Water, native plant communities, and air quality in Owens Valley, California (USA): an ecological-economic analysis of groundwater management sustaining alkali meadow communities

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Abstract

A dynamic ecological economic model was created to assess the net benefits of production (i.e., economic rent) from management of groundwater while requiring the producer to sustain native groundwater dependent vegetation and associated ecosystem services. The study system was a portion of the Owens Valley, California (the Taboose-Aberdeen well-field) where groundwater withdrawal has historically (and periodically) resulted in reduced vegetation cover, the drying of springs and seeps, and reduced soil stability. Los Angeles Department of Water and Power (DWP) manages water in the Owens River basin via surface water diversion and groundwater withdrawal (over 100 active pumping wells) for export to Los Angeles over 400 km away. Groundwater withdrawal is constrained by a water agreement with the Inyo County, California, and by the Clean Air Act, which would take effect if vegetation cover is reduced sufficiently to initiate wind erosion and PM-10 air pollution.

Findings of this study indicate an adaptive approach for groundwater management (pumping high volumes in wet years and low volumes in dry years) generates more economic rent of $82.6 million (in 2011 $) than status quo management of $30.5 million under baseline precipitation conditions. Costs of sustaining alkali meadow (including restoration costs and temporal loss of ecosystem services) have a present value of $2,020/acre ($4,989/hectare) for adaptive management compared to $41,822/acre ($103,300/hectare) for status quo management over 50 years. With reduced precipitation of 15% from climate change, adaptive management derived economic rent of $41.7 million while status quo management obtained just $4.5 million when internalizing restoration costs. Costs of sustaining alkali meadow under climate change totaled $8,512/acre ($21,025/hectare) for adaptive management compared to $53,005/acre ($130,922/hectare) for status quo management. Adaptive management generated higher economic rent while pumping less annual groundwater at respective levels of 73% (baseline = 6,830 acre-feet) and 56% (climate change scenario = 4,952 acre-feet) of average groundwater pumping under status quo management in the well-field. Findings of this study suggest that changing to an adaptive groundwater management strategy generates greater economic rent to the producer while supplying water, sustaining native alkali meadow and ensuring air quality than the status quo groundwater management strategy.

Keywords: groundwater management, temporal loss of ecosystem service, particulate matter, alkali meadow, restoration costs, air quality

JEL Codes: Q51, Q53, Q57

1. Introduction

In many arid mountain basins worldwide, groundwater is managed as a dynamic reservoir, providing additional water supply during years of insufficient surface runoff. In the Great Basin and range of the western United States, groundwater is often shallow and recharged to within the root zone of native plants annually. In such systems, groundwater withdrawal and recharge has potential to replace surface reservoirs and associated water losses through evaporation. However, shallow groundwater supports facultative wetland species, which provide important ecosystem services such as soil stability and air quality. Research into the hydroecology of these systems at our field site in the Owens Valley, California, has led to sufficient understanding to develop empirical relationships between snowpack runoff, groundwater depth, and vegetative cover within the native 'alkali meadow' plant community. Alkali meadow supports rare, threatened and endangered species, helps to maintain soil stability and enhanced air quality, is extensive throughout the Owens Valley and to a lesser extent in other valleys of the Great Basin and range, and is the target of conservation due to its dependence on shallow groundwater that is pumped for human use throughout most of its range.

Owens Valley in California has been subject to over 100 years of water diversion and intensive land management. Today, the Los Angeles Department of Water and Power (DWP) exports surface water (the Owens River) and groundwater (over 100 active pumping wells) from Owens Valley over 400 km south to Los Angeles (LA) via the LA Aqueduct (Danskin, 1998). Water diversions have had significant hydrologic effects on surface and groundwater as well as ecological effects on the native alkali meadow plant community in Owens Valley. For example, the original terminus of the Owens River was the Owens Lake, which due to surface water diversions is now a dry playa and the largest source of PM-10 (particulate matter, 10 microns) air pollution in the United States. North of the (dry) lake, groundwater pumping has caused the drying of many springs and seeps, and a nearly spatially continuous decline in water table levels over the valley floor over the past three decades (Elmore et al., 2003). Groundwater changes have caused a regional decrease in vegetation cover as compared with control regions (Elmore et al., 2006, 2003) and there is new evidence that groundwater-related declines in vegetation cover have caused dust source regions to develop in areas of previously dense meadow vegetation (Elmore et al., 2008; Vest et al., in press).

As groundwater is pumped below vegetation root zones, groundwater dependent vegetation (such as alkali meadow) decreases, increasing bare soil areas (Elmore et al., 2003; Elmore et al., 2006). These bare soil areas are prone to wind erosion that has the potential to generate PM-10 air pollution (Elmore et al., 2008; Vest, in press). Owens Valley has not attained the United States Environmental Protection Agency's (EPA) National Ambient Air Quality Standards (NAAQS) for PM-10 and the EPA took enforcement action against Los Angeles DWP forcing them to mitigate the sources for PM-10 (USEPA, 2009, 2007). Although it is presumed that most of the PM-10 originates from the dry Owens Lake, wind erosion has been documented in degraded alkali meadow to the north of the playa (USEPA, 2009, 2007; Vest, in press). Perhaps ironically, the planting and irrigation of alkali meadow grass species on the Owens Lake playa is currently one of the main air pollution control actions performed by Los Angeles DWP in its attempt to reach compliance with the Clean Air Act.

Alkali meadow is dominated by salt grass (*Distichlis spicata*) and alkali sacaton (*Sporobolus airoides*), and requires groundwater to remain within approximately 2.5m of the surface if high plant cover is to be achieved (Elmore et al., 2006). Alkali meadow is an important native plant community as it provides ecosystem services including soil stabilization that is directly related to clean air and human health. Grasses are superior to shrubs at stabilizing soil and preventing wind erosion, which makes maintaining and reestablishing the native alkali meadow communities an important goal for minimizing air pollution (Li et al., 2007). Alkali meadow is also an important source of biodiversity with plant cover dominated by facultative wetland species and meadows serving as essential habitat for numerous rare and endangered species (Elmore et al., 2006). Within Owens Valley, alkali meadow covers large areas usually located kilometers away from surface water (Pritchett and Manning, 2009). DWP surveyed the valley floor in the 1980s and recorded over 70,000 acres (28,328 hectares) dominated by native grasses (Holland, 1986). Approximately 24% of land currently owned by the City of Los Angeles is comprised of meadow or shrub-meadow communities and alkali meadow covers over 42,000 acres (16,997 hectares) of the valley floor (Elmore et al., 2003).

The EPA has designated the southern Owens Valley as an area in violation of the PM-10 National Air Ambient Quality Standards and has required Los Angeles DWP to achieve a 5% reduction in PM-10 emissions per year since 2006 with the goal of attaining the

NAAQS by March 23, 2012 (USEPA, 2007). The EPA previously estimated the Owens Lake playa emits 300,000 tons of PM-10 per year, including 30 tons of arsenic and 9 tons of cadmium (USEPA, 2010a, 2010b). In Keeler, California, located on the eastern shore of Owens Lake, the Great Basin Unified Air Pollution Control District (GBUAPCD) recorded violations of the federal PM-10 standard, on average, 19 times per year during the first 18 years of measurements being recorded (USEPA, 2010a, 2010b). In turn, California prepared a state implementation plan demonstrating how PM-10 emissions would be decreased through restoration of the dry Owens Lake by planting of alkali meadow, shallow flooding and use of gravel (GBUAPCD, 2008).

Ecosystem restoration is costly as evidenced by the estimated now $1 billion dollar expenditures for Owens Lake dust mitigation (LADWP 2011; LADWP, 2010; Palmer et al. 2004). Owens Lake as a whole is still out of compliance with the NAAQS and California Ambient Air Quality Standards (CAAQS; Schade, 2011), but the managed vegetation area has remained in compliance since implementation (GBUAPCD, 2008). Restoration was intended to create irrigated alkali meadow at dry Owens Lake (GBUAPCD, 2008), but degradation of alkali meadow up-valley from groundwater use may be offsetting some gains in dust mitigation. The total annual water usage of the dry Owens Lake restoration effort at 95,000 acre-feet exceeds the volume of water pumped from northern alkali meadow to the Owens Valley aqueduct annually (78,248 acre-feet in 2011; GBUAPCD, 2011, 2008; LADWP, 2011). As a result, Los Angeles DWP is pumping water from beneath meadows north of dry Owens Lake causing degradation of vegetation, potentially leading to further PM-10 emission.

In this study, a dynamic ecological economic simulation model was created to assess which groundwater management strategy in the Taboose-Aberdeen well-field of Owens Valley (see Figure 1) maximizes the net gains of groundwater production (i.e., economic rent) while sustaining or restoring native alkali meadow. In consideration of $1 billion dollars in outlays thus far for restoration of dry Owens Lake and the continued degradation of meadows to the north of the playa, this study analyzed the costs of restoration of alkali meadow, temporal loss of ecosystem services from meadow degradation, and compared these costs to net revenues generated from groundwater extraction. Restoration costs are relevant to analysis of the economic rents derived by DWP from groundwater pumping because historic agreements have required maintenance of alkali meadow and federal law requires a specified level of air quality. Los Angeles DWP is constrained by the *Inyo-LA Long Term Water Agreement* (LTWA; Los Angeles and County of Inyo, 1990) to avoid adverse impacts to native plant communities and is required to meet the particulate matter PM-10 standard of the NAAQS. Los Angeles DWP is required to manage groundwater resources in Owens Valley without causing significant ecological effects that cannot be successfully mitigated and to avoid causing decreases in vegetation cover or changes in vegetation community structure (Los Angeles and County of Inyo, 1990). Thus, an analysis of how groundwater can be managed to maximize economic rents while sustaining native alkali meadow in Owens Valley is imperative.

2. The model

A systems modeling approach was utilized to address the dynamics of hydrology, alkali meadow communities, and economic variables involved with water resource use in Owens Valley. A dynamic simulation model linking hydrology, ecology, and economics in the Taboose-Aberdeen well-field in Owens Valley was created with the modeling software STELLA™ with model runs over 50 years (2011-2060), a time-step of DT = 1 and totals derived with the Euler's integration method (see Appendix for model parameters, variables, and equations).

The main objective function of this model was to maximize the net gains of groundwater production (i.e., economic rent) while sustaining alkali meadow in the Taboose-Aberdeen well-field under varied water management strategies. The objective function is represented as follows:

$$\text{Max} \int_0^t \left((P * Q) - (\text{Cp} + RC + ES) \right) \times e^{-rt} dt \qquad (1)$$

with P = price per acre-foot of water, Q = quantity of groundwater pumped, Cp = pumping/conveyance costs, RC = restoration costs, ES = temporal loss of ecosystem services, r = discount rate, and t = time. To determine the groundwater management strategy that maximizes economic rent while sustaining meadow cover and assessing distribution of benefits and costs across society, our analysis required addressing three interrelated research questions concerning hydrology, ecology and economics: (1) how does the total annual Owens Valley runoff and annual groundwater extraction rate influence depth-to-water (DTW) levels in the well-field; (2) what are the ecological effects on native alkali meadow as the DTW fluctuates; and (3) what are the economic estimates of water revenue, the temporal loss of ecosystem services, restoration costs, and the net present value of economic rents under various groundwater extraction management strategies? Figure 2 presents a conceptual model of the interactions between hydrology, alkali meadow, and ecosystem services in Owens Valley.

2.1 Calibration of the model to the Taboose-Aberdeen well-field

2.1.1 Annual runoff, extraction and depth-to-water

The model was calibrated to three monitoring wells (T418, T419, and T502) located in the Taboose-Aberdeen well-field in Owens Valley to assess alkali meadow because of their historic depth-to-water levels in the root zone of native grasses. The Taboose-Aberdeen well-field was selected due to the following criteria: (1) it is centrally located in Owens Valley away from townships situated south of the Big Pine and north of the Thibault-Sawmill well-fields; (2) there are no significant settlements or fisheries located within the well-field that require water and thus the majority of groundwater extracted is exported via the Los Angeles Aqueduct; and (3) there exists only one 'exempt well' from water management provisions agreed upon to maintain alkali meadow with the exempt well designated as having "no impact on areas with groundwater dependent vegetation" (LADWP, 2011b).

Historically, the Taboose-Aberdeen well-field has experienced significant fluctuations in DTW levels caused by groundwater extraction and net of runoff (Inyo County Water Department, ICWD, 2010). Figures 3 and 4 summarize the Taboose-Aberdeen well-field pumping rates and runoff from years 1962-2010. Figure 3 displays two general time periods where groundwater from the Taboose-Aberdeen well-field was heavily extracted. From 1971 to 1977, Los Angeles DWP extracted an annual average of 31,433 acre-feet, and from 1985-1989 an annual average of 28,597 acre-feet was extracted (ICWD, 2010, 2009). Pumping rates during these periods were elevated partially due to the need to provide more water to the City of Los Angeles during prolonged droughts, and coincided with periods of low runoff in Owens Valley (ICWD, 2008; Kahrl, 1982; Los Angeles and County of Inyo, 1991). In comparison, the planned extraction rate for the Taboose-Aberdeen well-field in 2010 was 9,450 acre-feet (ICWD 2010; LADWP 2011b). Figure 4 presents annual runoff as a percentage of the 1956-2005 long-term mean annual runoff value of 411,975 acre-feet (LADWP, 2011b). Comparing Figures 3 and 4 highlights the historic pattern of high groundwater extraction rates from the Taboose-Aberdeen wellfield coinciding with years with below average Owens Valley runoff.

Historic depth-to-water levels and groundwater extraction rates from the Taboose-Aberdeen well-field and historic annual Owens Valley runoff totals were used to calibrate the model and to provide insight into possible management strategies (ICWD 2010; LADWP 2011b). Modeling of DTW fluctuations as a function of annual runoff and extraction rates was achieved by incorporating regression equations and coefficients developed by the DWP and Inyo County for the *Interim Management Plan* into the ecological economic simulation model (Los Angeles and County of Inyo, 2007). The model was calibrated to three specific monitoring wells (T418, T419, and T502) located in the Taboose-Aberdeen well-field with the following regression equations (from Los Angeles and County of Inyo, 2007):

$$DTW_{i+1} = C_1 + C_2 * DTW_i + C_3 * Q_{Pump} + C_4 * R_O \qquad (2)$$

Where: C_1, C_2, C_3, C_4 are regression coefficients (values listed in Appendix 1)

DTW_i: Depth-to-water in well from ground surface in April of current year

DTW_{i+1}: Depth-to-water in well from ground surface in April of next year

Q_{Pump}: Well-field pumping for the year in acre-feet

R_O: Forecasted Owens Valley runoff in acre-feet

To verify that the model was a close approximation of the runoff and pumping effects on depth-to-water levels in the Taboose-Aberdeen wellfield, the model was run utilizing historic pumping and runoff rates from 1976 to 2010 (ICWD 2010; LADWP 2011b). No statistical significant difference was found between the means of model runs and historic depth-to-water measurements paired by year for the three respective monitoring wells from 1976 to 2010 ($p<.05$, 2-tailed, paired t-test).

2.1.2 DTW effects on grass cover in alkali meadows

Pritchett and Manning (2009) assessed the effects of fire and groundwater extraction on alkali meadow habitat in Owens Valley, California, by measuring species composition, cover, and frequency in pre- and post-fire vegetation surveys. Our model incorporated the relationship between live grass cover and depth-to-water utilizing a sigmodial regression curve based on a pre-fire data set of 48 transects of alkali meadow assessed in June 2007 (Pritchett and Manning, 2009). The effect of DTW on grass cover in alkali meadow was modeled utilizing the natural log-transformed regression equation:

$$y = 3.78/(1+\exp(-(x - (-4.59))/0.83)) \qquad (3)$$

y = natural logarithm (ln) of live grass cover

x = Depth-to-water

Thus, exp(y) – 1 = % of live grass cover in the alkali meadow

Earlier baseline field measurements of alkali meadow located in the Taboose-Aberdeen well-field indicate there are 2,531 acres of alkali meadow (Elmore et al., 2003). Total acreage of alkali meadow in the Taboose-Aberdeen well-field allowed scaling of economic costs to a cost per acre of alkali meadow assessment.

2.2 Maintenance or restoration requirements for alkali meadow

This ecological economic model determines the economic rents of production for various groundwater management strategies while sustaining alkali meadow over the course of a 50-year time horizon (i.e. 2011-2060) with a time step of DT = 1 and totals estimated with the Euler's integration method. A groundwater manager is constrained over the 50-year period by the need to sustain alkali meadow while supplying water. The groundwater manager will seek to maximize economic rents of groundwater extraction balancing water revenue against restoration costs and, if internalized, the cost of temporal loss of ecosystem services to society (i.e., soil stabilization).

2.2.1 Maintaining live percent grass cover of alkali meadow

In the model, an alkali meadow is considered maintained or fully restored when the live percent grass cover is greater than or equal to 30%. This value is similar to maximum values of percent perennial cover historically measured in the Taboose-Aberdeen well-field (LADWP, 2010) and correlates to a modeled value of DTW less than or equal to 2.6 meters. A decline in the live percent grass cover below 30% is considered a temporal loss of ecosystem services until the percent grass cover fully restores to this 30% threshold.

2.2.2 Maintaining DTW in the root zone of alkali grass

Recent studies have indicated that the average maximum effective rooting depth for alkali meadow grasses of sacaton and saltgrass is approximately 2.5 meters (Elmore et al., 2006; Goedhart and Pataki, 2010; Pritchett and Manning, 2009). The model assesses average DTW for three monitoring wells (T418, T419 and T502) every 10 years (in 2021, 2031, 2041, and 2051) in order to ensure the maintenance of DTW in the root zone of native grasses. If DTW is greater than 2.5 meters after the 10 year interval, meadow restoration is required and groundwater pumping is ceased over the next five years unless DTW returns to a level less than or equal to 2.5 meters.

2.2.3 Estimating Owens Valley annual runoff

Historic Owens Valley annual runoff was acquired for the period 1935 to 2010 (ICWD, 2011). Over the historical period, it was determined that the $\log_{10}$(runoff) was normally distributed with a mean of -.02 and a standard deviation of 0.15. To project runoff into the future (to 2061) we annually selected a random runoff value such that future runoff maintained the same statistical distribution. To project annual runoff under climate change, we assumed a 15% decline in the mean runoff while maintaining the same standard deviation. Projected climate change impacts on precipitation in the southwestern U.S. are consistent with these assumptions (Seager et al., 2007).

2.3 Economics: restoration costs, temporal loss of ecosystem services and groundwater revenue

2.3.1 Restoration Costs

Restoration costs of alkali meadow are based on actual payments for restoration costs of managed vegetation at Owens Lake. Three main measures have been implemented for dust mitigation at dry Owens Lake: (1) shallow flooding, (2) gravel, and (3) managed vegetation. By May 2010, economic costs of shallow flooding over 35.2 mile^2 (91.2 km^2) included \$12.9 million/mile^2 (\$5.0 million/km^2) in capital costs and \$1.24 million/mile^2 (\$0.5 million/km^2) for annual water use (LADWP, 2010). Gravel covered 0.14 mile^2 (0.36 km^2) with capital cost payments of \$22 million/mile^2 (\$8.5 million/km^2) and managed vegetation was planted on 3.7 miles^2 (9.6 km^2) of the Owens Lake bed at a capital cost of \$15 million/mile^2 (\$5.8 million/km^2), equating to \$23,437 per acre (\$57,889 per hectare; LADWP, 2010). The model requires restoration of alkali meadow and incurs a fixed capital cost at the managed vegetation rate of $23,437 per acre ($57,889 per hectare; discounted over time) if at the ten-year assessment the DTW level is below 2.5 meters. The ecological economic model sums costs of restoration of alkali meadow incurred in the years 2021, 2031, 2041 and 2051. In addition to the capital cost of managed vegetation, if the DTW level is greater than 2.5 meters in any of the five years following an assessment, the pumps in the Taboose-Aberdeen well-field will be shut off. A moratorium on groundwater extraction during this period will lower the revenues derived from groundwater pumping while allowing time for the DTW level to rise, which is needed to maintain and/or restore the native groundwater dependent vegetation.

2.3.2 Temporal loss of ecosystem services

The value of the ecosystem service of dust mitigation by alkali meadow was estimated as a replacement cost from managed vegetation at dry Owens Lake. As Bockstael et al. (2000) indicate, replacement cost can be a valid measure of economic value if three conditions are met: (1) the human-engineered system provides functions that are equivalent in quality and magnitude to the natural function; (2) the human-engineered system is the least cost alternative way of performing this function; and (3) individuals in aggregate would in fact be willing to incur these costs if the natural function were no longer available. Thus, the replacement cost of the managed vegetation approach at dry Owens Lake was utilized because society has already paid for restoration once the natural function was no longer present, and is attempting in a cost-effective manner to restore the quality and magnitude of the original dust mitigation function. Annual water use (to replace the function of groundwater in the root zone) for the managed alkali vegetation is 1.5 acre-feet per acre (i.e., 0.19 hectare-meter per hectare) at a cost of $527/acre-foot, totaling $791/acre per year ($1,954/hectare per year; LADWP, 2010). Net present value of water costs to support managed alkali meadows in perpetuity was estimated at $26,367/acre ($791 per year/.03; r = 3%). The total ecosystem service of dust mitigation of alkali meadow was thus estimated at $49,804/acre ($123,015/hectare) adding the net present value of capital restoration costs ($23,437/acre; $57,889/hectare) and a water supply needed to continuously support the managed alkali meadow ($26,367/acre; $65,126/hectare). Temporal loss of ecosystem service was calculated as the discounted value of the ecosystem service multiplied by one minus the percentage achieved of the natural equivalency standard of 30% live plant cover (i.e., cover $\geq$ 30% incurs no temporal loss of the ecosystem service).

2.3.3 Water revenue and economic rents

A groundwater manager acting in a manner to maximize economic rents while sustaining alkali meadow will compare the net revenue (revenue minus pumping/conveyance costs) derived from further groundwater extraction against the increased restoration costs to be incurred from a possible degradation of alkali meadow. A manager that significantly limits or ceases groundwater extraction will reduce water revenue, but also will lower probable restoration costs thereby creating a possible gain in economic rent. Further, a manager that increases groundwater extraction and water revenue in a manner that does not lead to extensive degradation of alkali meadow could also obtain a gain in economic rent of production. Our model assesses these economic tradeoffs for five groundwater management strategies in a well-field. Water revenue to the producer is estimated as the quantity pumped in the well-field multiplied by $527/acre-foot (i.e., the 2011 rate for the Metropolitan Water District of Southern California). An estimate of pumping and conveyance costs in the western United States of $25/acre-foot was utilized (Libecap, 2005). Our analysis focuses on managing groundwater to maintain groundwater dependent alkali meadow while maximizing economic rents from extracting and selling groundwater.

2.4 Groundwater management strategies

We analyzed the economic rents derived from five groundwater management strategies while sustaining alkali meadow: (1) status quo management (based on historic action which increased pumping during dry years and decreased pumping during wet years); (2) constant pumping (at 9,450 acre-feet; equal to 2010 planned level); (3) no pumping; (4) constrained pumping (pumping 50% in dry years and 150% in wet years of the 1990-2010 well-field pumping average) and (5) adaptive management (pumping more in high runoff years and less in low runoff years). Figure 5 displays annual pumping rates for water management strategies as a function of annual runoff expressed as a percentage of average annual runoff in Owens Valley.

2.4.1 Status quo management

Similar to projected runoff volume, status quo groundwater management was derived from the statistical distribution of historic pumping by Los Angeles DWP in Owens Valley. Historic pumping volumes were acquired for the Taboose-Aberdeen well-field from 1962-2010 (ICWD, 2011, 2010, 2009). These data generally exhibited an inverse relationship between pumping and runoff, weighted towards low runoff and low pumping and no years with high runoff and high pumping (Figure 5). We found it possible to match this distribution by randomly selecting points from a normal distribution (mean = 1,000, standard deviation = 17,000), discarding all random points outside of the 2-dimensional space defined by the historic data. Figure 5 displays the status quo management strategy for the Taboose-Aberdeen well-field compared to historic management in the well-field and other potential groundwater management strategies.

2.4.2 Constrained management

Constrained pumping is a management scenario that responds to annual surface runoff in a limited way with a dichotomous choice of pumping 50% more or less than 6,679 acre-feet (the 1990-2010 average for the Taboose-Aberdeen well-field) contingent upon annual surface runoff relative to the Owens Valley runoff 25 year average of 411,975 acre-feet. Thus the constrained management scenario adapts to wet and dry years, but in a limited way by choosing only one of two options represented as follows:

$$\mathrm{Pump}(t) = \begin{cases} 3{,}339 & R_O(t) < 411{,}975 \\ 10{,}018 & R_O(t) \geq 411{,}975 \end{cases} \qquad (4)$$

2.4.3 Constant management

The constant pumping scenario pumps 9,450 acre-feet annually and no pumping results in zero groundwater extraction for the well-field irrespective of surface runoff.

$$\text{Pump}(t) = \{\ 9{,}450 \quad R_O(t)\ \ 0 < \infty \tag{5}$$

2.4.4 No pumping management

$$\text{Pump}(t) = \{\ 0 \qquad R_O(t)\ \ 0 < \infty \tag{6}$$

2.4.5 Adaptive Management

The adaptive groundwater management scenario is more responsive to forecasted annual runoff and pumping is lowered (1,000 acre-feet minimum) in dry years and increased in wet years (18,500 acre-feet maximum). The adaptive management strategy increases well-field pumping by 1,000 acre-feet when annual runoff increases from 200 thousand acre-feet to 250 thousand acre-feet. Well-field pumping increases by 1,500 acre-feet for every 50 thousand acre-feet increase in runoff for the range of annual runoff from 250 thousand acre-feet to 800 thousand acre-feet. The adaptive management strategy is represented as follows:

$$\text{Pump}(t) = \begin{cases} 1{,}000 & R_O(t) \ \underline{<}\ 200{,}000 \\ .02^{*}R_O(t)\text{-}3{,}000 & R_O(t)\ 200{,}000 \geq 250{,}000 \\ .03^{*}R_O(t)\text{-}5{,}500 & R_O(t)\ 250{,}000 \geq 800{,}000 \\ 18{,}000 & R_O(t) \geq\ 800{,}000 \end{cases} \tag{7}$$

3.1 Results and Discussion

Figures 6 and 7 display model results for depth-to-water and live percent cover in alkali meadow over 50 years in the Taboose-Aberdeen well-field for a representative model run. Results are displayed for four of the five management strategies to provide clarity in the figures (see Table 1 for constrained management results). Status quo management based upon historic action results in depth-to-water levels beyond the root zones of native alkali meadow with live percent cover dropping below 10% after 50 years. Adaptive management results in depth-to-water levels within the root zone (less than or equal to 2.5 meters) with percent live grass cover greater than 30% for the entire 50 years thereby achieving the goal of sustaining alkali meadow. A constant pumping strategy (9,450 acre-feet/year) generates relatively high water revenues (see Table 1) , but leads to depth-to-water deeper than the root zone and percent live grass cover less than 30% after 50 years. No groundwater pumping results in shallow depth-to-water levels and the greatest amount of live percent grass cover but with no revenue derived from water sales. Average annual volumes of water pumped under baseline climatic conditions for the management strategies include constant pumping at 9,450 acre-feet, status quo management at 9,146 acre-feet, adaptive management at 6,830 acre-feet, and constrained management at 6,170 acre-feet (see Table 1).

A climate change scenario of 15% decline in annual runoff and greater water scarcity indicates the status quo management scenario has greater impacts with DTW reaching depths of nearly 5 meters while percent live grass cover drops below 5% in a given year. Adaptive management in the face of climate change effects showed more variability in depth-to-water, but remained mostly in the root zone of grasses. No groundwater pumping kept depth-to-water levels within the root zone, but never less than 1 meter with percent live grass cover maintained above 30% for the entire 50 years. A constant pumping strategy (9,450 acre-feet/year) with climate change effects displayed greater variability in DTW with depths exceeding 3.5 meters and percent live grass cover dropping below 20%. Average annual volumes of water pumped under a climate change scenario were constant pumping at 9,450 acre-feet, status quo management at 8,760 acre-feet, adaptive management at 4,952 acre-feet, and constrained management at 4,713 acre-feet (see Table 1).

Table 1 presents the economic results of the model for groundwater management strategies that attempt to extract groundwater (or not) while sustaining alkali meadow. Findings of this study indicate an adaptive approach for groundwater management (pumping high volumes in wet years and low volumes in dry years) generates the greatest economic rents to the producer with a present value (in 2011 $) of $82.6 million over 50 years under baseline conditions. Status quo management generates $30.5 million of economic rents under baseline conditions while constant pumping (9,450 acre-feet) generated $41.9 million and constrained pumping yielded $67.4 million in economic rents over 50 years. No groundwater extraction results in no economic rents to the producer, but would serve as the best strategy among the alternatives if all other strategies resulted in negative values (i.e., costs exceed revenue).

Adaptive management generates the highest economic rents while pumping an average annual volume of 6,830 acre-feet in the well-field, a volume that is 73% of the average annual pumping under status quo management. If the social costs of temporal loss of ecosystem services (i.e., soil stabilization) were internalized onto the producer (see Table 1, last column), rents to the producer decline from $30 million to $17 million under status quo management, but remain at $82.6 million under adaptive management. Adaptive management by pumping strategically (less in dry years, more in wet years) and pumping 27% less water on average each year is able to sustain alkali meadow over 50 years with very little loss of ecosystem services to society and very little need for restoration. Status quo management incurred a cost of $41,822/acre ($103,300/hectare) to sustain alkali meadow over 50 years comprised of $36,463/acre ($90,063/hectare) in restoration costs and $5,359/acre ($13,237/hectare) in temporal loss of ecosystem service. After 50 years under status quo management, the percent live cover in alkali meadow was 24.2% (less than the required 30%) with depth-to-water beyond the root zone at 3.1 meters on average. Adaptive management sustained alkali meadow with a cost of $2,020/acre ($4,990/hectare) over 50 years with restoration costs representing the majority of the total at $2,012/acre ($4,970/hectare) and lost ecosystem service costs of only $8/acre ($20/hectare). After 50 years, adaptive management displayed alkali meadows with 34.2% live cover (above the required threshold) and average depth-to-water in the root zone of native grasses at 2.3 meters.

Considering climate change effects, the adaptive management strategy again generates the greatest economic rents at $41.7 million compared to $21.7 million for constrained pumping, \$9.6 million for constant pumping, and only \$4.5 million for status quo management. If the social costs of the temporal loss of ecosystem services are considered and internalized, then status quo management would result in costs exceeding revenue indicated by negative economic rents of -\$17.5 million. Here, it would be less costly to simply not extract groundwater (no pumping) in the well-field as higher restoration costs and the cost of lost ecosystem services over time outweigh water revenue. However, the adaptive management strategy indicates that \$41.6 million in economic rents can still be obtained from groundwater extraction while sustaining alkali meadow under climate change effects, but the average annual pumping volume is lowered to 4,952 acre-feet which is 44% below the average annual volume of water extracted under status quo management.

4. Conclusion

Findings of this study suggest that changing to an adaptive water management strategy in Owens Valley provides greater net benefits of production (i.e., economic rent) while supplying water, maintaining native alkali meadow, and ensuring air quality than status quo groundwater management strategies. Adaptive management generated higher economic rents while pumping less annual groundwater at respective levels of 72% (baseline = 6,830 acre-feet) and 56% (climate change scenario = 4,952 acre-feet) of average groundwater pumping under status quo management in the well-field. This study is unique in that groundwater management is influenced by federal regulation to protect air quality. Ultimately the constraint to a groundwater manager to sustain alkali meadow is determined under the Clean Air Act that requires particulate matter to be within National Ambient Air Quality Standards and also based upon vegetation requirements of agreements between Los Angeles DWP and Inyo County, California.

This study determined the costs of sustaining native alkali meadow per acre (including restoration costs and temporal loss of ecosystem service) to be much less with adaptive management (pumping more in wet years and less in dry years) and results in less annual pumping (27% less for baseline conditions; 44% less for a climate change scenario). Costs of sustaining alkali meadow under adaptive management were just $2,020/acre ($4,989/hectare; baseline) and $8,512/acre ($21,025/hectare; climate change scenario) compared to $41,822/acre ($103,300/hectare; baseline) and $53,005/acre ($130,922/hectare; climate change scenario) under status quo management.

In our analysis of water revenue and restoration costs, this study shows that status quo groundwater management in the Taboose-Aberdeen well-field can generate $122.9 million in rents (revenue minus production/conveyance costs) to the groundwater manager (DWP) over 50 years if DWP was not required to mitigate for the degraded native alkali meadow through restoration costs or consider the temporal loss of ecosystem service. In this situation, society will incur substantial negative external costs estimated at $92.3 million (restoration costs = $36,463/acre; $90,063/hectare) plus $13.6 million (temporal loss of ecosystem service = $5,359/acre; $13,237/hectare) over 50 years under baseline conditions of status quo management in the well-field. Society will incur 95% of the costs of groundwater extraction (pumping/conveyance = $6 million; restoration costs = $92.3 million; ecosystem service temporal loss = $13.6 million; $105.9 /$111.9 million = .95) under status quo management when the costs of sustaining alkali meadow are not internalized by the groundwater manager. Under adaptive groundwater management with costs not internalized, DWP can obtain $87.7 million in economic rents from the well-field with society incurring 54% of costs of groundwater extraction with $5.1 million in restoration costs ($2,012/acre; $4,970/hectare) and $20.2 thousand ($8/acre; $20/hectare) of temporal loss of ecosystem service under baseline conditions. A groundwater manager would have an obvious economic disincentive (a loss of $35.2 million) to switch from status quo management ($122.9 million = economic rent) to an adaptive approach ($87.7 million = economic rent) if not held accountable for costs of degrading native alkali meadow and air quality through increased particulate matter in Owens Valley. The Clean Air Act requires DWP to meet the National Air Ambient Air Quality Standards for particulate matter and DWP has spent over $1 billion in restoration and mitigation costs at the dry Owens Lake to lower particulate matter.

Our analysis is relevant as it displays that if the groundwater manager actually incurs the restoration costs (as it already has at Owens Lake) then DWP would maximize economic rents among alternative management approaches in the Tabosse-Aberdeen well-field with an adaptive strategy yielding $41.7 million (climate change scenario) to $82.6 million (baseline) in economic rents versus $4.5 million (climate change) to $30.5 million (baseline) with status quo management. Once restoration costs are internalized by the groundwater manager, an adaptive management approach would result in tens of millions of dollars in gains of economic rents while society incurs less than 1% of the costs of groundwater extraction in the well-field. This adaptive strategy would result in responsive groundwater pumping (more in wet years, less in dry years) at 73% (baseline = 6,830 acre-feet) and 56% (climate change scenario = 4,952 acre-feet) of average groundwater pumping under status quo management. Findings of this study suggest that changing to an adaptive water management strategy generates greater economic rents to the producer while supplying water, sustaining native alkali meadow and ensuring air quality than the status quo groundwater management strategy.

5. Acknowledgments

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Figure 1. Location of the Taboose-Aberdeen Well-field in Owens Valley, California (from Danskin, 1998).

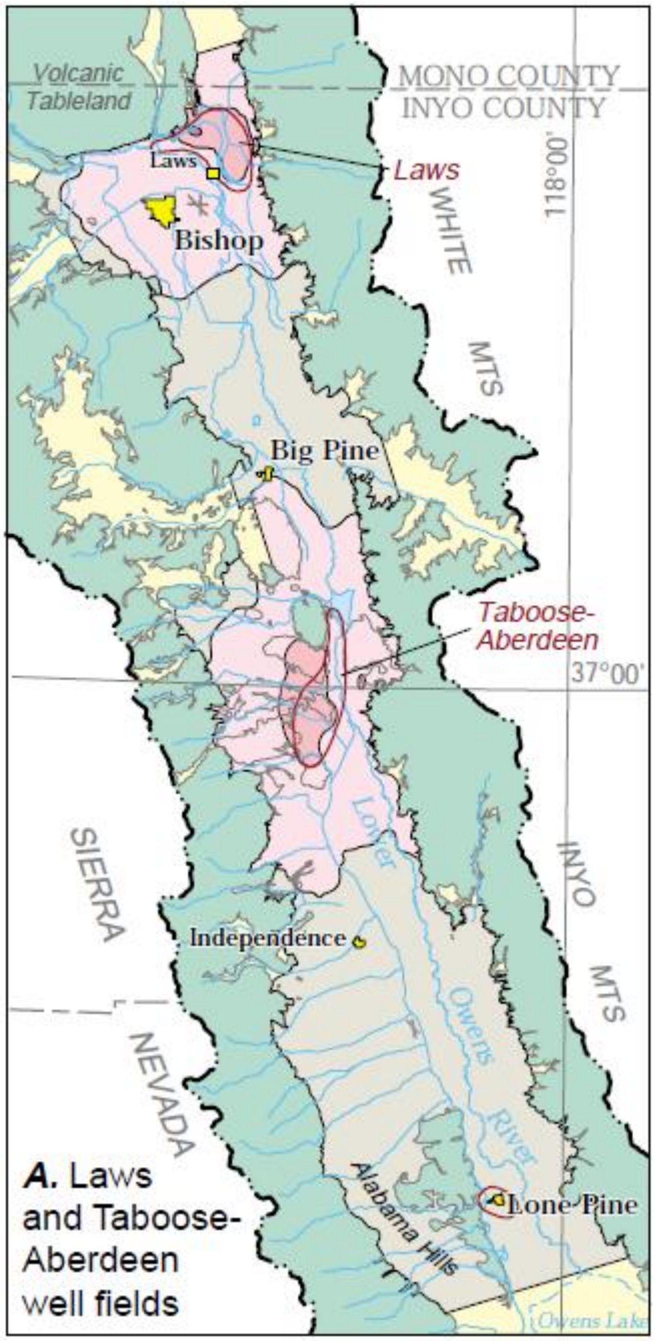


Figure 2. Conceptual Model of Groundwater Management in Alkali Meadow Communities.

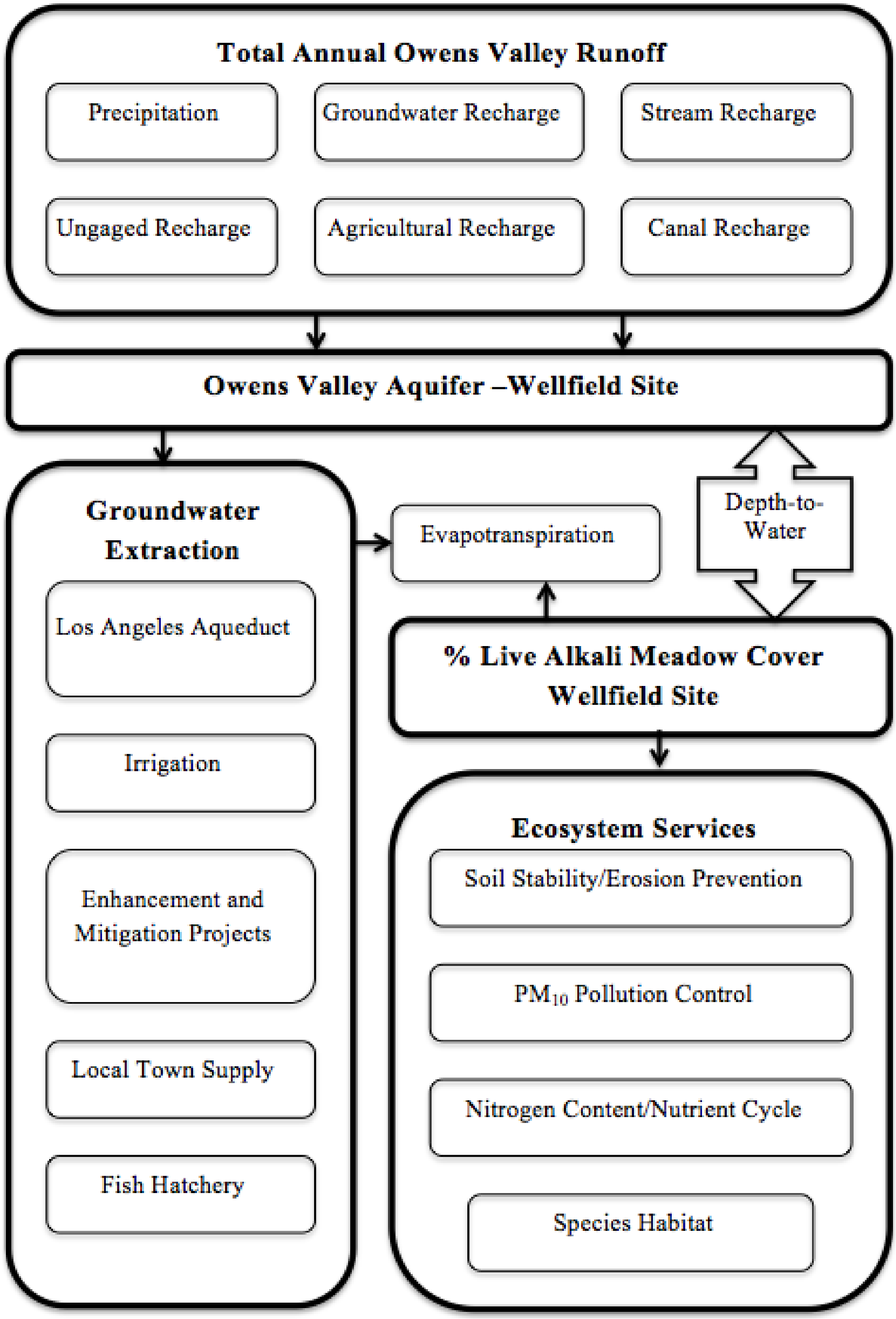


Figure 3. Historic Annual Pumping in the Taboose-Aberdeen Well-field (ICWD, 2009 - 2012).

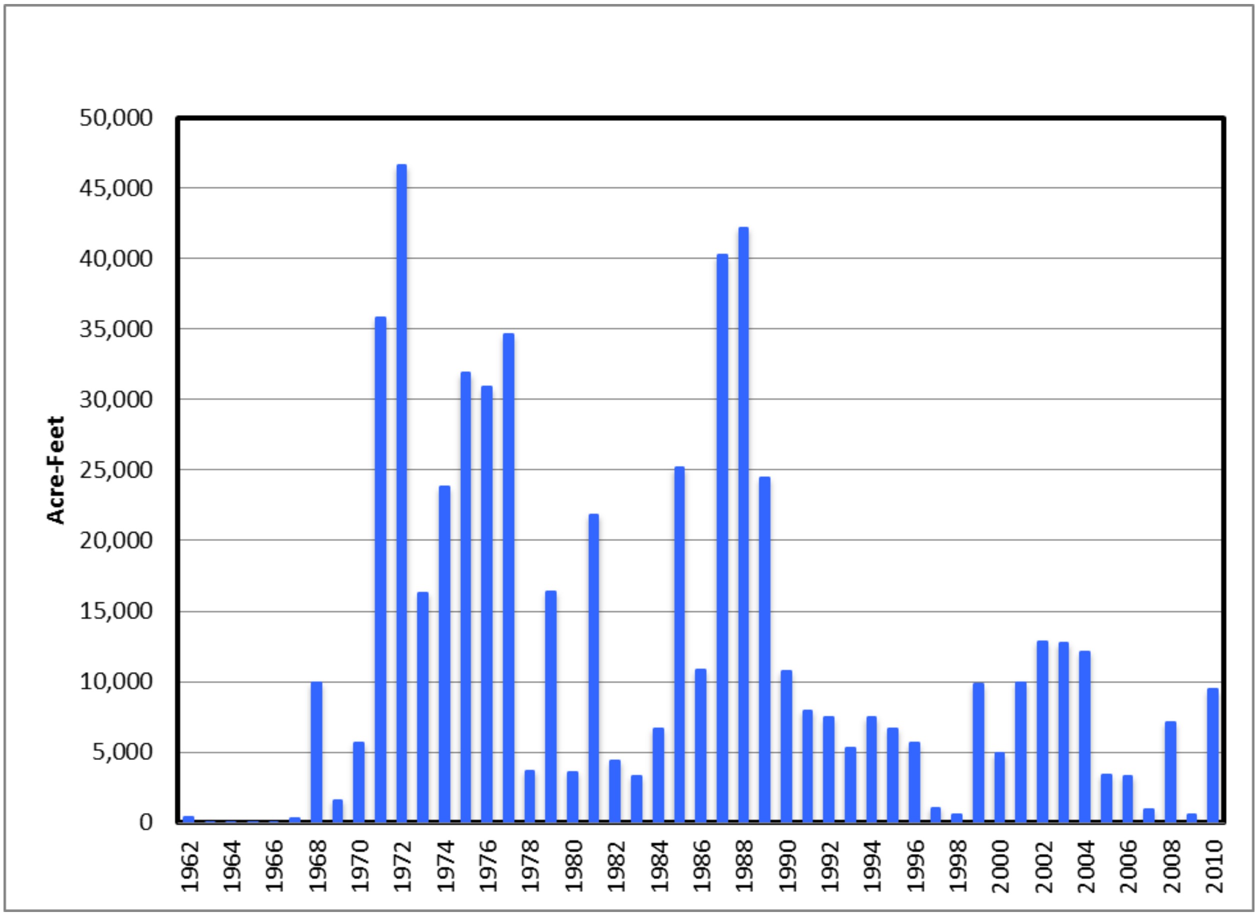


Figure 4. Owens Valley Annual Runoff from 1962-2010 as a Percent of a Long-term Average Annual Runoff. The designated “normal “baseline is the long-term average annual runoff from 1956-2005 of 411,975 acre-feet for Owens Valley (ICWD, 2009 – 2012; LADWP, 2011b)

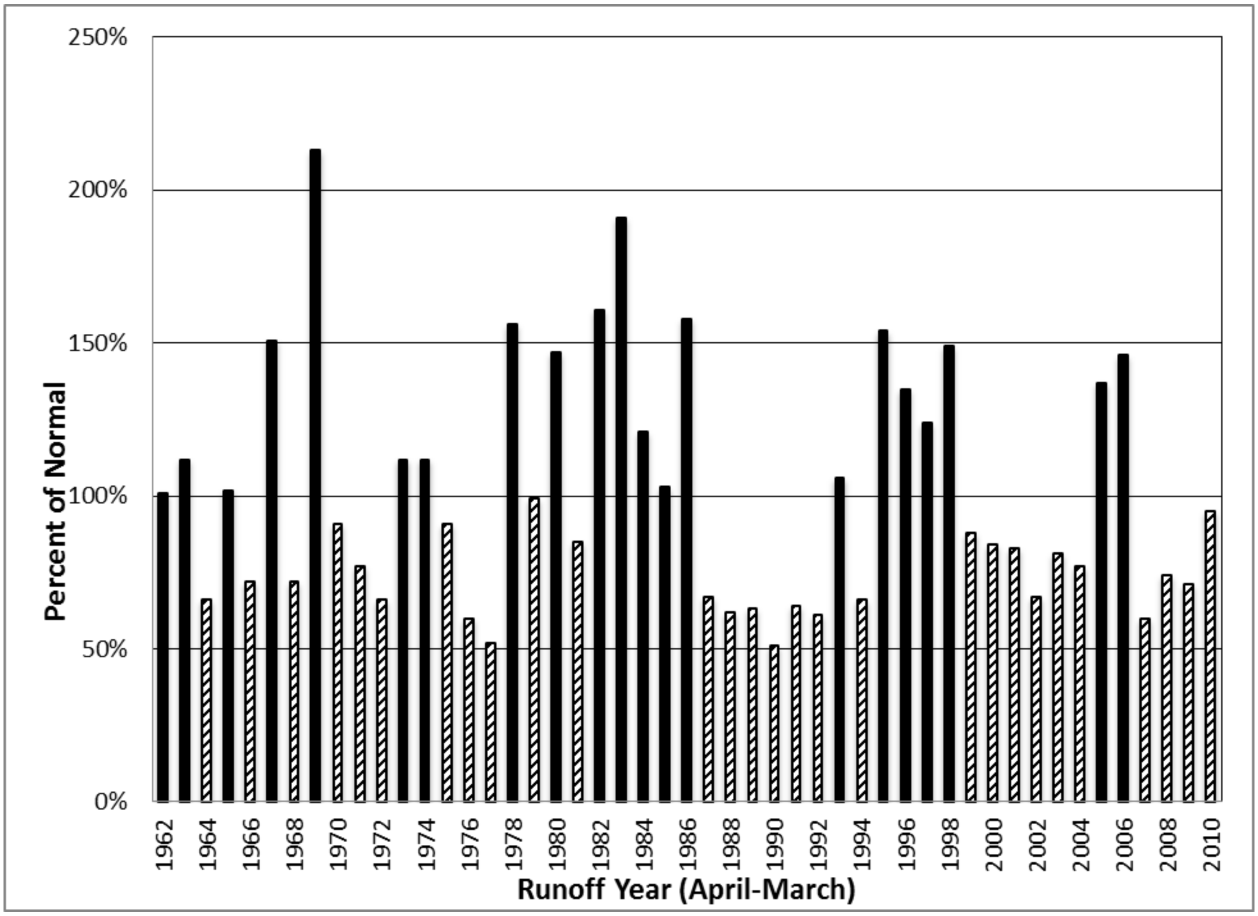


Figure 5. Groundwater pumping strategies as a function of annual runoff relative to the long term average for Owens Valley. Normal baseline is the long-term average annual runoff from 1956-2005 of 411,975 acre-feet for Owens Valley (LADWP, 2011b).

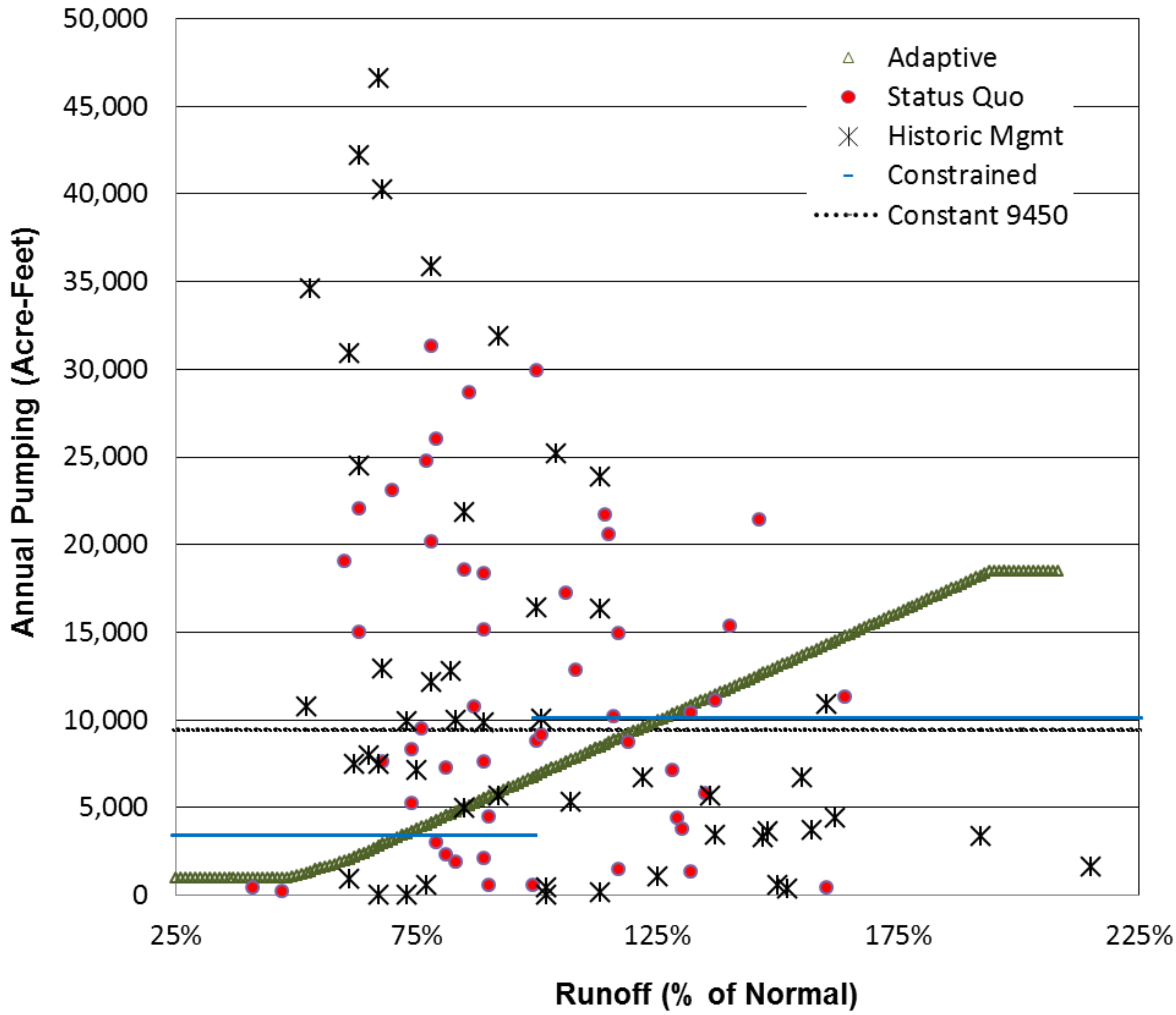
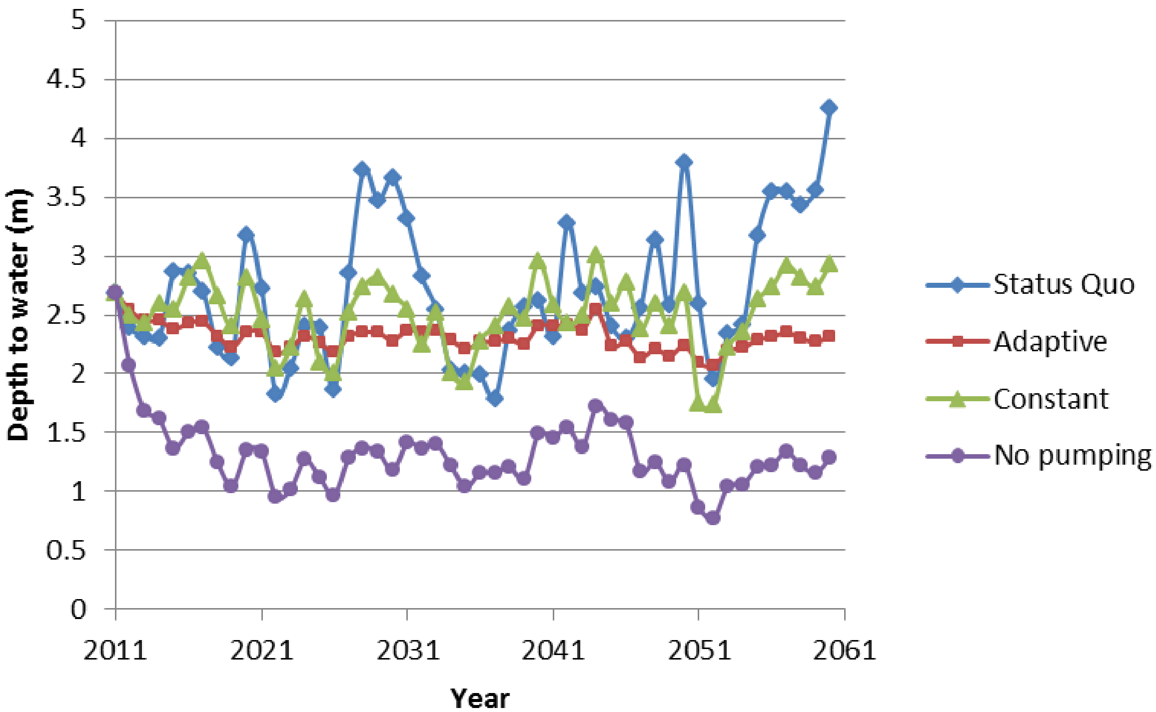


Figure 6. DTW and percent live grass cover of alkali meadow for water management strategies under baseline climatic conditions.



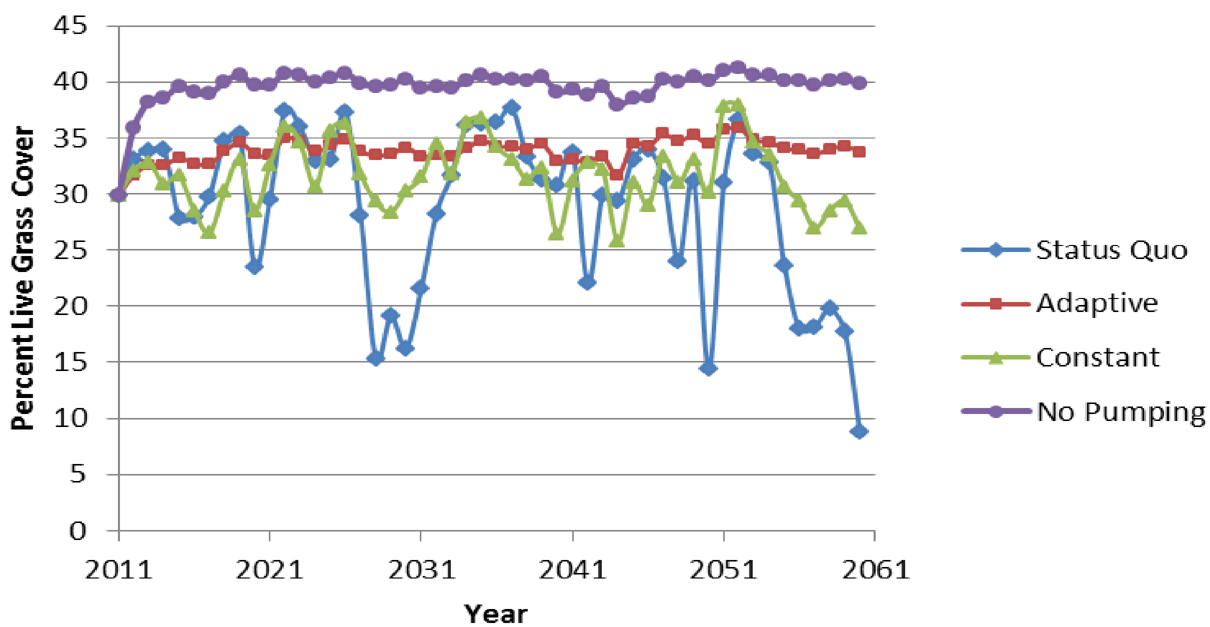


Figure 7. DTW and percent live grass cover of alkali meadow for water management strategies under projected climate change conditions.

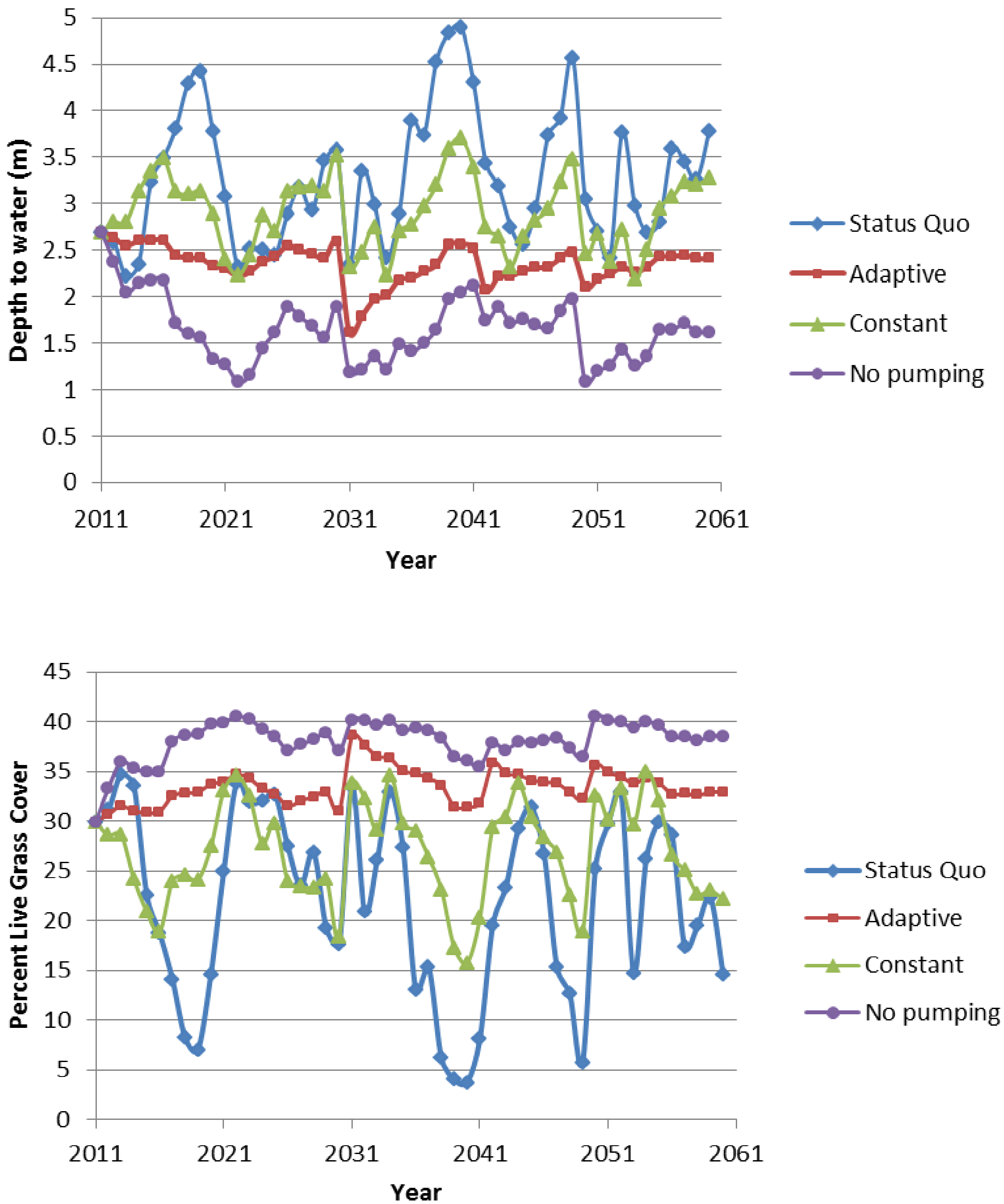


Table 1. Economics of Groundwater Management and Sustaining Alkali Meadow in the Taboose-Aberdeen Well-field

Management Scenario	Cost of Sustaining Alkali Meadow[a] ($ per acre)	Restoration Costs ($ per acre)	Temporal Loss of Eco. Service ($ per acre)	Year 50 DTW[b] (in meters)	Year 50 % live cover[b]	Annual Pumping[b] (acre-feet)	Revenue (millions $)	Economic Rent[c] (millions $)	Rent - eco. cost[d] (millions $)
Baseline Conditions									
Status Quo	$41,822	$36,463	$5,359	3.1 ±0.10	24.2 ±1.3	9,416 ±189	$128.9	$30.5	$17.0
Adaptive Management	$2,020	$2,012	$8	2.3 ±0.02	34.2 ±0.2	6,830 ±83	$92.1	**$82.6**	**$82.6**
Constant (9450 acre-feet)	$32,633	$31,242	$1,391	2.6 ±0.06	30.4 ±0.6	9,450	$127.0	$41.9	$38.4
No Pumping	$4	$0	$4	1.1 ±0.04	40.2 ±0.1	0	$0	$0	$0
Constrained Pumping	$4,616	$4,580	$36	2.2 ±0.04	35.1 ±0.3	6,170 ±68	$82.9	$67.4	$67.3
Climate Change Scenario									
Status Quo	$53,005	$44,344	$8,661	3.4 ±0.09	20.4 ±1.2	8,760 ±191	$122.6	$4.5	$ -17.4
Adaptive Management	$8,512	$8,487	$25	2.3 ±0.01	33.6 ±0.1	4,952 ±73	$66.3	**$41.7**	**$41.6**
Constant (9450 acre-feet)	$47,592	$44,014	$3,578	2.9 ±0.05	26.7 ±0.6	9450	$127.0	$9.6	$0.8
No Pumping	$11	$0	$11	1.4 ±0.04	39.2 ±0.2	0	$0	$0	$0
Constrained Pumping	$15,436	$15,312	$124	2.3 ±0.03	33.6 ±0.2	4,713 ±62	$63.4	$21.7	$21.3

[a]Present Value (in 2011 $) of economic costs, revenue and rents over 50 years averaged over 50 runs: Mean (n = 50)
[b]Annual groundwater pumping: Mean ± S.E. (n = 2500; 50 runs x 50 years); Year 50 depth-to-water and % live cover: Mean ± S.E. (n = 50)
[c] Economic Rent = Revenue for well-field (i.e. price * quantity of water pumped) – estimated pumping & conveyance costs – restoration costs in the well-field
[d] Rent considering temporal loss of ecosystem services = Economic Rent – Social Temporal Loss of Ecosystem Service in the Well-field

Appendix. Model Parameters, Variables and Equations

Name	Description	Value/Conversion	Units	Reference
Hydrologic Sector				
DTW418T	Depth-to-water for well 418T	8.9 (initial)	feet	Tillemans, 2011
DTW419T	Depth-to-water for well 419T	8.2 (initial)	feet	" "
DTW502T	Depth-to-water for well 502T	9.4 (initial)	feet	" "
DTW_T418_Next_Year	Depth-to-water for well 418T – next April	varies	feet	LA & Inyo County, 2007
DTW_T419_Next_Year	Depth-to-water for well 419T – next April	varies	feet	" "
DTW_T502_Next_Year	Depth-to-water for well 502T – next April	varies	feet	" "
Adaptive Pumping	Adaptive water management plan	function of R_O	acre-feet	*****
Average DTW m	Average depth-to-water for the 3 wells	varies	meters	*****
Average runoff	Long term mean of OV runoff	411975	acre-feet	LADWP, 2011
C1_T418	Regression coefficient 1 T418	-2.01786	*****	LA & Inyo County, 2007
C1_T419	Regression coefficient 1 T419	-2.29503	*****	" "
C1_T502	Regression coefficient 1 T502	-6.71824	*****	" "
C2_T418	Regression coefficient 2 T418	0.83938	*****	" "
C2_T419	Regression coefficient 2 T419	0.75478	*****	" "
C2_T502	Regression coefficient 2 T502	0.6135	*****	" "
C3_T418	Regression coefficient 3 T418	-0.000106922	*****	" "
C3_T419	Regression coefficient 3 T419	-0.000254269	*****	" "
C3_T502	Regression coefficient 3 T502	-0.0000813415	*****	" "
C4_T418	Regression coefficient 4 T418	0.00000375313	*****	" "
C4_T419	Regression coefficient 4 T418	0.00000674057	*****	" "
C4_T502	Regression coefficient 4 T502	0.00000858613	*****	" "
Constant_Pumping	Constant management plan	9450	acre-feet	*****
Constrained_Pumping	Constrained management plan	6679 +/ – (6679*.5)	acre-feet	*****
DTWn	Depth-to-water as a negative value	DTW(well)*-1	feet	*****
DTW(well) in meters	Depth-to-water expressed in meters	DTW(well)*.3048	meters	*****
No Pumping	No pumping management plan	0	acre-feet	*****

Percent Normal	Percent of long-term annual runoff mean	varies by year	percentage	*****
Pump	Annual pumping in wellfield	varies by plan	acre-feet	*****
R_O	Annual Owens Valley runoff	varies	acre-feet	*****
Status Quo Pumping	Status quo management plan	function of R_O	acre-feet	*****
Well Operational?	On/off switch for wellfield pumping	0 = off 1 = on	*****	*****

Ecological Sector

Average % Grass Cover	Mean percentage of live grass cover	varies with DTW	percentage	Pritchett and Manning, 2009
Total Acreage	Total acreage of alkali meadows in well-field	2531	acres	Elmore et al., 2003
Full Restoration	Percent live grass cover = full restoration	30	percentage	*****
Time of Restoration	Time interval of assessing restoration effort	10	years	*****

Economic Sector

Restoration Costs Per Acre	Costs of restoration of alkali meadows/acre	23437	U.S. dollars	LADWP, 2010
Discount rate	Rate of discounting future benefits & costs	3	percent	*****
Price Per Acre-Foot	Price paid per acre-foot of water	527	U.S. dollars	2011 MWD rate
Pumping/Conveyance Costs	Cost per acre-foot of pumping/conveying water	25	U.S. dollars	Libecap, 2005
Eco. service of soil stability	Ecosystem service of reduced soil erosion/acre	49804	U.S. dollars	LADWP, 2010
Lost ecosystem service/acre	Temporal loss of eco. service until restored	function of mgmt	U.S. dollars	*****
Revenue	Total revenue from water sales	varies	U.S. dollars	*****
Econ rents w/o res costs	Revenue minus pumping & conveyance costs	varies	U.S. dollars	*****
Econ rents with res costs	Econ rents net of restoration costs	varies	U.S. dollars	*****
Econ rents with res & eco	Econ rents net of res. & lost eco. service	varies	U.S. dollars	*****

Hydrologic Sector Equations

Q Pump = (Well Operational?*Chosen Groundwater Management Plan)

Ro = Average runoff*Percent Normal

DTW T418 Next Year = C1 T418+(C2 T418*(DTW T418))+(C3 T418*Pump)+(C4 T418*Ro)

DTW T419 Next Year = C1 T419+(C2 T419*(DTW T419))+(C3 T419*Pump)+(C4 T419*Ro)

DTW T502 Next Year = C1 T502+(C2 T502*(DTW T502))+(C3 T502*Pump)+(C4 T502*Ro)

Well Operational ? = IF(restoration cycle>=0)AND(restoration cycle<5)AND(Average DTW m<-2.5)AND(TIME>9)THEN(0)ELSE(1)

Ecological Sector Equations

Average ln Grass Cover = 3.78/(1+exp(-(Average DTW m- (-4.59))/0.83))

Average % Grass Cover = exp(Average ln Grass Cover)-1

% Restored = Average % Grass Cover/ Full Restoration

Restoration cycle = MOD(time, Time of Restoration)

Economic Sector Equations

dRevenue / dt = annual revenue = P*QPump*exp(- discount rate*time)

dEcon rents w/o res costs / dt = annual revenue - (pumping conveyance costs per acre-foot*QPump*exp(-discount rate*time))

dEcon rents with res costs / dt = annual rents without restoration costs - (discounted restoration costs/acre *total acreage)

dEcon rents with res & eco / dt = annual rents including restoration costs - (annual lost ecosystem service* total acreage)

dTemporal Loss of eco service / dt = annual lost ecosystem service = lost ecosystem service per acre*exp(- discount rate*time)

dRestoration costs / dt = decadal restoration costs

Decadal restoration costs = IF(restoration cycle=0)and(Average DTW m<=-2.5)then(discounted restoration costs per acre)else(0)

Discounted restoration costs per acre = restoration costs per acre *exp(- discount rate*time)

Economic costs of sustaining alkali meadows per acre = temporal loss eco service per acre + restoration costs per acre

Lost ecosystem service per acre = (1-percent restored) * value of ecosystem service of reduced soil erosion per acre *discount rate