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Agricultural and Recreational Impacts from Surface Flow Changes Due to Gold Mining Operations

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Nevada ranks third in the world in gold production. In order to operate the massive open pit gold mines, the State of Nevada granted mining companies a temporary permit to pump groundwater from near the open pits and dispose of it. Certain instream flows have nearly doubled relative to average historical flows in recent years. Following pit closure, surface flows will likely decline from historical levels. This study measures the impacts of these changing water supplies on downstream agricultural and recreational users. We argue that the creation of temporary changes in water rights for the downstream users would likely mitigate future losses both groups are expected to experience.

Key words: discrete stochastic programming, mine dewatering, water resource economics

Introduction

Conflicts over control of natural resources have shaped the West. Gold mining activities generated some of the earliest property rights issues influencing Western resource law (Libecap). The scale of modern gold mining operations and the appropriateness of institutions established over 137 years ago to assign property rights associated with mining contribute to the ongoing debate about the role of precious metal mining in the changing landscape of the West.

Current gold mining technology in the Great Basin is based upon large open pit gold mines that may extend 800 feet below the water table and cover over 500 acres of surface area. Such technology requires enormous quantities of water to be discharged from the pits to allow mining to continue.[1] Initiating this "dewatering" process called for temporary groundwater rights to be granted by Nevada's State Water Engineer to gold mining companies in northern Nevada's Humboldt River Basin (HRB). The magnitude of dewatering poses significant externalities on other water users within the basin. For

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[1] The extraction technique often used in Nevada is known as "heap leaching" and requires removal of vast quantities of rock containing microscopic particles of gold that are later separated from the ore via a chemical (cyanide) leaching process.

a period of approximately 15 years, instream flows in the Humboldt River Basin will double due to water discharges from pit dewatering. Mines have been disposing of nearly a half million (445,000) acre-feet per year. Approximately 65% of this water is discharged into tributaries of the Humboldt River. This discharge would be worth approximately $223 million if valued at $500 per acre-foot, the current price paid by the U.S. Fish and Wildlife Service to purchase water rights from farmers in a nearby irrigation district (Ise and Sunding).[2] Although rapid approval was granted to gold mining companies for temporary claims to discharged groundwater, lack of institutional flexibility may limit the ability of downstream users to enjoy temporary gains from the increased flows during gold mining activities. Similarly, downstream users may lose during the post-mining period as massive quantities of water are diverted to fill the abandoned open pits.

Most analyses of Western water use explore allocation of scarce supplies among competing users (Colby; Keplinger et al.; Willis and Whittlesey 1998a, b). The problem investigated here results from institutional water rights rigidities when historical flows within a watershed are temporarily changed due to upstream actions. The objective of this research is to quantify gains and losses resulting from gold mining operations to downstream agricultural and recreational water users. Programming techniques combine both agricultural and recreational users to measure expected impacts under current water rights agreements, as well as when downstream rights are temporarily modified in response to flow changes resulting from the gold mining operations.

Background on Nevada Water Allocation

Under a comprehensive water act passed by the Nevada legislature in 1913, all potential appropriators must make an application to the Office of the State Engineer for a permit [Nevada Revised Statutes (N.R.S.), ch. 48]. Federal laws, including interstate agreements and water rights given to Native Americans, are considerations in granting permits, in addition to the primary criterion that the water will be put to a beneficial use (Bingham and Gould). Groundwater in Nevada is still largely unadjudicated, but Nevada water law has been interpreted such that the groundwater near the mines belongs to the "people" of Nevada, making the State Engineer the trustee for this resource (Bingham and Gould). The mines' temporary water rights were not similarly matched with temporary water rights being given to downstream irrigators, generating at least a temporary disequilibrium in water rights institutions that have been in place for most of the 20th century.

Although surface water supplies in the basin increase during dewatering, downstream farmers operate under water rights firmly established over 70 years ago. Maximum application of irrigation water is set by the local irrigation district.[3] We hypothesize that these constraints limit the potential benefits farmers could gain from the temporary

[2] In their 1998 analysis, Ise and Sunding focus on the Truckee-Carson Rivers' Newlands Project, which is approximately 50 miles from our study area. The $500 price per acre-foot paid by the U.S. Fish and Wildlife Service reflects permanent transfer of the water from agriculture to the federal government, and may not be completely reflective of general market (within agriculture) transactions. However, as the mining operations may affect water allocation for more than 100 years, we use this estimate of sales value rather than a short-term rental market value.

[3] The board of directors of the irrigation district has the power to establish bylaws, rules, and regulations for the distribution and use of water in the district, under the 1913 Nevada Irrigation District Act (N.R.S. 539.233).

increase in flows. Benefits still do accrue to the irrigators because of the reduced probability of extremely low flows during droughts. However, these benefits are most properly considered as externalities since property rights are not granted to downstream users. We explore whether additional benefits could be realized if water rights were adjusted to allow temporary access to the increased water supplies.

Existing water storage facilities and distribution channels in the HRB were originally developed to service agricultural producers near the river's terminus. Most agricultural producers are members of the Pershing County Water Conservation District (PCWCD) located near the town of Lovelock, Nevada. The PCWCD was formed in 1926 to consolidate water rights for farmers in the region. This effort was part of the Humboldt Project, involving creation of approximately 38,000 acres of irrigable farmland. The PCWCD claims that the necessary water rights to farm the 38,000 acres were acquired by negotiating a contract with the U.S. Bureau of Reclamation. The exact nature of this contract, however, seems a matter of dispute (McColm). Following withdrawals from Rye Patch Reservoir, which is about 25 miles upstream of Lovelock, water not diverted into the PCWCD canals disappears into the ground a short distance downstream into an area known as the Humboldt Sink.[4]

Pumping of water from the pits will cease after the mines close. Though exact magnitudes have not been disclosed by the gold mines for competitive reasons, annual pumping costs are apparently substantial (Huszar, Netusil, and Shaw). It is virtually certain that no existing economic activity, including agricultural production, could warrant continued pumping and discharge of the water even if groundwater rights were transferred to downstream beneficiaries. It is expected that for a period of 100 years following mine closures, instream flows in the Humboldt River Basin will decrease as the gold mines cease pumping out the water and discharging to the river.[5] Net farm income is expected to decline in the future due to conversion to less water-intensive crops. Farm incomes are also expected to become more volatile as the probability of low flows increases, thus reducing crop production when supplies are inadequate to sustain irrigation during the growing period.

Recreational users at Rye Patch Reservoir represent the other significant group of downstream users currently affected by the northern Nevada mining operations. Conflicts have often arisen between recreational users and irrigators dependent on Rye Patch storage (see Huszar et al.). Annual visitation has averaged about 67,000 recreational visitors at Rye Patch State Park, the easiest access point to the reservoir. Visitor use increased an average of 6% annually between 1980 and 1996. The recreational value of Rye Patch is positively related to water levels in the reservoir (Huszar et al.).

Water levels at Rye Patch have generally been adequate to sustain the existing sport fishery, as well as other water-based recreational use of the reservoir. However, occasional shortages have temporarily diminished recreational values. For example, the 1992 draining of the reservoir to satisfy downstream PCWCD demands for irrigation

[4] The Humboldt Sink is the flat terminus area for the river, located just west of the town of Lovelock, which in turn is 90 miles from Reno, the largest city in northern Nevada. In wet years a shallow water pool in the sink may be visible, and in dry years no water may be seen at all. There is no active water-based recreation in the Humboldt Sink—with the possible exception of bird watching in some months. Highly variable flows make exporting any water remaining in wet years out of the basin a poor economic prospect.

[5] All estimates of instream flows during and after mining operations were derived from data provided in a 1997 report prepared by Hydrologic Consultants, Inc.

water killed millions of fish. Subsequent visitation at the reservoir declined during the post-draining period.

The 1992 fish kill may have been a violation of the public interest (Bingham and Gould; Huszar et al.).[6] Although complaints could have been filed with the State Engineer, the incident went unchallenged in Nevada. The fishery recovered in 1996, after much effort by the state fisheries agency. This incident highlights the rivalry between environmental groups favoring recreation interests and downstream farmers.

The impacts of flow increases during the dewatering period are uncertain. Increased reservoir volume may have a positive impact on recreational values. Conversely, increased water supplies could induce downstream irrigators to plant crops having higher water requirements. The impacts of reduced flows following mine closure are also uncertain. Water-based recreation values at Rye Patch may either increase or decrease depending upon downstream farmer planting decisions. A model capable of identifying costs and benefits to both user groups is thus necessary to determine the distributional impacts of the mining externalities.

In the section that follows, we describe a model developed to analyze impacts of changing flow rates on farm income in the PCWCD and recreational values associated with Rye Patch Reservoir. Farm income and recreational value changes are then examined based on both the current water rights held by farmers in the PCWCD, as well as potential gains if irrigators were allowed to benefit from the ephemeral increases in flow. A concluding section addresses the potential gains and losses to farmers and recreational users under a more flexible approach to water rights assuming temporary environmental changes.

The Model

A multiperiod discrete stochastic programming (DSP) model is developed to estimate the expected impacts of changes due to flow perturbations resulting from mine dewatering and subsequent filling of pit lakes.[7] The DSP model identifies a network of decision nodes linked over time. Each node is conditional upon past events and decisions. Given the state of nature existing at each node, decisions are made conditional upon expectations of future events. Past decisions can be modified, for example, by withholding water from low-value crops when intrayear water supplies are insufficient to irrigate all acres planted in the spring.

We assume that releases from Rye Patch Reservoir are controlled by the PCWCD water manager, and therefore coincide with irrigation needs expressed by farmers. Planting decisions are based on expectations of water availability, as well as dynamic cropping considerations for the two perennial crops grown in the area—alfalfa hay and alfalfa grown for certified seed production. The model is thus driven by farmer planting decisions, which are in turn based on expectations of water supplies over the year. Final

[6] The PCWCD maintains that legal authority to control reservoir levels rests with the district water master, but the threat of implementation of a doctrine of public trust similar to that exercised by the State of California in the Mono Lake controversy may suggest that the State Engineer, or the U.S. Bureau of Reclamation, should more carefully manage Rye Patch's fishery (Loomis; Huszar et al.).

[7] The dynamic stochastic programming model is widely used. Recent applications include those by Featherstone, Baker, and Preckel; Lambert and McCarl; and Keplinger et al.

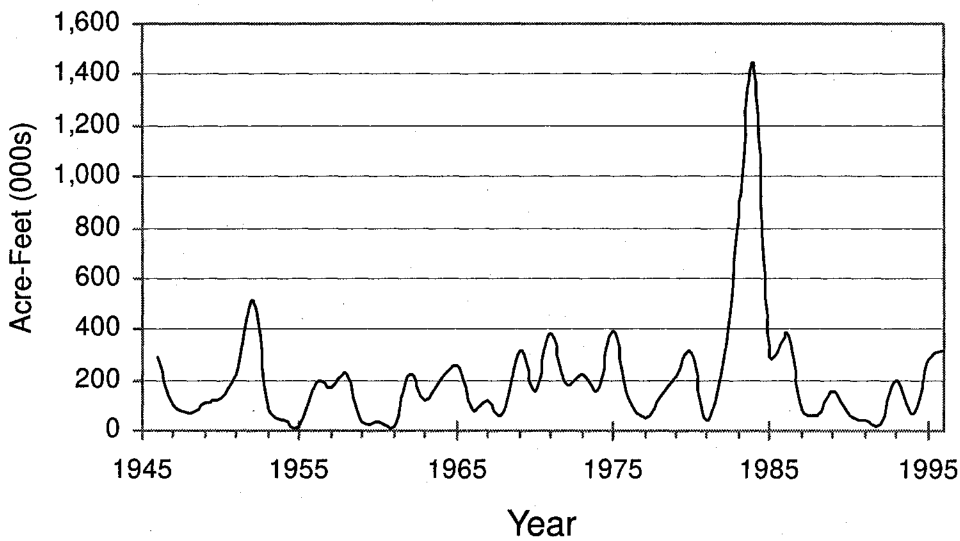

Figure 1. Historical annual flow (acre-feet) at the Humboldt River/Imlay gauging station, 1946–96

crop income is primarily a function of initial planting choices and water supplies actually experienced over the growing year.

Post-optimality analysis will determine the effects of alternative flow regimes upon recreational users' valuation of water-based activities at Rye Patch. In addition, the impacts of imposing a minimum volume of 3,000 acre-feet, suggested by officials of Nevada's Department of Wildlife (see Sevon), are derived to determine benefits to regional recreational users as well as costs on downstream irrigators.

The Regional Agricultural Sector Model

Summer high temperatures in this region often exceed 100°F. Average annual precipitation is only 6 inches, and the Humboldt River Basin experiences some of the highest evapotranspiration rates in the United States (State of Nevada, Department of Conservation and Natural Resources). Crop production in this semi-arid region depends upon irrigation. In addition to alfalfa hay and seed, wheat and barley may be grown, and minor amounts of grass hay are also produced. PCWCD water rights are sufficient for applying 3 acre-feet of water to the area's 37,504 irrigable acres in a normal water year. Average annual runoff of the Humboldt River is about 200,000 acre-feet (at the Imlay gauging station), but may vary between 5% and 370% of this average (figure 1). Estimates of annual evaporation from Rye Patch are in the range of 50 to 60 inches. Such annual flow fluctuations and evaporation rates illustrate the value to irrigators of water stored at Rye Patch.

Within-year temperature and water level variations are also important to growing crops. Crop water requirements are greatest in the summer months. Below-normal flows may result in inadequate water supplies to continue irrigating all planted acres. In this case, crop acres harvested may be less than planted acres. The DSP format allows incorporation of alternative future water conditions over the growing year, including inadequate supplies to grow all acres planted. Planting decisions will therefore reflect responses to the probabilities of low flows and subsequent loss of some planted acres. Either fewer acres may be planted, or crops may be planted that have lower water requirements.

The Regional Agricultural Sector and River Flows

To account for this within- and across-year variation, historical monthly flows into Rye Patch Reservoir serve as the basis for determining agricultural production plans under three alternative flow scenarios. Actual historical monthly flows from 1946–96 are used to estimate a time-series statistical model using quasi-likelihood methods (see Gourieroux, Monfort, and Trognon). Monthly flows are assumed to follow a gamma distribution, thus preventing predictions of negative flows. The results of this estimated model are:

$$(1)\quad \begin{aligned} E(Flow_t) = \exp\{ & \underset{(0.1842)}{1.1743} + \underset{(0.0481)}{0.9145}\ln(Flow_{t-1}+1) - \underset{(0.0467)}{0.1369}\ln(Flow_{t-2}+1) \\ & + \underset{(0.2375)}{0.7133}Jan + \underset{(0.1279)}{0.4211}Feb + \underset{(0.1562)}{0.8617}Mar + \underset{(0.1886)}{0.3527}Apr \\ & + \underset{(0.1943)}{0.0982}May + \underset{(0.1629)}{0.5259}Jun - \underset{(0.1643)}{0.2644}Jul - \underset{(0.1587)}{1.1563}Aug \\ & - \underset{(0.1460)}{0.9370}Sep + \underset{(0.2470)}{0.3425}Oct + \underset{(0.1824)}{0.0419}Nov\}, \end{aligned}$$

where the numbers in parentheses are White's robust standard errors.

Predicted flows from (1) form one of three states of nature in the programming model. Standard deviations of monthly flows were calculated using historical data. Predicted flows from (1) were then increased and decreased by one standard deviation to form two additional states of nature assumed for each branch of the decision problem. The DSP model yields a decision tree of the conditional states of nature over time. There are three states of nature (predicted, high, and low flows) in year 1. Each of these three first-year states resulted in three additional states (predicted, high, and low estimates, conditional upon year 1 state) in year 2. Consequently, nine (3^2) states existed in year 2. Each of these nine states resulted in three states in year 3, or 27 (3^3) states. Continuing this process yields 81 states in year 4 and, finally, 3^5 or 243 in year 5.

Monthly storage levels in Rye Patch Reservoir are determined dynamically from past storage and net changes from inflows and releases from the reservoir using the following:

$$(2)\qquad Volume_{mts} = Volume_{m-1,ts} + Flow_{mts} - Release_{mts},$$

where the subscripts represent month (m), year (t), and state of nature (s).[8]

[8] Given the conditional nature of the resolution of uncertainty in the DSP modeling approach, some simplification in notation is followed, as otherwise we must express all possible outcomes in each year. For example, by year 5 the full array of subscripts for s would involve 243 states or outcomes. For simplicity, we use s_1, s_2, s_3, s_4, and s_5 to denote each set of outcomes in years 1 through 5, respectively. Each of the 243 states of nature in year 5 are conditional upon the states occurring in year 4, which in turn depends upon year 3 outcomes, and so on. The single subscript s represents the current and previous (conditioning) states appropriate for year t.

We assume a constant proportions water production function for crops grown in the PCWCD. Thus, decreasing water supplies during the growing year may result in removing fields from production rather than inducing modifications in irrigation scheduling and subsequent yields such as modeled by Keplinger et al. Removal of fields is determined within the model by consideration of marginal value products of water applied to the different crops. Production activities in the PCWCD include crops traditionally grown in the area: alfalfa hay, alfalfa seed, wheat, barley, and grass hay. Total acres planted to crop c of age a in year t were bounded by the total number of irrigated acres in the district (*Irrland*):

$$(3) \qquad \sum_{c}\sum_{a} Plant_{cats} \leq Irrland \qquad \forall\, t \text{ and } s.$$

Characteristics of the harvested acres are determined by several sets of constraints. First, harvested acres cannot exceed acres planted to the different crops:

$$(4) \qquad Harvest_{cats} \leq Plant_{cats} \qquad \forall\, c, a, t, \text{ and } s.$$

Monthly (m) crop water requirements were derived from crop budget information compiled and made available by the Idaho Cooperative Extension Service:[9]

$$(5) \qquad \sum_{c}\sum_{a} Wateruse_{cam} Harvest_{cats} \leq Agwater_{mts} \qquad \forall\, t, s, \text{ and } m,$$

where *Wateruse* is the specific irrigation requirement for crop c of age a in month m. Annual water use was limited by the 3 acre-feet available for project lands over the production year, or

$$(6) \qquad \sum_{m} Agwater_{mts} \leq 3 \times Irrland \qquad \forall\, t \text{ and } s.$$

Total monthly water use is related to releases from Rye Patch Reservoir. Farmers' crop choices dictate monthly water requirements, which in turn generate storage and release decisions in the reservoir:

$$(7) \qquad Agwater_{mts} \leq \delta Release_{mts},$$

where δ is a loss coefficient between releases and actual field application of the irrigation water.[10]

Inter-year linkages are necessary to follow stands of advancing age of these perennial crops. The variable *Harvest* refers to actual harvested acres resulting from the state of nature dependent water supplies. Equation (8) limits acres of perennial crops of age 2 or greater to be no more than was left standing at the end of the previous year:

$$(8) \qquad Plant_{cats} \leq Harvest_{c,a-1,t-1,s} \qquad \forall\, t \geq 2, s, \text{ and } a \geq 2,$$

where crop (c) = alfalfa and seed. The model was constrained to limit reestablishment rates for the perennial crops:

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[9] Reliable production and crop budget information is unavailable in the state of Nevada. Therefore, crop budgets developed for southwestern Idaho were used, a region having similar agricultural characteristics to those existing in the PCWCD.

[10] A loss rate of 25% from upstream releases was assumed in the model. Exact rates of loss are unknown due to the variety of delivery systems in the district, but this percentage estimate is conservative.

(9) $$Plant_{c,a=1,ts} \leq Replant_c \sum_a Plant_{cats} \quad \forall\ t, s, \text{and } a,$$

where c = alfalfa and seed, and *Replant* = 0.25 for alfalfa hay and 0.33 for alfalfa seed.

A potential problem in mathematical programming formulations of agricultural management decisions comes from crop portfolios that represent corner solutions or, in some other way, do not accurately represent historical cropping patterns observed within a region. Several options exist for forcing decisions to positively reflect producer decisions (see Howitt; McCarl; El-Nazar and McCarl). We adopt activity analysis procedures similar to those recently used by Keplinger et al. Several historical cropping mixes are available as activities in the model. Optimal decisions are then formed as convex combinations of these available production activities. The following two constraints determine the optimal composite cropping pattern for each year in the model:

(10) $$\sum_a Plant_{cats} \leq \sum_{mix} \lambda_{mix,ts} Cropping_{c,mix} \quad \forall\ t, s, \text{and } c,$$

where $\lambda_{mix,ts}$ is the intensity variable of acres planted to cropping pattern *mix* in year t under state of nature s, and $Cropping_{c,mix}$ is the proportion of crop c included in cropping pattern *mix*. Further,

(11) $$\sum_c \sum_c Plant_{cats} \leq \sum_c \sum_{mix} \lambda_{mix,ts} Cropping_{c,mix} \quad \forall\ t \text{ and } s,$$

which determines total acreage planted in year t under s.

Net farm income (*NFI*) for farmers in the PCWCD equals per acre return to *Harvest* times acres harvested, minus planting and growing season costs conditional upon the *Plant* decisions. Explicit consideration of water use is determined by the cost of water applications on a per acre-foot basis:

(12) $$NFI_{ts} \leq \sum_c \sum_a \left(Returns_{ca} Harvest_{cats} - Costs_{ca} Plant_{cats}\right) - AppCost \sum_m Agwater_{mts}.$$

The values of growing crops at the end of the period are calculated as terminal values in the usual fashion:

(13) $$Terminal_s \leq \sum_c \sum_a F_{ca} Harvest_{cats},$$

where F_{ca} represents future discounted returns to crop c for the remaining years of its productive life.

Finally, the objective function for the DSP model maximizes the expected net present value (*NPV*) of returns:

(14) $$\text{Max } E(NPV) = \sum_{s1} \theta_{s1}\left(\frac{NFI_{1,s1}}{(1+r)} + \sum_{s2} \theta_{s2}\left(\frac{NFI_{2,s2|s1}}{(1+r)^2} + \sum_{s3} \theta_{s3}\left(\frac{NFI_{3,s3|s1,s2}}{(1+r)^3} + \sum_{s4} \theta_{s4}\left(\frac{NFI_{4,s4|s1,s2,s3}}{(1+r)^4} + \sum_{s5} \theta_{s5}\left(\frac{NFI_{5,s5|s1,s2,s3,s4} + Terminal_{s5|s1,s2,s3,s4}}{(1+r)^5}\right)\right)\right)\right)\right).$$

The conditional uncertainty of the model is illustrated by full use of subscripts in (14). Net farm income in year 2, for example, depends upon the state of nature that occurs in year 2 (s_2) conditional upon the preceding year's state (s_1). The probability of each state of nature occurring is represented by θ.

The Regional Recreation Sector

Primary water-based recreation in the Humboldt River Basin relates to use of Rye Patch Reservoir. Most visits to this 171,000 acre-feet capacity reservoir are water based, primarily fishing. Changes in Humboldt River flows due to upstream mining activities could potentially increase recreational use at the reservoir during dewatering. We expect this relationship to be true, as past data show that annual visitation is greater in higher than average water years (see Huszar et al.). Conversely, after cessation of mining activities, pit filling will decrease river flows for a period of up to 100 years. Decreased flow impacts are expected to be relatively small, but might increase the probability that irrigators will again drain Rye Patch under drought conditions.

Most past recreational demand studies focus on demand changes due to water quality or other environmental changes. Demographic changes and changes in water allocation infrastructure have generated recent research activity linking water quantity to water-based recreation demand (see, for example, Fadali and Shaw; Ward et al.; Loomis; Jakus, Dowell, and Murray; Eiswerth et al.).

Recreational demand at Rye Patch was estimated by Huszar et al. using county-level time-series data and a count data travel cost model of demand for trips to the site (see Hellerstein for a description of this modeling approach). Using county-level visitation data collected at the only (easily accessible) entry point for the reservoir over the period 1980–96, the following model was estimated by Huszar et al.:

$$(15) \qquad Trips_{ts} = \exp\Big(\underset{(0.335)}{5.8622} - \underset{(0.423)}{3.4427} Price + \underset{(0.018)}{0.0315} Awater_{ts} \Big),$$

where *Price* is travel cost to the reservoir based on county averages, and $Awater_{ts}$ is average water volume in the reservoir in year *t* under state *s*. Numbers in parentheses are White's robust standard errors.

The value (consumer's surplus) of the trips taken to Rye Patch Reservoir is derived from the predicted quantity of $Trips_{ts}$. Utilizing the Poisson specification underlying the demand equations, average (or "per trip") consumers' surplus can simply be calculated by $ACS_{ts} = Trips_{ts}/\gamma$, where γ is the coefficient on price in the estimated demand function. This is one of the attractive features of using the Poisson specification. Total consumers' surplus for each county can be obtained in an aggregate recreation model (again, see Hellerstein), and we extrapolate this county-level CS_{ts} to the state population in period *t*. Total consumers' surplus is then $TCS_{ts} = Population_t \times ACS_{ts}$.

Model Results

The DSP model is solved three times: once for the base case, once for the dewatering phase, and finally for the post-mine phase. The base case refers to model outcomes using stochastic flows based on historical observations at the Imlay gauging station (see figure 1).

Table 1. Mean Period Farm Income and Recreational Values ($ millions)

		Base Case		Dewatering Phase		Post-Mine Phase	
Year		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
1	Farm Income	4.918	2.317	7.498	0	4.992	2.358
	Recreation Value	3.55	0.063	3.55	0.056	3.55	0.064
2	Farm Income	5.391	0.489	5.498	0	5.347	0.611
	Recreation Value	3.70	0.063	3.66	0.054	3.70	0.066
3	Farm Income	5.623	0.403	5.736	0	5.568	0.397
	Recreation Value	3.76	0.053	3.68	0.043	3.76	0.055
4	Farm Income	5.661	0.293	5.638	0	5.623	0.381
	Recreation Value	3.83	0.045	3.79	0.047	3.83	0.045
5	Farm Income	5.677	0.209	5.690	0	5.639	0.233
	Recreation Value	3.95	0.101	3.92	0.059	3.95	0.101

The dewatering results reflect farmer decisions during the 1997–2011 period of maximum expected increases in the Humboldt River flows. The post-mining period results occur when flows are expected to fall between 3–4% from historical levels because of groundwater seeping back into the abandoned pits, thus reducing surface flows.

Table 1 reports the means and standard deviations of farm income and recreational values under each scenario. The expected net present value of farm income increases from $36,487,708 for historical flows to $39,316,575 under mine dewatering. Two significant changes underlie changes in farm incomes. First, as table 1 shows, each year's mean net farm income is expected to be higher during the dewatering period. This increase is especially pronounced in year 1, when mean net farm income is approximately 52% higher. The cause of the lower mean income under the base case illustrates the second change in farm income characteristics. Net farm incomes in the base case are approximately $6.6 million in states of nature 1 and 2 (the highest and middle instream flow scenarios). This income level is similar to those generated during dewatering. However, the low stream flows under the third state of nature produce abandonment of 41% of the district's four- and five-year-old alfalfa, as well as the loss of all acres planted to grass hay, wheat, and barley. Net farm income under this third state of nature in year 1 is only $1.6 million, causing the low mean and high standard deviation of incomes observed in year 1 in the base scenario. The zero standard deviation during mine dewatering reflects that water is no longer binding on cropping decisions. Cropping decisions during this period are limited by land and the 3-acre-foot water right.

Mine dewatering increases the shadow price of land in the PCWCD. First-year impacts of the increased water supplies result in the expected shadow price of land being $192, nearly five times the value under historical flows. Additional water supplies, assuming continuation of the 3-acre-foot water right, could permit bringing additional acres under irrigation in the district. The $192 shadow value reflects the expected value of additional income generated under a one-acre expansion of irrigated acres. Mine dewatering eliminates the possibility of inadequate flows to meet irrigation needs on the current 37,504 acres. Consequently, water supplies would be sufficient to expand irrigated acres.

Similar behavior underlies the shadow values of water rights under the different flow scenarios. In both the base case and the mine dewatering period, the marginal value of water rights is similar in those states of nature in which water supplies are adequate to irrigate and harvest all planted acres. Additional water rights would add approximately \$25–45 per acre-foot to *E(NPV)*. However, the 3-acre-foot constraint is not binding under low flow years in the base case (as well as under low flow states in the post-mine period). In cases where the constraint is not binding, the shadow value of the water right is zero. Conversely, positive marginal values occur under all states of nature in the mine dewatering phase. During these years, irrigation supplies are adequate to irrigate all acres under all states of nature. Additional temporary water rights under the mine dewatering period would allow producers to plant higher valued crops and take advantage of these transitory flow increases.

Table 1 also shows that recreational values are always smaller than the farm income for each scenario. The agricultural sector gains most of the benefits during the dewatering phase. In fact, the model predicts a smaller total value in the regional recreation sector during mine dewatering.

Mean visitor use at Rye Patch State Park drops slightly under the mine dewatering period. Flows into the reservoir increase due to dewatering, but mean reservoir volumes fall slightly as farmers plant more water-intensive crops and irrigate throughout the season. Larger releases are necessary to meet the greater irrigation demands. However, the standard deviation of the surplus associated with recreational use at Rye Patch decreases under dewatering. Storage levels are more uniform across states of nature during the mine dewatering period. Mean storage volumes decrease, but probabilities of a resource crash associated with reservoir draining are greatly reduced.

The Impact of Pit Lake Filling

Farmers and ranchers operating near the mine pits are concerned about the direct effects of changes in surface and subsurface water flows when the mining operations cease pumping and the pits fill with water. Because the exact relationship between pumping and the volume and shape of the area's aquifers is not known, it would be difficult to predict the economic impacts associated with the pit lakes filling in the mine areas. However, we can estimate downstream impacts from pit lake filling.

The expected net present value of the five-year model is \$36,257,833, a reduction of about \$230,000 (0.6%) from the base case. Each year's expected net farm income is similar to the incomes expected under the historical flows. However, the reduced flows under the post-mine period result in more states of nature in which irrigation supplies are inadequate to fully irrigate all planted acres through the growing season. There is also a larger variation across states of nature in planted acres under the post-mine flow scenario. As expected, farmers' planting decisions are sensitive to the probability distribution of expected irrigation supplies during the growing season.

Resource values are also expected to fall for farmers in the PCWCD when the mines close. Land values, as reflected in mean land shadow prices, are lower than under the base case in three of the five years of the model. Because there is an increased probability of receiving less than the full 3 acre-feet of irrigation water for all 37,504 acres of the district, the shadow price of the 3-acre-foot water right constraint is slightly reduced from the base case.

Maintenance of a Minimum Pool Volume in Rye Patch Reservoir

Prevention of the collapse of the sport fishery in Rye Patch Reservoir requires maintenance of a minimum pool volume of 3,000 acre-feet (Sevon). The DSP model was solved again with this volume constraint. Results were obtained for the current dewatering period, as well as the impact of the minimum volume constraint following mine closure.

There are no farm income impacts of this minimum pool constraint during the dewatering period. Instream flows are adequate due to the mine discharges to maintain the same optimal cropping mixture when no volume constraint is imposed. Impacts of the volume constraint are received solely as benefits to visitors to Rye Patch State Park. The expected consumer surplus of visitor use increases an average of $1,823 each year. The lowest increase in expected consumer surplus is $1,225 in year 2, and the greatest increase is $2,320 in year 3.

Imposition of the minimum pool constraint does change farm incomes during pit lake formation following mine closures. Maintaining a minimum 3,000 acre-feet of water in Rye Patch reduces annual net farm incomes by an average of $27,743 over the five years. Expected net present value over the five-year period falls $200,773 from the $36,257,833 expected with no minimum pool constraint. Increases in expected consumer surplus at Rye Patch State Park are similar to the increases expected under mine dewatering. The average increase is $847 per year, ranging from an increase of $222 in year 2 to $2,213 in year 5.

Relaxation of the 3-Acre-Foot Water Right Limit

A major objective of this study has been to quantify the cost to downstream users of rigidities in water rights institutions that prevent their ability to take advantage of the increased instream flows resulting from mine dewatering. Consequently, the 3-acre-foot water right limit was relaxed. During mine dewatering, relaxation of this limit increases the expected net present value of the five-year model by $1,035,288, to $40,351,841. Average water use over all states of nature is 3.112 acre-feet applied per acre. It is probable that more water could have been used profitably had constraints not been imposed to match historical cropping mixtures (constraints 10 and 11). The two lower valued crops, wheat and barley, were planted beyond rotational requirements because of the crop mix constraints.

The potential benefits of increasing agricultural water rights to the increased flows resulting from mine dewatering are illustrated by increases in the shadow prices of irrigated land. Significant increases in land shadow prices have already been mentioned. However, these shadow prices increased even more when farmers were able to utilize the increased flows by relaxing the 3-acre-foot constraint. Holding irrigated land constant at 37,504 acres, the potential gain of additional water rights during mine dewatering increases land values to an average of $215 per acre.

Summary and Conclusions

This study addresses an interesting resource allocation problem. For a period of about 15 years, typical instream flows in one of the driest watersheds in the United States are temporarily doubled due to ephemeral water rights granted to several large gold mining companies operating near the headwaters of the Humboldt River in northern Nevada. Although groundwater rights were quickly granted to the gold mines, subsequent downstream user rights were not adjusted to allow full enjoyment of the externality. Even with no increases in downstream user rights, agricultural producers and recreational users benefit by the reduction in flow volatility. However, economic benefits of securing agricultural rights in the increased flows are approximately $1 million in net present value of returns over the five years modeled. The shadow price of land increases approximately $100, reflecting conversion to higher valued, more water-intensive cropping patterns.

The potential for increasing recreational values also exists under the mine dewatering phase with additional institutional changes. Specifically, Nevada wildlife officials maintain that a 3,000 acre-foot minimum volume should be established to avoid loss of the sport fishery at Rye Patch Reservoir. Imposition of this requirement has no impact on agricultural irrigation values during the mine dewatering phase. Annual visitor values increase an average of $1,823 during dewatering with the minimum volume constraint.

New water rights claimants argue for changing the structure of rights established under earlier social and economic environments, but fundamental changes have generally evolved slowly in the West, often getting bogged down in litigation. In contrast to this often slow development, we have analyzed a rapid and significant shock in the structure of water rights which came about when the Nevada State Engineer granted temporary rights for groundwater extraction and disposal to gold mining corporations. A complete accounting of the economic and environmental impacts of such action in this arid state may not be known for decades.

We add a final word of caution about our results. While southern Nevada is very rapidly growing and contains the vast majority of the state's population, northern Nevada is very sparsely populated; Southern area residents do not visit the north, and recreational resources such as Rye Patch Reservoir are thus not widely used. Consider a traditional benefit-cost analysis where the benefits of an activity such as gold mining are pitted against the costs of concern to environmental interests. In any situation such as this, the benefits as calculated from producers' surplus estimates (i.e., those linked to profits from gold sales) are almost certain to dominate the environmental costs because the total economic damages measured in human terms will be small in the aggregate. This is simply because there are not many users over which to aggregate. Our analysis has not considered the benefits of environmental protection to nonusers, and we have attempted to consider future populations only in the simplest fashion. We would therefore caution against using our estimated dollar values in the broader context of comparing the benefits from gold mining to the costs of water-resource impacts.

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