Managing Groundwater for Agriculture, with Hydrologic Uncertainty and Salinity

By

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To my grandpa, Guozhu Yao,
I met you in the dream
when I finished the writing, and
you smiled and waved.
Merry Christmas!

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ABSTRACT

Coordinated management of groundwater, surface water, and crops across wet and dry water years is of growing importance in California and other (semi)arid parts of the world. Water agencies are seeking to manage agricultural water supplies while ending chronic groundwater overdraft with the least economic loss. Including salinity considerations makes this goal more complex and demanding.

Chapter 1 introduces the potential benefits and problems of conjunctive water management in California and summarizes conclusions from the following chapters which analyze and quantify the effect of conjunctive use and salinity in the context of agriculture in California's southern Central Valley.

Chapter 2 begins with a two-stage stochastic quadratic model to develop optimal intermediate (10-year) crop mix decisions and conjunctive water use operations with a stochastic surface water supply to maximize the net expected economic benefits of crop production and conjunctive use, given a fixed groundwater storage change target. Perennial crop planting decisions are made in the first stage. Decisions on annual crop planting, groundwater pumping, and land and water for recharging are made in the second stage with probabilistic hydrologic events. Without salinity, this model's results indicate conjunctive water management can greatly smooth hydrologic variability in water availability to stabilize crop decisions and productions and improve agricultural profitability across water year types, with greater pumping in dry years and refilling groundwater in wetter years.

In Chapter 3, groundwater salinity is added to this intermediate-term model, which makes perennial crop profit probabilistic as perennial crop yield depends on the salinity of irrigation water from groundwater and available surface water in each hydrologic event. Model results show that salinity suppresses pumping in dry years when fresh surface water limits ability to dilute saline groundwater from becoming too salty for salt-sensitive, high-value perennial crops. Groundwater salinity can fundamentally change and limit conjunctive use operations and benefits.

Chapter 4 extends the planning horizon. A 10-year inner stochastic quadratic model from Chapter 2 is embedded in a 10-stage (10 year per stage) outer dynamic programming (DP) optimization to develop optimal long-term (100-year) decisions on perennial and annual crop acreages and conjunctive water use operations with stochastic surface water availability. The best combination of groundwater storage and perennial crop acreage are found from the outer DP, while corresponding decisions on annual crop acreage, groundwater pumping and artificial recharge for each stage are found from the inner stochastic quadratic model. The DP results show that without salinity, it is most profitable to continue pumping at a slower rate until a long-term water balance is reached at a desired groundwater storage target.

Similarly, Chapter 5 embeds the 10-year stochastic quadratic model from Chapter 3 in a 10-stage DP optimization, with groundwater salinity as an additional state variable. The model results show perennial crop acreage decreases with time from accumulating groundwater salinity. Greatly reduced pumping and much earlier groundwater storage recovery slow salinity accumulation and prolong the agricultural utility of aquifer storage. Again, higher groundwater salinity can fundamentally alter optimal conjunctive use operations.

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Chapter 1: Conjunctive Water Management and the Future of California's Agriculture

California's Central Valley is a vast agricultural region supplied and drained by the Sacramento and San Joaquin Rivers. The region has about 75% of California's irrigated land, supplying 8% of U.S. agricultural output (by value) (Great Valley Center 1999) and more than 250 crop types (Great Valley Center 2005): about 1/4 of the country's food (Great Valley Center 1998) and 40% of the country's fruits and nuts (Bertoldi 1989). In producing such bounty, the Central Valley has the nation's second most pumped aquifer system (Reilly et al. 2008, Faunt et al. 2009).

The southern two-thirds of Central Valley is known as San Joaquin Valley, which is drier than the Sacramento Valley to the north. Meanwhile, water supply reliability for the San Joaquin Valley is decreasing, as Delta imports are limited by droughts, regulatory environmental flows, and growing water demands upstream, in Southern California, and elsewhere. Many farmers pump more groundwater to make up this unsupplied demand, causing groundwater overdraft. On average, the San Joaquin Valley's overdraft for agricultural water use averages nearly 2 MAF per year (Hanak et al. 2019).

Overdraft has numerous impacts on the Valley's agriculture. First, as groundwater levels decline, more energy and cost are required to pump. Wells also often yield water at declining rates and eventually go dry, reducing the aquifer's ability to supply water reliably during droughts (MacEwan et al. 2017). Second, aquifer with groundwater levels so low, reducing their connection with streams and neighboring aquifers, traps and concentrates pollutants and salts (Pauloo et al. in review), making groundwater less useful for irrigation. Third, aquifers can irreversibly compact from decreasing groundwater levels, causing land subsidence. This subsidence has reduced Friant-Kern Canal capacity by up to 60% (Fitchette 2018). Fourth, groundwater depletion increases surface stream losses, reducing surface water flows and downstream supplies. The problems of decreased groundwater storage are amplified during drought (Harou and Lund 2008).

To address the negative effects of groundwater overdraft, the 2014 Sustainable Groundwater Management Act (SGMA) requires local water agencies to halt overdraft and bring groundwater basins into sustainable use by about 2040. An immense challenge for San Joaquin Valley agriculture. Of 15 groundwater basins subject to SGMA in the San Joaquin Valley, 11 are classified as critically overdrafted. Obtaining additional surface water supply is becoming more expensive with limited availability, while reducing water demand by fallowing cropland means less profit (as well as many other changes).

Managing surface water and groundwater together, rather than in isolation, allows water managers the advantages of both resources to maximize overall benefits. Surface water is recharged to increase groundwater storage during wet periods and more groundwater is pumped in dry periods to offset surface water shortages. Conjunctive water management is often a relatively cost-effective way to end overdraft for the agriculture sector (Harou and Lund 2008, Dogan et al. 2019).

Well-planned conjunctive water management can improve water supply reliability, mitigate land subsidence, and improve water quality. These should benefit agriculture in the long term, though in the near term conjunctive water management incurs costs and can reduce lower-valued agricultural production to supply water and land for aquifer recharge. We discuss conjunctive water management of both supply and demand.

To increase supply, artificial recharge is most straightforward, using several methods listed in Table 1.1 (Hanak et al. 2018). Agricultural districts employ several recharge tools. With the enforcement of SGMA and the wettest-in-record 2017 water year, interest in expanding recharge programs has increased. Two traditional practices most considered are directing extra water to unlined canals and riverbeds and in-lieu recharge. These methods also contribute the second and third most volume to the total San Joaquin Valley recharge; recharge basins ranked first (Hanak et al. 2018). Potential barriers also are listed in Table 1.1. Extra irrigation is used surprisingly little as it is incompatible with efficient irrigation for crop productivity and lining canals which control groundwater quality. However, the San Joaquin Valley has more than 5 million acres of irrigated cropland, more than 40 percent of which is covered with drip and sprinkler irrigation instead of flood irrigation (Tindula et al. 2013).

Table 1.1. On-site Managed Aquifer Recharge methods and their specific implementation issues

<table>
<tr><th>Method Name</th><th>Method Detail</th><th>Method Constraints</th></tr>
<tr><td>Extra irrigation</td><td>• Applying extra irrigation water in growing season
• Spreading water during winter on field planted to some crops (alfalfa and deciduous perennials like almonds and grapes)</td><td>• Difficult to achieve with efficient irrigation and more energy intensive
• Canal and pipe linings restrict the extra water from percolating to aquifer
• Concerns about crop health and yield</td></tr>
<tr><td>Fallowed land recharge</td><td>• Active applying irrigation water on fallowed land</td><td>• Fallowed land may contribute to dust and weed problems that compromise air quality and neighboring farmland</td></tr>
<tr><td>Open space flood recharge</td><td>• No irrigation system involved</td><td>• No infrastructure support</td></tr>
<tr><td>In-lieu recharge</td><td>• Using extra surface water from water trade, allowing aquifer to refill naturally</td><td>• Legislature issues on water market</td></tr>
<tr><td>Unlined canals</td><td>• Directing the surplus surface water to riverbeds and earthen canals</td><td rowspan="2">• Less favorable on the valley’s west side due to poor soil permeability, salinity, and the presence of deep clay layers that prevent water from percolating</td></tr>
<tr><td>Recharge basin</td><td>• Recharging to suitable areas with highly permeable soils</td></tr>
<tr><td>Injection wells</td><td>• For area without good soil permeability</td><td>• Untreated surface water containing lots of sediment can clog the passageways
• High cost of infrastructure establishment</td></tr>
</table>

Water managers must consider numerous co-mingled factors. First is the ability to get additional surface water, which depends on districts’ existing physical capacities such as conveyance channels connecting districts to river and large aqueducts and, of course, surface water availability. The ability also is affected by regulatory approvals needed for diverting and storing additional surface water. San Joaquin Valley has nearly 20,000 irrigated farms, ranging from under 10 acres at a single location to thousands of acres spreading across several counties (Hanak et al. 2017). Small farms and districts far from surface streams who do not regularly use surface water are less likely to have substantial additional infrastructure and management investment.

Climate change makes the location and timing of available water more complex and less certain. There could be more precipitation in northern California, plus melting snowpack in the Sierra Nevada forming more runoff. However, most overdrafted basins and most suitable recharge lands (e.g., the Kern Basin) are in the direr southern valley. Climate change is likely to lead to greater variability with both larger floods and more frequent droughts (Swain et al. 2018). Furthermore, rising temperature causes water in recharge basins to evaporate faster. Without careful planning, monitoring, and adequate infrastructure, the excess water will not be captured and moved quickly from wetter, northern areas to the aquifers in the drier southern valley.

Besides adequate physical capacity and enhanced institutions to manage artificial recharge, adequate attention also should be paid to clarity about how much water is recharged and who may use the groundwater after recharge. Recharging on farmland can have costs to those who recharge, whereas the benefits of higher groundwater levels can spread more widely. Clarifying and enabling regulation or legislation are needed to guide and incentivize private farmers and landowners to participate in recharge programs for broader benefits. For example, SGMA agencies can develop a credit system in water or cash. This requires a standardized groundwater accounting, marketing and banking system.

Groundwater quality is another concern for recharge. Recharge may flush agricultural chemicals from active cropland or fallowed fields to the underlying aquifer. However, groundwater quality can improve with continued recharging at the same location for a decade or two with clean fresh water such as occasional flood flows from Sierra Nevada (Bachand et al. 2017). More saline surface water, such as recycled wastewater or Delta imports, needs more careful planning to reduce negative effects. State and federal regulatory agencies might allow temporary spikes in groundwater contamination while guaranteeing safe drinking and/or irrigation water from proper water marketing (Hanak et al. 2019).

Last, there is generally limited funding for conjunctive management projects. More collaboration and coordination are needed among State, federal, tribal, local and regional agencies and organizations (e.g. universities and laboratories) by sharing and building groundwater data, monitoring, and modelling as conjunctive water management tools. Then, these tools need to find use among farmers and districts. With effective planning, coordination, and regulatory enforcement, improving methods to manage water resources can expand benefits and incentives for investment.

On the demand side, higher irrigation efficiency can perform poorly in conjunctive use and groundwater overdraft management. The saved water from improved irrigation efficiency, which might have recharged the aquifer with flood or furrow irrigation (though rising temperature likely increases irrigation water evaporation), now may be used to grow more crops and increasing consumptive water use. Idling cropland or switching to crops that use less water seem to be the only ways to reduce agricultural net water use. So, we often put much more emphasis on increasing supply in conjunctive water management.

This dissertation **seeks to quantify the effects of conjunctive use and salinity in agricultural production for both short-term and long-term water planning, and to identify economically optimal short-term and long-term supply and demand management for long-term sustainability combined with profit maximization.** An illustrative example based on the San Joaquin Basin was used as a case study, considering only one method of artificial recharge on fallowed cropland. In the example case, net pumping of groundwater storage is nearly equal to a high agricultural water demand and net recharge to groundwater is close to reducing agricultural water demand as it physically restricts the crop acreage thus lowering demand.

Table 1.2 summarizes the overall structure and most important lessons of the next four chapters. Chapters 2 and 3 develop two-stage stochastic quadratic models for intermediate-term (e.g., 10 year) optimization of crop mix and conjunctive water use without and with groundwater salinity. In Chapters 4 and 5, these two models are embedded in a dynamic programming framework to extend the planning horizon (10 10-year stages) to explore agricultural and conjunctive operations optimized over multiple decades without and with groundwater salinity.

Table 1.2. Composition of subsequent four chapters

	Without Salinity		**With Groundwater Salinity**	
Short term	**Method**	Two-stage stochastic quadratic modelling		
	Chapter 2		**Chapter 3**	
	Key conclusion	Pumping and artificial recharge dampens variability in surface water availability	**Key conclusion**	Permanent crops are reduced and pumping gradually shifts to wetter years with more groundwater salinity
Long term	**Method**	Stochastic quadratic modelling nested in dynamic programming		
	Chapter 4		**Chapter 5**	
	Key conclusion	Less pumping than the than short-term optimal until minimum allowable storage is reached, keeping maximal perennial crops to maximize profit	**Key conclusion**	Aquifer recovery occurs earlier to restore groundwater and slow salinity increases to support as many perennial crops as possible

By column, we can compare conjunctive water management changes with groundwater salinization. Without salinity, profits are maximized when pumping occurs more in dry years to maximize high-value perennial crop acreage and not pumping too much in dry years to grow additional low-value annual crops, which would require additional artificial recharge in wetter years. However, with salinity, the timing and the amount of pumping needs to be more careful, and artificial recharge serves to both increase the groundwater storage and slow groundwater salinization.

By row, we see differences between short-term and long-term conjunctive water management. Long-term decisions emphasize the acreage of perennial crops to save establishment cost in later stages, no matter salinity is considered or not (because the fundamental reason to slow increases in groundwater salinity is to have more perennial crops). Therefore, at any stage, long-term decisions require more pumping in drier events compensated by more artificial recharge in wetter events than for intermediate-term decisions, raising operating costs and reducing total profit.

In the context of California's agriculture, conjunctive water management is believed to greatly smooth variability in water availability to stabilize crop decisions and production, improving agricultural profitability across water year types. This works quite well if groundwater salinity is low enough to not affect crop yield (Chapter 2). Still, in reality, salinity reduces farmers' revenues by $370 million/year in the southern Central Valley (MacEwan et al. 2016). Losses are greater in overdrafted basins, with about 250,000 acres of irrigated land retirement and 1.5 million acres of salt-impaired lands (CV-SALTS 2017), mostly on the west side of the San Joaquin Valley. Salinity losses for agriculture worsen if no measures are taken.

Conjunctive water management in the southern Central Valley seems likely to go through three phases (Table 1.3), with different parts of the valley often being in different phases at any given time. In Phase I, surface water and groundwater salinity is relatively small and can be neglected for crop production. From Chapter 4, it is most profitable in this condition to continue pumping at a slower rate to maximize high-value perennial crop production, until a long-term water balance, i.e., the time to keep no overdraft, has arrived. The minimum allowable groundwater storage, in other words, the signal of long-term balance, is reached when additional pumping cannot create the additional crop profit as much as the additional pumping cost. In this long-term balance, annual crop acreage in dry years is **still** greatly reduced, with artificial recharge required in wetter years to compensate for pumping in dry years, because maintaining maximal perennial crops makes the highest profit. If groundwater storage recovery is required in the future, without salinity, recharging is postponed to the end of planning horizon to minimize its present value cost. The long-term balance varies with the discount rate and final groundwater storage goal.

Many groundwater basins in southern Central Valley have already passed Phase I: their current groundwater storage is below the long-term balance in Phase I and groundwater salinity starts to affect crop yield. This is Phase II. In the short term, the demand for agricultural water use in dry years may not be satisfied by simply pumping more groundwater, because if annual crop acreage in dry years is the same as in wet years, the fresh surface water in dry years cannot dilute enough saline groundwater and the irrigation water (combining surface water and groundwater) will become too salty for salt-sensitive but high-value perennial crops (Chapter 3). Though annual crop acreages in dry years in Phases I and II are both reduced, dry year pumping in Phase I is encouraged to keep more perennial crops, while in Phase II pumping and permanent crop acreage are suppressed due to groundwater salinity.

Furthermore, even fresh surface water contains salt. If the groundwater basin is closed with no drainage to surface streams or other aquifers, salt accumulates in groundwater with each planting cycle, something common in the southern Central Valley. Therefore, pumped irrigation supplies may not always be the most desirable choice, as it increases salinity accumulation. This process can make artificial recharge more important for controlling groundwater quality and quantity. Though fewer perennial crops can be supported when the profit in present value is highest, artificial recharge should start early to help support higher perennial crop acreage in the middle of planning horizon to maximize the total profit. However, artificial recharge is still not more profitable than keeping no overdraft as long as groundwater salinity is not very high. Even in a long-term perspective (100 years), artificial recharge is needed only to stabilize salinity, and even with stable groundwater storage, salinity inevitably increases (Chapter 5).

Table 1.3. Three phases for agriculture and conjunctive use with salinizing aquifers

Phases	Characteristics	Solution
Phase I	Low groundwater salinity	Pump more in dry years and gradually reduce to a target long-term storage.
Phase II	Groundwater storage is too low and groundwater salinity is starting to impair crop yield	Dry-year pumping limited by aquifer salinity. Artificial recharge is used to slow groundwater salinization.
Phase III	High groundwater salinity	Pumping is restricted and limited by water quality in more years. When salinity is high, artificial recharge is used to reduce salinity until salinity is acceptable to keeping no overdraft for more crops until salinity is high again

With occasional artificial recharge to avoid overdraft, we enter Phase III, in which groundwater salinity is now high. In this phase, pumping is the least useful, because we pump groundwater only to blend with surface water or to dump it to avoid water logging (Chapter 3). In a long-term perspective, ending overdraft is more sustainable for agricultural production (Chapter 5). But without drainage, groundwater becomes saltier. If the water table is still not affecting the root zone, when groundwater salinity is too high for irrigation, more aggressive artificial recharge is needed to **reduce** salinity to a blendable level and land is fallowed to not grow crops with impaired yield until the groundwater is fresh enough to again irrigate crops. With salinity, this dynamic equilibrium, rather than simply keeping no overdraft, should be considered to maximize total net benefit. If groundwater storage is very high, externally discharging groundwater and replacing it with fresh water or other new technologies are required, which is beyond the scope of this dissertation.

In conclusion, successful conjunctive water management must address many problems. On the supply side, the most important need is water measurements and estimates to guide conjunctive water management, such as hydrologic forecasting, monitoring (water quantity and quality), and accounting (e.g., how much water is pumped and recharged). Next is the establishment of proper incentives for appropriate pumping, fallowing, and recharge decisions, including banking and marketing arrangements (e.g., how to pay for recharge). The development of these tools requires collaboration and coordination among institutions and organizations of different levels, including farmers. However, reduced applied use does not necessarily increase supply (e.g., applying drip irrigation to grow more crops, but reducing recharge). Indeed, some water needs to be stored in advance to secure groundwater storage and control groundwater salinity. The stakes are high. So are the costs of inaction.

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Chapter 2: Two-Stage Stochastic Quadratic Modeling of Crop Decisions and Conjunctive Water Use

Abstract

Allocating water supply to crops and aquifer recharge is of growing importance in California as the Sustainable Groundwater Management Act (SGMA) requires water agencies of critically over-drafted basins to halt overdraft. This paper presents a two-stage stochastic quadratic model to develop economically optimal intermediate (several-year) crop mix decisions and conjunctive water use operations with a stochastic surface water supply by maximizing the net expected benefits of crop production and conjunctive use. Perennial crop planting decisions are made in the first stage and annual crop planting decisions and corresponding decisions on water pumping and land and water for recharging are made in the second stage based on probabilities of different hydrologic events. For different boundary conditions (initial and final groundwater storage and incoming perennial crop acreage from previous stage), this model represents farmers' perennial and annual crop decisions and water operations with varying pumping cost. Model results indicate pumping groundwater with no limitation will not always provide the highest profit, because of rising pumping cost. Also, when increasing groundwater storage, maximizing more profitable perennial crops are economically best. Pumping may occur in drier events to support perennial crops, while no annual crops are planted during those driest events.

Keywords: Two-stage quadratic programming, Groundwater overdraft, Conjunctive operations, Artificial recharge, Perennial crops

1. Introduction

1.1 Overdraft

Overdraft is long-term groundwater extraction at unsustainable rates that exceed seasonal storage variation (Harou and Lund 2008). Overdraft can cause a variety of undesirable conditions, including high pumping and well costs, surface water depletion, water quality degradation, seawater intrusion, and land subsidence (Sophocleous 2003; Zekster et al. 2005).

Groundwater overdraft can threaten the sustainability of economic activities, society, and ecosystems. First, perennially lowered groundwater levels increase future pumping costs and capital costs for drilling deeper wells (MacEwan et al. 2017). Second, declining water tables can switch surface streams from gaining to losing and drain riparian and wetland areas. Third, reduced connection between surface water and groundwater restricts salt outflow from groundwater and concentrates pollutants in groundwater (Pauloo et al. in review). Fourth, land subsidence can increase flooding and disrupt water supply infrastructure. Finally, problems of decreased groundwater storage are amplified during drought for the areas heavily dependent on groundwater (Harou and Lund 2008; Gailey et al. 2019).

1.1 Sustainable Groundwater Management Act (SGMA)

Much of the world, including California, uses groundwater as a major water source along with surface water. In normal years, groundwater supplies about 30% of California's water; while in critical dry years, groundwater use exceeds 40% of total water use (DWR 2003). Due to few statewide regulations on groundwater, high streamflow variability and frequent droughts, water users often overexploit groundwater (Zekster et al. 2005). Annual statewide overdraft has been estimated between one to two million acre-feet (MAF) (DWR 2003).

To bring groundwater basins into sustainable use, the Sustainable Groundwater Management Act (SGMA) was signed in 2014, which requires local governments and water agencies to end overdraft by about 2040 (OPR 2014). However, ending overdraft with the least economic loss is a challenge, especially for agriculture. Conjunctive use of surface water and groundwater appears as the best way to halt overdraft with the least additional water-scarcity cost (Harou and Lund 2008; Dogan et al. 2019).

1.2 Climate Change in California

Climate change directly influences groundwater systems through changes in the timing and amount of recharge. The California Sierra Nevada water system, relying on the snowmelt runoff, is subject to changes in temperature and precipitation. Warming reduces snow accumulation, accelerates snowmelt, and increases winter precipitation as rain rather than snow (Miller et al. 2003; Vicuna et al. 2007). The earlier snowmelt and winter precipitation push the peak groundwater levels forward, and less snow accumulation means less spring and summer runoff (Taylor et al. 2012).

Climate change also impacts groundwater indirectly through complicated interactions with irrigated agriculture. In (semi-) arid areas, groundwater is a substantial part of irrigation water, something especially true in prolonged drought when surface inflow is less able to satisfy irrigation uses. Higher temperatures can accelerate crop growth to shorten the time for irrigation and crop maturity (Hopmans et al. 2008), but it also increases evapotranspiration (ET) rates of crops. Thus, it is unclear if climate change will increase or decrease overall irrigation demands. In the future, though great uncertainty persists on the impacts of climate change on average precipitation, there is more consensus on changes in extremes (Bates et al. 2008; Swain et al. 2018). Both droughts and rainfall may be more frequent and intense. These events may affect groundwater availability for irrigation.

2. Method

2.1 Conjunctive Use Modeling

The usual core idea of conjunctive use is to increase groundwater storage with surface water during wet periods and pump more groundwater in dry periods to offset surface water shortage. Groundwater storage can be increased in wet periods by direct artificial recharge, by infiltration or deep percolation from applied surface water, and in-lieu recharge from reduced groundwater pumping. Well-planned conjunctive water management can improve water supply reliability, mitigate land subsidence, and improve water quality.

Many simulation/optimization models have been developed to design and represent conjunctive operations by including surface water and aquifer interactions (Buras 1963; Burt 1964, 1966; Gorelick 1983, 1988; Peralta et al. 1995; Fredericks et al. 1998; Belaineh et al. 1999) and combining operating decisions involving surface reservoirs (Schoups et al. 2006). These methods provide important understanding of how surface and groundwater interact, and corresponding management implications. However, these models usually do not represent regional management reacting to water demands and available groundwater operations, especially for economically valuable agricultural regions (Marques et al 2010).

Previous studies (Bredehoeft and Young 1983; Philbrick and Kitanidis 1998) modeled optimal users' decisions and conjunctive operations through piece-wise linear relations between surface water and groundwater or a single shortage cost function based on the elasticity of demand for water, without considering the effect of artificial recharge on the pumping costs. Marques et al. (2010) and Zhu et al. (2015) combined a quadratic economic profit function with a two-stage programming approach to model cropping decisions and water operations with uncertain surface water supplies. In those models, perennial crop planting decisions are first stage decisions, and annual crop planting decisions and corresponding water operations of pumping and land for recharging are second stage decisions based on probabilities of hydrologic events. The results from those models help identify potential gains of conjunctive use operation and implications for cropping.

2.2 Quadratic Programing of Agricultural Production Decisions

Linear production models are limited in representing real crop production because of diminishing economic returns for the initially most profitable crops (Hazell and Norton 1986; Howitt 1995). An alternative approach uses a quadratic objective function representing the competitive market in which a price-taker will supply when marginal revenue (market price P_i) equals marginal cost:

$$P_i = \alpha_i + \gamma_i X_i \tag{2.1}$$

The right-hand side (marginal cost) of Equation (2.1) is the inverse supply function of crop i in the quantity X_i with intercept α_i and slope γ_i. Equation (2.1) then can be integrated on X to Equation (2.2) where Z is the total profit of crop i.

$$Z_i = P_i X_i - (\alpha_i + 0.5\gamma_i X_i) X_i \tag{2.2}$$

The intercept α_i and slope γ_i are calibrated with positive mathematical programming (PMP) (Bauer and Kasnakoglu, 1990; Howitt, 1995; Hatchett, 1997). The PMP approach adds calibration constraints to crops resulting in shadow values (λ_i) to first estimate the slope γ_i by solving Equation (2.3) with the observed acreage $\tilde{X}_i$ of the crop (Howitt, 1995). Then, the intercept α_i is calculated by substituting γ_i and the observed acreage $\tilde{X}_i$ in Equation (2.1), where P_i is observed unit price of the crop per acre.

$$\lambda_i = 0.5\gamma_i X_i \tag{2.3}$$

2.3 Model Formulation

Figure 2.1 depicts the model's structure. Perennial crop decisions are made in the first stage. Annual crop decisions, groundwater pumping, and land for artificial recharge are modeled in the second stage for a set of possible hydrologic events, each with an amount of surface water available and probability of occurrence.

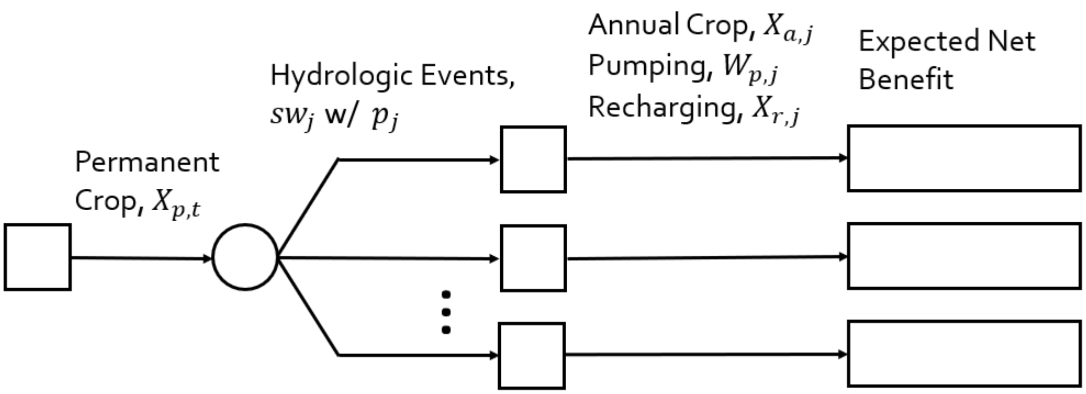

Figure 2.1 Problem decision tree

The decision variables are acreage of perennial crop $X_{p,t}$ in current planning horizon t; and annual crop acreage $X_{a,j}$, groundwater volume pumped $W_{p,j}$, and land used for artificial recharge $X_{r,j}$ in the hydrologic event j. For simplicity, we assume 50% of perennial crops are retired at the end of planning horizon, instead of perennial crops being retired annually by 5%.

The planning horizon T is 10 years. The objective function (Equation (2.4a)) includes the net benefits over the entire 10-year planning horizon in the first stage, $B1$, and the perennial crop establishment cost, $INIP$. In the second stage, each year is a realization of possible hydrologic events j assembled with probabilities of occurrence p_j and amounts of surface water available sw_j. For each possible event j, different decisions of annual crop acreage $X_{a,j}$ and conjunctive use decisions $X_{r,j}$ and $W_{p,j}$ are made, resulting in different net annual crop production benefits and water-related costs. Thus, the second stage of the model maximizes the expected economic return from annual crop and conjunctive use decisions, $B2$, subtracting the expected operational cost, $EXPC$.

The objective function (Equation (2.4a)) optimizes the crop production and conjunctive use decisions in the current planning horizon t and is subject to constraints on land (Equation (2.5)), water (Equation (2.6)), and expected groundwater mass balance (Equation (2.7a) and (2.7b)).

$$\min Z = -(B1 - INIP + B2 - EXPC) \tag{2.4a}$$

Where $B1$ is the sum of the products of perennial crop discounted profits (Equation (2.2)). Because the acreage of perennial crop over the entire planning horizon is always $X_{p,t}$, here $B1$ is a sum of geometric series (Equation (2.4b)). v_p and yld_p are the unit price and yield of perennial crop per acre; r is the constant discount rate.

$$
\begin{aligned}
B1 = & \left[(v_p yld_p)X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right)X_{p,t}\right] \div (1+r)^{tT+1} \\
& + \left[(v_p yld_p)X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right)X_{p,t}\right] \div (1+r)^{tT+2} + \cdots \\
& + \left[(v_p yld_p)X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right)X_{p,t}\right] \div (1+r)^{tT+10} \\
= & \left[(v_p yld_p)X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right)X_{p,t}\right] \frac{1-(1+r)^{-T}}{(1+r)^{tT} \times r} \qquad (2.4b)
\end{aligned}
$$

The perennial crop establishment cost, $INIP$, depends on the initial acreage of perennial crop at current planning horizon, $X_{p,t}$, and the incoming perennial crop acreage, $X_{p,t-1}$. If $X_{p,t} < X_{p,t-1}$, meaning the planting decision of a perennial crop in current planning horizon is less than the incoming acreage, there is no establishment cost. Otherwise, the establishment cost is the acreage of newly planted perennial crop acreage times the unit price of establishment cost, ini_p, multiplied by the discount factor.

$$
INIP = \max\left(X_{p,t} - X_{p,t-1}, 0\right) ini_p \div (1+r)^{tT+1} \qquad (2.4c)
$$

The expected net benefit of an annual crop over 10 years, $B2$, is the sum of yearly expected net benefits multiplied by discount factor, where the yearly expected net benefit is the product of annual crop profit in hydrologic event j and the probability of the that hydrologic event, p_j. v_a and yld_a are the unit price and yield of annual crop per acre. It is a sum of geometric series.

$$
\begin{aligned}
B2 = & \frac{1}{(1+r)^{tT+1}} \sum_{j=1}^{5} p_j \left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\
& + \frac{1}{(1+r)^{tT+2}} \sum_{j=1}^{5} p_j \left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] + \cdots \\
& + \frac{1}{(1+r)^{tT+10}} \sum_{j=1}^{5} p_j \left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\
= & \frac{1-(1+r)^{-T}}{(1+r)^{tT} \times r} \sum_{j=1}^{5} p_j \left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \qquad (2.4d)
\end{aligned}
$$

$EXPC$ is the expected water operational cost over 10 years. Similar to the calculation of net annual crop benefit, $EXPC$ is also a sum of a geometric series of yearly expected net water operational cost multiplied by discount factor, where the yearly expected water operational cost is the sum of products of annual water operational cost in hydrologic event j and the probability of the that hydrologic event, p_j. C_{pump} is the unit cost of pumping per acre-feet (AF), thus $C_{pump} \cdot W_{p,j}$ being the pumping cost; c_{land} is the unit cost of land per acre, making $c_{land} \cdot X_{r,j}$ be the cost of artificial recharge; c_{class1} is the unit price of $class1$ water (firm contract surface water) per AF; c_{class2} is the unit price of $class2$ water (surplus surface water) per AF. In some hydrologic events, the surface water inflow sw_j is even less than the $class1$ water, so $c_{class1} \cdot \min\left(sw_j,\ class1\right)$ is the cost of firm contract surface water, and $c_{class2} \cdot \max\left(sw_j - class1, 0\right)$ is the cost of surplus surface water.

$$EXPC = \frac{1-(1+r)^{-T}}{(1+r)^{tT} \times r} \sum_{j=1}^{5} p_j \left[C_{pump} \cdot W_{p,j} + c_{land} \cdot X_{r,j} + c_{class1} \cdot \min\left(sw_j, class1\right) + c_{class2} \cdot \max\left(sw_j - class1, 0\right)\right] \tag{2.4e}$$

Because this paper focuses on groundwater storage, pumping cost is further considered to change with groundwater level. Unit pumping cost is higher with lower groundwater level/storage. C_{pump} is a function of groundwater storage and amount of groundwater pumping. Pumping cost is the product of unit price of energy and the total energy to pump groundwater.

Therefore, $C_{pump} \cdot W_{p,j}$ in Equation (2.4e) expands to:

$$C_{pump} \cdot W_{p,j} = c_e \times \frac{W_{p,j} \times \left(\frac{1{,}233.5\ m^3}{AF}\right) \times H \times \left(\frac{0.3048\ m}{ft}\right) \times \rho g}{3.6 \times 10^6 \times \eta_p} \tag{2.4f}$$

where c_e is the unit cost of energy; H is the average of initial and final head (Figure 2.2 and Equation (2.4g)); and η_p is the pumping efficiency.

$$H = \frac{1}{2}(H_{t-1} + H_t) = \frac{1}{2}\left[\left(H_o + \frac{GW_o - GW_{t-1}}{L \cdot s_y}\right) + \left(H_o + \frac{GW_o - GW_t}{L \cdot s_y}\right)\right]$$
$$= H_o + \frac{1}{2L \cdot s_y}(2GW_o - GW_{t-1} - GW_t) = H_o + B_o - \frac{1}{2L \cdot s_y}(GW_{t-1} + GW_t) \tag{2.4g}$$

where H_o is the beginning depth of groundwater (pumping head) at planning horizon 0, GW_o is the groundwater storage at planning horizon 0; L is the total area for planting covering the aquifer; s_y is the specific yield of the aquifer; and B_o is the thickness of the aquifer at planning horizon 0.

Equation (2.5) limits the total area of planted perennial crop, annual crop, and the artificial recharge area to the total available land area for each hydrologic event j.

$$L - X_{p,t} - X_{a,j} - X_{r,j} \geq 0 \quad \forall j \tag{2.5}$$

Equation (2.6) is the water balance condition in each event j. The amount of water used to grow perennial and annual crops should not exceed the available surface water plus the pumped groundwater minus the surface water for artificial recharge. In Equation (2.6), aw is the applied water of an acre of crop; and cap is aquifer recharge capacity per acre of land per year.

$$sw_j + W_{p,j} - cap \times X_{r,j} - aw_p X_{p,t} - aw_a X_{a,j} \geq 0 \quad \forall j \tag{2.6}$$

To calculate the stochastic conservation of mass of groundwater storage, ideally the initial groundwater storage of current planning horizon, GW_{t-1}, plus the expected deep percolation over T years, plus the expected artificial recharge over T years, $T\sum_{j=1}^{5} p_j cap X_{r,j}$ (assume 100% of surface water used for artificial recharge reaches to the groundwater aquifer), minus the expected amount of pumped groundwater over T years, $T\sum_{j=1}^{5} p_j W_{p,j}$, equals to the final groundwater storage of current planning horizon, GW_t.

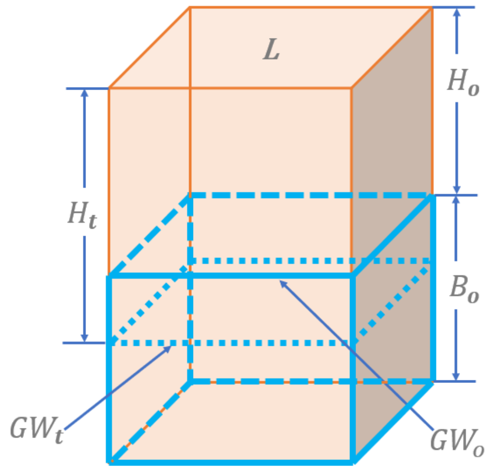

Figure 2.2. Model aquifer demonstration

There are two ways to calculate the deep percolation. First, from the water perspective: because surface water has two uses: irrigation and artificial recharge. And for simplicity, a single factor φ is used to estimate the percentage of water applied that deep percolates, the expected deep percolation from surface water over T years is $T\sum_{j=1}^{5} p_j \varphi(sw_j - capX_{r,j})$. Groundwater pumped is only used for irrigation, so the expected deep percolation from groundwater over T years is $T\sum_{j=1}^{5} p_j \varphi W_{p,j}$.

Second, from the crop perspective: the deep percolation from perennial crop over T years is: $T\varphi aw_p X_{p,t}$. And the expected deep percolation from the annual crop over T years is $T\sum_{j=1}^{5} p_j \varphi aw_a X_{a,j}$. Because we only retire the perennial crop once, at the end of the planning horizon, these two perspectives are compatible.

In this paper, the constraint of stochastic conservation of mass of groundwater storage has two equivalent representations (Equation (2.7a) and (2.7b)), which are:

$$GW_t = GW_{t-1} + T\varphi aw_p X_{p,t} + T\sum_{j=1}^{5} p_j \varphi aw_a X_{a,j} + T\sum_{j=1}^{5} p_j capX_{r,j} - T\sum_{j=1}^{5} p_j W_{p,j} \qquad (2.7a)$$

$$GW_t = GW_{t-1} + T\sum_{j=1}^{5} p_j \varphi sw_j + T\sum_{j=1}^{5} p_j (1-\varphi) capX_{r,j} - T\sum_{j=1}^{5} p_j (1-\varphi) W_{p,j} \qquad (2.7b)$$

Water from deep percolation and artificial recharge will be considered "available" even when applied water is pumped from groundwater. This assumes that (i) groundwater storage is large enough to not constrain the transfer of water from one hydrologic event to the other and (ii) the hydrologic event's time scale is long enough that water recharged in one event is available for any other event (Marques et al. 2005).

Though only one perennial crop and one annual crop are considered in this model, no irrigation method, urban water use, or water transfer decisions are considered, making this model less able to represent mixed agriculture and urban production as in the work of Marques et al. (2010) and Zhu et al. (2015). This model emphasizes on a more detailed representation of agricultural profit in a 10-year period. Furthermore, Marques' and Zhu's work requires that there is no overdraft, while the model in this paper can assign any reasonable values to both initial and final groundwater storage. Moreover, this model can include variable pumping cost for different initial and final groundwater storages.

3. Results and Discussion

3.1 Case Study Site

We create an example planting area and underlying aquifer, with parameters summarized in Table 2.1. The planting area is similar to the total of acreage of almonds and alfalfa in North San Joaquin Valley. The unit prices of class 1 and class 2 water are based on the Chowchilla water district. The unit price of energy is adopted from Statewide Agricultural Production (SWAP) model for North San Joaquin Valley (DWR 2012). The capacity of land for recharging is derived from USACE's Conjunctive Use for Flood Protection Study (USACE 2002).

Table 2.2 and Figure 2.3 summarize the current stationary surface water availability $sw \sim logN(\mu = 625{,}000\ AF,\ \sigma = 400{,}000\ AF)$. To simplify the problem first, the averaged surface water inflow of each hydrologic event is represented by the 10th-, 30th-, 50th-, 70th- and 90th- percentile of the distribution, hence we can assume the probability of each hydrologic event is the same, which is 1/5 * 100% = 20%.

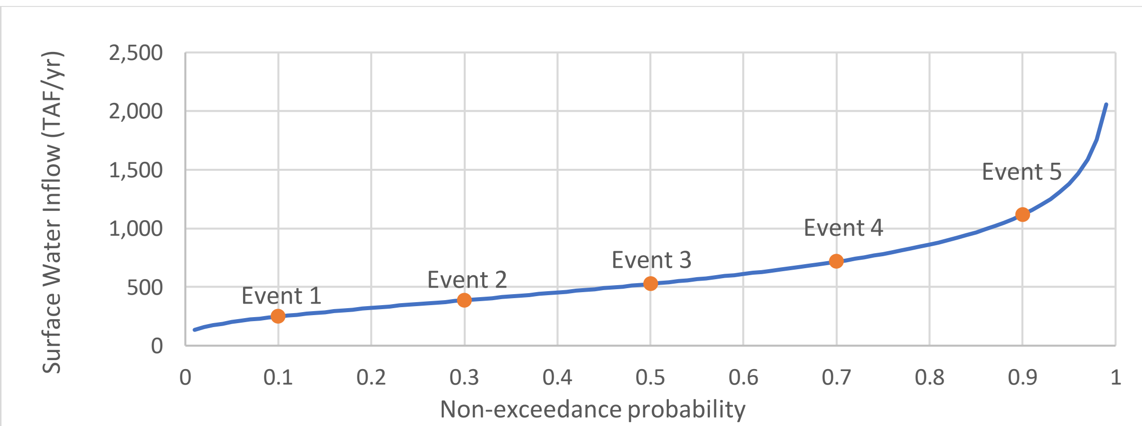

Figure 2.3. "Averaged" surface water inflow of each hydrologic event

Table 2.3 gives base year agricultural production parameters and estimated PMP production cost function parameters (Equation (2.1) to (2.3)). These production parameters and input costs are based on data in Statewide Agricultural Production (SWAP) model for North San Joaquin Valley in 2005.

Table 2.1. Input parameters of the case study site

Symbol	Parameter (unit)	Value
T	Length of planning horizon (yr)	10
L	Total available area (acre)	500,000
H_o	Initial pump head (ft)	200
B_o	Initial thickness of the aquifer (ft)	200
s_y	Aquifer specific yield	0.1
GW_o	Initial groundwater storage (MAF)	10
r	Constant discount rate	0.035
ini_p	Perennial crop initial establishment cost ($/acre)	12,000
c_{land}	Unit price of land for recharging ($/acre)	300
c_{class1}	Unit price of class 1 (firm contract) water ($/AF)	42
c_{class2}	Unit price of class 2 (surplus) water ($/AF)	30
$class1$	Amount of firm contract water (TAF)	500
c_e	Unit price of energy ($/kWh)	0.189
η_p	Pumping efficiency	0.7
ρ	Density of water (kg/m^3)	1,000
g	Gravitational acceleration (m/s^2)	9.81
cap	Capacity of land for recharging (AF/acre/yr)	15
$1-\varphi$	Irrigation efficiency	0.85
t	Current planning horizon	0

Table 2.2. Available surface water in each hydrologic event

Event j	Percentile	sw_j (TAF/yr)	p_j
Dry 1	10th	248	0.2
2	30th	387	0.2
3	Median	526	0.2
4	70th	716	0.2
Wet 5	90th	1,115	0.2

Table 2.3. Base year observations and estimated PMP production cost functions

	Parameter (unit)	Perennial Crop (Almond)	Annual Crop (Alfalfa)
Base year observations	Area $\tilde{X}$ (acre)	328,340	167,350
	Yield yld (t/acre)	1	8
	Price v ($/ton)	4226.68	157.28
	Applied water per acre aw (ft)	4.07	4.84
	Water use (AF)	1,336,344	809,974
	Land cost ($/acre)	812	317
	Other supply cost ($/acre)	1,678	544
	Labor cost ($/acre)	318	21
	Total cost ($/acre)	2,808	882
PMP cost function	Intercept α ($/acre)	1502.85	635.91
	Slope γ ($/acre^2)	0.00795	0.00294

3.2 Optimal Planning Results Summary

The first results explore if the model represents reasonable farmers planning on crop decisions and water operations over a decadal period, given different initial and final groundwater storage and incoming perennial crop acreage boundary conditions.

3.2.1 Fixed Initial Groundwater Storage (10 MAF) and Incoming Acreage of Perennial Crop (125,000 Acres)

Figure 2.4 shows perennial crop acreage decisions and total profit over the planting horizon. Here negativity in x axis means net groundwater pumping over 10 years, while the positive x's mean net increasing groundwater storage. More groundwater pumping expands perennial crops and vice versa. Total profit over the period falls with restoring groundwater storage, as less crops and more artificial recharge reduce profits. More groundwater recovery brings the more significant loss of profit. Net pumping of 3 MAF in 10 years makes the most profit. However, pumping of more groundwater does not mean more profit for this example because of greater pumping cost.

Figure 2.5 shows the model's overall optimal decisions for different groundwater storage change goals, where perennial crop acreage is in orange, annual crop acreage is in green, land used for artificial recharge is in blue on the left y axis, and groundwater pumped is in red on the right y axis. Numbers 1 to 5 represent hydrologic events (Table 2.2 and Figure 2.3), with event 1 being driest and event 5 being wettest.

When $\Delta GW < 0$ (net pumping), several patterns emerge: 1) Because of the high initial establishment cost for the perennial crop, the expansion of annual crops surpasses that of perennial crops. 2) Pumping evens differences across events. In events when pumping occurs, same acreages of annual crop are planted. The same value of Lagrange multipliers in those events (Section 3.3.1) agrees with the pattern. 3) One counter-intuitive phenomenon shows that:

although annual crops are planted most in the wettest event, fewer annual crops are planted from net pumping of 1 MAF to 3 MAF. This is because when net pumping is still small, few perennial crops are planted, and there is no pumping in the wettest event, meaning the annual crops in event 5 solely depend on the remaining surface water. As ΔGW becomes more negative, more perennial crops are planted, while there is still no pumping in the wettest event, so less surplus surface water exists in the wettest event for annual crop, resulting in fewer annual crops planted. And 4), no land is used to recharge surface water to groundwater.

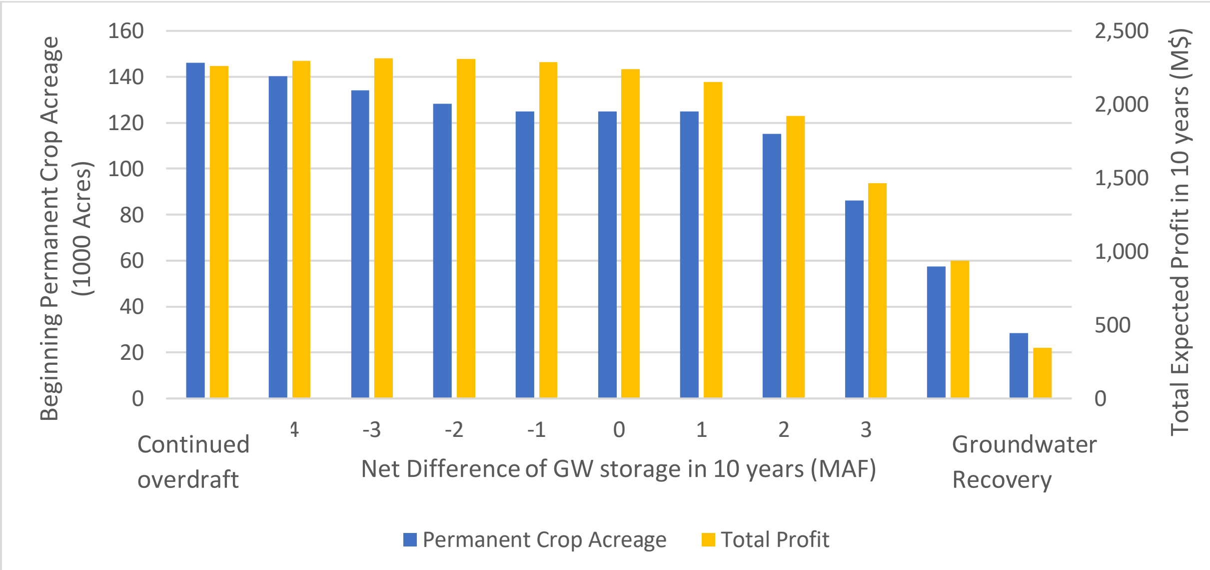

Figure 2.4. Perennial crop acreage and total profit given the different change in GW storage

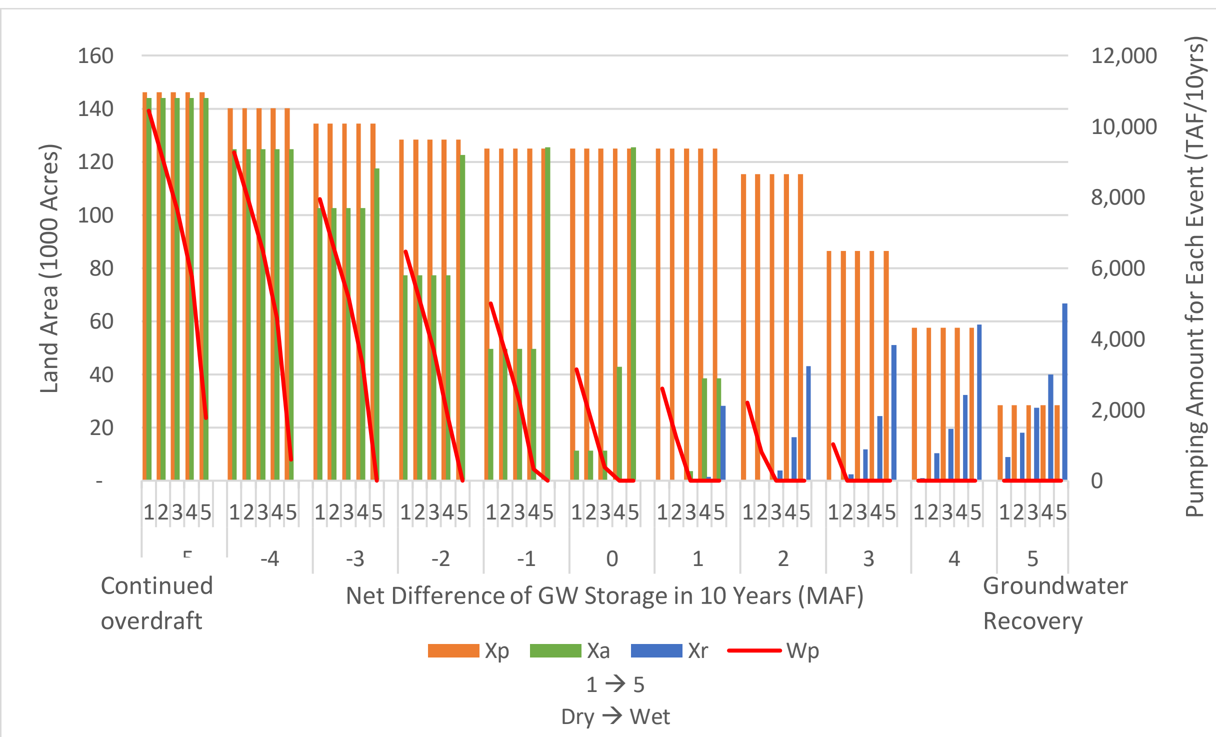

Figure 2.5. Crop mix and conjunctive use in different goals and events, $X_{p,t-1}$ = 125,000 acres

When ΔGW ≥ 0 (net recovering), there are several patterns: 1) Because of the high economic value of the perennial crop, they are maximally maintained. 2) After surface water is assigned to perennial crops and artificial recharge, the remaining surface water can be used to plant annual crops. So, annual crops are barely planted in wet events when ΔGW = 1 MAF, and no annual crop is planted when ΔGW > 1 MAF. 3) Pumping in drier events occurs when ΔGW ≤ 3 MAF to support perennial crops. Therefore, to balance the groundwater pumped in drier events and meet the net recovering goal, artificial recharge starts from the wettest event. And 4), when ΔGW ≥ 4 MAF, pumping ceases in all events, with artificial recharge occurring even in the driest event.

Figure 2.6 shows water management into/out of the aquifer. For no net change in groundwater storage over the planning horizon (ΔGW = 0), deep percolation from perennial and annual crops is enough to support pumping in drier events. For mild groundwater restoring (ΔGW < 3 MAF), most artificial recharge occurs in the wettest event to balance the pumping in drier events for more perennial crops. For demanding recovery goals (ΔGW > 3 MAF), artificial recharge occurs in all the events with most amount in wettest event. When lowering groundwater storage (ΔGW < 0), most pumping is in the driest event.

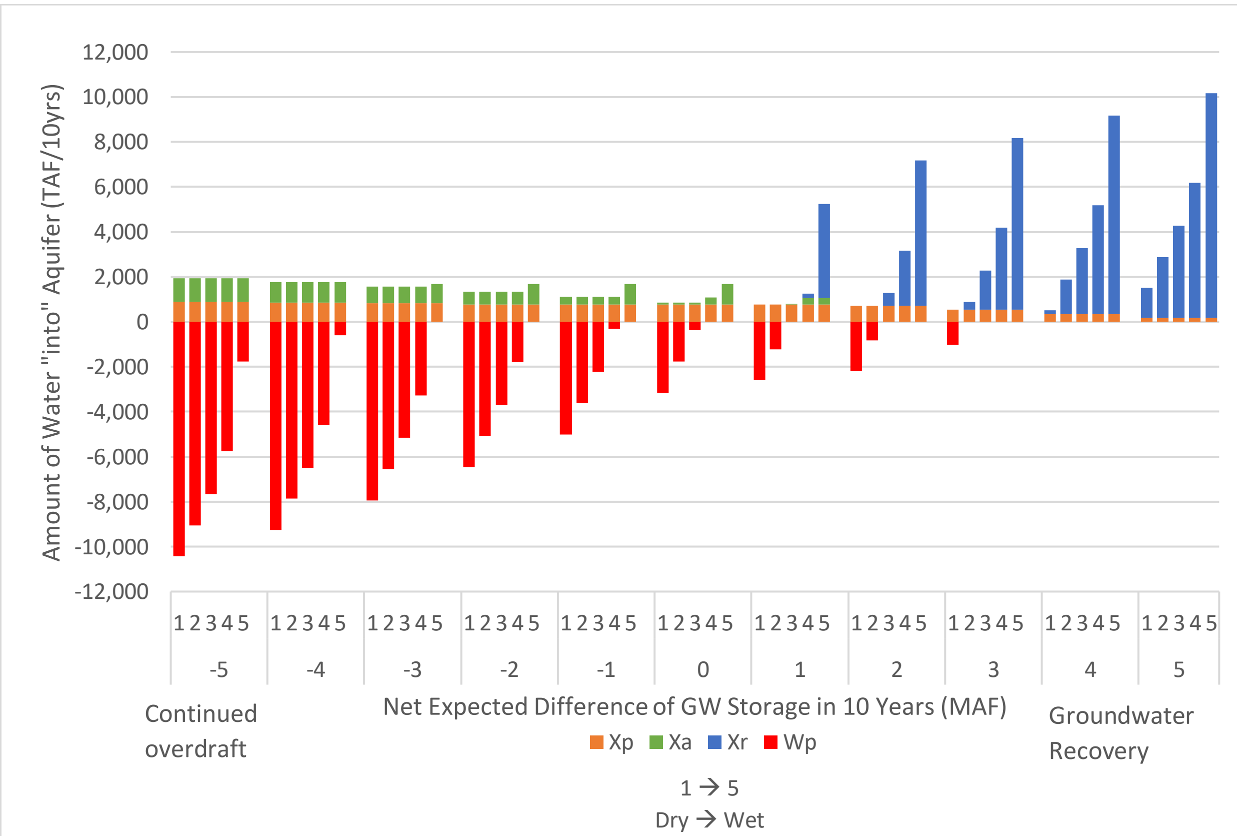

Figure 2.6. Water accounting for different GW storage goals

3.2.2 Comparison between Different Initial Groundwater Storage (10 MAF vs. 15 MAF)

Table 2.4 shows perennial crop decisions and corresponding profit for different initial groundwater storage and pumping/restoring. Though different initial groundwater storages make no difference in the decision of perennial crop acreage due to its high initial establishment cost, greater initial groundwater storage ends in higher or equal profit, because with a same value of ΔGW, greater initial groundwater storage means lower pumping cost if pumping occurs (Equation (2.4f) and (2.4g)).

Profits for different initial groundwater storages levels range from 0 to $116.13M. When ΔGW > 3 MAF, there is no difference because no pumping occurs in any events. When ΔGW is less positive and goes negative (except ΔGW = 0, which will be explained later), because groundwater is increasingly pumped, and the difference in pumping cost per unit of groundwater for different initial groundwater storage stays the same (Equation (2.4f) and (2.4g)), the profit differs more and more.

Maximum profit occurs in different pumping goals between different initial groundwater storages. When initial groundwater storage is 10 MAF, the optimal solution is to pump 3 MAF over the planning horizon with $2,313M profit, while the optimal solution is to pump 4 MAF resulting in $2,428M profit with the initial groundwater storage of 15 MAF. This finding confirms our expectation that with higher initial groundwater storage, more water is pumped with more profit.

Table 2.4. Comparison of perennial crop decisions and profits under different initial groundwater storage

ΔGW (MAF)	X_p (Acre)		Profit (M$)		
	GW_{t-1}=10 (MAF)	GW_{t-1}=15 (MAF)	GW_{t-1}=10 (MAF)	GW_{t-1}=15 (MAF)	Δ Profit (M$)
-5	146,251	146,251	2,260.30	2,419.92	159.62
-4	140,257	140,257	2,295.33	**2,427.90**	132.57
-3	134,264	134,264	**2,313.06**	2,418.56	105.50
-2	128,270	128,270	2,310.77	2,389.20	78.43
-1	125,000	125,000	2,287.68	2,339.05	51.37
0	125,000	125,000	2,239.75	2,266.38	26.63
1	125,000	125,000	2,151.06	2,168.64	17.58
2	115,231	115,231	1,922.72	1,936.64	13.92
3	86,325	86,325	1,464.58	1,469.32	4.74
4	57,420	57,420	939.04	939.04	0.00
5	28,514	28,514	346.78	346.78	0.00

Also, for most ΔGW values (except ΔGW = 0), the difference in initial groundwater storage does not change crop mix or conjunctive use operation decisions (i.e., all decision variables are the same). However, when ΔGW = 0, second stage decisions change (Table 2.5). When there is no net change in groundwater storage (ΔGW = 0), higher initial groundwater storage will result in more groundwater pumped because of lower pumping cost to support more annual crops in drier events (event 1 to 3), causing less annual crop acreage and additional cost of using land for artificial recharge in wettest event (event 5). Even though these different decisions only change profit by $2.4M over a 10-year horizon, very little compared to the total profit, this comparison shows the unit pumping costs matter, as lower unit pumping costs encourage both pumping and wet-event recharge.

Table 2.5. Comparison of annual crop and conjunctive water use decisions under different initial groundwater storage when no net change in groundwater storage (ΔGW = 0)

Event j	X_a (Acre)		X_r (Acre)		W_p (AF/year)	
	GW_{t-1}=10 (MAF)	GW_{t-1}=15 (MAF)	GW_{t-1}=10 (MAF)	GW_{t-1}=15 (MAF)	GW_{t-1}=10 (MAF)	GW_{t-1}=15 (MAF)
1	11,294	20,198	0	0	314,971	358,065
2	11,294	20,198	0	0	176,251	219,346
3	11,294	20,198	0	0	36,992	80,087
4	42,772	42,772	0	0	0	0
5	125,346	98,634	0	8,619	0	0

3.2.3 Comparison for Different Incoming Perennial Acreage (125,000, 62,500, and 250,000 Acres)

Figure 2.7 illustrates the influence of the incoming perennial crop (50% have already been retired), where 62,500 acres, 125,000 acres, and 250,000 acres of perennial crop are in yellow, green and blue respectively.

When the restoring goal is demanding (ΔGW ≥ 4 MAF), after surface water is allocated to artificial recharge, the remaining surface water can only support few acres of perennial crop, less than 62,500 acres. So, these cases end in the same perennial crop acreages and the same value of profit.

When ΔGW = 3 MAF, perennial cropping for all cases exceed 62,500 acres. In the yellow case ($X_{p,t-1}$ = 62,500), new perennial crops are planted, and initial establishment cost reduces total profit from the other two cases. When ΔGW = 2 MAF, the yellow case ends in fewer perennial crops than the other two cases due to the high perennial crop initial establishment cost. In the other two cases, no new perennial crop is planted and they have the same total profit.

When ΔGW is between 1 MAF (restoring 1 MAF) and -1 MAF (net pumping 1 MAF), the yellow case plants more perennial crops, but still less than 125,000 acres. The high initial establishment cost for perennial crop makes the big difference in the profit of the yellow case and other two cases, it also prevents the green case ($X_{p,t-1}$ = 125,000) from planting new perennial crops. On the other hand, the high profit of perennial crop forces the blue case ($X_{p,t-1}$ = 250,000) to maintain the perennial crops as many as possible, so no annual crop is planted, and the difference in total profit with other two cases' profits is increasing with the increasing in net pumping.

When net pumping exceeds 2 MAF (ΔGW ≤ - 2 MAF), the green case plants new perennial crop and has the same acreage as the yellow case. However, in yellow case, because much more new perennial crops are planted with high initial establishment cost, the total profit of yellow case is much less than that of green case. Both in the yellow and green cases, high initial establishment cost plus the increasing pumping cost decrease total profit as the net pumping goal increases. However, in the blue case, new perennial crop is never planted, the high profit of perennial crop makes the greatest profit when net pumping is 5 MAF.

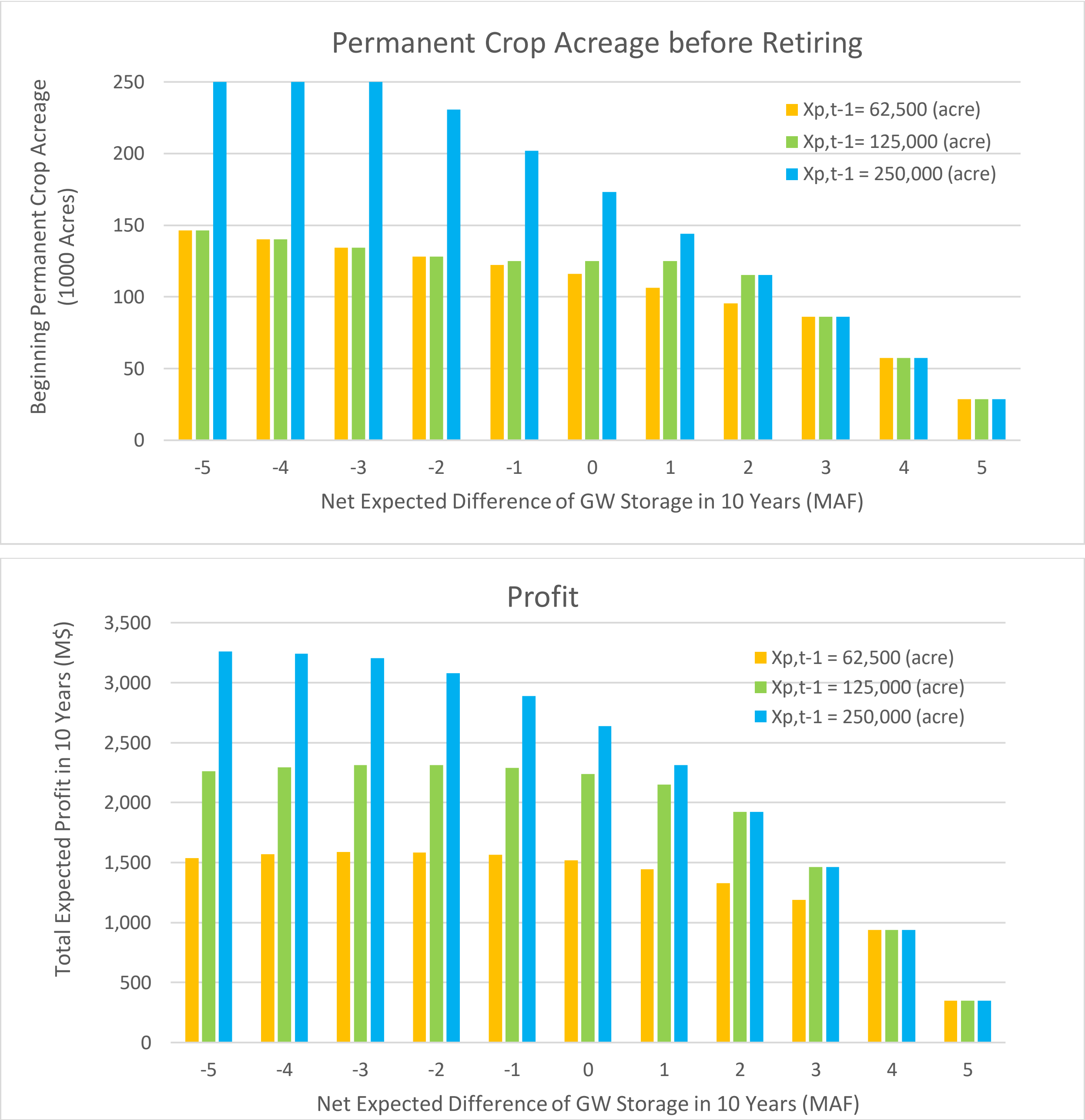

Figure 2.7. Perennial crop acreage before retiring and profit in current planning horizon for different initial perennial crop acreage and groundwater storage changes

Figure 2.8 shows the overall optimal decision when the incoming perennial crop acreage is 62,500 acres. Comparing with Figure 2.5, two cases have the same decisions on crop mix and conjunctive water use when $\Delta GW \geq 3$ MAF and $\Delta GW \leq -2$ MAF. When $\Delta GW = 1$ or 2 MAF, green case ($X_{p,t-1}$ = 125,000) plant less annual crop than yellow case ($X_{p,t-1}$ = 62,500). Because of the high initial establishment cost for perennial crops, it is more profitable in the yellow case to use some water for annual crops rather than planting too many perennial crops. While in the green case, perennial crops are maximally maintained due to their higher profitability. The difference in crop mix decision also brings different conjunctive water use operations. In Figure 2.8, yellow case tends to pump less water in the drier events as there are fewer perennial crops to irrigate, so in wetter events, less land is used for artificial recharge. This is another reason the yellow case makes such a decision that has less water operation cost. When ΔGW = 0 or -1 MAF, the pumping decisions for both cases are the same. The only difference is how these two cases allocate irrigation water to different crops.

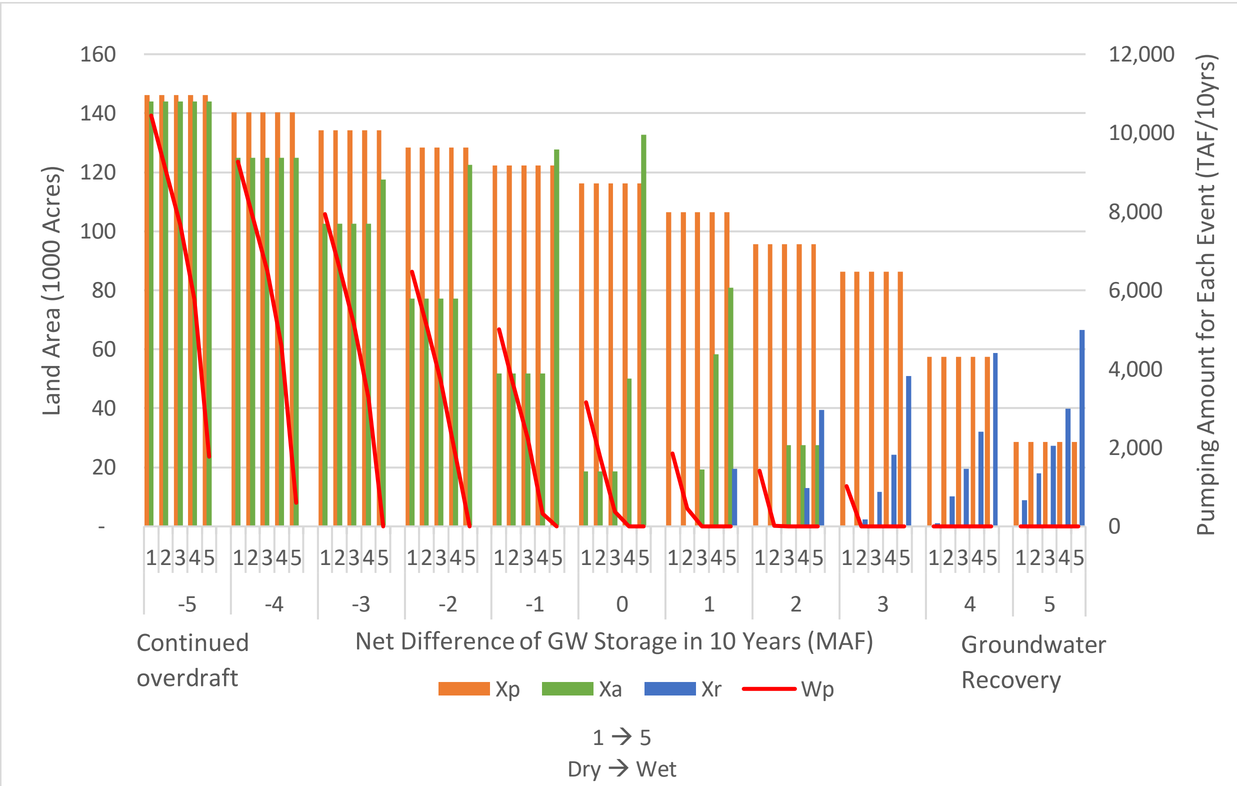

Figure 2.8. Crop mix and conjunctive use in different goals and events, $X_{p,t-1}$ = 62,500 acres

Figure 2.9 shows the overall optimal decision when the incoming perennial crop acreage is 250,000 acres. When ΔGW ≥ 2 MAF, because of limited available irrigation water, blue case ($X_{p,t-1}$ = 250,000) has the same decision as green case ($X_{p,t-1}$ = 125,000). When ΔGW is between 1 to -2 MAF, because of high initial establishment cost for perennial crop, in Figure 2.5, the acreage of perennial crop only increases a little when net pumping can be 2 MAF. While due to high profit of the perennial crop, in Figure 2.9, the acreage of perennial crop is maximally maintained with no annual crop planted. Even for the net pumping goals, artificial recharge occurs in the wettest event to support more groundwater pumping in the drier events. When ΔGW ≤ -3 MAF (net pumping of 3 MAF), the irrigation water can finally support all the incoming perennial crops, and annual crops start to be planted. Again, the pumping decision for the blue case is exactly the same as the other two cases when we can pump much groundwater. All three cases only differ in crop mix.

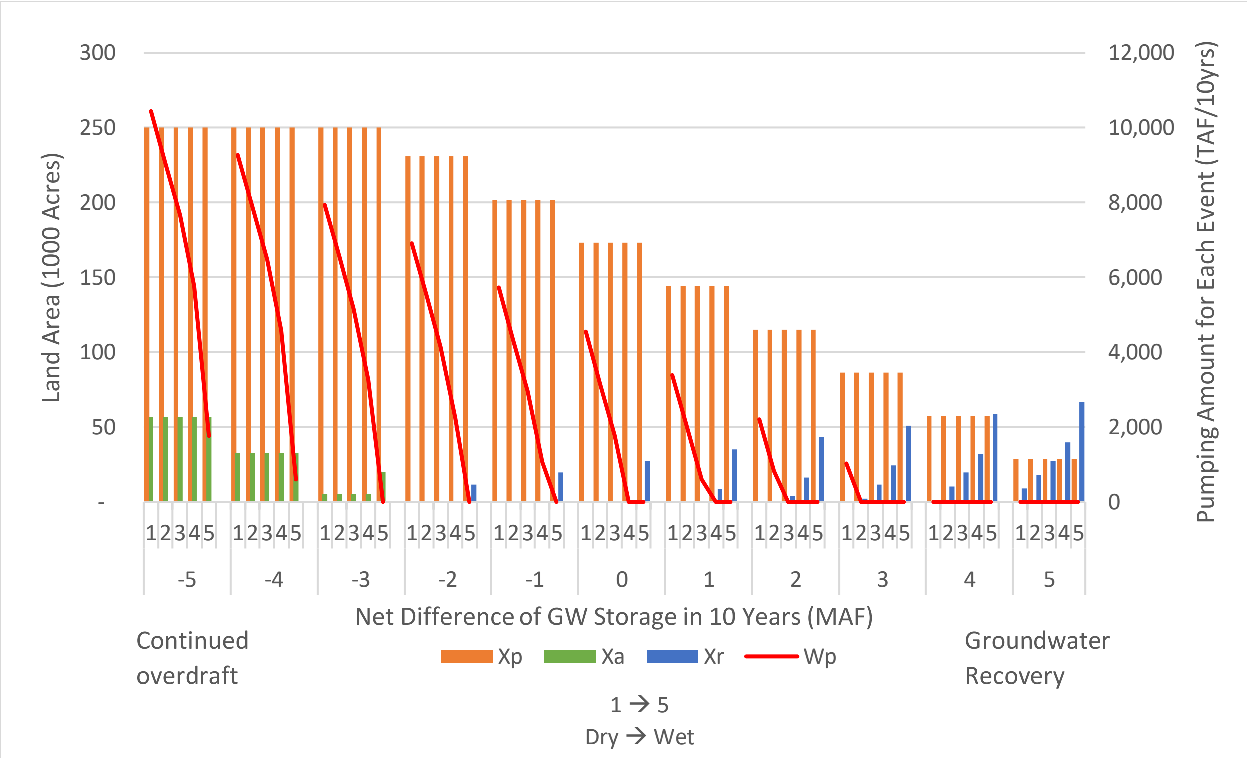

Figure 2.9. Crop mix and conjunctive use in different goals and events, $X_{p,t-1}$ = 250,000 acres

3.3 Sensitivity Analysis

Here we change some parameters to see if this model is sensitive, and results behave normally. The base case has boundary conditions of initial groundwater storage being 10 MAF and incoming perennial crop at 125,000 acres.

3.3.1 Lagrange Multipliers

From Equation (2.5) to (2.7), there are 11 Lagrange multipliers, five for the land constraint (one for each hydrologic event), five for the surface water constraint (one for each hydrologic event), and one for the stochastic conservation of mass for groundwater storage. Because the land is never entirely used in any event for any pumping/restoring goal, the land constraint never binds so its Lagrange multiplier is 0 and we need not discuss these five Lagrange multipliers. Table 2.6 summarizes the trend in water-related Lagrange multipliers. Because in the objective function we are trying to minimize the negative value of the profit, positive Lagrange multiplier values mean if we reduce one unit of water, we lose some profit. However, negative value Lagrange multipliers mean that using one less unit of water increases profit. Cells shaded blue are where artificial recharge occurs; cells shaded orange are where pumping occurs; and cells in bold and italic means annual crops are planted in the second stage.

In Table 2.6 for surface water, first, by column, as ΔGW goes from very negative to very positive, the value of Lagrange multiplier for each hydrologic event gradually increases for each event. By row, the values of Lagrange multipliers of drier events are always the greater or equal to those for wetter events. These two findings show growing water scarcity. For example, when ΔGW = 1 MAF, event 1 and 2 have greater Lagrange multipliers because if we use one unit less of the surface water, we sacrifice perennial crop; event 3 has a smaller Lagrange multiplier because annual crop with less profit is the first to be fallowed; event 4 and 5 have even smaller Lagrange multipliers because the surface water also supplies the artificial recharge, and one less unit of surface water may also mean less cost for artificial recharge.

Both pumping and artificial recharge dampen variability in incoming surface water, often ending in the same value of Lagrange multipliers and acreage of annual crops (Section 3.2.1). This finding agrees with our expectation of conjunctive water operation that pumping groundwater to plant the same acreage of crops as usual, supplied by artificial recharge in wetter years.

Table 2.6. Summary of Lagrange multipliers in different events in different goals ($/AF). Orange shade means pumping occurs. Blue shade means artificial recharge. Bold and italic value means annual crops are planted

ΔGW (MAF)	Constraints					
	Dry	Surface Water			Wet	Groundwater
	Event 1	Event 2	Event 3	Event 4	Event 5	
-5	***60***	***60***	***60***	***60***	***60***	-28
-4	***84***	***84***	***84***	***84***	***84***	-13
-3	***111***	***111***	***111***	***111***	***96***	3
-2	***142***	***142***	***142***	***142***	***96***	20
-1	***176***	***176***	***176***	***176***	***99***	40
0	***222***	***222***	***222***	***190***	***107***	65
1	333	333	***247***	***212***	***212***	123
2	936	936	820	820	820	427
3	1,071	959	959	959	959	496
4	1,096	1,096	1,096	1,096	1,096	565
5	1,206	1,206	1,206	1,206	1,206	620

For the Lagrange multiplier for groundwater mass balance constraint, everything is as expected. When ΔGW is most positive, each unit of groundwater has a great scarcity cost and a large Lagrange multiplier. For milder goals, the value goes down gradually. For net pumping the groundwater, the increasing pumping cost from the increasing pumping goal even makes the Lagrange multiplier negative when ΔGW ≤ -3 MAF, confirming that the total profit is highest when ΔGW = - 3 MAF, as it has the last positive groundwater Lagrange multiplier. Lagrange multipliers for groundwater are always smaller than the Lagrange multipliers for surface water, because: (a) one less unit of groundwater can mean one less unit of water available for irrigation, or more crops planted adding profit that result in one more unit of deep percolation; and (b), one less unit of groundwater being used can reduce pumping cost.

When ΔGW is between -1 MAF and 1 MAF, the Lagrange multipliers from Excel solver may not always be stable. For other pumping/restoring goals, the goal is demanding and clear enough to force the model to reach the global optima with reasonable Lagrange multipliers, while a goal with only a change of 1 MAF is too mild with many local optima and near-optima, so the result depends on the initial solution. The value in Table 2.6 is from a very good initial solution based on our conclusion in Section 3.2.1.

3.3.2 Discount Rate Effects (r = 3.5%, 5%, and 2%)

When recovering groundwater storage, different discount rates affect profit, with no effect on planting decisions and conjunctive operations. This is because for recovery goals, maximizing the acreage of perennial crop is the only method to increase profit, but the incoming surface water can barely support the base incoming acreage of perennial crop ($X_{p,t-1}$ = 125,000). So, no new perennial crop is planted regardless of discount rate.

However, if we can lower groundwater (net pumping) over 10 years, the discount rate affects decisions. Higher discount rates lead to less perennial crop (Figure 2.10) and more annual crop, with no difference in pumping. Given the same amount of irrigation water, more annual crops with lower profit rather than more profitable perennial crops are planted when the discount rate is higher, because higher discount rate reduces the difference between benefit of perennial crop yield and initial establishment cost.

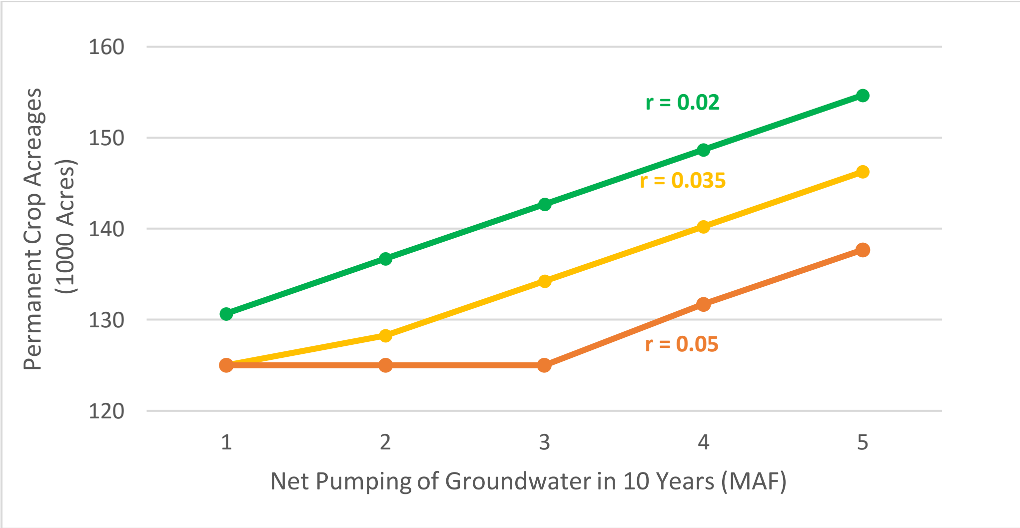

Figure 2.10. Different perennial crop decisions under different discount rate

3.3.3 Initial Establishment Cost for Perennial Crop (ini_p = \$10,000/acre, \$12,000/acre, or \$14,000/acre)

Here, we explore how the initial establishment cost affects perennial crop decisions. We are not interested in net profit as lower initial establishment cost always increases profit. Figure 2.11 compares perennial crop decisions for different initial establishment costs and different ΔGW. When ΔGW ≥ 2 MAF, after the surface water is allocated to artificial recharge, the remaining can only support the perennial crop acreage less than the incoming acreage of perennial crop, which is 125,000 acres. For lower ΔGW values, lower initial establishment cost increases perennial crop acreage. Also, Figure 2.11 shows this model is very sensitive to initial establishment cost. For the blue case (ini_p = \$10,000/acre), the incoming acreage of perennial crop is not a barrier as we start to plant new perennial crop when ΔGW = 1 MAF (though only 400 acres are planted), and we plant more perennial crops as net pumping increases. However, for the yellow case (ini_p = \$14,000/acre), the incoming acreage of perennial crop is always a barrier that new perennial crop is never planted no matter how much groundwater is available.

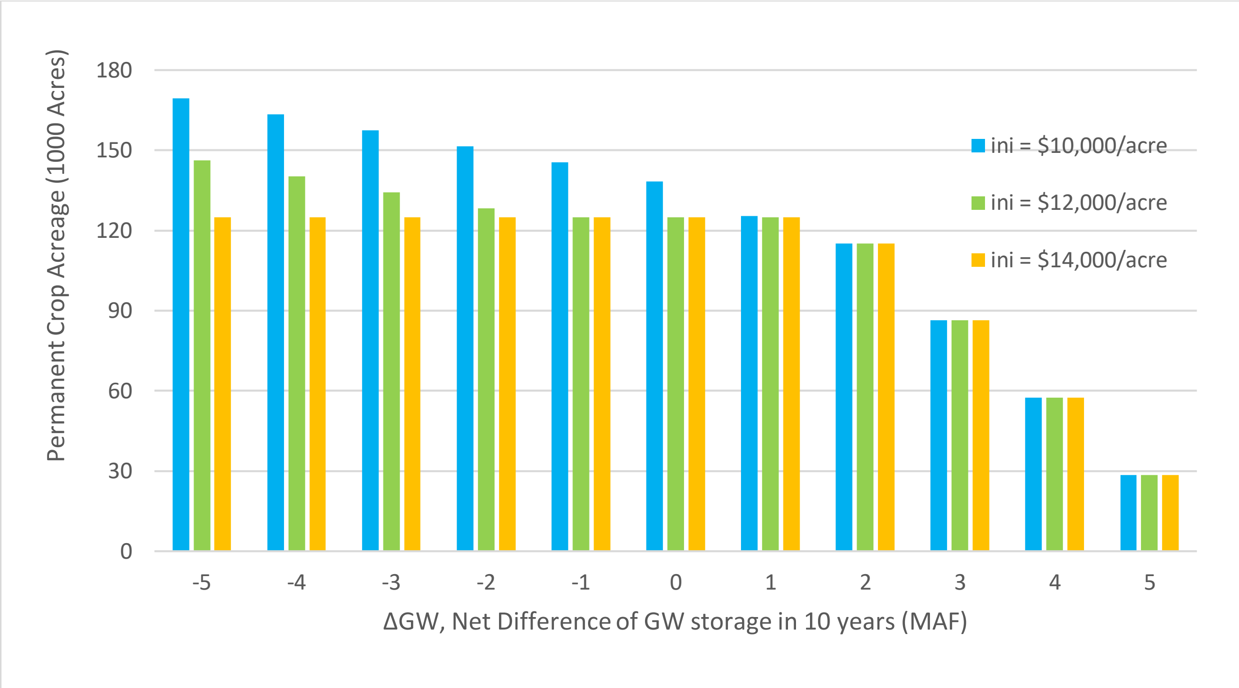

Figure 2.11. Different perennial crop decision under different pumping goals and different initial establishment cost

The initial establishment cost for perennial crop does not affect water operation decisions. As already seen in Section 3.2.2, 3.2.3, and 3.3.2, the optimal conjunctive use is relatively stable to the change in initial groundwater storage, incoming perennial crop acreage, discount rate, and initial establishment cost for perennial crop. This is probably due to the constraint of conservation of groundwater storage and the need to equalize the Lagrange multipliers to get the optimal objective value.

In this model, we first find out if it is clear enough to plant new perennial crops and if the pumping/restoring goal is demanding or not. If so, we then determine the optimal conjunctive use and allocate irrigation water to perennial and annual crops for each event. If not, for example: we can plant new perennial crop, but we finally decide not to do so because of the high initial establishment cost, then fix the perennial crop acreage to be the same as the incoming acreage, and finally decide the corresponding conjunctive operation.

3.3.4 Probabilities of Hydrologic Events

The last sensitivity analysis changes the probability of some hydrologic events to create drier and wetter scenarios. Table 2.7 summarizes the probability distribution of each event in each scenario.

Figure 2.12 illustrates the differences among scenarios. In the wetter scenario with more surface water, the most perennial and annual crops are planted for any pumping/restoring goals and in any hydrologic event. The expected net profit in the wetter scenario also is the highest for almost all the groundwater storage goals, except for net pump 5 MAF of groundwater. Also, the optimal groundwater storage change for the wetter scenario is at a net pumping of 2 MAF; while for other two scenarios, a net pumping of 3 MAF is the best. These two findings are reasonable because pumping more water is counterproductive in the wetter scenario.

Table 2.7. Hydrologic event probabilities in each climate

Event *j*		Drier	Normal	Wetter
Dry	1	0.25	0.2	0.15
	2	0.25	0.2	0.2
	3	0.2	0.2	0.2
	4	0.2	0.2	0.25
Wet	5	0.1	0.2	0.2
Expected incoming surface water (TAF/yr)		519 (-13%)	599	622 (+3.8%)

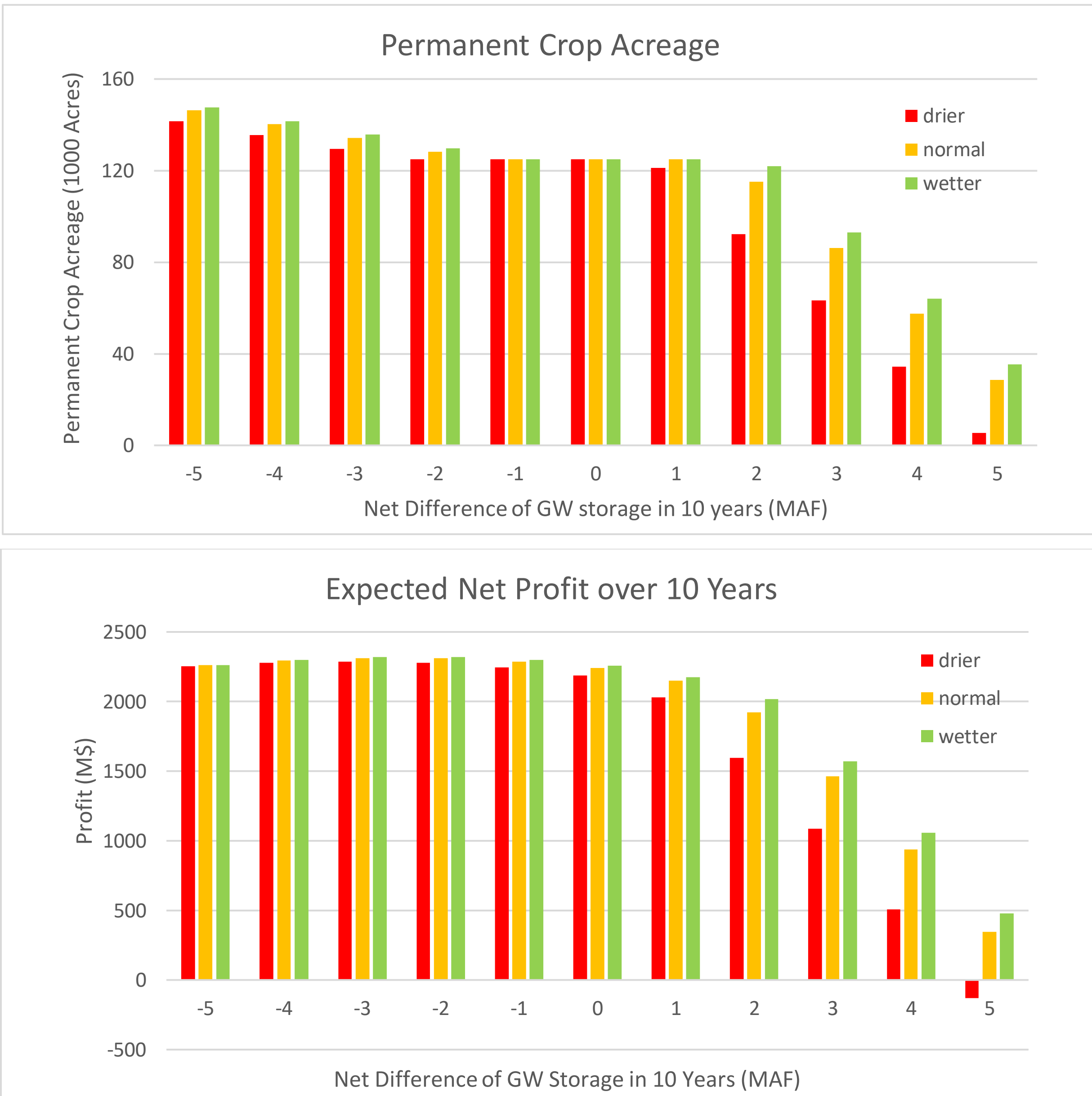

Figure 2.12. Perennial crop decisions and expected net profit under different scenarios

When groundwater is being drawn down ($\Delta GW < 0$), the drier climate has a small effect on crop decisions and nearly no effect on profit, since the pumped groundwater can offset the lack of surface water. However, the drier scenario greatly affects crop decisions and profit when we have a sizable restoring goal ($\Delta GW \geq 2$ MAF). Because expected surface water is less, (a), it becomes dangerous to maintain extensive perennial crops; and (b), less perennial crop means less deep percolation from surface water in wetter events, resulting in more surface water use for artificial recharge. With less profit from the perennial crop and higher cost for increasing artificial recharge, there are significant differences in perennial crop acreage and profit between the drier and the other two scenarios. Negative profit occurs in the drier scenario when we seek to restore 5 MAF over the 10-year horizon.

3.4 Limitations

The model has several limitations. These limitations are areas for future model improvement and development. First, this model simplifies agriculture and considers only one perennial crop and one annual crop with fixed crop parameters. (i) Fluctuation in crop prices can cause crop acreage changes in the long run. (ii) Crop yields are fixed with no stress irrigation considered, so perennial crop yields may be overestimated. (iii) Climate uncertainty is not considered in this model, which makes this model neglects varying ET when calculating applied water needs. (iv) Retirement of perennial crops at the end of planning horizon is too optimistic and does not completely represent the real farming process.

This model also simplifies the water operations. (i) No urban water use and water transfers are considered. (ii) This model assumes probabilities of water deliveries are known in advance. (iii) Water quality problems such as salinity are omitted from this model, which could reduce crop yields. (iv) Irrigation efficiency is constant in this study, meaning different types of irrigation methods not considered.

As a two-stage stochastic model, this model does not track groundwater storage explicitly. The constraint on groundwater storage is a stochastic conservation of mass. Also, there is no sequential timing of hydrologic events, making the annual crop acreage decisions and the corresponding conjunctive operations for each event have no direct meaning. This model also assumes surface water deliveries are known in advance. Nevertheless, solutions of this model still give useful insights.

Conclusions

By giving different boundary conditions (initial and final groundwater storage and incoming perennial crop acreage), the proposed model can help guide an agricultural planning on crop decisions and water operations over an intermediate period with varying pumping cost. This intermediate model (or its results) can then be placed in a longer-term dynamic programming model, as done in later chapters. Several conclusions arise from work in this chapter.

1. Pumping unlimited groundwater may not provide the highest profit. However, increasing groundwater storage with a demanding groundwater recovery goal is always the least profitable in the short term.
2. For steady groundwater storage boundary conditions (no overdraft or drawdown), deep percolation of crops is enough to support pumping in the driest event. However, restoring groundwater often makes artificial recharge valuable.

3. When increasing groundwater storage, maximizing perennial crops is economically best. If incoming perennial crop acreage is big, more artificial recharge is used to support groundwater pumping in drier events. If incoming perennial crop acreage is small, new perennial crop should be planted, limited by initial establishment cost.
4. Initial groundwater storage and unit pumping cost matter. Lower unit pumping cost under higher initial groundwater storage encourages both pumping and wet-event recharge to support more annual crop without affecting perennial crop acreage.
5. It is economically wise to first determine if the perennial crop acreage should change according to the groundwater storage change and climate which results in different amount of surface water. Then the conjunctive water use management rule is set up. Finally, the crop mix is determined given the available irrigation water for each hydrologic event.
6. Economic factors such as discount rate and initial establishment cost for perennial crop are not major factors determining the conjunctive water use management, but are major factors for crop mix decisions.

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Chapter 3: Conjunctive Water Use with Groundwater Salinity: Insights from Two-Stage Stochastic Quadratic Optimization

Abstract

Allocating water to crops and aquifer recharge is of growing importance in irrigation-dependent regions with hydrologic variability and groundwater storage, such as California. This problem can change dramatically when salts accumulate in a region's groundwater. Uncontrolled pumping of groundwater with high salinity reduces crop yield and revenues. This chapter examines the trade-off between crop profits and groundwater storage for different groundwater salinities. A two-stage stochastic quadratic model suggests optimal crop mix and conjunctive water use decisions with a stochastic surface water supply to maximize net expected benefits of crop production and conjunctive use, given groundwater storage change targets. Perennial crop planting decisions are made in the first stage and decisions on annual crop planting, water pumping, and land and water for recharging are made in the second stage with probabilities of surface water availability events. With groundwater salinity, perennial crop profit becomes probabilistic as its yield depends on the salinity of irrigation water composed of groundwater and available surface water in each hydrologic event. Furthermore, salinity's long-lasting harm to perennial crops in drought shifts groundwater pumping to wetter events, when more dilution of salts becomes possible. For different boundary conditions (initial and finial groundwater storage, incoming perennial crops from previous stage, and groundwater salinity), this model represent farmers' perennial and annual crop decision and conjunctive water operations with varying pumping cost. Results indicate that pumping groundwater primarily in the driest years will not provide the highest profit due to groundwater salinity reducing crop yield. When groundwater salinity is extremely high, recharging the aquifer and lowering the salinity in an unconfined aquifer can be more profitable than dumping irrigation water away only to achieve no-overdraft goal. Groundwater salinity can fundamentally alter patterns of optimal conjunctive use, and profoundly reduce long-term agricultural productivity.

Keywords: Two-stage quadratic programming, Groundwater salinity, Conjunctive operations, Artificial recharge, Perennial crops

1. Introduction

Irrigating with saline water can lead to soil salinization, reduce soil productivity and ultimately make soil unsuitable for farming, as salt in soil increases the osmotic potential, resisting the movement of water toward crop roots (Ayers and Westcott 1985). This forces crops to expend energy extracting fresh water which could have been used to grow, and decreases crop yields and profits (Allen et al. 1997).

Irrigation drainage can also make poorly drained aquifers more saline, especially in (semi)-arid areas. With higher evapotranspiration rates and lower precipitation, more irrigation water is applied to leach salts from soil, often becoming more saline groundwater recharge. The underlying aquifers with rising water-tables and water logging can both increase soil salinity through capillary action (Suarez 1989; Tanji and Kielen 2002; McMahon et al. 2006; Scanlon et al. 2007 and 2009; Pulido-Bosch 2017) and aquifer salinity (Milnes and Renard 2004). Furthermore, less precipitation and available surface water tends to increase groundwater pumping, which draws saline water deeper into the aquifer (Morris et al. 2003; Barlow and Reichard 2010; Shi and Jiao 2014).

Salinity-driven reductions in agricultural production are greater with overdrafted aquifers, as in California’s central and southern valleys (Medellin-Azuara et al. 2008, Schoups et al. 2010). In those basins, groundwater is first pumped for irrigation and combined with surface water containing natural salts. Crops extract the water but leave salts in root zone. But in many areas those salts deep percolate to groundwater. In every pumping-and-recharge cycle, the aquifer gains new salts from surface water and mobilization of salt from soils. Salinity in the San Joaquin Valley adversely affects almost 1.5 million acres of agricultural land (Great Valley Center 2005). Roughly 250,000 acres of cropland have already been retired (Hanak et al. 2019). Farmers in the Kern County, Tulare basin are experiencing $370M/year economic loss from high salinity (MacEwan et al. 2016).

Conjunctive use allows some utilization of more saline groundwater for irrigation by blending with fresher surface water (Rhoades 1987; Sharma and Rao 1998; Datta and Jong 2002; Yadav et al. 2004; Kaur et al. 2007). Research has been done on irrigation management to maximize crop production primarily for food security with wheat and maize rather than maximizing profits (Sharma et al. 1993; Oster and Grattan 2002; Mandare et al. 2008; Malash et al. 2008; Kan and Rapaport-Rom 2012; Rasouli et al. 2013; Al Khamisi et al. 2013; Ortega-Reig et al 2014). Conjunctive use with poor-quality water can have benefits from increasing agricultural production and productivity by maintaining root zone leaching, reducing salt export to prevent groundwater degradation, and controlling root zone waterlogging. However, these require careful management of agricultural drainage, or salinity accumulates in groundwater.

When modeling conjunctive use considering salinity, linear programming (LP) optimization has been used extensively (Tyagi and Narayana 1981 and 1984; Tyagi 1988; Schoups et al. 2006). These models compare various combinations of different water sources and select an optimal combination based on: maximum profit, least cost, minimum conveyance, acceptable water quality or resource conservation (Duckstein and Kisiel 1968; Maknoon and Burges 1978; Lingen and Buras 1987; O’Mara 1988; Vincent and Dempsey 1991; Peralta et al. 1995; Philbrick and Kitanidis 1998).

However, LP models may produce many equally optimal solutions (Singh 2014), and have difficulty representing real diminishing economic returns for the initially most profitable crops

(Hazell and Norton 1986; Howitt 1995). Nonlinear programming models have been formulated for conjunctive use planning through blending poor-quality groundwater and good quality surface water, which is less realistic than cycling irrigation water with different salinities (Khan 1982; Gupta et al., 1987). Moreover, annual crops (such as maize and wheat) are mostly considered in previous research, because conjunctive use in areas with poor-quality groundwater mainly aims to maximize food security. Nonetheless, salinity is seldom considered as a major factor by guaranteeing leaching with additional surface water in both short-term non-linear programming and long-term dynamic programming.

This chapter uses a two-stage stochastic quadratic optimization model for conjunctive water use operations with groundwater salinity. Perennial crop acreage is a first stage decision. Annual crop acreage, groundwater pumping and recharging are decided in the second stage with probabilities of different hydrologic events. Salinity affects the crops yield by salt concentration in irrigation water. For different boundary conditions (initial and final groundwater storage, incoming perennial crop acreage from previous stage, and initial salt concentration of groundwater aquifer), this model can present profit-maximizing farmers' conjunctive water operations. Though only two crops and blended water supplies are considered, this model provides a 10-year intermediate planning horizon of crop mix decisions and conjunctive water use operations with salinity and depth-varying pumping costs.

2. Method

2.1 Model Formulation

Figure 3.1 shows the model's structure. Perennial crop decisions are made in the first stage. Annual crop decisions, groundwater pumping, and land for artificial recharge are modeled in the second stage for a set of possible hydrologic events, each with an amount of surface water available sw_j and probability of occurrence p_j. Table 3.1 describes the notation of input parameters. For simplicity, we assume 50% of perennial crops are retired at the end of a T-year planning horizon. We also assume deep percolation from irrigation water and groundwater in aquifer are perfectly mixed during the planning horizon.

The planning horizon T is 10 years. The objective function (Equation (3.1a)) includes the expected net benefit of a perennial crop over 10 years, $B1$, and perennial crop establishment cost, $INIP$, in the first stage. In the second stage, each year is a realization of possible hydrologic events j assembled with probabilities of occurrence p_j and amounts of surface water available sw_j. Each possible event j has its net annual crop production benefits and water-related costs. $B2$ and $EXPC$ are the summation of T years' net expected annual crop profit and water-related costs, respectively.

$$\min Z = -(B1 - INIP + B2 - EXPC) \tag{3.1a}$$

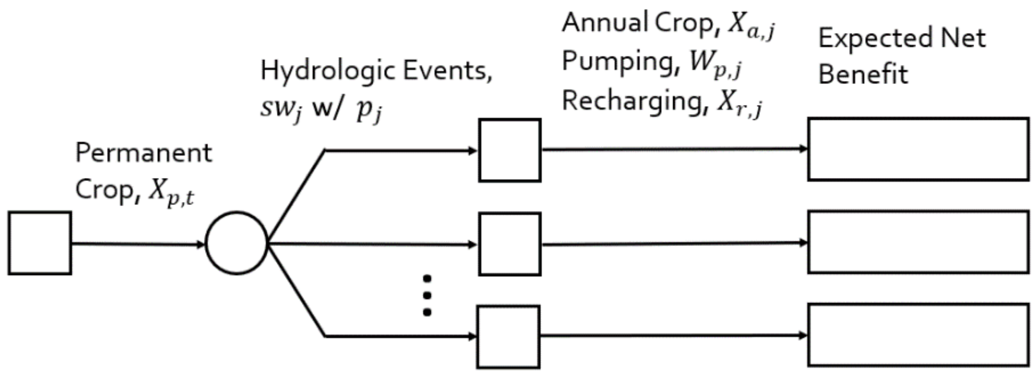


Figure 3.1. Problem decision tree

If we do not consider salinity, $B1$ is deterministic because the full yield is assumed to be achieved in all events. In this chapter, salinity makes $B1$ probabilistic, because the salt concentration in irrigation water, affecting perennial crop's yield, changes with amount of pumping $W_{p,j}$ and surface water sw_j in each hydrologic event j with its probability of occurring. In this model, we completely mix the surface water (minus any artificial recharge) and groundwater for irrigation. Thus, the salt concentration of irrigation for event j, $C_{irr,j}$, is a weighted average of surface water salinity, C_{sw}, and initial groundwater salinity, $C_{gw,t-1}$.

$$C_{irr,j} = \frac{C_{sw} \times (sw_j - cap \times X_{r,j}) + C_{gw,t-1} \times W_{p,j}}{sw_j - cap \times X_{r,j} + W_{p,j}} \tag{3.2}$$

The electrical conductivity (EC) of irrigation water for event j, $EC_{irr,j}$ can be derived from concentration $C_{irr,j}$ (Grattan 2002):

$$EC_{irr,j} = \begin{cases} \frac{C_{irr,j}}{640} & C_{irr,j} < 3{,}200 \\ 5 & 3{,}200 \geq C_{irr,j} < 4{,}000 \\ \frac{C_{irr,j}}{800} & C_{irr,j} \geq 4{,}000 \end{cases} \tag{3.3}$$

The salt stress coefficient of crop i ($i = p$ for perennial crop, a for annual crop) for event j, $K_{s-salt,i,j}$, is equal to 1 if $EC_{irr,j}$ is less than the threshold EC crop i, $EC_{t,i}$ (Figure 3.2), exceeding which will cause yield decrease. Otherwise,

$$K_{s-salt,i,j} = \begin{cases} 1, & EC_{irr,j} < EC_{t,i} \\ 1 - \frac{b_i}{K_{y,i}}(EC_{irr,j} - EC_{t,i}), & EC_{irr,j} \geq EC_{t,i} \end{cases} \quad for\ i = p, a \tag{3.4}$$

where $\frac{b_i}{K_{y,i}}$ is the decrease of yield of crop i per increment of EC of the irrigation water (Figure 3.2), and $K_{y,i}$ is the crop i's sensitivity to water stress (Allen et al. 1997). Unfortunately, there is no K_y value for almonds in FAO Irrigation and Drainage Paper No. 33. We assign a relatively high value (1.2) to $K_{y,p}$, meaning the perennial crop is sensitive to water stress.

Table 3.1. Input parameters

Symbol	Parameter (unit)	Value
C_{sw}	Salinity of surface water (mg/L)	400
$K_{y,p}$	Perennial crop sensitivity to water stress	1.2
$K_{y,a}$	Annual crop sensitivity to water stress	1.1
$EC_{t,p}$	Threshold EC with no perennial crop yield decrease (dS/m)	1.5
$EC_{t,a}$	Threshold EC with no annual crop yield decrease (dS/m)	2.0
b_p	Perennial crop yield decrease per increment of EC (%)	19
b_a	Annual crop yield decrease per increment of EC (%)	7.3
T	Length of planning horizon (yr)	10
L	Total available area (acre)	500,000
H_o	Initial pump head (ft)	200
B_o	Initial thickness of the aquifer (ft)	200
s_y	Aquifer specific yield	0.1
r	Constant discount rate	0.035
ini_p	Perennial crop initial establishment cost ($/acre)	12,000
c_{land}	Unit price of land for recharging ($/acre)	300
c_{class1}	Unit price of class 1 (firm contract) water ($/AF)	42
c_{class2}	Unit price of class 2 (surplus) water ($/AF)	30
$class1$	Amount of firm contract water (TAF)	500
c_e	Unit price of energy ($/kWh)	0.189
η_p	Pumping efficiency	0.7
cap	Capacity of land for recharging (AF/acre/yr)	15
$1-\varphi$	Irrigation efficiency	0.85
t	Current planning horizon	0
aw_p	Applied Water of perennial crop (ft)	4.07
aw_a	Applied Water of annual crop (ft)	4.84
yld_p	Maximum yield of perennial crop (ton/acre)	1
yld_a	Maximum yield of annual crop (ton/acre)	8
v_p	Unit price of perennial crop ($/ton)	4226.68
α_p	Perennial crop’s intercept of PMP cost function ($/acre)	1502.85
γ_p	Perennial crop’s slope of PMP cost function ($/acre^2)	0.00795
v_a	Unit price of annual crop ($/ton)	157.28
α_a	Annual crop’s intercept of PMP cost function ($/acre)	635.91
γ_a	Annual crop’s slope of PMP cost function ($/acre^2)	0.00294

The combined salt and water stress coefficient of crop i for event j, $K_{s,i,j}$, is the product of salt stress coefficient and water stress coefficient. Because stress irrigation is not considered in this study, $K_{s-water} = 1$.

$$K_{s,i,j} = \left(K_{s-salt,i,j}\right) \times \left(K_{s-water}\right) = K_{s-salt,i,j} \quad for\ i = p, a \tag{3.5}$$

The relationship between yield decrease of crop i and combined stress for event j is:

$$1 - \frac{Y_{i,j}}{Y_{max,i}} = K_{y,i}\left(1 - K_{s,i,j}\right) \quad for\ i = p, a \tag{3.6}$$

Rearranging Equation (3.6), we can solve for actual yield of crop i for event j, $Y_{i,j}$:

$$Y_{i,j} = \left(1 - K_{y,i}\left(1 - K_{s,i,j}\right)\right) Y_{max,i} \quad for\ i = p, a \tag{3.7}$$

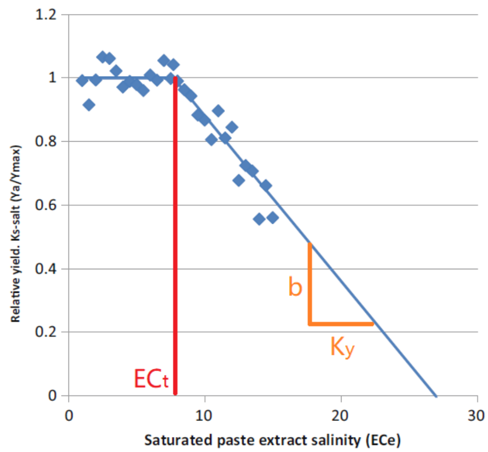


Figure 3.2. Graphical representation of Equation (3.4) (Allen et al. 1997)

For perennial and crop, $Y_{max,i}$ in Equation (3.7) is yld_p and yld_a, respectively. Similarly, $Y_{i,j}$ is represented by $Y_{p,j}$ and $Y_{a,j}$.

$$Y_{p,j} = \left(1 - K_{y,p}\left(1 - K_{s,p,j}\right)\right) yld_p \tag{3.7a}$$

$$Y_{a,j} = \left(1 - K_{y,a}\left(1 - K_{s,a,j}\right)\right) yld_a \tag{3.7b}$$

Here, the yield of perennial crop, $Y_{p,j}$, depends on the hydrologic event because the blended irrigation water salinity varies across events. We also consider the influence of drought (event 1) to represent a lagging effect of salinity in the root zone: If current year k is event 1 (driest event), the yield for this year is $Y_{p,1}$. In year k+1, no matter which hydrologic event it is, perennial crop yield is reduced by the high salinity of irrigation in the previous year, such that there is a 50% of chance the yield is still $Y_{p,1}$ (the lowest yield), and 50% of chance the yield is $Y_{p,2}$ (the second lowest yield). On the other hand, if in current year k, we are not in event 1, the yield of perennial crop in year $k + 1$ is independent of the hydrologic event in year k, thus being the same probability of the occurrence of each hydrologic event p_j (Table 3.2). So, perennial crop yield can be represented by a Markov chain. Take the normal climate scenario for example ($p_j = 0.2, \forall j$), Table 3.2 is the transition matrix in normal climate scenario.

Table 3.2. Probability transition matrix of $Y_{p,j}$ under base climate scenario

$j_k \backslash j_{k+1}$	1	2	3	4	5
1	0.5	0.5	0	0	0
2	0.2	0.2	0.2	0.2	0.2
3	0.2	0.2	0.2	0.2	0.2
4	0.2	0.2	0.2	0.2	0.2
5	0.2	0.2	0.2	0.2	0.2

With a transition matrix in Table 3.2, we can derive the probability of $Y_{p,j}$ for year k, $P_{k,j}$, as Table 3.3. Ever since year 2, $Y_{p,j}$ has a higher probability to be $Y_{p,1}$ or $Y_{p,2}$ because of the toxic effect of salinity on the yield. Also, due to the independence between year k and year $k+1$, the probability of $Y_{p,3}$, $Y_{p,4}$, and $Y_{p,5}$ are the same for each year k under normal climate scenario.

Table 3.3. Probability of $Y_{p,j}$ in year k, $P_{k,j}$ under base climate scenario

$k \backslash j$	1	2	3	4	5
1	0.200	0.200	0.200	0.200	0.200
2	0.260	0.260	0.160	0.160	0.160
3	0.278	0.278	0.148	0.148	0.148
4	0.283	0.283	0.144	0.144	0.144
5	0.285	0.285	0.143	0.143	0.143
6	0.286	0.286	0.143	0.143	0.143
7	0.286	0.286	0.143	0.143	0.143
8	0.286	0.286	0.143	0.143	0.143
9	0.286	0.286	0.143	0.143	0.143
10	0.286	0.286	0.143	0.143	0.143

Therefore, the expected net benefit of a perennial crop over 10 years, $B1$, is the sum of year k's expected net benefits multiplied by discount factor (k from 1 to 10), where the expected net benefit of year k is the sum of the product of perennial crop profit (PMP quadratic cost function) and the probability of $Y_{p,j}$ for year k, $P_{k,j}$.

$$\begin{aligned} B1 &= \frac{1}{(1+r)^{tT+1}} \sum_{j=1}^{5} P_{1,j} \left[\left(v_p Y_{p,j}\right) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right) X_{p,t} \right] \\ &\quad + \frac{1}{(1+r)^{tT+2}} \sum_{j=1}^{5} P_{2,j} \left[\left(v_p Y_{p,j}\right) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right) X_{p,t} \right] + \cdots \\ &\quad + \frac{1}{(1+r)^{tT+10}} \sum_{j=1}^{5} P_{10,j} \left[\left(v_p Y_{p,j}\right) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right) X_{p,t} \right] \\ &= \sum_{k=1}^{10} \frac{1}{(1+r)^{tT+k}} \sum_{j=1}^{5} P_{k,j} \left[\left(v_p Y_{p,j}\right) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t}\right) X_{p,t} \right] \end{aligned} \tag{3.1b}$$

The perennial crop establishment cost, $INIP$, depends on $X_{p,t}$ and the incoming perennial crop acreage, $X_{p,t-1}$. If $X_{p,t} < X_{p,t-1}$, there is no establishment cost. Otherwise, the establishment cost is the acreage of newly planted perennial crop acreage times the unit establishment cost, ini_p, multiplied by the discount factor.

$$INIP = \max\left(X_{p,t} - X_{p,t-1}, 0\right) ini_p \div (1+r)^{tT+1} \qquad (3.1c)$$

The expected net benefit of an annual crop over 10 years, $B2$, is the sum of yearly expected net benefits multiplied by discount factor, where the yearly expected net benefit is the product of annual crop profit in hydrologic event j and the probability of that hydrologic event, p_j. It is a sum of a geometric series. Unlike the perennial crop, for any year k, the probability of annual crop with yield of $Y_{a,j}$ equals p_j.

$$\begin{aligned}B2 &= \frac{1}{(1+r)^{tT+1}}\sum_{j=1}^{5} p_j\left[(v_a Y_{a,j})X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\ &\quad + \frac{1}{(1+r)^{tT+2}}\sum_{j=1}^{5} p_j\left[(v_a Y_{a,j})X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] + \cdots \\ &\quad + \frac{1}{(1+r)^{tT+10}}\sum_{j=1}^{5} p_j\left[(v_a Y_{a,j})X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\ &= \frac{1-(1+r)^{-T}}{(1+r)^{tT}\times r}\sum_{j=1}^{5} p_j\left[(v_a Y_{a,j})X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \qquad (3.1d)\end{aligned}$$

$EXPC$ is the expected water operational cost over 10 years, which is a sum of a geometric series of yearly expected net water operating cost multiplied by discount factor, where the yearly expected water operating cost is the sum of products of annual water operating cost for: (i) pumping (Equation (3.1f)), (ii) artificial recharge, $c_{land} \cdot X_{r,j}$, (iii) firm contract surface water, $c_{class1} \cdot \min\left(sw_j, class1\right)$, and (iv) surplus surface water, $c_{class2} \cdot \max\left(sw_j - class1, 0\right)$, in hydrologic event j and the probability of the that hydrologic event, p_j.

$$\begin{aligned}EXPC = \frac{1-(1+r)^{-T}}{(1+r)^{tT}\times r}\sum_{j=1}^{5} p_j\left[C_{pump}\cdot W_{p,j} + c_{land}\cdot X_{r,j} + c_{class1}\cdot \min\left(sw_j, class1\right) + c_{class2}\right. \\ \left.\cdot \max\left(sw_j - class1, 0\right)\right] \qquad (3.1e)\end{aligned}$$

where pumping cost is further considered to change with groundwater level:

$$C_{pump}\cdot W_{p,j} = c_e \times \frac{W_{p,j}\times\left(\frac{1{,}233.5\ m^3}{AF}\right)\times H \times\left(\frac{0.3048\ m}{ft}\right)\times \rho g}{3.6\times 10^6 \times \eta_p} \qquad (3.1f)$$

where H is the average of initial and final head (Figure 3.3 and Equation (3.1g)) and $H_o + B_o$ is the thickness of aquifer.

$$\begin{aligned}H &= \frac{1}{2}(H_{t-1} + H_t) = \frac{1}{2}\left[\left(H_o + \frac{GW_o - GW_{t-1}}{L\cdot s_y}\right) + \left(H_o + \frac{GW_o - GW_t}{L\cdot s_y}\right)\right] \\ &= H_o + \frac{1}{2L\cdot s_y}(2GW_o - GW_{t-1} - GW_t) = H_o + B_o - \frac{1}{2L\cdot s_y}(GW_{t-1} + GW_t) \qquad (3.1g)\end{aligned}$$

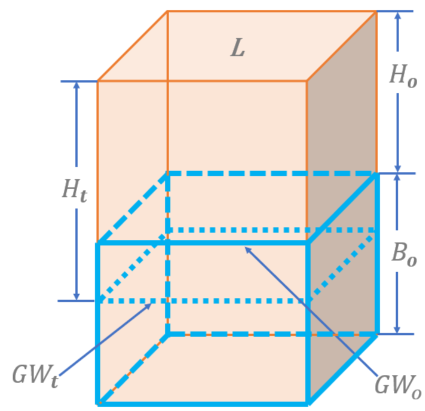


Figure 3.3. Model aquifer demonstration

Equation (3.8) limits the total area of perennial crop, annual crop, and the artificial recharge area to the total available land area for each hydrologic event j.

$$L - X_{p,t} - X_{a,j} - X_{r,j} \geq 0 \quad \forall j \tag{3.8}$$

Equation (3.9) is the water balance condition in each event j. The water used to grow perennial and annual crops should not exceed the available surface water plus the pumped groundwater minus the surface water for artificial recharge. These constraints do not have to be 0; it is possible to pump more groundwater than is used.

$$sw_j + W_{p,j} - cap \times X_{r,j} - aw_p X_{p,t} - aw_a X_{a,j} \geq 0 \quad \forall j \tag{3.9}$$

To calculate the stochastic conservation of mass for groundwater storage, ideally the initial groundwater storage GW_{t-1}, plus the expected total deep percolation, plus the expected total artificial recharge, $T\sum_{j=1}^{5} p_j capX_{r,j}$ (assume 100% of surface water used for artificial recharge reaches to the groundwater aquifer), minus the expected total amount of pumped groundwater, $T\sum_{j=1}^{5} p_j W_{p,j}$, equals to the final groundwater storage GW_t.

There are two ways to calculate deep percolation. First, from the water perspective (Equation (3.10a)), because surface water has two uses, irrigation and artificial recharge. For simplicity, a single factor φ is used to estimate the percent of water applied that deep percolates, the expected deep percolation from surface water over T years is $T\sum_{j=1}^{5} p_j \varphi(sw_j - capX_{r,j})$. Groundwater pumped is only used for irrigation, so the expected deep percolation from groundwater use over T years is $T\sum_{j=1}^{5} p_j \varphi W_{p,j}$.

Second, from the crop perspective (Equation (3.10b)), the total deep percolation from the perennial crop is $T\varphi aw_p X_{p,t}$. And expected total deep percolation from the annual crop is $T\sum_{j=1}^{5} p_j \varphi aw_a X_{a,j}$. Because we only retire the perennial crop once at the end of the planning horizon, these two perspectives are compatible as long as crops use all the irrigation water. Once we dump some irrigation water outside the basin, as noted in Equation (3.9), Equation (3.10a) and (3.10b) are no longer equivalent, and Equation (3.10a) will be invalid. So in this chapter, we always use Equation (3.10b) to represent the stochastic mass balance of groundwater.

$$GW_t = GW_{t-1} + T\sum_{j=1}^{5} p_j \varphi sw_j + T\sum_{j=1}^{5} p_j(1-\varphi)capX_{r,j} - T\sum_{j=1}^{5} p_j(1-\varphi)W_{p,j} \quad (3.10a)$$

$$GW_t = GW_{t-1} + T\varphi aw_p X_{p,t} + T\sum_{j=1}^{5} p_j \varphi aw_a X_{a,j} + T\sum_{j=1}^{5} p_j capX_{r,j} - T\sum_{j=1}^{5} p_j W_{p,j} \quad (3.10b)$$

2.2 Final Groundwater Salinity

We assume all salts from irrigation leach to groundwater through deep percolation, and the salts perfectly mix in the aquifer. Given the amount of incoming surface water for event j, we can calculate the concentration of groundwater (Figure 3.4).

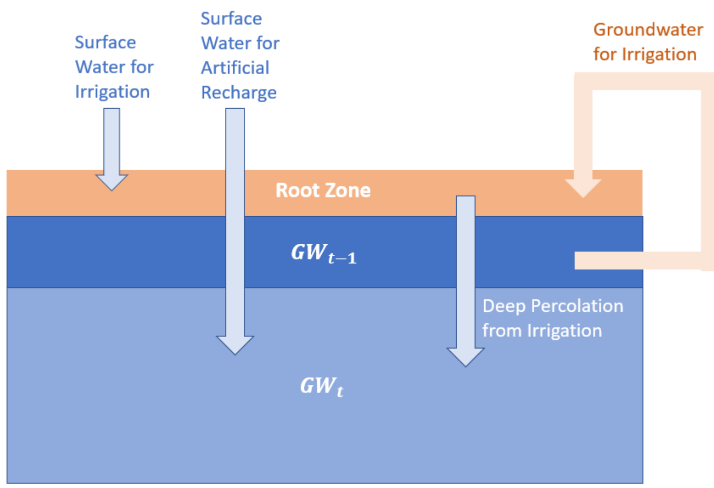


Figure 3.4. Representation of salinity mass balance model if no water is dumped

Considering the possibility that too salty irrigation water is directly dumped without returning to the aquifer, as with stochastic mass conservation of groundwater storage, we need to calculate the salt mass balance on a crop rather than water basis. Because we blend the surface water and groundwater before we irrigate, it is reasonable to calculate actual salt input from irrigation water in event j by multiplying actual amount of irrigation water used on crops in event j (Equation (3.11)) and salt concentration of irrigation water in event j, $C_{irr,j}$ calculated from Equation (3.2). Equation (3.12) calculates the expected total amount of salt input from irrigation $SALT_{irr}$ during the entire planning horizon. Equation (3.13) and Equation (3.14) calculates expected total salts from artificial recharge $SALT_{AR}$ and salts remaining in the aquifer $SALT_{gw}$, respectively. Finally, the expected concentration in groundwater at the end of planning horizon, $C_{gw,t}$, is the sum of $SALT_{irr}$, $SALT_{AR}$, and $SALT_{gw}$, divided by the final groundwater storage (Equation (3.15)).

$$IRR_{Actural,j} = aw_p X_{p,t} + aw_a X_{a,j} \quad (3.11)$$

$$SALT_{irr} = T\left(\sum_{j=1}^{5} p_j\, C_{irr,j} IRR_{Actural,j}\right) = T\left(\sum_{j=1}^{5} p_j\, C_{irr,j}(aw_p X_{p,t} + aw_a X_{a,j})\right) \quad (3.12)$$

$$SALT_{AR} = TC_{sw} \sum_{j=1}^{5} p_j capX_{r,j} \tag{3.13}$$

$$SALT_{gw} = C_{gw,t-1}(GW_{t-1} - T \sum_{j=1}^{5} p_j W_{p,j}) \tag{3.14}$$

$$C_{gw,t} = \frac{SALT_{irr} + SALT_{AR} + SALT_{gw}}{GW_t} \tag{3.15}$$

2.3 Model Assumptions

Several underlying assumptions are worth discussing. First, we assume soil salinity in the root zone is the same as for the irrigation water, which is not exactly the case, but they are well correlated. Also, groundwater salinity is assumed constant throughout the planning horizon rather than increasing year by year. Second, limited surface water availability prevents special leaching to the aquifer, but we assume adequate drainage exists to avoid salt accumulation in the root zone, and this drainage percolates to reach the aquifer. Furthermore, a rising water-table with brackish or saline water is not considered in this model because this model has a relatively low groundwater level, even under recharging goals, the water-table is not high enough to reach the root zone.

Only one perennial crop and one annual crop are considered, no urban water use or water transfer decisions are considered, making this model less able to represent mixed agriculture and urban production, but it emphasizes a more detailed representation of agricultural profit in a 10-year period. For further research, work by Maas and Grattan (1999) and Grattan (2002) can be applied to model salinity's effect on more common crops in California. Moreover, the model can assign any reasonable values to both initial and final groundwater storage. This model can include variable pumping costs. Finally, this model can include negative effects of salinity in groundwater, especially in drought.

3. Results and Discussion

3.1 Illustrative Example

The example application has a limited planting area and underlying aquifer, with parameters summarized in Table 3.1. The planting area is similar to the sum of acreage of almonds and alfalfa in northern San Joaquin Valley, California. The unit prices of class 1 and class 2 water are based on the Chowchilla water district. The unit price of energy is adopted from Statewide Agricultural Production (SWAP) model for North San Joaquin Valley (DWR 2012). The capacity of land for recharge is based on USACE's Conjunctive Use for Flood Protection Study (USACE 2002).

Table 3.4 and Figure 3.5 summarize the current stationary surface water availability $sw \sim logN(\mu = 625{,}000\ AF,\ \sigma = 400{,}000\ AF)$. To simplify the problem first, the averaged surface water inflow of each hydrologic event is represented by the 10th-, 30th-, 50th-, 70th- and 90th- percentile of the distribution, so we assume the probability of each hydrologic event is the same, which is 1/5 * 100% = 20%.

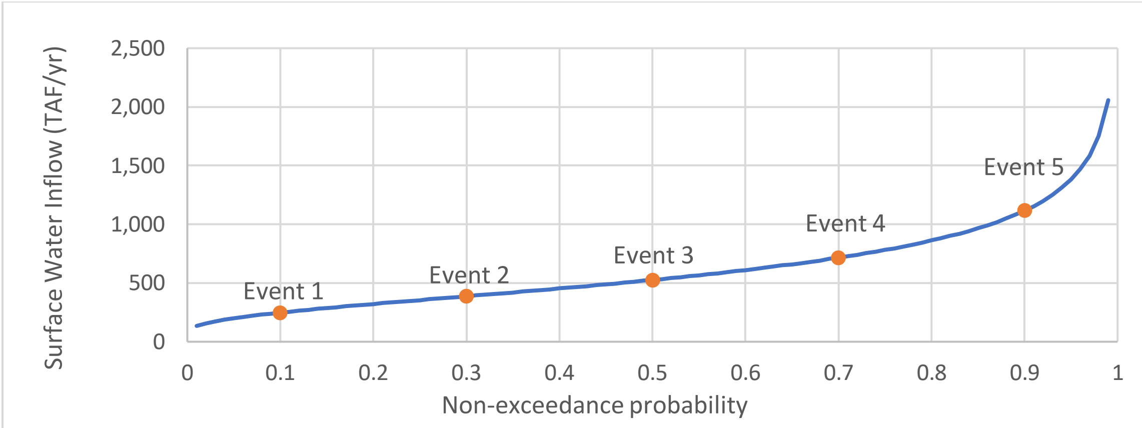


Figure 3.5. "Averaged" surface water inflow of each hydrologic event

Table 3.4. Available surface water in each hydrologic event

	Event j	Percentile	sw_j (TAF/yr)	p_j
Dry	1	10th	248	0.2
	2	30th	387	0.2
	3	Median	526	0.2
	4	70th	716	0.2
Wet	5	90th	1,115	0.2

3.2 Optimal Planning Results Summary

The first results explore how crop mix, net expected profit, and conjunctive use operation change with different groundwater salinities for a fixed initial groundwater storage (10 MAF) and incoming perennial crop acreage (125,000 acres). Optimized operations are discussed for no overdraft, net recharge, and net drawdown cases. One of the most important observations from this model is that the groundwater pumping pattern changes fundamentally because of groundwater salinity.

3.2.1 No Overdraft (ΔGW = 0)

Figure 3.6 shows perennial crop acreage and expected net benefit with no long-term change in groundwater storage (no overdraft) for different initial salinity levels. As salinity increases, both perennial crop acreage and expected net benefit diminish. The perennial crop acreage and expected net profit decrease by 15% and 36% respectively from the low-salinity case ($C_{gw,t-1}$ = 500 mg/L) to the severe-salinity case ($C_{gw,t-1}$ = 6,000 mg/L) due to salinity's long-lasting harm to perennial crops in the driest event, when groundwater salinity can be diluted least and perennial crop yield is most affected from high salinity of irrigation water. Figure 3.7 shows the model's overall optimal annual crop acreage decisions for different salinity levels without overdraft. More annual crops are planted in wetter years for higher groundwater salinities.

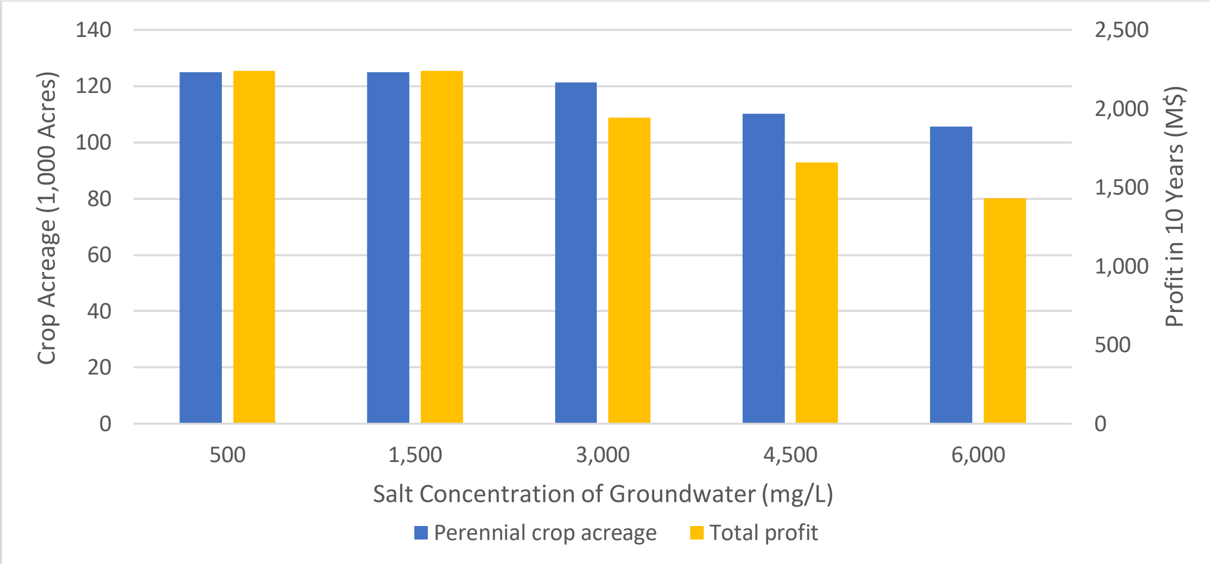


Figure 3.6. Perennial crop acreage and expected net profit under different salinity with no overdraft

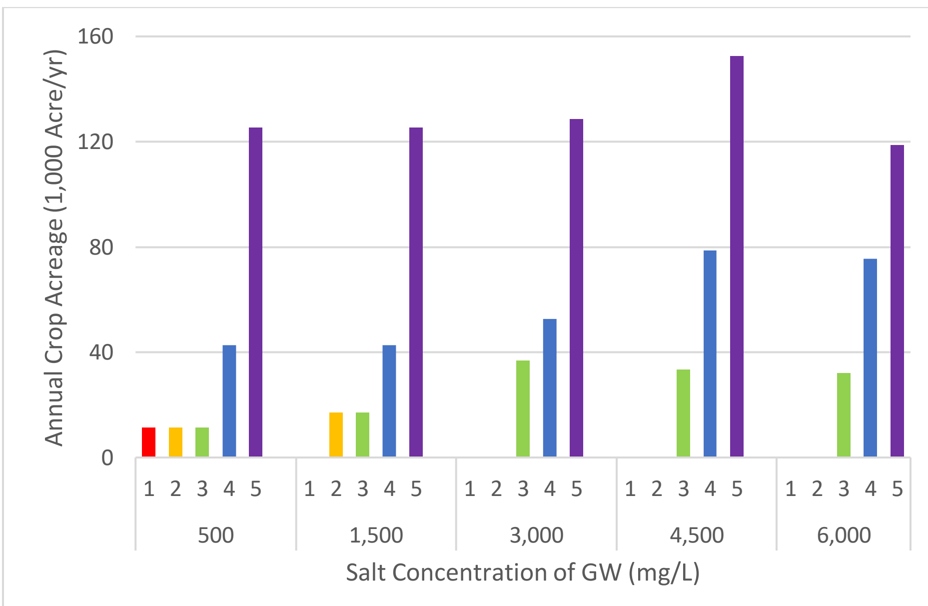


Figure 3.7. Annual crop acreage for different groundwater salinities without overdraft

Figure 3.8 shows optimal groundwater pumping in red on the left y axis, and corresponding EC of green on the right y axis. Figure 3.9 illustrates the difference between the amount of irrigation water supplied (gray lines with markers) and water required for perennial and annual crops (sum of the stacked columns). In these figures, numbers 1 to 5 represent hydrologic events, with event 1 being driest.

For the low-salinity case ($C_{gw,t-1}$ = 500 mg/L), pumping is greatest in the driest event, and diminishes as events become wetter. Pumping ceases in the two wettest events (Figure 3.8). With low salinity, pumping compensates for reduced surface water in events 1 to 3, which all have the same small acreage of annual crops (Figure 3.7).

With mild-salinity ($C_{gw,t-1}$ = 1,500 mg/L), the loss in expected net benefit is minimized (Figure 3.6) by shifting some pumping in the driest event in the low-salinity case to wetter events, as shown in Figure 3.8. Pumping in event 1 with mild-salinity is less than that with low-salinity, while pumping in events 2 and 3 with mild-salinity are higher than that with low-salinity.

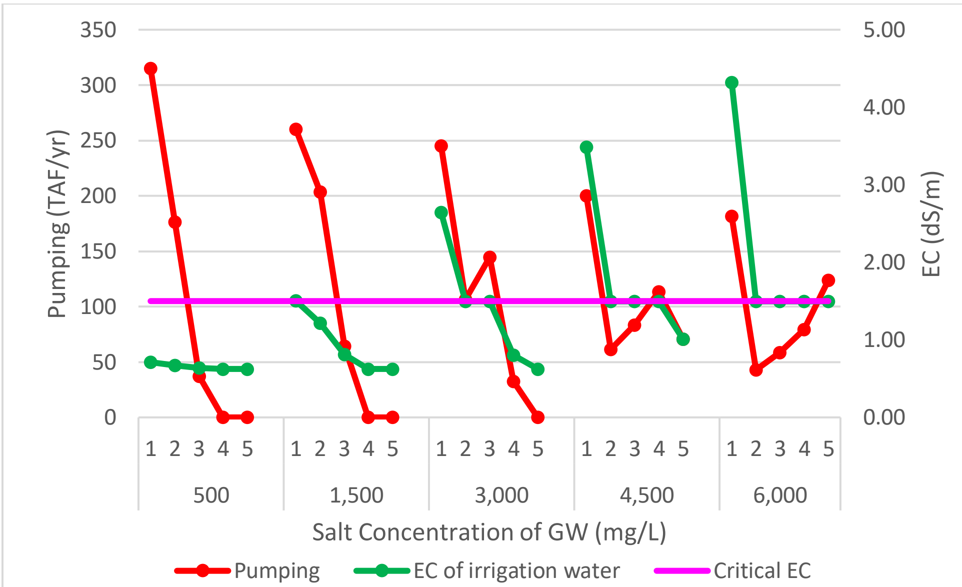


Figure 3.8. Relationship between pumping and EC of irrigation water with no overdraft

By decreasing pumping in event 1 so total irrigation water is just enough to support all incoming perennial crops (Figure 3.6) and eliminating irrigation for annual crops (Figure 3.7), the salinity of irrigation water in the driest event is as close as possible to the critical salinity threshold of the more profitable perennial crop (Figure 3.8) to minimally impair perennial crop yield (Allowing deficit irrigation might further reduce event 1 pumping). By increasing pumping in events 2 and 3 such that the salinity of irrigation water in both events are still less than this critical level, we grow more annual crops in those two events. From low-salinity to mild-salinity cases, with no difference in perennial crop acreage, slight decrease in perennial crop yield in event 1, and no change in total expected amount of pumping and total expected acreage of annual crops, we minimize loss in profit.

For the mid-salinity case ($C_{gw,t-1}$ = 3,000 mg/L), if we fix the salinity of irrigation water in event 1 to the perennial crop's critical salinity threshold, too many perennial crops are forced to retire and the total expected profit declines too much. So, first, event 1 is set aside and event 2 becomes the driest event having the critical irrigation water salinity threshold for permanent crops (Figure 3.8). The perennial crop yield in event 2 is kept as high as possible, because from Table 3.3, the probability of perennial crop yield equal to the yield in event 2, $P_{k,2}$, is always the highest of all events. Once the salinity of irrigation water in event 2 is determined, since the incoming surface water of all the events is given, we can calculate groundwater pumping in event 2.

In this mid-salinity case, total available irrigation water (sum of surface water and groundwater pumping) in event 2 cannot support all incoming perennial crops. So, in a second step, we let the beginning acreage of perennial crop in current planning horizon equal the amount of available irrigation water in event 2 divided by the applied water of perennial crop, aw_p. Then we come to the groundwater pumping in event 1 as the difference between the irrigation requirement of perennial crops and available surface water in event 1.

Certainly, the salinity of irrigation water in event 1 exceeds the critical perennial crop salinity threshold, substantially decreasing perennial crop yield in event 1 (Figure 3.8). However, this is more profitable than sparing some irrigation water in event 2 to plant annual crops and having less perennial crops with higher yield (still less or equal to full yield) in event 1. In the second step, we consider the trade-off between the perennial crop acreage and yield case by case.

Our next step is to determine pumping in wetter events. Because pumping in drier events is limited to impair perennial crop yield as little as possible, there is still much to pump to meet the no-overdraft goal. Therefore, we have salinity of irrigation water in event 3 at the critical level so we pump much groundwater while not decreasing perennial crop yield. Since event 3 has more fresh surface water to dilute salty groundwater, if we have the same salinity of irrigation water in both events 2 and 3, this means more groundwater pumping in event 3 than in event 2 (Figure 3.8), and that difference of pumping, combined with surface water, is used for annual crops (Figure 3.7). With higher salinity, the optimal conjunctive use strategy across wet and dry years changes, with salinity reducing pumping in the driest years and more in years with intermediate wetness, driven by the need to dilute more saline groundwater with limited fresher surface water.

Finally, we have the remaining required pumping in event 4 to avoid increasing groundwater storage, and cease pumping in event 5. One may ask why we must pump that much in event 3 to have salinity of irrigation water in at critical level, can we shift some pumping in event 3 to event 4 or 5? (A similar question occurs in the mild-salinity case: why we still plant the same annual crop acreage in events 2 and 3 and not plant more annual crops in event 3 than in event 2?) The answer is NO, because if we pump less groundwater in event 3, we plant fewer annual crops in event 3, and we pump more groundwater and grow more annual crops in events 4 or 5. However, the profit function of crop is quadratic (Equation (3.1d)), the marginal profit decreases as the crop acreage increases. Events 4 and 5 already have more annual crops than event 3 (Figure 3.7), meaning if we shift some pumping in event 3 to events 4 and 5, there is even less profit. So, we pump groundwater in event 3 as much as possible as long as annual crop acreage in event 3 does not surpass those in events 4 and 5 and the salinity of irrigation water will not affect perennial crop yield (the most profitable activity).

For the high-salinity case ($C_{gw,t-1}$ = 4,500 mg/L), as with the mid-salinity case, in the first step, we let salinity of irrigation water in event 2 be at critical level to allow perennial crops impaired to some degree in event 1. In the second step, we have all the irrigation water in event 2 irrigate perennial crops to maintain perennial crops as much as possible. In the last step, there is still a sizable amount of groundwater to pump to meet the groundwater storage target. We first have the salinity of irrigation water in event 3 hit the critical level. However, there is still much to pump, so we fix the salinity of irrigation water in event 4 to the critical level again and the remaining groundwater is pumped in event 5.

Compared with mid-salinity case, the peak of pumping (except for event 1) moves from event 3 to event 4 (Figure 3.8). Because in high-salinity case, events 3 and 4 are required to have the same critical salinity level, and event 4 has more available fresh surface water, allowing more groundwater use in event 4 than in event 3 and expanding annual crop acreage. We can imply a trend as the groundwater salinity increases, pumping shifts more to wetter events.

With severe-salinity ($C_{gw,t-1}$ = 6,000 mg/L), we follow the same process as in the mid- and high-salinity cases. Pumping shifts to event 5 (Figure 3.8) because all other drier events can only dilute limited amount of groundwater. The remaining groundwater pumped in event 5 just coincidentally makes the salinity of irrigation water in event 5 right at the critical salinity level. If the salinity of event 5 exceeds the critical level, the model still accepts it.

Take a closer look at Figures 3.7 and 3.8. From the low-salinity to mild-salinity case, we cease planting annual crops in event 1 and grow more annual crops in events 2 and 3 as some pumping shifts from event 1 to events 2 and 3. In the mid-salinity case, we stop planting annual crops in events 1 and 2, and grow more annual crops mostly in event 3 and slightly more in events 4 and 5, because perennial crop acreage decreases, and we pump much more groundwater in event 3. In the high-salinity case, we plant less annual crops in event 3 than mid-salinity case because less groundwater can be diluted in event 3 as salinity increases, meaning less irrigation water is available. And we plant more annual crops in events 4 and 5, because pumping shifts to those wet events. The severe-salinity case brings a slight decrease in annual crop acreage in events 3 and 4, as less groundwater can be diluted in those two events than in the high-salinity case, and a dramatic drop in annual crop acreage occurs in event 5. This is abnormal as more irrigation water should have resulted in more annual crops.

Figure 3.9 checks the difference between the irrigation requirement of perennial and annual crops (the height of bars) and the irrigation water supplied to the crops (marker of gray lines). With severe-salinity, we have not used all irrigation water in event 5 as there is a gap between the water needed and supplied, i.e., irrigation water is wasted only to meet the no-overdraft goal. This is because planting more annual crops in event 5 causes more deep percolation, and would increase the pumping needed. However, the additional annual crop profit in event 5 cannot offset the additional pumping cost and possible loss in perennial crop profit due to more pumping, as perennial crops use the same irrigation water as annual crops, more pumping increases salinity of irrigation water.

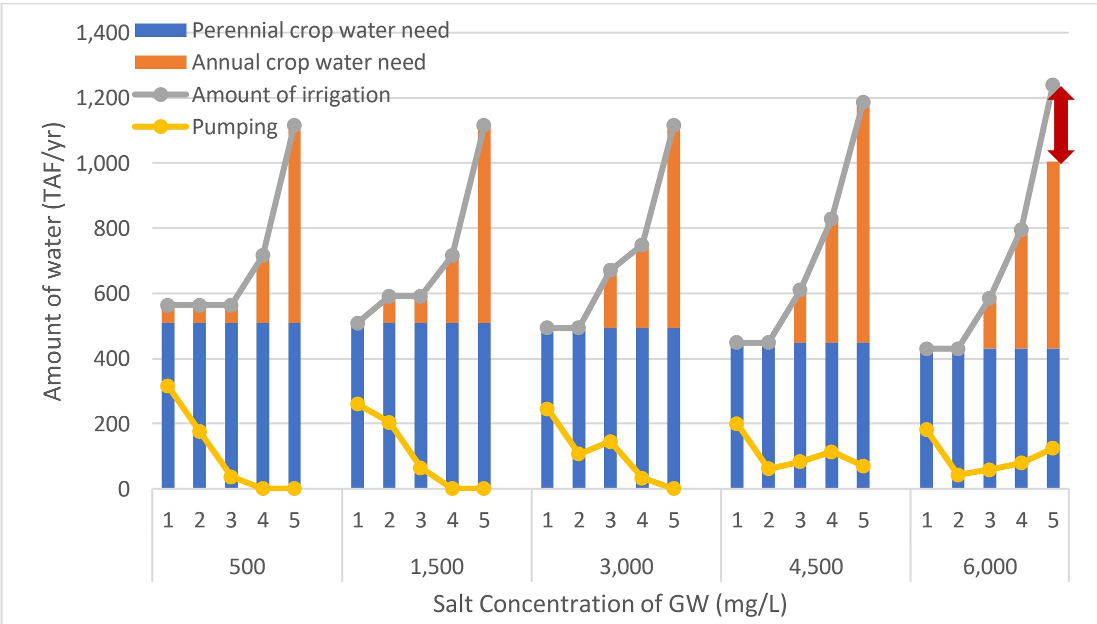


Figure 3.9. Relationship between crop water requirement and irrigation with no overdraft. Brown arrow of event 5 in the severe salinity case indicates the externally wasted water.

With severe groundwater salinity, groundwater can be externally discharged to meet the no-overdraft goal, which physically removes both salt and excess recharge. We may imply that a target to restore the aquifer can be more profitable, because less groundwater "needs" to be pumped and wasted, and the land used for artificial recharge can be reduced or avoided, though perennial crop profit will decrease.

3.2.2 Net Aquifer Recharge (ΔGW > 0)

Figure 3.10 shows the perennial crop acreage decisions for different net groundwater storage restoring goals for different groundwater salinities. Low-salinity ($C_{gw,t-1}$ = 500 mg/L), mid-salinity ($C_{gw,t-1}$ = 3,000 mg/L), high-salinity ($C_{gw,t-1}$ = 4,500 mg/L), and severe-salinity ($C_{gw,t-1}$ = 6,000 mg/L) are in blue, orange, gray, and yellow respectively. For all salinity levels, groundwater recovery reduces perennial crop acreage because some surface water is used for artificial recharge and less groundwater can be pumped.

However, higher salinities' long-lasting harm to perennial crops in the driest event reduces perennial crop acreage for the same net restoring goal. With a net groundwater storage increase goal of 1 MAF, from the low-salinity to the mid-salinity case (ΔC_{gw} = 2,500 mg/L), perennial crop acreage only decreases 3,800 acres. From mid-salinity to high-salinity (ΔC_{gw} = 1,500 mg/L), another 11,000 acres of perennial crops are retired. From the high-salinity to severe-salinity case (ΔC = 1,500 mg/L), a further 31,000 acres of perennial crops are retired.

Figure 3.11 shows total profit for different net restoring goals with different salinities. Restoring more groundwater storage significantly reduces profit, because fewer perennial crops are maintained and additional artificial recharge cost is required. As net restoring goals become more demanding, salinity becomes less important because less average net groundwater pumping is allowed.

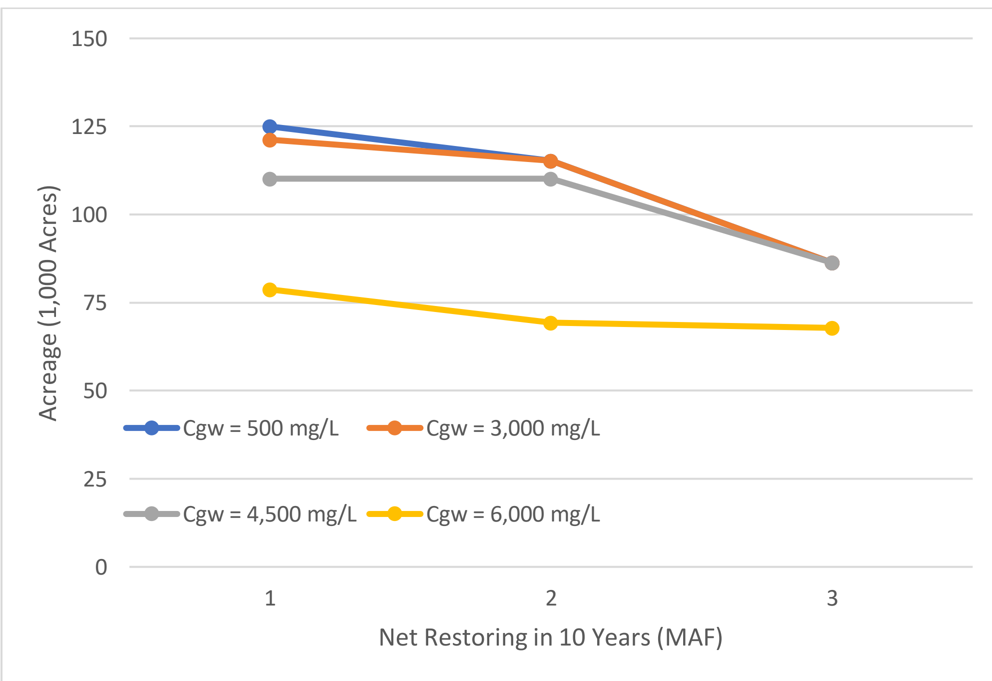


Figure 3.10. Perennial crop acreage given different groundwater restoring goals and salinities

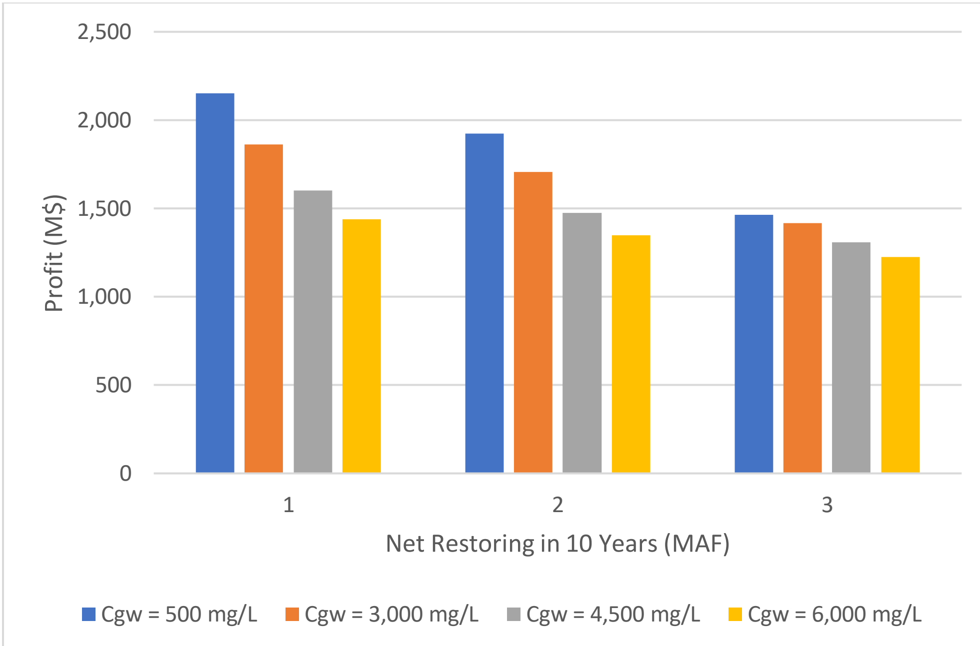


Figure 3.11. Total expected profit for different net restoring goals and groundwater salinities

Figures 3.12, 3.13 3.14, and 3.15 compare the model's overall optimal annual crop acreage, pumping, land for artificial recharge, and EC for each event for different net groundwater storage increase goals and different salinity levels.

For the same net restoring goal, as salinity becomes more severe, less groundwater pumping occurs in drier events (Figure 3.13), reducing the need to increase aquifer storage by recharge (Figure 3.14). Rather than maintaining perennial crops as much as possible, more annual crops are planted in events 2 to 5 with severe salinity (Figure 3.12).

With low-salinity, when recovery goals are high (ΔGW = 3 and 2 MAF), all available irrigation water goes to maintain as much perennial crop as possible with no irrigation water for annual crops (Figure 3.12) maximizing profit, because the overall salinity of irrigation water will not impair perennial crop yield. When the recovery goal is mild (ΔGW = 1 MAF), we could grow new perennial crops as we start to plant annual crops in event 3 (Figure 3.12), but we decide not to because of the high initial establishment cost of perennial crops. The quadratic property of crop profit makes us plant the same acreage of annual crops in events 4 and 5 again (Figure 3.12). So artificial recharge also dampens differences in surface water available in wetter events.

When salinity becomes a problem, aquifer recovery cannot be met simply by a universal algorithm based on salinity of irrigation water as in Section 3.2.1. With mid-salinity ($C_{gw,t-1}$ = 3,000 mg/L), when ΔGW = 1 MAF, the optimal decision is still driven by salinity at the beginning: first, we let the salinity of irrigation water in event 2 be at critical level (Figure 3.15) to allow perennial crops impaired to some degree in event 1. Second, we decide to have all the irrigation water in event 2 irrigate perennial crops to maintain most perennial crops as possible. Lastly, we make sure the events having artificial recharge (events 4 and 5) have the **same highest** number of annual crops (Figure 3.12).

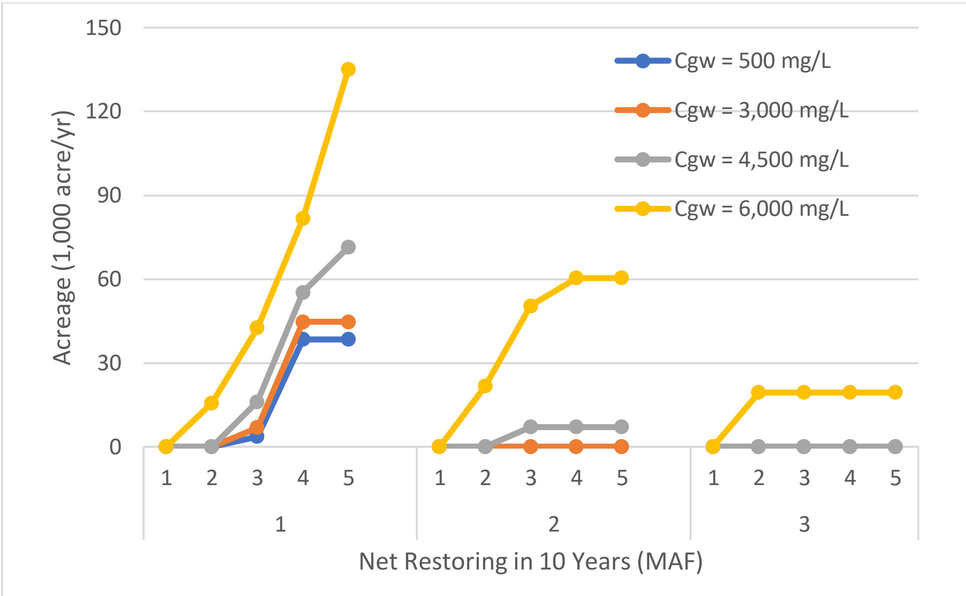


Figure 3.12. Annual crop acreage given different net recovery goals under different salinity

Because of groundwater salinity, 3,800 acres of incoming perennial crop are retired (Figure 3.10), making annual crop acreages in events 3, 4, and 5 higher than those in the low-salinity case (Figure 3.12). Fewer perennial crops also mean less pumping in the two driest events (Figure 3.13), so there is less artificial recharge in two wettest events (Figure 3.14).

When ΔGW > 1 MAF, the optimal mid-salinity decision is the same as for the low-salinity case (Figures 3.12 to 3.14), causing salinity in event 1 to exceed the critical level while salinity in event 2 is less than the critical level (Figure 3.15), because: a) aquifer restoring removes enough groundwater availability so it is not possible for event 2 to pump enough groundwater to keep irrigation water at the critical level salinity; while b) more acreages of impaired perennial crops due to lack of surface water in event 1 are more profitable than fewer acres of full-yield perennial crops for all events.

In the high-salinity case ($C_{gw,t-1}$ = 4,500 mg/L), when ΔGW < 3 MAF, similar as ΔGW = 1 MAF in the mid-salinity case ($C_{gw,t-1}$ = 3,000 mg/L), we first let irrigation water salinity in event 2 be at the critical level (Figure 3.15). Because groundwater is saltier than the mid-salinity case, more perennial crop acreage is retired (Figure 3.10) and less irrigation water is available for annual crops. Lastly, when ΔGW = 1 MAF, there is more annual crops in event 5 than in event 4 (Figure 3.12) and artificial recharge occurs only in event 5 (Figure 3.14). When ΔGW = 2 MAF, we must shift artificial recharge to events 3 and 4 to meet the demanding groundwater recovery goal (Figure 3.14) while keeping the annual crop acreages in those three events the same to make most profit (Figure 3.12).

When ΔGW = 3 MAF, the same decisions cross the low-salinity to high-salinity cases (Figures 3.12 to 3.14). The reductions in acreage and pumping needed to achieve this net aquifer recharge volume largely overwhelm the effects of increasing salinity, except for reductions in yield and profit.

In the severe-salinity case ($C_{gw,t-1}$ = 6,000 mg/L), as mentioned in Section 3.2.1, a net restoring goal of 1 MAF can be more profitable than the no-overdraft goal, for this example. This changing relative value of restoring aquifer levels with salinity implication is true for the broader example study. The net profit for a no-overdraft goal is 1,430 M$ over ten years, while the net profit for restoring 1 MAF over ten years is slightly more, 1,438 M$. Though we retire more than 46,000 acres of perennial crops and need to use some land for artificial recharge, we grow more annual crops to compensate the lost perennial crop profit and have less need to pump so the net profit for aquifer recovery of 1 MAF is more than with a no-overdraft goal.

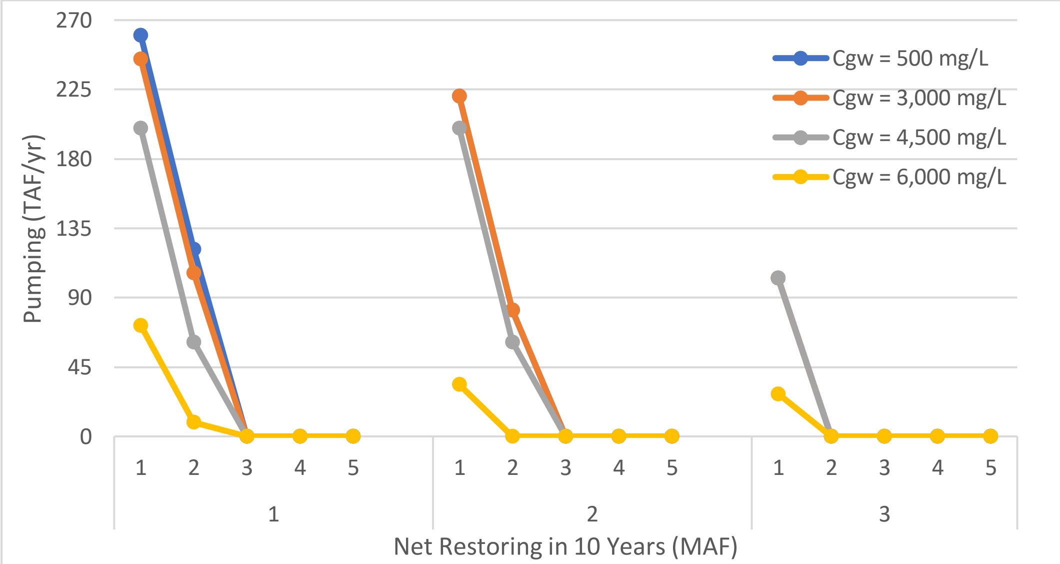


Figure 3.13. Pumping given different net recovery goals under different salinity

The severe-salinity case with net restoring goals best shows the trade-off between perennial crop yield and acreage. When the net restoring goal is 3 MAF, the salinity of irrigation water drives the decision. It is the only case where we pump groundwater to have the salinity of irrigation water in event 1 at the critical level (Figure 3.15), meaning the perennial crop of lower acreage with full yield is more profitable than those of higher acreage but of slightly impaired yield. Next, no irrigation occurs for annual crops in event 1 (Figure 3.12) because it is not optimal to pump in the driest event only to grow annual crops. Lastly, the high net restoring goal forces artificial recharge in all wetter events (Figure 3.14). So, we grow same numbers of annual crops in those events (Figure 3.12).

When the net restoring goal is 2 MAF, groundwater is not pumped in event 2 (Figure 3.13). Otherwise event 1's irrigation water will be too salty. Some surface water in event 2 is used for annual crops (Figure 3.12) to further decrease remaining perennial crops. However, unlike the restoring goal of 3 MAF, remaining perennial crop yield is impaired slightly in event 1 (Figure 3.15). This means profit from more slightly impaired perennial crops exceeds the combination of profit from fewer full-yield crops, profit from more annual crops in wetter events, and lower pumping cost.

With a net restoring goal of 1 MAF, in event 2, we pump (Figure 3.13), with the salinity of irrigation water less than the critical level (Figure 3.15), and grow annual crop (Figure 3.12). In more stringent cases, groundwater was pumped only to irrigate perennial crops, but in this case, surface water in event 2 is adequate for perennial crops. So, we pump groundwater to irrigate annual crops, because if we use all irrigation water to irrigate perennial crops, much more groundwater is needed for permanent crops in event 1. However, in this case, more severely impaired perennial crops are less profitable than fewer less severely impaired perennial crops. The model tries to balance between perennial crop yield and acreage in each case.

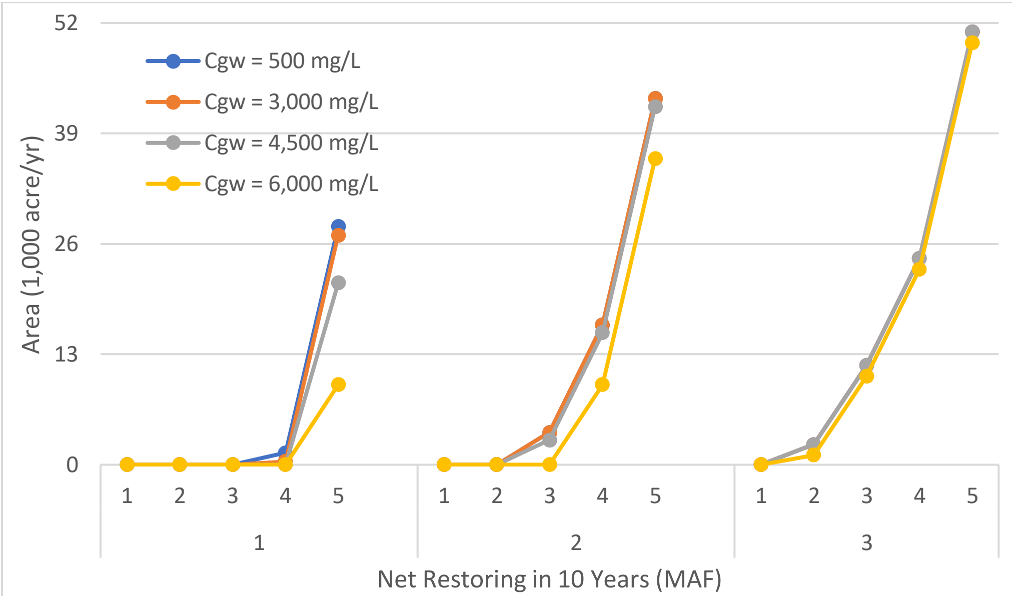


Figure 3.14. Artificial recharge area for different net recovery goals and groundwater salinities

In Chapter 2, pumping and artificial recharge dampen differences in surface water availability across hydrologic events. However, in this chapter with groundwater salinity, groundwater pumping can reduce perennial crop yield. So, with no-overdraft and net drawdown goals, pumping decisions are more based on irrigation water salinity. However, for net restoring goals, in wetter events, the perennial crop is irrigated solely by fresh surface water. So artificial recharge occurs in events such that annual crop acreages are the same.

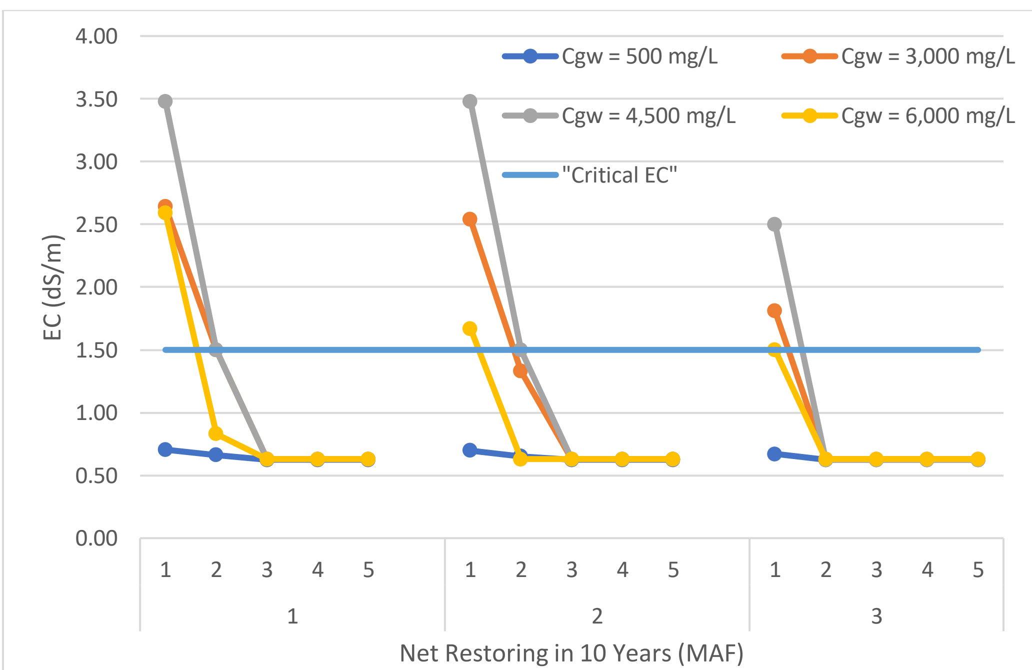


Figure 3.15. EC given different net recovery goals with different groundwater salinities

Table 3.5 shows the final groundwater salinity at the end of the planning horizon. For the no overdraft goal, groundwater salinities always end up with higher salt concentrations because deep percolation brings not only the salt from surface water but also nearly all the salt from pumping (except for the severe-salinity case, in which we dump the irrigation water outside the basin, but final groundwater salinity is still higher than in the beginning). For net aquifer recharge goals, final groundwater salinity continues decreasing as recharge goals become demanding, because more fresh surface water recharges the aquifer. Artificial recharge decreases the groundwater salinity more strongly if groundwater salinity is more severe.

Table 3.5. Final groundwater salinities (mg/L) from optimized operations for different groundwater storage goals

Net Recharging over Planning Horizon (MAF)	Initial Aquifer Salinity (mg/L)			
	1,500	3,000	4,500	6,000
0	1,739	3,239	4,739	6,195
1	1,581	2,945	4,309	5,672
2	1,450	2,700	3,950	5,200
3	1,338	2,492	3,646	4,800

3.2.3 Net Aquifer Drawdown (ΔGW < 0)

Figure 3.16 shows perennial crop acreage decisions for different net drawdown goals and aquifer salinities. The low-salinity ($C_{gw,t-1}$ = 500 mg/L), mild-salinity ($C_{gw,t-1}$ = 1,500 mg/L), and mid-salinity cases ($C_{gw,t-1}$ = 3,000 mg/L) are in blue, orange, and gray respectively. Since we pump and externally discharge to meet all net drawdown goals in the mid-salinity case, there is no need to further discuss the high- and severe-salinity cases.

With low aquifer salinity, more groundwater pumping expands perennial crops. However, the long-lasting negative effect of salinity on perennial crops in the driest event restricts acreage expansion. In the mild-salinity case, perennial crop acreage increases only 2% with extensive aquifer drawdown (ΔGW = -5 MAF). In the mid-salinity case, no new perennial crop is planted for any net drawdown goals because more perennial crops require more groundwater that increases irrigation water salinity.

Figure 3.17 and Table 3.6 show the expected total profit for different aquifer drawdown goals and salinities. Pumping more groundwater does not always increase profit. In the low-salinity case, net drawdown of 3 MAF over 10 years makes the most profit. Additional crop revenue from planting more crops that use more groundwater cannot offset the increasing pumping cost. With mild-salinity, net drawdown of 2 MAF makes the most profit, with slightly less profit with more net drawdown. Besides the greater pumping cost, higher irrigation water salinity with greater net drawdown decreases crop yields and profits.

In the mid-salinity case, net drawdown of 1 MAF makes the most profit among all the net drawdown goals (1,913 M$ over 10 years). However, this profit is less than no-overdraft goal's profit (1,943 M$) because we start to pump and waste groundwater with net drawdown goals. This urges to start sustainable groundwater management as soon as possible if the groundwater salinity is high. There is an obvious gap in profit with the other two salinity cases from the negative effects of groundwater salinity. As we pump more, profit falls faster than the other two cases. Therefore, the difference in profit with the other two cases increases.

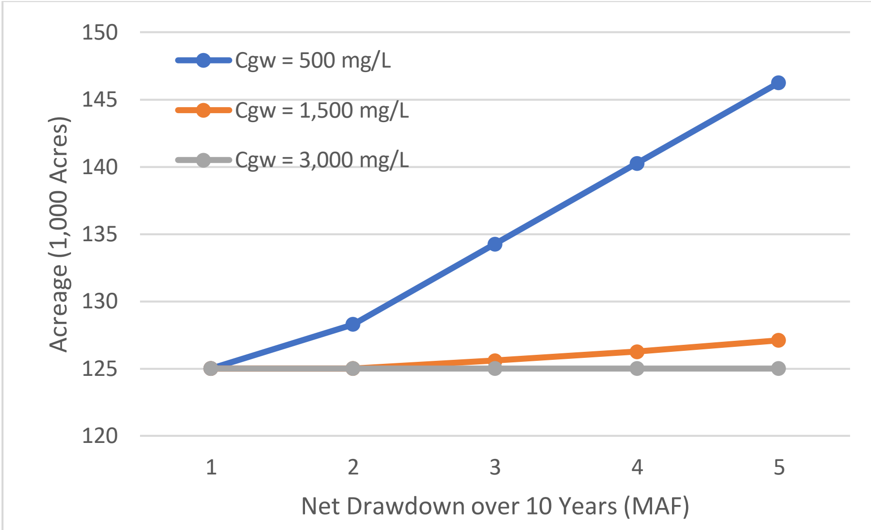


Figure 3.16. Perennial crop acreage given different net drawdown goals with different salinity

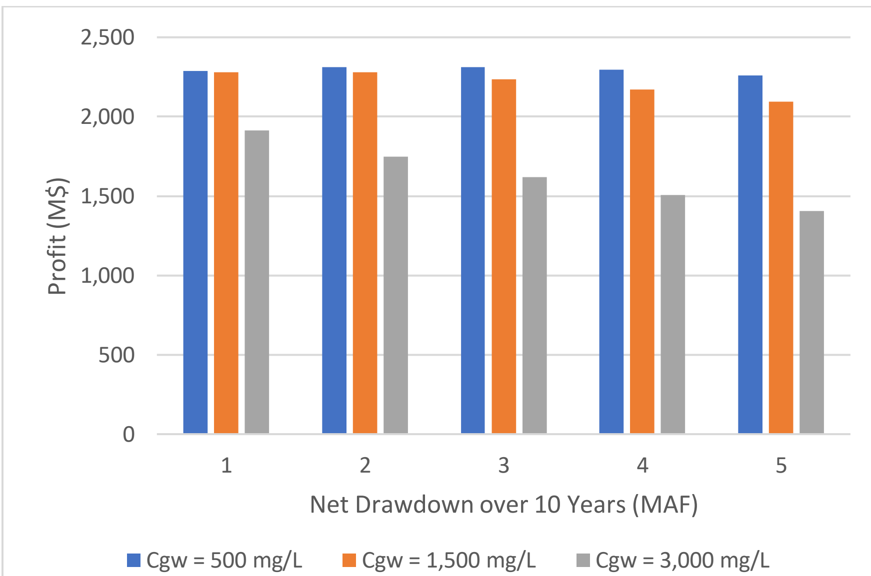


Figure 3.17. Total expected profit given different net drawdown goals and aquifer salinities

Figures 3.18 and 3.19 compare the model's overall optimal annual crop acreage and groundwater pumping for different net drawdown goals and aquifer salinities. Figure 3.20 further shows the relationship between optimal groundwater pumping (in red on the left y axis) and EC of irrigation water (in green on the right y axis). Figure 3.21 shows the difference between the amount of irrigation water supplied (gray lines with markers) and water required by perennial and annual crops (sum of the stacked columns).

With less aquifer salinity, pumping reduces differences among incoming surface water availabilities by pumping more in drier events (Figure 3.19) as annual crop acreages are always the same across the events which pump any groundwater (Figure 3.18). The quadratic property of crop profit tends to dampen variation in annual crop acreage.

Table 3.6. Total expected profit (M$) for different net drawdown goals and aquifer salinities (maximum profits in **Bold**)

Net Drawdown over Planning Horizon (MAF)	Aquifer Salinity (mg/L)		
	500	1,500	3,000
0	2,239.75	2,238.28	**1,943.66**
1	2,287.68	2,278.43	1,913.30
2	2,310.77	**2,279.23**	1,749.28
3	**2,313.06**	2,236.40	1,618.99
4	2,295.33	2,170.63	1,507.83
5	2,260.30	2,094.81	1,405.55

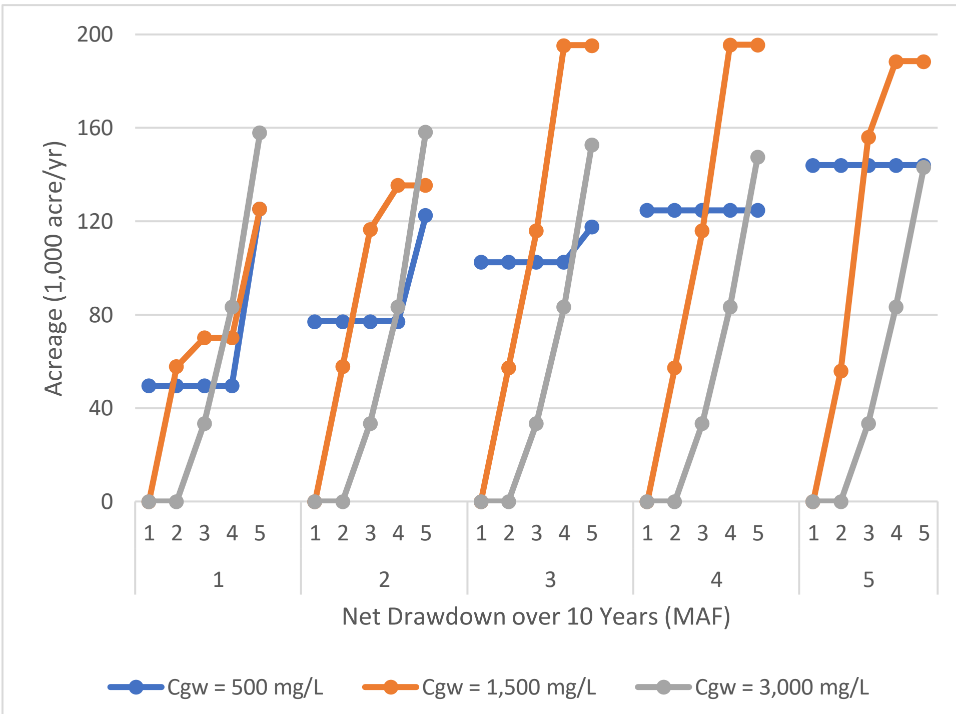


Figure 3.18. Annual crop acreage for different net drawdown goals and aquifer salinities

For mild salinity, the algorithm introduced in Section 3.2.1 is also valid. When ΔGW = -1 to -4 MAF, similar as no-overdraft goal, first we let event 2 be the driest event having the critical irrigation water salinity threshold (Figure 3.20a). Second, we do not use all irrigation water on perennial crops in event 2. With the perennial crop yield, incoming perennial crop acreage, perennial crop establishment cost, and annual crop profit considered, the model carefully decides new perennial crops to grow (Figure 3.16) to not pump too much groundwater in event 1 (Figure 3.20a). Lastly, there is still a sizable amount of groundwater to pump (to achieve the groundwater storage reduction target), we first have salinity of irrigation water in drier events hit the critical level. After that, there is not much to pump, so we allocate pumping so wetter events have the same annual crop acreages. With higher net drawdown goals, pumping further shifts to wetter events (Figure 3.19, 3.20a).

The only difference between the net drawdown goal of 5 MAF and other pumping goals is the pumping and salinity of event 3 (Figure 3.19, 3.20a). salinity of irrigation water in event 3 is highest among all events because the quadratic property of crop profit makes marginal profit higher when production is lower. So, we pump more groundwater in event 3 to grow more annual crops in event 3 rather than pumping more groundwater in event 5.

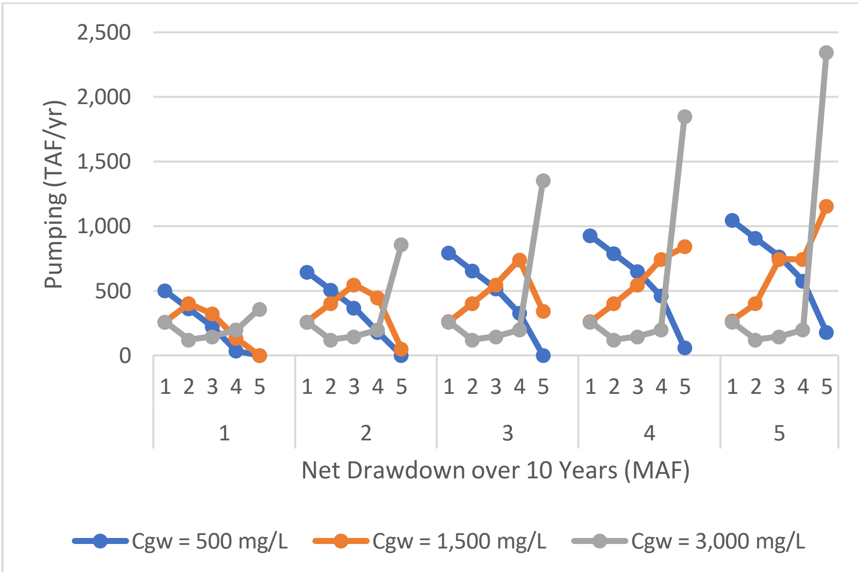
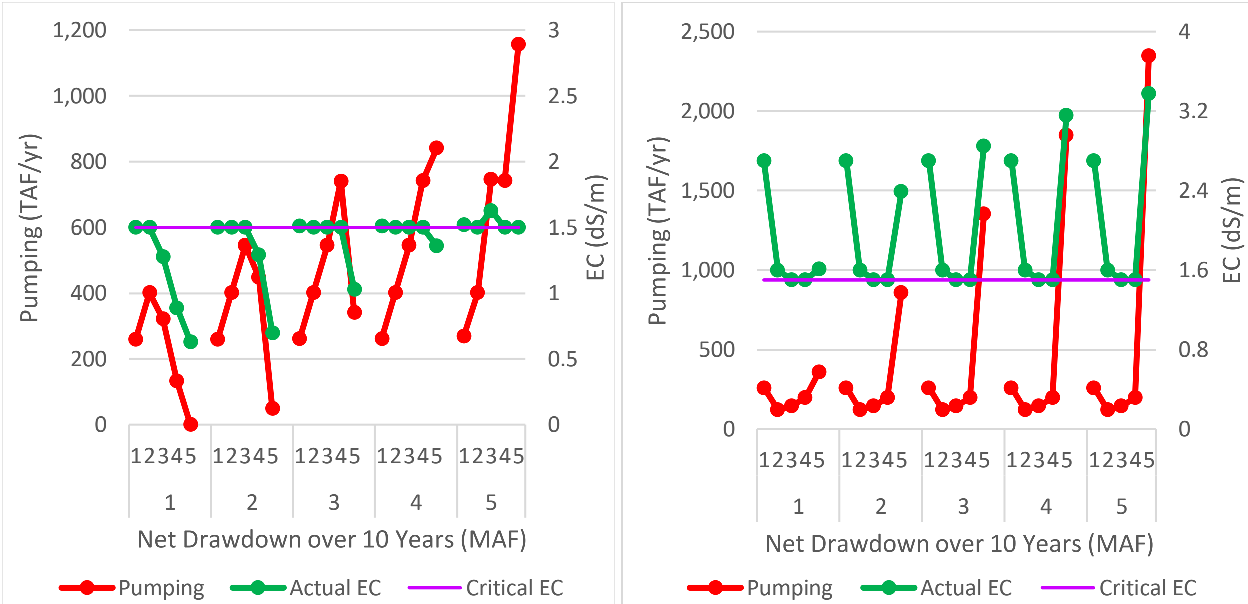


Figure 3.19. Groundwater pumping for different net drawdown goals and aquifer salinities

For the mid-salinity case, all net drawdown goals become undesirable. The algorithm still goes straightforward: event **3** is the first driest event to have critical salinity level in irrigation water. Second, if we plant new perennial crops, more groundwater needs to be pumped in events 1 and 2 that further impair crop yield, which is not optimal. Therefore, perennial crop acreage is kept the same as the incoming acreage, and some irrigation water is spared to annual crops in event 3. Lastly, because a huge amount of groundwater must still be pumped to achieve the drawdown target, the salinity of event 4 is also set to the critical level, and the rest is pumped in event 5.

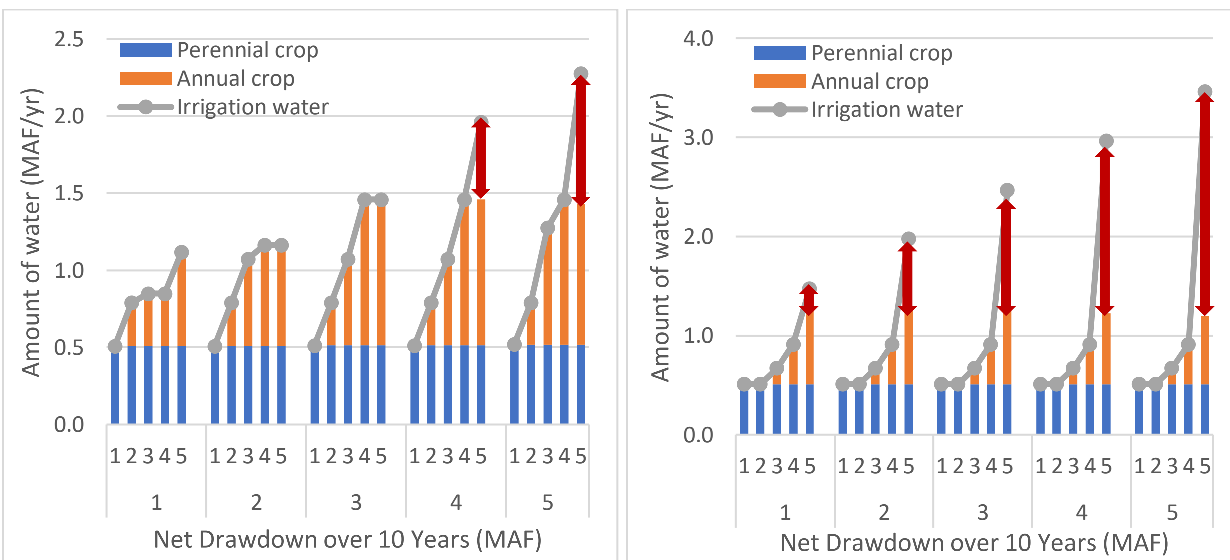
However, similar with event 3 with mild-salinity and a net drawdown goal of 5 MAF, the salinity of irrigation water in event 5 with mid-salinity can be even higher than salinity of event 1. The model makes this decision because we assume salinity is always highest in the driest event 1 and we only impose the long-lasting negative effect on event 1. We exploit this loophole in the model formulation because there is no penalty of having salinity too high in events other than event 1. To make the model as simple as possible, we will not make any modification to the model formulation, as these decisions are only made with extreme aquifer drawdown goals.

In Figures 3.18 and 3.19, for the mild-salinity case, when ΔGW is -4 MAF and -5 MAF, pumping is greatest in event 5, but we plant the same acreage of annual crops in events 4 and 5. Besides that, when ΔGW = -5 MAF, we plant fewer annual crops in both events 4 and 5 than ΔGW = -4 MAF with more pumping. Furthermore, we plant fewer annual crops in event 5 in mid-salinity case than in mild-salinity case, but we pump much more groundwater in event 5 in the mid-salinity case. Moreover, we plant fewer and fewer annual crops in event 5 in the mid-salinity case as the drawdown goal becomes more demanding. Figure 3.21 reveals that some irrigation water (the gap between the markers and the top of the bars) is dumped in event 5.



(a): $C_{gw,t-1}$ = 1,500 mg/L (b): $C_{gw,t-1}$ = 3,000 mg/L

Figure 3.20. Relationship between pumping and EC for different net drawdown goals



(a): $C_{gw,t-1}$ = 1,500 mg/L (b): $C_{gw,t-1}$ = 3,000 mg/L

Figure 3.21. Difference between water required and supplied for different net drawdown goals

Why is irrigation water dumped and not used to plant annual crops? Because the return flow to groundwater aw_a in this model is fairly high, with a single fixed rate of deep percolation φ, growing more annual crop means more irrigation water percolates to the aquifer. For demanding net drawdown goals, more deep percolation is undesirable as it must eventually be pumped and discharged. It is not economical to pump more groundwater which raises pumping cost and adds salt to irrigation water which harms perennial crop yield only to grow more annual crops. So, the model pumps and dumps groundwater rather than plant annual crops.

3.3 Sensitivity Analysis

Here we change some parameters to see if model results are sensitive. The base case for this sensitivity analysis has boundary conditions of initial groundwater storage being 10 MAF, incoming perennial crop being 125,000 acres, and groundwater salinity of 3,000 mg/L. Lagrange multipliers provide sensitivity analysis on major constraints. Sensitivities to changes in the probability distribution of surface water availability, and irrigation efficiency are explored.

3.3.1 Lagrange Multipliers

Constraint Equations (3.8) to (3.10) yield 11 Lagrange multipliers, five for the land constraint (one for each event), five for the surface water constraint (one for each event), and one for the stochastic expected conservation of mass groundwater storage constraint. Because land is never entirely used in any event for any drawdown or replenishment goal, it is never a binding constraint and needs no further discussion.

Tables 3.7 and 3.8 summarize the trend of water-related Lagrange multipliers with and without salinity. Because in the objective function we try to minimize the negative value of the profit, positive Lagrange multiplier values mean that if we reduce one unit of water, we lose some profit. However, negative Lagrange multiplier values mean that using one less unit of water increases profit. Though Excel and Python code end up with very close optimal solutions for all goals, their Lagrange multiplier values may differ due to numerical issues (and Excel's look more reasonable). Cells shaded blue are where artificial recharge happens; cells shaded orange are where pumping occurs; and cells in bold and italic means annual crops are planted in the second stage. With moderate salinity (Table 3.7), annual crops are never planted in events 1 and 2.

First, let's look at the Lagrange multipliers of surface water constraints. By column, unlike Table 3.8 in which the value of Lagrange multiplier for each hydrologic event gradually increases for all events as ΔGW goes from very negative to very positive, the trend of Lagrange multipliers in Table 3.7 is not monotonic (Figure 3.22). When ΔGW is negative (aquifer drawdown), the Lagrange multiplier increases as we pump more groundwater for the first four events because pumping more groundwater increases the salinity of irrigation water which already are at or exceed the critical level (Figure 3.20b). So, with salinity, surface water is more valuable when the net drawdown goal increases. However, the Lagrange multiplier for event 5 is always zero for all net drawdown goals, because we dump excess irrigation water, a mixture of surface water and groundwater, i.e., Equation (3.9) is not a binding constraint in event 5.

Lagrange multipliers for all events start to increase from ΔGW = -1 MAF to 0, as surface water scarcity starts to outweigh groundwater salinity in determining profit. However, the trend of Lagrange multipliers for groundwater recovery goals across events needs to be discussed for each event.

For event 1, the second stage decisions (annual crops, land for artificial recharge, and pumping) are exactly the same for no overdraft (ΔGW = 0) and modest groundwater recovery (ΔGW = 1 MAF), but the Lagrange multiplier grows with higher net recovery goals. One reason is that without overdraft, one less unit of surface water may mean requiring one more unit of groundwater, higher irrigation water salinity, lower perennial crop yield, and lower perennial crop acreage; whereas when ΔGW = 1 MAF (aquifer filling), one less unit of surface water may also reflect artificial recharge (buying land and less surface water for irrigation). As refilling goals for groundwater increase to 3 MAF, event 1 has growing weight to determine the perennial crop acreage as the tradeoff between crop yields and acreage occurs in event 1. Combined with surface water scarcity, the groundwater salinity makes the Lagrange multiplier of event 1 soar as the net filling goal becomes more demanding, because less available surface water decreases both crop yield and acreage. The Lagrange multiplier suddenly drops when ΔGW = 4 MAF because fresh surface water availability becomes more limiting than groundwater salinity, and the Lagrange multiplier increases a little when ΔGW = 5 MAF, solely from water scarcity.

Table 3.7. Lagrange multipliers ($/AF) in different events and aquifer goals for middle salinity ($C_{gw,t-1}$ = 3,000 mg/L). Numbers in parentheses are Lagrange multipliers from the Python Scipy.Optimize Trust-Region Constrained Algorithm. Orange shade means pumping occurs. Blue shade means artificial recharge. Bold and italic value means annual crops are planted

	ΔGW (MAF)	Constraints					
		Dry	Surface Water			Wet	Groundwater Mass Balance
		Event 1	Event 2	Event 3	Event 4	Event 5	
Net Drawdown	-5	828 (853)	1,322 (1,362)	***154*** ***(153)***	***104*** ***(97)***	***0***	-86 (-99)
	-4	807 (814)	1,301 (1,307)	***152*** ***(0)***	***101*** ***(10)***	***0***	-94 (-112)
	-3	773 (842)	1,267 (1,336)	***147*** ***(154)***	***97*** ***(100)***	***0***	-109 (-121)
	-2	709 (486)	1,202 (7)	***138*** ***(29)***	***88*** ***(-30)***	***0***	-139 (-390)
	-1	619 (555)	1,113 (1,048)	***126*** ***(119)***	***75*** ***(67)***	***0***	-181 (-216)
No overdraft	0	1,142 (1,050)	1,565 (1,557)	***198*** ***(187)***	***181*** ***(154)***	***105*** ***(81)***	69 (-23)
Net Refill	1	1,237 (1,081)	1,377 (1,564)	***243*** ***(233)***	***204*** ***(194)***	***204*** ***(185)***	119 (109)
	2	1,562	602	486	486	486	260
	3	2,017	625	625	625	625	329
	4	1,096	1,096	1,096	1,096	1,096	565
	5	1,206	1,206	1,206	1,206	1,206	620

For event 2, contrary to event 1, although the second stage decisions for event 2 when ΔGW = 1 MAF are exactly the same as those of ΔGW = 0, the Lagrange multiplier is lower for the positive net aquifer filling goal, as event 1 becomes more dominant. Then the Lagrange multiplier suddenly bottoms when ΔGW = 2 MAF because the salinity of event 2 is less than critical, meaning one less unit of surface water will not decrease perennial crop yield. Finally, the Lagrange multiplier gradually increases as the net aquifer recharge goal becomes more demanding.

For events 3, 4, and 5, because there is no salinity problem with net refilling goals, the Lagrange multipliers gradually increase with increasing demand for artificial recharge (Figure 3.22).

Table 3.8. Lagrange multipliers ($/AF) in different events in different goals without salinity. Orange shade means pumping occurs. Blue shade means artificial recharge. Bold and italic value means annual crops are planted

	ΔGW (MAF)	Constraints					
		Dry	Surface Water			Wet	Groundwater Mass Balance
		Event 1	Event 2	Event 3	Event 4	Event 5	
Net Drawdown	-5	***60***	***60***	***60***	***60***	***60***	-28
	-4	***84***	***84***	***84***	***84***	***84***	-13
	-3	***111***	***111***	***111***	***111***	***96***	3
	-2	***142***	***142***	***142***	***142***	***96***	20
	-1	***176***	***176***	***176***	***176***	***99***	40
No overdraft	0	***222***	***222***	***222***	***190***	***107***	65
Net Refill	1	333	333	***247***	***212***	***212***	123
	2	936	936	820	820	820	427
	3	1,071	959	959	959	959	496
	4	1,096	1,096	1,096	1,096	1,096	565
	5	1,206	1,206	1,206	1,206	1,206	620

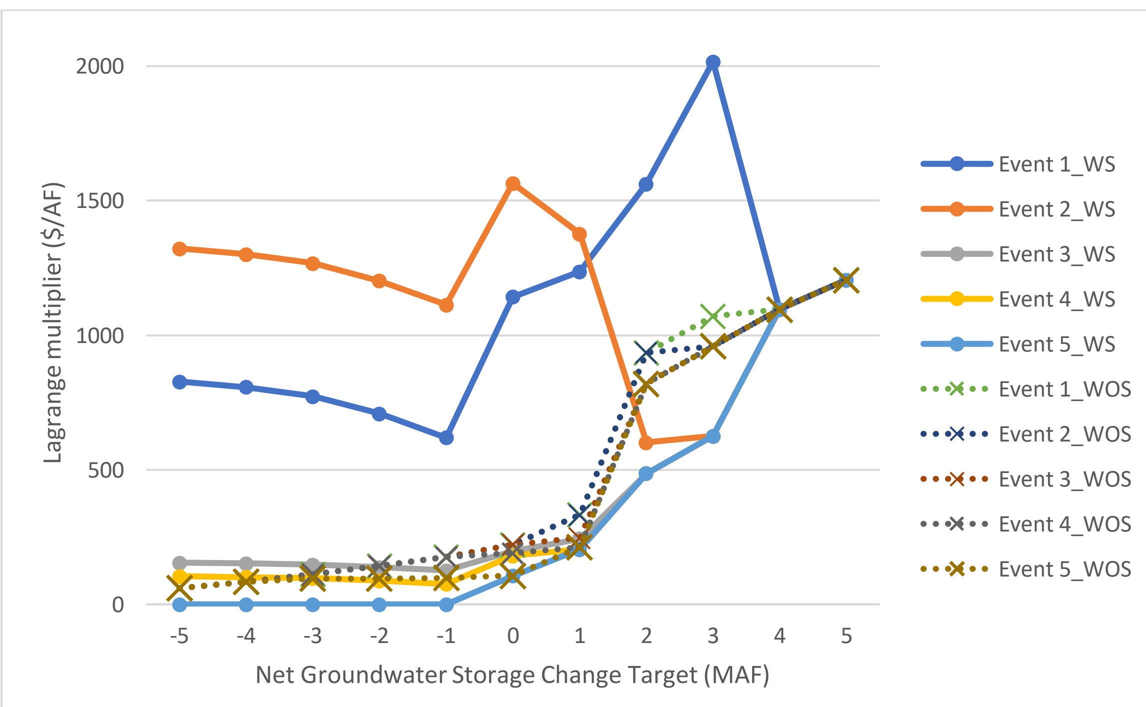


Figure 3.22. Lagrange multipliers of surface water for different events for aquifer storage changes with and without Salinity

By row, unlike Table 3.8 in which Lagrange multiplier values for drier events are never less than those for wetter events, the driest event (event 1) does not necessarily have the highest Lagrange multiplier in Table 3.7. The Lagrange multiplier of event 2 is greatest when ΔGW is less than 2 MAF (net refilling of 1 MAF, no overdraft, and all net drawdown goals) because the salinity of event 2 is right at or very close to the critical level under those goals. If surface water is limited, the perennial crop yield starts to drop; whereas the yield in event 1 is already impaired. Event 1 finally has a leading role in determining perennial crop acreage when ΔGW = 2 and 3 MAF, resulting in the highest Lagrange multiplier. For the most demanding restoring goals, as in Table 3.8, Table 3.7 has same value of Lagrange multipliers for all the events because artificial recharge dampens differences among events.

From Figure 3.22, another interesting phenomenon is that except for event 1, the Lagrange multipliers of the other 4 events with salinity can be less than those without salinity for the same groundwater storage change. When ΔGW = 1 MAF, the Lagrange multiplier values for events 3 to 5, with and without salinity, are very close to each other, but not the same. They are very close because we still grow annual crops in those events, which may be sacrificed first. They are not the same because one less unit of surface water can also mean one unit artificial recharge is missing, and one less unit of groundwater can be pumped in events 1 and/or 2. The saving from buying less land for artificial recharge and pumping one unit less of groundwater, and the increase in perennial crop yield in event 1 outweigh the decrease in perennial crop acreage. So, surface water Lagrange multipliers for events 3 to 5 with salinity are less than those events without salinity. When ΔGW = 2 MAF, no annual crops are planted in any event. So, the difference of surface water Lagrange multiplier values is not small anymore, and we lose less if we do not have that unit of surface water with salinity problems because we recharge less and pump less, but have a higher perennial crop yield.

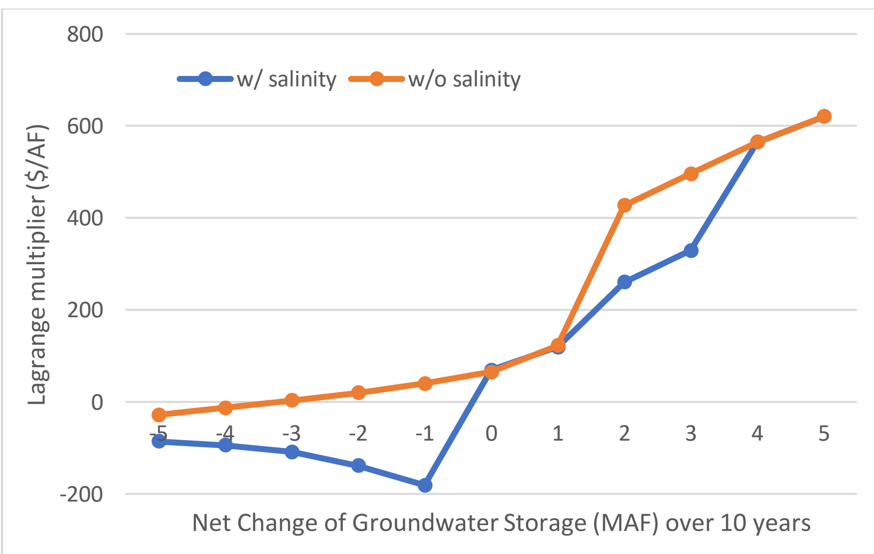


Figure 3.23. Groundwater goal Lagrange multipliers for different goals and aquifer salinity

Next, we look at Lagrange multipliers for the groundwater mass balance constraint. When ΔGW is most positive (refilling aquifer), each unit of groundwater has a great scarcity cost and a large Lagrange multiplier. For milder goals, the value diminishes gradually. For net drawdown of groundwater, unlike the low-salinity cases (Table 3.8), where the Lagrange multipliers turn negative when net pumping a **high** volume of groundwater (ΔGW > 3 MAF), both the increasing pumping cost and increasing salinity of the irrigation water from more pumping start to make the Lagrange multiplier negative as “early” as ΔGW = -1 MAF (or 0, if we take the reference from python’s Lagrange multiplier), confirming that total profit is highest when there is no overdraft (ΔGW = 0) in this example, as it has the least positive groundwater Lagrange multiplier. The increasing irrigation water salinity that decreases perennial crop yield also explains the Lagrange multiplier with salinity will be more negative than those without salinity for net aquifer drawdown.

Though still negative, the groundwater balance Lagrange multiplier does not become more negative as we pump more groundwater. Rather, the Lagrange multiplier becomes less and less negative (Figure 3.23). One explanation is we start to dump irrigation water as “early” as ΔGW = -1 MAF, and we dump more and more irrigation water as the net drawdown goal increases. So, that one unit of groundwater becomes a decreasing proportion of the total dumped irrigation water and less and less additional marginal profit we can have if we do not pump that unit of groundwater.

3.3.2 Probabilities of Hydrologic Events

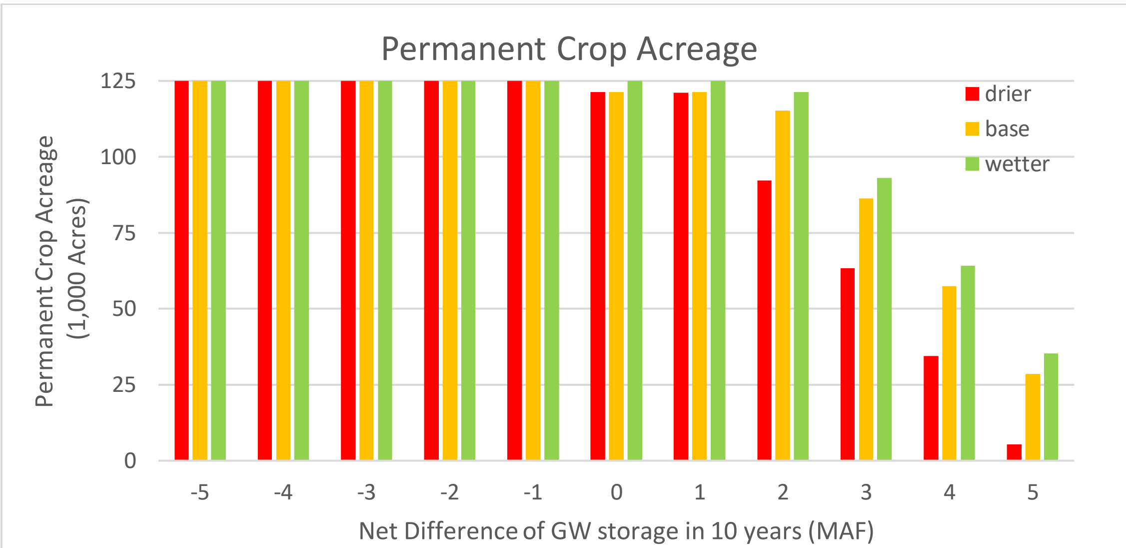
This part of sensitivity analysis changes the probability of some hydrologic events to create drier and wetter scenarios. Table 3.9 summarizes the probability distribution of each event in each case.

Table 3.9. Hydrologic event probabilities in each climate

Event *j*	Drier	Base	Wetter
Dry 1	0.25	0.2	0.15
2	0.25	0.2	0.2
3	0.2	0.2	0.2
4	0.2	0.2	0.25
Wet 5	0.1	0.2	0.2
Expected incoming surface water (TAF/yr)	519 (-13%)	599	622 (+3.8%)

Figure 3.24 illustrates the differences across scenarios. With net aquifer recharge goals, the wetter case with more surface water has the most perennial crops. The expected net profit in the wetter case also is the highest for almost all groundwater storage goals. On the contrary, the drier case greatly affects crop decisions and profit when we have a sizable net recharge goal (ΔGW ≥ 2 MAF). Because expected surface water is less available, a) it becomes dangerous to maintain extensive perennial crops; and b) less perennial crop means less deep percolation from surface water in wetter events, leading to more surface water use for artificial recharge in wetter events. With less profit from the perennial crop and higher cost for more artificial recharge, there are significant differences in perennial crop acreage and total profit between the drier and other cases. Negative profit occurs in the drier case when we seek to restore 5 MAF over the 10-year horizon. However, for higher net restoring goals, a drier climate has the least profit loss from the no-salinity cases because little groundwater is allowed to be pumped.

However, higher groundwater salinity dampens the difference among climate cases in determining perennial crop acreage for cases of aquifer drawdown (ΔGW < 0). And for all cases, the no-overdraft case has the highest profit because excess water is dumped and discharged even in the drier case when ΔGW = -1 MAF and no new perennial crops are planted. Also, in the two most demanding net drawdown goals, the base case has the lowest profit, because the drier case wastes less irrigation water, while the wetter case can dilute the irrigation water with more surface water.



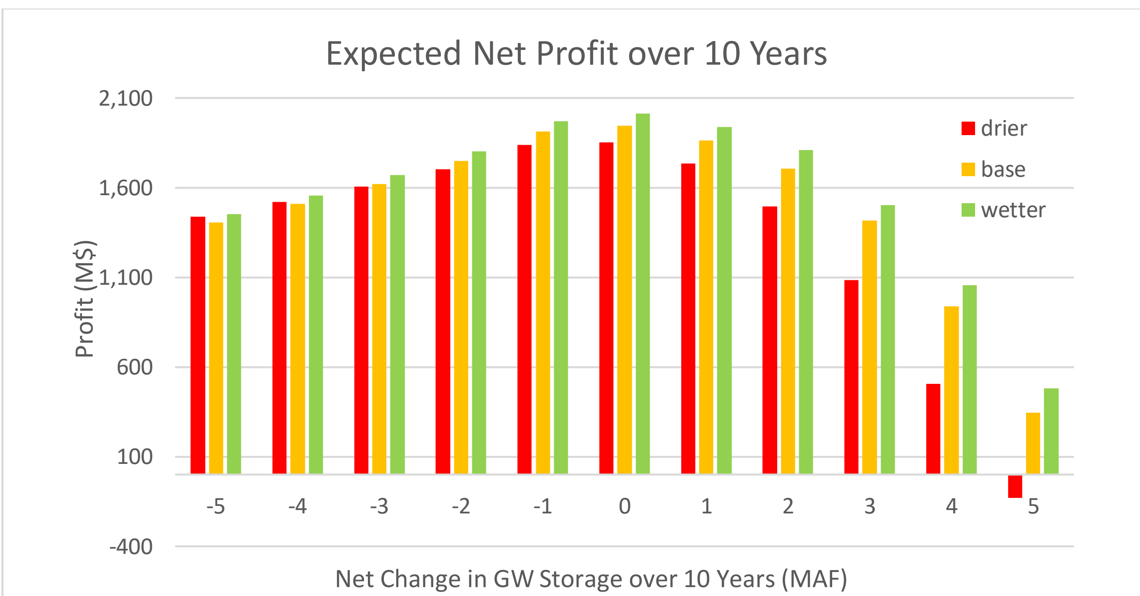


Figure 3.24. Perennial crop decisions and total expected net profit in present value under different climates with salinity ($C_{gw,t-1}$ = 3,000 mg/L)

3.3.3 Irrigation Efficiency Effects (φ = 0.15, 0.1, or 0.2)

Sections 3.2.2 and 3.2.3 show that with severe aquifer salinity no overdraft and even a net recharge goal can be the most profitable strategy as we dump irrigation water to meet the stochastic mass conservation of groundwater in net drawdown goals and the no-overdraft goal. Our intuition might be to increase irrigation efficiency (i.e., reduce deep percolation rate) a bit to see if net drawdown goals become more profitable.

Figure 3.25 shows differences in perennial acreage and total profit for different irrigation efficiencies. With net refilling goals, a lower irrigation efficiency (a higher return flow fraction φ) increases perennial crop acreage and profit, because deep percolation from irrigating perennial crops recharges groundwater and less land is needed for artificial recharge. Lower irrigation efficiency also works best in the no overdraft case.

However, with net aquifer drawdown goals, higher irrigation efficiency (less deep percolation) requires less pumping to accomplish groundwater drawdown, which reduces irrigation water salinity and increases perennial crop yield. Also, for substantial groundwater salinity ($C_{gw,t-1}$ = 3,000 mg/L), rather than the no overdraft case, the net drawdown goal of 1 MAF with high irrigation efficiency has the highest profit of all positive aquifer drawdown goals and irrigation efficiencies.

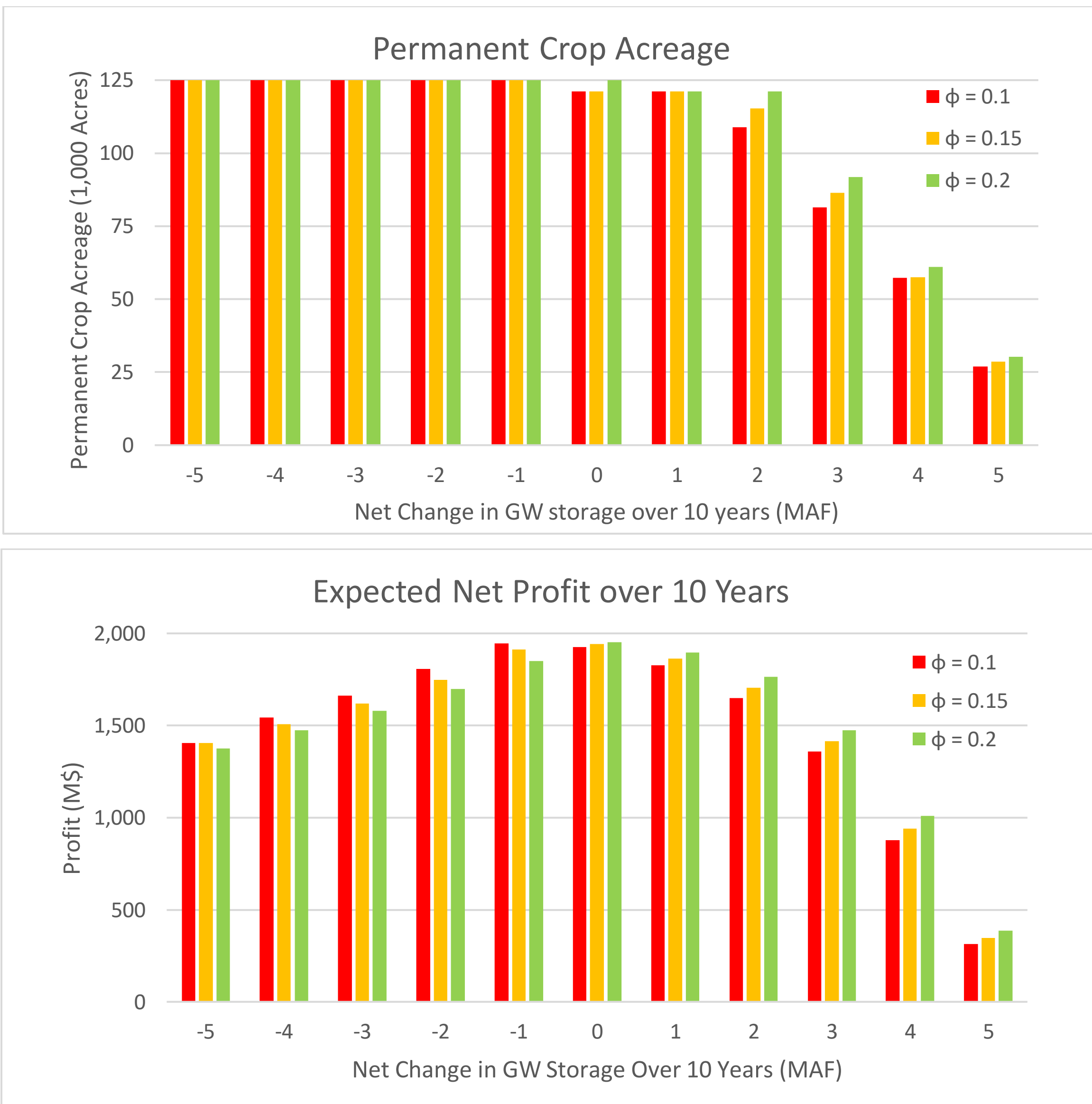


Figure 3.25. Perennial crop decisions and total expected net profit in present value under different irrigation efficiency, return flow fraction, with salinity ($C_{gw,t-1}$ = 3,000 mg/L)

When ΔGW ≥ 4 MAF, the sensitivity to irrigation efficiency is irrelevant with salinity because recovery goal is so demanding that water scarcity overwhelms water quality. There is no simple conclusion on sensitivity to irrigation efficiency with and without salinity for mild restoring goals and no-overdraft goal. For ΔGW = 0, 2 and 3 MAF, total profit is more sensitive to irrigation efficiency without salinity whereas for ΔGW = 1 MAF, total profit is less sensitive. The relationship among perennial crop acreage and perennial crop yield, and the cost for artificial recharge need to be discussed case by case. For net drawdown goals, because with salinity, different irrigation efficiencies result in different amount of irrigation water to be dumped, while without salinity there is no such problem, it is more sensitive to irrigation efficiency with salinity.

Conclusions

A hydroeconomic optimization model of conjunctive use for irrigated agriculture with groundwater salinity provides a variety of fundamental and applied insights for water and agricultural management in regions with brackish and salinizing aquifers, common in many parts of the world, and in California. The presence of groundwater salinity can dramatically change the optimal strategies for conjunctive use of groundwater and surface water for agriculture, especially when groundwater salinity is relatively high ($C_{gw,t-1}$ ≥ 3,000 mg/L).

1. Optimal conjunctive use changes profoundly as groundwater becomes more saline. Higher groundwater salinity reduces pumping in the driest years because less fresh surface water is available to dilute more saline groundwater. More groundwater is pumped in wetter years than without salinity, because wetter events have more surface water to dilute pumped groundwater and more pumping is needed in non-dry years to attain aquifer storage change goals.
2. The modelled salinity's longer-lasting harm to perennial crops in the driest event reduces overall profit and perennial crop acreage. Because groundwater salinity can be diluted least during the driest events, and perennial crop yield is most affected from high salinity of irrigation water. In these driest events, annual crops are not grown, because available surface water is better invested in perennial crop acres. When salinity is mild, profit loss can be minimized by shifting some pumping to wetter events. However, with higher groundwater salinity, profit loss increases and perennial crop acreage and yield further decrease.
3. Artificial recharge is not needed for groundwater drawdown (net drawdown) targets and, in this example, for a no-overdraft target. From the model's numerical optimization results, decisions on pumping and perennial and annual crop acreage with groundwater can be reduced to an algorithm which accounts for irrigation water salinity:
    - Step 1: based on the targeted groundwater storage change, the groundwater salinity, and incoming perennial crop acreage, select the driest event A to be the first event having the critical irrigation water salinity (EC) threshold not affecting perennial crop yield. Event A might not be the driest event (event 1), because if irrigation water salinity of event 1 is set to the critical level, many incoming perennial crops will be retired. Event A could be a less dry event, as more impaired perennial crop acres can have more profit than fewer perennial crop acres with full yield in the driest events.

- Step 2: considering the perennial crop yield decrease in events drier than event A and perennial crop initial establishment cost, find the perennial crop acreage for the planning horizon with the maximum expected profit. If all irrigation water in event A is used for perennial crops, events drier than event A must pump more groundwater, irrigating perennial crops with saltier water that decreases perennial crop yield. There is a tradeoff between the acreage and yield of perennial crops. More impaired perennial crops can have more or less profit than fewer perennial crops with full yield in event(s) drier than event A, so the perennial crop acreage needs to be determined case by case.
- Step 3: for events wetter than the pivotal event A, if there is still a sizable amount of groundwater to pump (to achieve the average groundwater storage target), let the drier event hit critical salinity threshold first. This increases annual crop acreage in that event compared to no salinity cases, although annual crop acreage should not be higher than in wetter events. If there is little groundwater left to pump, we pump the same as in no salinity cases that removes the difference of the incoming surface water among different events.

4. With high groundwater salinity, groundwater can be externally discharged (dumped) to meet the no-overdraft goal, where possible, which removes some salt mass and excess recharge, but adds pumping cost for groundwater not fully used for irrigation. A target to restore the aquifer can be more profitable, because some saved groundwater pumping cost and artificial recharge cost can offset some lost perennial crop production from less available irrigation water.
5. For groundwater storage targets that increase aquifer storage, pumping in drier events is not always based on irrigation water salinity. The trade-off between perennial crop acreage and yield needs to be calculated for each case. Some perennial crops can be retired to reduce groundwater pumping in the driest events, to help preserve perennial crop yield. However, artificial recharge still dampens variability in incoming surface water. As groundwater salinity increases, fewer perennial crops are maintained, more annual crops are planted in wetter years, and less pumping and artificial recharge occur.
6. Even saline groundwater makes fresher surface water more economically valuable in drier events, due to blending. This is especially true for the second driest event whose surface water Lagrange multiplier is the highest for most targets. Dry rather than critically dry water years can be the key water year type that determines perennial crop acreage. High surface water Lagrange multiplier values mean less surface water drives reduction in both perennial crop acreage and yield (due to less salinity dilution). Higher aquifer salinity also devalues groundwater. Lagrange multipliers for groundwater are more negative for net drawdown targets, which force more costs for pumping and disposal of less useful groundwater.
7. For net aquifer recovery goals, optimal perennial crop acreage decisions do not change with salinity for different climate cases, because groundwater is pumped less, and does not greatly reduce perennial crop yield. With or without salinity problems, a wetter climate is more profitable. However, for higher net restoring goals, a drier climate has the least profit loss from the low-salinity case because little groundwater is allowed to be pumped. For net drawdown goals, salinity dampens the difference from climate because

less irrigation water needs to be eliminated in drier climates, while more surface water can dilute groundwater in wetter climates.

8. Changing irrigation efficiency can help offset groundwater salinity. For net aquifer replenishment, lower irrigation efficiency increases profit by recharging more through deep percolation (decreasing cost for artificial recharge). With net drawdown goals, higher irrigation efficiency can make a net drawdown goal of 1 MAF the most profitable, because less deep percolation means less groundwater pumping and less salt in irrigation water to reduce perennial crop yield.

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Chapter 4: Long-term Optimization of Crop and Conjunctive Water Use Decisions without Groundwater Salinity

Abstract

Allocating water to crops and aquifer recharge is of growing importance in California and other parts of the world as water managers and regulators seek to end chronic groundwater overdraft. However, ending overdraft with the least economic loss is a challenge, especially for agriculture. This chapter examines the trade-off between crop profits and groundwater storage recovery where groundwater salinity is not a concern. A 10-year stochastic quadratic model (from Chapter 2) is embedded in a 10-stage (10 year per stage) dynamic programming optimization (outer model) to develop optimal long-term (100-year) decisions on perennial and annual crop acreages and conjunctive water use operations for various aquifer recovery goals with a stationary stochastic surface water availability, maximizing net expected economic benefits of crop production and conjunctive use. The best combination of groundwater storage and permanent crop acreage are found over stages from the outer (dynamic programming) model, with corresponding decisions on annual crop acreage, groundwater pumping and artificial recharge for each stage from the inner (quadratic programming) model. Model results indicate that without salinity, maximal possible perennial crops are planted since the beginning of the planning horizon until the last stage to reduce perennial crops' high initial establishment cost for later stages. For these conditions, groundwater storage always hits the minimum regardless of the initial groundwater storage, where it remains until late in the planning horizon, as the ultimate storage target takes control, rising with the aid of artificial recharge.

Keywords: Dynamic programming, stochastic quadratic programming, overdraft, conjunctive operations

1. Introduction

Groundwater overdraft can threaten the sustainability of economic activities, especially for irrigated agriculture in many parts of the world. The problems of groundwater depletion tend to worsen during drought (Harou and Lund 2008; Gailey et al. 2019). Higher-value perennial crops are more vulnerable to drought and reduced groundwater availability than annual crops because perennial crops cannot be fallowed easily for a single season without high additional re-establishment and replacement costs (Arellano-Gonzalez and Morre 2020). Allocating water supply to crops and aquifer recharge is of growing importance in globally and in California as SGMA requires water agencies of critically over-drafted basins to end overdraft.

Ending historical overdraft with the least economic loss is a challenge for irrigated agriculture. Conjunctive use of surface water and groundwater can greatly reduce the costs of ending overdraft (Harou and Lund 2008, Dogan et al. 2019). This chapter examines optimal long-term groundwater management with conjunctive use to both recover groundwater storage and maintain maximum agricultural profit.

Many simulation/optimization models have been developed to plan and evaluate conjunctive operations by including surface water and aquifer interactions. Four major groups of programming techniques used for conjunctive water use optimization are: Linear Programming (LP), Nonlinear Programming (NLP), Genetic Algorithms, and Dynamic Programming (DP) (Singh 2015). LP models may produce many equally optimal solutions (Gorelick et al. 1984; Sedki and Ouazar 2011; Singh 2014), and have difficulty representing real diminishing economic returns for the initially most profitable crops (Hazell and Norton 1986; Howitt 1995). These limitations lead to the use of NLP (Yeh 1985; Shang and Mao 2006), which is applied in Chapters 2 and 3.

The ability to model sequential decision-making with a nonlinear objective function, makes DP appropriate and popular for long-term water resources optimization (Yakowitz 1982). DP has been extensively used for conjunctive water use (Buras 1963; Burt 1964, 1966; Aron 1971; Panda 1992; Philbrick and Kitanidis 1998; Karamouz et al. 2004; Azaiez 2005). Computational efficiencies and costs are strongly influenced by the number and discretization of state variables. Therefore, DP has been limited to problems with few periods and two or three state variables.

The problem of irrigation scheduling from a limited seasonal water supply has been studied extensively for single crop situations (Jones 1983). However, many farming situations involve several crops grown in the same season (Yaron et al. 1987; Rao et al. 1990). DP optimization models, deterministic (Yaron and Dinar 1982; Paul et al. 2000; Karamouz et al. 2004; Prasad et al. 2006), stochastic (Dudley et al 1971; Dudley and Burt 1973; Gupta and Chauhan 1986; Davidsen et al. 2015; Soleimani et al. 2016; Anvari et al. 2017), or fuzzy (Safavi and Alijanian 2011) are also widely used for deriving optimal irrigation policies by allocating land and water resources in single- or multi- crop agricultural systems in (semi)arid areas.

Many studies apply DP to deriving an optimal **convergent** steady-state reservoir and/or aquifer operating policy (Buras 1963; Burt 1964; Aron 1971; Ghahraman and Sepaskhah 2002) because the hydrologic condition is assumed to be stationary (but stochastic) and there is no enforcement to recover groundwater storage. Others use DP to maximize the expected annual sum of relative crop yields regardless of the selling price of each crop (Vedula and Kumar 1996), or to meet agricultural water demands, to reduce pumping costs, and to control groundwater fluctuation (Karamouz et al 2004) as crop acreage is not a decision variable.

Though aquifer management is not part of their discussion, as reservoirs are their major focus, some studies use DP frameworks to derive both intra-seasonal and inter-seasonal optimal water allocation strategy (Yaron and Dinar 1982; Rao et al. 1990; Paul et al. 2000; Ghahraman and Sepaskhah 2002). The optimization is often divided into two modules. The first module, either LP, NLP or DP, maximizing the sum of crop net benefits (of either single- or multi- crop systems), is an intra-seasonal model for allocation decisions **within** a season, given seasonal inputs such as the reservoir storage at the beginning and end of the season. The second module uses DP to make decisions **across** seasons to maximize economic system performance.

This paper extends the two-module approach. The first module (inner model) is a short-term stochastic quadratic model for deriving economically optimal conjunctive water use operations and annual crop acreage, detailed in Chapter 2. The second module (outer model) is a long-term DP that takes output of inner model and obtains the best combination of groundwater storage and perennial crop acreage for each stage. Though basic irrigation parameters such as evaporation and soil moisture are represented by the term "applied water" in this model, making it less physically rigorous, this model can present a 100-year (10 10-year stages) long-term profit-maximizing farmers' conjunctive water use strategy and crop mix decision to meet a specific groundwater storage target without considering salinity or dynamic climate uncertainty.

2. Method

2.1 Model Formulation

The long-term planning horizon is composed of N+1 T-year shorter-term planning stages (from stage t = 0 to stage t = N, N = 9). T is set to 10 to represent that perennial crops acreage cannot be changed easily according to hydrologic events compared to annual crops. For simplicity, a fixed inflation-adjusted discount rate r converts future values to present value. So, the present value of profit in the k-th year of the t-th T-year stage is the future value of profit of that year discounted by a factor of $\frac{1}{(1+r)^{tT+k}}$.

For each stage t, two state variables are initial groundwater storage GW_{t-1} and incoming perennial crop acreage $X_{p,t-1}$; final groundwater storage GW_t and perennial crop acreage **BEFORE** retirement $X'_{p,t}$ are the two decision variables determined in the outer DP model. The final groundwater storage of stage t, GW_t, is the initial groundwater storage of **stage t+1**, while half of the perennial crops enter stage t+1 due to the retirement (i.e., $X_{p,t} = \frac{1}{2}X'_{p,t}$). The state of the system is governed by the stochastic conservation of mass of groundwater storage.

An objective function (inner model) describes the economic consequence of decisions and states. Let $P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right)$ be the expected net **present** economic value of having groundwater storage from GW_{t-1} to GW_t, and having perennial crop acreage of $X'_{p,t}$ before retirement with perennial crop acreage of $X_{p,t-1}$ already in place. The overall objective is to maximize the sum of expected net **present** value from stage t = 0 to stage t = N:

$$\text{Max} \sum_{t=0}^{N} P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right) \qquad (4.1)$$

The backward recursive function for this DP (outer model) is:

$$f_t\left(GW_{t-1},\ X_{p,t-1}, GW_t, X'_{p,t}\right) = \begin{cases} P_N\left(GW_{N-1},\ X_{p,N-1}, GW_N, X'_{p,N}\right), & t = N \\ P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right) + f^*_{t+1}\left(GW_t, X_{p,t} = \frac{1}{2}X'_{p,t}\right), & t = 0 : N-1 \end{cases} \tag{4.2}$$

When t = 0 to N-1, the recursion consists of two parts. $P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right)$ contains the direct present value of profit of the decision in stage t, GW_t and $X'_{p,t}$, given the state GW_{t-1} and $X_{p,t-1}$. $f^*_{t+1}\left(GW_t, X_{p,t}\right)$ is the accumulation of the best decisions from all later stages starting with groundwater storage GW_t and perennial crop acreage of $X_{p,t}$ (=$\frac{1}{2}X'_{p,t}$).

$P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right)$ is called the inner model (Equation (4.3)), because the negative value of P_t needs to be minimized to derive the optimal short-term (T-year) decision of annual crop ($X_{a,j,t}$) and conjunctive water operation (land for recharging $X_{r,j,t}$ and groundwater pumped $W_{p,j,t}$) in stage t with j possible hydrologic events having probabilities of occurrence p_j, given the initial and final groundwater storage, GW_{t-1} and GW_t incoming perennial crop acreage, $X_{p,t-1}$, and perennial crop acreage before retirement, $X'_{p,t}$.

$$\min\left[-P_t\left(GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}\right)\right] = -P_{p,t}\left(X_{p,t-1}, X'_{p,t}\right) - P_{a,t}\left(X_{a,j,t}\right) + C_t\left(X_{r,j,t}, W_{p,j,t}, GW_{t-1}, GW_t\right) \tag{4.3}$$

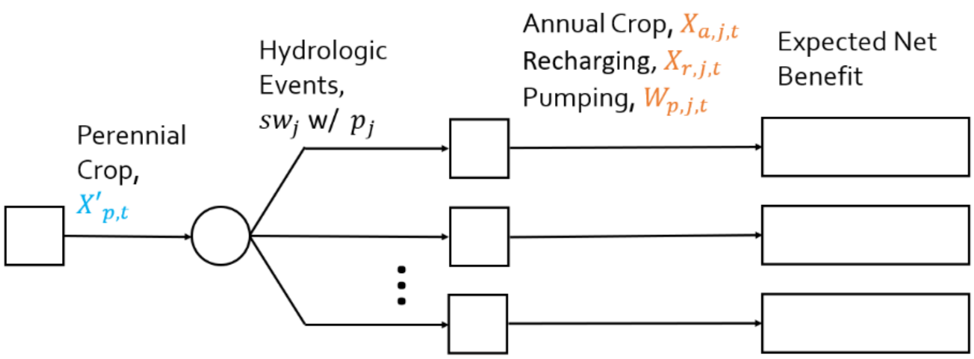


Figure 4.1. Problem decision tree for within-stage stochastic optimization (inner model)

Figure 4.1 depicts P_t's structure. In stage t, the incoming perennial crop acreage $X_{p,t-1}$ is both a state variable in outer DP and an input parameter of inner model; the perennial crop acreage before retirement $X'_{p,t}$ is a decision variable in outer DP but an input parameter for the inner model; the annual crop acreage decision $X_{a,j,t}$, the land used for artificial recharge $X_{r,j,t}$, and pumping $W_{p,j,t}$ for each hydrologic event j are decision variables in the inner model; and the initial groundwater storage GW_{t-1} (state variable of outer DP) and final groundwater storage GW_t (decision variable of outer DP), are input parameters for calculating pumping cost and appear in the binding constraint of Z_t, which is stochastic mass conservation of groundwater storage. The only difference between P_t and the two-stage stochastic quadratic model in Chapter 2 is that in P_t, the perennial crop acreage is given by the outer DP model as $X'_{p,t}$, rather than being determined so the profit is maximized. More detail of P_t function appears in Chapter 2.

2.2 Model Computation Speed-up

Dynamic programming is as brutal as enumeration within each stage, as we need to calculate P_t for every permutation of two state variables ($GW_{t-1}, X_{p,t-1}$) and two decision variables ($GW_t, X'_{p,t}$), with the other decision variables solved by the NLP from Chapter 2. However, the characteristic of P_t is so favorable that the optimal solution does not change with stage t once the input parameters ($GW_{t-1}, X_{p,t-1}, GW_t, X'_{p,t}$) are given. Following is the proof.

In Equation (4.3), we know P_t contains three parts: the expected net profit of perennial crops of stage t, $P_{p,t}$; the expected net profit of annual crops of stage t, $P_{a,t}$; and the expected water operational cost of stage t, C_t. Since for the inner model, $X'_{p,t}$ is now given, $P_{p,t}$ is irrelevant to the determination of $X_{a,j,t}$, $X_{r,j,t}$, and $W_{p,j,t}$.

$P_{a,t}$ is the sum of yearly expected net benefits of annual crops (the product of annual crop profit in hydrologic event j and the probability of the that hydrologic event, p_j) multiplied by the discount factor. It is a sum of a geometric series as p_j's remain the same throughout the entire planning horizon, for the stationary hydrology and crop prices. Having $P_{a,t}$ divided by $P_{a,t+1}$, we find the ratio is $(1+r)^T$, which is a constant. C_t and C_{t+1} have the same relationship as C_t is also a sum of geometric series.

So, we only need to derive the optimal solution vector ($X_{a,j,t}, X_{r,j,t}, W_{p,j,t}$) for all the combination of $GW_{t-1}, X_{p,t-1}$, GW_t, and $X'_{p,t}$ for one random t, record these optimal solutions, and feed the solution to Equation (4.3) for other stages instead of deriving the solution again and again. This greatly reduces computational time. This computational convenience would not be available where hydrology or other factors are non-stationary, making climate change studies more computationally challenging.

$$
\begin{aligned}
P_{a,t}(X_{a,j}) &= \frac{1}{(1+r)^{tT+1}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j,t}\right)X_{a,j}\right] \\
&\quad + \frac{1}{(1+r)^{tT+2}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] + \cdots \\
&\quad + \frac{1}{(1+r)^{tT+10}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\
&= \frac{1-(1+r)^{-T}}{(1+r)^{tT}\times r}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right]
\end{aligned} \tag{4.4}
$$

$$
\begin{aligned}
P_{a,t+1}(X_{a,j}) &= \frac{1}{(1+r)^{(t+1)T+1}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\
&\quad + \frac{1}{(1+r)^{(t+1)T+2}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] + \cdots \\
&\quad + \frac{1}{(1+r)^{(t+1)T+10}}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right] \\
&= \frac{1-(1+r)^{-T}}{(1+r)^{(t+1)T}\times r}\sum_{j=1}^{5} p_j\left[(v_a yld_a)X_{a,j} - \left(\alpha_a + \frac{1}{2}\gamma_a X_{a,j}\right)X_{a,j}\right]
\end{aligned} \tag{4.5}
$$

2.3 Model Assumptions

Several underlying assumptions are worth discussing. First, for simplicity, we assume 50% of perennial crops are retired at the end of each 10-year planning period, instead of retiring 5% of perennial crops annually. This imperfectly represents the farming reality, but this assumption avoids the reallocation of water from more continuous perennial crop retirement. Second, water from deep percolation and artificial recharge will be considered available within a stage. This is possible when groundwater storage is large enough and the stage time scale is long enough not to constrain the transfer. Third, because salinity is not considered, full crop yield is always achieved. Lastly, the state of the system is governed by the stochastic conservation of mass for groundwater storage, meaning the final groundwater storage is actually an expected one rather than an exact one, and so might overestimate or underestimate total profit.

Only one perennial crop and one annual crop are considered, no urban water use or water transfer decisions are considered, making this model less able to represent mixed agriculture and urban production. Also, to reduce computational burden, the discretization of groundwater storage and perennial crops is coarse, making the derived groundwater management strategy subject to change once discretization becomes finer. Still, it emphasizes a more detailed representation of agricultural profit in a 100-year period. Further, the model can derive an optimal solution from any initial groundwater storage to one specific final storage as long as they are available in the discretization with variable pumping costs due to groundwater storage change being considered.

2.4 Illustrative Example

The example application has a limited planting area and underlying aquifer, with parameters summarized in Table 4.1. The planting area is similar to the sum of acreage of almonds and alfalfa in northern San Joaquin Valley, California. The unit prices of class 1 and class 2 water are based on the Chowchilla water district. The unit price of energy is adopted from Statewide Agricultural Production (SWAP) model for North San Joaquin Valley (DWR 2012). The capacity of land for recharge is based on USACE's Conjunctive Use for Flood Protection Study (USACE 2002). This example has a range of initial groundwater storages (from 8 to 12 MAF), and a range of incoming perennial crop acreages (from 25,000 to 75,000 acres) at the first stage. The discretization of groundwater storage and perennial crop acreage in the dynamic program are 0.5 MAF and 10,000 acres, respectively.

Table 4.2 and Figure 4.2 summarize the current stationary annual surface water availability $sw \sim logN(\mu = 625{,}000\ AF,\ \sigma = 400{,}000\ AF)$. To simplify the problem, the averaged surface water inflow of each hydrologic event is represented by the 10th-, 30th-, 50th-, 70th- and 90th-percentile of the distribution, so we assume the probability of each hydrologic event is the same, which is 1/5 * 100% = 20%.

Table 4.1. Basic parameters of crops and irrigation area

Symbol	Parameter (unit)	Value
T	Length of planning horizon (yr)	10
L	Total available area (acre)	500,000
H_o	Initial pump head (ft)	200
B_o	Initial thickness of the aquifer (ft)	200
s_y	Aquifer specific yield	0.1
r	Constant discount rate	3.5%
ini_p	Perennial crop initial establishment cost ($/acre)	12,000
c_{land}	Unit price of land for recharging ($/acre)	300
c_{class1}	Unit price of class 1 (firm contract) water ($/AF)	42
c_{class2}	Unit price of class 2 (surplus) water ($/AF)	30
$class1$	Amount of firm contract water (TAF)	500
c_e	Unit price of energy ($/kWh)	0.189
η_p	Pumping efficiency	0.7
cap	Capacity of land for recharging (AF/acre/yr)	15
$1-\varphi$	Irrigation efficiency	0.85
aw_p	Applied Water of perennial crop (ft)	4.07
aw_a	Applied Water of annual crop (ft)	4.84
yld_p	Maximum yield of perennial crop (ton/acre)	1
yld_a	Maximum yield of annual crop (ton/acre)	8
v_p	Unit price of perennial crop ($/ton)	4226.68
α_p	Perennial crop's intercept of PMP cost function ($/acre)	1502.85
γ_p	Perennial crop's slope of PMP cost function ($/acre^2)	0.00795
v_a	Unit price of annual crop ($/ton)	157.28
α_a	Annual crop's intercept of PMP cost function ($/acre)	635.91
γ_a	Annual crop's slope of PMP cost function ($/acre^2)	0.00294

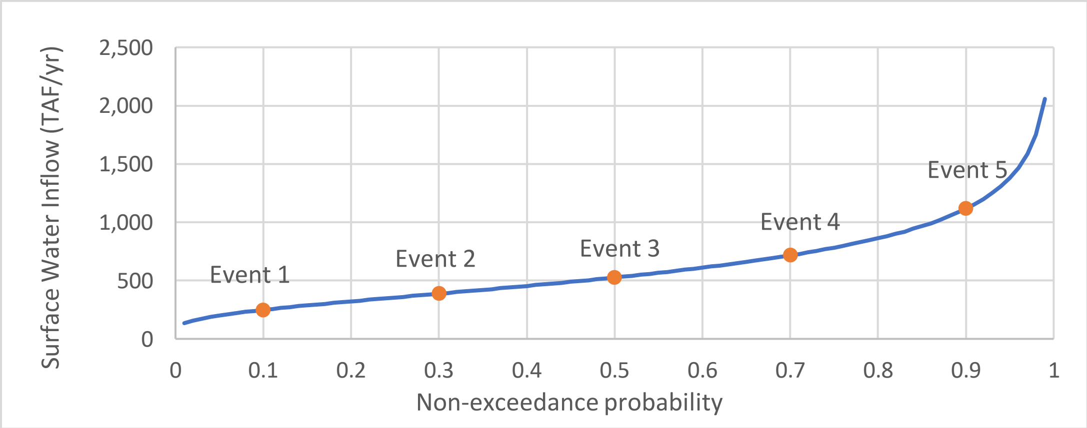


Figure 4.2. "Averaged" surface water inflow of each hydrologic event

Table 4.2. Available surface water in each hydrologic event

	Event j	Percentile	sw_j (TAF/yr)	p_j
Dry	1	10th	248	0.2
	2	30th	387	0.2
	3	Median	526	0.2
	4	70th	716	0.2
Wet	5	90th	1,115	0.2

3. Results and Discussion

The first results explore how many perennial crops should be planted at the beginning of each stage and the corresponding conjunctive use operation at each stage. One of the most important observations from this model is that a higher discount rate drives artificial recharge to be deferred until the last stage to minimize overall present value cost.

3.1 Base Case

Base case is the situation where $X_{p,o}$ = 50,000 acres, r = 3.5%, with base climate and an ending storage target = 10 MAF.

Table 4.3. Net present value of total profit (M$) over 10 stages increases with starting groundwater storages and perennial crop acreages (discount rate = 3.5%, ending storage = 10 MAF)

Initial groundwater storage, GW_o (MAF)	Initial perennial crop acreage, $X_{p,o}$ (Acres)				
	30,000	40,000	50,000	60,000	70,000
8	4,791	4,906	5,022	5,138	5,254
8.5	4,829	4,945	5,061	5,177	5,293
9	4,861	4,977	5,093	5,209	5,325
9.5	4,890	5,006	5,122	5,238	5,354
10	4,917	5,033	5,149	5,265	5,381
10.5	4,944	5,060	5,176	5,292	5,408
11	4,971	5,087	5,203	5,319	5,435
11.5	4,997	5,113	5,229	5,345	5,461
12	5,024	5,140	5,256	5,372	5,488

Table 4.3 shows the net present value of total profit over 10 stages (100 years) with different initial groundwater levels (GW_o) on rows and different incoming perennial crops in the first stage ($X_{p,o}$) by column. Redder shades mean less profit, and greener shades higher profit. By column, with the same incoming perennial crops in the first stage, greater initial groundwater storages have higher profits, because more groundwater can be pumped to grow more crops without worrying about salinity. By row, with same initial groundwater storage, more incoming perennial

crops results in higher profits. This is also reasonable, but we want to see if $X_{p,o}$ only affects the profit of the first stage.

For the most unfavorable initial groundwater storage, 8 MAF, different $X_{p,o}$ do not affect the perennial crop acreage decision. The model always selects 150,000 acres (the highest alternative) of perennial crops in the first stage. So, later in this section, we use $X_{p,o}$ = 50,000 acres to present comparisons for different initial groundwater storages.

The decision of 150,000 acres of perennial crops in the first stage, even for lowest groundwater storage (8 MAF), itself is interesting. Table 4.4 shows the difference between a short-sighted solution (optimal solution for **any single stage** from Chapter 2) and a solution that leads to the long-term optimal solution (optimal solution for **the first stage** from this chapter) for a no-overdraft goal with initial groundwater storage of 8 MAF. The shorter-sighted model in Chapter 2 gives an optimal beginning perennial crop acreage of 116,283 acres. However, with the model in Chapter 2 now embedded in a DP framework, the long-term DP optimal solution starts the perennial crop acreage with 150,000 acres, regardless of the incoming perennial crop acreage.

Table 4.4. Comparison of short-term steady-state solution and longer-term DP solution when GW_o = 8 MAF (lowest allowable groundwater storage), with no-overdraft for Stage 1

		Short-term (Chapter 2)	Longer-term DP (Chapter 4)
Final groundwater storage (MAF)		8	8
Perennial crop acreage (acre/stage)		116,283	150,000
Annual crop acreage (acre/yr)	Events 1 - 3	18,624	0
	Event 4	50,103	21,750
	Event 5	132,676	75,136
Land for artificial recharge (acre/yr)	Events 1 - 4	0	0
	Event 5	0	9,418
Groundwater pumping (AF/yr)	Event 1	314,971	362,058
	Event 2	176,251	223,339
	Event 3	36,992	84,080
	Events 4 - 5	0	0
Profit of the stage in present value (M$)		1,364	1,309

The greater perennial crop acreage reduces the corresponding annual crop acreage and changes conjunctive water use decisions in each hydrologic event. The first and greatest difference is that the longer-term DP solution at stage 1 employs artificial recharge in the wettest event, because incoming surface water in drier events cannot support all perennial crops without supplemental groundwater banked from wetter years. So, much more groundwater is pumped in the three drier events and no annual crops are planted in drier events. Lastly, the annual crops in the two wettest events are much less than those in the short-term solution because in event 4 more perennial crops leave less surface water for annual crops and in event 5 some surface water is used for artificial recharge.

Though more perennial crop acreage increases benefits from perennial crop production, greater initial establishment cost for the additional 33,717 acres of perennial crops and conjunctive water operation cost for pumping and artificial recharge, and lower annual crop profit drag down final profit of the longer-term DP solution from short-term solution by $55 million (1,364 – 1,309 M$). The longer-term DP solution chooses a less profitable solution in the first stage because planting highest allowable acreage of perennial crops increases profit in later stages as more perennial crops enter next stage and less initial establishment cost for perennial crops is required. A short-term solution does not support the optimal solution over the entire 10 stage horizon.

Figure 4.3 shows the groundwater storage change across stages with different initial groundwater storage from 8 MAF to 12 MAF and with incoming perennial crop acreage of 50,000 acres. The discount rate of 3.5% is relatively high, so the present value of costs in later stages is lower and becomes less important. Therefore, pumping and net profits occur in early stages until we reach lowest allowable storage, 8 MAF, then no further overdraft occurs until stage 9, then groundwater is recovered to the ending target value in the last stage. Again, except for the last stage, with base climate, maximal acreage of perennial crops is planted (Table 4.4).

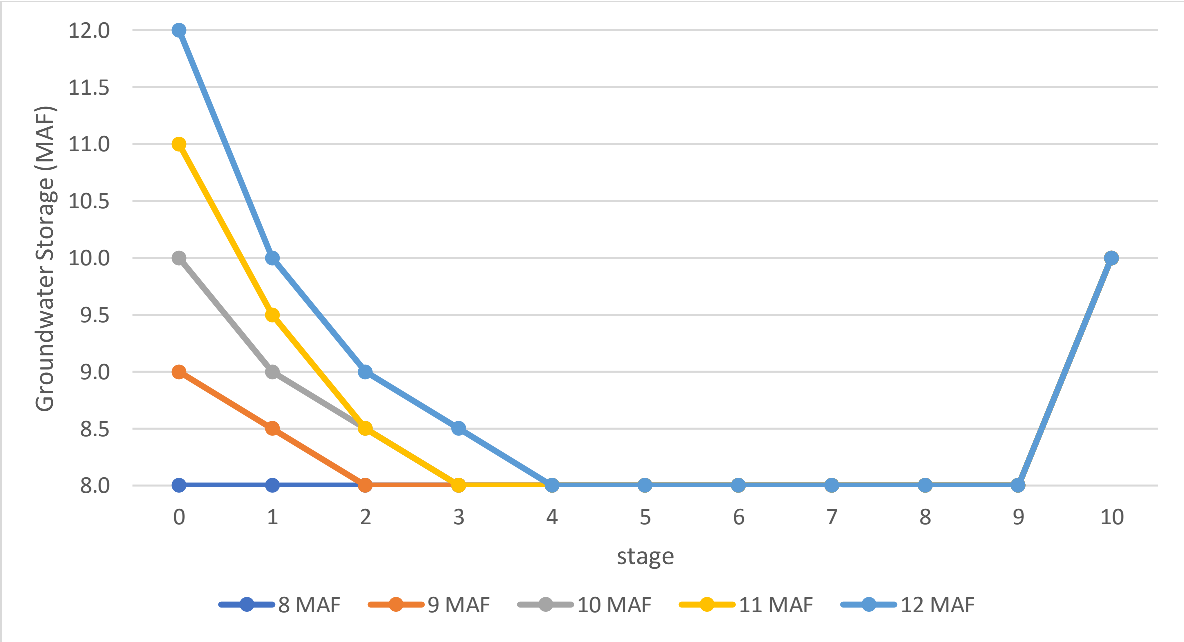


Figure 4.3. Groundwater storage change over stages with r = 3.5%

Because the discount rate is relatively high, and without salinity, more pumping increases profit (see Chapter 2 for details). So, the model pumps more in earlier stages, pumping gradually less in later stages until the lowest allowable storage is finally reached. For example, when starting with 12 MAF, the first stage pumps 2 MAF, then 1 MAF in the second stage, and only pump 0.5 MAF per stage in stages 3 and 4. However, from Chapter 2, 3 MAF has the highest profit.

Table 4.5 compares pumping decisions for the short-term steady state and the longer-term DP solutions for GW_o = 12 MAF with a pumping goal for Stage 1. First, rather than pumping 3 MAF as short-term solution, the longer-term DP solution only pumps 2 MAF in the first stage. It is reasonable to save some groundwater to increase profit in later stages and increase summed discounted profit over 10 stages. Second, even only pumping 2 MAF in the first stage, to save initial establishment cost for the next stage, the model has 150,000 acres of perennial crops, while the short-term solution has only 134,264 acres of perennial crops with 3 MAF pumped. Because there are more perennial crops with less groundwater to pump, there is less profit from fewer annual crops. Although there are lower pumping cost and higher perennial crop benefits, more initial establishment cost for perennial crops and less profit from annual crops still make total profit over the first stage for the longer-term DP solution less by $34 million (1,486 –1,452 M$) than that of the short-term solution. Again, the short-term solution does not guarantee the optimal solution for the entire 10 stages.

Table 4.5. Comparison on short-term solution and solution leading to global best when GW_o = 12 MAF with a pumping goal for Stage 1

		Short-term (Chapter 2)	Longer-term DP (Chapter 4)
Final groundwater storage (MAF)		9	10
Perennial crop acreage (acre/stage)		134,264	150,000
Annual crop acreage (acre/yr)	Events 1 - 4	102,526	58,909
	Event 5	117,556	104,323
Land for artificial recharge	Events 1 - 5	0	0
Groundwater pumping (AF/yr)	Event 1	794,236	647,177
	Event 2	655,517	508,458
	Event 3	516,258	369,199
	Event 4	326,909	179,850
	Event 5	0	0
Profit of the stage in present value (M$)		1,486	1,452

As mentioned in the previous paragraph, even for the lowest allowable groundwater storage (8 MAF) with fewest available perennial crops entering to a stage (25,000 acres), the model supports 150,000 acres of perennial crops in stage 1. Except in the last stage (the only stage with a recharging goal), under any groundwater level, the model supports 150,000 acres of perennial crops. In the last stage, because we must recover 2 MAF of groundwater storage, and there is no need to prepare for the next stage, the model only supports 100,000 acres of perennial crops with reasonable conjunctive water operation cost, same as the short-term solution.

In this chapter, the model in Chapter 2 is embedded in a longer-term DP framework. Therefore, the perennial crop acreage $X'_{p,t}$ is now a decision variable in outer DP and a fixed input parameter of the inner model. Annual crop acreage $X_{a,j,t}$, land used for artificial recharge $X_{r,j,t}$, and groundwater pumping $W_{p,j,t}$, the second stage decisions of the inner model, can still be derived from inner model given $X'_{p,t}$ is now known, and the conclusion in Chapter 2 that without salinity, pumping and artificial recharge serve to dampen the difference of incoming surface water still holds.

Also, though pumping cost varies with the initial and final groundwater storage, pumping cost is not the dominant factor that changes pumping (it is only true for this example with groundwater storage ranging from 8 MAF to 12 MAF, as in Chapter 2 different decisions are made for GW_o being 15 and 10 MAF with no overdraft goal, but they do not differ much), so the second-stage decisions in the inner model stay the same for any change in groundwater storage (ΔGW), regardless of initial and final groundwater storage. From Figure 4.3, since there are only six ΔGW's: 0, -0.5, -1, -1.5, -2, and 2 MAF, there are only six patterns of crop mix decision and conjunctive water operation for the entire 10 stages (Table 4.6, Figures 4.4 and 4.5).

Table 4.6. Six possible crop mix and conjunctive water use decision under the base climate, for different changes in groundwater storage

Groundwater storage change per stage (MAF)		2	0	-0.5	-1	-1.5	-2
Perennial crop acreage, X_p (acre/stage)		100,000	150,000	150,000	150,000	150,000	150,000
Annual crop acreage, X_a (acre/yr)	Events 1 - 2	0	0	10,527	28,525	43,717	58,909
	Event 3	21,347	0	10,527	28,525	43,717	58,909
	Event 4	21,347	21,750	21,750	28,525	43,717	58,909
	Event 5	21,347	75,136	104,323	104,323	104,323	104,323
Land for artificial recharge, X_r (acre/yr)	Events 1 - 2	0	0	0	0	0	0
	Event 3	1,073	0	0	0	0	0
	Event 4	13,697	0	0	0	0	0
	Event 5	40,340	9,418	0	0	0	0
Groundwater pumping, W_p (AF/yr)	Event 1	158,558	362,058	413,010	500,118	573,648	647,177
	Event 2	19,839	223,339	274,290	361,399	434,929	508,458
	Event 3	0	84,080	135,032	222,140	295,670	369,199
	Event 4	0	0	0	32,791	106,321	179,850
	Event 5	0	0	0	0	0	0

When ΔGW = 2 MAF (the last stage), artificial recharge occurs in the three wetter events, resulting in the same acreage of annual crops planted in those events (Figure 4.4), which also compensates for pumping in the two drier events used to support perennial crops. When ΔGW is negative, annual crop acreages in events that require pumping are the same (Figure 4.4), but are smaller than annual crop acreages from the short-term solution as we have more perennial crops. Also, because salinity is not considered yet, pumping is always more in drier events (Figure 4.5).

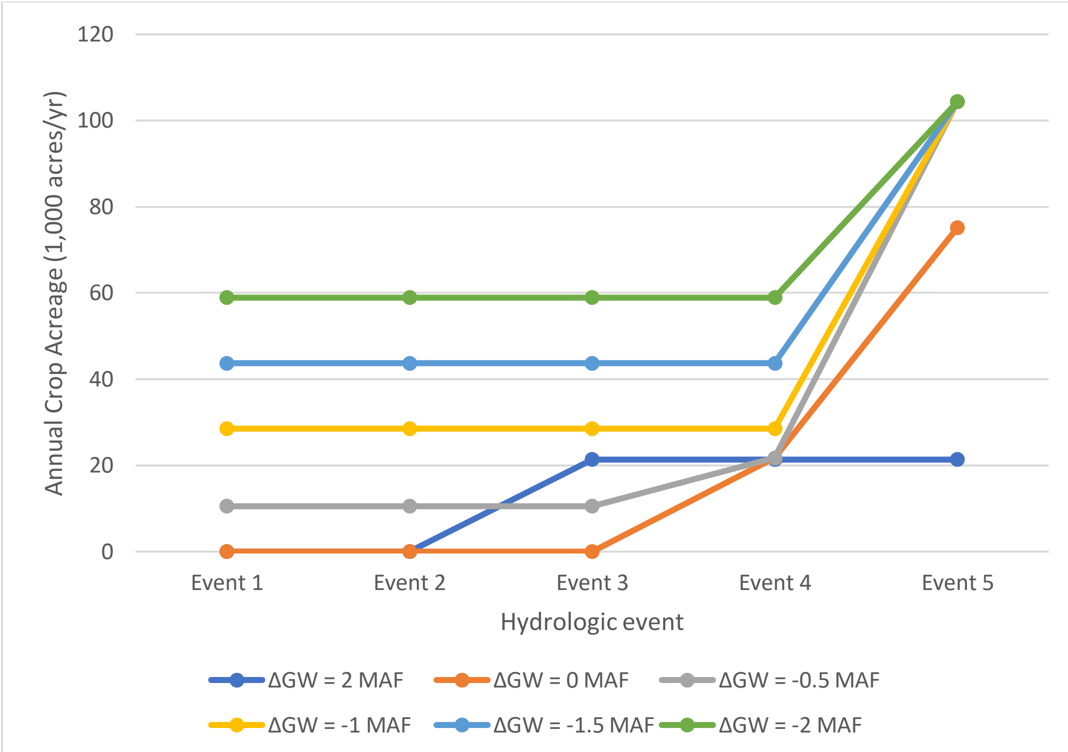


Figure 4.4. Annual crop decision for each hydrologic event for different groundwater storage changes

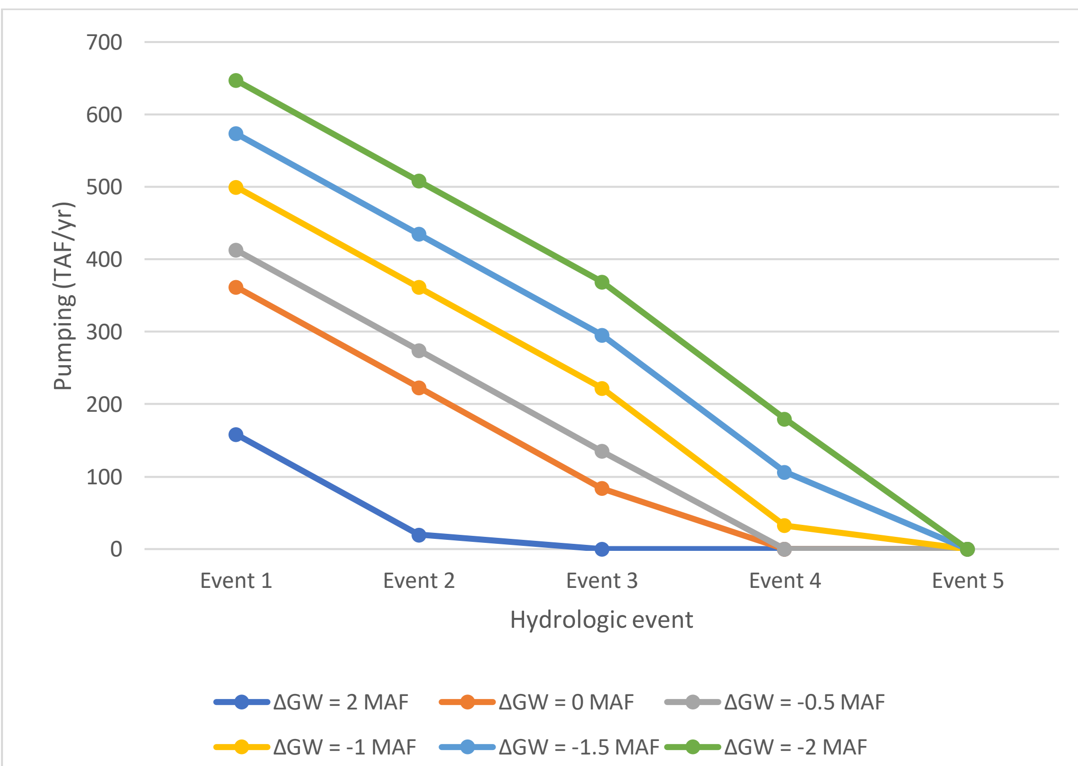


Figure 4.5. Pumping decision for each hydrologic event for different groundwater storage changes

3.2 Sensitivity Analysis

3.2.1 Discount Rate Effects (r = 5%, 3.5%, 2%, and 1%)

In Chapter 2, higher discount rates reduce perennial crop acreage, because perennial crop's initial establishment cost only occurs in the first year of the stage which is least discounted, but the profit is a sum of geometric series, a higher discount rate makes later years in the stage less important. In this chapter, the discount rate does not affect perennial crop acreage decisions in first nine stages (but still affects the perennial crop acreage in the last stage (Figure 4.6), because having more perennial crops entering the next stage can save perennial crop establishment costs in later stages.

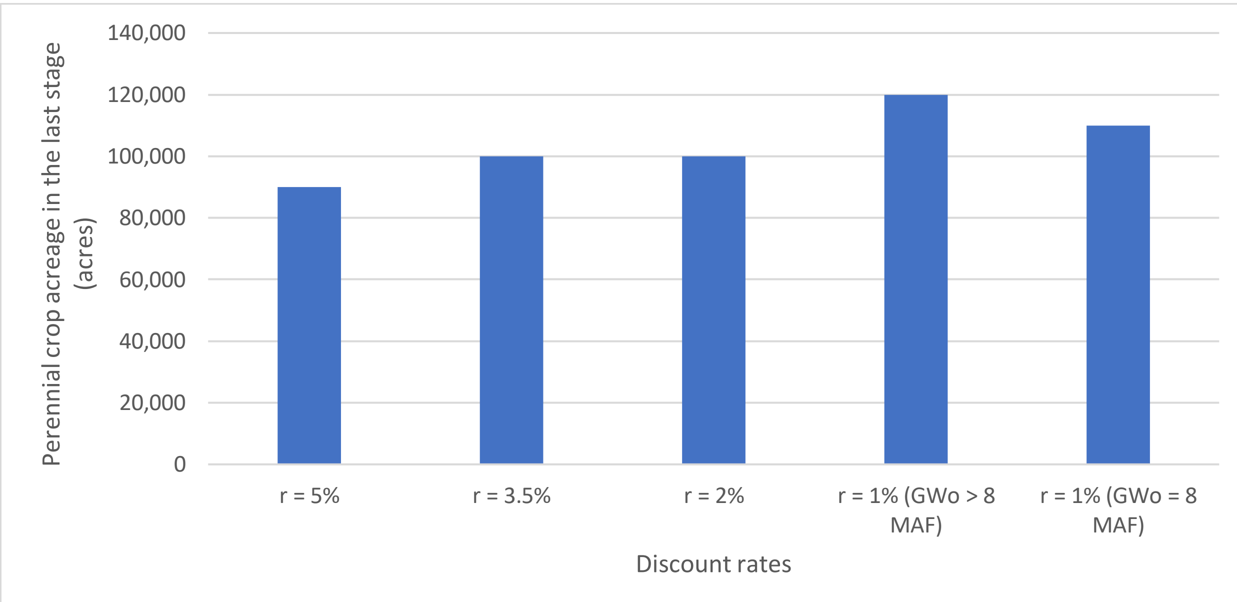


Figure 4.6. Perennial crop acreage in the last stage

However, discount rates do affect groundwater storage management. When r = 5%, earlier stages make larger proportions of total profit. So, pumping is more aggressive than with lower discount rates to make more profit in earlier stages and reach the lowest groundwater level (8 MAF) no later than stage 3 (Figure 4.7).

When r = 2% (Figure 4.8), for all GW_o, groundwater storage falls to the minimum (8 MAF) later with no artificial recharge until the last stage. Because the middle stages become more important, we pump less to leave more groundwater for later stages. For instance, when GW_o = 10 to 12 MAF, less groundwater pumping occurs than when r = 3.5% and 5% in the first stage (Figure 4.10c to 10e), and we reach minimum groundwater storage (8 MAF) later. Though this reduces profit in the first stages, there is more net total net present value from greater profit in stages 4 and 5.

When r = 1%, the groundwater management strategy shifts, because now each stage is almost equally important. And later costs for recharging hurt more, as cost must be paid for artificial recharge while the water used for artificial recharge cannot irrigate crops and make profit. Therefore, except for GW_o = 8 MAF, which is already at the minimum, we no longer pump much groundwater. In Figure 4.9, when GW_o = 9 MAF, we keep no overdraft until stage 9 and recharge 1 MAF in the last stage to the end target. And when $GW_o \geq 10$ MAF, we pump 0.5 MAF per stage until we reach 9.5 MAF, then we keep no overdraft until stage 9 and recharge 0.5 MAF in the last stage. When GW_o = 8 MAF, rather than recharging only in the last stage, we start to recharge 0.5 MAF at stage 9, with 150,000 acres of perennial crop. The reason that recharge begins one stage earlier when GW_o = 8 MAF, keeping no overdraft when GW_o = 9 MAF, and pumping to no less than 9.5 MAF when $GW_o \geq 10$ MAF, is that we can have a less challenging recharging goal crops in the final stage and use more surface water to grow more perennial crops (Figure 4.6).

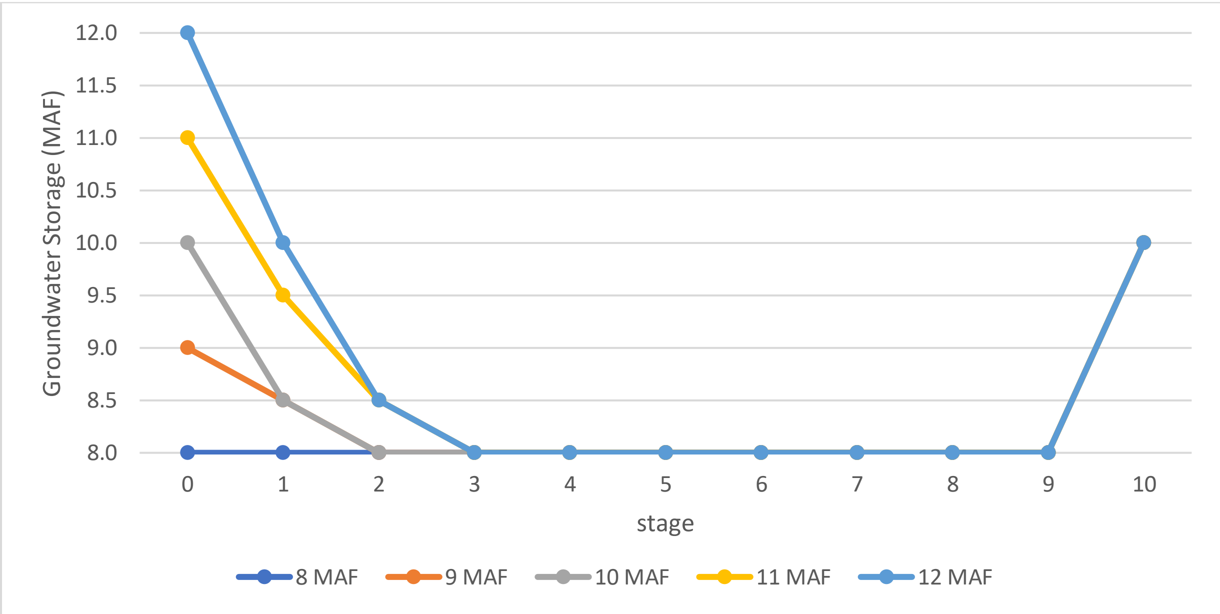


Figure 4.7. Groundwater storage change over stages with r = 5%

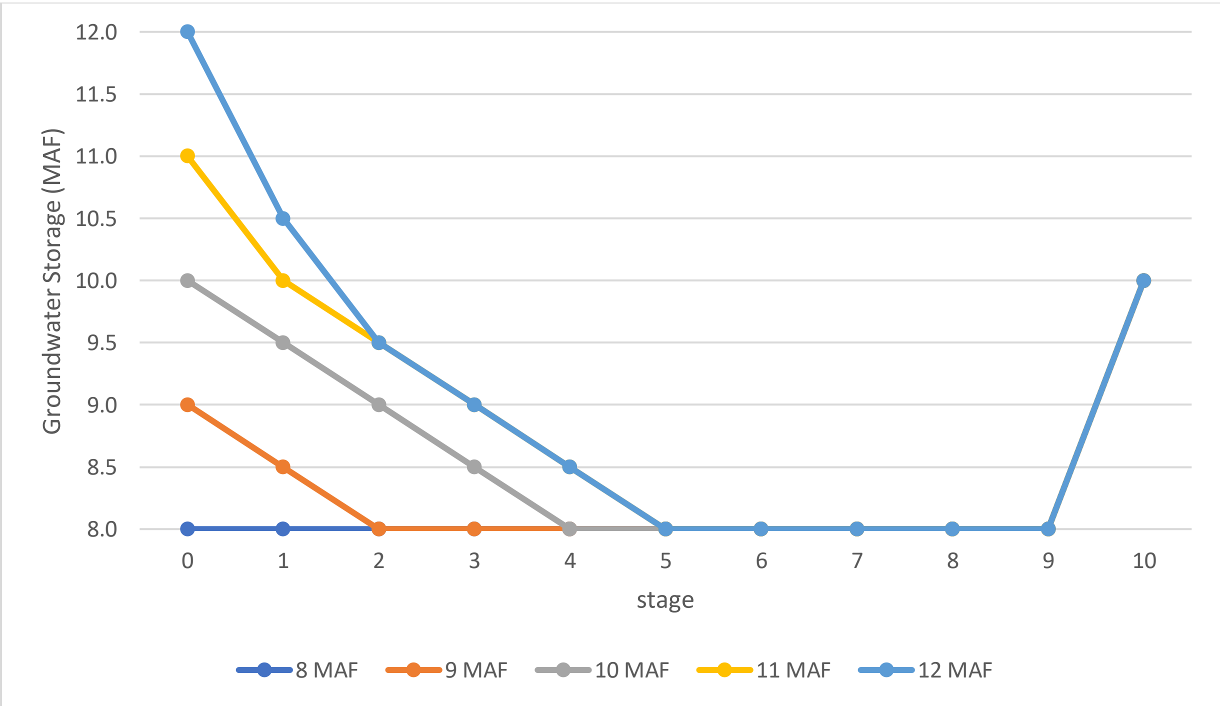


Figure 4.8. Groundwater storage change over stages with r = 2%

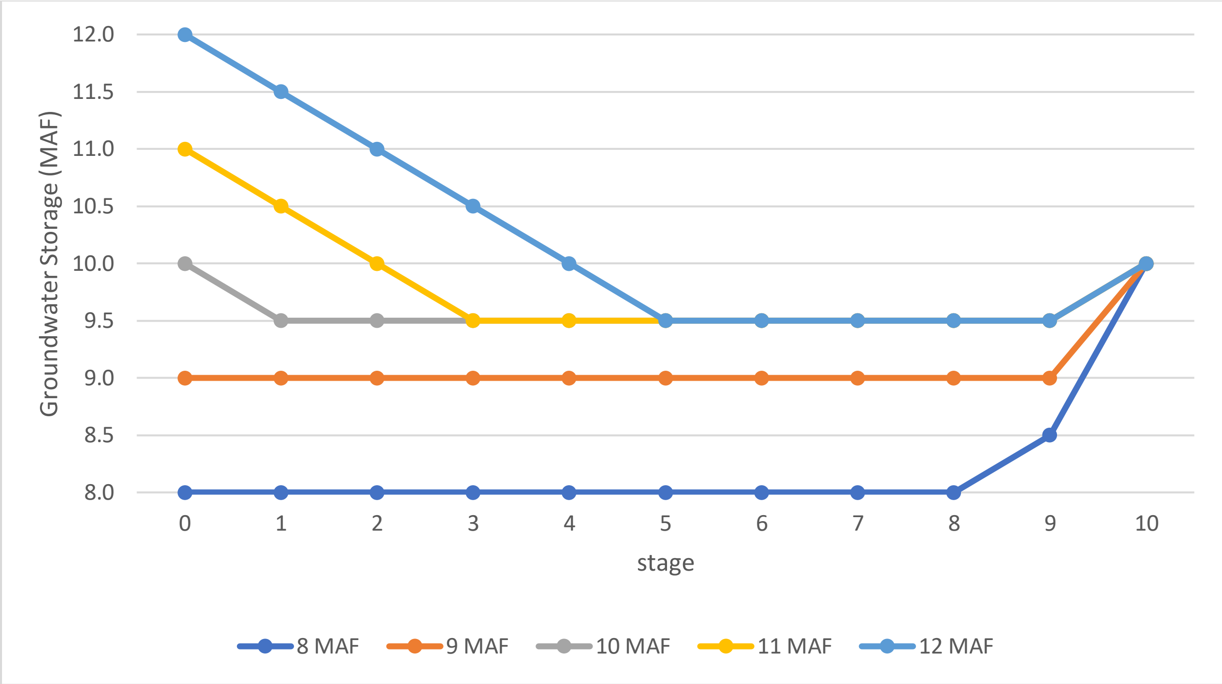
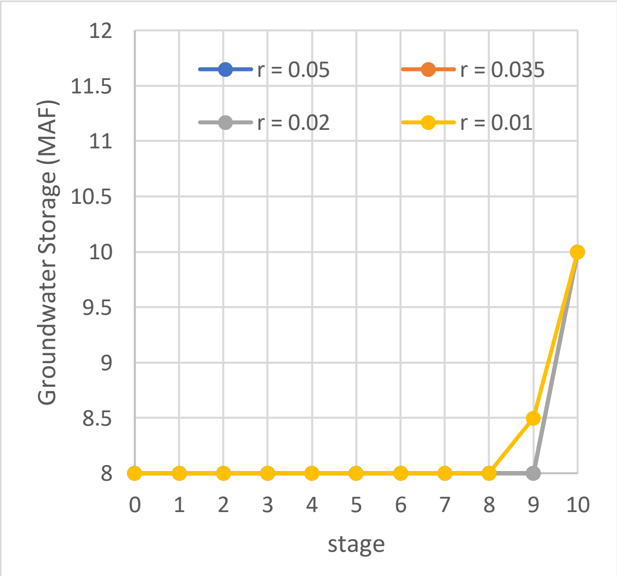
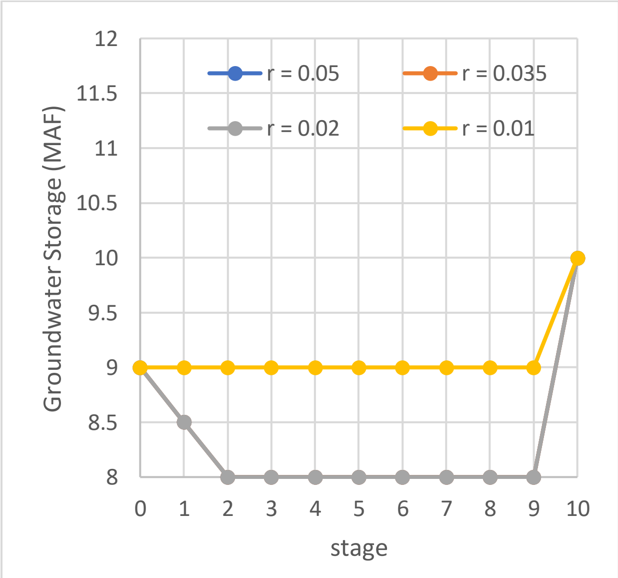


Figure 4.9. Groundwater storage change over stages with r = 1%

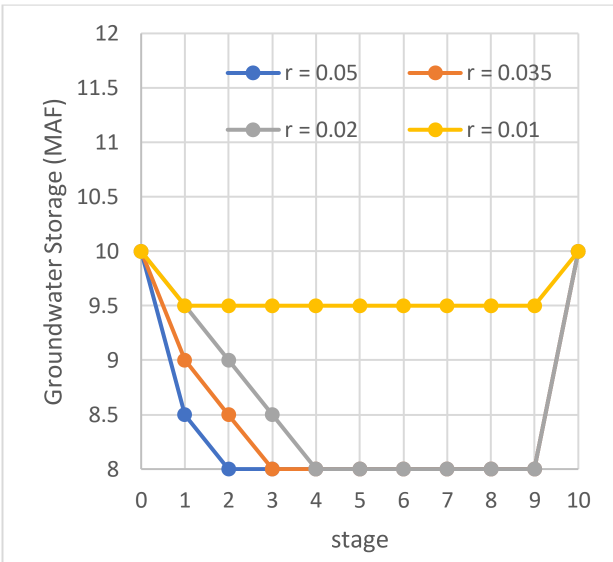
Overall, higher discount rates increase groundwater pumping in earlier stages. If the discount rate is very low, we are less likely to pump groundwater to the lowest allowable storage as we wish to reduce recharge cost in later stages.



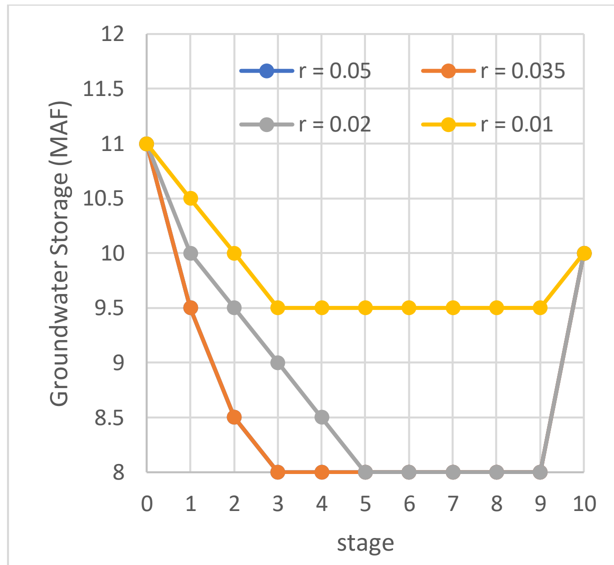
(a): GW_o = 8 MAF



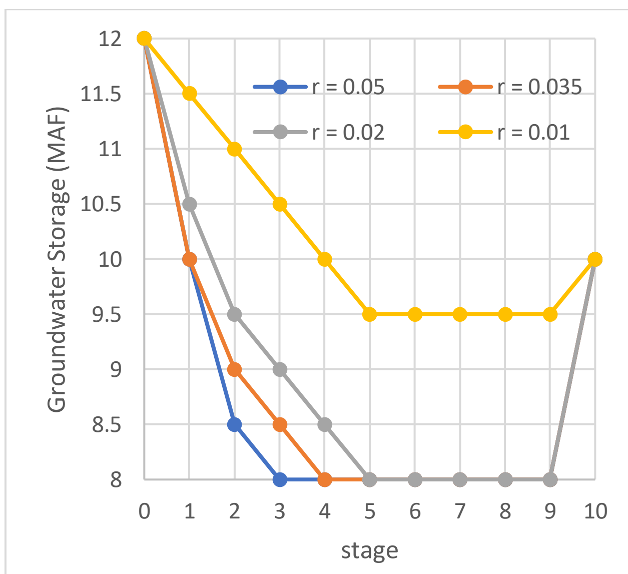
(b): GW_o = 9 MAF



(c): GW_o = 10 MAF



(d): GW_o = 11 MAF



(e): GW_o = 12 MAF

Figure 4.10. Groundwater storage management with different discount rates

3.2.2 Probabilities of Hydrologic Events

This part of sensitivity analysis changes the probabilities of wetter and drier hydrologic events to create 2 drier scenarios, shown in Table 4.7.

Table 4.7. Hydrologic event probabilities in each climate

	Event j	Driest	Drier	Base
Dry	1	0.3	0.25	0.2
	2	0.3	0.25	0.2
	3	0.2	0.2	0.2
	4	0.1	0.2	0.2
Wet	5	0.1	0.1	0.2
Expected incoming surface water (TAF/yr)		479 (-20%)	519 (-13%)	599

Table 4.8 shows total profit over 10 stages for different climate scenarios and different initial groundwater storages. Total profit decreases as climate becomes drier. Comparing columns in Table 4.9 shows value of surface water. Table 4.10 compares values for groundwater for the different climates.

Table 4.8. Total profit (M$) over 10 stages by different initial groundwater storage and climate scenario

Initial groundwater storage, GW_o(MAF)	Climate		
	Driest	Drier	Base
8	4,574	4,751	5,022
9	4,690	4,858	5,093
10	4,782	4,932	5,149
11	4,858	4,996	5,203
12	4,929	5,059	5,256

From the base to drier cases, we lose 80 TAF/year of surface water (0.8 MAF over 10 stages). From drier to even drier cases, we lose a further 0.4 MAF over 10 stages. The difference in total profit between different climate scenarios (difference between adjacent columns of Table 4.8) divided by the corresponding volume of lost surface water, gives the value of surface water (Table 4.9). Drier climates make surface water more valuable (the left column is higher than the right column).

The value of groundwater (Table 4.10) is calculated as the difference between two adjacent rows in Table 4.8. In drier climates, groundwater has higher value. And groundwater value decreases as initial groundwater storage increases. Comparing Table 4.9 and Table 4.10, surface water is more valuable than groundwater, because (i) it does not require pumping; (ii) part of it serves as artificial recharge to be pumped again to irrigate crops; (iii) one less unit of groundwater can either mean one less unit for irrigation or one more unit of groundwater from deep percolation from crops making profit.

Table 4.9. Average surface water value ($/AF) in 10 stages between different climate change

Initial groundwater storage, GW_o (MAF)	Climate change	
	Driest to drier	Drier to base
8	443	340
9	420	293
10	375	271
11	343	259
12	327	245

Table 4.10. Groundwater value (M$/MAF) in 10 stages between different climate scenarios

Groundwater storage change (MAF)	Climate		
	Driest	Drier	Base
8 to 9	117	107	70
9 to 10	92	74	56
10 to 11	76	63	54
11 to 12	70	64	52

Different climate scenarios also change groundwater management strategy. The strategy is to pump the minimal required groundwater to have maximal possible perennial crop acreage until minimum groundwater storage is reached, and if more groundwater than required is available, use it as soon as possible. Then, keep no overdraft and grow maximal allowable perennial crop acreage and recharge in the last stage.

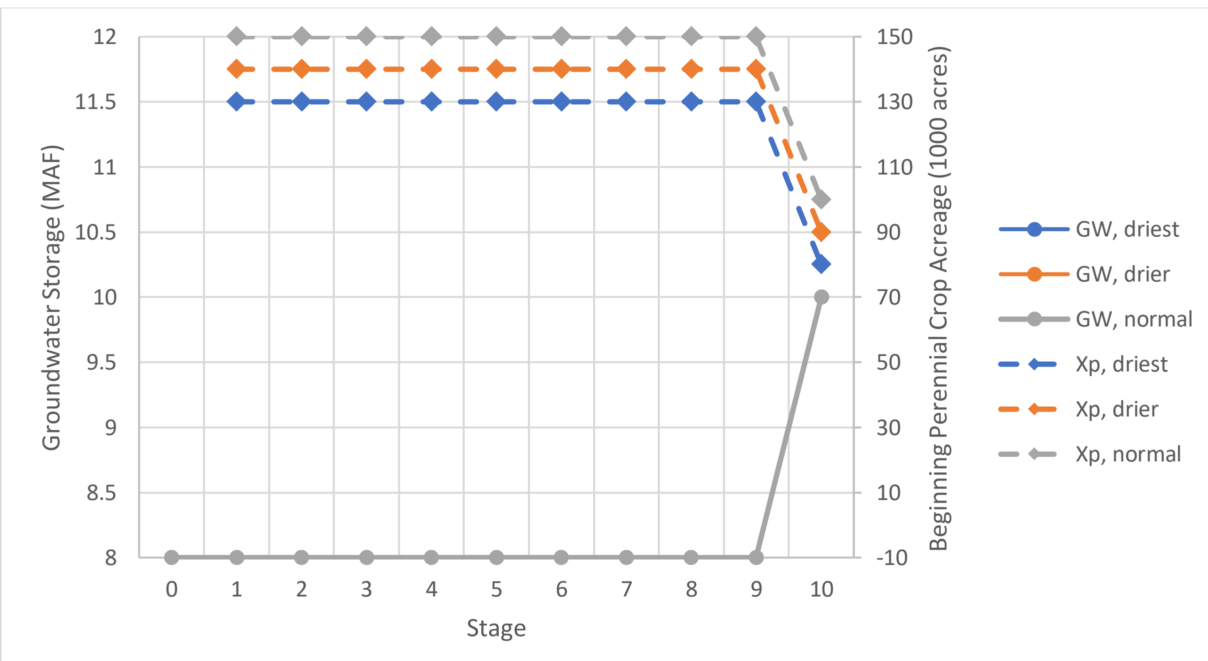
When GW_o = 8 MAF (Figure 4.11a), because r = 3.5% (relatively high), no overdraft occurs in the first nine stages and artificial recharge occurs in the last stage, regardless of climate scenario. But climate physically affects the acreage of perennial crops: drier and even drier climates can only support 140,000 and 130,000 acres of perennial crops with a no overdraft goal, respectively.

When GW_o = 9 and 10 MAF (Figures 4.11b and 4.11c), more groundwater pumping occurs in earlier stages when climate becomes even drier. This initially seems unreasonable, but the high discount rate means the first two stages have a greater proportion in the present value of total profit over 10 stages. The previous section and Chapter 2 showed how more pumping can increase profit as long as we do not pump more than 3 MAF for this example. So, pumping becomes more aggressive in first two stages to increase profit. Otherwise, we can support fewer perennial crops without economically excessive artificial recharge.

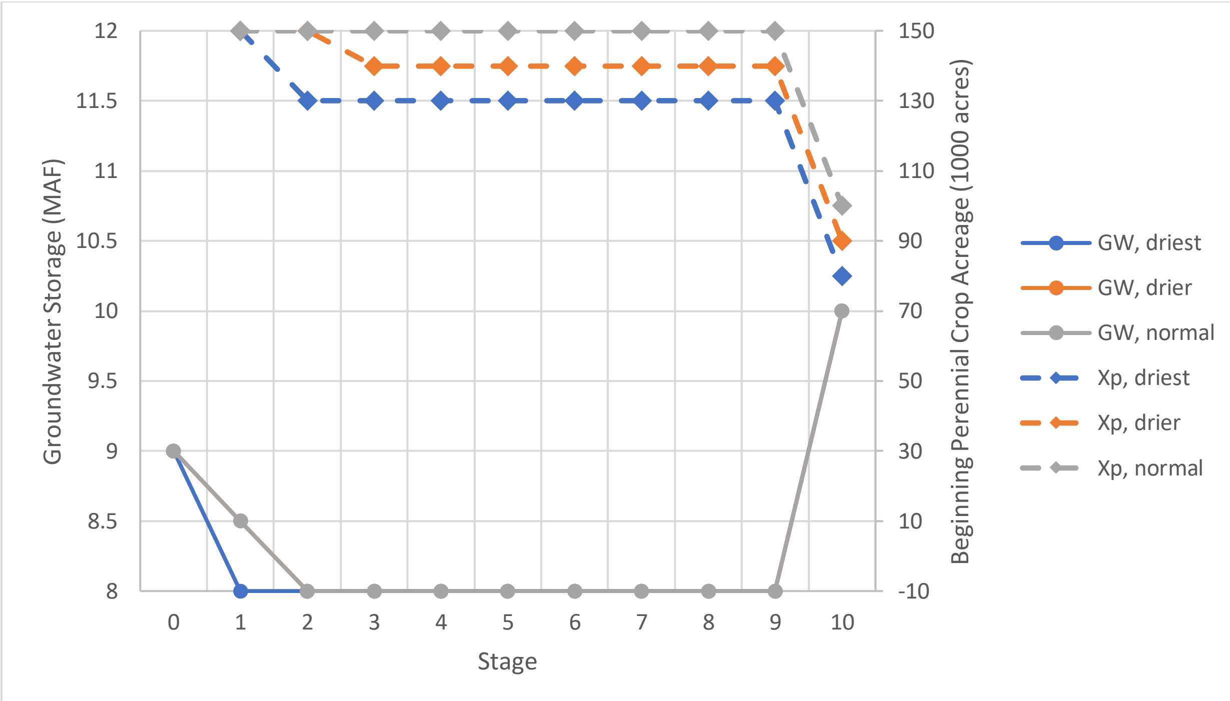
When GW_o = 11 MAF (Figure 4.11d), pumping is less for the drier climates, but pumping occurs as with the base climate when climate becomes even drier. With the drier case, since pumping 0.5 MAF of groundwater can still support maximal acreage of perennial crops (150,000 acres), there is no need to pump more than that only to grow annual crops. When the climate is even drier, 1 MAF of groundwater must be pumped to support 150,000 acres of perennial crops, while with the base case, pumping 1 MAF and growing more annual crops in the first stage is more profitable than having remaining groundwater grow annual crops in later stages. So, the base climate has the same pumping strategy as the even drier climate case.

For GW_o = 12 MAF (Figure 4.11e), first, with a discount rate of 3.5%, it is usually best to reach the minimum at the end of stage 4 as the high discount rate makes later stages less important. Second, we know that for drier and base climate cases, pumping 0.5 MAF is enough to support the maximal perennial crop acreage without too much burden of artificial recharge in wetter events, while for the even drier case, we need to pump 1 MAF. With this background, we can solve how to allocate net groundwater pumping of 4 MAF in four stages.

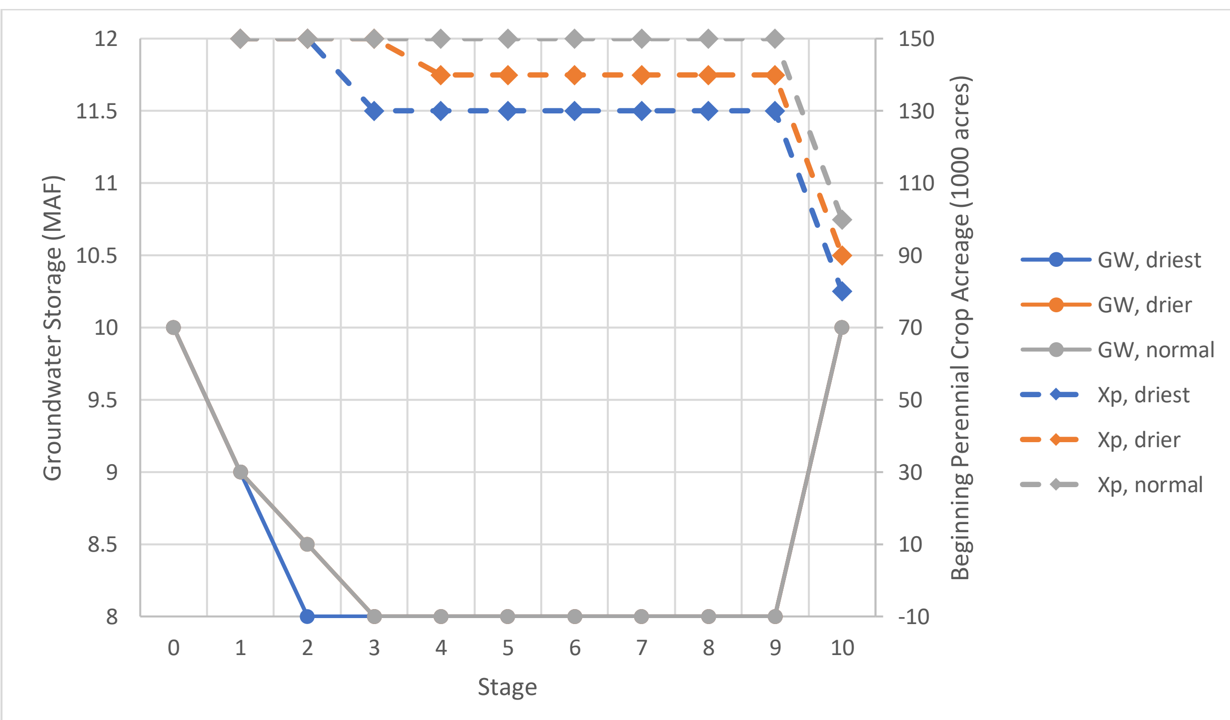
With the even drier climate, we could pump 1 MAF per stage, but since discounting makes stage 4 much less important than stage 1, we move 0.5 MAF in stage 4 to stage 1 to grow more annual crops, although perennial crop acreage at stage 4 can no longer reach the maximum (Figure 4.11e). With the drier and base climates, besides the basic 0.5 MAF for each stage, we have 2 MAF more groundwater to pump. Allocating 1.5 MAF to the first stage and 0.5 MAF to the second stage results in the highest present value profit. That is why in Figure 4.11e, we pump more (stage 3), same (stages 2 and 4), or less (stage 1) volume of groundwater with the even drier climate than other two climate cases.



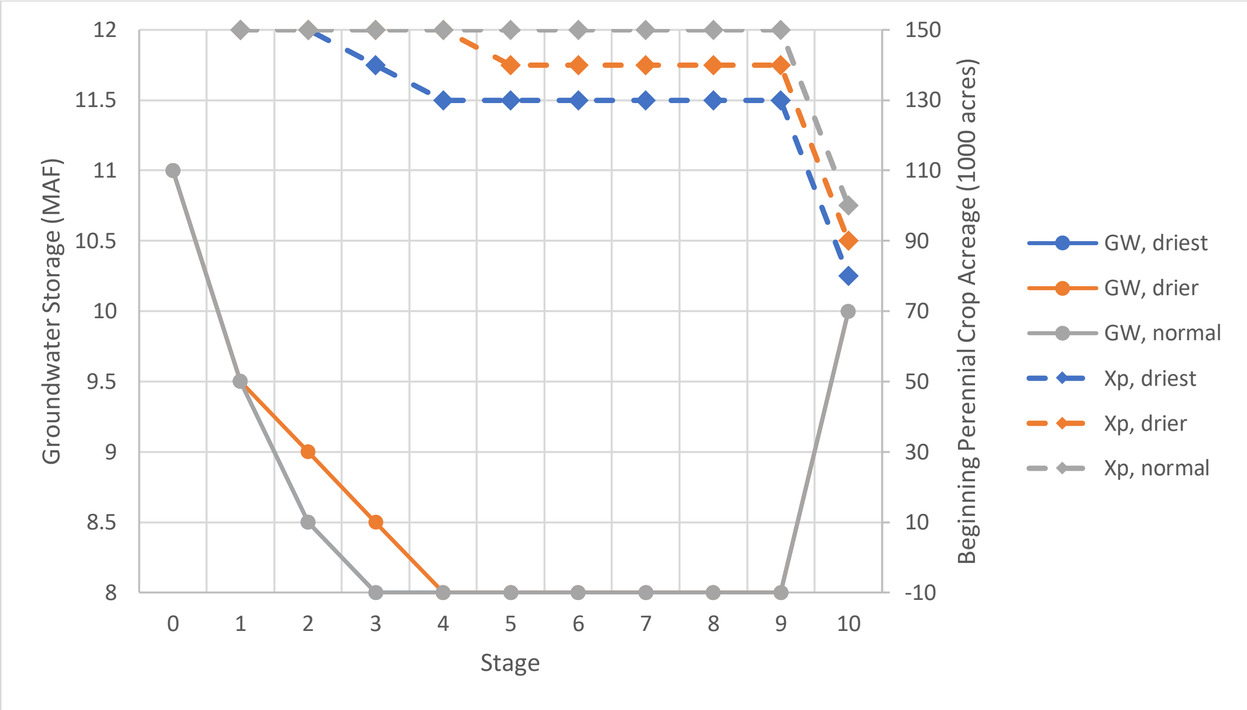
(a): GW_o = 8 MAF



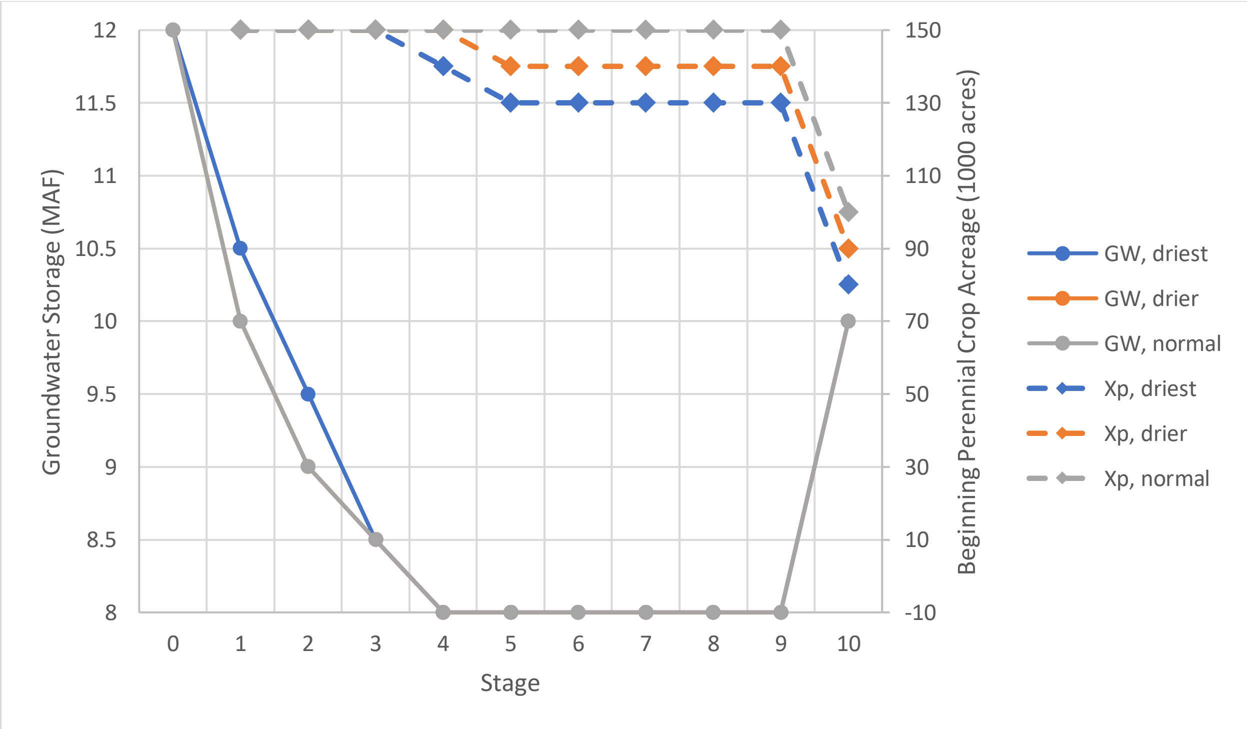
(b): GW_o = 9 MAF



(c): GW_o = 10 MAF



(d): GW_o = 11 MAF



(e): GW_o = 12 MAF

Figure 4.11. Groundwater storage change and perennial crop acreage in each stage for different initial groundwater stage under different climate scenarios

Conclusions

The hybrid NLP-DP analysis of conjunctive use without groundwater salinity and with a stationary climate indicates that although intermediate-term conjunctive use without groundwater salinity is well-examined in Chapter 2, longer-term groundwater management is affected by longer-term economic and hydrologic conditions, particularly discounting. The discount rate determines the relationship between stages: more discounting makes the first stages are more important requesting for more pumping, whereas lower discount rate tends to emphasis on the higher cost of artificial recharge.

To maximize total present value profit when groundwater salinity does not affect crop production, maximum possible perennial (higher profit) crop acreage should be maintained regardless of climate and discount rate. This means more pumping in drier events compensated by more artificial recharge in wetter events, and less annual crops planted, while additional pumping to grow annual crops in dryer events is not recommended.

1. Without salinity, greater initial groundwater storage increases profit because more groundwater is available to pump and irrigate crops in earlier stages. More incoming perennial crops in the first stage also increases profit by reducing establishment costs for perennial crops in the second stage as more perennial crops enter stage 2.
2. Longer planning horizons for conjunctive use affect optimal short-term cropping and groundwater management. A short-term solution (with the highest profit in a single stage) differs from the optimal solution and strategy over a long planning horizon. With no groundwater salinity, a longer-term DP solution recommends having maximal perennial crop acreage in any stage except the last stage, with fewer annual crops planned, more land used for artificial recharge, and more pumping in drier events.
3. A short-term solution may pump too much in early stages. A longer-term DP solution spares some groundwater for middle stages to lengthen the net pumping period to increase summed discounted profit over the longer planning horizon.
4. Once profit-maximizing changes in groundwater storage (ΔGW) are found, for any stages other than the last stage, because the perennial crop acreage is forced to be maximal, the corresponding second-stage decisions (annual crop acreage, land for artificial recharge, and groundwater pumped for each hydrologic event) within each DP stage for each ΔGW are fixed. For the last stage, because the incoming perennial crop is maximal (half of the maximal acreage of perennial crops planted in stage 9 enter stage 10) and ΔGW = 2 MAF for the base case, the second-stage decision for last stage is also fixed. In all, ΔGW has six values, so there are only six patterns of crop mix decision and conjunctive water operation through the 10 stages.
5. Higher discount rates make earlier stages more important, so pumping is more aggressive. If the discount rate is very low (1%), each stage is almost equally important, and the cost of aquifer recharging is more important for total profit. If initial groundwater storage is high, it is not economical to reduce storage to the allowed minimum. Also, if initial groundwater storage is at the lowest allowed, aquifer recharging starts one stage earlier.
6. Without salinity, drier climates reduce profit because fewer perennial crops can be supported in any stage. Drier climates also make both surface water and groundwater

more valuable. However, surface water remains more valuable than groundwater because it does not require pumping. Also, marginal groundwater value decreases as groundwater availability increases.

7. Changes in groundwater management strategy for different climates cannot be abstracted as a trend (e.g., drier climates increase pumping), but can still be summarized as pumping the lowest required groundwater to have maximal perennial crop acreage in early stages (in the driest climate, 1 MAF must be pumped to support 150,000 acres of perennial crops), then if more groundwater than required is available, use it as soon as possible.

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Chapter 5: Long-term Optimization of Conjunctive Water Use and Crop Decisions with Groundwater Salinity

Abstract

In California and other parts of the world, water agencies are seeking to manage agricultural water supplies while ending chronic groundwater overdraft with the least economic loss. Including salinity considerations makes this goal more complex and demanding. This chapter examines water and crop management decisions and the trade-off between crop profits and aquifer recovery when groundwater salinity threatens crop yield. A 10-year stochastic quadratic optimization model (from Chapter 3) is embedded within a 10-stage (10 years per stage) dynamic programming optimization (outer model) to develop optimal long-term (100-year) decisions for perennial and annual crop acreages and groundwater management for various aquifer recovery goals with a known trajectory of stochastic surface water availability, maximizing net expected economic benefits of crop production and conjunctive use. The best combination of groundwater storage and permanent crop acreage is found over stages from the outer (dynamic programming) model, with corresponding decisions on annual crop acreage, groundwater pumping and artificial recharge under a range of hydrologic conditions within each stage using the inner (quadratic programming) model. For this example, model results show that groundwater salinity decreases perennial crop acreage with time regardless of the final groundwater storage target (either net recharging or net extraction) from salts accumulating in groundwater. Groundwater management with accumulating salinity differs from that without groundwater salinity, with greatly reduced pumping and much earlier groundwater storage recovery to slow salinity accumulation and prolong the utility of aquifer storage.

Keywords: Dynamic programming, stochastic quadratic programming, overdraft, conjunctive operations, salinity

1. Introduction

Allocating available water to crops and aquifer recharge is of growing importance in arid and semi-arid regions as groundwater overdraft threatens irrigation sustainability, especially during droughts. However, irrigation with more saline groundwater can further salinize soil and reduce crop yields (Ayers and Westcott 1985; Allen et al. 1997). Also, higher-value perennial crops tend to be more sensitive than annual crops to salinity and have high establishment and replacement costs. Moreover, aquifers in areas with less precipitation and more evaporation can become more saline from irrigation, as more irrigation water containing salts is needed to leach salt from soil. The eventual fate of all undrained unconfined aquifers underlying irrigated lands may be to become too saline for irrigation. Salinity adds further difficulty for ending overdraft with the least economic loss to irrigated agriculture.

Numerous practices exist to manage salinity and drainage for irrigated agriculture, including crop rotations, volume and timing of irrigation water, installing subsurface drainage systems, reusing drainage water and so on (Knapp 2010). Conjunctive use provides dilution to allow some saline groundwater use with fresher surface water for irrigation (Rhoades 1987; Sharma and Rao 1998; Datta and Jong 2002; Yadav et al. 2004; Kaur et al. 2007). From an economic perspective, these actions are evaluated by effects on crop output and revenue, and water opportunity and production costs.

Research has emphasized maximizing annual crop production for food security rather than maximizing profits from high-value perennial crops (Sharma et al. 1993; Oster and Grattan 2002; Mandare et al. 2008; Malash et al. 2008; Kan and Rapaport-Rom 2012; Rasouli et al. 2013; Al Khamisi et al. 2013; Ortega-Reig et al 2014), so short-term linear programming (LP) and non-linear programming (NLP) optimization have been used to identify the annual optimal irrigation strategies, maximizing profit or minimizing cost, with consideration of crop water requirements and soil and water salinity (Tyagi and Narayana 1981 and 1984; Srinivasulu et al 1997; Tyagi 1988; Vincent and Dempsey 1991; Peralta et al. 1995; Philbrick and Kitanidis 1998; Schoups et al. 2006).

The ability to model sequential decision-making with either linear or nonlinear economic objective functions makes Dynamic Programming (DP) appropriate for long-term irrigation strategies (Yakowitz 1982). DP also has been used to study salinity problems for conjunctive use (Buras 1972; Yaron and Olian 1973; Matanga and Marino 1979; Dinar and Knapp 1986; Letey and Knapp 1990; Knapp 1992(a), (b), (c); Dinar et al., 1993). These models use data-derived, empirical objective functions, account for damages from salt accumulation in the root zone, and make a succession of water decisions to maintain salt concentration in the root zone at a level tolerated by crops without yield declines over irrigation seasons, in which initial salinity is affected by salt accumulation in previous periods.

However, DP suffers from computational requirements and costs, which limit DP to problems with few stages and few state and decision variables. So, the above models either have one kind of crop, perennial (Yaron and Olian 1973) or annual (Matanga and Marino 1979; Dinar and Knapp 1986; Knapp 1992(a), (b), (c); Dinar et al., 1993), or only have salinity as a state variable in the DP, assuming a stationary but stochastic rainfall during the planning horizon. The decision variable(s) of DP may be restricted to volume of water applied to leaching and/or irrigation. Lastly, as most existing research mainly focuses on annual crop production, one stage usually means one year. These models aim to derive convergent annual irrigation rules for a single type of crop.

In this chapter, analysis of irrigated agriculture with groundwater salinity incorporates several elements seldom considered: (i) crop mix has two representative crops, one perennial crop (almond) and one annual crop (alfalfa); (ii) groundwater management enforces a specific groundwater storage target (either net drawdown or net recovery of groundwater storage); and (iii) an extended planning horizon.

The optimization model in this chapter has two modules: the first module (inner model) is a short-term stochastic (two-stage) quadratic model for deriving optimal conjunctive water use operations and annual crop acreage that maximizing net profit in present value with groundwater salinity, detailed in Chapter 3. The second module (outer model) is a long-term DP that takes output of inner model and obtains the best combination of groundwater storage and perennial crop acreage for each stage. Although less physically rigorous in terms of irrigation, this model can present a 100-year (ten 10-year stages) long-term profit-maximizing farmers' conjunctive water management strategy and crop mix decisions to meet a specific groundwater storage target with salinity.

2. Method

2.1 Model Formulation

The long-term planning horizon is composed of N+1 T-year (T = 10, representing the "permanent" characteristic of perennial crops) shorter-term planning stages (from stage t = 0 to stage $t = N$, N = 9). A fixed inflation-adjusted discount rate r converts future values to present value. So, the present value of profit in the k-th year of the t-th T-year stage is the future value of profit of that year discounted by a factor of $\frac{1}{(1+r)^{tT+k}}$.

For each stage t, **three** state variables are initial groundwater storage GW_{t-1}, incoming perennial crop acreage $X_{p,t-1}$, and initial groundwater salt concentration $C_{gw,t-1}$; final groundwater storage GW_t and perennial crop acreage before retirement $X'_{p,t}$ are the two decision variables determined in the outer DP model. The final groundwater salinity, $C'_{gw,t}$, is not a decision variable, because once the final groundwater storage and perennial crop acreage are determined, groundwater salinity can be derived according to mass balance in the inner model (see Chapter 3 for more detail).

The final groundwater storage of stage t, GW_t, is the initial groundwater storage of **stage *t*+1**, while, for simplicity, half of the perennial crops enter stage t+1 expected to be retired (i.e., $X_{p,t} = \frac{1}{2}X'_{p,t}$). The state of the system is governed by the stochastic conservation of mass equations for groundwater storage and salinity. However, it is nearly impossible for final groundwater salinity $C'_{gw,t}$ to exactly equal to any discretized value available for initial groundwater salinity in the next stage $C_{gw,t}$, so we must further covert $C'_{gw,t}$ to $C_{gw,t}$ by Equation (5.1), where ΔC is the discretization of groundwater salinity. By setting the final groundwater salinity to the closest available salinity level $C_{gw,t}$ higher than $C'_{gw,t}$, we always underestimate the profit.

$$C_{gw,t} = \begin{cases} \left\lceil \frac{C'_{gw,t}}{\Delta C} \right\rceil \times \Delta C & C'_{gw,t} \le 5{,}000 \\ 5{,}000 & C'_{gw,t} > 5{,}000 \end{cases} \tag{5.1}$$

An objective function (in the inner model, from Chapter 3) describes the economic consequence of decisions and states. Let P_t be the expected net **present** economic value of having groundwater storage from GW_{t-1} to GW_t and having perennial crop acreage of $X'_{p,t}$ before retirement with perennial crop acreage of $X_{p,t-1}$ already in place, with the initial groundwater salinity of $C_{gw,t-1}$. The overall objective from the outer model (DP) is to maximize the sum of expected net **present** value from stage t = 0 to stage t = N:

$$\text{Max} \sum_{t=0}^{N} P_t\left(GW_{t-1}, X_{p,t-1}, C_{gw,t-1}, GW_t, X'_{p,t}\right) \tag{5.2}$$

The backward recursive function for this DP (outer model) is:

$$f_t\left(GW_{t-1}, X_{p,t-1}, C_{gw,t-1}, GW_t, X'_{p,t}\right)$$
$$= \begin{cases} P_N\left(GW_{N-1}, X_{p,N-1}, C_{gw,N-1}, GW_N, X'_{p,N}\right), & t = N \\ P_t\left(GW_{t-1}, X_{p,t-1}, C_{gw,t-1}, GW_t, X'_{p,t}\right) + f^*_{t+1}\left(GW_t, X_{p,t} = \frac{1}{2}X'_{p,t}, C_{gw,t}\right), & otherwise \end{cases} \tag{5.3}$$

When t = 0 to N-1, the recursion has two parts. P_t contains the direct present value of profit from the decision in stage t, GW_t and $X'_{p,t}$, given the state GW_{t-1}, $X_{p,t-1}$, and $C_{gw,t-1}$. f^*_{t+1} is the accumulation of the best decisions from all later stages starting with groundwater storage GW_t, perennial crop acreage of $X_{p,t}$ (=$\frac{1}{2}X'_{p,t}$), and groundwater salinity of $C_{gw,t}$.

P_t is also called the inner model (Equation (5.4)), because the negative value of P_t needs to be minimized to derive the optimal short-term (T-year) decision of annual crop ($X_{a,j,t}$) and conjunctive water operation (land for recharging $X_{r,j,t}$ and groundwater pumped $W_{p,j,t}$) in stage t with j possible hydrologic events having probabilities of occurrence p_j, given the initial and final groundwater storage, GW_{t-1} and GW_t, incoming perennial crop acreage, $X_{p,t-1}$, perennial crop acreage before retirement, $X'_{p,t}$, and initial groundwater salinity $C_{gw,t-1}$. More detail of P_t function appears in Chapter 3. The only difference between P_t and the model in Chapter 3 is that perennial crop acreage is given by the outer DP model as $X'_{p,t}$ rather than being determined be the shorter-term inner model.

$$\min\left[-P_t\left(GW_{t-1}, X_{p,t-1}, C_{gw,t-1}, GW_t, X'_{p,t}\right)\right]$$
$$= -P_{p,t}\left(X_{p,t-1}, C_{gw,t-1}, X'_{p,t}, X_{r,j,t}, W_{p,j,t}\right) - P_{a,t}\left(C_{gw,t-1}, X_{a,j,t}, X_{r,j,t}, W_{p,j,t}\right)$$
$$+C_t\left(X_{r,j,t}, W_{p,j,t}, GW_{t-1}, GW_t\right) \tag{5.4}$$

Figure 5.1 depicts P_t's structure. If we do not consider salinity, $P_{p,t}$ is deterministic because the full yield is assumed to be achieved at all times. Now, salinity makes $P_{p,t}$ probabilistic, because the salt concentration in irrigation water, affecting perennial crop yield, changes with amount of the groundwater pumping $W_{p,j}$ and the surface water subtracted by artificial recharge $sw_j - cap \times X_{r,j}$, in each hydrologic event j with its probability of occurring.

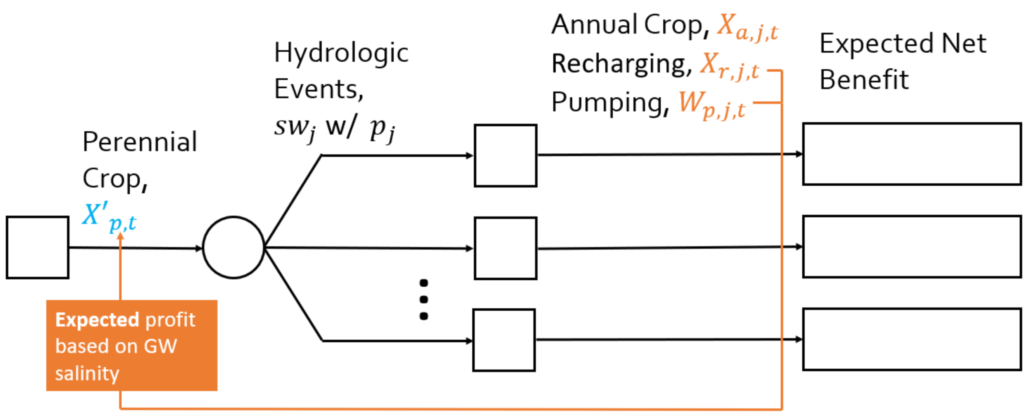


Figure 5.1. Problem decision tree for within-stage stochastic optimization with groundwater salinity (inner model)

2.2 Model Computation Speed-up

As in Chapter 4, the characteristic of P_t is so favorable that the optimal solution of the inner model does not change with stage t once the input parameters GW_{t-1}, $X_{p,t-1}$, $C_{gw,t-1}$, GW_t, and $X'_{p,t}$ are given (for this stationary hydrology example). The ratio between C_t and C_{t+1} is $(1+r)^T$ in Chapter 4. Now we start to prove that $P_{p,t}$ and $P_{p,t+1}$, and $P_{a,t}$ and $P_{a,t+1}$ have the same ratio, for stationary hydrologic and economic conditions (crop prices, etc.).

$$\begin{aligned} P_{p,t} = &\frac{1}{(1+r)^{tT+1}} \sum_{j=1}^{5} P_{1,j} \left[(v_p Y_{p,j}) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t} \right) X_{p,t} \right] \\ &+ \frac{1}{(1+r)^{tT+2}} \sum_{j=1}^{5} P_{2,j} \left[(v_p Y_{p,j}) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t} \right) X_{p,t} \right] + \cdots \\ &+ \frac{1}{(1+r)^{tT+10}} \sum_{j=1}^{5} P_{10,j} \left[(v_p Y_{p,j}) X_{p,t} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t} \right) X_{p,t} \right] \end{aligned} \quad (5.5)$$

$$\begin{aligned} P_{p,t+1} = &\frac{1}{(1+r)^{(t+1)T+1}} \sum_{j=1}^{5} P_{1,j} \left[(v_p Y_{p,j}) X_{p,t+1} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t+1} \right) X_{p,t+1} \right] \\ &+ \frac{1}{(1+r)^{(t+1)T+2}} \sum_{j=1}^{5} P_{2,j} \left[(v_p Y_{p,j}) X_{p,t+1} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t+1} \right) X_{p,t+1} \right] + \cdots \\ &+ \frac{1}{(1+r)^{(t+1)T+10}} \sum_{j=1}^{5} P_{10,j} \left[(v_p Y_{p,j}) X_{p,t+1} - \left(\alpha_p + \frac{1}{2}\gamma_p X_{p,t+1} \right) X_{p,t+1} \right] \end{aligned} \quad (5.6)$$

where $P_{1,j}$, …, $P_{k,j}$, …, $P_{10,j}$ are the probabilities of perennial crop having yield of $Y_{p,j}$ in event j, determined by the probability of occurrence of each event and are not functions of $W_{p,j}$ and $X_{r,j}$. Though $Y_{p,j}$ is a function of $W_{p,j}$ and $X_{r,j}$, if we divide the scaler part of each term in Equation (5.5) by the corresponding one in Equation (5.6), we can easily find the products are always $(1+r)^T$. We can use the same method to prove that the ratio of $P_{a,t}$ and $P_{a,t+1}$ is $(1+r)^T$. In all, P_t and P_{t+1} have the ratio of $(1+r)^T$, which is irrelevant to t. For these stationary conditions, this result allows the model to run more quickly as P_t needs to be computed far less frequently.

2.3 Model Assumptions

Several underlying assumptions are worth discussing. First, for simplicity, we assume 50% of perennial crops are retired at the end of each 10-year planning period, and those kept to next stage are “reset” to be unimpaired by salinity, which imperfectly represents the farming reality. Second, additional water applications for leaching salts to the aquifer is not considered, but we assume adequate deep percolation and drainage exists to avoid salt accumulation in the root zone, and this drainage percolates to the unconfined aquifer and mixes completely in the aquifer (this avoids representing aquifer layers and locations which would require multiple aquifer state variables). We also assume that without drainage to another aquifer or region, salts will accumulate in the region’s groundwater, perhaps slowed or reversed temporarily by recharge with fresher surface water (Pauloo et al, in review). Third, the state of the system is governed by stochastic conservation of mass for groundwater storage and salinity, meaning the final groundwater storage and salinity in each stage are averaged (over 10 years), and so might overestimate or underestimate total profit. Lastly, we assume soil salinity in the root zone is the same as the irrigation water, which is not exactly the case, but they are well correlated.

Only one perennial crop and one annual crop are considered, no urban water use or water transfer decisions are considered, making this model less able to represent mixed agriculture and urban production. Also, to reduce computational burden, the discretization of state variables (groundwater storage, perennial crops, and groundwater salinity) is coarse, making the derived groundwater management strategy subject to change with finer discretization. Still, it illustrates results likely from a more detailed optimal groundwater management maximizing agricultural profit in a 100-year period under the goal of aquifer recovery considering groundwater salinity.

2.4 Illustrative Example

The example application has a limited planting area and underlying undrained aquifer, with parameters summarized in Table 5.1. The planting area is similar to the sum of acreage of almonds and alfalfa in northern San Joaquin Valley, California. The unit prices of class 1 and class 2 water are based on the Chowchilla water district. The unit price of energy is adopted from Statewide Agricultural Production (SWAP) model for North San Joaquin Valley (DWR 2012). The capacity of land for recharge is based on USACE’s Conjunctive Use for Flood Protection Study (USACE 2002). This example has a range of initial groundwater storages (from 8 to 12 MAF), a range of incoming perennial crop acreages (from 25,000 to 75,000 acres), and a range of initial groundwater salinities (from 500 mg/L to 5,000 mg/L) at the first stage. The discretization of groundwater storage, perennial crop acreage, and groundwater salinity in the dynamic program are 0.5 MAF, 10,000 acres, and 250 mg/L respectively.

Table 5.1. Basic parameters of crops and irrigation area

Symbol	Parameter (unit)	Value
C_{sw}	Salinity of surface water (mg/L)	400
$K_{y,p}$	Perennial crop sensitivity to water stress	1.2
$K_{y,a}$	Annual crop sensitivity to water stress	1.1
$EC_{t,p}$	Threshold EC with no perennial crop yield decrease (dS/m)	1.5
$EC_{t,a}$	Threshold EC with no annual crop yield decrease (dS/m)	2.0
b_p	Perennial crop yield decrease per increment of EC (%)	19
b_a	Annual crop yield decrease per increment of EC (%)	7.3
T	Length of planning horizon (yr)	10
L	Total available area (acre)	500,000
H_o	Initial pump head (ft)	200
B_o	Initial thickness of the aquifer (ft)	200
s_y	Aquifer specific yield	0.1
r	Constant discount rate	0.035
ini_p	Perennial crop initial establishment cost (\$/acre)	12,000
c_{land}	Unit price of land for recharging (\$/acre)	300
c_{class1}	Unit price of class 1 (firm contract) water (\$/AF)	42
c_{class2}	Unit price of class 2 (surplus) water (\$/AF)	30
$class1$	Amount of firm contract water (TAF)	500
c_e	Unit price of energy (\$/kWh)	0.189
η_p	Pumping efficiency	0.7
cap	Capacity of land for recharging (AF/acre/yr)	15
$1-\varphi$	Irrigation efficiency	0.85
t	Current planning horizon	0
aw_p	Applied Water of perennial crop (ft)	4.07
aw_a	Applied Water of annual crop (ft)	4.84
yld_p	Maximum yield of perennial crop (ton/acre)	1
yld_a	Maximum yield of annual crop (ton/acre)	8
v_p	Unit price of perennial crop (\$/ton)	4226.68
α_p	Perennial crop's intercept of PMP cost function (\$/acre)	1502.85
γ_p	Perennial crop's slope of PMP cost function (\$/acre^2)	0.00795
v_a	Unit price of annual crop (\$/ton)	157.28
α_a	Annual crop's intercept of PMP cost function (\$/acre)	635.91
γ_a	Annual crop's slope of PMP cost function (\$/acre^2)	0.00294

Table 5.2 and Figure 5.2 summarize the current stationary surface water availability $sw \sim logN(\mu = 625{,}000\ AF,\ \sigma = 400{,}000\ AF)$. To simplify the problem, the averaged surface water inflow of each hydrologic event is represented by the 10th-, 30th-, 50th-, 70th- and 90th-percentile of the distribution, so we assume the probability of each hydrologic event is the same, which is 1/5 * 100% = 20%.

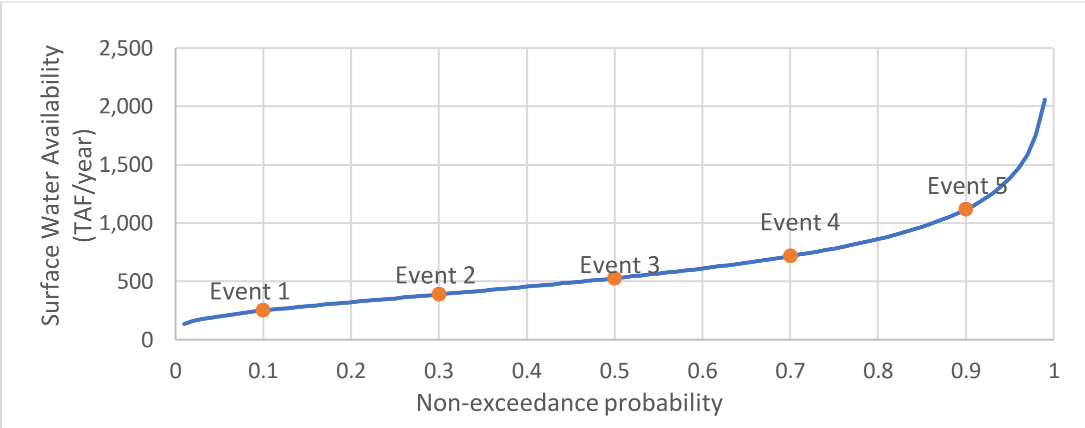


Figure 5.2. "Averaged" surface water inflow of each hydrologic event

Table 5.2. Available surface water in each hydrologic event

	Event j	Percentile	sw_j (TAF/yr)	p_j
Dry	1	10th	248	0.2
	2	30th	387	0.2
	3	Median	526	0.2
	4	70th	716	0.2
Wet	5	90th	1,115	0.2

3. Results and Discussion

The first results explore how many perennial crops should be planted at the beginning of each stage and the corresponding groundwater storage at each stage. The most important difference between the result of this model and that of Chapter 4 (without groundwater salinity) is that with groundwater salinity even a high discount rate cannot defer artificial recharge until the last stage, when groundwater salinity severely reduces perennial crop yield and artificial recharge is needed and pumping is restricted to slow the rise in groundwater salinity.

3.1 Base Case

Base case is the situation where $X_{p,o}$ = 50,000 acres, r = 3.5%, with base climate and an ending storage target = 10 MAF.

Table 5.3 shows total profit over 10 stages (100 years) with different initial groundwater levels (GW_o) on rows and different initial groundwater salinity ($C_{gw,o}$) by column (the first column omits salinity). Redder shades show less profit, and greener shades show more profit. Since total profit is overestimated for any $C_{gw,o}$ over 2,500 mg/L (when GW_o = 9 MAF and $C_{gw,o}$

= 3,000 mg/L, we reach 5,000 mg/L earlier than stage 9), we only show total profit from $C_{gw,o}$ = 500 to 2,500 mg/L.

By column, greater initial salinity decreases total profit. Table 5.4 further shows the impact of groundwater salinity by subtracting adjacent columns considering salinity of Table 5.3. As salinity rises, profit drops more (left column is less than the right). Higher initial groundwater storage suffers more as salinity increases (upper rows are less than the bottom).

Table 5.3. Net present value of total profit (M$) over 10 stages by different starting groundwater storages and salinity levels (discount rate = 3.5%, ending storage = 10 MAF)

Initial groundwater storage, GW_o (MAF)	Initial groundwater salinity, $C_{gw,o}$ (mg/L)			
	No Salinity	500	1,500	2,500
8	5,022	4,817	4,518	4,089
9	5,093	4,885	4,539	4,094
10	5,149	4,992	4,623	4,099
11	5,203	5,017	4,633	4,106
12	5,256	5,073	4,645	4,116

Table 5.4. Loss of total profit in present value (M$ over 10 stages) due to salinity

Initial groundwater storage, GW_o (MAF)	Salinity change (mg/L)	
	500 to 1,500	1,500 to 2,500
8	299	429
9	346	445
10	369	524
11	384	527
12	428	529

Comparing rows of Table 5.3, higher initial groundwater storage increases total profit, especially when initial groundwater salinity is relatively low (≤1,500 mg/L), there is a large increase in total profit from GW_o = 9 MAF to 10 MAF (equal to the final goal) showing the severe cost of recovering the aquifer (highlighted in Table 5.5). However, groundwater has diminishing value as salinity increases (see Table 5.5 by column).

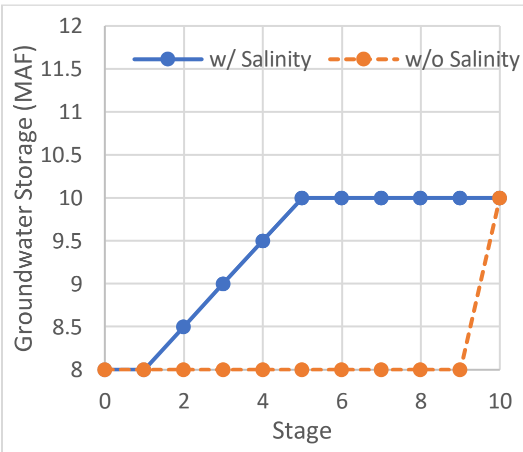
Table 5.5. Groundwater value ($/AF) over 10 stages by salinity level

Initial groundwater storage change, GW_o change (MAF)	Initial groundwater salinity, $C_{gw,o}$ (mg/L)		
	500	1,500	2,500
8 to 9	68	21	5
9 to 10	107	84	5
10 to 11	25	10	7
11 to 12	56	12	10

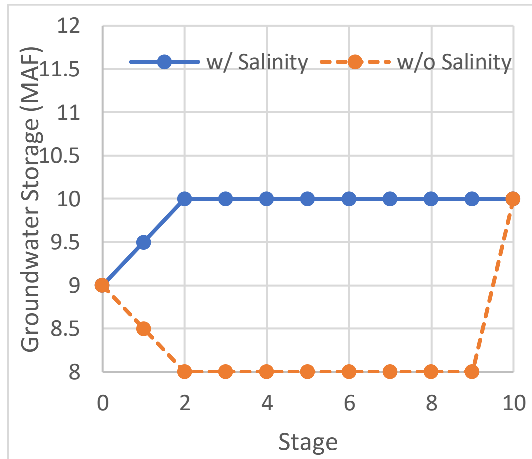
3.1.1 Low initial groundwater salinity ($C_{gw,o}$ = 500 mg/L)

Figure 5.3 shows groundwater storage trajectory over stages without and with low groundwater salinity (500 mg/L), for initial groundwater storages from 8 MAF to 12 MAF and initial perennial crop acreage of 50,000 acres. Without salinity, groundwater is pumped to the lowest storage level (8 MAF) for all initial groundwater positions (GW_o) and only recharged in the last stage, because pumping groundwater with no salinity makes more profit, which should tend to occur in earlier stages, and the cost of recharging is put in later stages, due to discounting.

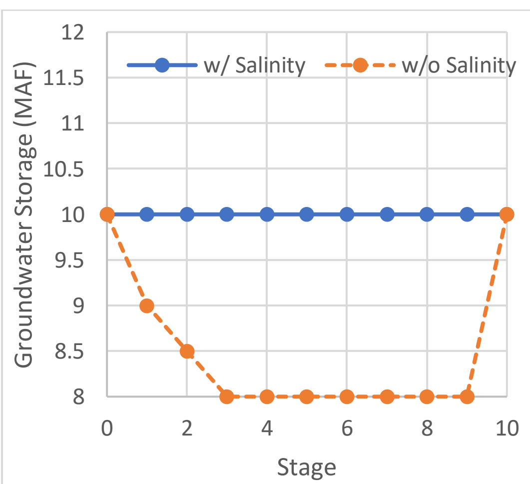
Modest salinity can greatly change economically driven groundwater management and profits. Rather than pumping to the minimum 8 MAF, optimization with groundwater salinity reaches the final storage goal, 10 MAF, sooner, because pumping in early stages increases groundwater salinity faster and decreases crop yields sooner. Once the 10-MAF goal is hit, the model maintains no-overdraft operation until the last stage.



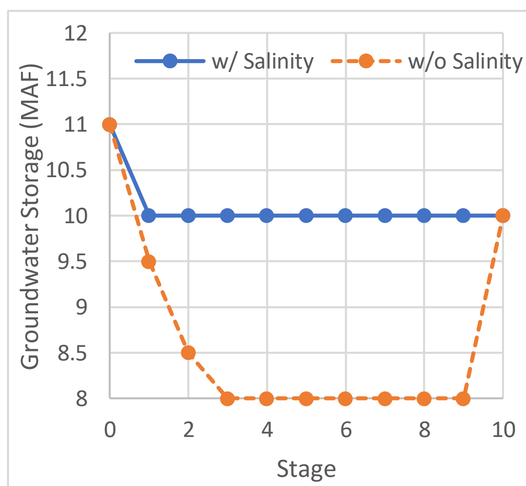
(a): GW_o = 8 MAF



(b): GW_o = 9 MAF



(c): GW_o = 10 MAF



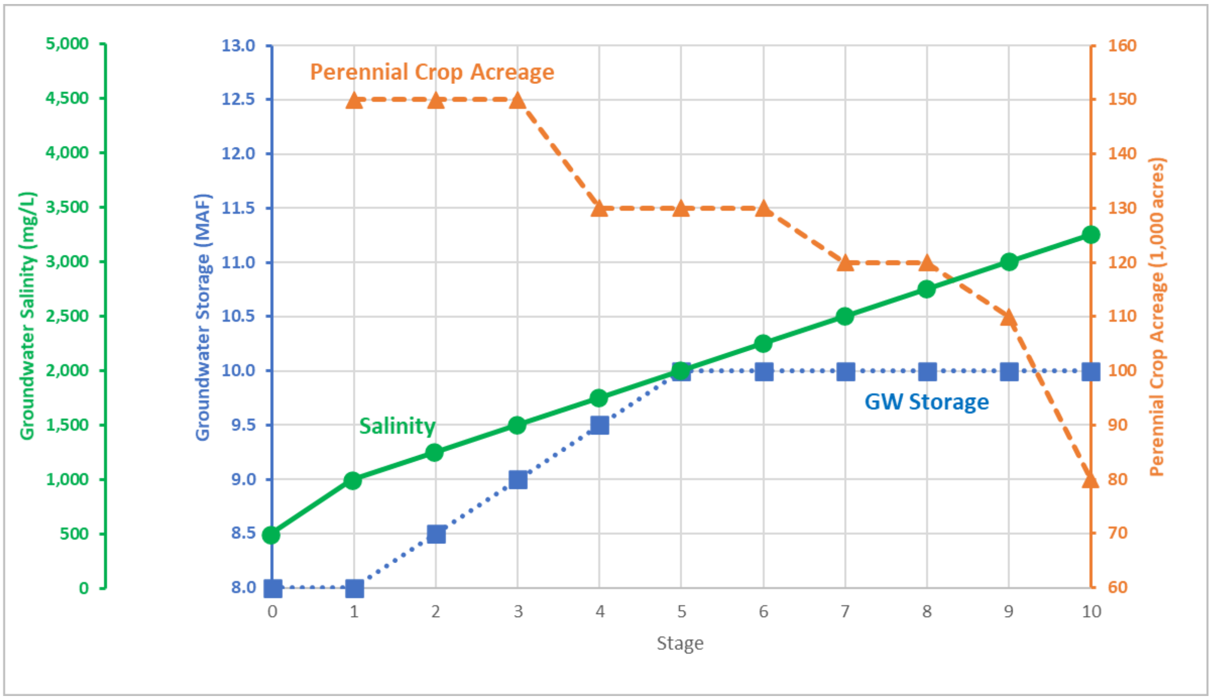
(d): GW_o = 11 MAF

Figure 5.3. Groundwater management strategy changes greatly with modest salinity ($C_{gw,o}$ = 500 mg/L, r = 3.5%)

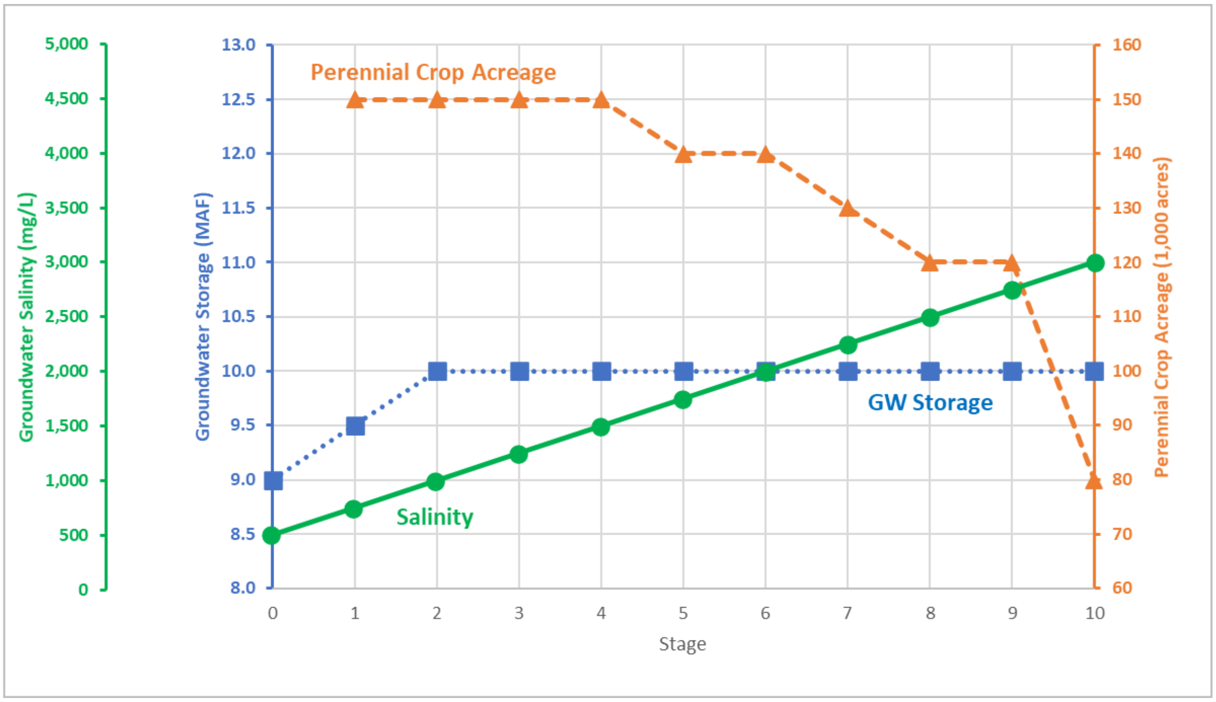
Figure 5.4a shows final groundwater storage, perennial crop acreage decisions, and final groundwater salinity at each stage for initial groundwater storage GW_o = 8 MAF and initial groundwater salinity $C_{gw,o}$ = 500 mg/L. Because profit in the first stage is least discounted in terms of present value, and groundwater salinity is also the least (500 mg/L), and does not yet reduce perennial crop yield, and being already at the minimum groundwater storage (8 MAF), a no-overdraft goal supports the maximum allowed perennial crops in the first stage. But this decision increases groundwater salinity by 500 mg/L for the next stage.

Starting from the second stage, 0.5 MAF of surface water is recharged to the aquifer per stage until the final goal, 10 MAF, is reached at stage 5. If we do not start recharging that early, groundwater salinity increases by 500 mg/L per stage, which harms perennial crops. Though recharging 0.5 MAF in one stage still increases salt concentration by 250 mg/L, recharging 1 MAF per stage is still not recommended because salinity will not fall by doing so, and this decreases profitable perennial crop acreage. For the base climate in this example, the surface water is not enough to both support the maximal perennial crop acreage and 1-MAF artificial recharge. It is uneconomical not to have maximal perennial crop acreage when salinity is low (groundwater of 1,000 mg/L of salt does not impair perennial crop yield in this example). After stage 5, groundwater storage remains at 10 MAF through the end of the planning horizon. Groundwater storage is enough so a no-overdraft goal only increases groundwater salinity by 250 mg/L.

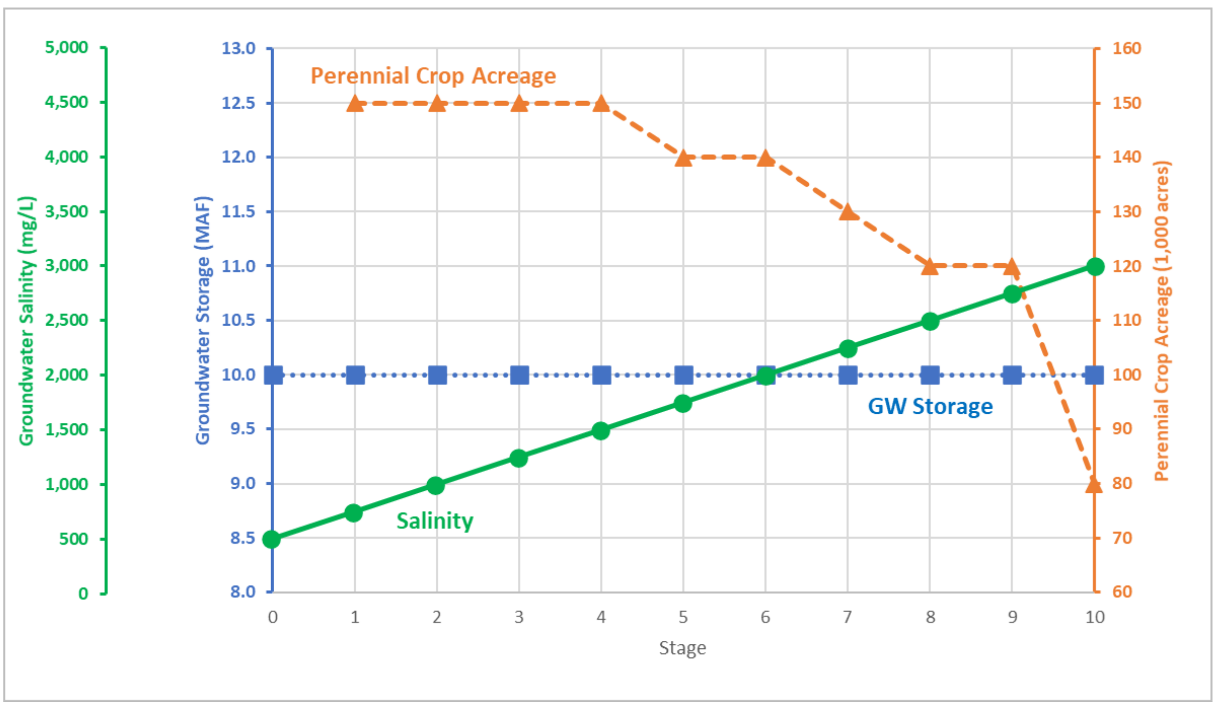
Perennial crop acreage decisions are driven mostly by groundwater salinity. From stage 1 to stage 3, low groundwater salinity allows the maximal acreage of perennial crops. In stage 4, groundwater salinity reaches 1,500 mg/L, starting to reduce perennial crop yield in the driest event (see Chapter 3 for more detail), perennial crop acreage drops to 130,000 acres. Perennial crop acreage further decreases when groundwater salinity reaches higher levels (2,250 mg/L in stage 7 and 2,750 mg/L in stage 9).



(a): GW_o = 8 MAF



(b): GW_o = 9 MAF



(c): GW_o = 10 MAF

Figure 5.4. Groundwater storage and salinity, and perennial crop acreage decision of each stage ($C_{gw,o}$ = 500 mg/L, r = 3.5%)

The DP's optimal long-term perennial crop acreage for stages 1 to 9 usually exceeds that of a short-term decision, saving initial establishment costs in later stages. For example, we plant maximal perennial crops in the first three stages, two of which are recharging stages where artificial recharge in the two wettest events compensates for pumping in the two driest events (Table 5.6). Even if salinity affects perennial crop yield, because for model simplification, the perennial crops entering next stage are "reset" to a state unimpaired by salinity, still more perennial crops are planted in a long-term DP decision than a short-term decision by using much surface water otherwise allocated to annual crops (Table 5.7). In the last stage, the lack of need to prepare more perennial crops for the future allows short-sighted and long-term decisions to converge - 80,000 acres of perennial crops are planted, a sudden drop in Figure 5.4.

Comparing Figure 5.4a and 5.4b, perennial crop acreage of initial groundwater storage GW_o = 9 MAF is always equals or exceeds that of GW_o = 8 MAF, which makes GW_o = 9 MAF more profitable by 68 M$ (Table 5.5). Because when GW_o = 9 MAF, we recharge the aquifer in the first stage, groundwater salinity of GW_o = 9 MAF is less than that of GW_o = 8 MAF by 250 mg/L in any stage. Also, as mentioned previously, it is unwise to recharge 1 MAF in one stage to sacrifice the acreage of perennial crops when salinity is still low, so, instead of recharging 1 MAF in either stage 1 or stage 2, the 1-MAF aquifer recovery target is averaged over the first two stages.

Since storage of 10 MAF is large enough, maintaining no overdraft increases salinity by only 250 mg/L, the salinities of GW_o = 9 and 10 MAF in any stage are the same (Figure 5.4b and 5.4c). So, perennial crop acreages for any stage given GW_o = 9 and 10 MAF are the same. The only difference between GW_o = 9 and 10 MAF is that when GW_o = 10 MAF, there is no need for aquifer recharge. From Table 5.5, we know the large cost of aquifer recovery: 107 M$ in present value over the entire planning horizon.

Table 5.6. Comparison of short-term and longer-term DP solutions for a net restoring goal from 8 MAF to 8.5 MAF in stage 2 of 10 where GW_o = 8 MAF ($C_{gw,1}$ = 1,000 mg/L)

		Short-term (Chapter 3)	Long-term DP at stage 2 (Chapter 5)
Perennial crop acreage (acre/stage)		112,059	150,000
Annual crop acreage (acre/yr)	Events 1-2	0	0
	Event 3	14,533	0
	Event 4	53,655	18,059
	Event 5	127,455	18,059
Land for artificial recharge (acre/yr)	Events 1 - 3	0	0
	Event 4	0	1,191
	Event 5	2,831	27,835
Groundwater pumping (AF/yr)	Event 1	207,639	362,058
	Event 2	68,920	223,339
	Event 3	0	84,080
	Events 4 -5	0	0
Profit of stage 2 in present value (M$)		1,152	1,092

The similarity of decisions with GW_o = 11 and 12 MAF are that groundwater is pumped to the final goal, 10 MAF, in the first stage (Figure 5.5). When GW_o = 11 MAF, more groundwater is pumped compared to the no-salinity case (Figure 5.3d). Groundwater salinity always increases by 500 mg/L for a drawdown goal due partly to the coarse discretization. Also, as long as we do not pump too much (≥ 3.5 MAF in one stage), final groundwater salinity at a stage is indifferent to pumping. Take GW_o = 11 MAF as an example, two 0.5-MAF pumping stages increase groundwater salinity by 500+500=1,000 mg/L (though the first 0.5-MAF pumping stage only causes an increase of salinity of 252 mg/L, which is set to 500 according to Equation (5.1)). But if we pump 1 MAF in the first stage and keep no overdraft in the second stage, groundwater salinity increases only by 500+250=750 mg/L. So, it is uneconomical to lengthen the pumping phase as it makes groundwater saltier in later stages, which decreases perennial crop acreage and yield. So, more groundwater is pumped in the first stage for more annual crops.

Table 5.7. Comparison of short-term solution and longer-term DP solution for a no-overdraft goal from 10 MAF to 10 MAF in stage 7 of 10 where GW_o = 8 MAF ($C_{gw,6}$ = 2,250 mg/L)

		Short-term (Chapter 3)	Long-term DP at stage 7 (Chapter 5)
Perennial crop acreage (acre/stage)		87,541	120,000
Annual crop acreage (acre/yr)	Event 1	0	0
	Event 2	41,103	13,808
	Event 3	80,775	32,687
	Event 4	80,775	46,977
	Event 5	156,845	129,550
Land for artificial recharge (acre/yr)	Events 1 - 5	0	0
Groundwater pumping (AF/yr)	Event 1	107,851	239,958
	Event 2	168,070	168,070
	Event 3	220,821	120,186
	Event 4	31,472	0
	Event 5	0	0
Profit of stage 7 in present value (M$)		191	181

In summary, without salinity, groundwater storage is always kept at minimum and recharge occurs only in the last stage to meet the 10-MAF goal, while with salinity, recharge occurs much earlier to create a more profitable environment for later stages, even with a high discount rate of 3.5%. This means keeping groundwater salinity as low as possible is important to increase total profit. So, pumping is greatly restricted to cases where initial groundwater storage exceeds the final goal, 10 MAF, though it is possible to pump more aggressively in one stage only to grow annual crops (GW_o = 11 MAF).

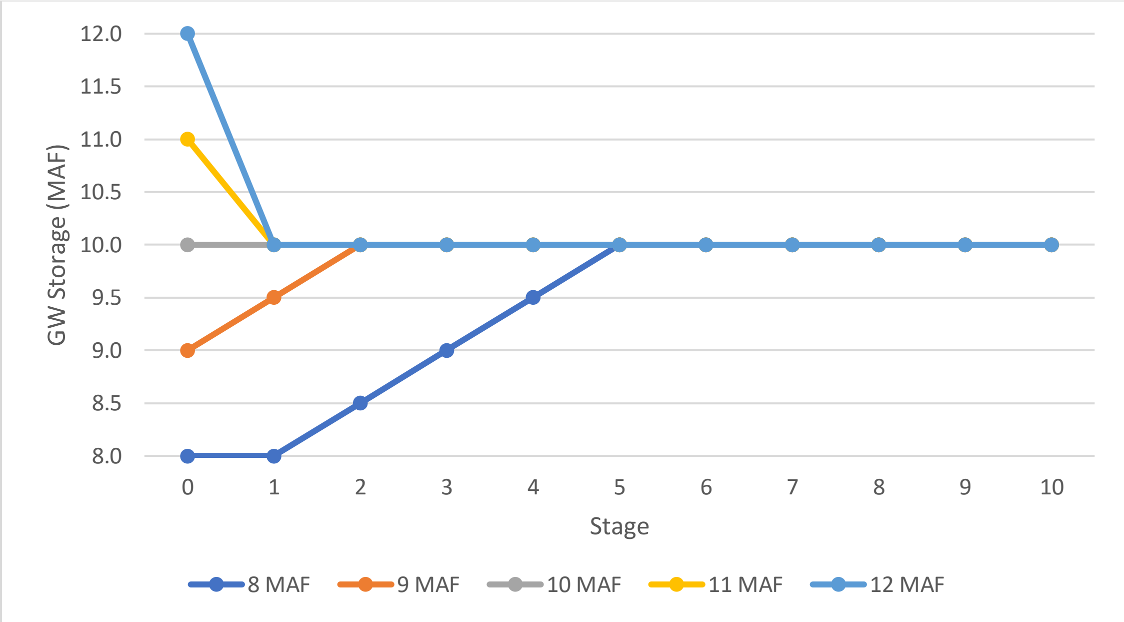


Figure 5.5. Groundwater storage change over stages ($C_{gw,o}$ = 500 mg/L, r = 3.5%)

3.1.2 Moderate initial groundwater salinity ($C_{gw,o}$ = 1,500 mg/L)

At an initial groundwater salinity of 1,500 mg/L, perennial crop yield begins to decrease. Figure 5.6 shows groundwater storage change over stages with different initial groundwater storages from 8 MAF to 12 MAF, with incoming perennial crop acreage of 50,000 acres, and initial groundwater salinity of 1,500 mg/L. Comparing with Figure 5.5 shows several major differences. First, when GW_o = 8 MAF, recharging starts even earlier and becomes more aggressive. Second, when GW_o = 11 and 12 MAF, rather than occurring in the first stage, pumping occurs in the last stages.

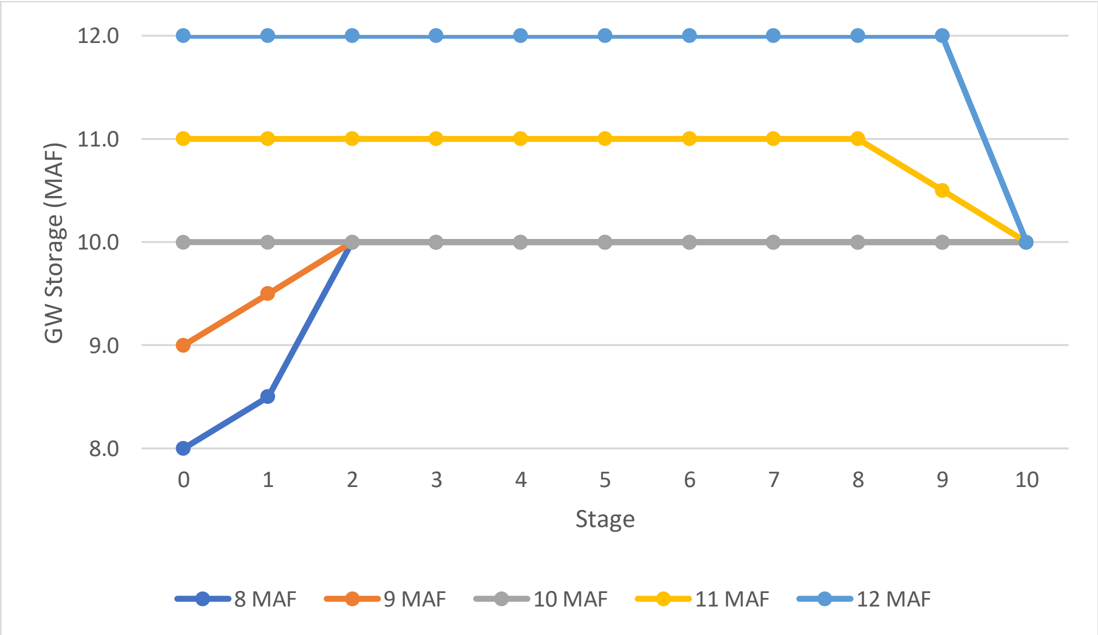


Figure 5.6. Groundwater storage change over stages ($C_{gw,o}$ = 1,500 mg/L, r = 3.5%)

As mentioned in the previous section, keeping salinity low improves total profit. For GW_o = 8 MAF, optimized groundwater salinity increases only by of 250 mg/L in the first two stages. Figure 5.7a shows the detail: rather than gradually recharging 0.5 MAF per stage for four stages (which increases salinity by 2*250=500 mg/L at the end of stage 2), we recharge 0.5 MAF in the first stage (with an increase of 250 mg/L) and recharge 1.5 MAF in the second stage (with zero increase in salinity). Only by doing so, the 250-mg/L increase goal is met, with a higher profit. It is too desperate to recharge 2 MAF in the first stage and decrease perennial crop acreage too much as a salinity of 1,500 mg/L just starts to impair perennial crop yield in the driest events. Keeping no overdraft in the first stage already increases groundwater salinity by 500 mg/L. Recharging 1.5 MAF in the first stage still increases groundwater salinity by 250 mg/L (so, at the end of stage 2 groundwater salinity increases by 250+250 = 500 mg/L).

Comparing Figure 5.7a (GW_o = 8 MAF for moderate salinity) and Figure 5.4a (GW_o = 8 MAF for low salinity), in the first two stages, perennial crop acreage in Figure 5.7a is less than in Figure 5.4a from the heavier recharge burden. At the end of stage 2, Figure 5.4a and Figure 5.7a have groundwater salinities of 1,250 mg/L and 1,750 mg/L, respectively. The 500-mg/L difference greatly changes perennial crop acreage since stage 3. With a 250-mg/L increase of salinity per stage, perennial crop acreage can stay the same for a couple of stages in Figure 5.4a, while it decreases much faster in Figure 5.7a, with a 299 M$ loss of total profit (Table 5.4).

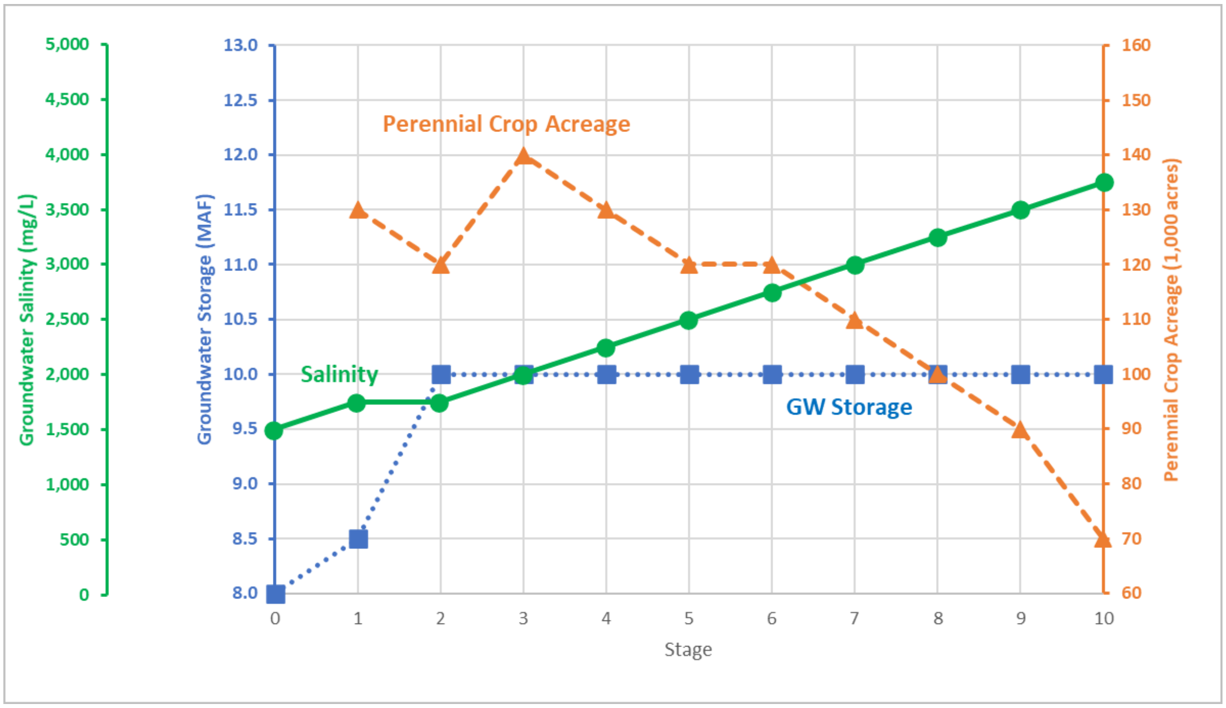
When GW_o > 8 MAF, the recharging phase is not long and intense enough to prevent groundwater salinity from rising fast. So, we move to the second best: an increase of 500 mg/L in salinity in two stages. When GW_o = 9 MAF, the 1-MAF recharging target is averaged to the first two stages (i.e., 250-mg/L increase in salinity per stage), so more perennial crops can be grown in the first stage (Figure 5.7b). Without recharge in the first stage, groundwater salinity increases by 500 mg/L.

Comparing Figure 5.7a (GW_o = 8 MAF) and 5.7b (GW_o = 9 MAF), after stage 3, GW_o = 9 MAF cannot have more perennial crops than GW_o = 8 MAF, and perennial crop acreage in GW_o = 9 MAF starts to decrease one stage earlier than that in GW_o = 8 MAF, because salinity for GW_o = 9 MAF is always 250 mg/L higher than that of GW_o = 8 MAF.

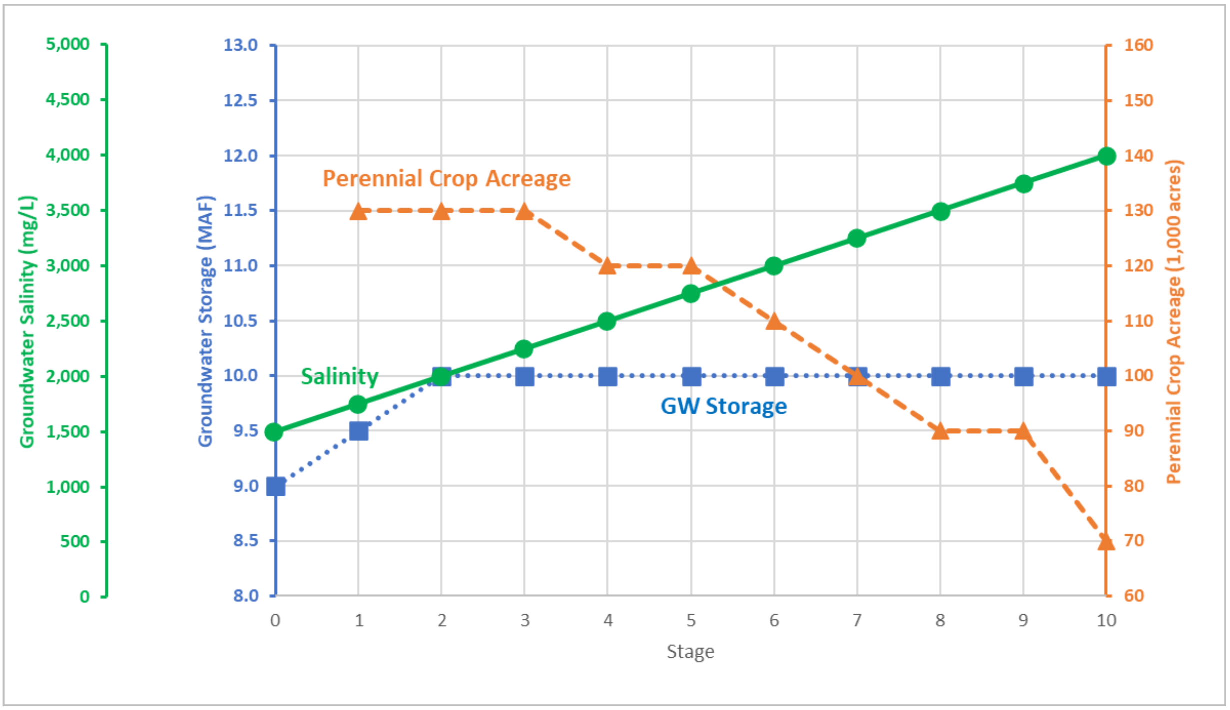
Also, comparing Figure 5.4b (GW_o = 9 MAF for low salinity) and 5.5b (GW_o = 9 MAF for moderate salinity), a huge decrease in perennial crop acreage occurs from a 1,000-mg/L increase in salinity. Also, from the decrease in crop yield, the increase in salinity reduces total profit by 346 M$ (Table 5.4).

When GW_o = 10 MAF, groundwater storage is enough, and maintaining average groundwater storage increases groundwater salinity by 250 mg/L rather than 500 mg/L. So, we keep no overdraft from the beginning to the end, letting groundwater salinity increase by 250 mg/L in every stage. From Table 5.4, the consequence of a 1,000 mg/L increase in initial groundwater salinity is 369 M$, which reduces both perennial crop acreage and yield.

Because pumping groundwater by 0.5 MAF always increases groundwater salinity by 500 mg/L in this example due to coarse discretization, which is unfavorable for perennial crops in later stages, similar for GW_o = 10 MAF, we keep no overdraft when GW_o = 11 and 12 MAF until the last one or two stages (Figure 5.6), because we still have 1 MAF and 2 MAF to be pumped to hit the final 10-MAF goal, respectively.



(a): GW_o = 8 MAF



(b): GW_o = 9 MAF

Figure 5.7. Groundwater storage and salinity, and perennial crop acreage decision of each stage ($C_{gw,o}$ = 1,500 mg/L, r = 3.5%)

When GW_o = 11 MAF, we pump 0.5 MAF at stage 9, but because groundwater salinity in stage 9 is already 3,500 mg/L, we only grow 100,000 acres of perennial crops. From Chapter 3, we suspect that we will dump irrigation water in the last two stages (Figure 5.8). This is also the dilemma for GW_o = 12 MAF, where we sacrifice the last stage and dump a large amount of irrigation water.

Though total profits of GW_o = 11 and 12 MAF are still the highest two among all GW_o (Table 5.3), it is so ironic that with moderate initial groundwater salinity, higher initial groundwater storage is already a disadvantage in this example, as surplus groundwater cannot be used when groundwater salinity is still low, and must be dumped at the end of planning horizon, which only adds pumping costs but no profit.

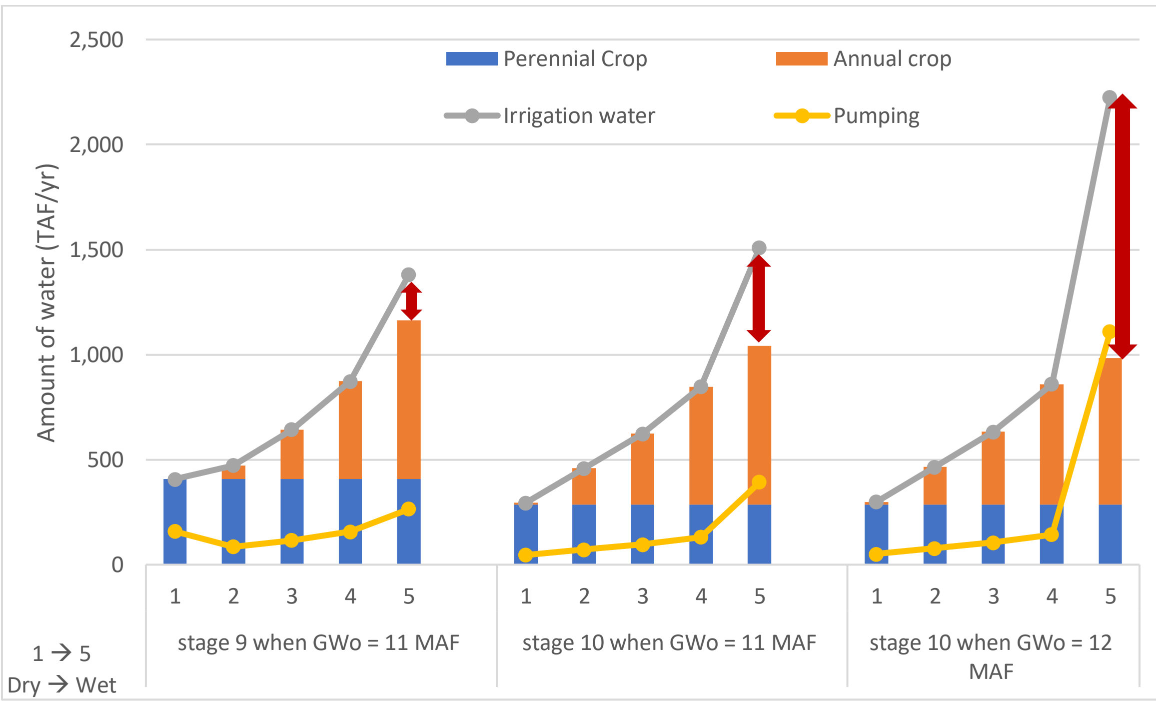


Figure 5.8. Relationship between crop water requirement and irrigation at last stages for higher initial groundwater storage. Brown arrows in event 5 indicate externally spilled irrigation water (a mix of surface water and groundwater).

3.1.3 High initial groundwater salinity ($C_{gw,o}$ = 2,500 mg/L)

Figure 5.9 shows groundwater storage changes over stages for different initial groundwater storage conditions, for initial perennial crop acreage of 50,000 acres and initial groundwater salinity of 2,500 mg/L. Except for the highest initial groundwater storage (GW_o = 12 MAF) (the model cannot exceed groundwater storage of 12 MAF), recharging occurs for at least 1 stage at the beginning of the planning horizon.

Because initial groundwater salinity is 2,500 mg/L, high enough compared to surface water salinity, to be manipulated easily, unlike GW_o = 8 MAF with moderate salinity, where recharge of 1.5 MAF is needed to affect salinity, recharging 1 MAF is enough to prevent groundwater salinity from rising. When GW_o < 10 MAF, recharging meets the final 10-MAF goal (major reason) and stabilizes groundwater salinity (as a by-product). When $GW_o \geq 10$ MAF, recharging has only one purpose - to keep groundwater salinity at 2,500 mg/L for one more stage.

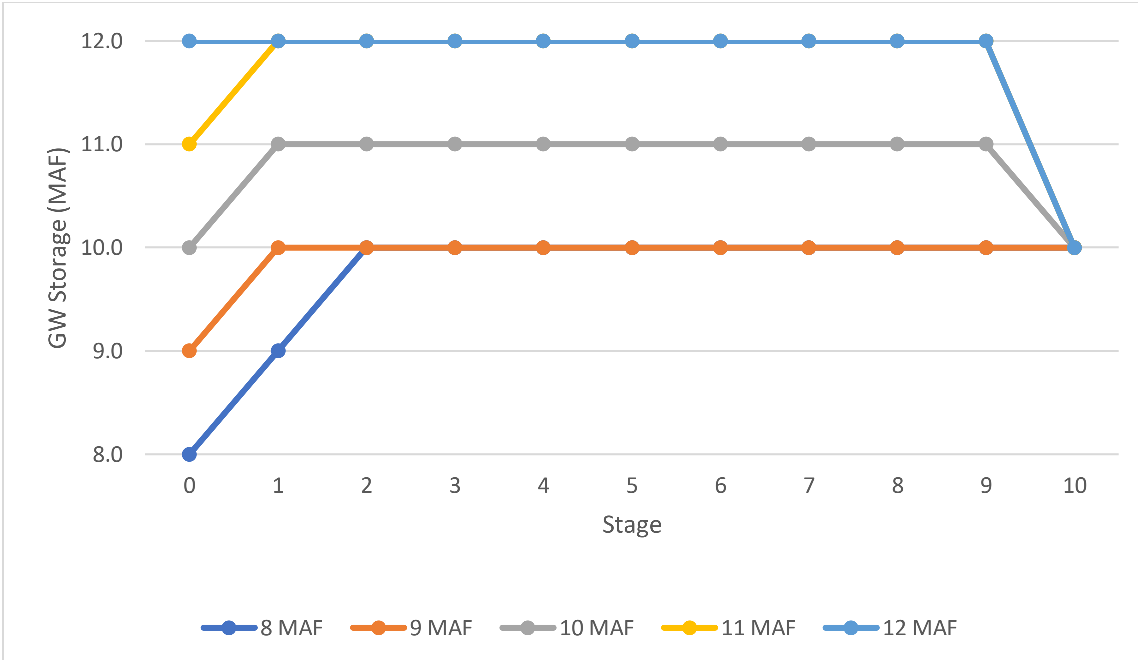


Figure 5.9. Groundwater storage change over stages ($C_{gw,o}$ = 2,500 mg/L, r = 3.5%)

Why not recharge to 12 MAF for all GW_o < 12 MAF to keep groundwater salinity at 2,500 mg/L even longer? First, as long as salinity is not too high (less than 4,500 mg/L), recharging is never more profitable than keeping no overdraft. Second, as mentioned in previous section, any additional groundwater above the 10-MAF storage goal is probably wasted at the end of planning horizon. It is uneconomical to sacrifice perennial crop in early stages to recharge the aquifer with too much water to be dumped later. When excess groundwater must be pumped and dumped, it is done at the end of the planning horizon, when present value cost is least.

3.2 Sensitivity Analysis

Here we change values for some parameters to explore the sensitivity of model results. The discount rate, the probability distribution of surface water availability, and coarseness of salinity discretization in the dynamic programming framework all change patterns of optimal groundwater management.

3.2.1 Discount rate effects (r = 3.5% and 2%)

A lower discount rate emphasizes the importance of recharging in early stages and makes pumping unfavorable for most of time.

3.2.1.1 Low initial groundwater salinity ($C_{gw,o}$ = 500 mg/L)

Figure 5.10 compares average groundwater storage trajectory with initial groundwater storages of 8, 11, and 12 MAF, with incoming perennial crop acreage of 50,000 acres, initial groundwater salinity of 500 mg/L, and a discount rate of 2% and 3.5% (model behaves the same for initial groundwater storages of 9 and 10 MAF in this case with two different discount rates). First, when GW_o = 8 MAF, most aggressive recharging starts as early as the first stage. Second, when GW_o = 11 MAF, pumping occurs in stage 9, rather than in the first stage. Lastly, when GW_o = 12 MAF, in the first stage pumping is minimal (0.5 MAF/stage), the other 1.5 MAF of groundwater is pumped and/or dumped in the last two stages. These differences are mostly salinity driven. When r = 3.5%, making groundwater salinity as low as possible is already key to increasing total profit. With r = 2%, later stages now become more important, so ways to stabilize groundwater salinity become even more important.

Figure 5.11 shows why 1 MAF of surface water must be recharged in the first stage when GW_o = 8 MAF. Recharging 0.5 MAF is not enough to lower the increase in salinity from 500 mg/L to 250 mg/L. Once reaching 9 MAF, 0.5 MAF of surface water is enough to let groundwater salinity only increase by 250 mg/L. Comparing Figure 5.11 (GW_o = 8 MAF, r = 2%) and Figure 5.4a (GW_o = 8 MAF, r = 3.5%), salinity in Figure 5.11 is always one level (250 mg/L) less than in Figure 5.4a.

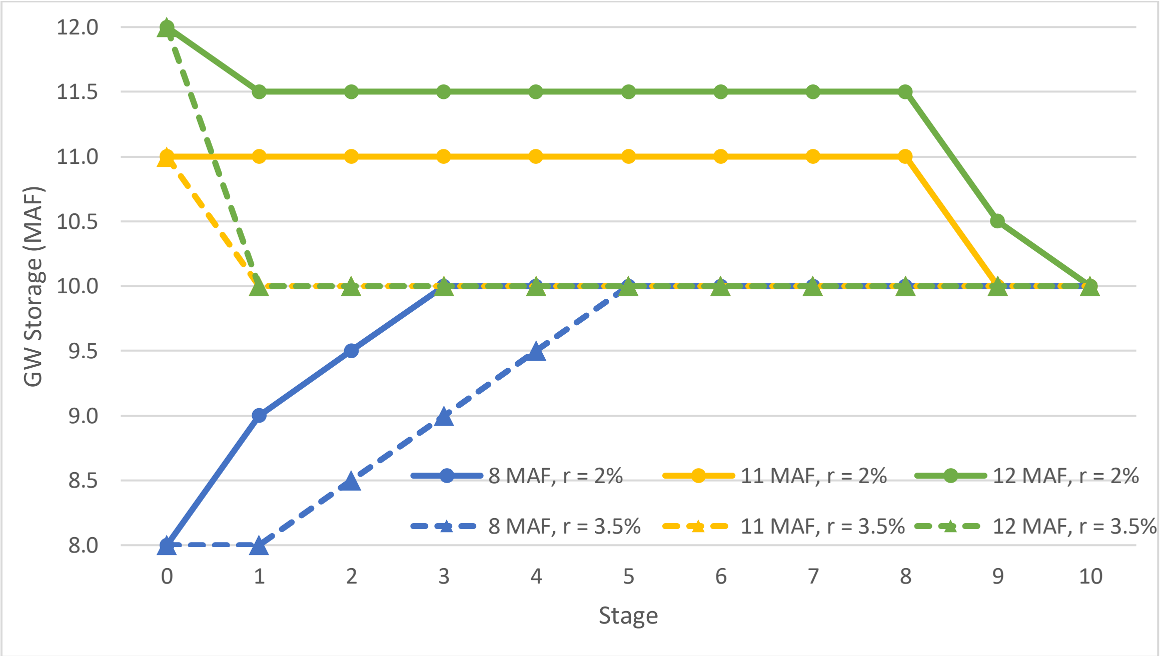


Figure 5.10. Groundwater storage change over stages ($C_{gw,o}$ = 500 mg/L, r = 2% vs. 3.5%)

Also, more perennial crops are grown at lower discount rates, causing the initial establishment cost of perennial crops in the next stage to effectively decrease. In Figure 5.4a, initial groundwater salinity at stage 4 is 1,500 mg/L, for 130,000 acres of perennial crop. While in Figure 5.11, groundwater salinity at stage 6 is 1,750 mg/L, but 150,000 acres of perennial crop are grown to reduce initial establishment cost in the next stage. Indeed, 1,750 mg/L is the highest allowable salinity to grow maximal perennial crops for all GW_o when r = 2%, while for r = 3.5%, it is 1,500 mg/L. This means more perennial crops will be impaired in any stages except for the first and last stages when the discount rate is lower, and our coming to this decision is mainly from a loophole in the model formulation: the perennial crops entering next stage are “reset” to a state unimpaired by salinity.

When GW_o = 11 MAF, to lower groundwater salinity, pumping moves from the first stage to the ninth one. Why not pump in the last stage? Because the initial groundwater salinity at stage 9 is 2,750 mg/L, 1 MAF of groundwater diluted with surface water is still acceptable by crops. If we save that 1 MAF to stage 10, the 3,000-mg/L groundwater will be wasted (pumped and dumped) according to Chapter 3.

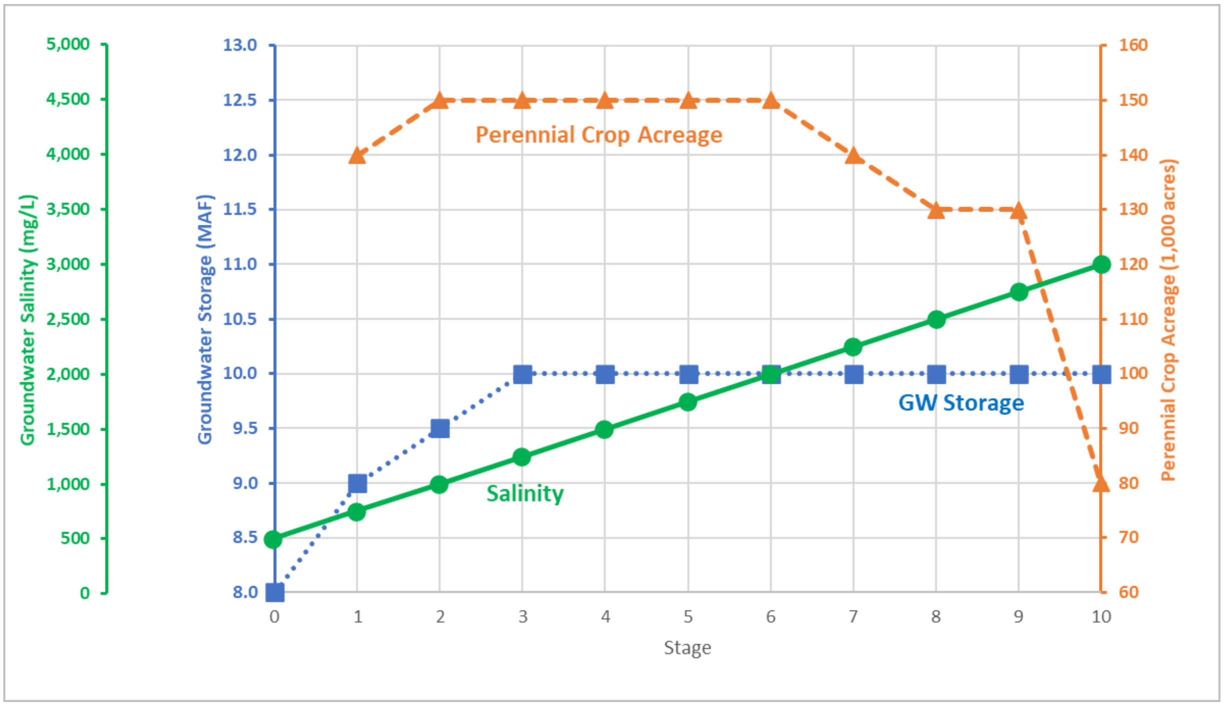


Figure 5.11. Groundwater storage and salinity, and perennial crop acreage decision of each stage (GW_o = 8 MAF, $C_{gw,o}$ = 500 mg/L, r = 2%)

When GW_o = 12 MAF, groundwater storage is so large that pumping 0.5 MAF only increases groundwater salinity by 250 mg/L, same as keeping no overdraft. So, this 0.5 MAF of groundwater is pumped in the first stage as pumping groundwater with the lowest salinity makes higher profit than keeping no overdraft and recharging. Similar as GW_o = 11 MAF, anther 1 MAF is pumped at stage 9. The last 0.5 MAF is pumped in the last stage.

3.2.1.2 Moderate initial groundwater salinity ($C_{gw,o}$ = 1,500 mg/L)

Figure 5.12 compares groundwater storage change over stages with different initial groundwater storage of 9, 10 and 12 MAF, with incoming perennial crop acreage of 50,000 acres, and initial groundwater salinity of 1,500 mg/L for a discount rate of 2% and 3.5%. When GW_o = 9 MAF, we behave the same way as GW_o = 8 MAF (in which the DP model behaves the same with different discount rates) so groundwater salinity only increases by 250 mg/L in the first two stages, even though we reach 11 MAF (higher than 10-MAF goal) at the end of stage 2.

This proves that recharging 0.5 MAF in the first stage and 1.5 MAF in the second stage is the most profitable solution for initial groundwater storages lower than the final target, which cares more about the later stages. When GW_o = 10 MAF, to stabilize groundwater salinity at 2,500 for one more stage, another 1 MAF of surface water is recharged in stage 5, despite some recharged water being wasted in the last stage.

When GW_o = 12 MAF, rather than pumping the entire 2 MAF groundwater in the last stage, 0.5 MAF of groundwater is pumped in stage 9. Though dumping irrigation water occurs in stages 9 and 10, because the discount rate is lower, stage 10 is nearly as important as stage 9, we share some of the pumping cost of dumping to stage 9. For GW_o = 11 MAF, which is not showing in Figure 5.12 as we use the same groundwater storage management strategy regardless of the discount rate. However, the reasons for the decision differ. When r = 3.5%, GW_o = 11 MAF is a unique case to share pumping evenly in the last two stages to support more perennial crops compared to other GW_o's growing in stage 9 (still, some water is pumped and dumped). For r = 2%, same as GW_o = 12 MAF, pumping sharing in GW_o = 11 MAF is just not to make the profit in stage 10 too low due to dumping that lower the total profit.

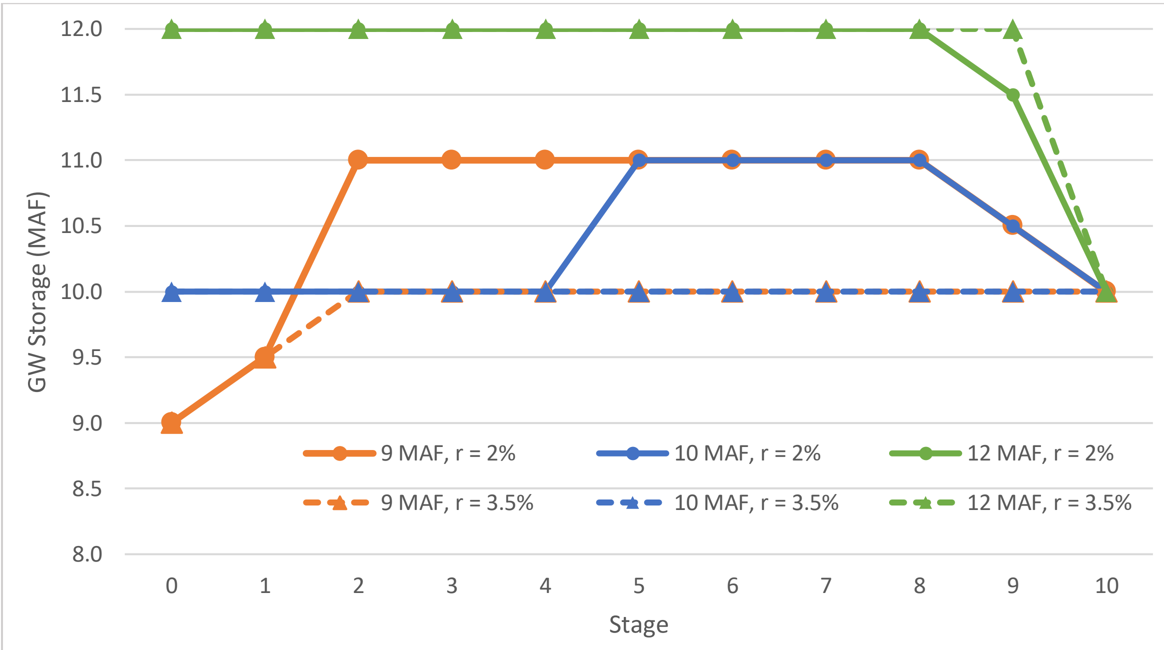


Figure 5.12. Groundwater storage change over stages ($C_{gw,o}$ = 1,500 mg/L, r = 2% vs. 3.5%)

3.2.1.3 High initial groundwater salinity ($C_{gw,o}$ = 2,500 mg/L)

Figure 5.13 compares groundwater storage change trajectory with initial storages from 8 MAF to 10 MAF, with incoming perennial crop acreage of 50,000 acres, initial groundwater salinity of 2,500 mg/L, and a discount rate of 2% and 3.5% (as an initial groundwater storage of 11 and 12 MAF with such high groundwater salinity has no other ways to stabilize the salinity). With a lower discount rate, rather than only recharging 1 MAF for one or two stages, recharge to the maximum (12 MAF) is used to keep groundwater salinity at 2,500 mg/L as long as possible, because groundwater of 2,500 mg/L is already unfavorable for perennial crops, and the lower discount rate is only 2%, increasing the present value of later profits.

For GW_o = 8 MAF, four stages are used for recharge (i.e., 2,500 mg/L can last for four stages), and for GW_o = 9 MAF, only three stages are used for recharge (i.e., 2,500 mg/L can only last for three stages), and so on. As for larger initial groundwater storages, groundwater salinity starts to increase earlier, and losses of perennial crop production of high initial groundwater storages in later stages exceed aquifer recharge cost of low initial groundwater storages in earlier stages. So, total profit decreases as initial saline groundwater storage increases (Figure 5.14). With high groundwater salinity and a lower discount rate, more groundwater is undesirable.

GW_o = 8 MAF has an additional advantage over other GW_o's as at the beginning of stage 9, where the groundwater salinity is 3,500 mg/L, lowest among all the GW_o. So, 0.5 MAF of groundwater is pumped in advance in stage 9 to grow 30,000 acres more perennial crops than GW_o = 10 to 12 MAF with some dumping of irrigation water (Figure 5.15). When GW_o = 9

MAF, because the groundwater salinity is 3,750 mg/L at the beginning of stage 9, though a net pumping goal is rejected, 10,000 acres more perennial crops are planted compared to GW_o = 10 to 12 MAF.

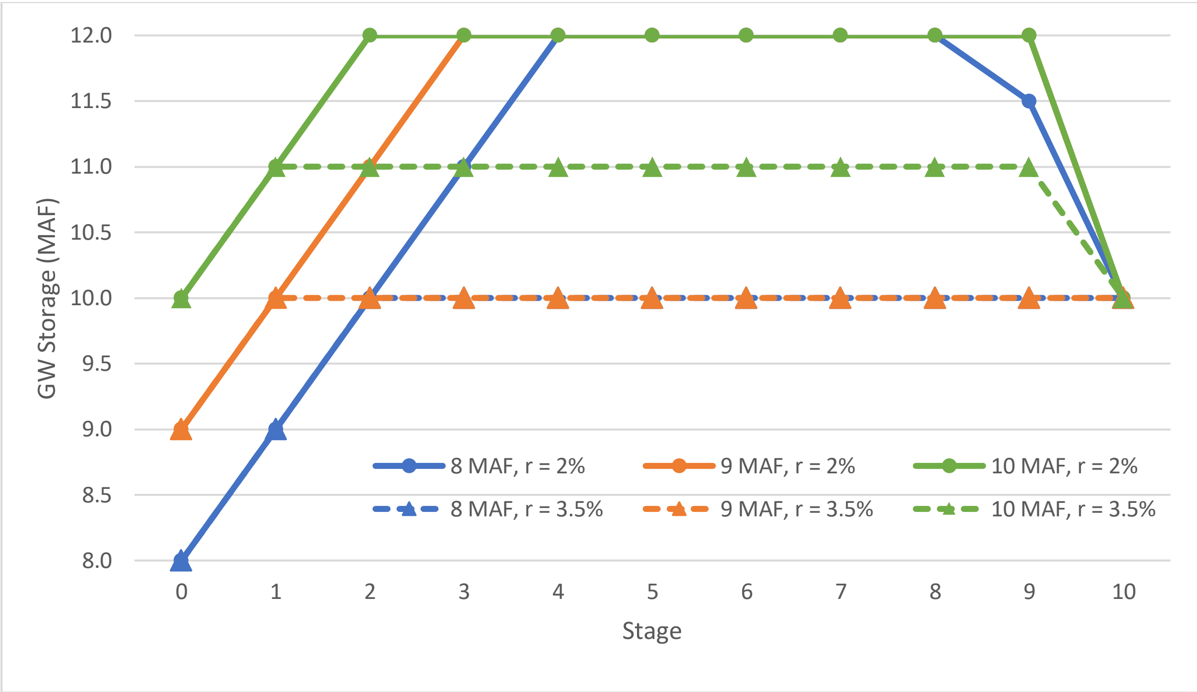


Figure 5.13. Groundwater storage change over stages ($C_{gw,o}$ = 2,500 mg/L, r = 2% vs. 3.5%)

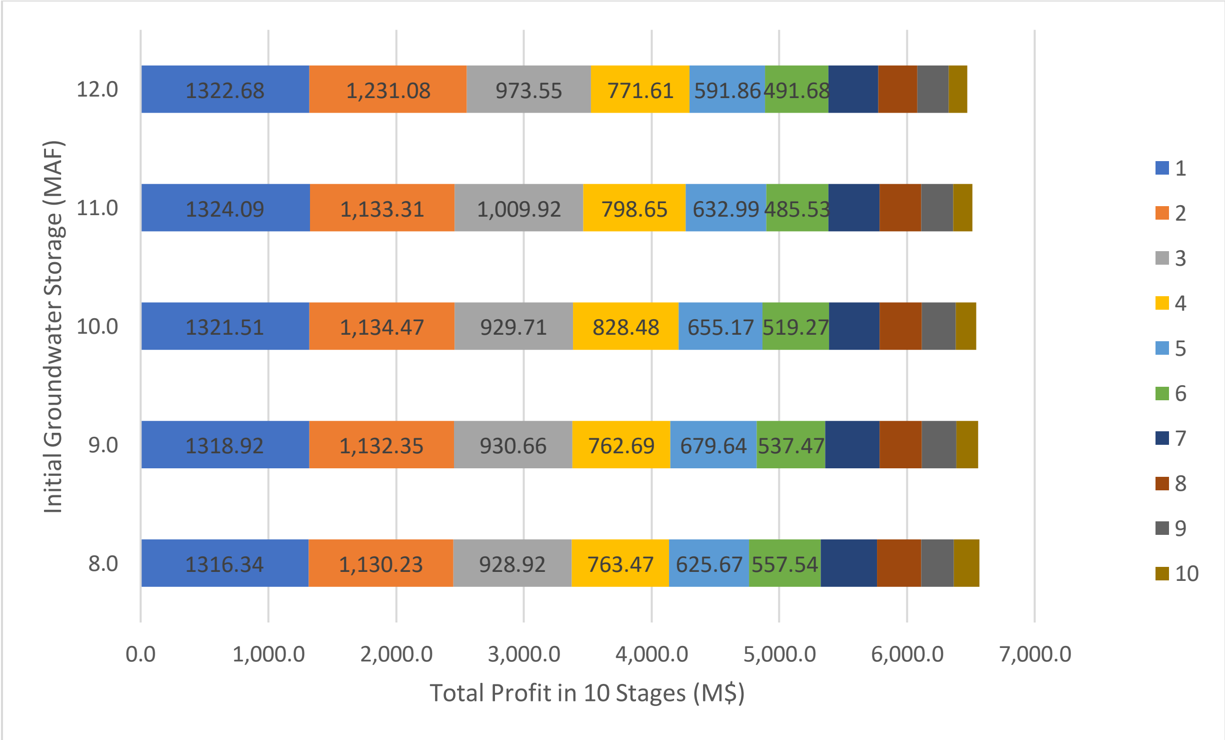


Figure 5.14. Sum of profit in present value for different initial groundwater storages across stages 1 to 10 ($C_{gw,o}$ = 2,500 mg/L, r = 2%)

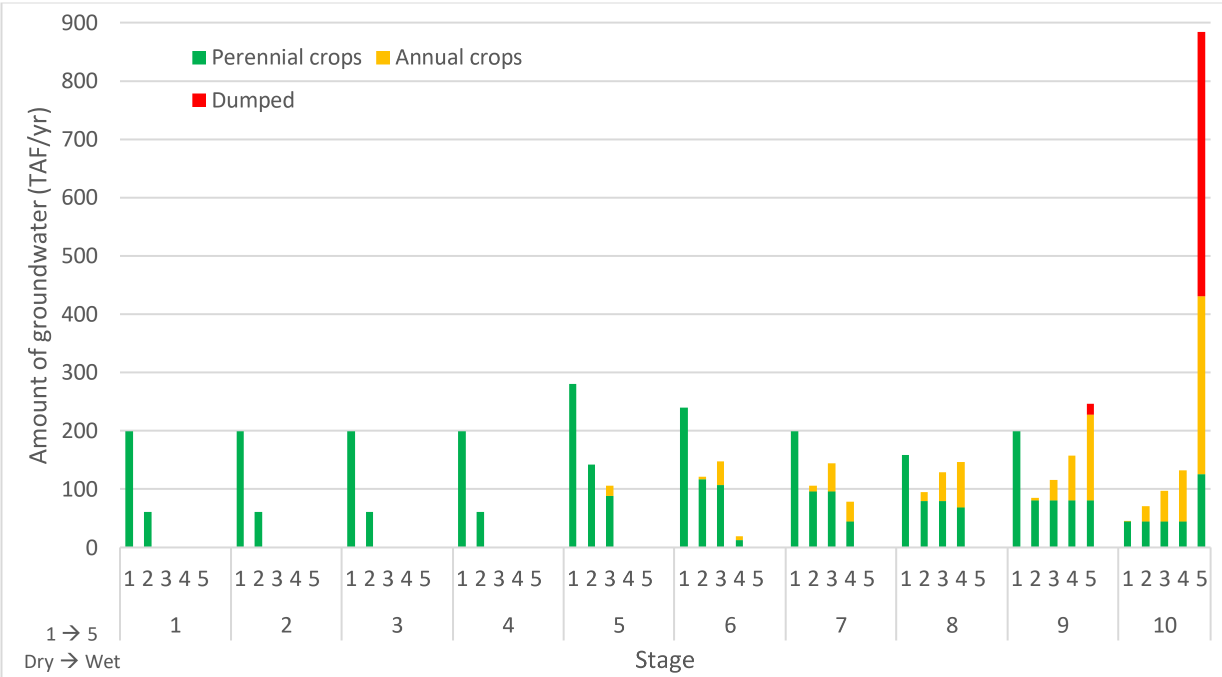


Figure 5.15. Allocation of groundwater for each hydrologic event in each stage (GW_o = 8 MAF, $C_{gw,o}$ = 2,500 mg/L, r = 2%) In stage 5, more groundwater is pumped because the goal changes from net recovery to no overdraft and more perennial crops are planted

In summary, a lower discount rate increases the length and intensity of recharging in earlier stages to lengthen the period of low salinities. It moves early pumping stages, if there is one with a higher discount rate, to later stages. A lower discount rate also moves some (GW_o = 12 MAF, $C_{gw,o}$ = 500 mg/L) or all (GW_o = 11 MAF, $C_{gw,o}$ = 500 mg/L) the "burden" of pumping to stage 9 if the initial groundwater salinity at stage 9 is still acceptable for perennial crops while with a higher discount rate, pumping usually only occurs in stage 10 (GW_o = 12 MAF, $C_{gw,o}$ = 1,500 mg/L).

3.2.2 Hydrologic Event Probabilities

This sensitivity analysis uses the drier climate in Table 5.8. Due to lack of surface water in drier climate, less recharge occurs in earlier stages. Instead, pumping increases in earlier stages when initial groundwater storage is high and groundwater salinity is lower.

Table 5.8. Hydrologic event probabilities in each climate

	Event *j*	Drier	Base
Dry	1	0.25	0.2
	2	0.25	0.2
	3	0.2	0.2
	4	0.2	0.2
Wet	5	0.1	0.2
Expected incoming surface water (TAF/yr)		519 (-13%)	599

3.2.2.1 Low initial groundwater salinity ($C_{gw,o}$ = 500 mg/L)

Figure 5.16 compares groundwater storage change trajectory for initial storages from 8 MAF to 12 MAF, incoming perennial crop acreage of 50,000 acres, and initial groundwater salinity of 500 mg/L for the base and drier climates. Following are several groundwater management findings.

First, the drier climate replaces recharging with pumping. Because less surface water is available, recharging in early stages means fewer perennial crops can be grown when the groundwater salinity is at this lower level. For example, with the base climate it is still possible to grow maximal perennial crops (150,000 acres) with a recharging goal of 0.5 MAF (Table 5.6). However, with the drier climate, a no-overdraft goal can barely support 140,000 acres of perennial crops. So, except for GW_o = 8 MAF, we pump groundwater for all other initial groundwater storages, for instance, when GW_o = 9 MAF, rather than recharging, we pump 0.5 MAF in the first stage to grow maximal perennial crops.

Second, slowing salinity increase improves profit. So, we recharge 0.5 MAF for GW_o = 8 MAF to reduce groundwater salinity to 750 mg/L rather than 1,000 mg/L at the end of stage 1. The value of slowing increase in salinity also explains why we only pump 0.5 MAF when GW_o = 10 and 11 MAF in the first stage.

However, pumping more mildly (e.g., GW_o = 11 MAF under different climate) does not always increase profit - we should pump cleverly. With the same increase in groundwater salinity, we should pump as much as possible, because the discount rate makes earlier profit more important and the climate is less favorable, so we pump more to retain perennial crops: 1 MAF is pumped in the second stage when GW_o = 10 MAF, because pumping 0.5 MAF also increases groundwater salinity by 500 mg/L. This is another exploitation of the model formulation as the groundwater salinity interval is coarse at 250 mg/L.

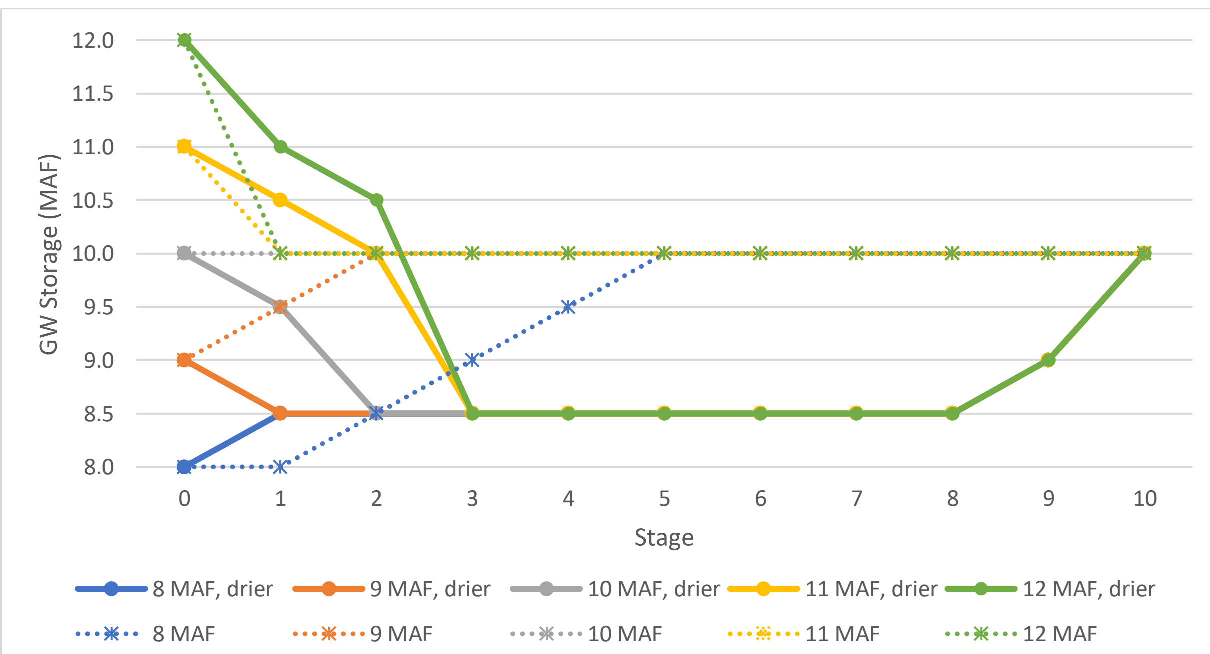


Figure 5.16. Groundwater storage change over stages ($C_{gw,o}$ = 500 mg/L, r = 3.5%, base vs. drier climate)

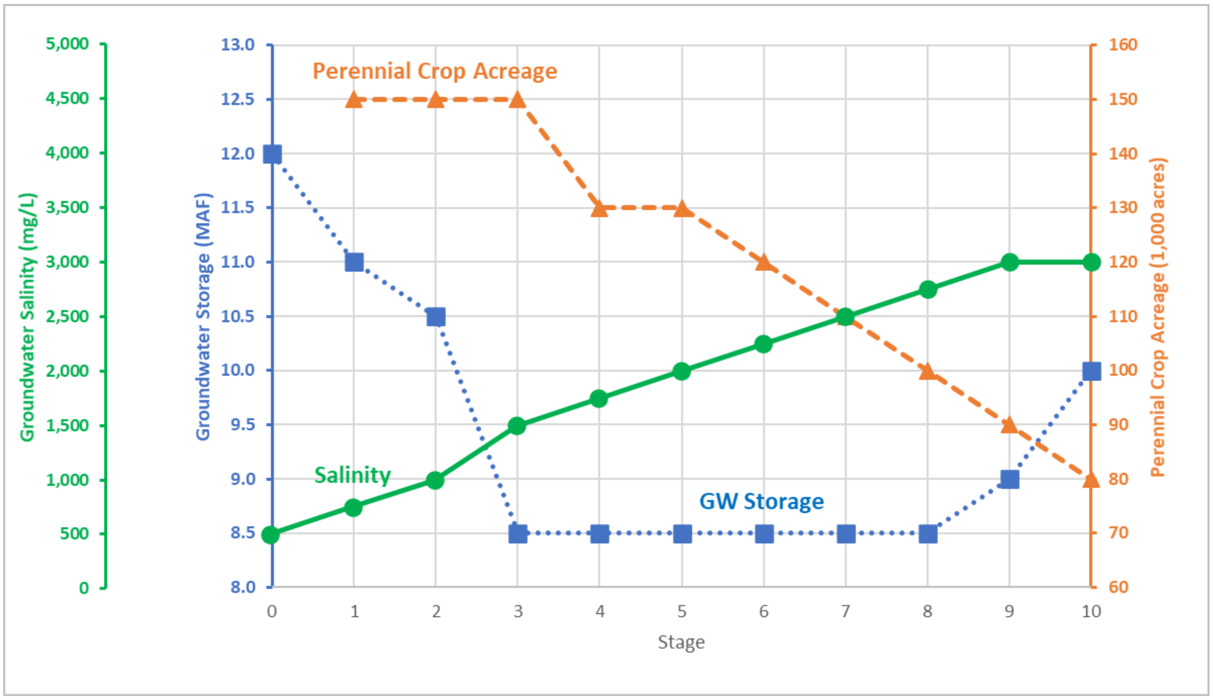


Figure 5.17. Groundwater storage and salinity, and perennial crop acreage decision of each stage (GW_o = 12 MAF, $C_{gw,o}$ = 500 mg/L, r = 3.5%, drier climate)

GW_o = 12 MAF is a great example of optimal pumping (Figure 5.17), where groundwater salinity is kept as low as possible in the first stages while maintaining maximal perennial crop acreage. In stage 1, because groundwater storage is enough, pumping 1 MAF only increases groundwater salinity by 250 mg/L. But in the second stage, to only increase groundwater salinity by 250 mg/L, we can only pump 0.5 MAF. In the third stage, net pumping of 0.5 MAF, 1 MAF, 1.5 MAF or 2 MAF always increases groundwater salinity from 1,000 mg/L to 1,500 mg/L. So, we pump 2 MAF. For higher profit, pump the largest allowable amount of groundwater while slowing groundwater salinity increase as much as possible.

Finally, the drier climate increases the cost of recharging because less available surface water can dilute less groundwater, meaning the decrease in both perennial crop acreage and yield, and less deep percolation requesting for more artificial recharge in wetter years for the aquifer recovery. So recharging moves to the end of planning horizons. The cost of recharging is so big that even though stage 10 is least important and there is no need to grow additional perennial crops for the future, some burden of recharging (0.5 MAF) is still moved to stage 9.

3.2.2.2 Moderate initial groundwater salinity ($C_{gw,o}$ = 1,500 mg/L)

Figure 5.18 compares groundwater storage trajectory for initial storages of 8, 9 and 12 MAF, with incoming perennial crop acreage of 50,000 acres and initial groundwater salinity of 1,500 mg/L for the base and drier hydrology (the model makes the same decision for 10 and 11 MAF for both climates). A drier climate prevents recharging too much in earlier stages and moves recharging to the end of planning horizon. A drier climate also may trigger pumping in early stages when the initial groundwater storage is enough, but as the initial salinity is starting to impair perennial crops, pumping is stopped once the final target, 10 MAF, is met.

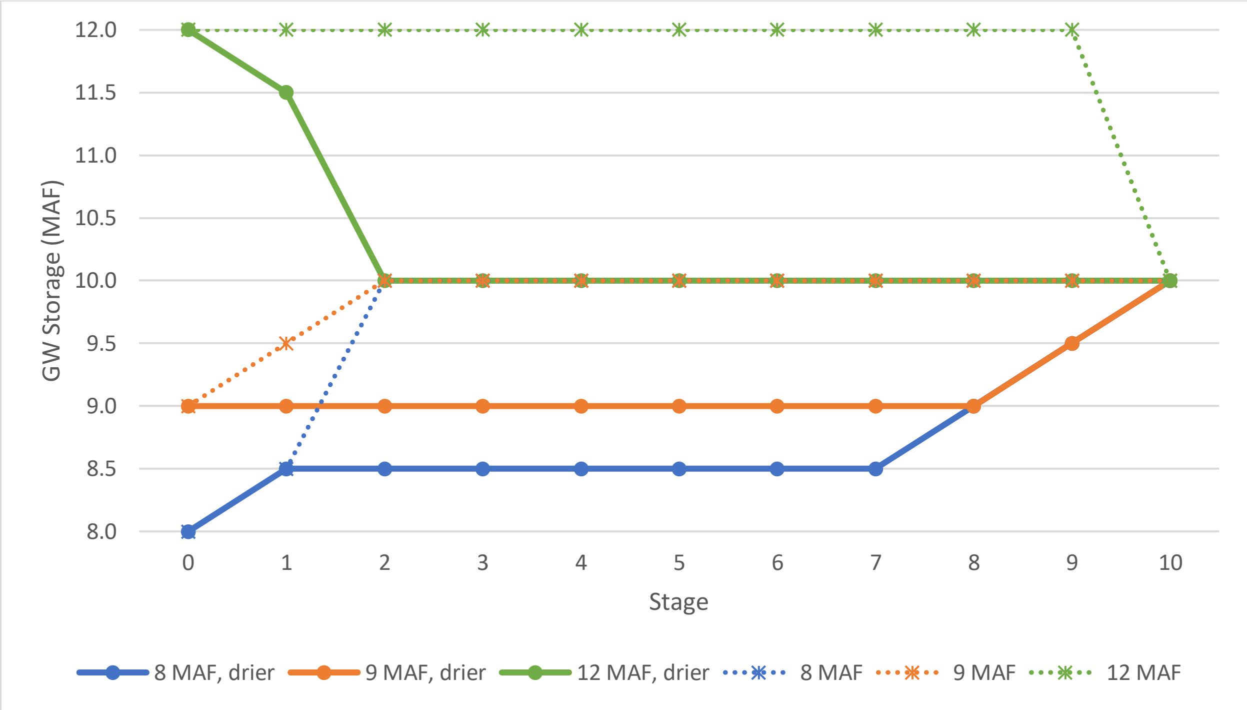


Figure 5.18. Groundwater storage change over stages
($C_{gw,o}$ = 1,500 mg/L, r = 3.5%, base vs. drier climate)

It is the battle between recharging to keep groundwater salinity low and making more profit from more perennial crops. Because groundwater of 1,500 mg/L starts to impair crop yield, this makes recharging attractive for early stages. However, with a drier climate, recharging requires some loss of perennial crops, making pumping and keeping no net overdraft, also attractive. So, groundwater management needs to be examined case by case when groundwater salinity is not low together with a drier climate.

When GW_o = 8 MAF, not recharging 0.5 MAF in stage 1 would increase groundwater salinity by 500 mg/L, creating an unfavorable environment for later stages. However, the drier climate precludes a 1.5-MAF recharging goal in stage 2. So, ever since stage 2, groundwater salinity with the drier climate is 250 mg/L higher than with the base climate. This leads to a 191 M$ loss in total profit (Table 5.9). Also, the drier climate makes recharging too costly (in terms of lost permanent crop revenues), so we can only afford to recharge 0.5 MAF per stage in later stages.

When GW_o = 9 MAF, recharging the aquifer cannot stop groundwater salinity from increasing (e.g., recharging 1 MAF in the first stage still increases groundwater salinity by 58 mg/L, but we treated it pessimistically as an increase of 250 mg/L to ease the model computation with large salinity discretization) and fewer perennial crops can be grown. Also, unlike increasing groundwater salinity by 500 mg/L under the base climate, keeping no overdraft only increases salinity by 250 mg/L with the drier climate. This sounds weird, but less surface water available means less salt from surface water enters the aquifer; the same situation happens when GW_o = 12 MAF. Therefore, we move expensive recharging to more discounted late stages. Though groundwater salinity stays the same for the two climates, lacking surface water means fewer perennial crops and 143 M$ loss in total profit (Table 5.9).

When GW_o = 10 MAF, keeping no-overdraft throughout the planning horizon is the safest solution as salinity of 1,500 mg/L is not high enough to merit recharging in early stages and having to dump recharged water in later stages. However, the 211 M$ drop in total profit for the drier climate (Table 5.9) exceeds that of GW_o = 9 MAF. When GW_o = 9 MAF for base climate, perennial crops give way to recharging in the first two stages, so the difference of perennial crop acreage in first two stages between two climates is smaller than that for GW_o = 10 MAF. Also, although in the drier climate recharge occurs in the last two stages, the last stage does not need to prepare for the future. So, the difference of perennial crop acreage in the last two stages between two climates is not bigger when GW_o = 9 MAF than that of GW_o = 10 MAF. In all, GW_o = 10 MAF suffers more with the drier climate than GW_o = 9 MAF, for 1,500 mg/l initial salinity.

Table 5.9. Impact of drier climate on total profit (M$/10 yrs) of different initial groundwater storage and salinity

Initial groundwater storage, GW_o (MAF)	Initial groundwater salinity, $C_{gw,o}$ (mg/L)		
	500	1,500	2,500
8	188	191	184
9	165	143	167
10	196	211	161
11	167	213	164
12	162	167	163

When GW_o = 11 MAF, we know pumping in the end of planning horizon means some water will be dumped (Section 3.1.2); this is also true for the drier climate. Despite the undesirable dumping, it is still more profitable than pumping in the early stages to cause additional increase in groundwater salinity (from 250 mg/L to 500 mg/L).

However, GW_o = 12 MAF is different. While with the base climate, pumping 0.5 MAF increases groundwater salinity by 500 mg/L, pumping 0.5 MAF in the drier climate only increases the groundwater salinity by 250 mg/L. So, we pump 0.5 MAF and grow 140,000 acres (not 150,000 acres because salinity of 1,500 mg/L starts to affect perennial crop yield). The second stage is interesting. If we keep no overdraft, although groundwater salinity only increases by 250 mg/L, dumping occurs at the end of planning horizon, as with GW_o = 11 MAF. So, we would rather pump to 10 MAF and have groundwater salinity increase by 500 mg/L (pumping 0.5 MAF, 1 MAF, and 1.5 MAF causes the same salinity increase due to the coarse salinity discretization), at least all the groundwater is fully utilized.

3.2.2.3 High initial groundwater salinity ($C_{gw,o}$ = 2,500 mg/L)

Figure 5.19 compares groundwater storage trajectory for initial groundwater storages of 8 MAF to 11 MAF (12 MAF has no better choice), with incoming perennial crop acreage of 50,000 acres and initial groundwater salinity of 2,500 mg/L with the base and drier climate. We find recharging no longer occurs in the first stage for initial storages exceeding 8 MAF due to lack of surface water. When GW_o = 8 MAF, recharging shortens to one stage from two stages in the base climate. Interestingly, recharging for GW_o = 8 and 9 MAF ends one stage earlier than the last stage, serving to both meet the final 10-MAF goal and stabilize the groundwater salinity for one more stage.

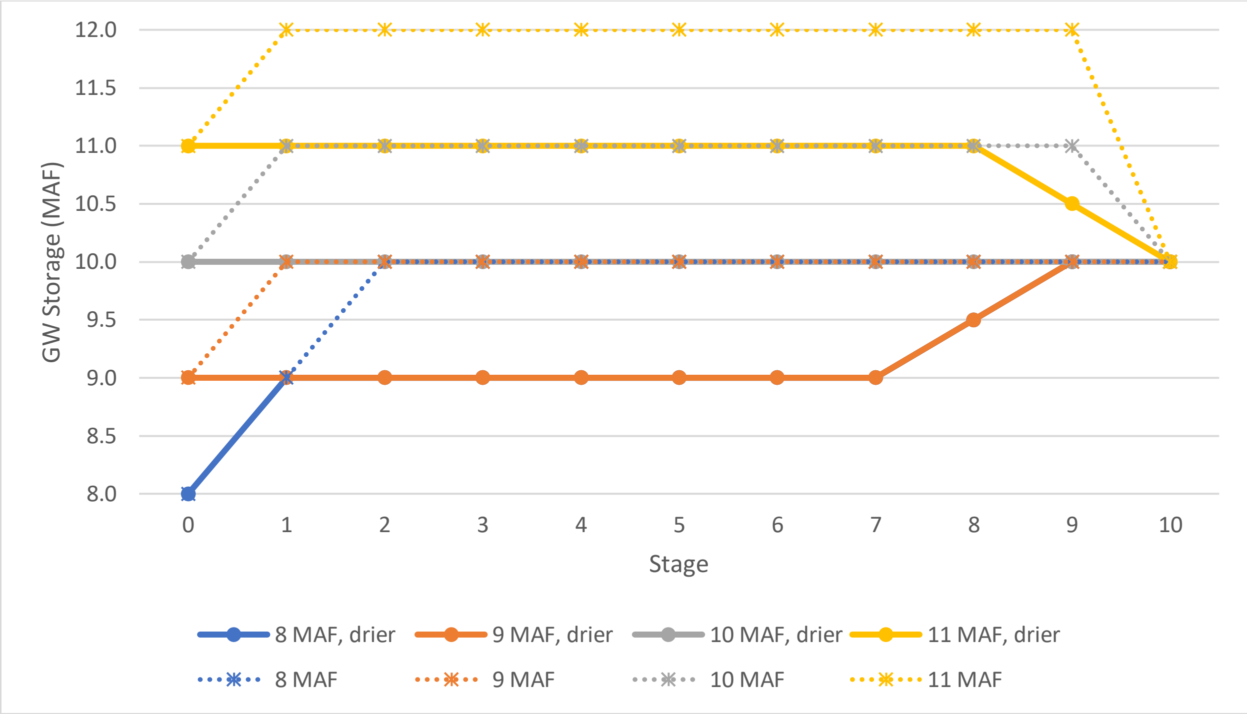


Figure 5.19. Groundwater storage change over stages
($C_{gw,o}$ = 2,500 mg/L, r = 3.5%, base vs. drier climate)

In summary, the drier climate supports fewer perennial and annual crops, which is the first cause of lower total profit. Second, a drier climate usually moves costly recharging to the end of planning horizon, so groundwater salinity for each stage is higher than that with the base climate, which further limits planting of perennial crops.

3.2.3 The effect of salinity discretization in the DP (ΔC = 250 mg/L and 500 mg/L)

Figure 5.20 compares groundwater storage changes over stages with different initial groundwater storage of 8, 10, and 12 MAF, with incoming perennial crop acreage of 50,000 acres and initial groundwater salinity of 1,500 mg/L, and the salinity interval of 250 mg/L vs. 500 mg/L. Groundwater storage management changes greatly with different salinity discretization. The salinity discretization of 500 mg/L is so big that it removes the advantage of early recharging and/or keeping no overdraft (since an increase of 5 mg/L is treated as an increase of 500 mg/L). So, pumping (for GW_o = 8 MAF, keeping no overdraft) always occurs first to making profit as high as possible in first two stages with salinity increasing by 500 mg/L in each stage, due mostly to the discretization. Then intense recharging lasts for several stages to stabilize groundwater salinity. The huge difference in groundwater management tells us a 500-mg/L discretization is too coarse to be trusted. Although a 250-mg/L interval is still too coarse compared to an increase around 50 mg/L (e.g., 58 mg/L in Section 3.2.2.2), the long-term solution now seldom recharges and pumps both aggressively and continuously, meaning the groundwater trajectory looks milder. A salinity discretization of 250 mg/L seems fine enough to lead to the right groundwater management strategy, while being computationally feasible.

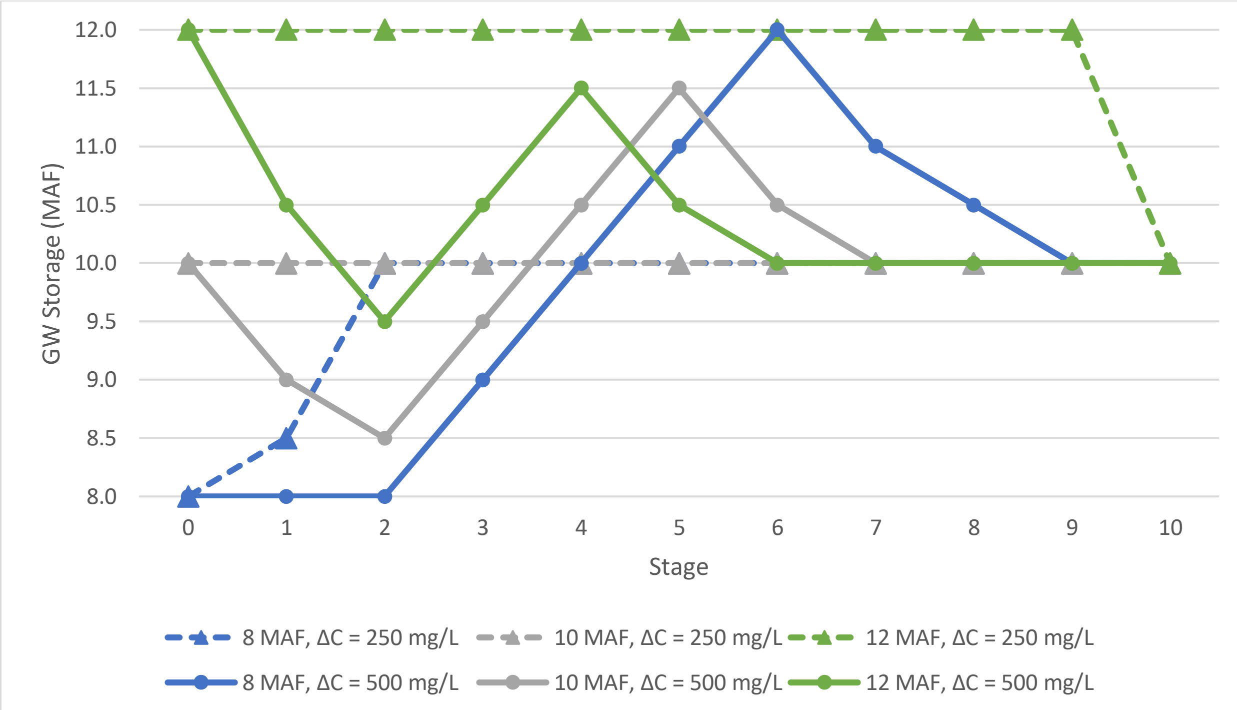


Figure 5.20. Groundwater storage change over stages
($C_{gw,o}$ = 1,500 mg/L, r = 3.5%, salinity discretization = 500 mg/L vs. 250 mg/L)

3.2.4 Discussion: further research

Several areas for further research come to mind:

1. Aquifer structure and heterogeneity. The aquifer in this model was treated as a homogeneous box without connection to other aquifers. This greatly simplifies the real-world situation. In reality, farmers are growing crops over a more heterogeneous aquifer, and the aquifer may have several layers. They can drill wells where the specific yield is higher and to the layer where salinity is lower. As long as the layer with cleaner groundwater is not so deep that the pumping cost is even higher than the loss in profit due to salinity, the real profit could be higher than in this study. For instance, the farmer might pump groundwater from the second layer (a confined aquifer) with low salinity. But the salt in soil is leached first to the first layer (an unconfined aquifer) and it takes long to reach the second layer. Therefore, the groundwater pumped is always good enough to irrigate the crops.

2. The importance of artificial recharge in controlling groundwater salinity should not be neglected. Even with the example above, groundwater in the second layer may be depleted by wanton pumping, and the salinity problem in the first layer will eventually affect the soil above and the second layer beneath it. This further leads to the discussion of methods of artificial recharge, as recharge basin and deep percolation cannot replenish the second layer, and only well injection will do. Therefore, if more layers are to be considered as state variables in the DP framework, so do the means of artificial recharge. This will make the DP too demanding to compute in a reasonable time.

3. The model can be improved by presenting more farming reality. One is stress irrigation that affects crop yield is not considered. The other one is to better model soil salinity and

evapotranspiration. Another one is that more crops can be considered in later works. Coupled with points 1 and 2, a groundwater model such as MODFLOW or IRFM may be applied to further model the irrigation cycle. Also, other water supply and demand such as urban water use and water transfer and reservoirs are not included in this

4. Through all the chapters, the hydrology of surface water is always assumed to be stationary, though drier climate cases are discussed in every chapter. It would be super interesting to see how long-term DP will behave if the climate gradually changes from the base case to the drier case. We believe it is worth the further research, but seems likely to also increase computation requirements.

Conclusions

Groundwater salinity can fundamentally affect optimal conjunctive use operations and plans. Of all variables included in this chapter: salinity, climate, discount rate and initial groundwater storages, the model results show that salinity has the largest effect on planting decisions and groundwater storage management. The discount rate further underscores the importance of artificial recharge in stabilizing groundwater salinity, while a drier climate physically prohibits recharging as less surface water is available thus groundwater management seems more like that without salinity.

1. Without salinity, with the base climate and a high discount rate, groundwater storage is kept at the minimum level and recharge occurs only in the last stage to meet the final 10-MAF goal. However, modest salinity can greatly change economically optimal groundwater management and lower the total profit.
2. Under any circumstances, slowing salinity increase is key to improve profits. So, recharge occurs much earlier and can be more aggressive, and can even occur for initial groundwater storages exceeding the final groundwater storage goal, to delay crop yield reductions in later stages.
3. Whether salinity affects perennial crop yield or not, model simplification having perennial crops entering next stage “reset” to a state unimpaired by salinity makes optimal long-term perennial crop acreage for stages other than last stage usually exceed that of a short-term decision to reduces initial establishment cost in later stages.
4. Higher initial groundwater salinity decreases perennial crop acreage for most stages for same initial groundwater storage to avoid unnecessary perennial crop yield decrease, relying more on fresher surface water for these more profitable crops.
5. High groundwater salinity can make it undesirable to have initial groundwater storages higher than final storage goal. Because pumping increases groundwater salinity faster, worsening salinity for later stages, it is shifted to the end of the planning horizon. However, pumping in the last stages is costly because the groundwater pumped is to be dumped as its salinity is too high for crops.
6. A lower discount rate increases the intensity and/or length of early recharging to lengthen the period of lower salinities. A lower discount rate further restricts pumping in early stages. Because pumping in later stages is for dumping excess groundwater, a lower discount rate makes the last stage drives a shift of some pumping to earlier stages.

7. A drier climate physically restricts recharging in early stages as surface water is less available and moves most recharging to the end of planning horizon. A drier climate also makes recharging more costly in terms of opportunity costs from reduced perennial crops.
8. The model discretization treats an increase of 50 mg/L and 250 mg/L in groundwater salinity across stages the same, meaning it is possible to pump more but resulting in the same salinity increase. So, pumping should be as much as possible to grow more crops as long as the salinity increase is the same.
9. To find an optimal groundwater management strategy, a finer salinity level is recommended. A finer salinity level also increases the utility of aquifer recharging.

In general, with the base climate, if initial groundwater storage is lower than the final goal, recharging is both ways to meet the goal and helps stabilizing groundwater salinity. If else, keeping no overdraft rather than meeting the goal is more sustainable for agricultural production.

The assumptions such as complete mixing of salt in groundwater, the salt in root zone being equivalent to the salt in irrigation water, the lack of effective drainage system, and the coarse interval of salinity as a state variable, makes this model decision pessimistic as groundwater (irrigation water) salinity is doomed to increase with stages unless extreme artificial recharge is applied. However, there is an important takeaway that aquifer recovery, though expensive especially in terms of opportunity cost from fewer high-value perennial crops, is a more sustainable alternative than pumping.

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