Urban Conjunctive Use
A Proof of Concept and Case study

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Abstract

Water agencies with mixed surface and groundwater assets must determine how to best implement conjunctive use, balancing cost minimization with supply reliability. After a sustainable yield of a basin has been selected, a conjunctive use strategy is developed to meet it. This process requires managers to weigh alternatives to achieve objectives within system constraints. Optimization modeling can suggest promising conjunctive use strategies for the current system. Adjustments in system constraints and parameters can be used to better understand options, performance, and trade-offs. As a result, the value of infrastructure, contracts, and conservation can be examined and operational plans can be assessed. This method is applied to the Sacramento Suburban Water District in California as a proof of concept

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Chapter 1) Introduction

Groundwater is a valuable and finite resource. Its use has allowed arid regions to be developed. In California, enormous quantities of irrigated land and millions of people rely on groundwater. Roughly 30% of the state's water demand is met with groundwater in a normal year. During drought it can be as high as 60%. This reliance has depleted the supply of groundwater, with about two million acre feet (MAF) being over-drafted on average annually (Hanak et al, 2011).

The State Groundwater Management Act (SGMA) requires the formation of local groundwater management agencies to address groundwater overdraft. These groundwater sustainability agencies will be tasked with preventing groundwater overdraft and maintaining groundwater levels. Along with the possibility of groundwater yield restrictions, their mission will require effective conjunctive use.

Conjunctive use is the combined management of groundwater and surface water to maintain supply reliability and reduce cost. It includes facilitating natural and artificial recharge, groundwater banking and exchanges, and surface water transfers (Jenkins, 1992). Each method is subject to the availability of necessary infrastructure and is limited by natural, legal, and economic constraints. The evaluation of these constraints informs investment decisions and will be discussed in later chapters.

Hydrologic variability is a challenge for water supply reliability in California. Many municipalities depend on surface water to meet demand. Surface water reservoirs increase water availability by storing water in wet seasons and years to be released during dry periods. There is a combined surface storage capacity of 41 MAF in the state of California (Hanak et al, 2011). This storage is sufficient to maintain supply reliability during a single year drought. For multiple year droughts, surface water storage may not be sufficient (Hanak, 2011).

Groundwater acts a buffer against drought (Tsur, 1991) and is essentially the state's largest storage reservoir. The combined capacity of the state's groundwater basins is 1,459 MAF (Hanak et al, 2011). This is about 35 times more than surface water storage in the state. The long term management of groundwater will affect supply reliability and cost.

Usually, a first step in the managing of groundwater basins is to estimate acceptable groundwater withdrawals. When a so-called "sustainable yield" is selected, a plan must be devised to meet it. An urban water purveyor can meet an acceptable yield with conjunctive use of surface and groundwater. Various conjunctive use strategies are available and a method of evaluation is required for efficient water supply planning and operations.

A brief introduction to groundwater flow, sustainable groundwater yields, groundwater modeling, conjunctive use, and system analysis is given as background. The remaining chapters focus on how an urban water purveyor can implement and analyze conjunctive use from reliability and least-cost perspectives.

Groundwater Flow

All groundwater originates as surface water. In areas termed zones of recharge, surface water infiltrates into the ground (Theis, 1940). This recharge can take place under surface water bodies or can result from direct infiltration of precipitation through soils. Infiltrated water percolates to the groundwater table and begins to move with the hydraulic gradient. The hydraulic gradient provides energy for flow in a groundwater system; the steeper the gradient, the more rapid the flow.

In pristine systems, the groundwater will have zones of discharge where groundwater discharges to surface water bodies, a processes known as base flow. Groundwater pumping changes the hydraulic gradient and therefore base flow. A steeper hydraulic gradient and lower groundwater levels occur with groundwater pumping. The steeper hydraulic gradient induces more surface water capture and reduces base flow discharge (Theis, 1940). A new equilibrium with a lower groundwater table, reduced base flow, and increased stream capture, can occur, assuming pumping is not enough to disconnect the stream from groundwater (Banks, 1953). If the pumping is great enough, the increased capture will not be sufficient to create a new equilibrium, causing surface water to become disconnected from the groundwater table and groundwater to fall and accumulate overdraft.

Sustainable Yield and Groundwater Modeling

The definition of an acceptable groundwater yield has been in flux over the last century and is still debated in the scientific community (Alley, 2004). Safe yield of groundwater supply was first defined from an engineering water supply prospective in the early 20th century. Lee (1915) defined it as an amount of groundwater that could be pumped "regularly and permanently without dangerous depletion of the storage reservoir" (Alley, 2004). Banks (1953) recognized that increased pumping would increase stream capture to create a new equilibrium. He suggested groundwater pumping increases recharge (within limits) and the safe yield is therefore a range, with differing effects on groundwater levels and surface water bodies. Because safe yield is a range, an optimal yield can be evaluated as function of its resulting economic and environmental effects taking into account changes in: groundwater levels, surface water capture, and the timing of water availability.

The term sustainable yield entered the field of groundwater management with an increase in emphasis on the environmental impacts of pumping (Alley, 2004). The natural ecosystem evolved for pristine conditions without groundwater pumping. As groundwater pumping occurs, the natural base flow of groundwater into surface water bodies decreases and recharge of surface water into groundwater increases. This can reduce the quantity and quality of natural habitat. Groundwater-fed perennial surface water systems can become intermittent, having harmful negative environmental consequences. A sustainable yield can take the impact of long-term pumping on the environment into account (Alley, 2004). It typically is not the limit for any given year, but a goal for a long-term average.

Integrated surface and groundwater numerical modeling is a powerful tool for analyzing the hydrology of a groundwater basin. Groundwater systems are complex, but are still subject to the laws of physics. Numerical models simulate the physics of groundwater flow in three dimensions with governing equations. This is accomplished by discretizing a simplified version of the system through space and making assumptions about the systems physical properties (Freeze, 1966). As a result, numerical models can simulate the effects of pumping and surface water releases on groundwater levels, recharge rates, and surface water flow rates through time (Yeh, 1992). An integrated surface and groundwater numerical model can inform water managers on the limits of pumping and its effects on surface water, but cannot determine a least-cost strategy to work within those limits. Additional water system analysis modeling can incorporate the limits on pumping and determine a least-cost alternative, while maintain supply reliability (Gorelick, 1983).

Conjunctive Use

Surface water is subject to intermittent scarcity as a function of hydrological variability, demand, and storage capacity. Although groundwater can be used during drought, it is subject to long-term depletion. Conjunctive use of groundwater and surface water help ensure a sustainable water supply. Urban water purveyors have several options to implement conjunctive use.

Conjunctive use begins with the use of surface water in times of ample availability. A water purveyor with surface water rights may construct a surface water treatment plant or enter into an agreement with an existing water treatment facility. The use of surface water to meet demand reduces groundwater pumping during wet periods. This situation is called *in lieu* recharge and allows groundwater levels to naturally recover (Jenkins, 1992).

Groundwater also can be recharged via active Aquifer Storage and Recovery (ASR). ASR can include passive percolation with spreading basins or direct injection of surface water through groundwater wells. Spreading basins can be less costly, but require substantial land area with suitable hydrogeological characteristics for recharge (Jenkins, 1992). In urban areas spreading basins may not be viable, as land availability is low and property values are high. The direct injection of surface water is sometimes more practical for urban areas, but comes at a high cost for construction and operation of injection wells. Environmental restrictions further increase cost of direct ASR, because injected water typically is required to be treated before injection. Spreading basins are limited by the natural properties of the subsurface and can incur significant evaporation; direct injection provides higher rates of recharge.

Access to water surface water conveyance and water markets can further expand the utility of conjunctive use, by allowing for more flexible water access and a means to transfer water to the greatest economic value (Newlin, 2002). The State Water Project and the Central Valley Project provide a means to transport large quantities of surface water to much of California. During drought, purveyors with access to groundwater may transfer surface water to others lacking sufficient groundwater access. This type of transfer is an in lieu transfer, as groundwater is used in lieu of surface water (Jenkins, 1992). It benefits the transferor with financial compensation, which could be reinvested into the water system. The transferee benefits with increased reliability, reduced scarcity, and reduced capital cost in the form of a decreased need to invest in additional infrastructure (i.e. groundwater wells).

Water Resource Systems Analysis Modeling

Systems analysis has been extensively applied water resource problems. This type of analysis accounts for system constraints and operational decisions, and evaluates performance based on specified criteria. Operational decisions may involve reservoir releases, production from surface water treatment facilities, groundwater pumping, or any action taking place within a water system. Performance criteria can range from cost minimization, supply reliability, or any measurable system feature. Constraints place limits or requirements on operational decisions. Within water resources, constraints typically involve: economics, hydrology, policy, and engineering.

Hydrologic constraints account for the natural physical availability of water. Economic constraints accounts for demands and costs. The economic cost of water consists of a willingness to pay, capital and operating costs of delivery, and economic damages from shortage. Engineering constraints may include capacity constraints and other infrastructure limitations. Examples of engineering constraints may include capacities of storage reservoirs, conveyance systems, treatment plants, or groundwater wells. Policy constraints involve restrictions of access to the natural available water. Examples of policy constraints include water rights, building and operational permits, and environmental flow restrictions.

Simulation models have been developed to analyze local and regional systems. A simulation model accounts for the most important system constraints. Operational decisions are assigned to the system and the model is run through a time series with hydrologic inputs. The performance of the modeled alternative can be evaluated by specified criteria. For large systems, computational time can be extensive and involve numerous operational decisions. These combined factors limit the ability of simulation models to identify the most efficient use of resources.

Optimization models have been developed to identify the most efficient use of water resources given system constraints. They are separated into two general categories, deterministic and stochastic. Both deterministic and stochastic optimization models use an objective function. The objective function is used to quantify the benefit of operational decisions and can be defined to represent many performance criteria. Similar to simulation models, deterministic optimization models usually use a time series as input. The time series is a representation of events occurring in the system, it can be a historical record or synthetically generated. The difference between a deterministic optimization model and simulation model is the incorporation of the operational decisions and objectives. Deterministic optimization models output the set operational decisions based on an objective function which is unique to the time series input. Simulation models use decisions as inputs to the model. Stochastic models differ from deterministic models by using the probability of events occurring in the system, rather than a record of events themselves.

Linear programing is commonly used for the optimization of large water systems. The CALVIN (California Value Integrated Network) model is an example of a deterministic linear program used to optimize a regional water system (Draper, 2003). It has been extensively used to evaluate California's water storage and conveyance system. In the CALVIN model, water storage and demand locations are represented as nodes. Conveyance infrastructure is represented as links. Various penalty and benefit functions represent the economic value of water distributed at nodes and used in the objective function (Draper, 2003). Costs are assigned to links, which can vary with time. Hydrologic constraints are introduced in the form of sink nodes and conveyance losses along links. A monthly time series input of inflow data is used to represent the natural inflows into the system. The output of the model is a set of optimized least-cost decisions for the given time series (Draper, 2003). It has been used to model conjunctive use within large basins. Harou (2008), used the CALVIN model to optimize conjunctive use in the Tulare Basin of California.

Such a deterministic model of this type has perfect foresight, meaning that the decisions given are optimal only for that exact set of inflow inputs (Draper, 2003). For example, if a drought occurs within a time series, the linear program decision outputs will be affected. The decisions preceding the drought will be influenced by the coming drought, such as reduced reservoir releases and perfect hedging before the drought. In actual operations, the occurrence of a drought would not be known in advance. Although there is likely a correlation between the probabilities of future events with the historical record, the historical record will not be repeated. As a result, the creation of system operating rules from such a model may be difficult (Zhu et al, 2015).

Stochastic models are able to output practical operating rules and practices as decision variables. These models use the probability of events within a system. Zhu et al (2015) uses the probability of annual water availability to optimize conjunctive use practices in a system with urban and agricultural users. A volumetric range of possible annual water availabilities is discretized to define hydrologic year types. The probability of year types is derived from a synthetic distribution generated with statistics of observed data (Zhu et al, 2015). Decisions are made for each year type involving conjunctive use, conservation, and crop selection. Agricultural users seek to maintain groundwater levels and maximize profit through crop selection and conjunctive use (Zhu et al, 2015). Urban users seek to ensure reliability and minimize the cost of drought through conservation and surface water transfers (Zhu, 2015). Constraints are placed on the total land available for planting and artificial recharge. Groundwater pumping is constrained not by a set physical capacity, but by ensuring a balance between recharge and pumping. The objective function involves non-linear equations, which is solved with a General Algebraic Modeling System (GAMS) (Zhu, 2015). The result is a well-defined conjunctive use scheme responsive a variety of conditions.

The remainder of this paper focuses on a similar method to analyze a water distribution system and implement conjunctive use for an urban water purveyor from a least-cost perspective. It will not use a time series as input or produce decisions discretized through time as output. Instead, it uses the probability of water availability conditions as input and outputs decisions in the form of operating rules under specified conditions. The result is a simple and efficient means to suggest promising production schedules and evaluate constraints for planning and investment purposes, from the perspective of an urban water purveyor seeking to maintain supply reliability and reduce cost.

Chapter 2) Urban Conjunctive Use: Approaches and Concepts

Water purveyors serving urban areas often have a portfolio of water resources. These resources can include several sources of treated surface water and groundwater. The costs and availability of these sources vary. Surface water is particularly subject to inter-annual fluctuation of hydrologic conditions and water contracts. Groundwater has less inter-annual fluctuation, but can suffer from long term depletion. To prevent overdraft, efforts can be made to identify the sustainable yield of a basin and shape conjunctive use.

Water purveyors seek to reliably meet customer demand at a reasonable cost. Groundwater pumping is often the least expensive alternative, but sustainable yield restricts the amount of groundwater available. In any given year a utility may extract more groundwater than the sustainable yield, but not on a long term average. If water demands exceed a utility's share of the sustainable yield, then surface water or additional conservation (water use reduction) must be employed. When demand is steady and surface water is available every year, then the required annual surface water production is simply the difference between the annual demand and the sustainable groundwater yield. The production of surface water becomes more complicated when it is not available every year. Two general approaches exist for managing this situation: long term observation and reactive adjustment or a formal optimization formulation.

Long term observation and adjustment can be used to reach a sustainable yield. This approach employs a conservative amount of surface water, when available, and a groundwater accounting framework to monitor extractions. The groundwater balance is used for surface water production adjustments to maintain a sustainable yield. This approach is practical, but not economical. A long period of time is needed for adjustments and it can result in an over or under production of surface water.

A simple formal optimization for conjunctive use is possible, given probabilities for surface water availability. This may be accomplished by defining water year types. The Sacramento area's Water Forum Agreement in California provides an example of this.

Water year types are defined by the Water Forum Agreement by the expected unimpaired runoff into Folsom Reservoir (WFA, 2000). The probability of each water year type can then be estimated with the historical record (GMR, 2014). Maximum surface water deliveries during each water year type have been agreed to. These assumptions allow for the application of a formal optimization analysis.

The following examples illustrate a formal analytical approach. They are not meant to represent an actual system, but rather to provide a simple conceptual background. Each example, has two water year types, surface water is more expensive than groundwater, and annual demand exceeds the sustainable groundwater yield (Table 2-1).

Table 2-1: Example scenarios are shown below. The annual production from these scenarios is shown in (figure 2-1).

Example Scenarios	Wet Year Probability	Dry Year Probability	Dry Year Groundwater Exports (TAF/yr)	Annual Demand (TAF)	Sustainable Yield (TAF)
A	1	0	0	40	35
B	0.5	0.5	0	40	35
C	0.5	0.5	10	40	35

Example A) Abundant Surface water availability

Surface water is available every year and surface water production is simply the difference between the annual demand and the sustainable yield (Eqn 1).

Eqn 1) $Surface\ Water\ Prodcution = Annual\ Demand - Sustainable\ Yield.$

Example B) Varying surface water availability with no exports

Surface water is no longer available every year. Extraction beyond the safe yield is needed in dry years to meet demand. Additional surface water is needed in wet years to make up for increased pumping in dry years. The amount of surface water needed in wet years can be calculated with equation 2.

Eqn 2) $Wet\ year\ Surface\ Water\ Production = \frac{(Demand - Sustainable\ Yield)}{Probability\ of\ Wet\ Year}$

Example C) Varying surface water availability with exports

Addition pumping occurs in dry years for exports. The amount of surface water needed in wet years is increased and determined by equation 3.

Eqn 3) $Wet\ year\ Surface\ Water\ Production =$

$$\frac{([Demand + (Probability\ Dry\ Years\ \times Exports\ in\ Dry\ Years)] - Sustainable\ Yield)}{Probability\ of\ Wet\ Year}$$

Although simple, the three examples describe basic conjunctive use principles. When demand exceeds the sustainable yield, surface water is required. The probability of water availability controls the amount of surface water used in wet years. Groundwater exports increase the need for surface water. A visual representation of annual production of each case is provided in Figure 2-1.

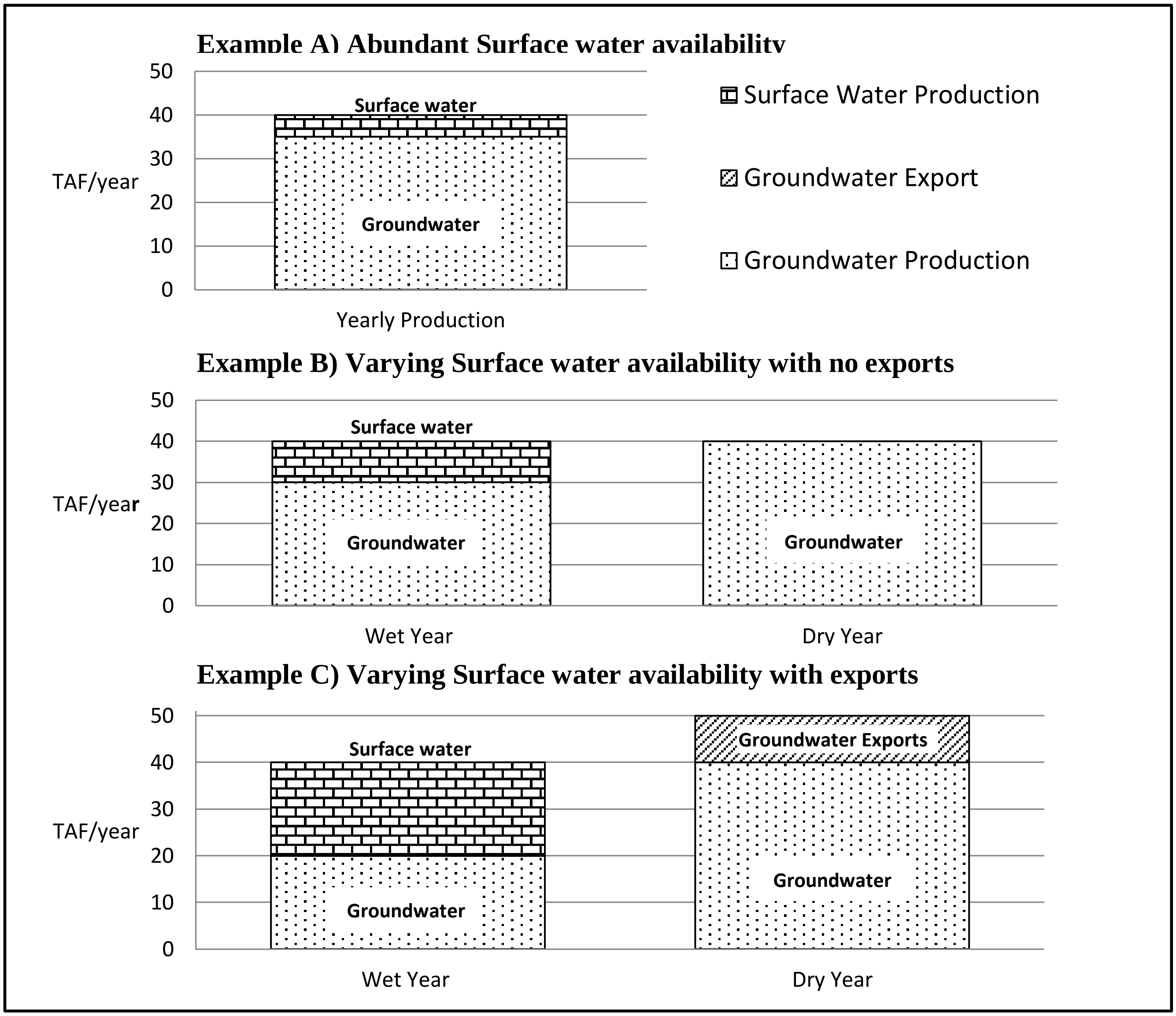

Figure 2-1: A simplified annual production schedule is shown above. In each example the annual demand is 40 TAF with a sustainable yield of 35 TAF. In example C there is a requirement for 10 TAF of exports during dry years.

Additional conjunctive use equations would become complex if more water year types, surface water sources at different costs, infrastructure constraints, or variable market prices for exports were included. A satisfactory water supply plan for an urban purveyor would require a method to incorporate all of the above to effectively optimize conjunctive use operations, say to minimize cost or maximize reliability. Linear programing can provide such solutions.

Optimization Using Linear programming

Linear Programming is a form of optimization for systems of linear objectives and constraints. The objective and each constraint is directly or indirectly a linear function of the decisions, represented as decision variables. The decision variables are the subject of the optimization and inform decision makers on operations. The constraints restrict the decision variables to a feasible region within the decision space. The system of equations is solved numerically to minimize the objective function with set of optimal decisions within the limits of constraints.

A simple example of how a water purveyor may use a linear program to optimize its conjunctive use planning is provided below. Here, there are three sources of water: groundwater and two surface water sources. Each source can produce water for district demand or be sold to an outside agency. The production cost, transfer price, and total availability vary with source and water year type. A water year type is a hydrologic condition describing water availability for each source. The probability of each water year type is estimated with an exceedance plot from the historical record. The model minimizes cost and insures sustainability by deciding production and transfer amounts for each source during each water year type. Constraints ensure sustainability by restricting annual groundwater pumping to an expected value equal to a predetermined sustainable yield, insure internal demands are met, and restrict production of each source to its annual availability.

Linear program Formulation

The mathematical formulation is organized by decision variables, an objective function, and constraints.

Decision Variables:

X_{ij}= Production Amount for Source $j$during Year type i

Y_{ij}= Export Amount for Source $j$during Year type i

Objective Function:

Min: Total Cost = $\sum_{i=1}^{n}\sum_{j=1}^{m} p_i\left(c_{ij} \times X_{ij}\right) - p_i(k_{ij} \times Y_{ij})$

Constraints:

$X_{ij} + Y_{ij} \leq a_{ij}$ [Production and Export cannot exceed availability for any source or year type]

$\sum_{i=1}^{n} p_i(X_{i1} + Y_{i1}) \leq Safe\ Yield$ [Average groundwater use cannot exceed a set amount]

$\sum_{j=1}^{m} X_{ij} \geq d_i$ [The sum of production must equal or exceed demand]

$Y_{ij} \leq l_{ij}$ [Exports cannot exceed limits] where:

p_i = Probability Year Type
c_{ij}= Unit Production Cost for Source $j$during Year type i
k_{ij}= Unit Export Profit for Source $j$during Year type i
a_{ij}= Amount Available for Source $j$during Year type i
d_i= Demand during Each Year Type
l_{ij}=Limit on Export for Source $j$during Year type i

m= number of water sources
n= number of Year Types

i=1=Wet Year
i=2=Average Year
i=3=Dry Year
i=4=Driest Year

j=1=Ground Water
j=2=Surface Water Source A
j=3=Surface Water Source B

Conceptual System Application

To demonstrate the utility of the model, a hypothetical system is described. The optimal production for a variety of alternatives is calculated. For each alternative the expected total annual cost as a function of demand is graphed and used to evaluate each alternative.

The hypothetical urban water purveyor has a mix of groundwater and surface water. A single source of surface water, Surface Water 'A', is currently available. It is treated by an outside agency at a cost of $350 per acre foot. Its availability depends on water year type and is a function of infrastructure, demand, legal and contractual constraints. Exports from Surface Water 'A' and groundwater can be made in drier years. Groundwater is less expensive at $75 per acre foot, but cannot be solely utilized to meet demand due to overdraft concerns. To reduce overdraft, the purveyor will operate on average within a sustainable groundwater yield of 35 TAF per year. The current demand of 40 TAF per year requires surface water to ensure sustainable groundwater yield and meet demand.

A second surface water source, Surface Water 'B', can be available to the district with the construction of a surface water treatment plant (WTP). Due to environmental concerns, water from Surface Water 'B' will be available up to 40 TAF per year, but only during wet year types. Two plant sizes have been suggested: a large WTP with 40 TAF per year capacity and a small WTP with 10 TAF per year capacity. They have annualized construction costs of $1.2 million and $0.4 million a year and per unit operating costs of $120 and $150 per acre foot respectively (Table 2-1).

An additional option is groundwater exports (sales) in dry years. The demand for exports during dry and driest years is 20 and 30 TAF per year with a sales price of $400 and $800 per acre foot respectively. Groundwater exports will require the construction of additional interties and booster pumps at an annualized cost of $150 thousand dollars (Table 2-2).

Table 2-2 The Annualized project cost and system constraints are shown below for each alternative.

Example Alternatives	Annualized project cost ($/yr)	Maximum Use Surface Water B (ac-ft/yr)	Maximum Dry year Exports (ac-ft/yr)	Maximum Driest year Exports (ac-ft/yr)	Production Cost Surface Water B ($/ac-ft)
No Groundwater Exports: No WTP	$ -	0	0	0	$ -
No Groundwater Exports: Small WTP	$ 400,000	10,000	0	0	$ 150
No Groundwater Exports: Large WTP	$ 1,200,000	40,000	0	0	$ 120
Groundwater Exports: No WTP	$ 150,000	0	20,000	30,000	$ -
Groundwater Exports: Small WTP	$ 550,000	10,000	20,000	30,000	$ 150
Groundwater Exports: Large WTP	$ 1,350,000	40,000	20,000	30,000	$ 120

The model can be used to optimize annual production and ensure a sustainable yield under a variety of alternatives. These alternatives included: no treatment WTP, a small WTP, and a large WTP. For each treatment alternative a variant alternative is included for groundwater exports. An optimized annual production schedule is shown for each alternative at annual demand of 40TAF/yr (Figure 2-2).

The optimized annual production is the least cost production schedule that meets the sustainable yield. Examinations of optimal production allow for alternative comparison. For example at an annual demand of 40 TAF (Figure 2-2), the presence of groundwater exports requires approximately 9 TAF of additional surface water in wet years. When there is no WTP a small WTP, this increased use of surface water is met by the more expensive Surface additional surface water is provided by Water 'A', the most expensive source. With a large WTP the increased use of surface water in wet years is met entirely by less expensive Surface Water 'B'. Alternatively, when there are no groundwater exports, the amount of Surface Water 'B' treated in the large WTP is only marginally more than the small WTP.

Each of the optimal production schedule has an expected annual cost. The expected annual production cost for each alternative can be graphed as a function of annual demand. The construction of a water treatment plant and additional infrastructure for groundwater exports will have an annualized project capital cost. To better compare the true cost of each alternative, the annualized project capital cost can be added to the annual production cost (Figure 2-3).

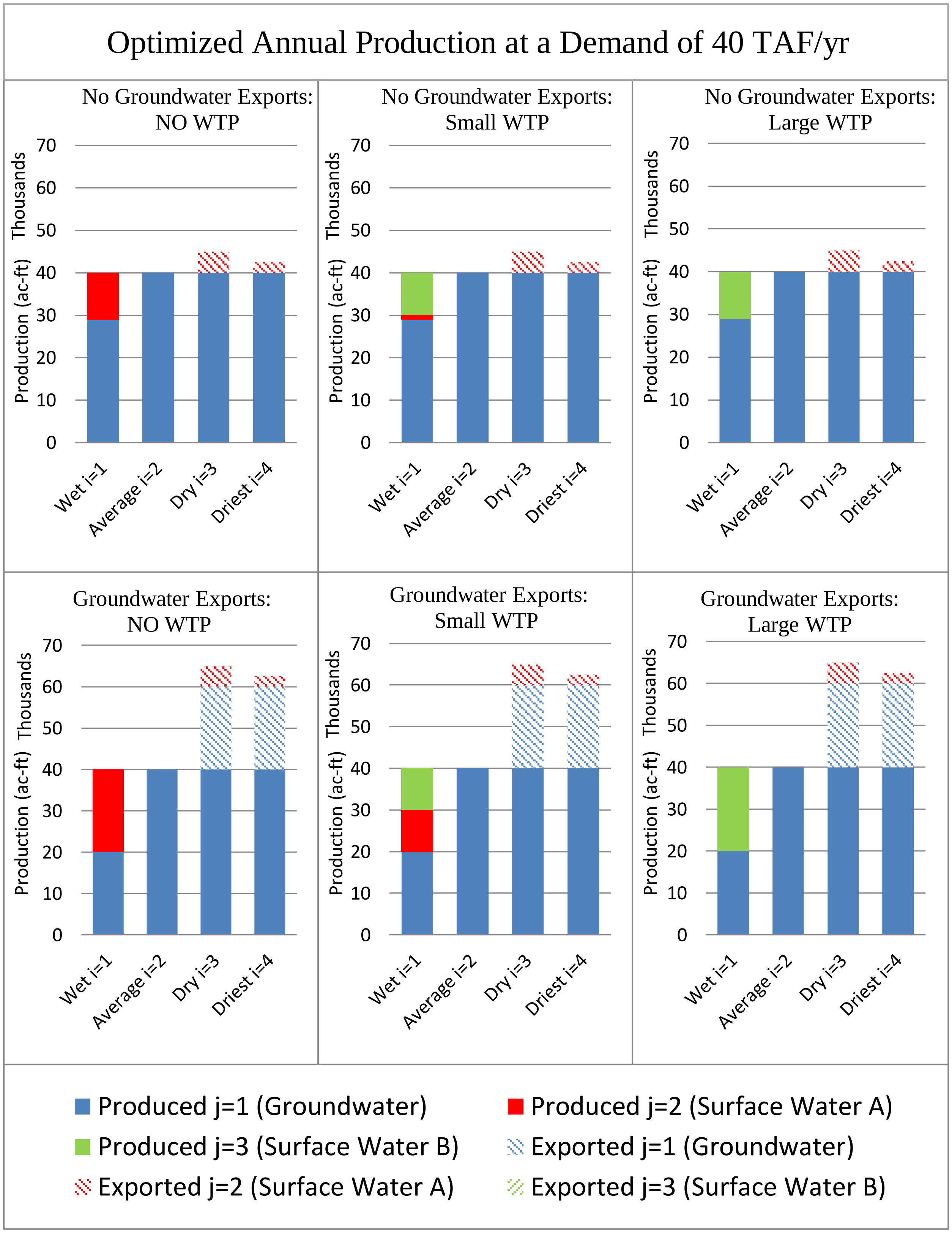

Figure 2-2: The optimized annual production for each alternative at an annual demand of 40 TAF/yr is shown above.

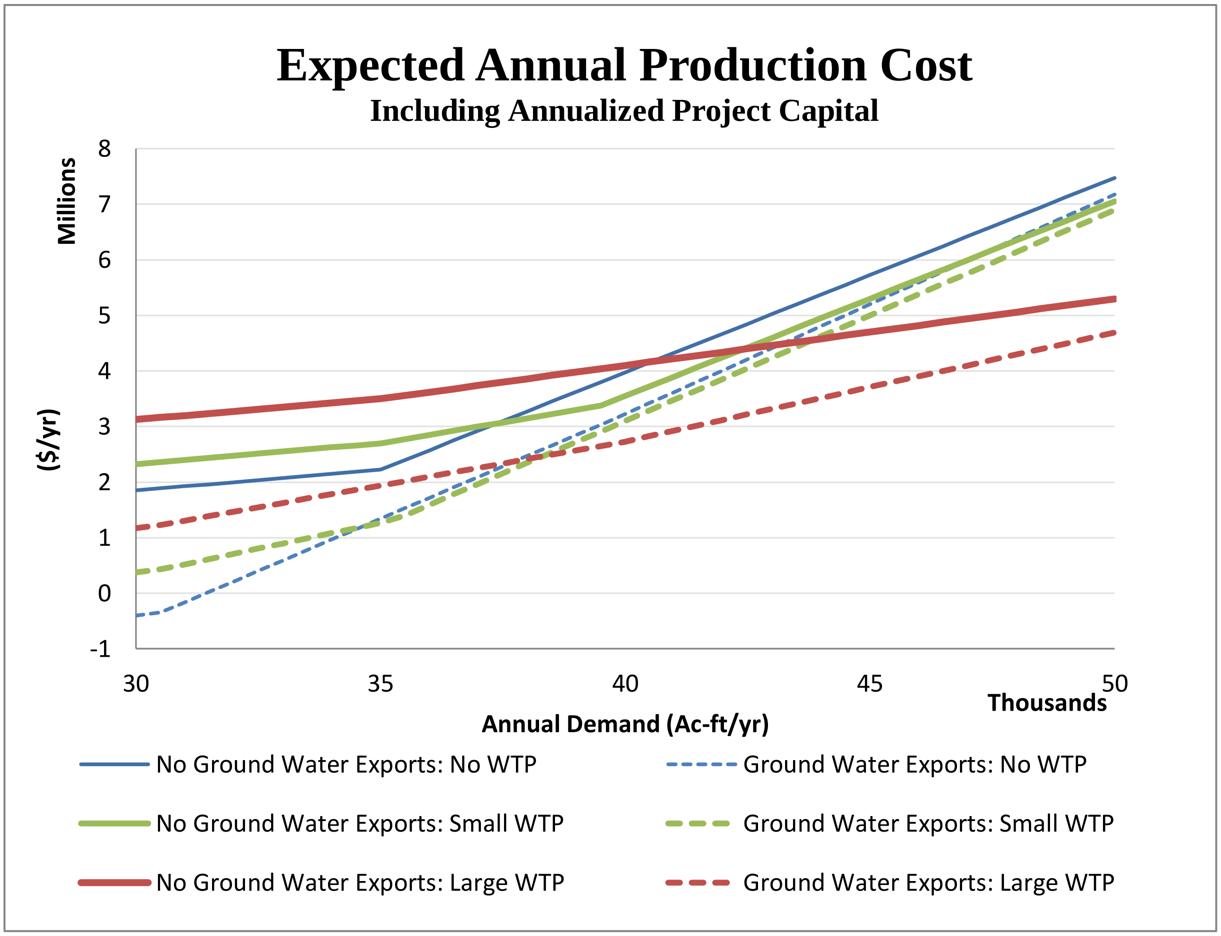

Figure 2-3: The expected annual production cost including annualized project capital is shown as a function of demand for each alternative. The linear program generates the optimal production for each alternative through a range of annual demand. The expected production least-cost solutions are noted for each range of water demand is added to the annualized project cost for each alternative.

For any given annual demand, the expected annual production cost (including annualized project capital as a function of annual demand) (Figure 2-3) allows for identification of the least cost alternative. The expected annual benefit for each alternative is calculated as a function of annual demand. It is the difference between the expected annual production cost (including annualized project capital) for each alternative and the current system (no groundwater exports and no WTP) (Figure 2-4).

The expected annual benefit graph (Figure 2-4) suggests groundwater exports would be desirable for any WTP alternative. The decision for treatment plant size is slightly more complex. Near the current demand of 40 TAF/yr, the three alternatives for treatment with groundwater exports converge. A water manager may use this graph qualitatively. If the annual demand were expected to increase, then the large WTP would provide the greatest benefit. If the annual demand were expected to decrease, then a surface water treatment plant might not be needed. Although there is optimal benefit of a small treatment plant when groundwater exports are made and annual demand is between 35 and 38 TAF/yr, the added benefit is small. For annual demands less than 35 TAF/yr, no WTP is optimal. If groundwater exports were not possible due to environmental or political concerns, then magnitude of benefit and point in demand in which treatment alternatives become optimal would change.

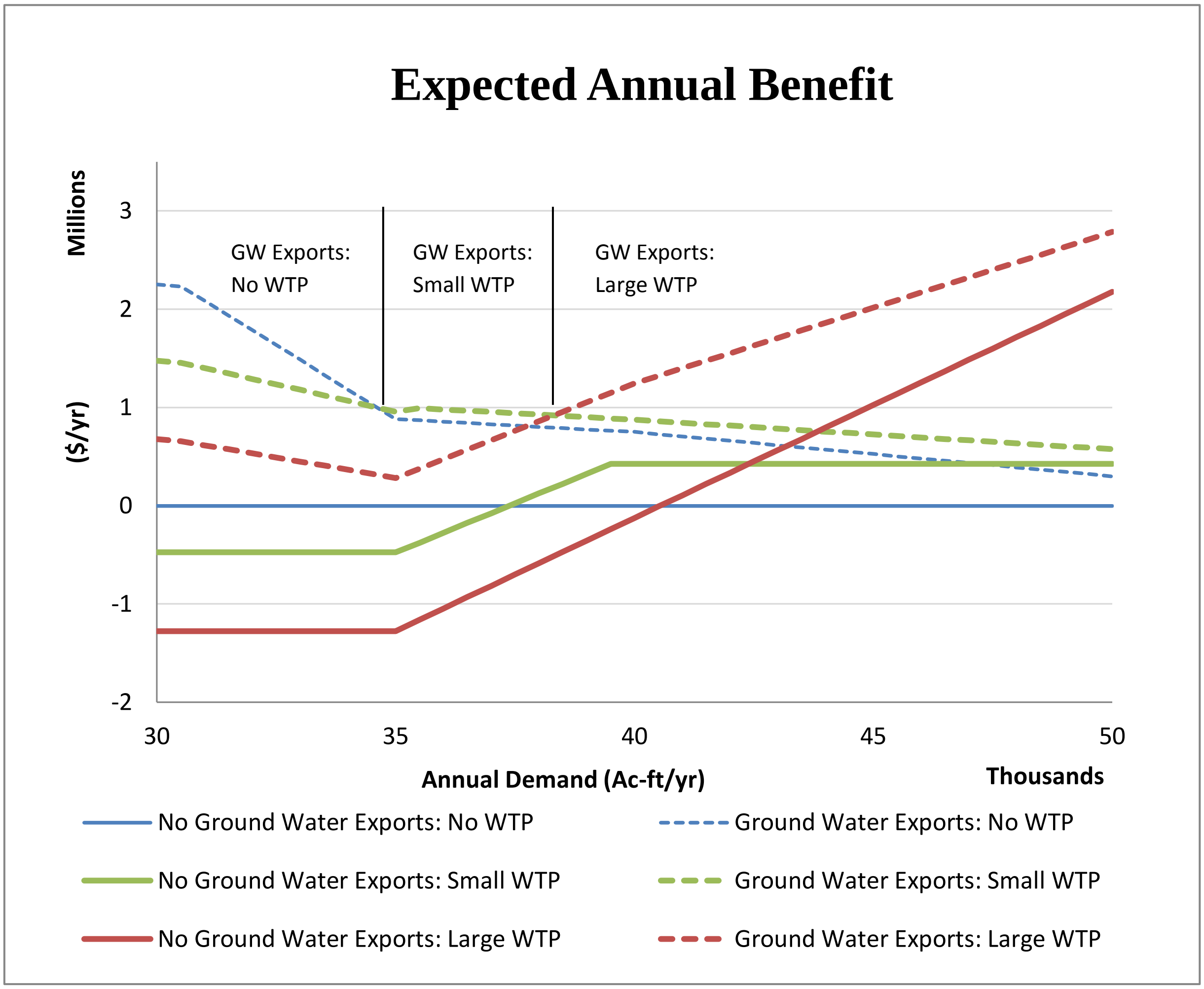

Figure 2-4: The expected annual benefit of each alternative is shown as a function of demand. It is the calculated by taking the difference between the expected annual production cost (including annualized project capital) of each alternative and the current system (no ground water exports: no WTP).

The value of water use conservation within each alternative, year type and demand level is evaluated with the linear program sensitivity outputs. A Lagrange multiplier is the unit cost of increase or savings per unit reduction for a given constraint. Thus the value of conservation is the Lagrange multiplier for the demand constraint normalized by the year type probabilities. Conservation is evaluated by running the model over a range of demands and storing the demand constraint's Lagrange multiplier. An example of this is included for the alternative for a groundwater exports and a small WTP over an annual demand range of 30 to 50 TAF/yr (Table 2-3).

Table 2-3 The per unit value ($/ac-ft) of conservation with groundwater exports and a small WTP is shown for each year type over a range of demand.

Year Type	Demand (TAF/yr)				
	30	35	40	45	50
Wet	$ 75	$ 120	$ 350	$ 350	$ 350
Average	$ 75	$ 120	$ 350	$ 350	$ 350
Dry	$ 75	$ 120	$ 475	$ 475	$ 475
Driest	$ 875	$ 875	$ 875	$ 875	$ 875

The system is better understood through an evaluation of water use conservation. The added benefit of water use conservation varies with year type and annual demand. For the example given (Table 2-3), wet and average year types have a unit value of conservation equal to the most expensive source necessary to meet demand. The same is true for dry year type with demand up to 35 TAF/yr. By 40 TAF/yr, dry year exports are reduced due to groundwater pumping infrastructure and the unit value of conservation is increased to the unit profit of groundwater exports. For the Driest year type, exports are limited by groundwater pumping infrastructure and the unit value of conservation remains the unit profit of groundwater exports.

Uncertainty in annual water availability, export demand, and price of water will affect the results. To evaluate the sensitivity to these uncertainties, additional scenarios can be included in the analysis. A wetter and a dryer climate scenario is included to evaluate sensitivity to future annual water availability. The probability for these scenarios was selected arbitrarily (Table 2-4).

Table 2-4: The probability of water year type for each climate scenario is shown below.

	Wet i=1	Average i=2	Dry i=3	Driest i=4
Baseline	0.45	0.35	0.15	0.05
Wetter	0.50	0.37	0.10	0.03
Drier	0.40	0.33	0.20	0.07

Changes in the probability of water availability affect the expected annual benefit (Figure 2-5). The magnitude of expected annual benefit for each alternative is changed by the climate scenarios, but general trend remains the same. The drier climate further increases the benefit of groundwater export. For demands larger than 40 TAF the larger plant remains optimal. There is still a degree of ambiguity for demand less than 40 TAF. Managers still use the graph to make qualitative assessments.

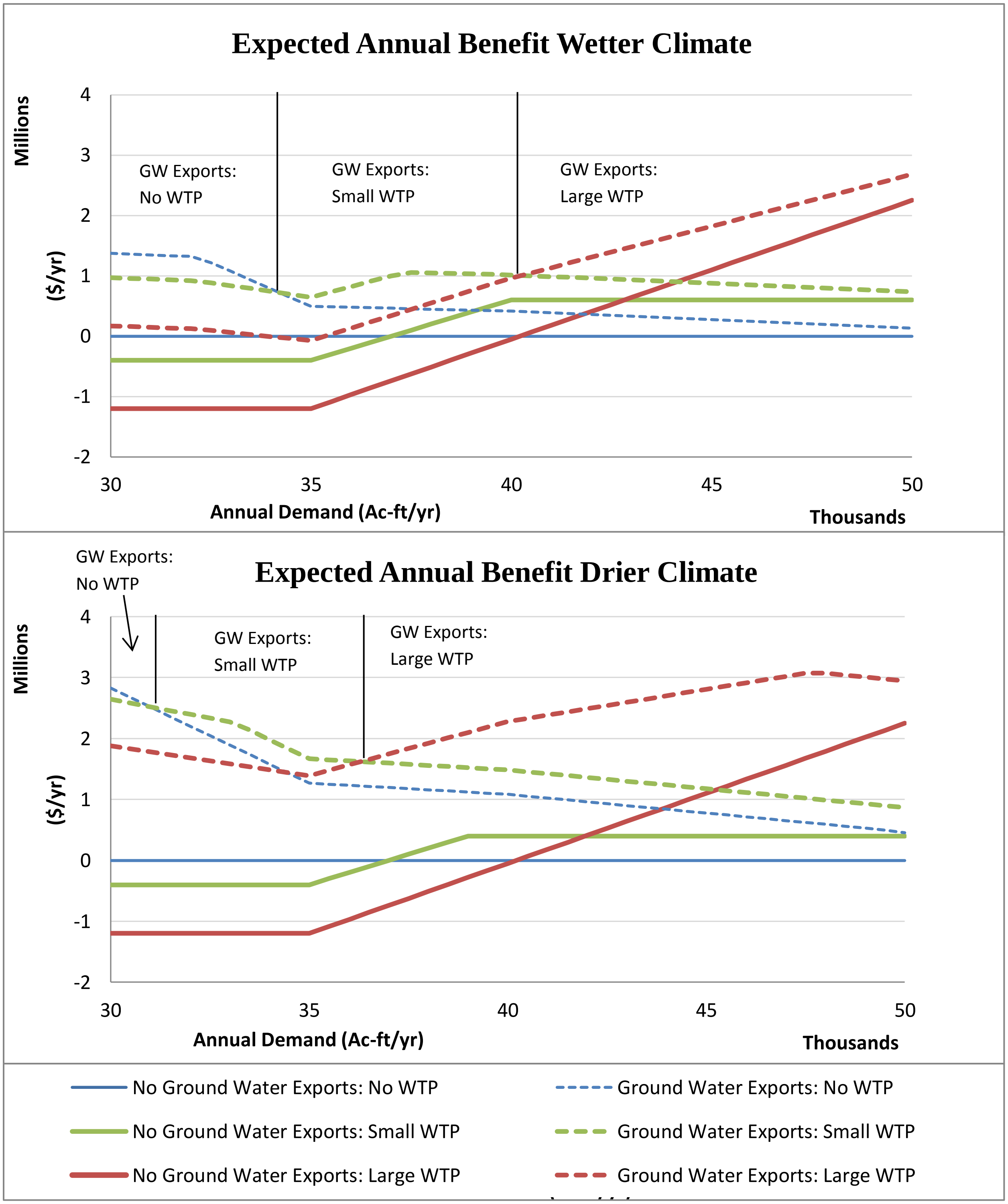

Figure 2-5: The expected annual benefit of each alternative is shown as a function of demand for a wetter and drier climate scenario. It is the calculated by taking the difference between the expected annual production cost (including annualized project capital) of each alternative and the current system (no ground water exports: no WTP). The probabilities of water year types is shown in table 2-4.

Chapter Conclusions

Groundwater is subject to long-term depletion. Restrictions on pumping, such as the implementation of a long-term sustainable groundwater yield, limit its use. Surface water or additional water use reduction must be incorporated in a water supply if the annual demand exceeds the sustainable groundwater yield. The amount of surface water needed will be a function of water demand and availability. Linear programming can be used to optimize annual water production and insure a reliable water supply. Optimal production is a function of system constants and costs used to represent alternatives.

A management alternative is a set of demands, production costs, water prices, water availability, and system delivery limitations. A proposed water treatment plant, expansion of a well field, construction of a water transmission line, signing of a water transfer agreement, creation of additional storage, or increased water conservation, or any combination of such actions can be modeled as separate alternatives. With each alternative, the optimal production and expected production cost will change. The expected production cost for an alternative can be turned into a function of annual demand by running the model through a range of demands. The value of each alternative can then be graphically expressed by taking the difference between the expected optimized production costs of alternatives. This difference is the expected annual benefit of an alternative.

The expected annual benefit of an alternative as a function of demand informs managers for investment decisions. Different alternatives may become optimal as demand changes. Uncertainty will change the magnitude of benefit for various alternatives, but general trends may be evident. Mangers can make assumptions about projected demand and use graphs of expected annual benefit to assess system investments.

Chapter 3) Sacramento Suburban Water District System Background

The Sacramento Suburban Water District can be used to illustrate the approach described in chapter two. The district has two sources of treated surface water and well-established groundwater infrastructure. There are opportunities to transfer surface water to the state water market and groundwater to neighboring districts. The best operation of these resources under different conditions is an important question. Linear programing can generate conjunctive use strategies for reduced cost, while maintaining supply reliability. The district's strategy depends on several constraints. A good understanding of the water system is needed for formulating the constraints, selecting decision variables, and creating alternatives. System awareness also aids with approximations and understanding of model limitations.

Regional Background

The district is along the eastern edge of the Sacramento Valley of California near the confluence of the American River and Sacramento River. It operates in unincorporated metropolitan areas of Sacramento County and borders the City of Sacramento to the west, the American River to the south, Placer County to the north, as well as a mix of small water purveyors. The area is primarily flat, with a grade from east to west. The minimum and maximum elevation in the system is 161 and 30 ft respectively.

Hydrology/Climate

The Mediterranean climate and Sierra Nevada Mountains drive the region's hydrology and water availability. Precipitation is highly seasonal, primarily occurring from November through April with little occurring in other months. Storms typically come from the west. Moist air condenses as it rises over the Sierra resulting in precipitation, which increases with elevation. In winter, precipitation typically occurs as snow at elevations above 5,000 ft. Snow acts as a storage reservoir in the Sierras, typically accumulating in the late fall through winter. By early spring the snow begins to melt at an increasing rate. Peak snow melt occurs typically between April and June resulting in large inflows. The magnitude and timing of peak snow melt has been shifting over the last century (Reclamation, 2014). Warmer temperatures in the Sierras have increased the portion of precipitation falling as rainfall, decreasing the magnitude and accelerating peak snow melt.

American River Watershed and Reservoir Operations

The Sacramento Suburban Water District relies on the American River watershed for surface water. The watershed is 4,821 square km (hydra.edu) and provides a median runoff of 2.6 million acre feet annually. The annual outflow of the watershed is highly variable (Figure 3-1). Reservoirs within the American River watershed buffer some inter-annual variability. The combined storage capacity of the 13 largest reservoirs is 1.9 Million acre feet (USBR.com). Folsom reservoir is the largest and terminus in the system, with a capacity of 1 million acre feet. It is operated by the U.S Bureau of Reclamation. The Bureau must balance an often competing set of benefits. These include: water supply, flood control, hydropower, recreation and ecosystem management.

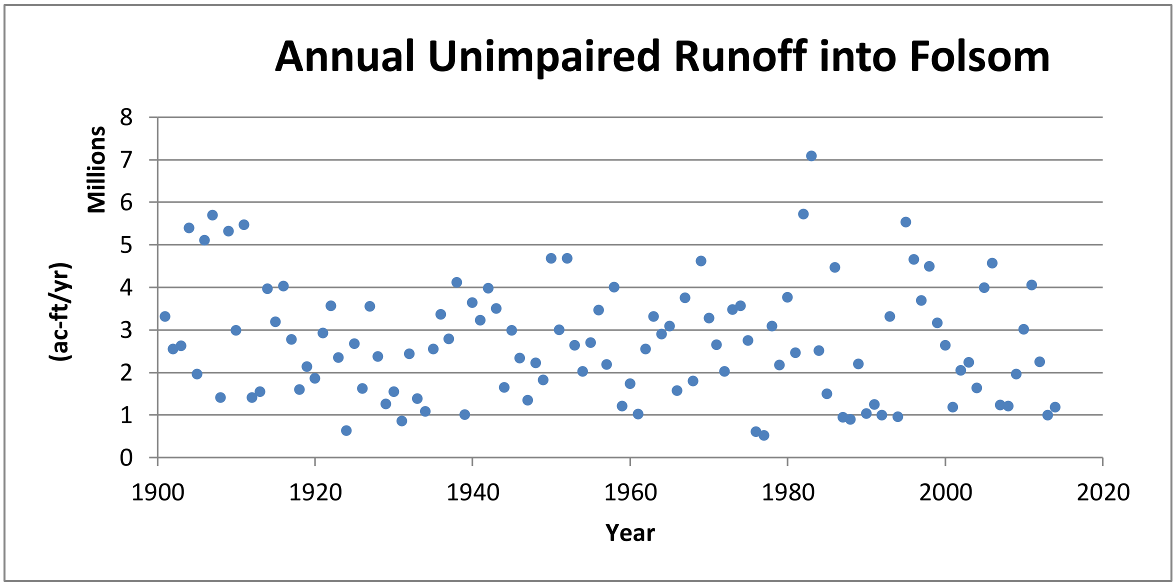

Figure 3-1: The historical annual flow of the American River Watershed is shown as the unimpaired runoff into Folsom. It is assumed to be equal to the fair oaks gauge on the American River (California Data Exchange Center).

From a water supply reliability standpoint, the reservoir should be kept as full as possible, but flood control considerations prevent this. Substantial storage capacity must be kept empty during peak runoff season to reduce flood risk. This is accomplished operationally by following reservoir release curves. These curves call for reduced water storage in winter and early spring to provide storage space for large storms and spring runoff. If reservoir storage is above the release curve it must be drawn down with flood control releases. The Bureau allows water purveyors to purchase and utilize these releases, as Section 215 purchases. The availability of Section 215 water is a result of hydrologic and operational conditions. The expansion of Folsom spillway and further advances in meteorological forecasts will reduce the flood storage space required. This will reduce the amount and change the timing of flood control releases. As a result, surface water available under Section 215 may be reduced.

Ecosystem management also can affect water supply reliability. The primary ecosystem management consideration involves salmon on the lower American river. Salmon require cold water within the lower American river for spawning. Water temperatures on the lower American River are regulated with reservoir releases from Folsom Reservoir. The operation of Folsom Reservoir affects the timing, frequency, duration, and magnitude of surface water available on the lower American River.

Sacramento Suburban Water Supply

The Sacramento Suburban Water District has two separate service areas, a North and South service area. Each service area operates independently. Both service areas have surface and groundwater supplies. Surface water in the north is from Peterson Water Treatment plant diverting water from Folsom reservoir. Surface water in the south is from Fairbairn Water Treatment Plant on the American River. Each plant diverts from a separate water rights from a variety of contracts. See Figure 3-2 for a map of the system and Figure 3-3 for a system schematic.

Demands

The district services approximately 160,000 customers, in a consolidation of two former water districts, Arcade in the south and North Ridge in the north (UWMP, 2011). The district also inherited the former McClellan Air Force base which is now an industrial park. Single family residential is the primary land use in the district. Annual water demand for the district can fluctuate, but has been on the decline. Demand varies through the day, year, and location (Figures 3-4, 3-5).

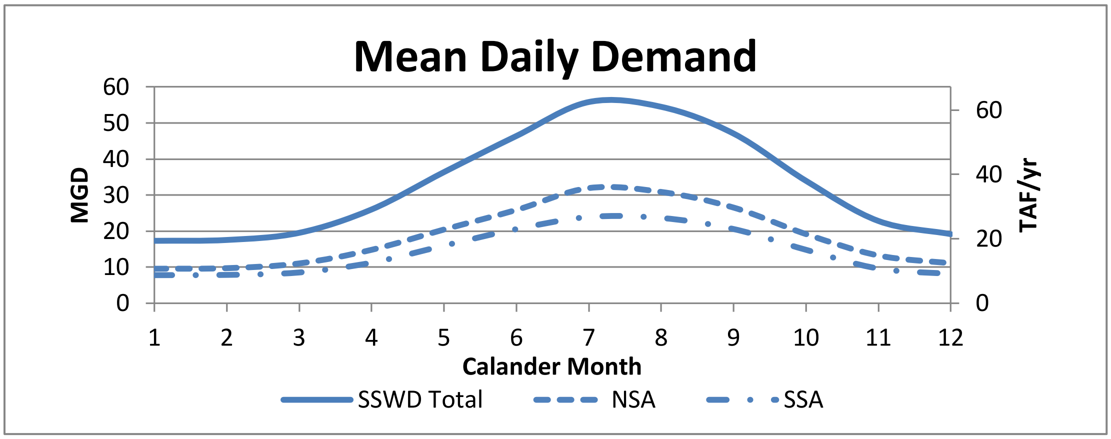

Figure 3-4: The mean daily demand for calendar months is shown above. The mean is period of 2007 to 2012. Generated from production data provided by SSWD.

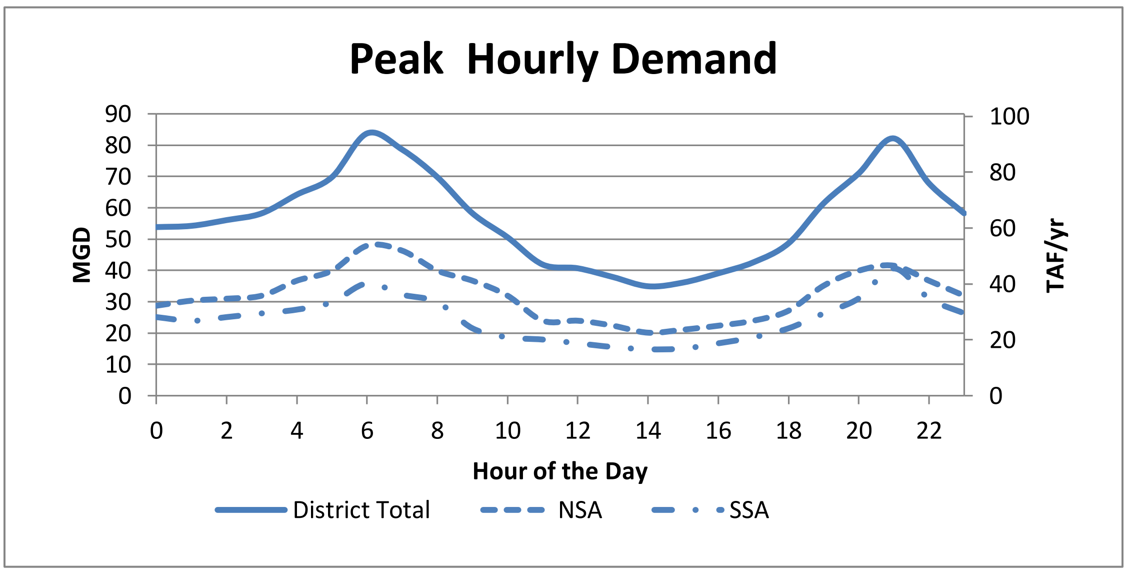

Figure 3-5: The peak hourly demand is estimated with a peaking factor (WSMP) and the mean daily demand in the month of July.

Peterson Water Treatment Plant

Peterson treatment plant provides surface water to the North Service Area. The plant is owned and operated by San Juan Water District (SJWD). It has a capacity of 150 MGD and serves several water agencies within the San Juan Wholesale Area, including SJWD, Fair Oaks Water District, Orange Vale Water Company, Citrus Heights Water District, and parts of the City of Folsom. Water treated at the plant is diverted from Folsom Reservoir under a Warren Act "wheeling" agreement with the United States Bureau of Reclamation. Water treated at the plant is stored in Hinkel Reservoir and distributed. The reservoir has a capacity of 70 million gallons. Treated water from Hinkel Reservoir is delivered to the North Service Area through the San Juan Cooperative Transmission pipeline (CTP). The CTP has a capacity of 59.2 MGD. The head difference between Hinkel reservoir and the district inlet (~300 ft) allows water to be delivered by gravity. The pressure at the district inlet is 120 psi and a pressure reducing valve drops the pressure to 70 psi.

The district agreement with San Juan Water District allows for access to unused capacity at Peterson WTP. This "shoulder" capacity restricts availability of treated surface water to the district. Other water agencies' needs, with higher priority, must be met before the district can receive treated surface water from Peterson WTP (WSMP,2009). The district is 14th in priority for the plant, so, the timing of delivery is highly variable. The fluctuation in daily and seasonal demand in the North Service area along with limited storage and plant capacity further constrain actual deliveries. The treatment cost is subject to change, most recently $75 per acre foot.

Untreated water is available for treatment at Peterson WTP under two contracts. A long-term agreement exists with Placer County Water Authority and occasional section 215 "Spill Water" water available from the United States Bureau of Reclamation (UWMP,2011).

Placer County Water Authority Supply Agreement

The Placer County Water Authority Supply Agreement provides Sacramento Suburban Water District with an Annual Entitlement of 12,000 TAF/yr of untreated water. This water is subject to shortage provisions, most notably the Water Forum Agreement (described on page 39). Sacramento Suburban Water District also may request up to 29,000 TAF/yr, which must be approved by Placer County Water Authority (UWMP, 2011).

This contract is a "take or pay agreement", meaning that if the water is available, the district must pay for its full Annual Entitlement regardless if it was used. If Sacramento Suburban Water District does not take its full Annual Entitlement amount, in a year that it was available, the Annual Entitlement will be reduced by an amount equal to 50% of the amount which Sacramento Suburban Water District did not take or pay (amendment 1).

The unit reserve cost can fluctuate and is based on the highest of three rates. These per acre foot rates include: $35 per ac-ft, 175% the rate at which Placer County Water Authority charges the City of Roseville, and 150% of the fee and charges paid to the United States Bureau of Reclamation. The historical rate has been $35 per ac-ft (amendment 1).

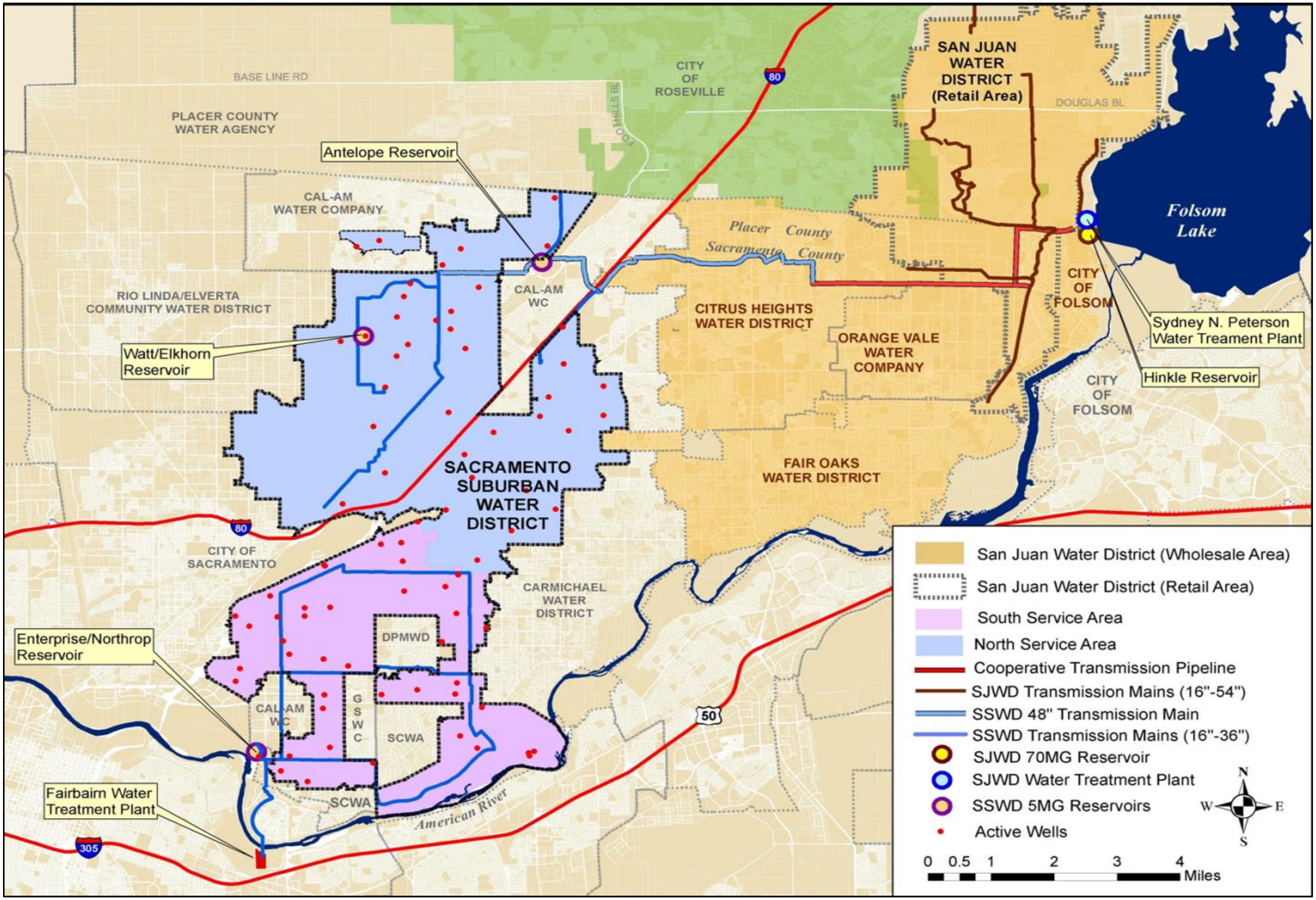

Figure 5-2: A Map of the Sacramento Suburban Water District is shown above (Map provided curtesy of SSWD).

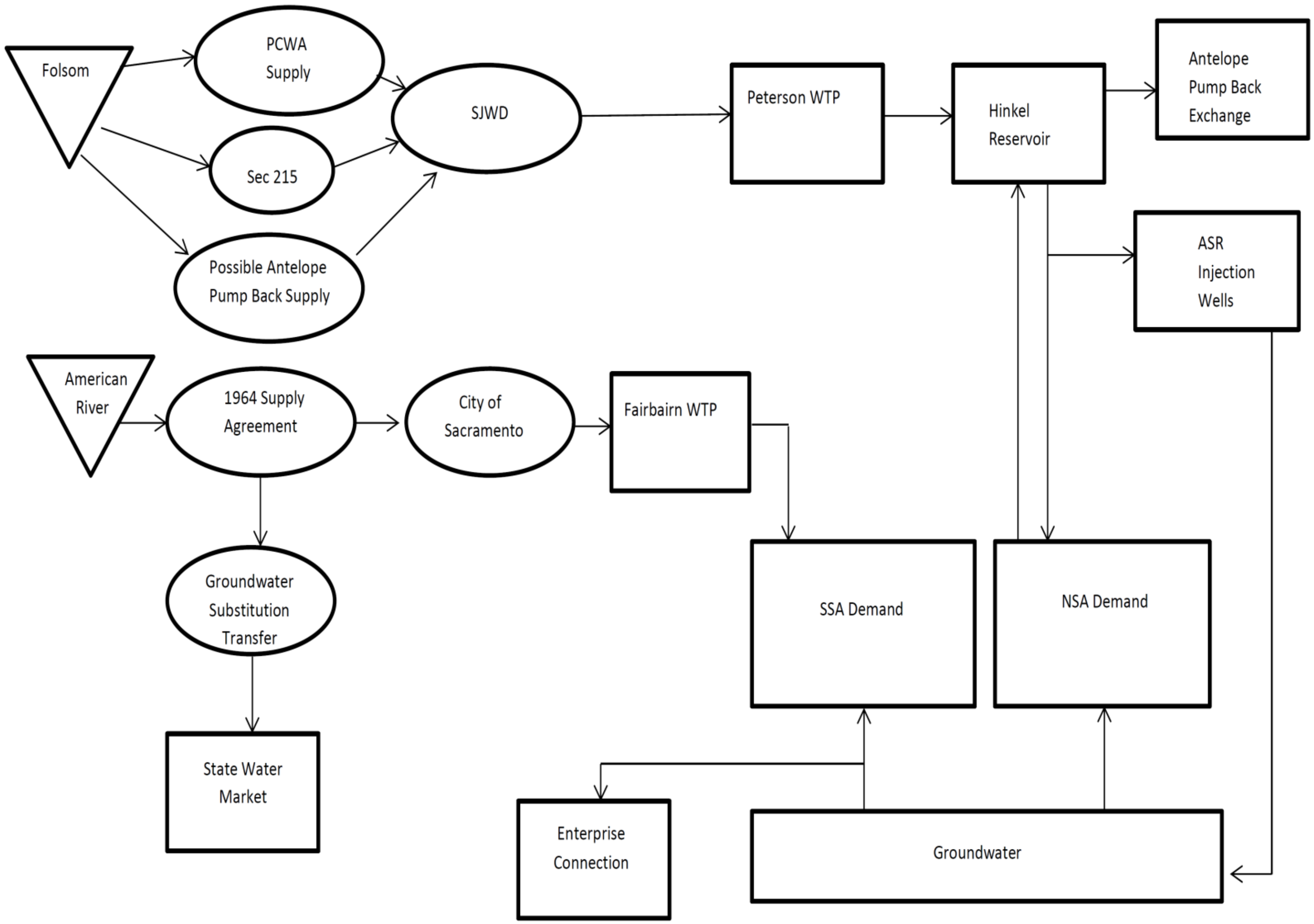

Figure 5-3: A schematic of the Sacramento Suburban Water District is shown above. Contracts are shown in ovals and physical locations and infrastructure is shown in squares.

If the full Annual Entitlement is available, the Sacramento Suburban Water District pays the reserve cost up to the Annual Entitlement, regardless of if the full amount is taken. Any amount taken above the Annual Entitlement, upon approval from Placer County Water Authority, will be charged a per unit reserve cost (amendment 1).

United States Bureau of Reclamation Arrangements

The United States Bureau of Reclamation is involved in the water supply by two arrangements. These include annual Warren Act "wheeling" and Section 215 "spill water" (WSMP,2009).

Warren Act "wheeling" is the term for the transfer and delivery of water using the USBR's Folsom Reservoir (WSMP,2009). The USBR must agree to Warren Act Wheeling on an annual basis. Without this approval water cannot be delivered to Peterson Treatment Plant. The historical price has fluctuated, but is generally $20 per ac-ft.

Section 215 is considered flood control release water. This water can be purchased at a variable rates set by the USBR. Section 215 water availability is highly variable and depends on hydrology and reservoir operation. Since 2007, section 215 has been available to Sacramento Suburban Water District twice. The district utilized 950 ac-ft and 1350 ac-ft, during 2010 and 2012, respectively.

Fairbairn Water Treatment Plant

The City of Sacramento's Fairbairn Water Treatment Plant provides treated surface water to the South Service Area. It has a capacity of 160 MGD. Water treated at the plant is diverted from the American River. The water is delivered to the South Service Area through the Howe Avenue transmission main. The Howe Avenue transmission main has a capacity of 60 MGD and is delivered at pressures of 30-35 psi. Rights to untreated surface water originate from the 1964 Water Supply Agreement. Rights to treat water at Fairbairn WTP originate from the Wholesale Water Agreement between the City of Sacramento and Sacramento Suburban Water District.

1964 Water Supply Agreement

In 2001, the district inherited rights to a 1964 Water Supply Agreement from the consolidation of Arcade Water District. The 1964 Water Supply Agreement included rights to divert up to 26 TAF per year of the City of Sacramento's "permit supply". The City of Sacramento's "permit supply" is a mix of pre and post 1914 water rights along with settlement contracts under the USBR (City of Sacramento Wholesale water supply agreement). It does not give the district an explicit pre-1914 appropriative rights and is restricted by the Water Forum Agreement (described on page 39) and Hodge flows (described on page 45).

Wholesale Agreement with the City of Sacramento

In 2003, the District entered into a wholesale water agreement with the City of Sacramento. Under this agreement the District could receive both an instantaneous flow and daily maximum flow rate of 20 MGD. The maximum annual diversion remains subject to the 1964 Water Supply Agreement, 26 TAF per year. The district retains the rights to divert untreated surface water under the 1964 Water Supply agreement. Rights to treated surface water remain subject to the Water Forum Agreement and Hodge Flows.

The cost of treated water from Fairbairn WTP consists of an annual fixed cost, interment capital improvement cost, and per unit production cost. The annual cost consists of a reserve cost and administrative fee. The reserve cost can fluctuate and is based on the actual amount delivered. The most recent cost has been $39,000 $/yr. The administrative cost is $200 dollars per month. A capital improvement cost covers the district's share transmission main rehabilitation and treatment plant upkeep. The per unit treatment cost has steadily increased over the years. In 2010, it was $180 per ac-ft and is currently $330 per ac-ft.

Groundwater Substitution Transfers

Sacramento Suburban Water District may temporarily transfer its share of post-1914 appropriative water rights acquired from the 1964 Water Supply Agreement, with approval from the State Water Resources Control Board. California water code sec 1725 allows for a temporary change in the point of diversion, place, and purpose of use, for appropriative water rights if that water would have been otherwise used. It is commonly referred to as a groundwater substitution transfer. The district must show that its appropriative water rights have been exercised in the past and water that would have been consumptively used by the water right will be substituted with groundwater. This requires the use of Fairbairn WTP during wet years. Additionally, they must prove that no other water user or instream beneficial uses will be harmed by the transfer.

Surface water transfers are made possible by the State Water Project and Central Valley Project. Transferred water remains instream to the Sacramento–San Joaquin River Delta and pumped into the California Aqueduct where it can be delivered to contactors on either project. Additional diversion options include the Freeport Intake on the Sacramento River for delivery to the East Bay Municipal Utility District. Diversion through the California Aqueduct is constrained by pumping restrictions in the Delta. This can limit the window for surface water transfers to a few months.

Sacramento Suburban Water District has made groundwater substitution surface water transfers in the past. Since 2009, the district has transferred a total of 9.6 TAF during the years of 2009, 2010 and 2013.

Groundwater Assists

Groundwater supplies exist in both the North and South services areas. The North Service area has 40 active wells with a total capacity of 66 MGD. The south service area has 42 active wells with a total capacity of 67 MGD. The need to maintain adequate pressure within the system reduces the actual available production of groundwater. When the well field is not operating at full capacity, the older less efficient wells are not used, which reduces energy cost. The approximate operating cost of the groundwater pumping is $75/ac-ft. At full pumping capacity the cost increases.

Historical Conjunctive use

The district has incorporated surface water since 1998, beginning with surface water deliveries to the North Service Area from the Peterson WTP. Deliveries from the Fairbairn WTP to the South Service Area began in 2007. The annual district production from each source is shown from 1998 through 2014 (Figure 5-6). Water year criteria for wet years changed in 2010 under the Water Forum Agreement making wet years less frequent. Therefore, in years prior to 2010, there was more availability of treated water from Peterson WTP.

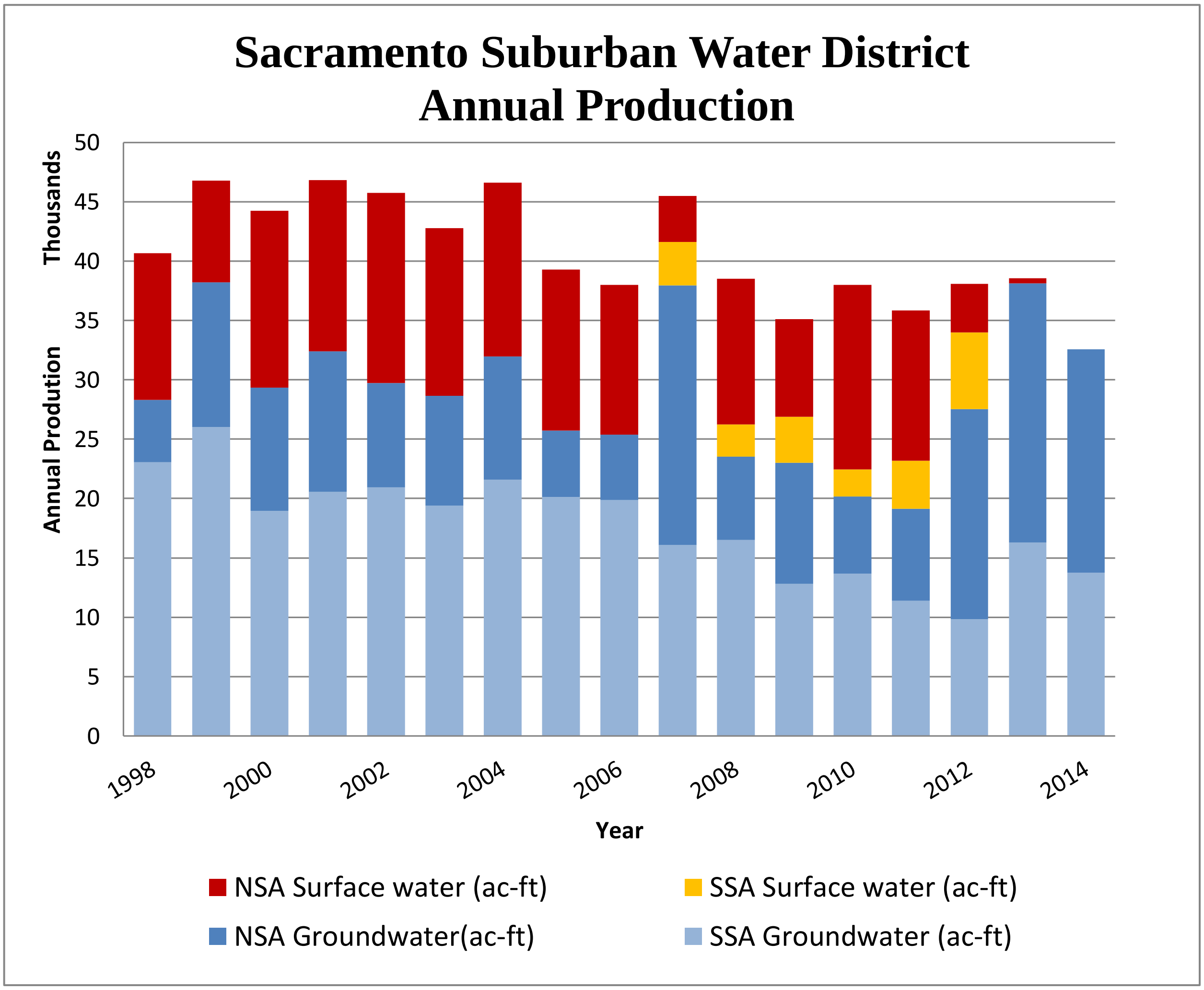

Figure 3-6: Annual Sacramento Suburban Water District production for the period of 1998 to 2014 is shown above.

Storage

The district has a total surface water storage capacity of approximately 15.3 MG (47 ac-ft). There is 5 MG (15.4 ac-ft) in the south and 10.3 MG (31.6 ac-ft) in the north. Storage buffers daily demand fluctuations. District storage can be filled at non-peak hours and drained during peak hours. This reduces cost and increases total water availability.

For example, the district may not have access to surface water from Peterson WTP during peak hours (especially during the summer peak season), due to the capacity constraints and the district's low priority at the plant, but surface water may be available beyond the district's demand during non-peak hours. District storage can be filled at that time and drained when surface water is not available. Local storage can only buffer daily fluctuation.

Similarly, the reduced cost from storage is a result of daily demand fluctuation. During the summer when demand is highest, energy prices vary greatly. The district is a commercial customer for Sacramento Municipal Utility District, which provides the district's electricity at variable rates. During peak days, electricity can be roughly three times more expensive from one part of the day to another. This is an opportunity for the district to increase pumping during low cost energy hours to fill storage tanks. The storage then can be drawn down when energy costs are high.

Water Forum Agreement

The Water Forum is a group of water agencies, business leaders, environmental groups, community organizations, and local government within Sacramento County (WFA, 2000). In 2000, they came together with the signing of the Water Forum Agreement to address gridlock involving: water supply reliability, environmental degradation, fisheries habitat, water quality, and economic development in the greater Sacramento area. The Water Forum Agreement is a "Memorandum of Understanding" and nothing more than a "political and moral commitment" (The Agreement). The explicit objectives of the Water Forum Agreement are to: "Provide a reliable and safe water supply for the region's economic health and planned development to the year 2030; and Preserve the fishery, wildlife, recreational, and aesthetic values of the Lower American River" (WFA, 2000). The Water Forum process has also facilitated legal binding commitments among its members. Most notable of these, is a joint powers agreement creating the Sacramento Groundwater Authority (created prior to the signing of the Water Forum Agreement) and a separate agreement to constrain surface water diversions during specified conditions.

Water Forum Agreement Water Year Types

The Water Forum Agreement restricts on the availability of surface water. The Agreement defines water year types based on projected March through November Unimpaired Inflow to Folsom Reservoir (UIFR). The UIFR is estimated based on runoff and snowpack within the American River Watershed. Estimations are made monthly from February through May, by the California Department of Water of Recourses (technical memorandum 1). The water year type may fluctuate during the estimation period, but the May water year type selection is fixed through the following January.

The four water year types are: Wet, Average, Dry, and Driest. A UIFR of greater than 1.6 MAF per year is defined as Wet. A UIFR between 1.6 and 0.9 MAF per year is defined as Average. Between 0.9 and 0.4 MAF is a dry year and below 0.4 is defined as driest.

The California Department of Water Resources maintains a database of historical stream flow. Adjustments can be made to account for flow that would have occurred had it not been impaired by upstream storage. This is termed unimpaired flow. The historical record of UIFR can be used to estimate the probability for each water year type. Using the historical record from 1901 to 2014, an exceedance probability graph is generated (Figure 3-7). The exceedance probability can be used to estimate the probability of each water year type (Table 3-1).

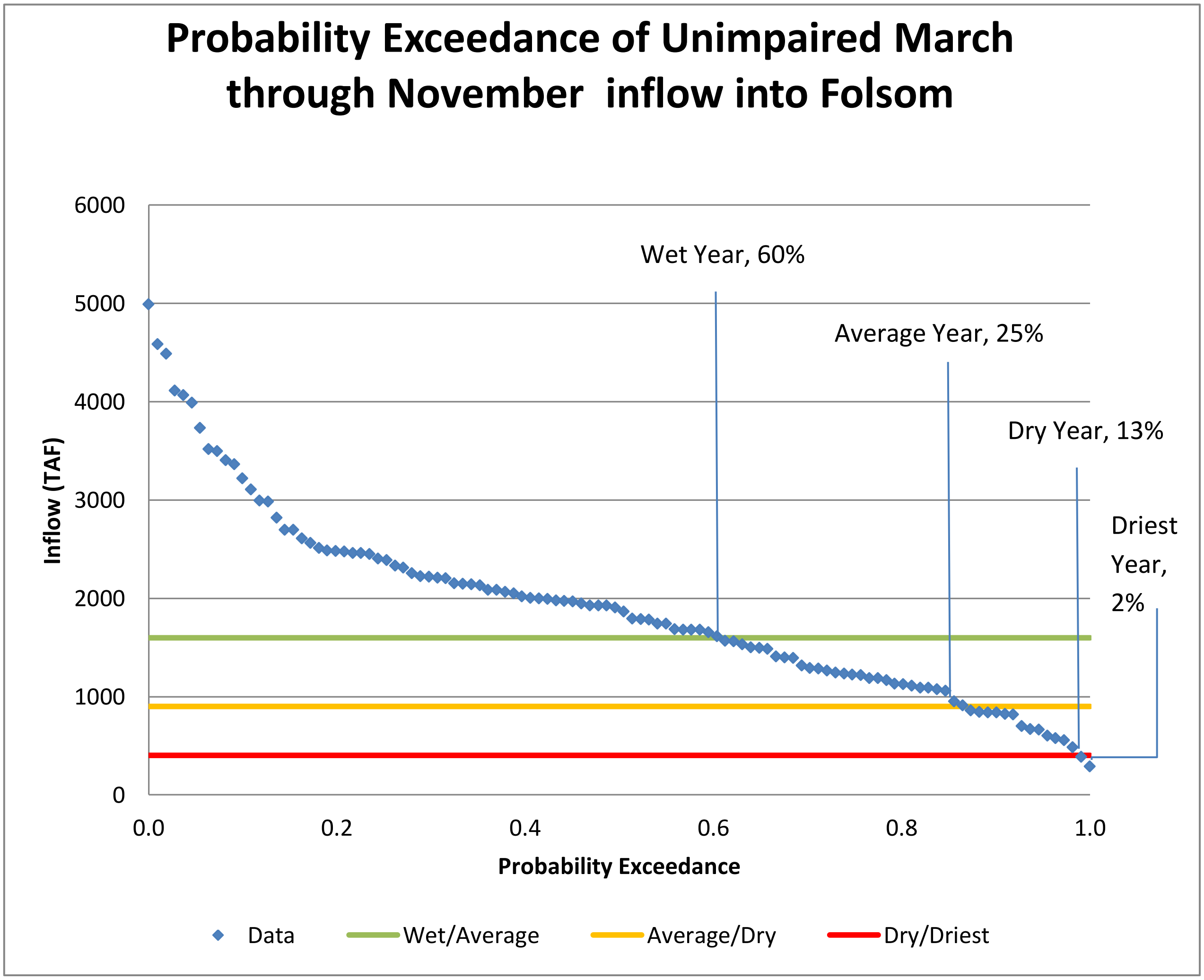

Figure 3-7: The historical exceedance probability of unimpaired March through November inflow into is shown for a period 1901 to 2014. Horizontal lines are displayed to show thresholds of water year types. Data provided by Sacramento groundwater Authority and the California Data Exchange Center.

Table 3-1 Probabilities of water form year types from the historical record of unimpaired flow into Folsom from 1901 to 2014.

Water Year	Wet	Average	Dry	Driest
Probability	0.60	0.25	0.13	0.02

Redefining water year types

The Water Forum Agreement defines four water year types based on expected runoff into Folsom. Driest year types occur infrequently, with a probability of 0.02. The available time series is insufficient to accurately estimate the driest year types, and non-stationarity in long-term climate may add further inaccuracies.

There is significant surface water storage within California. The statewide water system can usually maintain reliability during a single dry or driest year, but shortages can be expected over multiple year droughts. If dry or driest years occur following wet years, shortage is expected to be less. For this reason, the dry and driest year types defined by the Water Forum Agreement have been redefined and replaced with different criteria.

Droughts are defined for the purpose of the model as beginning when a water year is average or drier and do not end until the occurrence of a wet year. A dry or driest year after the first year of a drought is defined as critical. Dry or driest years following a wet year are defined as dry. Average water years during a drought remain classified as average years. This allows for a better estimation of water year probabilities, water transfer demand, and price during drier year types (Table 3-3).

Table 3-3: Redefined model year types events are shown.

Critical Years	1931	1988
	1934	1992
	1961	2013
	1977	2014
Dry Years	1924	1990
	1939	1994
	1959	2001
	1976	2007
	1987	

The probability of water year types is an important input. Trends in the probability of water year types can be identified by considering a 30 year moving average through the historical record. It appears that the probability of wet years may be declining, while drier years appear to be increasing (Figure 3-8).

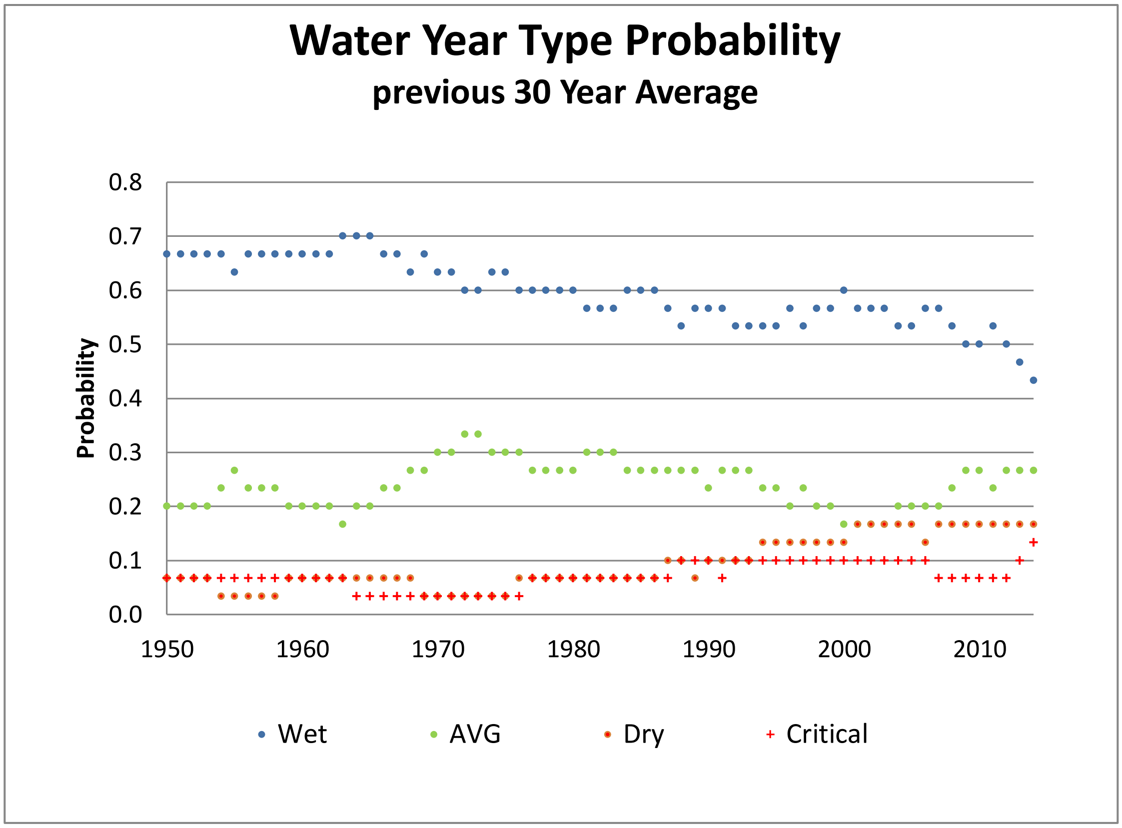

Figure 3-8: A 30 year moving average is taken for the probability of water year types from 1950 to 2014. Trends in the occurrence of water year types are seen.

Water Forum Agreement Surface Water Constraints

The Water Forum Agreement restricts PCWA diversion at Folsom Reservoir into the NSA to water forum wet years. It recommends a minimum flow standard on the American River for the use of USBR section 215 water from Folsom Reservoir, set as an attempt to protect fish on the American River. The minimum flow standard is 190 cfs at the mouth of the American River. There is a provision that under extraordinary conditions the flow standard could be "relaxed if reallocating that volume of water to another time in the year would be more beneficial for the fishery." (WFA, 2000). This provision affects surface water availability for the south service area by limiting diversions through Fairbairn WTP.

The Water Forum Agreement places additional constraints on the use of surface water from Fairbairn WTP. Fairbairn WTP diverts water from the American River. Diversions to Fairbairn are therefore subject to the Hodge decision. Constraints are added by the Water Forum Agreement. They consist of upper and lower bound for diversions. The upper bound is 3100 cfs, 200 MGD, with no explicit yearly limit when unimpaired inflow into Folsom Reservoir exceed 400 TAF. The lower bound is 1550 cfs, 100 MGD, with an explicit limit of 50,000 ac-ft per year.

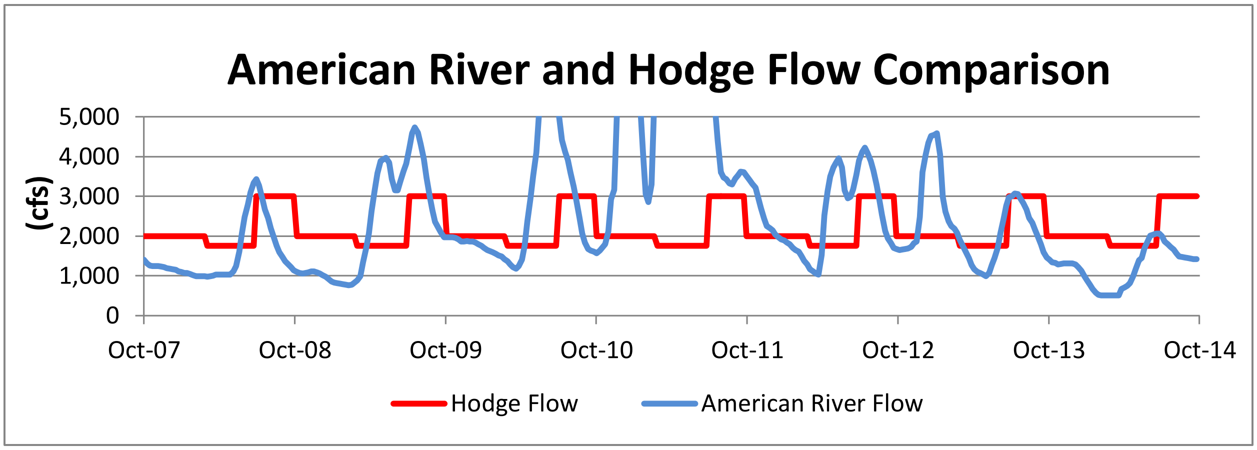

Figure 2-9: Hodge flow is compared to American river Flow. Diversions from the American river can only be made when river flow is above Hodge.

Hodge Flows Surface Water Constraints

Diversions from Fairbairn WTP are limited by Hodge flows. Hodge flows restrict diversions on the American river when discharge at the Fair Oaks gauge is less than specified limits, which vary through the year (Table 3-3). A graph of Hodge flow and American River flow over a 7 year period is provided to illustrate the timing and duration of Hodge flow diversion limitations (Figure 3-9).

Table 3-3: Hodge flow restrictions are shown below

Hodge Period	Oct. 15 -Feb	March - June	July - Oct. 15
Hodge Flows (cfs)	2,000	3,000	1,750

The mean daily flow of the American River at Fair Oaks was considered over the period from 1974 to 2013. The number of days above Hodge levels was calculated for each year. Years were then grouped into the Water Forum water year types and the mean number of days above Hodge level was calculated (Table 3-4).

Table 3-4: The mean, median, and standard deviation is included for the mean number of days in a year the American flow is above Hodge for each water year .type.

Hodge Flow statistics	Water Year Type		
Day above Hodge	Wet	Average	Dry & Critical
Mean	268	159	57
Median	283	159	61
Standard deviation	54	60	29

Sacramento Groundwater Authority

The County of Sacramento is divided into North, Central, and South basin. The Sacramento Groundwater Authority operates in the North Basin. It was created in 1998 as a joint powers agreement among: the City of Citrus Heights, the City of Folsom, the City of Sacramento, and the County of Sacramento. The joint power agreement transferred local land use and policing powers to the Sacramento Groundwater Authority. Its primary purpose is to conserve groundwater resources and maintain a sustainable yield in the North Basin "for the common benefit of all water users within the County of Sacramento" (JPA).

North Basin Area

The North Basin is in the southern portion of the North American sub-basin as defined by Bulletin 118 (GMP). It is further divided into Western, Central, and Eastern areas. Sacramento Suburban Water District is in the Central area.

Surface water availability varies between each North Basin area. The Western and Eastern areas were developed prior to the Central area, and so have greater and more senior surface water rights (GMP). The water system infrastructure in Western and Eastern areas is primarily developed for surface water. The Central area has limited access to surface water and has primarily developed groundwater. As a result, a cone of depression exists in the Central basin.

Groundwater infrastructure within the district is well developed and self-sustained. Areas to the east of the district tend to have less developed groundwater infrastructure because of their reliance on more senior water rights, primarily from Folsom reservoir. These areas are more susceptible to shortages during droughts. In 2014, the areas to the east of the district were at a high risk for water shortage. The water level in Folsom came close to falling below the diversion intake. This spurred drought contingency efforts including the Antelope Pump Back project, which will allow export of SSWD groundwater to the eastern basin area.

Hydrogeology

The District sits atop alluvial fill, a mix of sand, silt, and clay deposited as river, lacustrine and volcanic sediments. Major water baring formations are a late tertiary and quaternary unconfined alluvium occupying the first 200-300ft. The Mehrten formation is an older semi-confined volcanic aquifer formation occupying varying depths of 300-1200ft DWR-118.

Decades of overdraft in the region has resulted in a large cone of depression under laying the district. Several contaminate plumes exist around the periphery of SSWD. The hydraulic gradient of the cone of depression increases the rate of contaminant transport into the district. Reduced groundwater production will slow contaminant transport by decreasing the hydraulic gradient.

Aquifer Storage and Recovery

Several recharge areas exist with in the North Basin area. Coarse grained sediments in eastern areas of the basin provide the greatest opportunities. Recharge is more difficult in the central part of the North Basin Area, including the SSWD. The fine grained sediments and clays within the SSWD limit the use of percolation basins for recharge. Direct injection of treated surface water for Aquifer Storage and Recovery (ASR) is an option.

ASR of treated surface water is possible with some adjustments to the current system. Surface water from Peterson WTP is delivered to the district under high pressure. At present the pressure is reduced before it enters SSWD's water system. The reduction of pressure results in a loss of energy. It has been proposed that this excess energy be utilized for the direct injection of surface water, by diverting the flow into converted ASR wells in the NSA. This would increase water availability from Peterson WTP in the same way as water storage in the district, but would be effectively available for years.

Sustainable Yield

Sustainable yield is defined by the Water Forum Agreement as the amount that can be extracted from the basin on an estimated annual basis that will maintain both water supply reliability and water quality. The Sacramento County Integrated Groundwater and Surface Water Model, in May of 1997, established a sustainable yield of the basin (WSMP). It determined a sustainable of 131,000 acre-feet per year would bring the North Basin into balance by 2030.

The Central area of the North Basin has been a focus to meet the sustainable yield. Baseline groundwater extraction from 1993 through 1997 was 101,784 acre-feet per year (WAF). The eight water agencies in the Central area agreed to reduce extractions to an average of 90,000 acre-feet per year. Each water agency was assigned a pumping target. Sacramento Suburban Water District was assigned 35,035 acre-feet/year.

A network of threshold wells was identified to monitor groundwater levels in the North Basin. Groundwater levels are monitored once a year in the Spring. Each well has an upper and lower groundwater elevation threshold. If groundwater levels drop below the threshold corrective actions may be taken. This may include, but is not limited to, changes in the sustainable yield.

Water Accounting Framework

To incentivize conjunctive use Sacramento Groundwater Authority has developed a Water Accounting Framework. It provides a set of operating rules that could be used to facilitate groundwater banking programs (WAFW II). The Water Accounting Framework consists of a Basin Sustainability Balance and Exchangeable Water Balance which are calculated on an annual basis. Currently, only the Central Basin has an active accounting process, although some pumping restrictions exist for the Eastern area. The current Water Accounting Framework took effect in 2012, but accounts for historical water use through 1998.

The Basin Sustainability Balance is the difference between the pumping target and actual volume pumped. While the Exchangeable Water Balance is the volume of surface water put to beneficial use beyond that necessary to meet the pumping target. Sustainability Balances are not transferable to the Exchangeable Water Balance or to another agency. Exchangeable Water Balances are transferable to the Sustainability Balance or to another agency. An agency must have a positive Sustainability Balance to participate in surface or groundwater transfers.

The Sacramento Suburban Water District has reduced its demand and incorporated a large amount of surface water since 1998. As a result it has a large Exchangeable Water Balance. The District's Exchangeable Water Balance was 187,880 acre-feet in 2014. This will provide the district with extensive groundwater banking and water market opportunities.

Antelope Pump Back Exchange

As a direct result of the drought beginning in 2012, coordinated drought contingency actions took place within North Basin under the direction the Sacramento Groundwater Authority. These actions included adding interties between systems to increase delivery of groundwater to systems dependent on surface water. One of the more ambitious projects is the Antelope Pump Back.

Sacramento Suburban Water District has robust groundwater infrastructure. It is sufficient for the District's demand with capacity to spare. The District has delivered groundwater to adjacent systems in the past. A large potential customer for groundwater during times of drought is the San Juan Water District wholesale area. These purveyors have numerous surface water rights and have not developed groundwater infrastructure on a large scale. During drought these purveyors are susceptible to shortage. The Antelope Pump Back Project was developed to deliver them District groundwater during drought.

Surface water is delivered from Peterson WTP to the North Surface area. This water is held in Hinkel Reservoir after treatment and delivered to the members of the San Juan Water District wholesale area including Sacramento Suburban Water District. The District receives this water through the Cooperative Transmission pipeline. The Antelope Pump Back project will retrofit the existing pipeline to accommodate booster pumps to pump District groundwater about 300 ft up to Hinkle reservoir. At Hinkle reservoir the water can be delivered to other members of the San Juan Water District wholesale area. This project could greatly reduce water shortages in the eastern part of the North Basin Area during drought.

Need for a conjunctive use strategy

To maintain long term basin sustainability and reasonable cost for customers, the district will need to continue implementing conjunctive use. They will need to maximize efficiency with existing infrastructure and determine cost effective investment in the system. This process can start with a production strategy and plan for each year type. The production strategy for each year type will assist operators by assigning targets for surface water and groundwater. Investment in ASR, groundwater export infrastructure, and additional water supply contracts can be evaluated by comparing alternatives.

The prospect for groundwater exports out of the district will require managers to closely examine the amount the district should be willing to export on a long term basis. Complications can arise with exports. If the district exports too much groundwater via the Antelope pump back, then additional surface water from Fairbairn may be needed to maintain a sustainable yield. Surface water from Fairbairn is expensive, so the district should place limits on groundwater exports through the project. These limits will be a function of the expected surface water availability, the financial compensation provided, and the sustainable yield. The optimization can help determine the right balance of exports.

Chapter 4) Sacramento Suburban Water District Model

The formulation described below applies the method in chapter two to water system described in chapter three. The linear program works to minimize the expected annual production cost by suggesting annual production targets for each source during each year type. Infrastructure and contract limitations are applied as availability constraints varying with water year type and source. Demands in the North Service Area and South Service Area are applied as separate demand constraints and the average value of long term pumping is applied as a sustainable yield constraint.

Description of District Model

The district model formulation is a list of decision variables, constraints, and an objective function tailor made for SSWD. Decision variables consist of options to treat water at Peterson WTP under the PCWA and a proposed Antelope Pump Back contracts, treat water at Fairbairn WTP or transfer surface water from the 1964 Water Agreement contract, inject treated water from Peterson WTP, and export groundwater through the Antelope Pump Back and Enterprise Connection. Constraints consist of limitations on the decision variables. Many are subject to the structure of water supply contracts and permitting regulations.

For example, a hypothetical surface water supply contract for the Antelope Pump Back Exchange is included in this formulation. Under this proposed contract, the district will receive monetary compensation and one unit of surface water for every unit of groundwater exported. Surface water provided by this contract is treated at Peterson WTP and only taken during wet years. An additional constraint is included to represent the annual maximum limit of surface water that can be supplied in wet years. In comparison, the district will receive only monetary compensation and no additional surface water for groundwater exported on the Enterprise Connection. For both the Antelope Pump Back and Enterprise Connection groundwater bank credit exchanges are not included. The formulation can be adjusted to account groundwater bank credit exchanges by adjusting the constraint representing the groundwater bank withdrawal (*GW Bank withdrawal* described on page 59).

Many of the constraints in the model represent yearly limitations, which can be difficult to estimate. For example, surface water delivered from Fairbairn WTP is limited by a flow rate of 20 MGD and an annual amount of 26 TAF/yr. A proper constraint on this source would not be simply the minimum of the two. A separate analysis is needed to incorporate the timing of demand and available storage. This is beyond the scope of this work, but if it were to be conducted, values from such an analysis can be used. For the purpose of this paper, a value of 22 TAF/yr was used as the capacity constraint on Fairbairn WTP.

The capacity constraint on Fairbairn WTP was further restricted by incorporating Hodge Flows. The mean portion of the year above Hodge for each year type was calculated from the historical record (See page 45). By taking the product of the mean portion of the year above Hodge and the capacity constraint, a limit on the amount of surface water that can be delivered via Fairbairn WTP was established.

Similarly, surface water transfers were limited by incorporating the mean portion of the year above Hodge flow during the transfer period, which is assumed to be the July through September. The constraint was further reduced by the length of the transfer period (*Hodge Flow Limit on transfers* described on page 57). In addition, constraints on surface water transfers require any dry year surface water transfer be no more than wet year production. This constraint is added to qualify for the groundwater substitution transfer; because the district is required to show that surface water transferred could have been consumptively used.

The limitation for surface water from Peterson WTP was broken into two types. The first includes an annual limit that can be consumptively used in the NSA without ASR given the plant capacity, timing of demand, and available storage. The second includes ASR.

The availability of section 215 is sporadic and uncertain. It is not well defined by year type and its addition to the formulation would add unnecessary complexity. Sec 215 was neglected for the purpose of this proof of concept.

District Model Formulation

The linear program optimizing conjunctive for SSWD described above. appears below.

Decision Variables for each year type:

PCWA up to "Take or Pay" (ac-ft/yr) is the amount of PCWA contract water up to the "Take or Pay" amount, diverted at Folsom, treated at Peterson WTP by SJWD, wheeled by the USBR and delivered to the NSA.

PCWA above "Take or Pay" (ac-ft/yr) is the amount of PCWA contract water up to the "Take or Pay" amount, diverted at Folsom, treated at Peterson WTP by SJWD, wheeled by the USBR and delivered to the NSA.

APBE SW (ac-ft/yr) is the amount of surface water received in exchange for groundwater exported from the district through the Antelope Pump Back Exchange (APBE). It is diverted at Folsom, treated at Peterson WTP by SJWD, wheeled by the USBR, and delivered to the NSA.

Fairbairn WTP Applied Demand (ac-ft/yr) is the amount of surface water diverted from the American River, treated at Fairburn WTP by the City of Sacramento, and applied to the South Service Area demand.

APBE GW Export (ac-ft/yr) is the amount of groundwater exported out of the North Service Area to the San Juan Whole Sale Area through the Antelope Pump Back Exchange.

EC GW Export (c-ft/yr) is the amount of groundwater exported out of the South Service Area to the City of Sacramento through the Enterprise Connection (EC).

1964 SW Transfer (ac-ft/yr) is the amount of surface water from the 1964 Supply Agreement transferred to the state water market via the American River.

Peterson ASR (ac-ft/yr) is the amount of Aquifer Storage and Recovery (ASR) made via injection of treated surface water from Peterson WTP through infrastructure in the NSA.

SSA GW Applied Demand (ac-ft/yr) is the amount of district produced groundwater applied to the South Service Area (SSA).

NSA GW Applied Demand (ac-ft/yr) is the amount of district produced groundwater applied to the NSA Service Area (NSA).

Objective Function:

Min: $Expected\ Annual\ Production\ Cost = \sum_{i=1}^{n} p_i(Year\ Type\ Net\ Cost_i\ )$

n = number of Year Types
i = Year Type
p = Probability of Year Type

Constraints

1) *PCWA Used <=PCWA Contract Max* (The amount of PCWA water used must be contractually available).

2) *APBE GW Export <=APBE Demand/Capacity limit* (Exports made on the Antelope Pump Back Exchange are limited by an annual limit that accounts for the timing of export demands, district demands, and the infrastructure capacity).

3) *APBE SW <=APBE SW Available* (Surface water transferred in exchange for groundwater exports on the Antelope Pump Back Exchange are limited by a maximum contractual allotment).

4) *APBE GW Export >=APBE Transfer Required Amount* (Groundwater exports made on the Antelope Pump Back Exchange must meet a minimum contractual amount).

5) *EC GW Export <=EC Demand/Capacity limit* (Exports made on the Enterprise Connection are limited by an annual limit that accounts for the timing of export demands, district demands, and infrastructure capacity).

6) *1964 SW Transfer <=1964 Supply Transfer SW Demand* (Surface water transferred to the state water market is limited to the demand on the state market).

7) *EC GW Export >=EC Transfer Required Amount* (Groundwater exports made on the Enterprise connection must meet a minimum contractual amount).

8) *1964 SW Transfer <=Hodge Flow Limit on transfers* (Surface water transfers from the 1964 Supply Agreement to the state water market is limited by Hodge flow).

9) *NSA Physical withdrawal <=NSA Maximum Annual Pumping* (Groundwater pumping in the NSA is limited by capacity).

10) *SSA Physical withdrawal <=SSA Maximum Annual Pumping* (Groundwater pumping in the SSA is limited by the capacity).

11) *Peterson ASR <=ASR Capacity* (ASR is limited by capacity).

12) *SSA Demand Met >=South Service Area Demand* (Demand in the SSA must be met).

13) *NSA Demand Met >=North Service Area Demand (*Demand in the NSA must be met).

14) *Antelope Exchange SW EV limit <=Antelope exchange GW EV* (The expected value of surface water in exchange for ground water exports on the Antelope Pump Back Exchange is limited contractually to the expected value of exports made).

15) *Total Peterson Treated Water w/ ASR <=Peterson Contract* (Water treated at Peterson WTP is limited by an amount of water that is contractually available).

16) *Expected Annual GW Withdrawal <=Sustainable Yield* (The expected annual groundwater withdrawal is limited by a sustainable yield requirement).

17) *Total Peterson Treated Water w/ASR <=NSA Demand w/ ASR Limit w/ Peterson Capacity* (Water treated at Peterson WTP for district consumption and ASR is limited by the timing of demands and available infrastructure).

18) *Peterson WTP Applied to demand <= NSA Demand w/ Peterson Capacity limit* (Water treated at Peterson WTP for district consumption is limited by the timing of demands and available infrastructure).

19) *1964 water supply Utilized <= Hodge Flow Limit on Demand* (Water rights exercised under the 1964 Water Supply Agreement are limited by the amount the SSA consumptively use).

20) *Fairbairn WTP Applied to demand <= SSA Demand w/ Fairbairn Capacity limit* (Water treated at Fairbairn WTP and delivered to the district is limited by the timing of demand, infrastructure capacity, and contractual flow limitations.

21) *PCWA Contract up to "Take or Pay" <=PCWA Take or Pay Water Available* (PCWA contract water used up to the "Take or Pay" amount is contractually limited).

22) *1964 SW Transfer <=Fairbairn WTP in Wet year* (Surface water transfers are limited by wet year Fairbairn WTP diversions).

Where:

Sustainable Yield (ac-ft/yr) is the long term annual groundwater withdrawal goal for the district.

PCWA Reserve Cost ($/ac-ft) is the cost paid to PCWA per unit for available water.

Peterson Treatment Cost ($/ac-ft) is the cost per unit of water treated at Peterson WTP.

USBR Wheel Cost ($/ac-ft) is the cost per unit paid to USBR for water diverted from Folsom.

NSA Demand w/ Peterson Capacity limit (ac-ft/yr) is the maximum surface water that can be annually applied to demand in the North Service Area due to timing of North Service Area demand and spare capacity at Peterson WTP.

NSA Demand w/ ASR Limit w/ Peterson Capacity (ac-ft/yr) is the maximum surface water that can be annually consumed or injected in North Service Area due to timing of demand, spare capacity at Peterson WTP, and capacity of ASR wells.

PCWA Take or Pay Water Available (ac-ft/yr) is the amount of water that is reserved under PCWA contract. The reserve cost is paid regardless if used.

APBE SW Available(ac-ft/yr) is the contractual maximum amount of surface water that can be made available for the Antelope Pump Back Exchange surface water transfers.

PCWA Contract Max (ac-ft/yr) is the contractual maximum surface water entitlement amount under the PCWA Contract supply.

Sacramento Wholesale Reserve Cost ($/yr) is the cost to reserve treatment capacity at Fairbairn WTP.

Sacramento Wholesale Administrative Cost ($/yr) is the administrative cost paid to the City of Sacramento for access to Fairbairn WTP.

Fairbairn Treatment Cost ($/ac-ft) is the per unit cost of treatment at Fairbairn WTP.

1964 Supply Transfer SW Price ($/ac-ft) is the sales price for surface water in the state market.

1964 Supply Transfer SW Cost ($/ac-ft) is the administrative cost of surface water transfers.

Portion of year above Hodge: is the mean portion of the year that flow on the American River is above Hodge flow.

Portion above Hodge in Transfer Period is the mean portion of the transfer period with flow above Hodge. The transfer period is assumed to be three months to account for demand and delta pumping constraints.

SSA Demand w/ Fairbairn Capacity limit (ac-ft/yr) is the maximum surface water that can be annually consumed in SSA due to SSA demand and the timing of capacity at Fairbairn.

1964 Supply Transfer SW Demand (ac-ft/yr) is the demand for district surface water in the state water market market.

SSA GW Unit cost ($/ac-ft) is the per unit groundwater pumping cost in the SSA.

SSA Maximum Annual Pumping (ac-ft/yr) is the limit on total annual groundwater pumping for the South Service Area, both for demand and exports. It is a result of an instantaneous pumping capacity, the timing of demand within the district, and the need for fire flow.

NSA GW Unit cost ($/ac-ft) is the per unit groundwater pumping cost in the NSA.

NSA Maximum Annual Pumping (ac-ft/yr) is the limit on total annual groundwater pumping for the North Service Area, both for demand and exports. It is a result of an instantaneous pumping capacity, the timing of demand within the district, and the need for fire flow.

ABPE Transfer unit Cost ($/ac-ft) is the per unit cost paid by the district to pump water to the buster pumps for delivery through the Antelope Pump Back.

APBE Transfer unit Price ($/ac-ft) is the per unit price paid to the district for groundwater exported under Antelope Pump Back Exchange.

APBE Demand/Capacity limit (ac-ft/yr) is the maximum annual amount of groundwater that can be exported out of the basin through Antelope Pump Back Exchange due to infrastructure capacity and timing of both demands for exported water and district demands.

APBE Transfer Required Amount (ac-ft) is the required amount of groundwater water that must be delivered under the Antelope Pump Back Exchange.

EC Transfer unit Cost ($/ac-ft) is the cost paid by the district to deliver water through the Enterprise connection.
EC Transfer unit Price ($/ac-ft) is the per unit price paid to the district to deliver water through the Enterprise connection.

EC Transfer Required Amount ($/ac-ft) is the required amount of groundwater that must be delivered under the Enterprise Connection.

EC Demand/Capacity limit (ac-ft/yr) is the maximum amount of groundwater that can be exported through the Enterprise connection due to infrastructure capacity and timing of both demands for exported water and district demands.

ASR Capacity (ac-ft/yr) is the maximum annual capacity of the ASR well field.

ASR Unit cost ($/ac-ft) is the per unit cost of injection.

North Service Area Demand (ac-ft/yr) is the demand in the North Service Area.

South Service Area Demand (ac-ft/yr) is the demand in the South Service Area.

District Demand (ac-ft/yr) is the total demand in the NSA and SSA.

$$North\ Service\ Area\ Demand + South\ Service\ Area\ Demand$$

GW Bank withdrawal (ac-ft/yr) is the amount of water deducted from the groundwater bank account. Groundwater export amount may or may not be included depending on if the district receives GW bank credit. For the model runs in chapter 5, the exports are included, meaning no groundwater credit is received for groundwater export.

$$APBE\ GW\ Export\ +\ EC\ GW\ Export\ +\ SSA\ GW\ Applied\ Demand \\ +\ NSA\ GW\ Applied\ Demand\ -\ ASR\ From\ Peterson$$

Total GW Physical withdrawal (ac-ft/yr) is the total amount of groundwater pumped in the district. This includes groundwater produced for district demand and groundwater exports.

$$APBE\ GW\ Export\ +\ EC\ GW\ Export\ +\ SSA\ GW\ Applied\ Demand \\ +\ NSA\ GW\ Applied\ Demand\ -\ ASR\ From\ Peterson$$

SSA Physical withdrawal (ac-ft/yr) is groundwater pumped from the SSA.

$$EC\ GW\ Export + SSA\ Applied\ Demand$$

NSA Physical withdrawal (ac-ft/yr) is groundwater pumped from the NSA

$$APBE\ GW\ Export + NSA\ Applied\ Demand$$

SSA Demand Met (ac-ft/yr) includes all sources applied to SSA demand.

$$SSA\ GW\ Applied\ Demand +\ Fairbairn\ WTP\ Applied\ to\ demand$$

NSA Demand Met (ac-ft/yr) includes all sources applied to NSA demand.

$$NSA\ GW\ Applied\ Demand + \ Peterson\ WTP\ Applied\ to\ demand$$

1964 water supply Utilized (ac-ft/yr) is the amount of surface water utilized under the 1964 supply agreement. It includes surface water treated at Fairbairn WTP and transferred to the state water market.

$$Fairbairn\ WTP\ Applied\ to\ demand + \ 1964\ SW\ Transfer$$

Antelope Exchange SW EV Limit (ac-ft/yr) is the expected value of Antelope Pump Back Surface water transferred to the district in exchange for groundwater exports. It is the weighted average over each year type.

$$\sum_{i=1}^{n} p_i (APBE\ SW_i)$$

Antelope exchange GW EV (ac-ft/yr) is the expected value of Antelope Pump Back groundwater exports. It is a weighted average over each year type.

$$\sum_{i=1}^{n} p_i (APBE\ GW\ Export_i)$$

PCWA Used (ac-ft/yr) is the total PCWA Contract water used. It is the sum of up to and above the "take or pay amount".

$$PCWA\ Contract\ up\ to\ \text{"Take or Pay"}\ + \ PCWA\ above\ "Take\ or\ Pay"$$

Peterson Contract (ac-ft/yr) is the total amount of surface water that is contracted to be treated at Peterson WTP. It is the sum of " PCWA Contract Max" and “APBE SW”.

$$PCWA\ Contract\ Max + APBE\ SW$$

Peterson WTP Applied to Demand (ac-ft/yr) is the amount of water treated at Peterson WTP water applied to the NSA demand. It does not including water used for ASR.

$$PCWA\ Used + APBE\ SW - \ ASR\ From\ Peterson$$

Total Peterson Treated Water w/ ASR (ac-ft/yr) is the total amount of water treated at Peterson WTP including ASR.

$$PCWA\ Used + APBE\ SW$$

Hodge Flow Limit on transfers (ac-ft/yr) is the annual limit for transfers due to Hodge Flow and the 1964 Supply Agreement. It is assumed that the transfer period is three months.

$$(SSA\ Demand\ w/Capacity\ limit \times Portion\ above\ Hodge\ in\ Transfer\ Period) \times 0.25$$

Hodge Flow Limit on Demand (ac-ft/yr) is the annual limit for Fairbairn WTP due to Hodge Flow, plant capacity, contractual flow limitations, storage, and the timing of demand.

$$Portion\ of\ year\ above\ Hodge \times SSA\ Demand\ w/\ Fairbairn\ Capacity\ limit$$

ASR Net Cost ($/yr) is the net cost of all ASR. It does not include the treatment cost pre-injection.

$$ASR\ From\ Peterson \times ASR\ Unit\ cost$$

Enterprise Connection Net Cost ($/yr) is the net cost of surface water deliveries and groundwater exports through the Enterprise Connection.

$$EC\ GW\ Export \times (EC\ Transfer\ unit\ Cost - EC\ Transfer\ unit\ Price)$$

APBE Net Cost ($/yr) is the net cost of surface water deliveries and groundwater exports through the Antelope Pump Back Exchange.

$$(\text{ABPE Transfer unit Cost} - \text{APBE Transfer unit Price}) \times APBE\ GW\ Export + (Peterson\ Treatment\ Cost + USBR\ Wheel\ Cost) \times APBE\ SW$$

SSWD GW Net Cost ($/yr) is the net cost of groundwater pumping to meet district demand.

$$(SSA\ GW\ Applied\ Demand \times SSA\ GW\ Unit\ cost) + (NSA\ GW\ Applied\ Demand \times NSA\ GW\ Unit\ cost)$$

1964 Supply SW Transfer Net Cost ($/yr) is the net cost of surface water transfers from 1964 water supply agreement.

$$(1964\ Supply\ Transfer\ SW\ Cost - 1964\ Supply\ Transfer\ SW\ Price) \times 1964\ SW\ Transfer$$

Fairbairn Treatment Net Cost ($/yr) is the net cost of Fairbairn WTP surface water.

$$(Fairbairn\ WTP\ Applied\ to\ demand \times Fairbairn\ Treatment\ Cost) + Sacramento\ Wholesale\ Reserve\ Cost + Sacramento\ Wholesale\ Administrative\ Cost$$

PCWA Cost Up to "take or pay" Net Cost ($/yr) is the net cost of water treated at Peterson WTP up to the "take or Pay amount"

$$(PCWA\ Reserve\ Cost\ \times\ PCWA\ Take\ or\ Pay\ Water\ Available) + (\ Peterson\ Treatment\ Cost +\ USBR\ Wheel\ Cost)\ \times\ PCWA\ above\ "Take\ or\ Pay"$$

PCWA Cost above "take or pay" Net Cost ($/yr) is the net cost of water treated at Peterson WTP above the "take or Pay amount"

$$(PCWA\ Reserve\ Cost +\ Peterson\ Treatment\ Cost +\ USBR\ Wheel\ Cost\ )\ \times\ PCWA\ above\ "Take\ or\ Pay"$$

Year Type Net Cost ($/yr) is the total annual production cost for each year type.

$$ASR\ Net\ Cost +\ Enterprise\ Connection\ Net\ Cost +\ APBE\ Net\ Cost\ + SSWD\ GW\ Net\ Cost +\ 1964\ Supply\ SW\ Transfer\ Net\ Cost\ + Fairbairn\ Treatment\ Net\ Cost +\ PCWA\ Cost\ Up\ to\ \text{take or pay} Net\ Cost + PCWA\ Cost\ above\ "take\ or\ pay"\ Net\ Cost$$

Expected Annual Production Cost ($) is the expected annual production cost over the long run

$$\sum_{i=1}^{n} p_i (Year\ Type\ Net\ Cost_i\ )$$

Chapter 5) Sacramento Suburban Water District Model Application

The optimization model can explore a variety of alternatives. These alternatives can include changes in demands, production costs, water prices, water availability, and system delivery limitations. The combinations of such changes are numerous. To provide a proof of concept for this method, several alternatives are analyzed. They include renegotiation of the annual PCWA contract entitlement, export of district groundwater through the Antelope Pump Back and Enterprise Connection, and ASR of surface water from Peterson WTP.

Two sets of alternatives are included. Each considers a renegotiated annual PCWA contract entitlement as a range of surface water options for wet years, from 0 to 30 TAF/yr in increments of 6 TAF/yr. The current reserve cost of $35/ ac-ft is assumed. Each set of alternatives evaluates a range of demand. It is assumed that demand is split equally between the North and South service areas. The first set focuses on evaluating the Antelope Pump Back as a for revenue generating asset, with additional surface water provided to the district in wet years to support groundwater exports in dry and critical years (Appendix 5-1 to 5-1d). The Enterprise Connection will also support exports for revenue in dry and critical years, but additional surface water in exchange for exports will not be provided. The first set of alternatives is:

Alternative set 1:

1a) Groundwater Exports With ASR (Appendix 5-1a)

1b) No Groundwater Exports With ASR (Appendix 5-1b)

1c) Groundwater Exports Without ASR (Appendix 5-1c)

1d) No Groundwater Exports Without ASR (Appendix 5-1d)

A second set of alternatives focuses on limits of exports made through the Antelope Pump Back when export revenue is not permitted. The Antelope Pump Back was created as a mutual aid effort. It will reduce risk of water shortage for purveyors within the eastern basin area through the export of SSWD groundwater. The designation of the Antelope Pump Back as a mutual aid project forbids the district from generating revenue. A set of alternatives (2a-2b) is given to model the limits of groundwater exports though the Antelope Pump Back in critical years, when operated as a mutual aid (Appendix 5-2 to 5-2b). The first (2a) considers no exports through the Enterprise connection, while the second (2b) considers exports with revenue made through the Enterprise Connection during critical years. Revenue from the Antelope Pump Back is restricted by setting the compensation to the district for exports made on the Antelope Pump Back equal to the per unit cost of surface water from Peterson WTP under the PCWA contract.

Alternative set 2:

2a) Antelope Pump Back as mutual aid with Enterprise Connection exports (Appendix 5-2a)

2b) Antelope Pump Back as mutual aid without Enterprise Connection exports (Appendix 5-2b)

Results

The linear program suggests the least-cost annual production for each alternative for any given district demand. Annual production graphs over a range of annual demand from 30 to 50 TAF in increments of 5 TAF for annual PCWA entitlements at 12 and 24 TAF/yr are included for alternative set 1. (Appendix 5-3a through 5-3f). Additional production comparisons are provided below (Figure 5-1 and 5-2).

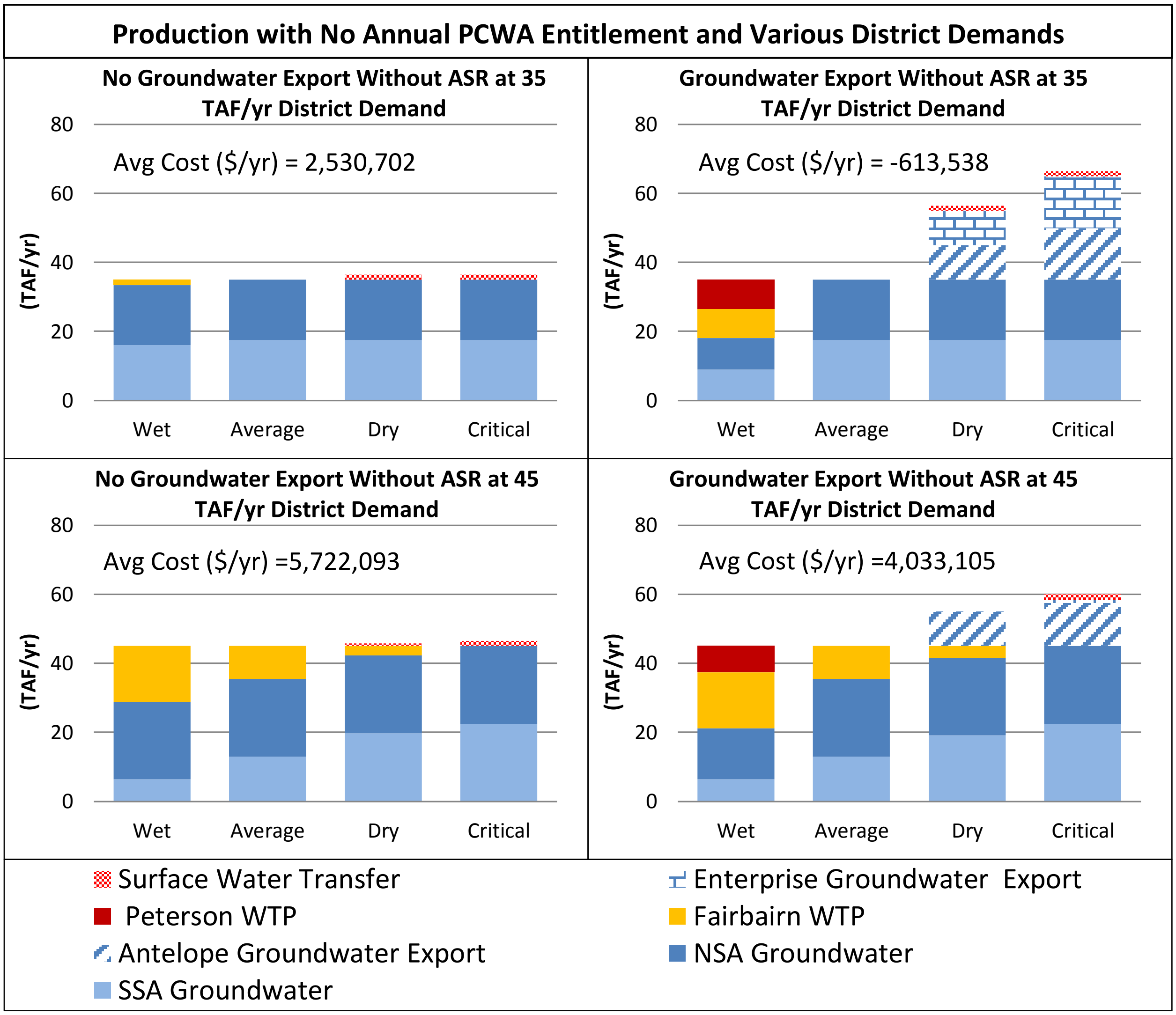

Figure 5-1: The production schedule for alternatives 1c and 1d, with no annual PCWA entitlement, at Demands of 35 TAF/yr and 45 TAF/yr is shown.

Figure 5-1 compares least-cost production with no PCWA use or entitlement for alternatives 1c and 1d at different annual demands. Several conclusions can be made by comparing production schedules. For example, the district can export groundwater in dry years and meet the sustainability requirement without an annual PCWA entitlement. When demand is low (35 TAF/yr), exports are made on both the Enterprise Connection and the Antelope Pump Back. As annual demand grows to 45 TAF/yr, exports on the Enterprise Connection are eliminated. This is a function of water availability. When the annual demand is 45 TAF/yr, nearly all water availability from Fairbairn WTP is used. The structure of the Antelope Pump Back contract within alternative set 1, allows surface water to be exchanged in wet years for groundwater exports made on the Antelope Pump Back in drier years. This additional source allows exports to be economical on the Antelope Pump Back even at high district demand. Without the added surface water from the APBE contract, exports cannot be sustained due to limited of surface water availability. The Enterprise Connection export does not provide additional contractual surface water to the system and so is limited at high demands. The addition of a PCWA annual entitlement and ASR can support groundwater exports at high district demands (Figure 5-2).

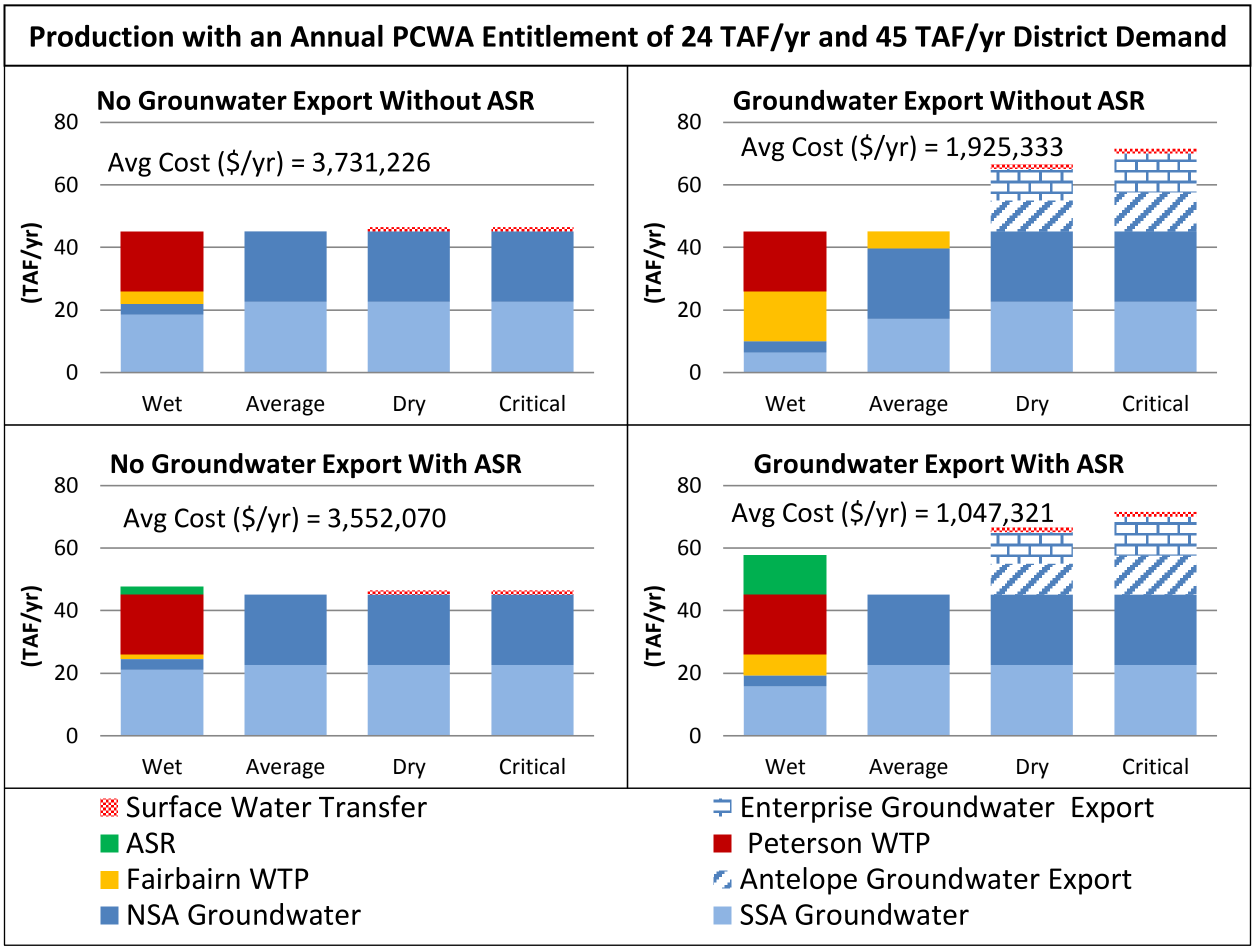

Figure 5-2: The production schedule for alternative set 1a- 1d with an annual PCWA entitlement of 24 TAF/yr and annual demand of 45 TAF/yr is shown above.

Figure 5-2 shows annual production for each alternative in set 1, with an annual PCWA entitlement of 24 TAF/yr and annual demand of 45 TAF/yr. The graph suggests groundwater exports can be maintained through the Enterprise Connection when district demand is high (45 TAF/yr) (Figure 5-2). When ASR is added to the system less of the expensive Fairbairn WTP source is needed. When groundwater exports are eliminated, less ASR is used. This is a result of a reduced need for surface water when no groundwater exports are made.

The expected annual production cost is calculated for alternative set 1, for water demands from 30 to 50 TAF/yr (Appendix 5-4a through 5-4d). The expected annual cost is a weighted average given the probabilities of year types. These can be used to evaluate the benefits of groundwater export, ASR, and renegotiated PCWA contract as described below.

The value of each individual action depends on other actions. For example, the value of ASR changes with the introduction of groundwater exports and vice versa. To evaluate their worth, combinations of actions are evaluated and compared to a baseline alternative. For this case the baseline alternative is: no groundwater export, ASR, or PCWA surface water contract (alternative 1d with an annual PCWA contract of 0 TAF/yr). The difference in expected annual production cost between the baseline alternative and any combination of groundwater export, ASR, and annual PCWA entitlement can be taken to evaluate the expected benefit of any particular action or combination of actions. For example, the combined expected annual benefit of groundwater exports and ASR through a range of possible PCWA annual entitlements is given (Figure 5-3). It was calculated by taking the difference in expected annual production cost of the baseline alternative (alternative 1d with an annual PCWA contract of 0 TAF/yr) and the expected annual production cost of an alternative with groundwater exports and ASR (alternative 1a), through a range of annual district demand.

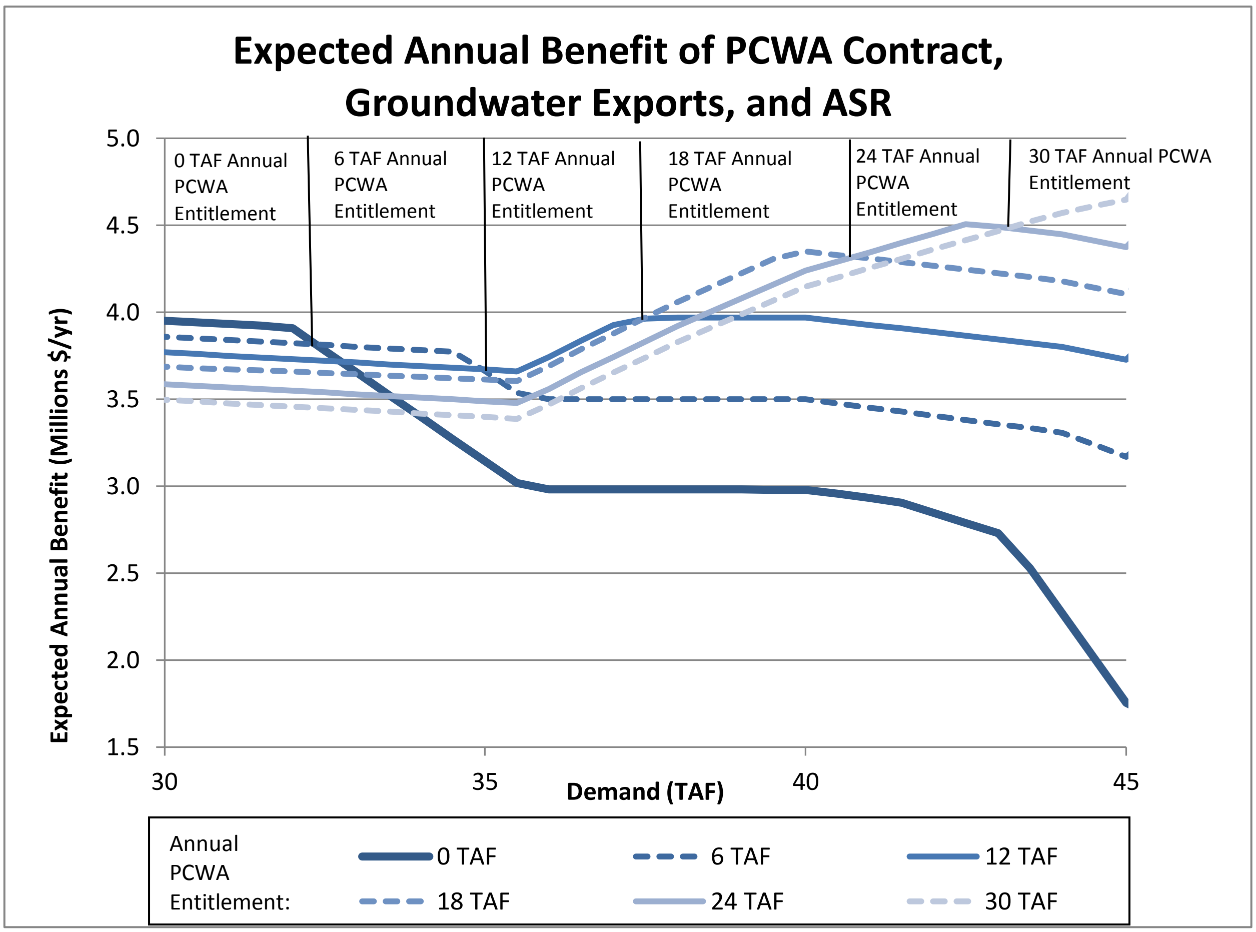

Figure 5-3: The combined benefit of groundwater exports and ASR is shown as a function of demand. Compare to figure 5-4 to note the benefit of ASR for demand greater than 36 TAF and surface water contracts greater than 6 TAF.

With Figure 5-3 a manager can compare the combined expected annual benefit of an alternative with groundwater exports and ASR (alternative 1a), through a range of possible PCWA annual entitlements and district demands. Some general trends can be seen. For example, groundwater exports and ASR will benefit the district through any level of PCWA annual entitlement, including a zero allotment. Net benefit changes with demand. At various levels of annual demand, different levels of PCWA annual entitlement become optimal.

The benefit of groundwater exports and a PCWA contract can also be evaluated in the absence of ASR. Similarly, it is accomplished by calculating difference between the baseline alternative and those with groundwater export, a PCWA contract, but no ASR (Alternative 1c) (Figure 5-4).

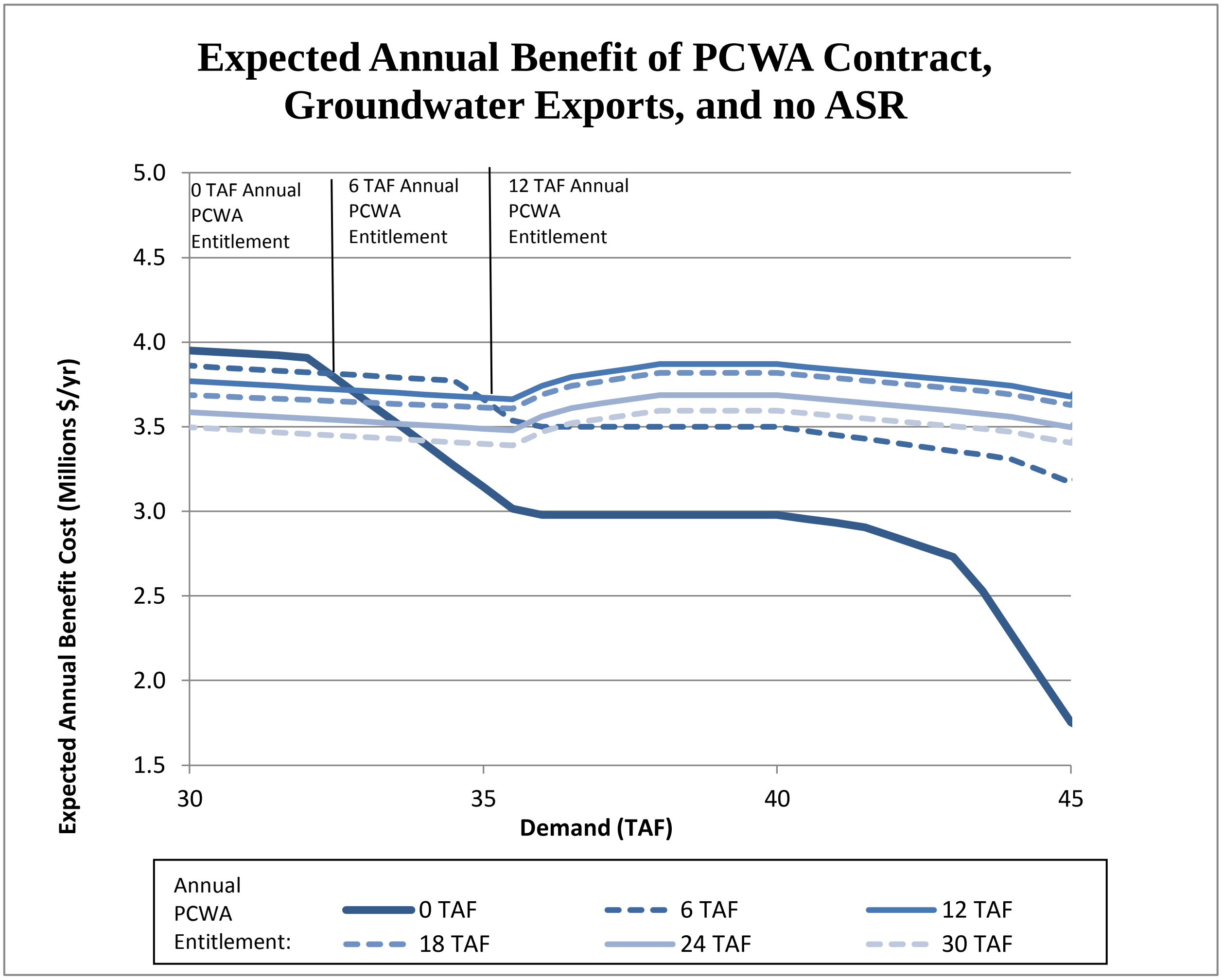

Figure 5-4: The benefit of a PCWA Contract, groundwater exports and no ASR is provided as a function of demand.

Figure 5-4 suggests that even without ASR, the benefit of groundwater exports remains substantial. Comparing Figure 5-3 and 5-4 suggests identical net benefits at annual demands less than 36 TAF, but greater benefits with ASR for greater demands. The net value of ASR (Figure 4 minus Figure 3) appears in Figure 5-5.

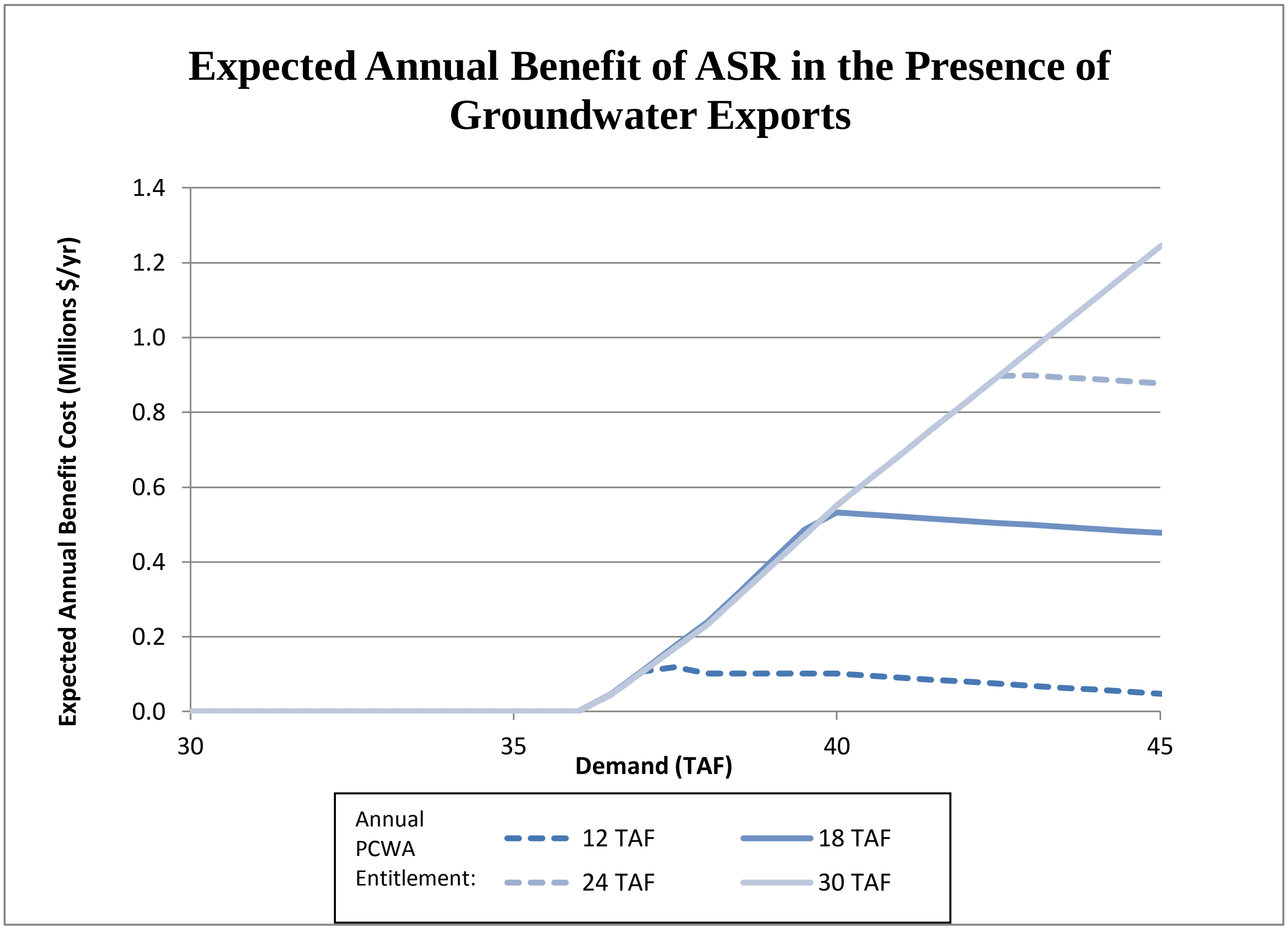

Figure: 5-5 The additional added Benefit of ASR in the presence of Groundwater Exports is provided.

Figure 5-5 allows for the expected annual benefit of ASR in the presence of groundwater exports to be isolated. ASR does not provide a benefit until annual demand exceeds of 36 TAF/yr. The magnitude of benefit is a function of the PCWA annual entitlement and the annual demand. This graph can be used to decide limits on investment in ASR. For example, if the PCWA annual entitlement is 18 TAF and the annual demand was expected to be 40 TAF/yr, then the isolated expected annual benefit of ASR would be $500 thousand dollars per year. This would limit the annualized construction cost of retrofitting the water system for ASR to that amount.

The expected annual benefit of a PCWA annual entitlement can be calculated for an alternative without groundwater exports or ASR (alternative 1d) (Figure 5-6). With no groundwater exports, no ASR, and with annual demand greater than 35TAF, there is a benefit for a PCWA annual entitlement only for demands less than 35TAF/yr, there is actually a greater expense with a PCWA annual entitlement. This is a function of the reserve cost. When the demand is low there is no need for surface water to maintain a sustainable yield. The reserve cost is paid regardless if the water is used. High PCWA annual entitlements with low annual demand are sub-optimal, because the district would pay for water not needed for sustainable yield maintenance. As demand grows the additional surface water from the PCWA entitlement provides inexpensive surface water to maintain sustainable yield.

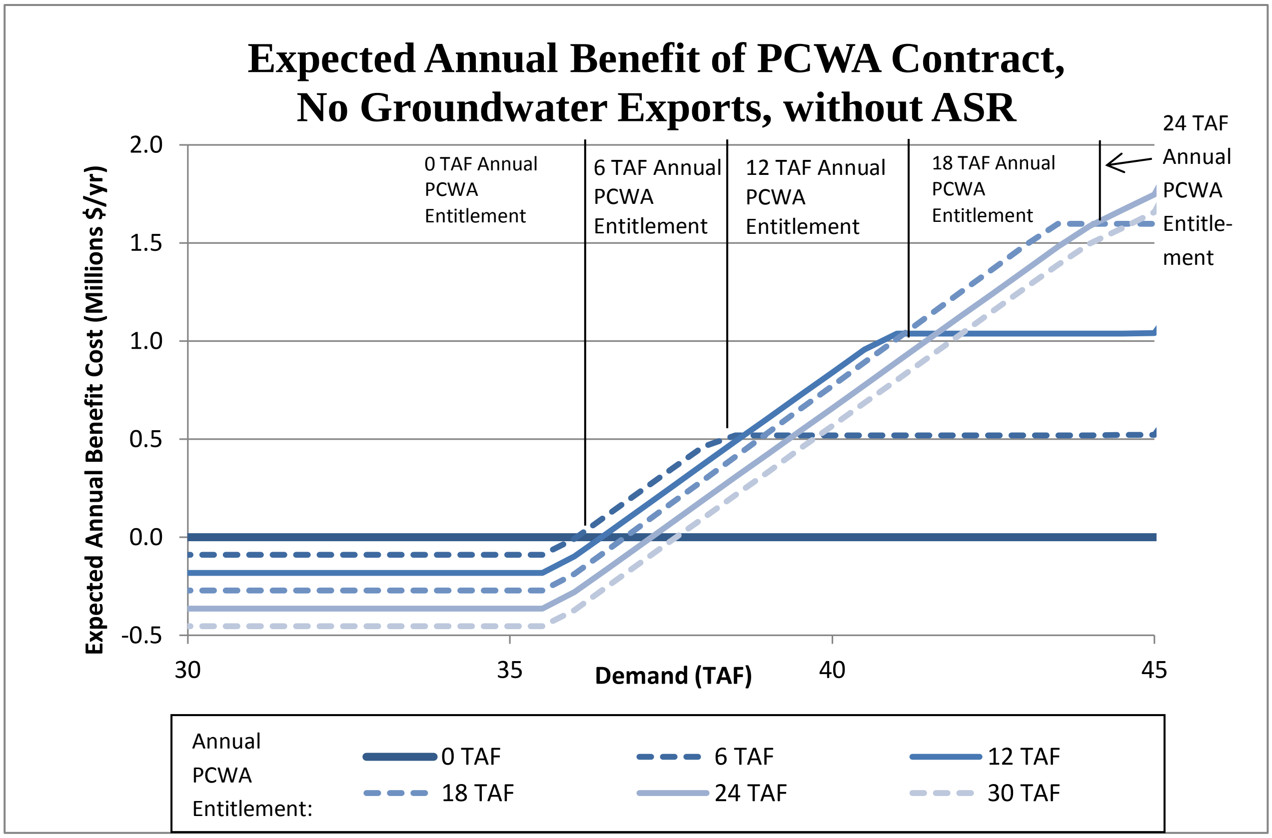

Figure 5-6: The benefit of a PCWA Contract, without groundwater exports and no ASR is provided as a function of demand.

Conservation can be evaluated with the linear program sensitivity outputs. The marginal value of conservation is the Lagrange multiplier's for the demand constraint of each year type and service area, normalized by the probability of year type. The marginal value of conservation for alternative 1a (Groundwater exports with ASR) with an annual PCWA entitlement of 24 TAF/r is included through a range of demand (Table 5-1).

Table 5-1 The marginal value of conservation for alternative 1a with an annual PCWA entitlement of 24 TAF/yr is shown as the Lagrange multiplier for the NSA and SSA normalized by the probability of each year type.

Marginal Value of Conservation ($/ac-ft)				Annual District Demand		
				35 TAF	40 TAF	45 TAF
Alternative 1a Groundwater Exports with ASR and a 24 TAF/yr PCWA Entitlement	NSA	Short Term	Wet	$ 95	$ 170	$ 330
			Average	$ 95	$ 170	$ 330
			Dry	$ 95	$ 170	$ 330
			Critical	$ 95	$ 800	$ 960
		Long Term		$ 95	$ 254	$ 414
	SSA	Short Term	Wet	$ 95	$ 170	$ 330
			Average	$ 95	$ 170	$ 330
			Dry	$ 95	$ 170	$ 330
			Critical	$ 95	$ 330	$ 800
		Long Term		$ 95	$ 191	$ 393

The evaluation of the marginal value of conservation can provide useful insight (Table 5-1). It can show which year types and service location have the greatest return on investment for conservation. Short-term conservation is included for actions taking place within a particular year type, reducing the production cost any particular year type. The long-term value of conservation is included as the expected value of conservation for a demand reduction across all year types. General trends suggest a greater benefit of conservation as demand increases, with the most benefit in the NSA.

The data shows a low value of conservation ($95/ac-ft) for all year types at 35 TAF/yr. This is because the expensive water from Fairbairn WTP is not used, ASR is not conducted, and groundwater exports are not limited by water availability or groundwater pumping capacity. At demand of 40 TAF/yr ASR is conducted and groundwater exports are limited in the NSA, increasing the conservation benefit. By a demand of 45 TAF/yr marginal values are further increased, because ASR has reached capacity, Fairbairn WTP deliveries are made, and groundwater exports are limited by infrastructure in both service areas. The data suggest that short-term conservations efforts would have the greatest return on investment during critical years when demand exceeds 45 TAF/yr, with the largest returns in the NSA. The NSA has a higher value of conservation, because additional surface water is made available for exports made to the NSA.

Mutual Aid export limitations on the APBE are evaluated with alternative set 2 (Mutual Aid of Antelope Pump Back with and without Enterprise Connection) through a range of district demand and PCWA annual entitlements (Figure 5-7).

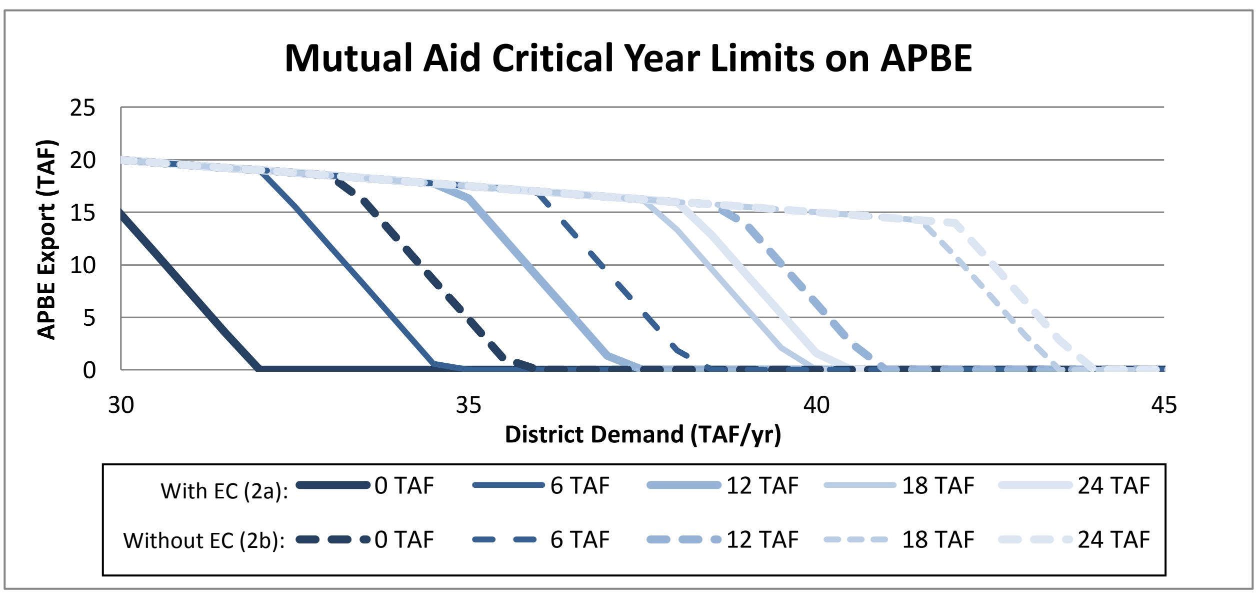

Figure 5-7: Mutual aid export limitations on the APBE during critical years are shown for alternative 2a-b.

Figure 5-7 establishes groundwater export limitations when the APBE is operated as a mutual aid. For each alternative and annual PCWA entitlement, there are two slopes to the export limit curve. The shallow slope represents exports limited by infrastructure. The steeper slope represents limitations associated with increased cost. When the NSA can no longer use additional water from Peterson WTP during wet years, cost is increased by a need for water from Fairbairn WTP. If exports on the APBE are made at greater quantity than the graph suggests, the district will be financially subsidizing the mutual aid effort.

Chapter Conclusions

This method evaluated the PCWA annual entitlement, groundwater exports, and ASR as a function of annual district demand. The value of any single action is sensitive to other actions. For example, the value of ASR is increased with groundwater exports and increases in the PCWA entitlement.

The preliminary results suggest some general insights:

1) Groundwater exports reduce overall cost at all demand levels.

2) A PCWA entitlement is not necessary to meet demands up to 45 TAF/yr.

3) For district demands below the sustainable yield, any level of PCWA entitlement increases total cost.

4) ASR begins to become cost-effective with groundwater exports, a PCWA entitlement greater than 12 TAF/yr, and district demands greater than 36 TAF/yr.

5) The benefit of conservation varies with demand level, year type, and service location.

Chapter 6) Limitations and overall conclusions

Water year type probabilities

A major limitation of the model is uncertainty in the probability of water year types. The historical record is used to estimate the probability of year types. There are two reasons why this historical record may not provide accurate probabilities. First, the record may not be sufficiently long. Second the system maybe non-stationary, meaning that there are long term shifts in the climate. This is evident in the drying trend of the 30 year averaged probability of water year type. If the probabilities of wet years are over-estimated and the probabilities of drier years are under-estimated, then insufficient surface water and unsustainable groundwater exports would be suggested by the model. Conversely, if wet years are under-estimated and drier years are over-estimated then a surplus of surface water and lower than optimal groundwater exports would be produced.

There is a downward trend in wet year and a upward trend in the drier year probability from 1950 to present. To test the utility of the model this range of probabilities was used. The model was run as a simulation from 1950 to present. For each year the probability of water year type was corrected with the hydrology of that year. The conjunctive use production was changed each year with the updating probabilities and the amount of groundwater produced during the year was noted based upon the year time. This enabled the monitoring of a hypothetical water bank balance since 1950. It represents the water bank balance if this method were to be used and and the water bank balance accounted for since 1950. The balance is shown with three different types of estimates: an updating historical record, a 50 year average, and a 30 year average. The results are shown below (Figure 6-1).

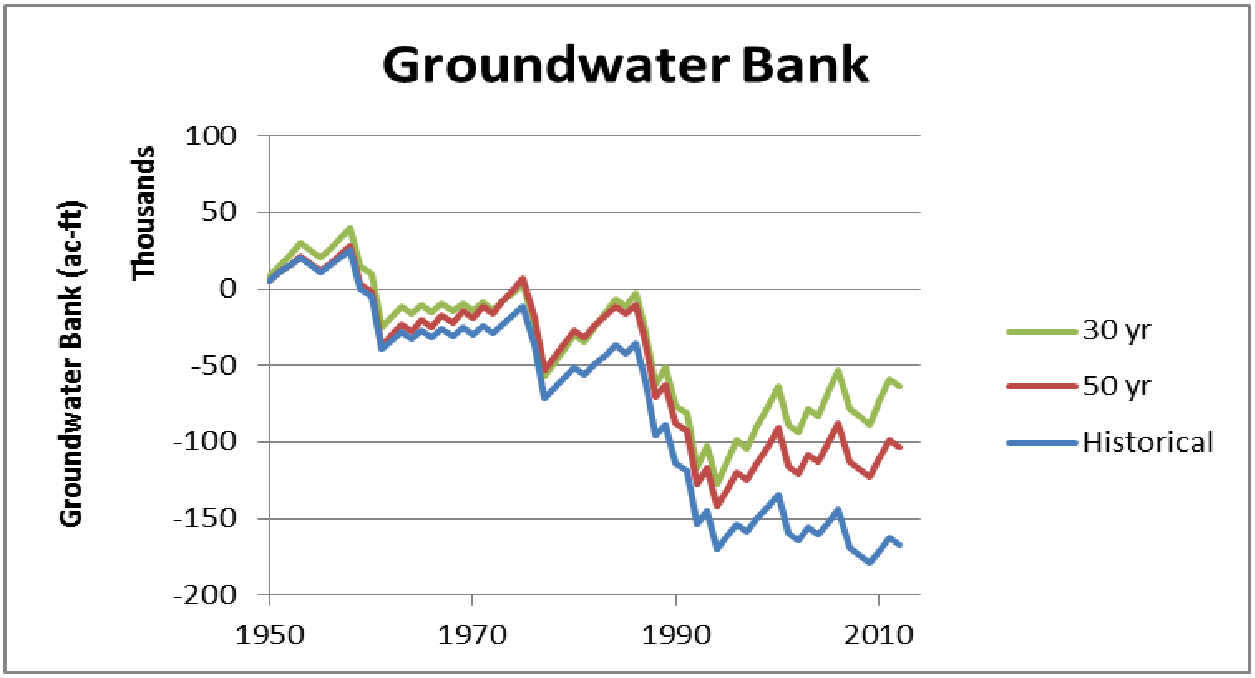

Figure 6-1: A hypothetical groundwater bank is shown above. It is the balance of the groundwater bank if the method outlined in this paper were to be used and groundwater accounted for since 1950.

This graph indicates that the model over-produces groundwater and under-produces surface water. This is a result of non-stationarity. There is a downward trend in the occurrence of wet years and an upward trend in drier years. When the 30 year rolling average is used, trends are more easily accounted for. The utilization of the full historical record does not sufficiently account for the trend. The 30 yr average may have an issue with over-adjustments, as a single year will have more influence. This may actually be a benefit. An over-adjustment in the probability will work to buffer the system. For example, if there is a short-term anomaly with several wet years occurring together, then the probability of wet years will have been raised more than an accurate amount. During that time, more surface water than optimal will have been taken. The spike in wet year probability will cause a reduction in the future surface water production. If several drier years occur in a row, future groundwater exports will decrease and future wet year production will rise.

Over the period 1950 to present with the 30 year averaged probabilities, the model over-produced groundwater by 60 TAF. Although the model over-produces groundwater over the period 65 year period, it may still be useful. If further drying trends continue, this method would continue to over-produce groundwater. The current ground water balance is on the order of 180 TAF and is likely large enough to buffer long-term drying.

Risk neutrality

The model uses the expected value of water availability, making it risk neutral. The linear program does not have time steps, although it can be turned into a simulation with time steps as described above. It does not account for the risk of production above the sustainable yield. Over-production of groundwater can increase risk of water quality degradation, i.e. greater contaminant transport from the surrounding plumes resulting from an increase in the gradient of the groundwater table. Over-production of groundwater also risks falling into overdraft preventing exports and reducing profitability.

One way to make the model more risk averse would be to adjust the modeled sustainable yield. By lowering the sustainable yield the production would shift toward lower exports and increased surface water production.

Different ways to use the model

The benefit of a rising water table or the penalty of a lowering water table can be accounted for with some adjustments to the linear program. This could include a benefit function for the sustainable yield. For example, a lower sustainable yield may provide benefit in terms of decreased contaminate transport into the district. Groundwater modeling may provide some estimation of a sustainable yield benefit. The sustainable yield benefit function can be added to the current objective function and the value of the sustainable yield can become a decision variable. This would allow for consideration of water quality concerns. Similarly, the environmental benefit of added base flow to the American River, based upon a lower sustainable yield, can be incorporated. Although, such a benefit function may be more subjective.

Conclusion

Urban and regional conjunctive use can be formally optimized as described in this paper. First, the linear program described generates a least-cost production schedule for water year types that will ensure a sustainable yield for any alternative. Then the program can examine a range of demands to generate the expected annual production cost as a function of demand. The value of any action or set of actions can be evaluated by comparing the production cost of alternatives. This method provides operators targets for production and managers insights for system investment.

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Appendix

Appendix 5-1 Common Parameters in Set 1 and 2

Sustainable Yield (ac-ft/yr)		35,000			
Year Type		Wet	Average	Dry	Critical
Probability Water Year		0.43	0.27	0.17	0.13
Folsom	PCWA Reserve Cost ($/ac-ft)	35	0	0	0
	Peterson Treatment Cost ($/ac-ft)	75	75	75	75
	USBR Wheel Cost ($/ac-ft)	20	20	20	20
	NSA Demand w/ Peterson Capacity limit (ac-ft/yr)	19,000	19,000	19,000	19,000
	NSA Demand w/ ASR Limit w/ Peterson Capacity (ac-ft/yr)	50,000	50,000	50,000	50,000
	PCWA Take or Pay Water Available (ac-ft/yr)	Variable	0	0	0
	APBE SW Available (ac-ft/yr)	10,000	0	0	0
	PCWA Contract Max (ac-ft/yr)	Variable	0	0	0
American River	Sacramento Wholesale Reserve Cost ($/yr)	39,000	39,000	39,000	39,000
	Sacramento Wholesale Administrative Cost ($/yr)	2,400	2,400	2,400	2,400
	Fairbairn Treatment Cost ($/ac-ft)	330	330	330	330
	1964 Supply Transfer SW Price ($/ac-ft)	0	0	500	1,000
	1964 Supply Transfer SW cost ($/ac-ft)	0	0	50	50
	Portion of year above Hodge	1	0	0	0
	Portion above Hodge in Transfer Period	1	0	0	0
	SSA Demand w/ Fairbairn Capacity limit (ac-ft/yr)	22,000	22,000	22,000	22,000
	1964 Supply Transfer SW Demand (ac-ft/yr)	0	0	10,000	10,000
SSA GW	SSA GW Unit cost ($/ac-ft)	75	75	75	75
	SSA Maximum Annual Pumping (ac-ft/yr)	35,000			
NSA GW	NSA GW Unit cost ($/ac-ft)	75	75	75	75
	NSA Maximum Annual Pumping (ac-ft/yr)	35,000			

Appendix 5-1a: Groundwater Exports with ASR

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	400	800
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	10,000	15,000
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	400	800
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	10,000	15,000
ASR	ASR Capacity (ac-ft/yr)	30,000	30,000	30,000	30,000
	ASR Unit cost (ac-ft)	0	0	0	0

Appendix 5-1b: Groundwater Exports without ASR

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	400	800
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	10,000	15,000
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	400	800
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	10,000	15,000
ASR	ASR Capacity (ac-ft/yr)	0	0	0	0
	ASR Unit cost (ac-ft)	0	0	0	0

Appendix 5-1c: No Groundwater Exports with ASR

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	0	0
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	0	0
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	0	0
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	0	0
ASR	ASR Capacity (ac-ft/yr)	30,000	30,000	30,000	30,000
	ASR Unit cost (ac-ft)	0	0	0	0

Appendix 5-1d: No Groundwater Exports without ASR

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	0	0
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	0	0
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	0	0
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	0	0
ASR	ASR Capacity (ac-ft/yr)	0	0	0	0
	ASR Unit cost (ac-ft)	0	0	0	0

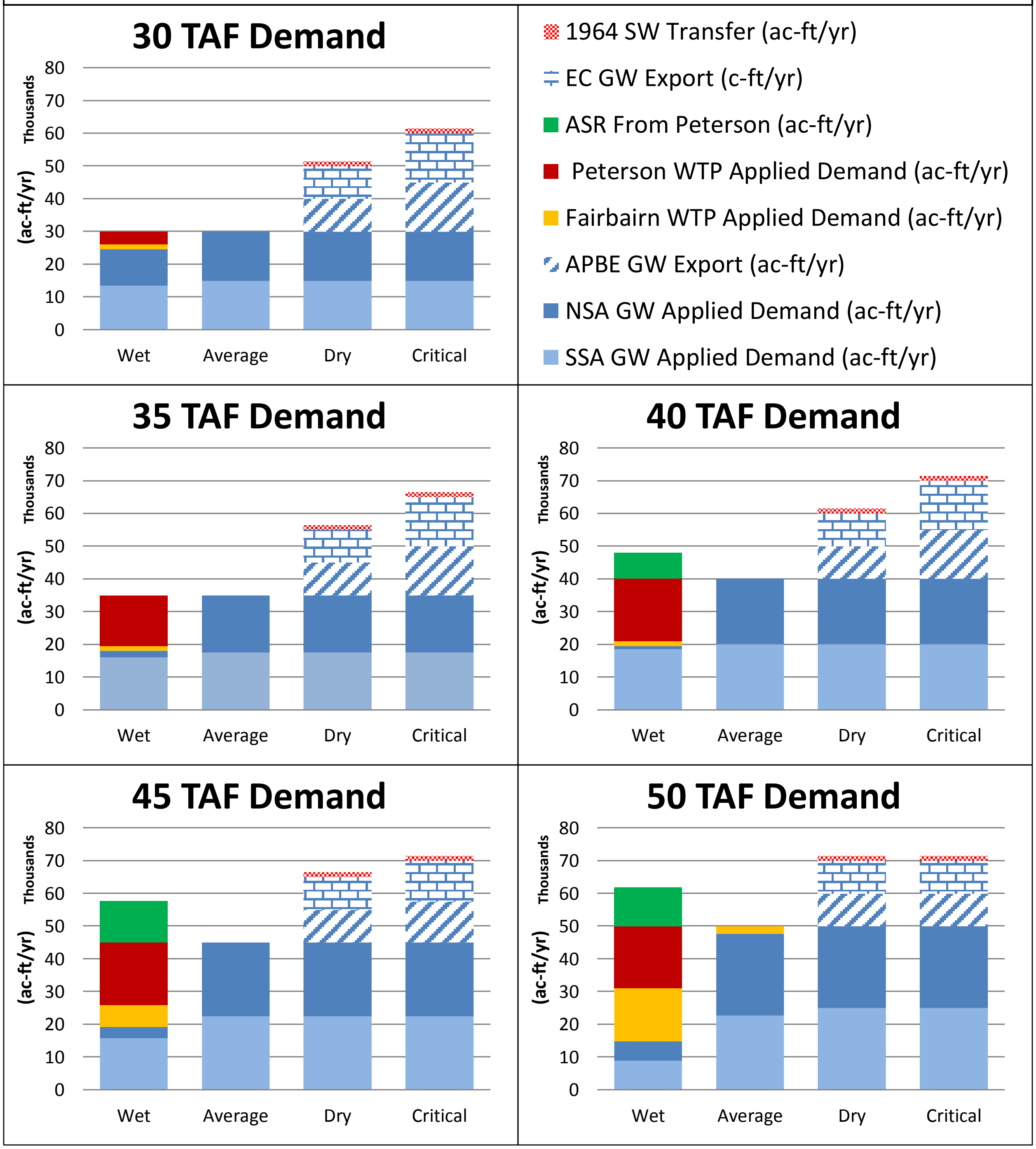
Appendix 5-2a: Antelope Pump Back as mutual aid with Enterprise Connection exports

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	0	135
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	0	15,000
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	0	0
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	0	0
ASR	ASR Capacity (ac-ft/yr)	30,000	30,000	30,000	30,000
	ASR Unit cost (ac-ft)	0	0	0	0

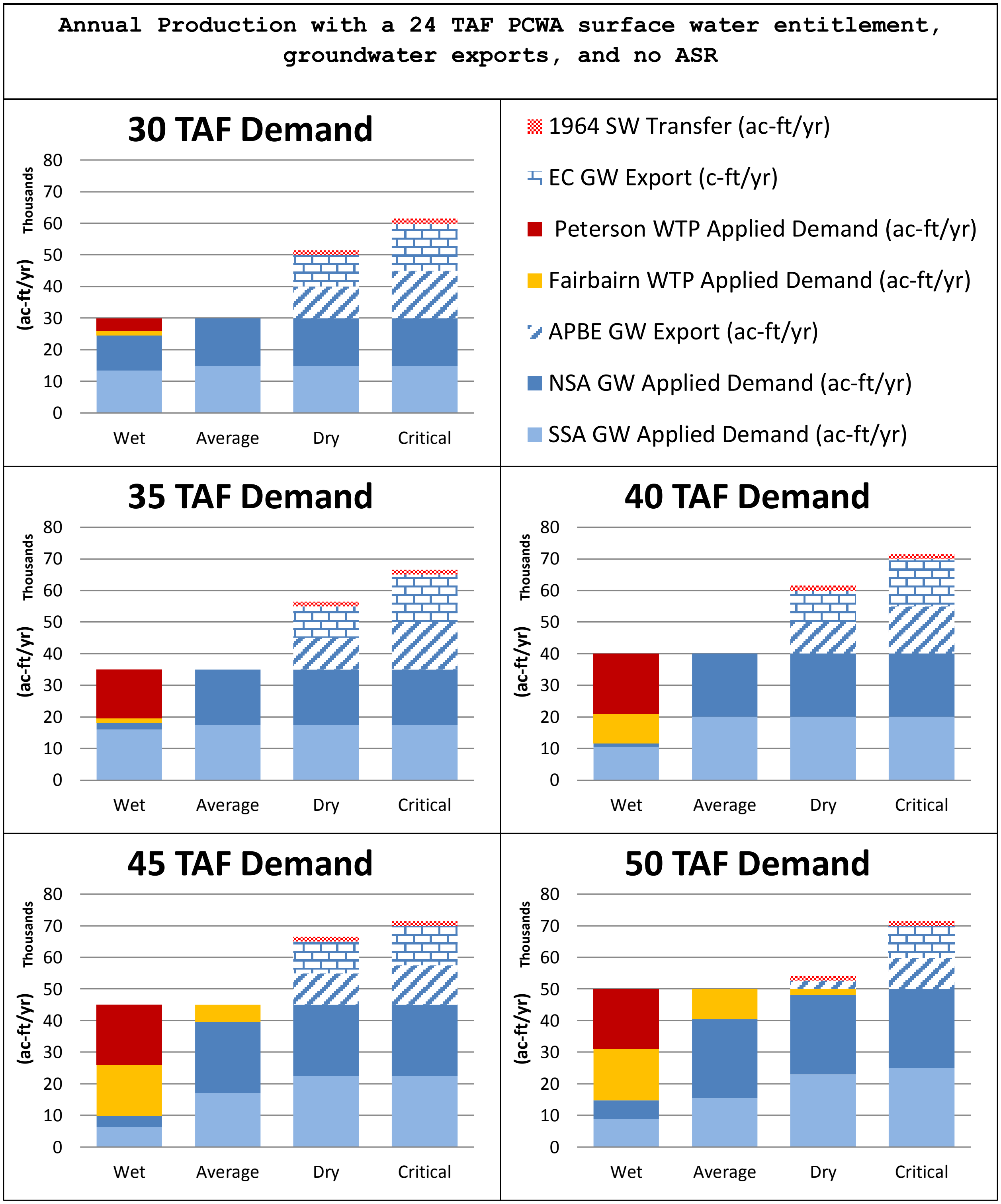
Appendix 5-2b: Antelope Pump Back as mutual aid without Enterprise Connection exports

Antelope Pump Back Exchange (ABPE)	ABPE Transfer unit Cost ($/ac-ft)	75	75	75	75
	APBE Transfer unit Price ($/ac-ft)	0	0	0	0
	APBE Demand/Capacity limit (ac-ft/yr)	0	0	0	0
	APBE Transfer Required Amount ($/ac-ft)	0	0	0	0
Enterprise Connection (EC)	EC Transfer unit Cost ($/ac-ft)	75	75	75	75
	EC Transfer unit Price ($/ac-ft)	0	0	0	0
	EC Transfer Required Amount ($/ac-ft)	0	0	0	0
	EC Demand/Capacity limit (ac-ft/yr)	0	0	0	0
ASR	ASR Capacity (ac-ft/yr)	30,000	30,000	30,000	30,000
	ASR Unit cost (ac-ft)	0	0	0	0

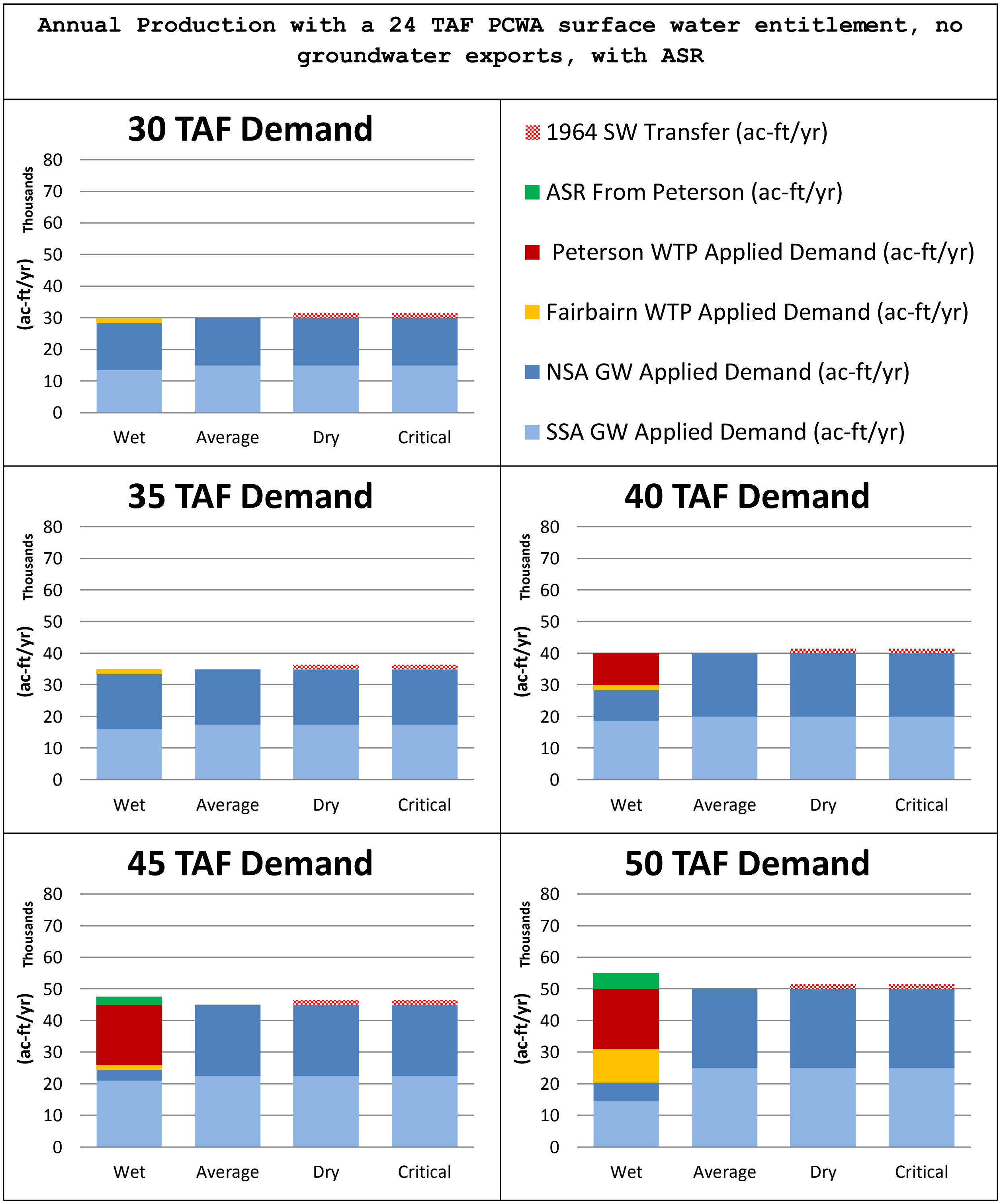
Annual Production with a 24 TAF PCWA surface water entitlement, groundwater exports, and ASR



Appendix 5-3a: The annual production for each year type with a 24 TAF per year PCWA wet year entitlement, groundwater exports, and ASR is shown through a range of annual district demand.

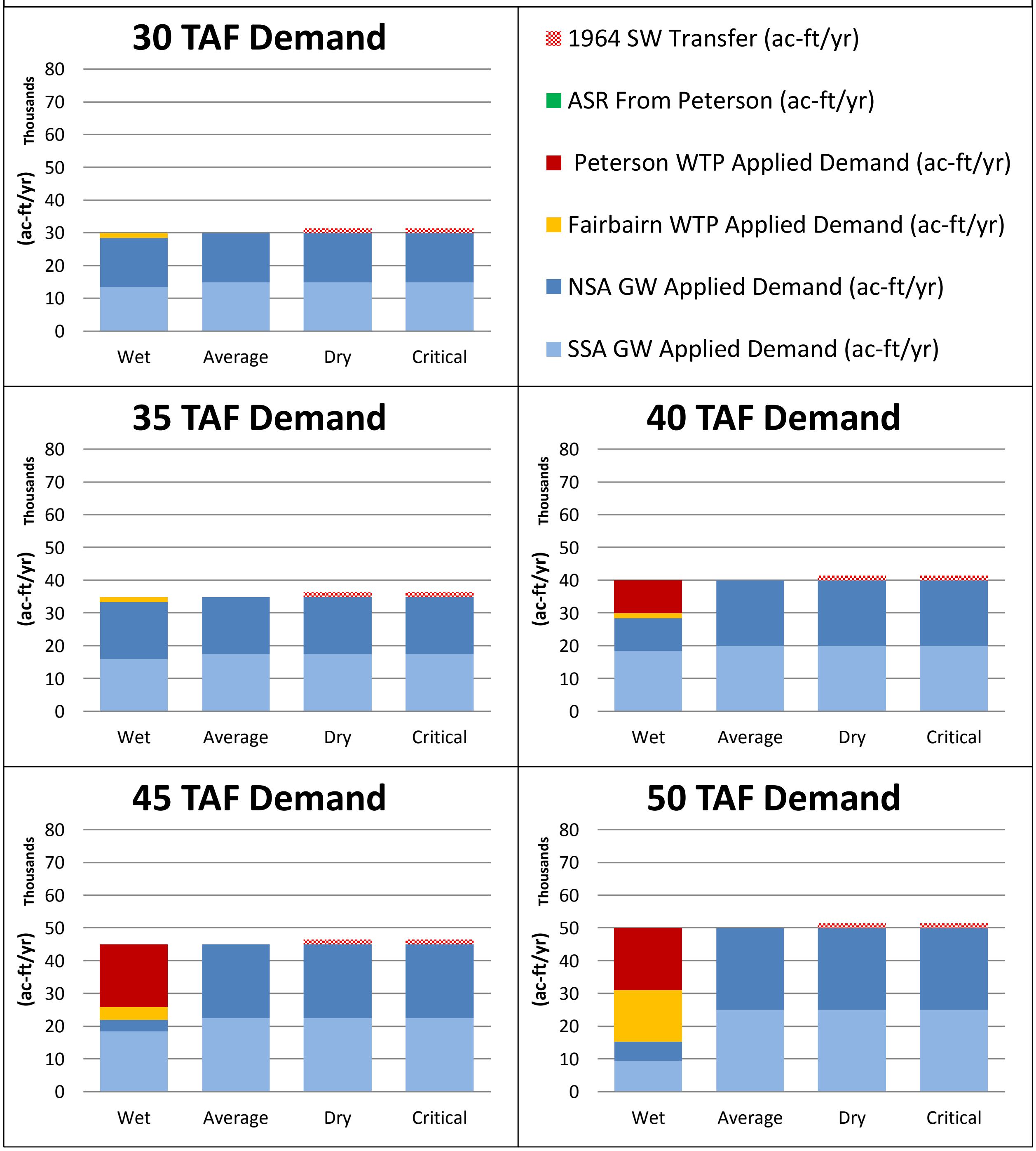


Appendix 5-3b: The annual production for each year type with a 24 TAF per year PCWA wet year entitlement, groundwater exports, and no ASR is shown through a range of annual district demand.



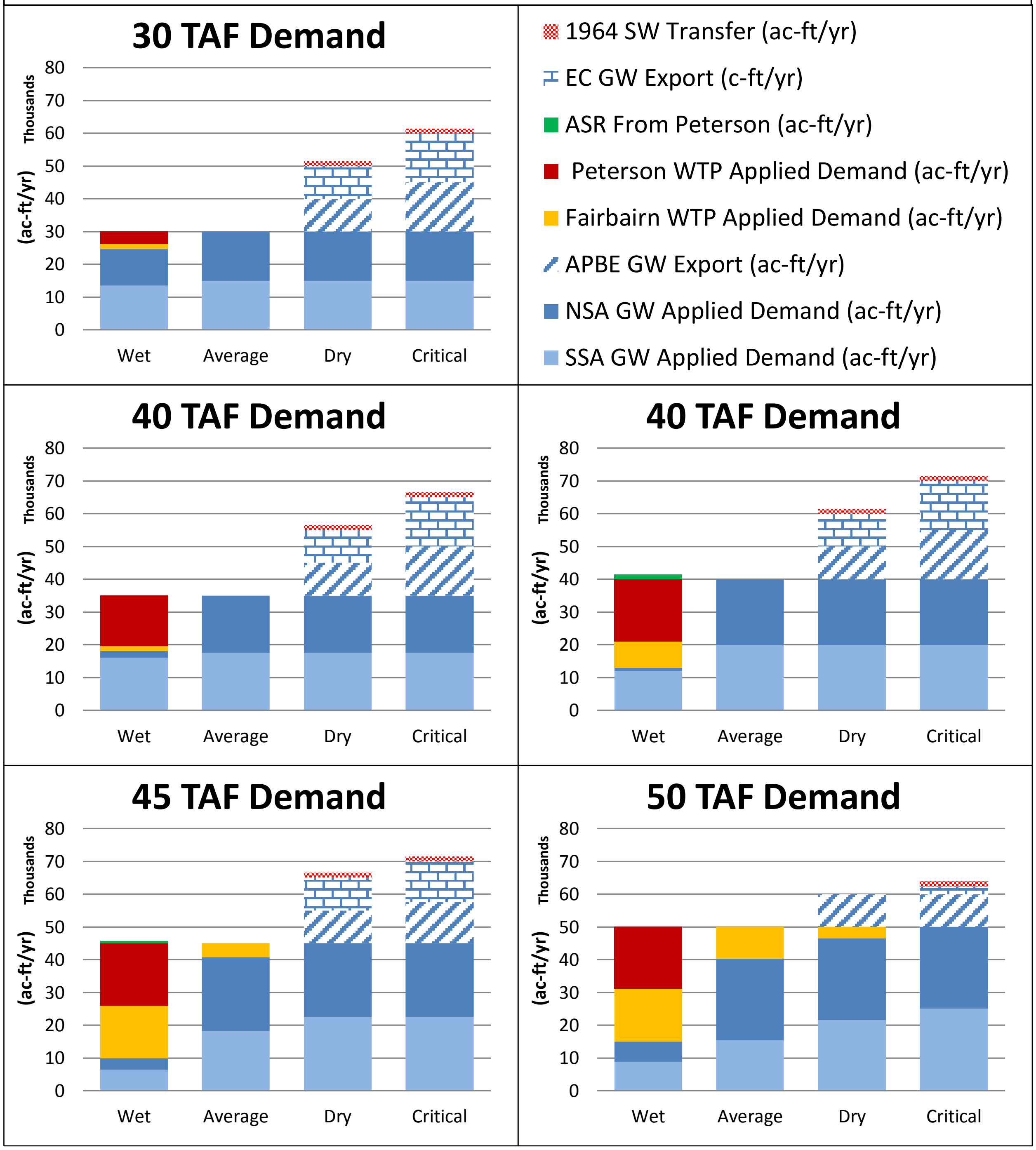
Appendix 5-3b: The annual production for each year type with a 24 TAF per year PCWA wet year entitlement, no groundwater exports, or ASR is shown through a range of annual district demand.

Annual Production with a 24 TAF PCWA surface water entitlement, no groundwater exports, no ASR



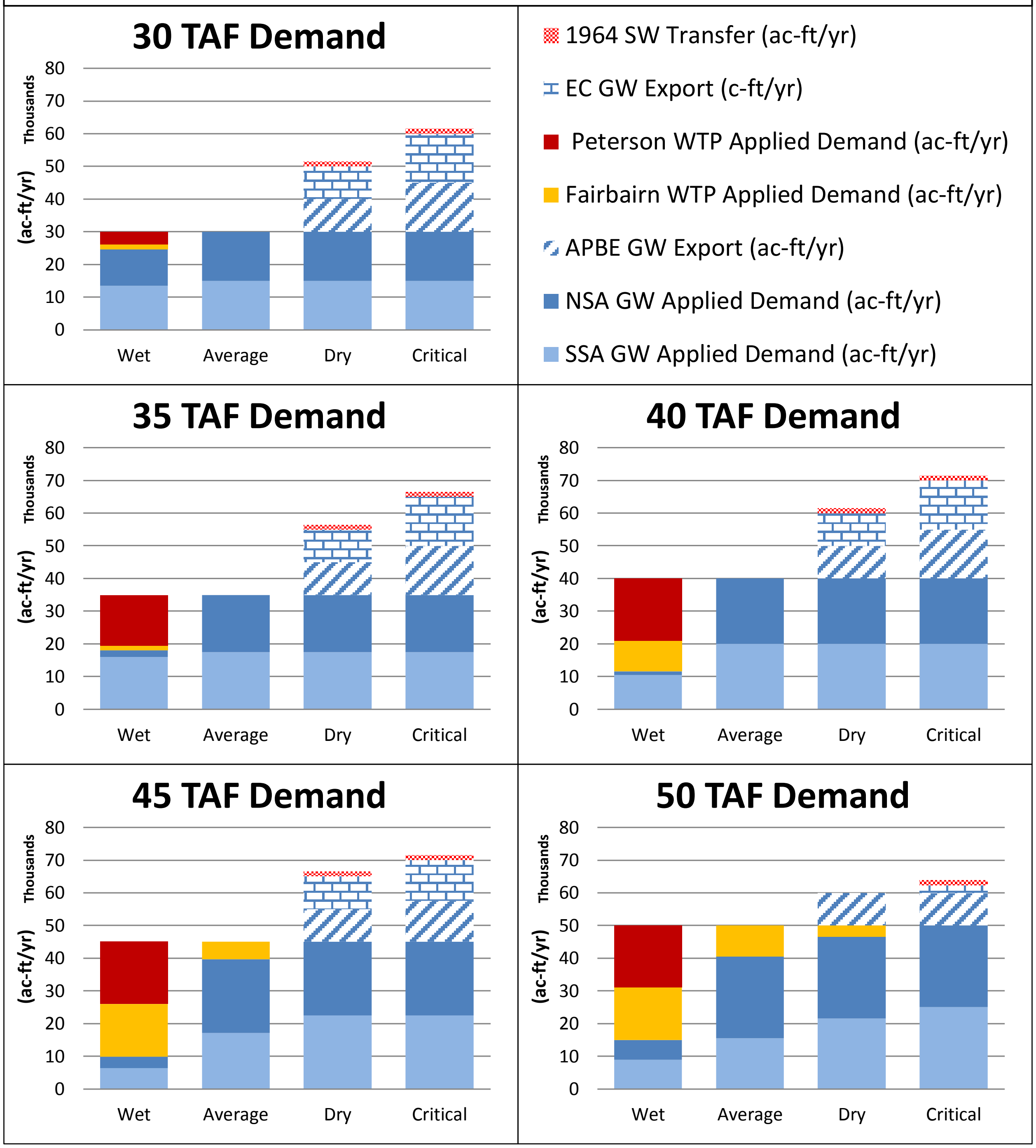
Appendix 5-3c: The annual production for each year type with a 24 TAF per year PCWA wet year entitlement, no groundwater exports, with ASR is shown through a range of annual district demand.

Annual Production with a 12 TAF PCWA surface water entitlement, groundwater exports, and ASR



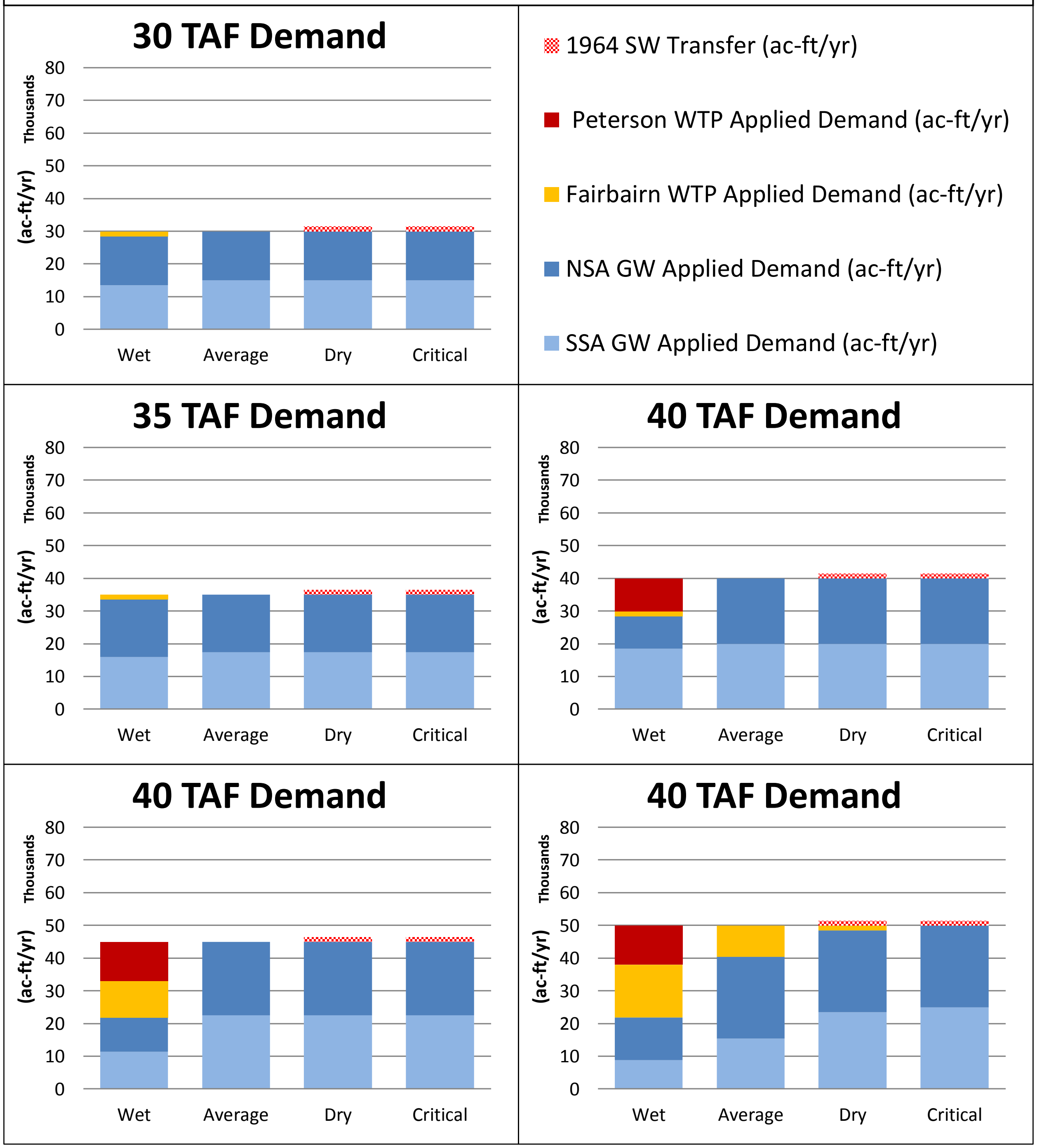
Appendix 5-3d: The annual production for each year type with a 12 TAF per year PCWA wet year entitlement, groundwater exports, and ASR is shown through a range of annual district demand.

Annual Production with a 12 TAF PCWA surface water entitlement, groundwater exports, and no ASR



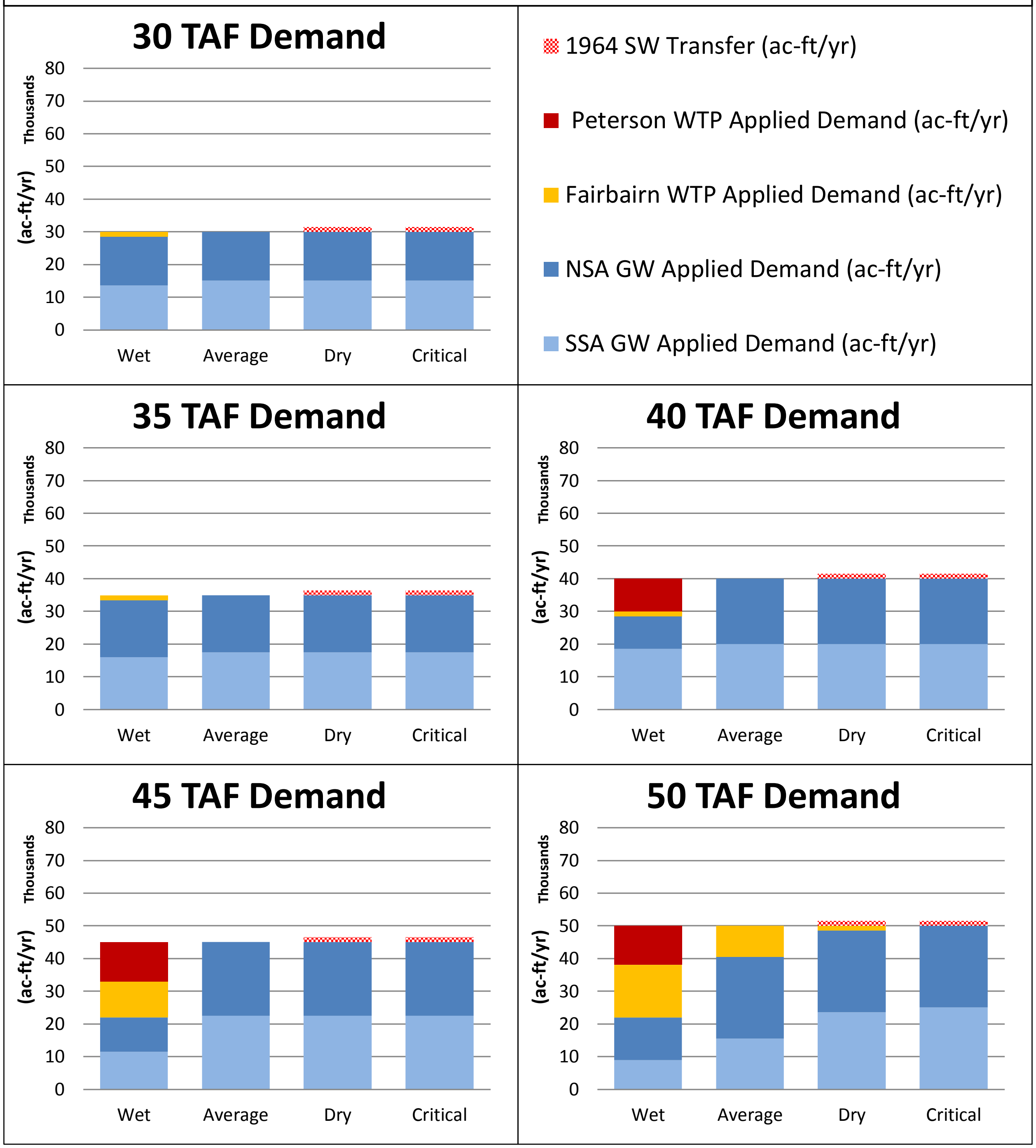
Appendix 5-3e: The annual production for each year type with a 12 TAF per year PCWA wet year entitlement, groundwater exports, and no ASR is shown through a range of annual district demand.

Annual Production with a 12 TAF PCWA surface water entitlement, no groundwater exports, and ASR

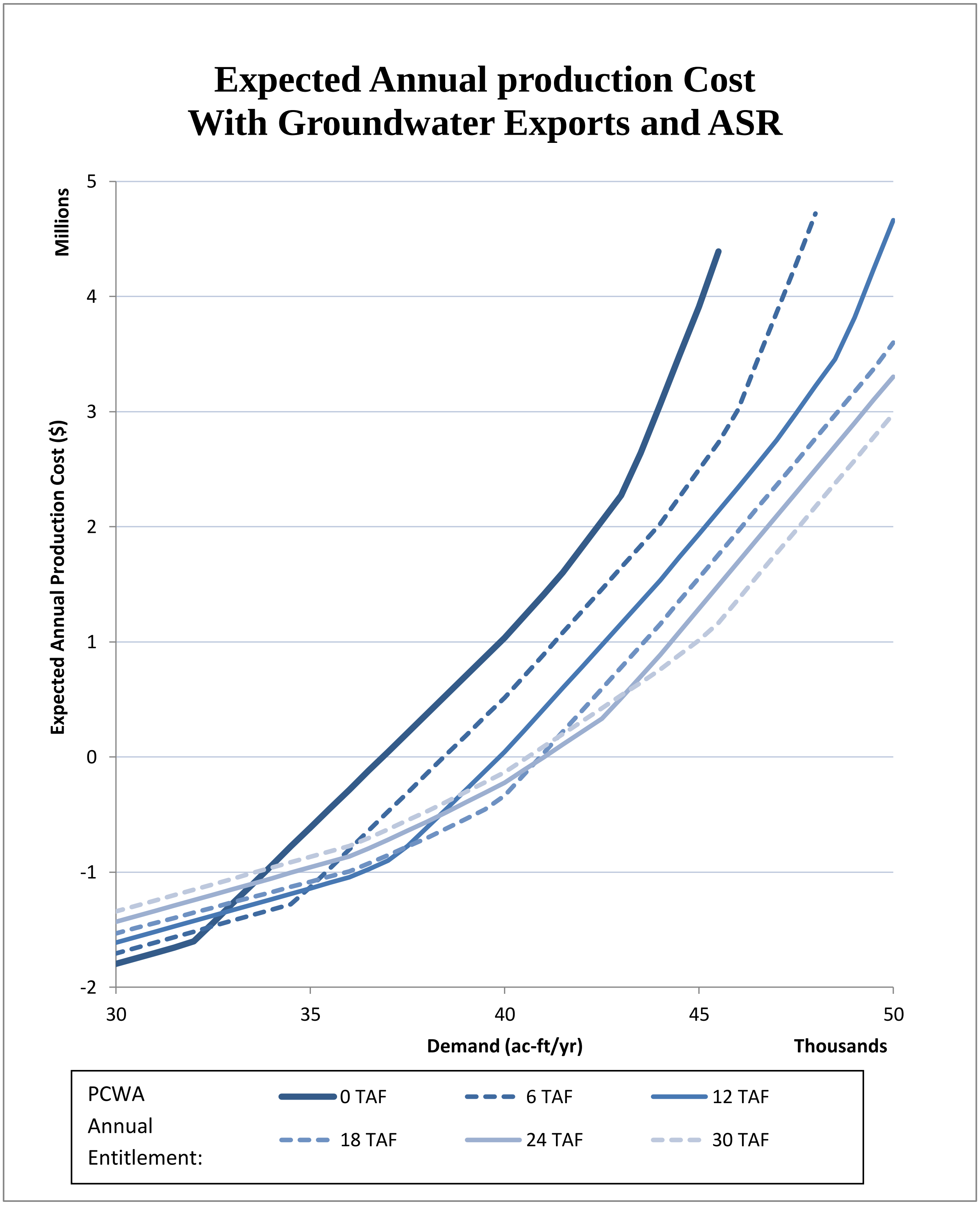


Appendix 5-3f: The annual production for each year type with a 12 TAF per year PCWA wet year entitlement, no groundwater exports, and ASR is shown through a range of annual district demand.

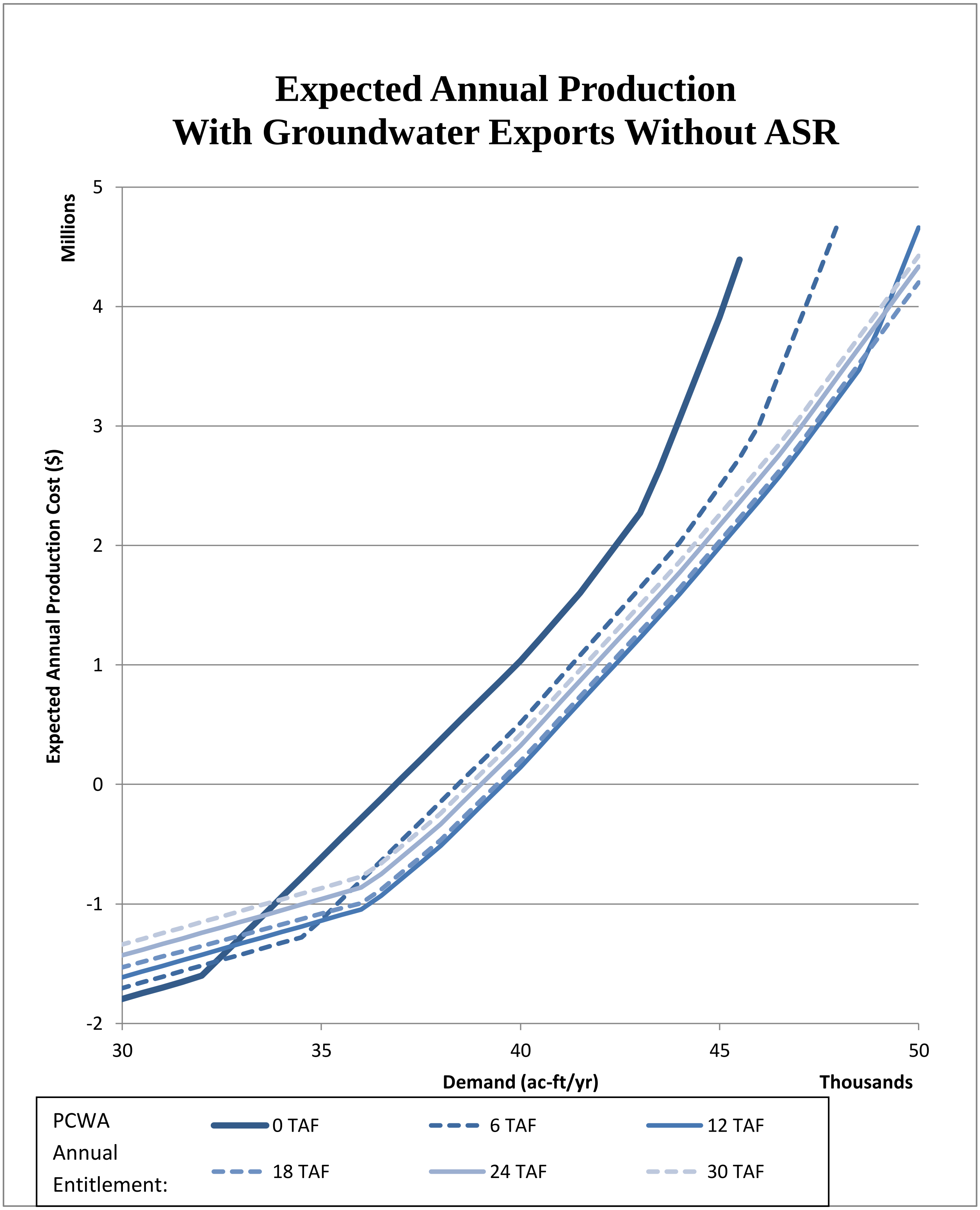
Annual Production with a 12 TAF PCWA surface water entitlement, no groundwater exports, no ASR



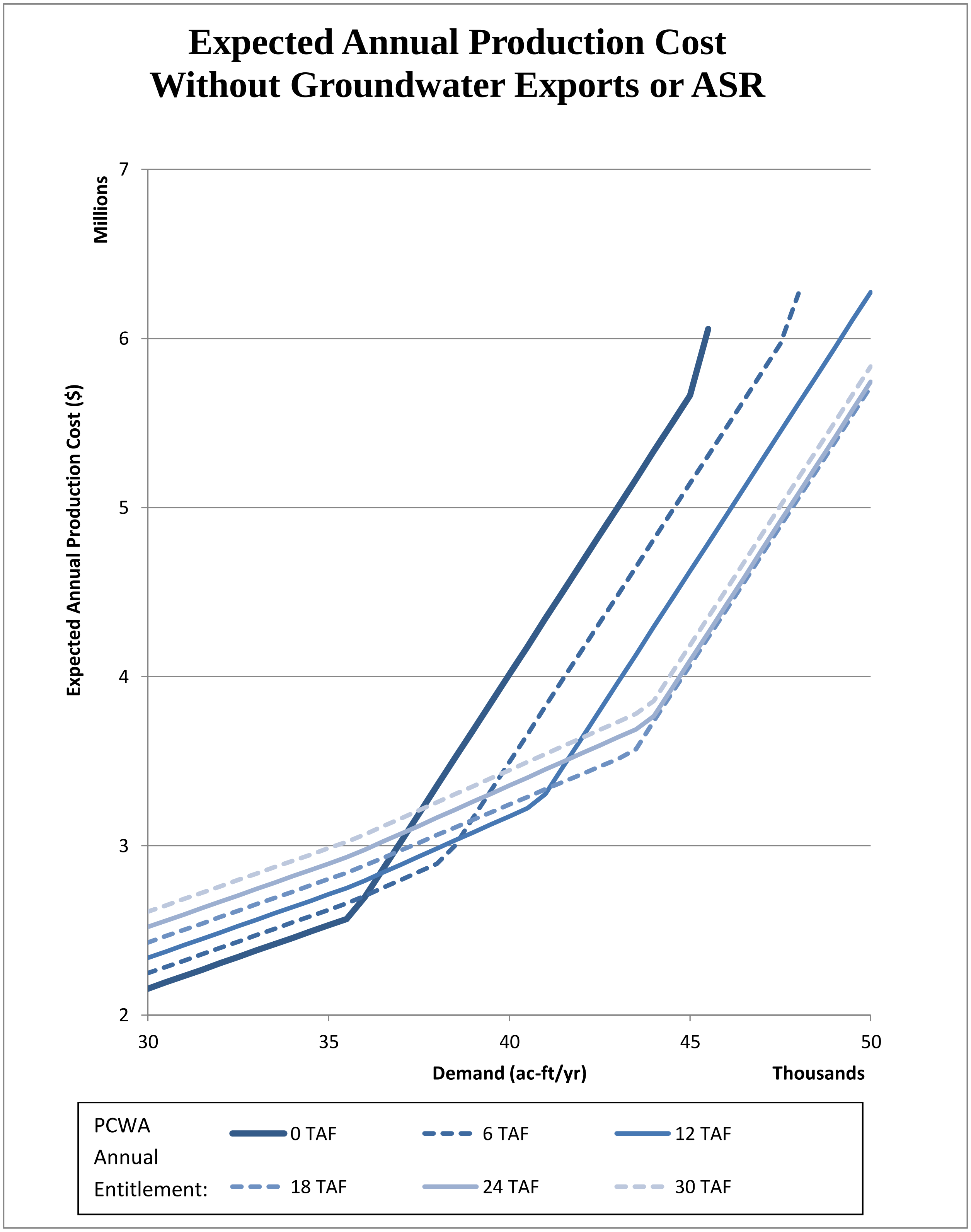
Appendix 5-3g: The annual production for each year type with a 12 TAF per year PCWA wet year entitlement, no groundwater exports, and no ASR is shown through a range of annual district demand.



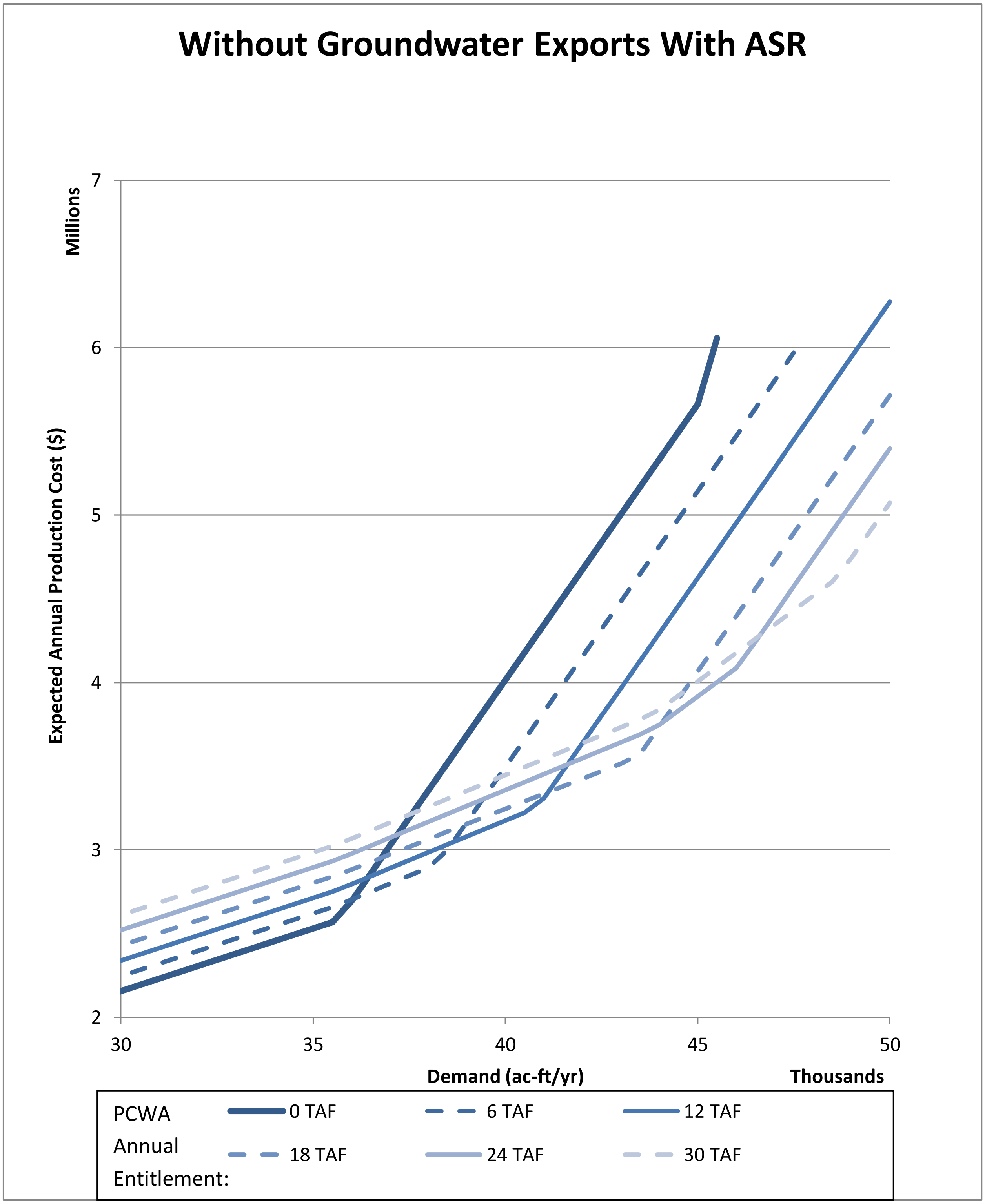
Appendix 5-4a: The Expected Annual Production With Groundwater Exports With ASR is shown as a function of demand. Note the benefit of ASR can be seen by reduced production cost for demand greater than 40 TAF and PCWA contracts greater than 18 TAF Compare to figure 5-10. Note that the contracts amounts less than 12 TAF are truncated because of insufficient surface water. Also compare with figure 5-12 to note the value of groundwater exports.



Appendix 5-4b : The Expected Annual Production With Groundwater Exports Without ASR is shown as a function of demand. Note the benefit of ASR can be seen by reduced production cost for demand greater than 40 TAF and PCWA contracts greater than 18 TAF Compare to figure 5-9. Note that the contracts amounts less than 12 TAF are truncated because of insufficient surface water. Also compare with figure 5-13 to note the value of groundwater exports.



Appendix 5-4c: The Expected Annual Production Without Groundwater Exports Without ASR is shown as a function of demand. Note the benefit of ASR can be seen by reduced production cost for demand greater than 40 TAF and PCWA contracts greater than 18 TAF Compare to figure 5-13. Note that the contracts amounts less than 12 TAF are truncated because of insufficient surface water. Also compare with figure 5-9 to note the value of groundwater exports.



Appendix 5-4d: The Expected Annual Production Without Groundwater Exports With ASR is shown as a function of demand. Note the benefit of ASR can be seen by reduced production cost for demand greater than 40 TAF and PCWA contracts greater than 18 TAF Compare to figure 5-12. Note that the contracts amounts less than 12 TAF are truncated because of insufficient surface water. Also compare with figure 5-10 to note the value of groundwater exports.