Economic returns of groundwater management sustaining an ecosystem service of dust suppression by alkali meadow in Owens Valley, California

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Abstract

This paper addresses the economic tradeoff between pumping groundwater and maintaining a native plant community that provides an ecosystem service of dust suppression. A dynamic ecological economic simulation model was created to assess net benefits of production (i.e., economic rent) from groundwater management while requiring a producer to maintain or restore native groundwater dependent vegetation in a well-field in Owens Valley, California. Historic groundwater withdrawal during dry conditions followed by recharge during wet conditions has reduced vegetation cover, soil stability and contributed to the drying of springs and seeps. Findings indicate adaptive management that pumps less water, but high volumes in wet years and low volumes in dry years, generates greater economic rent while supplying water, sustaining alkali meadow and maintaining dust suppression. Adaptive management generates economic rent of \$82.6 million (in 2011 \$) compared to status quo management of \$30.5 million over 50 years pumping less annual groundwater than status quo at respective levels of 73% (6,830 acre-feet; baseline conditions) and 56% (4,952 acre-feet; climate change scenario). Under a climate change scenario and a 2.0 meter root-zone or less, it would be cost effective to cease groundwater pumping rather than incur substantial restoration costs of the native plant community.

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

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 of the western United States, groundwater is often shallow and recharged annually to within the root zone of native plants. 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 dust suppression, 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 (see Figure 1). 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.

Valuation of market and non-market ecosystem services and the incorporation of these values into natural resource decision-making have increased over the last two decades (Daily, 1997; deGroot et al., 2002; Polasky, 2008; deGroot et al., 2010; Wratten et al.,

2013). Extensive valuation studies have been conducted on an array of ecosystem services such as, but not limited to, carbon sequestration, water supply and purification, flood and drought buffering and biodiversity (Van Wilgen et al., 1996; Daily, 1997; Gutrich and Howarth, 2007; deGroot et al., 2010; Wratten et al., 2013). Yet few studies have addressed the ecosystem service of dust suppression by plant communities and the links to hydrology and water management (Krieger, 2001; deGroot et al., 2002; deGroot et al., 2010). This study contributes significantly to efforts to capture the non-market value of ecosystem services in natural resource decision-making by articulating the non-market value of dust suppression by native alkali meadow plant communities and utilizing it to inform groundwater management strategies.

A dynamic ecological economic simulation model was created to assess which groundwater management strategy in the Taboose-Aberdeen well-field of Owens Valley maximizes the net gains of groundwater production (i.e., economic rent) while sustaining or restoring native alkali meadow. In consideration of over \$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 by the Los Angeles Department of Water and Power (DWP). 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 National Ambient Air Quality Standards (NAAQS) under the Clean Air Act. 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 and the ecosystem service of dust suppression in Owens Valley is imperative.

2. Methods

2.1 Site description

The Owens Valley extends roughly north-south in eastern California between the Sierra Nevada and the White-Inyo Range. It is a broad, relatively flat mountain valley with an elevation of approximately 1,000m, bordered on both sides by mountains reaching well above 4,000m. Runoff and snowmelt primarily from the Sierra Nevada, supports numerous streams entering the valley and recharging groundwater enroute to the Owens River. Shallow groundwater aquifers are found within 5 m of the surface across much of the valley floor (Hollett et al., 1991). However, the Owens Valley floor itself receives minimal direct precipitation (~13cm/year). Precipitation and mountain runoff are variable, and have the potential to become more variable as a consequence of climate change. A distinct drought between 1987 and 1992 caused wide-spread water shortages throughout California. A more recent drought continues, with total snow pack in 2015 measured at just 6% of normal. Several recent studies suggest that the current

drought is not unusual, either in comparison to the geologic record or future predictions from climate models (Seager et al, 2007; Cook et al., 2015).

Owens Valley has been subject to over 100 years of water diversion and intensive land management. Today, the Los Angeles 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 PM₁₀ (particulate matter 10 micrometers or less in diameter) 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., 2003, 2006) 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., 2013).

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 et al., 2013).

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, 2007, 2009). 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, 2007, 2009; Vest et al., 2013). 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 dust suppression 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. Further, alkali meadow comprised of facultative wetland plant species serve 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 (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 over \$1 billion dollar expenditures for Owens Lake dust mitigation (LADWP 2011; LADWP, 2010; Palmer et al. 2004; Suding et al., 2015). 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.

2.2 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:

$$\text{Max} \int_0^t ((P * Q) - (C_p + RC + ES)) \times e^{-rt} dt \quad (1)$$

with P = price per acre-foot of water, Q = quantity of groundwater pumped, C_p = 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 1 presents a conceptual model of the interactions between hydrology, alkali meadow, and ecosystem services in Owens Valley.

2.3 Annual runoff, extraction and depth-to-water

The ecological economic model simulates the dynamics of three monitoring wells (T418, T419, and T502) located in the Taboose-Aberdeen well-field in Owens Valley to assess alkali meadow cover due to their historic depth-to-water levels in the root zone of native grasses. The Taboose-Aberdeen well-field was selected according 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 2 and 3 summarize the Taboose-Aberdeen well-field pumping rates and runoff from years 1962-2010. Figure 2 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 3 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 2 and 3 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, groundwater extraction rates from the Taboose-Aberdeen well-field and historic annual Owens Valley runoff totals were previously used by water managers to derive regression equations and correlations in order to provide insight into possible groundwater management strategies (City of Los Angeles (LA) and County of Inyo, 2007; ICWD 2010; LADWP 2011b). Modeling of DTW fluctuations as a function of annual runoff and extraction rates in the ecological economic model

presented here was achieved by incorporating regression equations and coefficients developed by the DWP and Inyo County for the *Interim Management Plan* (Los Angeles and County of Inyo, 2007). The ecological economic model simulates DTW for three specific monitoring wells (T418, T419, and T502) located in the Taboose-Aberdeen well-field utilizing the following regression equations (from Los Angeles and County of Inyo, 2007):

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

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 good representation of runoff and pumping effects on depth-to-water levels in the Taboose-Aberdeen well-field, correlation coefficients were derived and indicated a strong correlation of DTW model results and actual DTW field data from 1976-2011 for each respective well ($r=.94$ for well T418; $r=.97$ for well T419 and $r=.91$ for well T502). To assess validation of this hydrologic sub-model, we compared simulation results after 2007 of DTW as a function of runoff and pumping to field data (DTW for years 2008 – 2012) that was not part of the original data set utilized to derive the regression equations (years ≤ 2007 ; City of Los Angeles and County of Inyo, 2007). No statistical significant difference was found between the means of simulation model runs and validation depth-to-water measurements paired by year for

the three respective monitoring wells from 2008 to 2012 ($\alpha = .05$, 2-tailed, paired t-test).

2.4 DTW effects on grass cover in alkali meadow communities

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 sigmoidal regression curve based on a pre-fire data set of 48 transects of alkali meadow assessed in June 2007 (Pritchett and Manning, 2009; see Figure 4). The effect of DTW on grass cover in alkali meadow was modeled utilizing the natural log-transformed regression equation :

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

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.

2.5 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). 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 and dust suppression).

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.

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.

2.6 Owens Valley annual runoff and sensitivity of the model

Historic Owens Valley annual runoff was acquired for the period 1935 to 2010 (ICWD, 2011). Over the historical period, it was determined that the $\log_{10}(\text{runoff})$ 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).

In the model, we assessed not only the sensitivity of runoff variability on the main state variable of economic rents, but also the sensitivity of various groundwater management strategies (see section 2.10) and the depth-to-water of the critical root zone to maintain alkali meadow. Our sensitivity analysis compared the effect of three differing depth-to-water root zone thresholds of 1.5m, 2.0m and 2.5m on economic costs and rents (see Table 2). Sensitivity runs were conducted under historic baseline climatic conditions and a future climate change scenario of 15% less annual runoff. The 1.5m root zone threshold is the most restrictive concerning groundwater pumping and the 2.5m depth-to-water threshold was the standard utilized for analysis as indicated by a previous study on alkali meadow in Owens Valley (Elmore et al., 2006).

2.7 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 mile² (91.2 km²) included \$12.9 million/mile² (\$5.0 million/km²) in capital costs and \$1.24 million/mile² (\$0.5 million/km²) for annual water use (LADWP, 2010). Gravel covered 0.14 mile² (0.36 km²) with capital cost payments of \$22 million/mile² (\$8.5 million/km²) and managed vegetation was planted on 3.7 miles² (9.6 km²) of the Owens Lake bed at a capital cost of \$15 million/mile² (\$5.8 million/km²), 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.

2.8 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 required under the Clean Air Act. 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).

383

384 **2.9 Water revenue and economic rents**

385 A groundwater manager acting in a manner to maximize economic rents while
386 sustaining alkali meadow will compare the net revenue (revenue minus
387 pumping/conveyance costs) derived from further groundwater extraction against the
388 increased restoration costs to be incurred from a possible degradation of alkali meadow.
389 A manager that significantly limits or ceases groundwater extraction will reduce water
390 revenue, but also will lower probable restoration costs thereby creating a possible gain
391 in economic rent. Further, a manager that increases groundwater extraction and water
392 revenue in a manner that does not lead to extensive degradation of alkali meadow could
393 also obtain a gain in economic rent of production. Our model assesses these economic
394 tradeoffs for five groundwater management strategies in a well-field. Water revenue to
395 the producer is estimated as the quantity pumped in the well-field multiplied by
396 \$527/acre-foot (i.e., the 2011 rate for the Metropolitan Water District of Southern
397 California). An estimate of pumping and conveyance costs in the western United States
398 of \$25/acre-foot was utilized (Libecap, 2005). Our analysis focuses on managing
399 groundwater to maintain groundwater dependent alkali meadow while maximizing
400 economic rents from extracting and selling groundwater.

401

402 **2.10 Groundwater management strategies**

403 We analyzed the economic rents derived from five groundwater management strategies
404 while sustaining alkali meadow: (1) status quo management (based on historic action
405 which increased pumping during dry years and decreased pumping during wet years);
406 (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). Allen and Gunderson (2011) indicate adaptive management is best applied when both uncertainty and controllability are high. Here, we model highly uncertain annual runoff from snowmelt while pumping rates are highly controllable. However, adaptive management is narrowly defined in our study as adaptation of pumping rates to variable runoff and does not include highly iterative processes of knowledge accumulation from pumping management strategies over time as highlighted in other adaptive management studies (Williams et al., 2009; Convertino et al., 2013). The pumping strategy was termed adaptive management in this study as it adapts to the interaction of annual runoff from snowmelt and the volume of groundwater pumped which affects depth-to-water in an effort to maintain groundwater within the root zone of alkali meadow – resulting in a more adaptive approach than historic status quo management. 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.

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, 2009, 2010, 2011). 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.

Constrained, constant and no pumping 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:

$$\text{Pump}(t) = \begin{cases} 3,339 & \text{Ro}(t) < 411,975 \\ 10,018 & \text{Ro}(t) \geq 411,975 \end{cases} \quad (4)$$

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.

$$\text{Pump}(t) = \begin{cases} 9,450 & \text{Ro}(t) < \infty \end{cases} \quad (5)$$

No pumping management results in no groundwater extraction:

$$\text{Pump}(t) = \begin{cases} 0 & R_o(t) < \infty \end{cases} \quad (6)$$

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:

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

3. 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).

Tables 1 and 2 present 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; see Table 2).

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

527 need for restoration. Status quo management incurred a cost of \$41,822/acre
528 (\$103,300/hectare) to sustain alkali meadow over 50 years comprised of \$36,463/acre
529 (\$90,063/hectare) in restoration costs and \$5,359/acre (\$13,237/hectare) in temporal
530 loss of ecosystem service. After 50 years under status quo management, the percent live
531 cover in alkali meadow was 24.2% (less than the required 30%) with depth-to-water
532 beyond the root zone at 3.1 meters on average. Adaptive management sustained alkali
533 meadow with a cost of \$2,020/acre (\$4,990/hectare) over 50 years with restoration
534 costs representing the majority of the total at \$2,012/acre (\$4,970/hectare) and lost
535 ecosystem service costs of only \$8/acre (\$20/hectare). After 50 years, adaptive
536 management displayed alkali meadows with 34.2% live cover (above the required
537 threshold) and average depth-to-water in the root zone of native grasses at 2.3 meters.

538

539 Considering climate change effects, the adaptive management strategy again generates
540 the greatest economic rents at \$41.7 million compared to \$21.7 million for constrained
541 pumping, \$9.6 million for constant pumping, and only \$4.5 million for status quo
542 management. If the social costs of the temporal loss of ecosystem services are
543 considered and internalized, then status quo management would result in costs
544 exceeding revenue indicated by negative economic rents of -\$17.5 million. Here, it
545 would be less costly to simply not extract groundwater (no pumping) in the well-field as
546 higher restoration costs and the cost of lost ecosystem services over time outweigh water
547 revenue. However, the adaptive management strategy indicates that \$41.6 million in
548 economic rents can still be obtained from groundwater extraction while sustaining alkali
549 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.

Table 2 highlights sensitivity analysis on the effect of differing depth-to-water root zone thresholds for alkali meadow on economic rents and costs. A standard depth-to-water of 2.5m was utilized for results presented in Table 1 and based on previous fieldwork on alkali meadow in Owens Valley (Elmore et al., 2006). Table 2 highlights the sensitivity and importance of the critical root zone threshold concerning the economic returns of adaptive management of groundwater versus no pumping in the well-field. Under baseline climatic conditions, adaptive groundwater management generates higher economic returns at both depth-to-water thresholds of 2.5m and 2.0m. However, if the root zone thresholds require depth-to-water of 1.5m then adaptive management generates a loss of -19.5 million dollars versus a loss of -16.3 million dollars by choosing not to pump. The very shallow root zone of 1.5m reflects the importance of climate variability and makes it more likely that restoration costs will be required under this strict threshold totaling \$6,453/acre under baseline climatic conditions and \$26,285/acre under a climate change scenario. Adaptive management generates millions in economic rents under both baseline climatic conditions (\$82.6 million) and climate change conditions (\$41.7 million) with a root-zone threshold of 2.5m. However, with *both* climate change and stricter root zone thresholds of 2.0m or 1.5m, it would be more cost effective to cease groundwater pumping rather than incur substantial restoration costs.

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.

Our analysis also highlights important equity issues beyond economic efficiency.

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 to society. 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; $\$105.9 / \$111.9 \text{ million} = .95$) 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.

If management actually incurs the restoration costs of groundwater decline (as it already has at Owens Lake) then DWP would maximize economic rents among alternative management approaches in the Taboose-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 (in a 2.5m root zone) generates greater economic rents to the producer by supplying water and sustaining native alkali meadow that ensures air quality by providing the ecosystem service of dust suppression. However, under a climate change scenario of 15% decline in average runoff and root zone thresholds of 2.0 meters or less, it would be cost effective to cease groundwater pumping rather than incur substantial restoration costs of native plant communities.

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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)	<u>Revenue</u>	<u>Economic Rent^c</u> (millions \$)	<u>Rent - eco. cost^d</u>
<i>Baseline Conditions</i>									
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
<i>Climate Change Scenario</i>									
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	\$0.6
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

^aPresent Value (in 2011 \$) of economic costs, revenue and rents over 50 years (2011-2060); averaged over 50 runs: Mean (n = 50)

^bAnnual 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)

^cEconomic Rent = Revenue for well-field (i.e. price * quantity of water pumped) – estimated pumping & conveyance costs – restoration costs in the well-field

^dRent considering temporal loss of ecosystem service = Economic Rent – Social Temporal Loss of Ecosystem Service in the Well-field

Table 2. Economic Results Based on Varied Depth-To-Water Threshold for Alkali Meadow

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	Economic Rent ^c (millions \$)	Rent - eco. cost ^d
Baseline Conditions									
Adaptive Management									
2.5m threshold	\$2,020	\$2,012	\$8	2.3 ±0.02	34.2 ±0.2	6,830 ±83	\$92.1	\$82.6	\$82.6
2.0m threshold ^e	\$4,353	\$4,349	\$4	1.6 ±0.03	38.3 ±0.2	3,685 ±46	\$49.8	\$36.4	\$36.4
1.5m threshold ^f	\$15,477	\$15,473	\$4	1.3 ±0.04	39.6 ±0.2	1,519 ±22	\$20.6	-\$19.5	-\$19.5
No Pumping									
2.5m threshold	\$4	\$0	\$4	1.1 ±0.04	40.2 ±0.1	0	\$0	\$0	\$0
2.0m threshold	\$4	\$0	\$4	1.1 ±0.04	40.2 ±0.1	0	\$0	\$0	\$0
1.5m threshold	\$6,457	\$6,453	\$4	1.1 ±0.04	40.2 ±0.1	0	\$0	-\$16.3	-\$16.3
Climate Change Scenario									
Adaptive Management									
2.5m threshold	\$8,512	\$8,487	\$25	2.3 ±0.01	33.6 ±0.1	4,952 ±73	\$66.3	\$41.7	\$41.6
2.0m threshold ^e	\$22,278	\$22,263	\$15	1.9 ±0.03	37.1 ±0.2	2,475 ±41	\$33.4	-\$24.5	-\$24.6
1.5m threshold ^f	\$34,639	\$34,626	\$13	1.6 ±0.04	38.6 ±0.2	940 ±22	\$12.9	-\$75.3	-\$75.4
No Pumping									
2.5m threshold	\$11	\$0	\$11	1.4 ±0.04	39.2 ±0.2	0	\$0	\$0	\$0
2.0m threshold	\$2,867	\$2,856	\$11	1.4 ±0.04	39.2 ±0.2	0	\$0	-\$7.2	-\$7.3
1.5m threshold	\$26,296	\$26,285	\$11	1.4 ±0.04	39.2 ±0.2	0	\$0	-\$66.5	-\$66.5

^aPresent Value (in 2011 \$) of economic costs, revenue and rents over 50 years (2011-2060); averaged over 50 runs: Mean (n = 50)

^bAnnual 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)

^cEconomic Rent = Revenue for well-field (i.e. price * quantity of water pumped) – estimated pumping & conveyance costs – restoration costs in the well-field

^dRent considering temporal loss of ecosystem services = Economic Rent – Social Temporal Loss of Ecosystem Service in the Well-field

^e2.0m threshold adaptive management = .55 * (adaptive management for 2.5m threshold); see Equation 7 and explanation in text.

^f1.5m threshold adaptive management = .25 * (adaptive management for 2.5m threshold); see Equation 7 and explanation in text.

Figure 1. Conceptual Model of Groundwater Management in Alkali Meadow Communities.

Figure 2. Historic Annual Pumping in the Taboose-Aberdeen Well-field (ICWD, 2009 - 2012).

Figure 3. 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 4. Percent live plant cover in alkali meadow as a function of depth-to-water. Derived from $y = 3.78 / (1 + \exp(-(x - (-4.59)) / 0.83))$ where y = natural logarithm (ln) of % live grass cover and x = depth-to-water (from Prichett and Manning, 2009).

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.