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SUSTAINABLE AGRICULTURE IRRIGATION MANAGEMENT: THE WATER-ENERGY-FOOD NEXUS IN PAJARO VALLEY, CALIFORNIA

BY

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Abstract

The water-energy-food (WEF) nexus is quickly becoming one of the most critical global environmental challenges of the twenty first century. However, WEF systems are inherently complex; they typically are dynamic and span multiple land or agro-ecosystems at a regional or global scale. Addressing this challenge requires a systems approach to optimal and sustainable resource management across multiple dimensions. To that end, using Pajaro Valley (California) as a case study, our research aims to (1) highlight synergies and tradeoffs in food and water production, (2) build a dynamic framework capable of examining intertemporal resource relationships, and (3) detail the steps required to develop incentive-compatible financing of the resulting management plans when benefits are not distributed uniformly across users. Using a stylized model, we find that in the long run, inland growers benefit from the halting of seawater intrusion (SWI) due to overpumping of groundwater. We also calculate that the water provided by the proposed College Lake Multi-Objective Management Program—a plan designed to halt SWI and support sustainable water and agricultural development in the region—will generate net revenue of $40-58 million per year, compared to an annualized cost of less than $3 million. An equal cost-sharing plan would be desirable if the benefit of the project exceeded $1,268 per year for each well owner. Since this may not necessarily be the case for smaller well owners, one possible alternative is to allocate costs in proportion to expected benefits for each user.

Keywords: water-energy-food nexus, sustainable agriculture, groundwater management, saltwater intrusion, cost-benefit analysis, Pajaro Valley

Introduction

The water-energy-food (WEF) nexus describes the connectivity between three basic but indispensable resources. Water is an input to agricultural production and is used for cooling at energy generation facilities; energy is necessary to produce, treat, and distribute water, as well as power farm machinery; and food fuels the labor force required to produce both water and energy. The concept of WEF is not new, but it has received increasing international attention in recent years in response to population and economic growth, increased globalization, and climate change (Allen et al., 205; Leck et al., 2015; Rasul and Sharma, 2015; Finley et al., 2014; Hoff, 2011). Given its scale and potential to create conflicts both within and across political boundaries, the WEF nexus is quickly becoming recognized as one of the biggest global environmental challenges of the twenty first century (Scott et al., 2015).

Much effort has been put into identifying, understanding, and quantifying important synergies and tradeoffs within the WEF nexus (Endo et al., 2015a; Endo et al., 2015b; Loring et al., 2013; Taniguchi et al., 2013). Designing policies that take into account those tradeoffs is particularly challenging when considering global population and climate change projections over the next century and beyond. From a long-term planning perspective, management of WEF systems should address not only contemporaneous tradeoffs, but also intertemporal ones. Thus questions of sustainability, or more specifically, sustainable resource use, naturally arise in WEF nexus research (Gurdak et al., 2016; Velasco et al., 2016). Studies on the sustainable management of each individual component of the nexus are not uncommon. For example, (economically) optimal water management has been shown to be sustainable in many circumstances, provided that externalities and supply-side substitutes are properly accounted for (Roumasset and Wada, 2010). However, addressing all of the pieces of the nexus simultaneously in a sustainable manner remains a challenge (Hussey and Pittock, 2012). To that end, our research focuses on the sustainable management of water and food production in Pajaro Valley, California. Our primary objectives are to (1) highlight synergies and tradeoffs in food and water production, (2) build a dynamic framework capable of examining intertemporal resource relationships, and (3) detail the steps required to develop incentive-compatible financing of such multi-dimensional plans when benefits are not distributed uniformly across users.

Our study focuses on the College Lake Multi-Objective Management Project, which is located in Pajaro Valley, adjacent to Monterey Bay in central California. Pajaro Valley is only 310 km^2, but is one of the most productive agricultural regions in California with an estimated annual value of over $800 million in agricultural production (PVWMA-CE, 2014). Similar to other coastal regions, Pajaro Valley is nearly 100% reliant on local groundwater to support its large-scale irrigated crops. Thus, any water policy or project in Pajaro Valley naturally lies within the WEF nexus. Water management in the area is further complicated by current and projected seawater intrusion (SWI). SWI is both a spatial and temporal problem; groundwater pumping in one area of the basin can cause SWI intrusion in another area, and future SWI is determined both by pumping (historical and future) and climate variability and change.

Seawater intrusion in the Pajaro Basin was first documented in the early 1950s (PVWMA-CE, 2014). In response, the Pajaro Valley Water Management Agency (PVWMA) engaged in a multi-year process of developing a basin management plan (BMP) with the goals of improving the use of available freshwater supplies and solving the problems of overdraft and seawater intrusion (SWI). In 2002, PVWMA revised the BMP to include more specific guidelines for major projects and programs. More recently (2010), the PVWMA Board of Directors established a BMP Committee to develop, with input from community stakeholders, an update to the BMP. Using information on historical and existing conditions of groundwater within the PVWMA service area, results from the Pajaro Valley Hydrological Model (Hanson et al., 2014) suggest that continued overdraft over the next 30 years will lead to a basin shortfall of approximately 12,000 AFY (PVWMA-CE, 2014). To address this shortfall, an updated BMP was put into action in 2012. The three primary components of the plan are: (1) to develop new water supplies (4,100 AFY), (2) to use water more efficiently (5,000 AFY), and (3) to optimize the use of existing supplies (3,000 AFY). Within the primary component (1), the College Lake Diversion Project is expected to provide 2,100 to 2,400 AFY of new water supply (RCDSC-CBEC, 2014).

Under current management by the College Lake Reclamation District, pumps are used to dewater College Lake beginning in April of each year to allow for farming on the dry lake bottom during the summer. The water from the lake is pumped into Salsipuedes Creek, and eventually flows into Monterey Bay. The proposed PVWMA project would instead put the College Lake water to beneficial use by pumping it to the Coastal Distribution System (CDS), which is a network of pipes that brings water to farmers in the coastal area that is impacted by SWI. After the College Lake water is pumped into the CDS, it will be blended with other supplemental water sources such as recycled water, and be used as irrigation supply in-lieu of groundwater production. Reducing groundwater pumping in the coastal area is a key component of the BMP. Modeling has shown that the most effective way to stop SWI in the upper aquifers is by reducing or eliminating groundwater pumping along the coast. Benefits include the immediate value of lake water for irrigation, as well as the reduction of SWI for the entire valley. Other benefits include the continuation of agriculture and secondary economic drivers associated with the workforce such as housing, as well as benefits to local businesses such as restaurants and supermarkets. An improved diversion facility and operation will provide a benefit to federally listed steelhead trout and possibly a large variety of water fowl. Costs include construction and maintenance of an adjustable weir (to allow for increased storage in the lake) and a pumping/distribution system, as well as lost revenue for lake farming; the stored lake water is most beneficial when stored beyond April, which means that the summer growing season could be significantly shortened for lake bed farmers.

The remainder of the article is organized as follows. We begin by developing a stylized groundwater management model with SWI. We then discuss how the results change when incorporating a groundwater alternative, in this case, water from the College Lake project. Finally, we combine crop production data from the region with project cost data to provide a rough approximation of the expected net benefit of the project. We find that aggregate net benefits are positive, even before accounting for the long-run avoided costs of SWI at the basin-scale, although inland farmers may not see benefits in the short term.

1 Methods

The most clearly quantifiable benefit of the project is the freshwater provided by College Lake for coastal farmers already affected by SWI, but the largest benefit is likely something more difficult to measure: the value of avoiding SWI for the entire basin. This may include some ecological benefits resulting from balancing the aquifer owing to, for example, increased submarine groundwater discharge to nearshore waters. There is also the benefit to inland water users who would, in the face of future SWI, be forced to use costly sources other than groundwater or cease agricultural production. If the rate of intrusion given the current state of overdraft and individual agriculture production functions are known, then it is possible to estimate the avoided cost of SWI attributed to the College Lake project. In the remainder of this section, we develop a stylized groundwater economics framework to illustrate the benefit of preventing SWI.

2.1 Stylized Groundwater Model without the College Lake Project

We begin with a basic water balance model for a coastal aquifer. Although each resource user could be linked to a unique spatial set of coordinates, we group users, variables, and parameters into two spatial categories to keep the model tractable: inland user (n) and coastal user (o). All recharge or inflow to the aquifer is aggregated and denoted by R. Outflow is equal to the sum of coastal pumping (q_o) and inland pumping (q_n). The change in groundwater volume (V) is then

$$\dot{V} = R\text{-}(q_n + q_o) \tag{1}$$

However, we are also interested in how the head level, defined here as the vertical distance between mean sea level and the top of the water table in the upper aquifer, changes over time in each location because it is natural to specify the pumping cost as a function of head rather than volume. Because of heterogeneities in hydraulic properties in the aquifer, the head level at each location will change by a different amount for a given change in volume. Thus, we prescribe unique height-volume conversion coefficients for each location: α_n and α_o. The equations of motion for head level at each location are

$$\dot{h}_n = \alpha_n \dot{V} = \alpha_n [R\text{-}(q_n + q_o)] \tag{2}$$

$$\dot{h}_o = \alpha_o \dot{V} = \alpha_o [R\text{-}(q_n + q_o)] \tag{3}$$

We begin by examining the water management problem under the assumption that the College Lake project is not implemented. A benevolent social planner's objective would be to maximize the net present value (NPV) of the aquifer:

$$(4) \qquad \max_{q_n, q_o} \int_0^\infty e^{-\rho t}\{B_n(q_n) + B_o(q_o) - c(h_n)q_n - c(h_o)q_o\}\,dt$$

subject to equations (2) and (3) and a positive discount rate ρ. The benefit (B) depends on the amount pumped for each user. In this particular example, B could be represented by total revenue for each farmer i, $p_i f(q_i)$, where p is the price of the crop and $f(q_i)$ is the production function. The marginal extraction cost for groundwater ($c(h_i)$) is a function of the head level because as h declines, more energy is required to lift the water a greater distance to the surface. We also assume that if the head level at each location is drawn below the level $h_{min,i}$, the well becomes unusable, i.e. SWI has occurred. The current value (CV) Hamiltonian corresponding to equation (4) is

$$(5) \qquad H = B_n(q_n) + B_o(q_o) - c(h_n)q_n - c(h_o)q_o$$

$$+\lambda_n \alpha_n [R - q_n - q_o] + \lambda_o \alpha_o [R - q_n - q_o]$$

The maximum principle requires that the following conditions hold

$$(6) \qquad B'_n(q_n) - c(h_n) - \lambda_n \alpha_n - \lambda_o \alpha_o \leq 0, \qquad \text{if < then } q_n = 0$$

$$(7) \qquad B'_o(q_o) - c(h_o) - \lambda_n \alpha_n - \lambda_o \alpha_o \leq 0, \qquad \text{if < then } q_o = 0$$

$$(8) \qquad \dot{\lambda}_n - \rho\lambda_n = c'(h_n)q_n$$

$$(9) \qquad \dot{\lambda}_o - \rho\lambda_o = c'(h_o)q_o$$

If both groups are optimally using groundwater, then

$$(10) \qquad B'_n(q_n) - c(h_n) = B'_o(q_o) - c(h_o)$$

Otherwise, more pumping could be allocated to the group with higher marginal net benefit to increase the NPV. Because water is being drawn from the same aquifer, each user must take into account the effect of his pumping on the marginal user cost (λ) of the other user. The marginal user cost captures the idea that a single user's decision to pump water today reduces the total water available for all users in the future. Pumping will be optimally zero at the coast and positive inland only if

(11) $B'_o(q_o)\text{-}c(h_o) < B'_n(q_n)\text{-}c(h_n)$

Now suppose instead that there is no benevolent planner, and users act in their own self interest, i.e. resource use is open access. In that case, the pumping externality effects are ignored, and each user aims to maximize his/her own profit regardless of the implications for total social welfare. Pumping for each user is determined by the following:

(12) $B'_i(q_i) \leq c(h_i)$ for i = n, o

If B is total revenue, then (12) is the standard optimality condition for a profit-maximizing firm: produce until marginal revenue is equal to marginal cost. Since marginal user costs or shadow prices are non-negative, at each head level, socially optimal pumping is always lower than open access pumping. This theoretical result is intuitive, as users would pump less if they must take into account the effects of pumping decisions on other users.

2.2 Incorporating the College Lake Project as a Groundwater Alternative

Although the College Lake project will supply lake water to both inland growers along the new water main and coastal users, we assume that the water is only available to coastal users.

This assumption allows us to examine key tradeoffs in the simplest way possible. The modified social welfare maximization problem is

$$(13) \qquad \max_{q_n, q_o, l_o} \int_0^\infty e^{-\rho t}\{B_n(q_n) + B_o(q_o, l_o) - c(h_n)q_n - c(h_o)q_o - \gamma l_o\}\, dt$$

where l_o is the quantity of lake water used for agricultural production by the coastal user and γ is the unit cost of lake water. If there is an upper bound to the amount of lake water available in each period, the problem should also include a constraint that$l_o \leq l_{max}$. In addition to necessary conditions (6)-(9), maximizing the objective function in (13) requires the following

$$(14) \qquad B'_o(q_o, l_o) - \gamma \leq 0, \qquad \text{if < then } l_o = 0$$

Together with the necessary conditions for the baseline case, (14) implies that it is optimal to use lake water but not groundwater at the coast only if

$$(15) \qquad \gamma < c(h_o) + \lambda_n \alpha_n + \lambda_o \alpha_o$$

In other words, optimality requires exclusive use of the resource(s) with the lowest marginal opportunity cost. If it were cheaper to use groundwater even after accounting for the pumping externality, then using lake water in place of groundwater would actually lower the NPV. The College Lake project is socially optimal as long as the NPV^{CL} (calculated by plugging the optimized values back into the objective function in equation (13)) exceeds the NPV^0 for the baseline case by more than the cost of implementing the College Lake project (PVC^{CL}).

Now, consider again the case where resource use is open access. The coastal user will only choose to irrigate with lake water if

$$(16) \qquad \gamma \leq c(h_o)$$

Since the shadow prices are non-negative, lake water will be implemented at a higher head level by the social planner than by the coastal open-access user because the planner takes into account the pumping externality, while the coastal user does not. Moreover, the inland farmer will have little incentive to share the cost of the project if resource use is open access because his or her individual optimizing behavior is still described by (12), which does not account for the scarcity value of water; the potential long run benefit of the project to inland farmers is captured by that missing component.

With only two farmers, the College Lake project always generates some benefits for the inland farmer. This is especially clear for the case where $q_o = 0$; the coastal head level h_n is drawn down more slowly (indirectly as a result of inland pumping), which means that the inland head level h_n is also drawn down more slowly. Consequently, groundwater becomes less scarce to the inland user, and higher benefits can be enjoyed for a longer period of time. The question of whether or not the costs of the project are justified by these benefits is addressed in section 3. The result is less clear when there are multiple farmers within each group. An individual inland-user cannot necessarily count on the groundwater saved as a result of coastal substitution for lake water. Neighboring inland-users will increase pumping because their marginal pumping costs decline at the higher head level. In other words, the potential spatial and intertemporal gains will not be fully realized if resource use remains open access.

2.3 The Net Present Value Criterion and Financing Options

Recall that we defined NPV as the sum of net benefits from water use over time, discounted at rate ρ. Since the objective of our optimization problems (4) and (13) is to maximize NPV, the optimal NPV in each case is determined by first solving the problem for the optimal trajectories of pumping (q*) and head (h*), and then plugging those vectors back into the objective function. Letting NPV^{CL} and NPV^{0} represent the optimal net present values with and without the College Lake project respectively, implementing the project is desirable only if $(NPV^{CL} - NPV^{0})$ exceeds the PV cost (PVC^{CL}) of building, maintaining, and operating the diversion infrastructure. If groundwater is scarce in the region and project construction costs are relatively low, it is likely that $(NPV^{CL} - NPV^{0}) > PVC^{CL}$. Each user should then be indifferent to equal cost-sharing as long as $(NPV^{CL}_{j} – NPV^{0}_{j}) > PVC^{CL}/m$ for users j=1,..,m.

The equal cost-sharing condition may not hold if, for example, aggregate benefits are disproportionately distributed across user groups. In our case, we expect that all users benefit from the project, but the average coastal user benefits more than the average inland user. An alternative approach that might be viewed as more fair would be to allocate costs of the project in proportion to the benefits received. In other words select the value θ to satisfy the following:

$$(17) \quad \theta(NPV^{CL}_{o} - NPV^{0}_{o}) + \theta(NPV^{CL}_{n} - NPV^{0}_{n}) = PVC^{CL}$$

$$\text{or } \theta = PVC^{CL}/(NPV^{CL}_{o} + NPV^{CL}_{n} - NPV^{0}_{o} - NPV^{0}_{n})$$

The inland farmer, for example, would be responsible for paying $\theta(NPV^{CL}_{n} – NPV^{0}_{n})$, a fraction of the project costs. Equation (17) is easily extended to allow for multiple users (j=1,…m) spread across the two groups. Although theoretically straightforward, proportional cost-sharing is more difficult to implement than equal cost-sharing because information about individual benefit and cost functions is required to calculate user-specific NPVs for the former. In the case of equal cost-sharing, it is sufficient to show that the user who benefits the least from the project benefits by more than his/her share of the cost.

3 Results and Discussion

The College Lake project is expected to provide 2,400 AFY of supplemental irrigation supply water that would otherwise flow into the ocean. The NPV calculation described in the previous section determines the value of the lake water in agricultural production. However, if the data required to solve the entire dynamic optimization problem is not available, net revenue from production using lake water as an input provides an estimate of benefits. Aggregated over time and discounted, those benefits are compared to PVC^{CL} as a rough way to approximate the component of the NPV related directly to coastal farmers; the effect of reducing the pumping externality for inland farmers is not included. We also estimate some indirect costs and discuss ecological benefits.

3.1 Benefits of College Lake Water for Coastal Farmers

For illustration, we suppose initially that the water is used for irrigation of strawberries, a crop grown throughout inland and coastal Pajaro Valley; a similar calculation could be made for any other type of crop (as shown in Table 1). 7,068 acres in Pajaro Valley were used for growing strawberries in 2009, and 13,338 AF of water were applied that year, which amounts to 2.36 AF of water per acre of strawberries, after adjusting for an acreage factor that accounts for the fact that only a fraction of the surface area of each farm is used for crop production (Lin et al., 2013). Assuming 2,400 AFY from College Lake, the benefit in terms of farm production is calculated as

(18) 2,400 AFY ÷ 2.36 AFY/acre = 1,017 acres of strawberries

We can think about the benefit of the lake water as the avoided loss of not irrigating 1,017 acres of strawberries if SWI were to occur along the coast. Because water is a necessary input to food production, i.e. one could not substitute more labor or capital for water beyond a threshold, the net revenue for farm production could be viewed as an approximation of the benefit, provided that there are no alternative feasible water supply options available to meet the projected basin shortfall. A recent report by the Monterey County Agricultural Commissioner (2012) estimated a total value for the 11,537 acres of strawberries produced in the county of $784.8 million. Assuming that production efficiency is similar across farmers, the value of strawberries is approximately $68,000 per acre. Multiplying by the total acres that could be irrigated using the College Lake water gives an estimate of total benefit:

(19) $784.8 million ÷ 11,537 acres × 1,017 acres = $69.2 million per year

The value presented in (19) is the gross revenue or benefit, which does not account for costs to farmers. After adjusting for labor and capital costs, the net profit is estimated as lying somewhere between $40,417 and $40,500 per acre (Lin et al., 2013). Assuming a net profit of $40,500, the adjusted benefit (net of farm production costs) is

(20) $40,500/acre × 1,017 acres = $41.2 million per year

We also calculate the benefits for two other crop-mix scenarios. It is apparent from the results in Table 1 that the benefit of the lake water will depend on the particular end use. For example, even though leaf lettuce requires more water on a per-acre basis than strawberries, the benefit or avoided loss for lettuce growers is smaller because the value of crop produced per acre with that water is smaller.

Table 1. Benefits of College Lake water for coastal growers

Crops	Water Required (AF/acre)*	Acres Supported	Per-acre Crop Value ($/acre)**	Gross Benefits (M$/year)	Farmer Costs ($/acre/year)*	Net Benefits (M$/year)
100% strawberries	2.36	1016.95	68,025	69.2	27,500	**41.2**
50% strawberries	2.36	508.47	68,025	34.6	27,500	20.6
50% nurseries	4.21	285.04	205,852	58.7	75,500	37.2
					Sub-total:	**57.8**
33% strawberries	2.36	338.98	68,025	23.1	27,500	13.7
33% nurseries	4.21	190.02	205,852	39.1	75,500	24.8
33% leaf lettuce	2.67	299.63	9,870	3.0	6,000	1.2

Sub-total:	**39.7**

*Source: Lin et al. (2013)
**Source: Monterey County Agricultural Commissioner (2012)

3.2 Direct Costs of the College Lake Project

The project will include construction of a new adjustable weir structure to increase total storage capacity of the lake to 272 acres, a new pump station, a filtration plant with disinfection, and 5.8 miles of new water main to connect the different pieces to the coastal distribution system. The total capital cost is estimated at \$31.5 million. Given a projected annual operations and maintenance cost of \$340,000, the annualized cost is roughly \$2.6 million, assuming 30-year capital recovery and a 6% interest rate (RCDSC-CBEC, 2014):

$$(21) \qquad \frac{\$31{,}500{,}000}{\left[1-\frac{1}{(1+0.06)^{30}}\right]/0.06} + \$340{,}000 = \$2{,}600{,}000$$

Subtracting the result of (21) from the sub-totals in the last column of Table 1 yields an annual net benefit ranging from \$37.1 to \$55.2 million before accounting for indirect costs and basin-wide benefits owing to reduced seawater intrusion. An equal cost-share plan would require that each of the approximately 850 agricultural well owners and 1,200 domestic well owners in the valley (PVWMA-CE, 2014) pay an additional \$1,268 annually to finance the project. An inland farmer should not object to the increase in cost as long as his/her PV benefit of preventing SWI exceeds the PV of the stream of annual \$1,268 payments. Given that pumpage varies greatly across existing wells, an alternative cost-sharing plan that may be viewed as more fair would be to allocate costs in proportion to some measure of historical use.

3.3 Indirect Costs of the College Lake Project to Lakebed Farmers

In the past, lake farmers planted as many as 320 acres of row crops in the dry lake bed after College Lake was drained every spring. More recently, that number has been estimated at closer to 20-24 acres in the Lake Bottom and about 70 acres on higher ground within the lake bed (RCDSC-CBEC, 2014). Because many types of crops can be planted along the lake's edges, crops can be planted earlier, allowing for more than one crop rotation; for those 70 acres, draining the lake later would not largely disrupt production. Because the updated College Lake management plan would delay draining until at least July in most years, the number of crop rotations at the bottom of the lake would be reduced (e.g. from 2 to 1). Given information about the types of crops planted and costs to lake farmers, one could calculate typical net profits under current management. If lake farming is scaled back, the lost net revenue should be calculated as a cost. For illustration, if the row crops include primarily head lettuce as detailed in the table above, then the total cost of losing two rotations of 20 acres at the lake bottom is

(22) ($9,870/acre - $6,000/acre) × (20 acres/rotation) × (2 rotations) = $154,800/year

3.4 Ecological Benefits and Costs of the College Lake Project

The current configuration and operation of the lake pumps impede migration of steelhead trout. The new pump and weir will provide a structure to facilitate upstream and downstream passage; the goal is to maintain or improve the existing level of upstream migration for spawning steelhead. Delaying the draining of the lake may also affect the habitat of various local and migrant bird species. Inundation beyond May could provide support for late migrants and resident summer fowl. But at the same time, vegetation needs to be maintained to ensure adequate food supply during the extended inundation period. If the management plan succeeds in at least maintaining the existing ecosystem function of College Lake, there should be no associated ecological benefits or costs. Implementation costs are included in the planning and construction costs.

4 Conclusions

Given the complexity of WEF systems, joint management of even two of the three components presents a formidable challenge. Decision-making can be further complicated when sustainable resource use is viewed as a desirable characteristic of long-run planning. Although centralized resource allocation is not always possible, planners are often faced with the challenge of choosing from a variety of candidate projects designed to augment existing resource use. Using a stylized model, we show that when resource use is open access, there may be little incentive to finance a project that could potentially increase benefits for all users. In the case of SWI, inland users may be better off with the project in the long-run under optimal management. But neighboring growers' open-access incentive to increase pumping at lower costs eliminates potential gains, leading to premature drawdown of the saved water. If growers can be incentivized to pump water (approximately) optimally, then an equal or proportional cost-sharing finance plan should not be blocked as long as the PV benefits of preventing SWI for each inland user exceeds his/her share of the PV project cost.

Using data for Pajaro Valley, we find that the planned College Lake diversion project (2,400 AFY) would generate approximate direct PV benefits in the range of $39.7-57.8 million. The annualized $2.6 million direct cost of the project suggests that an equal cost-share program would be feasible as long as the additional benefit of SWI prevention to each inland user is at least $1,268 per year. Alternatively, the cost could be distributed in proportion to expected benefits, which could be estimated using information on historical pumpage, i.e. high volume users would be responsible for a higher proportion of the annualized cost. A fixed lump sum fee for each user would create the least distortion if growers are already incentivized in some other way to pump at the social optimum. A volumetric surcharge would push pumping toward the optimum if users are overpumping but would distort incentives if water is already priced according to its scarcity value.

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