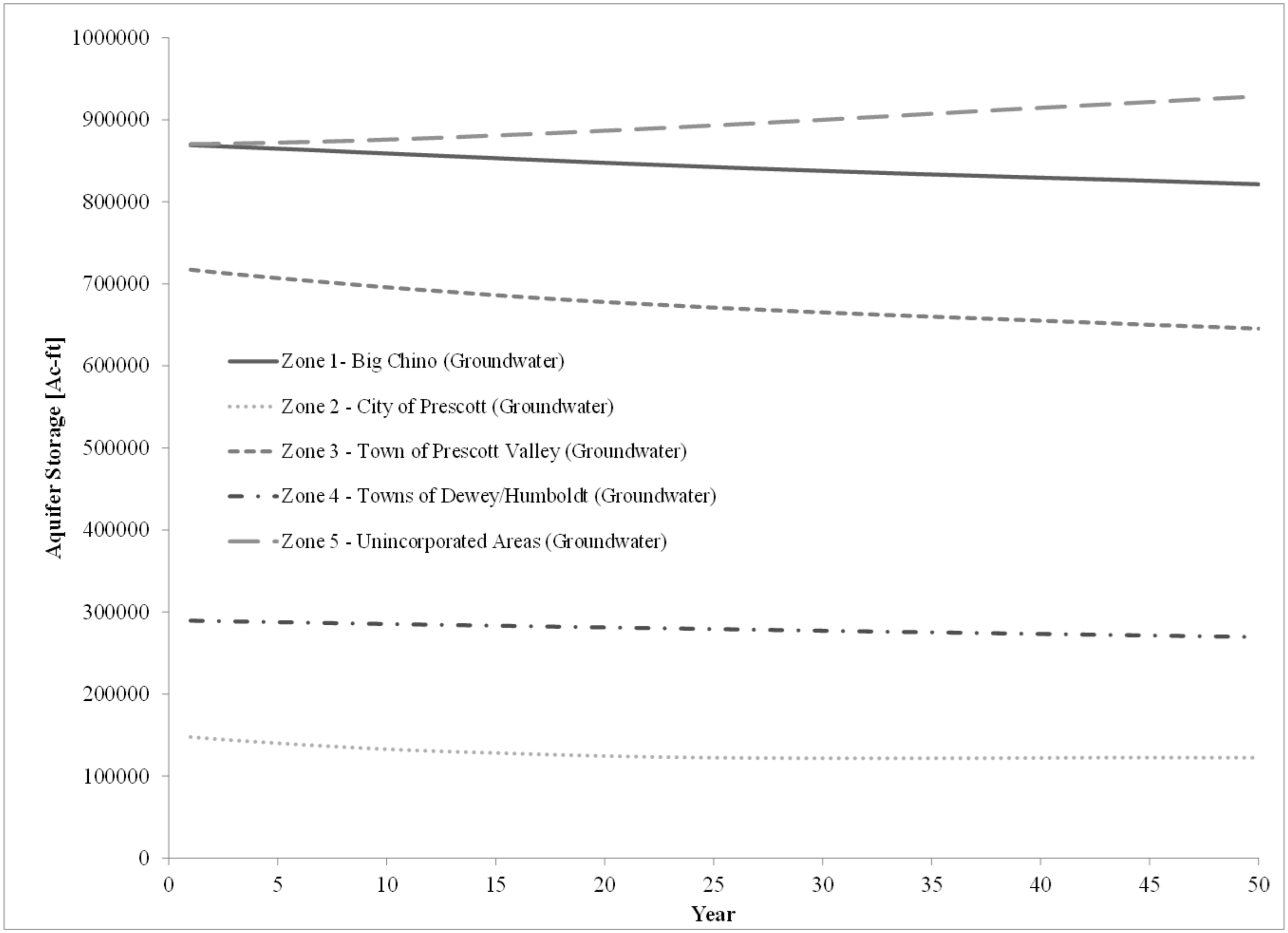


Figure D.26. Change in storage for Scenario 1 (non-linear form of the LTM objective).



# APPENDIX E.

## GAMS CODE

```
*2-20-2014
*Short term model
*Robert Oxley (roxley@asu.edu)
*To impose a reservoir on the river supply, uncomment and comment the appropriate lines


Option Limrow =15000;
*Option Limcol = 2000;

Scalars
****From LTM model****
y Year of model
generationID ID of the current generation
parentID ID of the current parent
***

w Objective function weighting
EnergyPrice Cost of the energy in $ per kWH
;



y=%modelYear%;
generationID=%generationID%;
parentID=%parentID%;
*y=1;
*parentID=1;
*generationID=1;

*Higher values for w equate to a preference for maximizing benefits
*Lower values for w equate to a preference for minimizing expenses
w=0.5;
EnergyPrice=0.05;



Sets

i Index of sources
/
1*9
/
j Index of demands
```

```
/
1*16
/
t Index of unit time
/
1*12
/
k Index of constraining cost functions
/
1*11
/

;

Table LCost(k,*)
        a                     b
1       0                     0
2       0                     1376.42
3       -67.7                   2053.38
4       -269.68                   3063.28
5       -721.65                   4569.88
6       -1620.69                  6817.47
7       -3297.19                  10170.46
8       -6298.44                  15172.55
9       -11522                    22634.78
10       -20427.88                  33767.13
11       -35374.64                  50374.64

;

Parameters

d (j,t) Demand at demand (j) for period t
/
$ondelim
$include C:\GAMS_proj\STM\output\demands.csv
$include C:\GAMS_proj\STM\output\river_demand.csv
$offdelim
/

s (i) Supply available at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\supply.csv
```

```
$offdelim
/

s_input(i,t) Supply input at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\s_input.csv
$include C:\GAMS_proj\STM\output\reservoir_int.csv
$offdelim
/

benefit (j) Benefit of water supplied to a demand (j)
/
$ondelim
$include C:\GAMS_proj\STM\output\benefit.csv
$offdelim
/

theta (j) Minimimum percentage of demand that must be satisfied at demand (j)
/
$ondelim
$include C:\GAMS_proj\STM\output\theta.csv
$offdelim
/

Capacity (i,j) Maximum supply that may be transferred from source (i) to demand (j)
/
$ondelim
$include C:\GAMS_proj\STM\output\capacity.csv
$offdelim
/

DevCostCoefficient (i) Unit cost associated with developing supply at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\DevCostCoefficient.csv
$offdelim
/

HeadEle (i,j) Elevation head between source (i) and demand (j)
/
$ondelim
$include C:\GAMS_proj\STM\output\elevation_head.csv
$offdelim
```

```
/

TypeOfSource(i) Type of source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\typeSource.csv
$offdelim
/

InitialStorage(i) Initial storage at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\initial_storage.csv
$offdelim
/

MaxStorage(i) Maximum storage at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\max_storage.csv
$offdelim
/

MinStorage(i) Minimum storage at source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\min_storage.csv
$offdelim
/

MaxStorageOutput(i) Maximum output from source (i)
/
$ondelim
$include C:\GAMS_proj\STM\output\max_output.csv
$offdelim
/

ConsumerUnits(j,t) Consumer units at demand (j) in time (t) (Passed for DB only)
/
$ondelim
$include C:\GAMS_proj\STM\output\consumer_units.csv
$offdelim
/
```

```
ConsumptionRate(j,t) Consumption rate at demand (j) in time (t) (Passed for DB only)
/
$ondelim
$include C:\GAMS_proj\STM\output\consumption_rate.csv
$offdelim
/


;


Variables

Objective Objective value
Z_1(i,j,t) Benefit surrogate
Z_2(i,j,t) Cost surrogate

x(i,j,t) Volume of water supplied from a source (i) to a demand (j) for period (t)

AvailableSupply(i,t) Volume of supply available at source (i) in period (t)

RiverWaste(t) Volume not used by the river

DevelopmentCost (i,j,t) Cost associated with developing source (i) in period (t)
DeliveryCost(i,j,t) Cost associated with delivering supply from source (i) to demand (j) in
period (t)
DepletionCost(i,t) Cost associated with depleting groundwater source (i) in period (t)
supplyModifier(t) Reservoir supply modifier based on Big Chino aquifer storage levels

;

*Minimum constraints
x.lo(i,j,t) = 0;
RiverWaste.lo(t) = 0;
AvailableSupply.lo(i,t) = MinStorage(i);

*Maximum constraints
x.up(i,j,t) = Capacity(i,j);
AvailableSupply.up(i,t) = MaxStorage(i);



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```

```
*++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
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Equations

NetBenefit Objective function

DetermineBenefit(i,j,t) Benefit of consuming supply at demand (j) in period (t)
DetermineCost(i,j,t) Cost of developing and delivering supply from source (i) to demand
(j) in period (t)
DetermineDevelopmentCost(i,j,t) Determines the development costs at source (i) in
period (t)
DetermineDeliveryCost(i,j,t) Determines the delivery costs associated with delivering
supply from source (i) to demand (j) in period (t)
DetermineSupplyModifier(i,t) Determines the reservoir supply modifier

TotalSupply(i) Limit amount supplied to all demand (j) to the supply available at source
(i)
TotalOutput(i,t) Limit output from source to source capacity
DetermineAvailableSupply(i,t) Determines the supply currently from source (i) in period
(t)
OnlySupplyDemand(j,t) Limit amount supplied to amount demanded
MinimumFill(j,t) Minimum demand that must be met
ConstrainDepletionCost(i,j,t,k) Linear cost of depletion constraint

;

***Objective Function***

NetBenefit .. Objective =e=     w*sum((i,j,t),Z_1(i,j,t)) - (1-w)*sum((i,j,t),Z_2(i,j,t));

***Constraining equations***

DetermineBenefit(i,j,t) .. Z_1(i,j,t) =e= benefit(j)*x(i,j,t);

DetermineCost(i,j,t) .. Z_2(i,j,t) =e= DevelopmentCost(i,j,t) + DeliveryCost(i,j,t) +
DepletionCost(i,t)$((Capacity(i,j)>0)$(TypeOfSource(i) = 3));

*Exclude River (no reservoir)
DetermineDevelopmentCost (i,j,t) .. DevelopmentCost(i,j,t) =e=
DevCostCoefficient(i)*x(i,j,t)$(ord(j)<>16);
*Include river (reservoir)
*DetermineDevelopmentCost (i,j,t) .. DevelopmentCost(i,j,t) =e=
DevCostCoefficient(i)*x(i,j,t);
```

```
DetermineDeliveryCost(i,j,t) .. DeliveryCost(i,j,t) =e=
(2.13*x(i,j,t)*HeadEle(i,j)*EnergyPrice);

ConstrainDepletionCost(i,j,t,k)$((Capacity(i,j)>0)$(TypeOfSource(i) = 3)) ..
DepletionCost(i,t) =g= ((LCost(k,'a')+LCost(k,'b')*(InitialStorage(i)-
AvailableSupply(i,t))/InitialStorage(i)));

TotalSupply(i) .. sum((j,t),x(i,j,t)) =l=  s(i) + sum(t,s_input(i,t));

TotalOutput(i,t) .. sum((j),x(i,j,t)) =l= MaxStorageOutput(i);

*For no reservoir
DetermineAvailableSupply(i,t) .. AvailableSupply(i,t) =e= s(i)$(ord(t)=1) +
AvailableSupply(i,t-1)$(ord(t)>1) - sum((j),x(i,j,t)) + s_input(i,t)-
supplyModifier(t)$(ord(i)=9) - riverWaste(t)$(ord(i)=9);
*For reservoir
*DetermineAvailableSupply(i,t) .. AvailableSupply(i,t) =e= s(i)$(ord(t)=1) +
AvailableSupply(i,t-1)$(ord(t)>1) - sum((j),x(i,j,t)) + s_input(i,t)-
supplyModifier(t)$(ord(i)=9);

OnlySupplyDemand(j,t) .. sum((i),x(i,j,t)) =l= d(j,t);

MinimumFill(j,t) .. sum((i),x(i,j,t)) =g= d(j,t)*theta(j);

*Determine the Big Chino Supply modifier
*The modifier is based on the Big Chino aquifer storage volume, so the source ID should
correspond.
*However, note that the supply modifier value is not source specific.
DetermineSupplyModifier(i,t)$(ord(i)=1) .. supplyModifier(t) =e= (0.0104 *
(InitialStorage(i)- AvailableSupply(i,t)$(ord(t)=1) - AvailableSupply(i,t-1)$(ord(t)>1)));


*+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
++++++++
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++++++++
*$onlisting;


Model Allocation  /all/;

Solve Allocation using lp maximizing Objective;
```

```
file model_stats;
put model_stats 'Optimality status    ' Allocation.modelstat /;
put model_stats 'Optimality status text    ' Allocation.Tmodstat /;
put model_stats 'Solver status    ' Allocation.solvestat /;
put model_stats 'Solver status text    ' Allocation.Tsolstat /;

file model_stats_db;
put  model_stats_db;
model_stats_db.pc=5;
put model_stats_db generationID, parentID, y, Allocation.modelstat, Allocation.solvestat,
Objective.l/;

file f_demand; put f_demand; f_demand.pc=5; f_demand.nr=3;
loop(j,
        put generationID, parentID, y, "12", j.te(j), sum(t,d(j,t)), ConsumerUnits(j,"12"),
ConsumptionRate(j,"12"), sum((i,t),x.l(i,j,t)), sum((i,t),Z_1.l(i,j,t)), sum((i,t),Z_2.l(i,j,t))/
);


file f_supplied; put f_supplied; f_supplied.pc=5; f_supplied.nr=3;
loop(j,
        loop(t, put generationID, parentID, y,  j.te(j), t.te(t), d(j,t), sum((i),x.l(i,j,t))/)
);

file f_supply; put f_supply; f_supply.pc=5; f_supply.nr=3;
loop(i,
        put generationID, parentID, y, "12", i.te(i), AvailableSupply.l(i,"12"),
sum((j,t),x.l(i,j,t)), sum((j,t),DevelopmentCost.l(i,j,t)), sum((j,t),DeliveryCost.l(i,j,t)),
sum(t,DepletionCost.l(i,t)), sum((j,t),Z_1.l(i,j,t)), supplyModifier.l("12")/
);


file f_source_one; put f_source_one; f_source_one.pc=5; f_source_one.nr=3;
loop(i$(ord(i)=9),
        put generationID, parentID, y, i.te(i), loop(j, put sum(t,x.l(i,j,t)))
);
```

# APPENDIX F.

# DEVELOPED PHP FILES AND CLASSES

There were several PHP files and classes created in the development of the presented model. These are provided here with a brief description in list form for reference.

- baseLineData
    - The baseline comparison data (target flows) object. This is used for the RVA analysis
- config
    - Metadata for the model application. Includes database configuration and read/write paths
- core
    - Database connection manager
- dailyFlowsBase
    - Creation of the daily flow supply from the STM's monthly output
- decisionVariable
    - Creates decision variable set based on the model requirements. This is the basis for the individual in the genetic algorithm (LTM)
- demandGroup
    - The demand node group object
- demand
    - The demand node object

- dvConstraint
    - The decision variable constraints object
- dvInitial
    - The decision variable initial value object
- ga
    - The genetic algorithm object. This is based on work by Rafael C.P. (rcpinto@inf.ufrgs.br)
- gaParent
    - The genetic algorithm parent object
- iha
    - The IHA object. This was created by Ever Daniel Barreto (ever@borealishq.com) based upon the pseudo code presented in Appendix B
- LTM
    - The LTM object
- rva
    - The RVA object. This was created by Ever Daniel Barreto (ever@borealishq.com) based upon the pseudo code presented in Appendix B
- rVAGroup
    - The RVA group object
- sources

    - The source node object
- sustainabilityIndexGroup
    - The sustainability index group object