

Past and Future Water Conflicts in the Upper Klamath Basin:
An Economic Appraisal

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Abstract

The water conflict in the Upper Klamath Basin typifies the growing competition between agricultural and environmental water uses. In 2001, drought conditions triggered Endangered Species Act-related requirements that curtailed irrigation diversions to the Klamath Reclamation Project, costing irrigators tens of millions of dollars. Although this event has significantly elevated the perceived risk of future economic catastrophe in the basin (and therefore the level of conflict among water users), several key changes related to water availability have occurred since 2001. These changes include reduced ESA requirements and increased groundwater pumping capacity, which have lowered the actual risk and severity of future water shortages. In this paper, we use a mathematical programming model to evaluate how these changes alter the likelihood and economic consequences of future shortages. We also consider the effect of more flexible transfers among irrigators via water markets. Our analysis indicates that future drought conditions like those seen in 2001 would have more modest economic impacts than in 2001, and that when combined with contingent groundwater supplementation and water transfer mechanisms such as water markets, both the likelihood and magnitude of economic losses among irrigators would be greatly reduced.

1. INTRODUCTION

In many parts of the western United States, conflicts over water have increased due to population growth as well as competition between agricultural uses and environmental demands including protection of critical habitat. One such situation is the Upper Klamath Basin on the Oregon-California border, which gained national prominence in 2001 and 2002. In 2001, drought conditions led to severe restrictions on irrigation diversions to the Bureau of Reclamation (hereafter “Reclamation”) Project in response to Endangered Species Act (ESA)-related requirements for minimum instream flows and lake levels deemed – at that time – to be necessary to provide critical habitat for three endangered fish species. That curtailment of irrigation diversions to over 100,000 acres of farmland is estimated to have cost irrigators between \$27 and \$46 million (Oregon State University and University of California, 2002).

In the following year, partly in response to the 2001 events, less restrictive ESA flow and lake level rules were applied, allowing irrigators to divert more water. In September of that year, however, tens of thousands of Chinook salmon (*Oncorhynchus tshawytscha*) and coho salmon (*Oncorhynchus kisutch*) died in the lower portion of the Klamath River due to parasite blooms. An analysis by the California Department of Fish and Game (CADFG 2003) conclude that the parasite bloom was an indirect result of low flows in the Klamath River which contributed to high water temperatures, triggering the parasites.

Both these events have heightened concern about water conflicts and controversies in the region. These conflicts occur in the driest summer months when water needs are crucial for both fish and farmers, but when limited summer precipitation, restricted surface water storage, and the existing groundwater pumping capacity are insufficient to meet both demands. Proposed

solutions for this problem have included both demand management (e.g., permanent or temporary land idling, more efficient irrigation infrastructure), as well as supply augmentation (e.g., increased surface water storage, improvements in groundwater management). Since 2001 some improvements have occurred, including additional wells that have expanded groundwater-pumping capacity considerably. Reclamation has also financed a variety of demand management and supply enhancement activities including land idling and groundwater supplementation to provide greater supply certainty in the basin – as mandated by the 2002 National Oceanographic and Atmospheric Administration (NOAA) Biological Opinion (BO).

In this paper, we examine the potential effects of changes in circumstances in the Upper Klamath Basin, and evaluate how they may alter both the likelihood and impact of future water shortages. In particular we evaluate a) the effect of current, less restrictive ESA requirements (compared to 2001), b) the additional capacity of groundwater pumping that now exists for supplementation during drought, and c) the possibility of more extensive water transfers that may be possible in the future via water markets or water banks. Other potential solutions have been proposed to ease water conflicts in the Basin, including additional surface water storage, reduced agricultural use through increased irrigation efficiency, importation of water from adjacent basins, or lowering ESA requirements. These options, however, are beyond the scope of the current study.

In the case of groundwater, we consider the potential of conjunctive use to alleviate water supply shortfalls in drought years. In the case of water markets, we revisit a question explored by Jaeger (2004) and Burke et al. (2004) on the economic benefits of water markets during shortage situations in the basin. Jaeger's analysis, however, is based on a single-period model reflecting average annual economic and hydrological parameters, whereas the current analysis is based on a

model that is much more temporally and spatially disaggregated. With these existing, or potential, changes in groundwater availability and market flexibility in mind, we ask whether economic impacts similar to those of 2001 are likely in future years.

We evaluate these questions with a linear programming (LP) optimization model constructed to represent the opportunities and constraints facing irrigators and managers in the Upper Klamath Basin. The model is based on economic, agronomic and hydrologic data including spatial Geographic Information System (GIS) information; it reflects farmer behavior by maximizing net farm revenues within the bounds of the institutional and physical constraints imposed. The model is calibrated to reflect conditions and constraints in 2001 as a base case, and then modified some parameters to reflect policy and technical changes that have occurred since 2001. We also allow for water reallocation among irrigators in ways that have not been possible in the past, but may be possible in the future with a water bank or water market.

Our results indicate that the dire economic consequences of the situation in 2001 were caused by an unprecedented combination of factors including: a) extremely low water inflows, b) extremely high ESA in-stream flow and lake level requirements, c) limited capacity to supplement surface water irrigation with groundwater, and d) the absence of water transfer mechanisms such as water markets. Given the easing of ESA requirements as of 2006 compared to 2001, and with increased groundwater pumping capacity, we find that – especially if water markets were available – the kinds of severe economic drought impacts seen in 2001 could be largely alleviated.

These observations are made in the context of ongoing negotiations over the future of water in the Klamath. Beginning in 2004 a group of 26 government, agricultural, tribal, energy, and environmental stakeholder groups have been meeting to negotiate a comprehensive

settlement agreement to the longstanding water disputes involving water diversions, fisheries, agricultural communities, and removal of four PacifiCorp dams near the Oregon-California border. Among the most contentious aspects of the negotiation are the removal of the four dams to allow fish passage, fulfilling tribal treaty rights, and reducing the threat of curtailed water withdrawals for irrigators and their agricultural communities.

2. PRIOR RESEARCH

Although the physical characteristics of water and the structure of western water rights under the prior appropriations doctrine have limited the extent of market allocation, economists have noted the advantages and potential efficiency gains from more flexible market system for decades (Vaux and Howitt, 1984; Howe et al., 1986; Easter et al., 1998). The introduction of market mechanisms to achieve efficiency when allocating between consumptive use and instream flow has also been examined (e.g., Griffin and Hsu, 1993; Murphy et al. 2008). In environments of fully committed water resources (such as in the Colorado basin and Southern California), water markets have been shown to effectively reallocate water between competing users (Bjornlund 2003). Studies have also been conducted demonstrating institutional constraints present in Reclamation projects (Moore and Negri 1992) and on the efficiency gains to both irrigators and taxpayers from transfers of Reclamation-subsidized water to both project and non-project users (Wahl 1989). In the presence of minimum environmental flow requirements, Willis and Whittlesey (1998) demonstrate that water markets can be a cost-effective policy.

The potential in the Upper Klamath Basin for improved water allocation with market mechanisms to mitigate the costs to farmers when environmental uses conflict with irrigation diversions has also been examined. In one prior study involving the entire Upper Klamath Basin, Jaeger (2004) concluded that if the necessary institutions and infrastructure had been available in 2001 voluntary water trading between and among Project and non-Project irrigators could have reduced the economic cost of the 2001 irrigation curtailment by \$25 million, or 75%. This striking result is attributed to the large differences in soil productivity between highly productive Project lands and the relatively less productive non-project lands, giving rise to a 10-fold difference in the marginal value of irrigation water. In another study focused exclusively on the Klamath Project areas, Burke et al. (2004) concluded that a water bank could improve allocative efficiency within the Klamath Reclamation Project, although within-Project benefits from trade were modest compared to those found by Jaeger when lands outside the Project are included. Burke et al. also notes, however, the implementation challenges for water trading due to conflicting jurisdictions and the incomplete adjudication of water rights in the Oregon portion of the Upper Basin.

Indeed, in the absence of fully adjudicated water rights, prospects for market solutions remain tentative, and the potential for increased reliance on groundwater remains unclear. Increased institutional flexibility that makes mutually beneficial transfers between water users of varied economic and geographic circumstances is understood to reduce costs and uncertainty (Vaux 1986); and although Jaeger (2004) found that water trading led to substantial benefits in the basin under 2001 conditions, the potential of trading under a broader range of expected hydrological and institutional conditions in the basin has not been explored – especially with regard to intra-seasonal constraints. In the case of groundwater, uncertainty remains about the

quantity of water physically available for monthly pumping and the sensitivity of the economic system to its provision (McFarland, et al. 2005).

3. STUDY AREA AND BACKGROUND

3.1 Study Area

The Upper Klamath Basin straddles the Oregon-California border just east of the Cascade Mountains (see Map 1). It includes all of the area that drains into the Klamath River above Iron Gate Dam, which is located in California just south of the Oregon border. The area covers 5.1 million acres, and is entirely contained within Klamath County in Oregon and Siskiyou and Modoc Counties in California. Elevations in the basin range from 4,000 to 9,000 feet above sea level. Lying in the rain shadow of the Cascades, the region is categorized by cold, moderately wet winters and hot, dry summers (Cho 1996).

The basin contains a national park, a national monument, two national forests and six wildlife refuges. Irrigators, commercial and recreational fishing interests, Native American tribes, threatened and endangered species, and six federal wildlife refuges compete for water in the basin. The area's wetlands are an essential stopping point for migratory waterfowl passing along the Pacific Flyway of the West Coast (Burke 2001). The basin contains the largest population of bald eagles in the U.S. outside of Alaska, and its hydrological contributions to Klamath River flows help to maintain populations of steelhead (*Oncorhynchus mykiss*), Chinook salmon, and coho salmon. The basin lakes also support two endangered species of fish: the Lost River sucker (*Deltistes luxatus*) and shortnose sucker (*Chasmistes brevirostris*).

The Williamson, Wood, and Sprague Rivers flow through irrigated agriculture (northern basin areas) and into Upper Klamath Lake. From there water enters the project through a

complex system of canals. The Lost River (so-called because it is a self-contained basin) flows from Clear and Gerber Lakes into the Lost basin areas, and then through the project where it is augmented by Klamath River water, and then flows into the California portion of the project and to the two national wildlife refuges. Excess water flowing out of the refuges (in some years) is then pumped west into the Klamath River, which flows past Keno Dam, and finally Iron Gate Dam.

Central to the Basin's agricultural economy are the approximately 400,000 acres of irrigated land that generates about \$30 million in net farm income annually. About half of the irrigated land in the basin is pasture, 20% is alfalfa, 15% cereal grains including barley and wheat, and 5% is other hay. The most profitable crops per acre are grown on relatively small areas, including potatoes, onions and peppermint. About 190,000 acres of the total irrigated land is contained within the federal Reclamation Project. Non-irrigated agriculture in the region is dominated by livestock production. Crop and livestock gross sales in Klamath County exceeded \$220 million in 2007.

FIGURE 1 here

3.2 Water Situation Background

In 1988, the U.S. Fish and Wildlife Service (FWS) listed the local Klamath populations of Lost River and shortnose suckers as endangered species, and subsequently produced a BO mandating minimum Upper Klamath Lake levels in 1992. The coho salmon, whose local habitat extends from the Pacific Ocean to Iron Gate Dam (at the southern terminus of the study area), was listed in 1997 and a BO was submitted in 1999 requiring minimum monthly flows at Iron Gate Dam. In 2001, new BOs for the suckers and coho were issued, increasing both lake level

and flow requirements in the basin (Hathaway and Welch, 2003). Under the provisions of the ESA (Section 7), federal agencies whose operations may affect an endangered or threatened species within its habitat must proactively work toward species recovery (Endangered Species Act 1973). In the Klamath basin, this makes Reclamation responsible for meeting both monthly lake levels and flow requirements. Following the severe curtailment of irrigation in 2001, Reclamation has relied on several incentive-based approaches to meet ESA required levels, including land idling and groundwater pumping.

Groundwater is an important component of the basin's hydrological system. It provides steady inflows to the major streams in the basin, and tends to spread the effects of annual variations in climatic conditions over multiple years. Thus, a dry year such as 2001 decreases groundwater recharge to the surface-water system over multiple years (Risley et al. 2005a). An extremely wet year, on the other hand, would have the opposite effect. Typically, groundwater levels have fallen during multi-year dry periods, but have recovered completely during subsequent wet periods. Groundwater pumping in the basin outside the project area in the 2000 water year was approximately 150,000 acre-feet (Gannett et al. 2007). Reclamation water payments have provided further incentives for pumping, resulting in roughly 56,000 and 76,000 acre-feet of additional pumping in 2003 and 2004, which is a 37 and 51 percent increase, respectively, in groundwater pumping over 2000 levels (McFarland, et al. 2005). In 1998, the USGS and Oregon Water Resources Department (OWRD) initiated a study of the groundwater dynamics that, when completed, will contribute to our understanding of groundwater and surface water interactions and sustainable rates of groundwater pumping (M. Gannett, 2007).

Between 2002 and 2006, FWS and NOAA established much lower lake level and flow requirements that eased the burden on irrigators compared to 2001. Following a federal court

ruling in 2005, somewhat higher requirements were established, but at levels significantly lower than in 2001. At about the same time irrigators faced rising energy prices due to the expiration of a 50-year power contract under which they paid electricity rates less than one-tenth those paid by irrigators in other areas. The power rates, which significantly affect the cost of using sprinkler irrigation, began a phased increase in 2006 that is expected to result in as much as a 10-fold increase over six years. These increases in energy rates are estimated to produce only small effects on acres cultivated (2 percent), but could reduce net farm revenue by one-third (Boehlert 2006). These results are sensitive, however, to assumptions about farmers' ability to switch from energy-intensive sprinkler irrigation to flood irrigation (more below). The combined, uncertain effects of these changes created great anxiety among irrigators in the basin, both about the economic viability of irrigated agriculture and also how future water shortages would affect them under policy rules that differed from those existing in 2001.

Given the changes that have taken place or are evolving in the region since 2001, many questions arise about future water management, the risk of repeating a crisis like the one in 2001, and tools currently available to reduce the potential economic costs of future water shortages. To address some of these questions, we have constructed a mathematical programming model that characterizes key elements of the economic and hydrological systems in the Upper Klamath basin. With this model, we are able to characterize a broad range of conditions based on historical data, and simulate likely outcomes for those conditions under alternate policies and conditions. The three main sets of model modifications we explore involve varying assumptions or constraints on: a) ESA streamflow and lake level requirements, b) groundwater pumping, and c) water allocation mechanisms such as water markets. In the next section we describe the data used to construct the model.

4. DATA

The portions of the basin where irrigated agriculture occurs can be divided into 14 areas in Klamath County, Oregon, and two areas in Siskiyou and Modoc Counties in California, based on information provided in the Certified Farm Use Study from the Klamath County Assessor. The Farm Use Study includes information on sub-basins and irrigation district boundaries in the basin, as well as acreage and economic data by soil capability class (from class II (high quality) to class V (low quality)), and typical crop rotations for each soil class-farm use area combinations. The geographic boundaries of the farm use areas were defined based on data provided by the Assessor and the California Department of Water Resources (CDWR).

These data were incorporated into a GIS geodatabase, which produced 43 unique “soil units” across the basin; each of these was further disaggregated by irrigation technology (i.e., flood or sprinkler) based on GIS data compiled by the Natural Resources Conservation Service (NRCS). In total, the basin was divided into 78 “irrigation units”, each representing a specific soil class (and associated crop rotation), irrigation technology, and location within a specific farm use area.

The cropping patterns and rotations chosen by farmers for specific lands in the basin are determined mainly by the soil and climate. Soil capability classes within each area provide a reliable predictor of the crop rotation choices a farmer will make. The water consumption of an acre of agricultural land is, in turn, dependent upon the crops planted. Depending on elevation and latitude within the basin, the growing season may vary from 50 to 120 days (Burke 2001). In the colder, higher elevation regions north of Upper Klamath Lake, the primary crops include

alfalfa, hay and pasture, whereas in the eastern and western projects south of Upper Klamath Lake, potatoes, mint, sugar beets, horseradish, onions and barley are more prevalent.

Evapotranspiration estimates for each of these crops in each month between March and October were gathered from the Reclamation Agrimet system—which is comprised of a network of automated climate-data gathering stations spread throughout the U.S.—for the years 1999 to 2005. To estimate the quantity of water consumed annually on a representative acre of each of the 78 irrigation units, monthly evapotranspiration values for each crop are multiplied by the share of each crop in the representative crop rotation and summed over the irrigation season. Note that although the irrigation efficiency (IE, defined as crop evapotranspiration/applied water) of sprinkler systems is generally higher than for flood irrigation, given the relatively low volume of water lost to deep percolation in most areas of the basin (due to hydrogeological separation of deep and shallow groundwater systems) the majority of excess water applied tends to return to streams and canals either for reuse by other irrigators or ultimately to the Klamath River (Burke 2001). These two technologies are therefore assumed to have the same net evapotranspiration from any given acre. Each of the systems has different capital costs, and variable costs, however, which are incorporated into the economic modeling. Of the 112,321 acres in the upper basins, only 11,923 are sprinkler-irrigated (10.6 percent) and the remaining 89.4 percent are flood-irrigated. In the Lost Basin and project, on the other hand, 58.6 percent of the 211,489 acres are sprinkler-irrigated.

The economic component of our model is intended to reflect the choices made by farmers when allocating land, labor, water, capital and other inputs in order to maximize profits for a given set of physical, technological and economic opportunities and constraints. Our approach takes advantage of the detailed data assembled allowing us to characterize the key economic and

technical parameters for each acre of irrigable land, and to disaggregate water use and constraints on a monthly basis. These data enable us to estimate the economic gains/losses when irrigating/idling each acre of land, or for selecting flood versus sprinkler irrigation, or when pumping groundwater.

Profits or net revenue for each acre's activity options are estimated based on farmland market prices. Applying the theory of Ricardian rents we assume that the purchase price of farmland reflects the discounted future stream of expected net revenues from putting the land to its highest value use. In the Klamath basin these market values vary widely across soil capability classes because of their agricultural productivity and economic potential. Land value data were available from county assessor offices in Klamath, Modoc and Siskiyou Counties. Per acre land values ranged from \$250 on soil class V lands in the Williamson Valley to \$2600 for soil class II lands in several Project areas, or a ten-fold increase from lowest to highest value land. The annual net revenue can be determined from these market prices, assuming a constant stream of profits in perpetuity, by multiplying the land price by the discount rate. The annual agricultural profits (or rents) therefore, are simply the land value multiplied by the current discount rate. The range of these profits is from \$15 to \$156 per acre per year within the basin. Incorporating per acre evapotranspiration estimates, the range of average marginal water values we estimate is from \$9 per acre-foot on class V soils to \$105 per acre-foot on class II soils, which compares favorably to those estimated in a hedonic price analysis in nearby Malheur County, Oregon, which range from \$32 to \$105 per acre foot for class V to II soils (Faux and Perry 1999).

These marginal values represent the potential profit from irrigating a particular acre of land within a given soil unit. However, to estimate losses when irrigation water is withheld, a more detailed accounting of revenues and costs is required. When land is idled (left un-irrigated) in the

short run, the farmer loses the revenue from that land, but also avoids the variable costs associated with cultivation. Fixed costs remain, however. These losses can be estimated by computing crop revenues minus variable costs, or equivalently, net revenues plus fixed costs. The latter approach is taken here, combining net revenue estimates from the Ricardian approach with fixed cost estimates from crop enterprise budgets for the area (compiled by the Oregon State University Extension Service). We assume that idling of land will occur with equal probability for each year during a specified crop rotation. (e.g., year zero to five of a five-year alfalfa rotation). This ignores the possibility that farmers may be able to adjust rotations to minimize losses during a year when land must be idled. This simplification in the model may overstate the costs of withholding water in some cases. Other simplifications in the model may lead to understated costs. For example, labor is implicitly assumed to find other employment when land is idling.

The model divides the surface water system into three components: the northern sub-basins, the Lost River sub-basin, and the Reclamation Project (divided into Oregon and California project areas). The project can receive water from either of the other two, but the Lost and northern sub-basins are only allowed to receive water from sources contained within their boundaries. Figure 2 displays the organization of sub-basins in the Upper Klamath Basin. The Williamson, Wood, and Sprague Rivers flow through irrigated agriculture (northern sub-basins) and into Upper Klamath Lake, which delivers water to the project and to the Klamath River. The Lost River flows from Clear and Gerber Lakes, which delivers water to the Lost River sub-basin areas. The Lost River flows through the project, is augmented by Klamath River water, and then flows into the California portion of the project and to the wildlife refuges. Water flowing out of

the refuges is then pumped back up along the Klamath Strait Drain and into the Klamath River, which flows past Keno Dam, and finally Iron Gate Dam.

FIGURE 2 here

Water enters the basin through precipitation and subsurface inflow. Although the magnitude of subsurface inflow is unknown, it is likely very small (Gannett et al. 2007). Precipitation varies widely across the basin, from a long-term average of 12 to 14 inches annually at Klamath Falls to approximately 65 inches at Crater Lake (Rykbost and Todd 2003). Snowfall in the higher elevations within the basin accumulates during the winter months and provides snowmelt inflows during late spring and summer after rainfall has often stopped providing flows.

The northern sub-basins above Upper Klamath Lake comprise the Wood, Williamson and Sprague river drainages. Each of these channels water from the higher elevations in the northern portions of the basin through agricultural fields and into Upper Klamath Lake. The area of Upper Klamath Lake ranges from 60,000 to 90,000 acres depending on lake levels, and has an average depth of eight feet. It is the primary water storage reservoir in the basin, but its shallow depth makes storage of significant excess water between seasons infeasible.

Irrigation season inflow data are derived primarily from Reclamation's "Modsum" spreadsheet of hydrological data for the basin, which has data spanning the period from 1961 to 2005 for inflows to Upper Klamath Lake, Clear Lake, Gerber Reservoir, and accretions between Keno and Iron Gate Dam (see Figure 2 for spatial orientation). Reclamation calculated these inflows by summing the monthly volumetric changes in lake level with outflow volumes and

lake evaporation. Seasonal inflows varied widely over the 1961 to 2005 period, from roughly 450,000 acre-feet (1992) to over 1.8 million acre-feet (1983).

Potential unaccounted sources of inflow include inflows to the basin through springs, groundwater and other streams, and outflows through deep percolation, evapotranspiration from non-crop vegetation and evaporation from standing surface water. In the model, these were accounted for by including an estimate of unaccounted inflows – which could be either positive or negative – to compensate for differences between total annual basin inflows and outflow from Iron Gate Dam in Reclamation’s historical data. Note that these unaccounted inflows capture all measurement error in the system, which may not be random. For a detailed investigation of these measurement errors, see Burt and Freeman (2003).

Lakes in the basin serve an important role in intra-seasonal storage and transfers of water between sub-basins. We therefore model the water balance and short-term storage at short time steps. The model includes monthly water stocks and flows, with lake volumes estimated as a function of lake levels based on data from Reclamation for Upper Klamath Lake, Gerber Reservoir, and Clear Lake.

A number of institutional constraints on water allocation are also included in the model. Lake level requirements imposed by FWS to promote recovery of the Lost River and shortnose suckers involve four different “year types” defined based upon historic April through September inflows to Upper Klamath Lake. Annually, the year-type is determined at the beginning of each irrigation season based upon inflows projected by the NRCS: lower estimated inflows result in lower lake level requirements (see FWS 2002). Clear Lake and Gerber Reservoir each have a single minimum lake level requirement for the entire irrigation season.

In addition to minimum lake level requirements, NOAA requires minimum stream flows at Iron Gate Dam for recovery of the coho salmon in the Klamath River. In the case of instream flows, NOAA has designated five “year types” also based upon the historic patterns of seasonal inflows to Upper Klamath Lake. These year types include: wet, above average, average, below average and dry. Lower expected inflows to Upper Klamath Lake result in lower Iron Gate Dam flow requirements.

The differences in ESA water requirements are illustrated in Figure 3, which indicates total monthly requirements in 2001 and post-2006. The ESA requirement each month are the total monthly flow volume required at Iron Gate Dam (i.e., cubic feet per second requirements are converted to acre-feet per month), plus the volume needed to achieve changes in the Upper Klamath Lake level requirements from one month to the next (i.e., if higher lake levels are required in April than in March, the increased storage volume is captured in the April total

FIGURE 3 here

5. THE MATHEMATICAL MODEL

Our analysis is based on a linear programming (LP) mathematical model that integrates models of the hydrology of the upper basin with the economics of its agricultural system.

LP models are optimization models that find the maximum (or minimum) value of an objective function subject to a set of linear constraints. They have been widely used in agriculture and other fields, including being extensively used in water resource planning and management (see Hadley 1962; or Baumol 1977 for method details).

In our model, net farm revenue (or profits) is maximized subject to physical, hydrologic, agronomic, technical, economic and institutional constraints. The model links a sequence of

irrigation seasons (from March to October), which are hydrologically interconnected by groundwater and lake levels. The model uses historical data from 1962 to 2002 from Reclamation to provide a representative set of potential future water conditions in the basin. Multiple versions of the model are constructed to represent alternative policy interventions or other kinds of situations such as ESA requirements, groundwater availability, water market opportunities, or energy prices.

The farm-level activities included in our model are characterized as fixed coefficient, Leontief, production functions. This linear programming (LP) approach assumes a given crop rotation activity for each acre of land, based on observed behavior tied to the soil and climate conditions. The agricultural components of the model are thus calibrated at the parcel level: crops choices and rotations are constrained to those observed for each irrigation district and soil capability class. With the water availability parameters calibrated as discussed above, and with economic and other technical parameters reflecting multi-year and long-term averages, these constraints produced model results consistent with observed levels of crop production, water use and farm income in the region.

This approach has advantages in the Upper Klamath Basin because of the availability of detailed and highly disaggregated information on soils and production choice for each acre of irrigated land in the basin. Other modeling approaches such as non-linear mathematical models based on econometrically-estimated production functions would have advantages over our approach if the required data were available, but no data are available in the region from which to estimate, for example, elasticities of substitution among factors of production including water.

Hybrid approaches such as positive mathematical programming (PMP; Howitt 1995a, 1995b) have been used when production function estimates are unavailable (see, for example,

Burke et al. 2004 for an application to the Klamath Project). However, a PMP approach relies on adding calibration constraints to an LP model, as a substitute when structural model specifications and validation are unavailable (Henry de Frahan et al. 2007), and this can limit the reliability of the approach (Heckelei and Wolff, 2003). The LP model alternative is to include farmers' choices among technologies explicitly as separate activities rather than devising an implicit representation in continuous form. Given the importance in the Klamath context of modeling intra-seasonal water requirements and water allocations under alternative ESA policies that vary month-by-month, non-linear or positive mathematical programming methods would be extremely difficult to construct with existing data.

LP models have been used previously in the Upper Klamath Basin. Jaeger (2004) used an LP model to estimate the potential benefits of water markets in the basin. Adams and Cho (1998) apply an LP model along with hydrological and yield models to assess the impacts of various Upper Klamath Lake level restrictions on the Klamath Project, and Burke et al. (2004) use a hybrid model incorporating elements of an LP model into a positive mathematical programming approach to evaluate the potential benefits of Klamath Project water banks to provide water for environmental purposes.

The current model extends significantly beyond this prior work in several important ways. First, in contrast to Jaeger (2004) which is based on a single-period, aggregate model, the spatial and temporal resolution of the data on which the current model is based makes it possible, for example, to evaluate water scarcity intra-seasonally, to distinguish energy costs between sprinkler and flood irrigation, and to limit irrigation technology choices based on topography. The characteristics of each acre of irrigable land are based on GIS information about location, soil capability class, slope, crop rotation, and profits. And by replicating a sequence of

hydrological conditions for a historical 41-year period, outcomes for wide range of year-types under various institutional and economic constraints can be evaluated. Second, other economic studies of irrigation in the Klamath Basin evaluate only the Federal Project rather than all of the irrigated lands in the Upper Basin. Project acres represent less than half of the Basin's irrigated acreage, and the variability in the productivity of lands is much greater between Project and non-Project areas than within the Project. These productivity differences due primarily to soil class are especially important when estimating the potential gains from water banks or markets.

Several computer programs can be used to solve mathematical programming optimization models, including Generalized Algebraic Modeling System (GAMS), which was used in this analysis (see Brooke, et al. 1998). In addition, GIS (ArcView) software was used extensively to generate descriptive components of the model based on several spatial datasets (e.g., acreage, soil class, irrigation type, elevation and slope). Key parameters in the LP model were computed based on a spatial Geographic Information System (GIS)-based model of hydrologic, agronomic and economic data. The following sections describe details of our model, including the objective function, constraints, and alternative institutional conditions introduced for alternative scenarios.

5.1 Farm profits

Our economic model includes estimates of farm profits (or losses) for each acre of potentially irrigable land in the basin. These are based on estimates of revenues and costs for the pertinent crop rotations as well as the costs associated with production of these crops. Average profits over the course of a typical rotation can thus be defined as:

$$\pi_{ij} = \sum_n (p_n y_{ijn} - v_n - f_n) s_{ijn} \quad (1)$$

where p = price, y = yield, s = share of each crop in the rotation (fraction of years cultivated over total years in rotation), v = variable costs and f = fixed costs, and where their values differ across farm use areas (i), soil classes (j), and crops (n) in a given rotation. If a specific parcel of land is not irrigated, the farmer will still incur fixed costs.

As explained briefly above, profits are estimated on the basis of Ricardian rents (see Conradie and Hoag 2004 for a more detailed explanation) where land prices reflect the present value of expected net revenues or;

$$P = \sum_{t=1}^{\infty} \pi (1+r)^{-t} \quad (2)$$

Where P is the market price for land, t is the year, and r is the discount rate. For an infinite time in which π is assumed constant each year, this expression reduces to $P = \pi/r$ so that $\pi = Pr$. Expected profits are based on market data, which are assumed to reflect expected revenues and costs, whereas fixed costs data are based on relevant crop enterprise budgets for the basin. If irrigation is curtailed in the short term, then irrigators will forego their expected profit from irrigating, π , but will continue to incur fixed costs, denoted as $F_{ij} = \sum_n f_n s_{ijn}$. As a result, profit when not irrigating will be $-F_{ij}$, rather than zero.

Profits on idled land can be greater than $-F_{ij}$, however, due to subirrigation. In many parts of the basin where the water table is near the surface for some or all of the growing season, idled or non-irrigated land will still support some plant growth due to sub-irrigation from groundwater. On any given acre, sub-irrigation provides from an average of 1.04 acre-feet in the Wood River

and Williamson River areas, to 1.5 acre-feet in the Sprague River area, to 2.25 acre-feet for the Project and Lost Basin (see Boehlert [2006] for more detail). This can result in a significant increase in productivity on idled lands. To account for this productivity gain, we estimate a parameter α_{ij} as the amount of sub-irrigation divided by the crop evapotranspiration requirements in acre-feet per acre. Using this coefficient, the estimated net revenues on idled acres is $\alpha_{ij}\pi_{ij} - (1 - \alpha_{ij})F_{ij}$, so that for $\alpha=1$ (i.e., crops receive all needed water through subirrigation), net revenues are unaffected and remain at π_{ij} , and where $\alpha=0$ (i.e., crops receive no water through subirrigation), net revenues are $-F_{ij}$, as above.

Our objective function can thus be written as

$$\Pi_t = \text{MAX} \sum_i \sum_j \sum_k \pi_{ij} a_{ijkt}^I + [\alpha_{ij}\pi_{ij} - (1 - \alpha_{ij})F_{ij}] a_{ijkt}^C - \psi e_{it}^I \sum G_{amt} \quad (3)$$

where Π is basin-wide net revenues from irrigated agriculture, and irrigation technology includes flood ($k=1$) and sprinkler ($k=2$), so that total net revenues are summed across irrigated acres, a_{ij}^I , losses summed across curtailed or idled acres, a_{ij}^C , and where added energy costs, e_{it} (energy requirements for irrigation technology I at price ψ), accrue to groundwater pumping G_{amt} (for more details, see Boehlert [2006]).

The term $\pi_{ij} a_{ijkt}^I$ represents the profits accruing to all flood and sprinkler acres across all i, j , and k defined areas, soil classes, and irrigation technologies (flood or sprinkler). Each of the agricultural acreages defined by a particular i, j , and k are assumed to have homogeneous crop rotation and thus similar evapotranspiration characteristics.

5.2 Constraints

The model's constraints include the physical, technical and institutional constraints that limit profits for irrigation in the area. Irrigable land is limited annually by existing water rights; water is limited in the model monthly by inflows and other sources.

All land with irrigation water rights in each farm use area will either be irrigated or idled, and this is reflected in the following constraints:

$$\sum a_{ijkt}^I \leq A_{ijk} \quad (4)$$

and

$$\sum a_{ijkt}^I + a_{ijkt}^C = A_{ijk} \quad (5)$$

The overall water balance in the basin each year is given by equating the monthly amount of water evapotranspired by agriculture to the monthly system inflows less the water accounted for by changes in lake levels less the outflow through Iron Gate Dam plus groundwater inputs, or for any year, t (see Figure 2 above). System inflows, N , and groundwater pumping, G , are specific to each land use area: northern sub-basins, Lost River sub-basin, and the Reclamation Project. Inflows, which are described above, are based on historical gauge data gathered upstream of the lakes and irrigated areas, and are therefore exogenous to the model.

Algebraically, water balance is constrained as:

$$\sum_i \sum_j \sum_k a_{ijkt}^I \varepsilon_{ijm}^I + a_{ijkt}^C \varepsilon_{ijm}^C \leq \sum_a N_{amt} - \sum_q L_{qmt} - D_{mt} + \sum_a G_{amt} \quad (6)$$

where

L Lake storage: subscript q for Upper Klamath Lake, Clear Lakes, or Gerber Reservoir.

a, m, t	Subscripts for land use area (northern sub-basins, Lost River sub-basin, or Reclamation Project), month (March to October), and year
N	Inflow to each area, in each month and year
D	Outflow at Iron Gate Dam in each month and year
G	Groundwater pumping in each land use area and month
ε_{ijm}^I	Evapotranspiration for irrigated land by farm use area, soil class, and month
ε_{ijm}^C	Evapotranspiration for idled land by farm use area, soil class, and month

If the right hand side of the constraint above is less than the agricultural water requirements for all lands, in any given month, the profits will be limited by maximum water availability. If water is sufficient for these water requirements in all months, then profits will be limited only by the water rights appertaining to irrigable land.

As modeled, annual inflows to the system, in addition to the precipitation and snowmelt captured and released by Upper Klamath Lake, Clear Lake, Gerber Reservoir, come in the form of groundwater accretions between Keno and Iron Gate Dams. These exogenous inflows are monthly and yearly historical data from Reclamation intended to replicate historical conditions. Lake water use is dependent upon whether lake levels increase or decrease any given month, and is institutionally constrained by FWS requirements. Minimum Iron Gate Dam flow is constrained by NOAA requirements, and groundwater pumping is constrained by maximum rates, which are allowed to vary in a sensitivity analysis. In addition to the overall basin water balance, we impose constraints that restrict the water use in each land use area (i.e., upper basins, Lost River basin, and the project) to less than the sum of the total inflows plus groundwater inputs in that portion of the basin. One of the inflows to the project is surplus water from the upper basins and Lost River basin.

Lake level constraints maintain a minimum equal to those required by the USFWS for Upper Klamath Lake, Gerber Reservoir, and Clear Lake, and a maximum of the lake's capacity. Monthly flows in or out of each lake correspond to changes in lake level. These flows represent a critical choice variable for irrigation district managers to distribute water over the course of the season through short-term storage in these reservoirs. Monthly changes in lake levels are explicitly limited to historical maxima. Although this creates a binding constraint and therefore limits the model's flexibility in finding optimum solutions, absent such a constraint, monthly variations in water level would be unrealistically high. Monthly diversions from each lake are limited to available water, and outflows at Iron Gate Dam are constrained by NOAA flow requirements for each month and year type. In addition, using separate constraints, changes in Iron Gate Dam flow from month-to-month are constrained by historic maximum increases and decreases.

Absent hydrological or institutional restrictions on groundwater pumping within the model, water availability would not be a binding constraint because, as the model is constructed, an unlimited amount of groundwater could be pumped to meet any surface water deficits at any location in the basin. With the phase-in of higher energy prices, however, the cost of groundwater pumping could add \$6 to \$28 per acre for pumping lifts in the range of 10 to 50 feet. Although it is uncertain how much groundwater could be sustainably pumped in a given year, it is clear that groundwater pumping affects surface water availability in the basin (Risley et al. 2005a). Accordingly, we assume that certain institutionally imposed maximum pumping levels will occur in the future. Based on discussions with the USGS and given the response of the groundwater system to recent water bank pumping, we pattern this institutional limit based on pumping volumes observed in 2004. Given that the total amount of additional groundwater

pumping in the basin that year was approximately 20,000 acre-feet during the summer months (a total of 80,000 acre-feet was pumped over the year), our base case model assumes a 20,000 acre-feet limit each month. These constraints are distributed spatially throughout the basin to reflect the dispersed locations of both pumps and groundwater resources. The Upper and Lost basins are allowed 5,000 acre-feet per month, and the Project is allowed 10,000 acre-feet per month, for a total of 160,000 acre-feet for the system annually. We evaluate the sensitivity of the model to this constraint by considering a scenario – discussed in greater depth below – where 320,000 acre-feet are available annually (i.e., 20,000 acre-feet per month in the Project and 10,000 acre-feet per month in each of the Upper and Lost basins).

6. MODEL RESULTS

The model described above is used here to simulate agricultural outcomes for a range of alternative sets of assumptions and constraints. For each version of the model representing different institutional and policy scenarios, the model is solved for a series of hydrological conditions based on those observed from 1962 to 2002. From this we can report average outcomes for alternative scenarios as well as the distribution of outcomes for the sample of hydrological conditions.

This sequence of simulations is repeated for two policy settings involving ESA lake level and flow requirements (2001 requirements versus post-2006 requirements). Our first objective is to evaluate how these different environmental flows affect farm profits under conditions like those observed between 1962 and 2002. Our second objective is to vary the amount of groundwater that is allowed to be pumped and to evaluate how this constraint affects farm profits. Our third objective is to evaluate the impact of water trading on farm profits. We

compare the model's results when water allocation is allowed maximum flexibility to alternative results that concentrate water curtailment within the federal Reclamation Project – as was the case in 2001.

We are especially interested in looking at the ways in which the results for each of these different considerations interact with each other: How does the change in ESA requirements affect the cost of limited groundwater pumping? How beneficial are water markets for a situation like 2001, versus likely future situations? How do the costs of the 2001 events compare with likely future costs in light of the differences that exist now, or could be present in the future (e.g., the possibility of voluntary water transfers between and within land use areas? Groundwater availability is assumed to take two levels, zero groundwater use and the levels indicated above. Water trading flexibility is assumed to be zero, or fully flexible. These trading scenarios are achieved by simply allowing water to be allocated to its highest value use, with limits only on inter-basin transfers that are physically infeasible. The “no trade” scenario is achieved by introducing a priority structure in the objective function that replicates the priority structure observed in 2001. Within each priority area, water is allocated in equal proportions across soil classes.

When all 324,000 surface-water irrigated acres in the basin are irrigated, total profits are estimated at \$20.7 million. Under 2001 hydrological and institutional conditions, the losses (reductions in profits compared to the \$20.7 million) are estimated at \$19.8 million (a 96 percent reduction of net revenues). These estimates of losses in 2001 differ from Jaeger's (2004) estimate of \$35 million for three reasons: 1) that greater flexibility is built into the current model, allowing the model to reach higher levels of profits than in Jaeger's replication of 2001 conditions including the partial gains due to subirrigation; 2) more land (and idled land) is

included in Jaeger's model (roughly 420,000 acres versus 320,000 acres); and 3) we calibrate total outflows and inflows for 2001 (generating a slack variable), which may not result in a water deficit equal to that implicit in Jaeger's land restrictions.

In the following discussion, we evaluate how these modeled 2001 losses respond in the presence of less stringent ESA requirements, greater groundwater availability, and flexible water markets. In addition, we report losses in more typical years, which we define as all years except the five driest between 1962 and 2002: 1981, 1991, 1992, 1994, and 2001.

6.1 Changes in ESA Requirements

The exceptionally low flows in 2001 were coupled with exceptionally high ESA requirements. How different might the water shortage of 2001 look if the ESA requirements had been instead those that were in effect after 2006? As indicated in Figure 3 (above), between the higher early season Iron Gate Dam flow requirements and the late season Upper Klamath Lake level requirements, ESA demands in 2001 were approximately 222,000 acre-feet higher between April and September than post-2006 requirements. This differential corresponds to enough water to irrigate roughly 100,000 acres. The economic impact of these differences in ESA requirements are estimated with a version of our model constrained to reflect 2001 conditions (no water trading and no additional groundwater). Figure 4 indicates how modeled net revenues varied for inflows observed between 1962 and 2002. Note that under the 2001 and post-2006 ESA requirements, the majority of years give rise to losses less than \$6 million in net revenue (30 percent). Shifting from 2001 to post-2006 requirements moves seven additional years into this category.

FIGURE 4 here

6.2 Energy prices

Following the end of a 50 year contract that secured very low energy prices to irrigators for pumping water, a 10-fold increase in energy prices began to be gradually phased-in over a seven year period beginning in 2006. This change will have a significant effect on the profits and land values of irrigators and landowners in the basin, and on the choice of flood irrigation versus sprinkler irrigation (per acre-foot, sprinkler irrigation consumes approximately 15 times more energy than flood irrigation). However, given the assumption that sprinkler-irrigated areas can convert to flood irrigation if their slopes are sufficiently low, our modeling results suggest marginal effects on acreages irrigated. Model scenarios reflecting these higher energy prices indicate that profits decline by \$6.7 million, or about one-third of total profits. At the same time, however, irrigated land is reduced by only 2 percent, or 6,200 acres. Farm profits were significantly affected for many areas, especially those using sprinkler irrigation and unable to switch to flood irrigation due to the slope of their land. These reduced profits can be expected to be capitalized into land prices and land lease rates, but will have much smaller effects on production decisions.

6.3 Groundwater

Our next query asks how increased groundwater pumping capacity since 2001 could have altered past shortages, and how it may affect future shortages. Although nearly 70,000 acre-feet of groundwater were pumped during the 2001 season to supplement surface water flows, much of it was later in the irrigation season after the majority of economic losses had been incurred (McFarland et al. 2005). Present pumping capacity allows between approximately 20,000 to

40,000 acre-feet to be pumped per month, adding to a theoretical capacity of 160,000 to 320,000 acre-feet for the season. Had this pumping capacity been in place early in the season in 2001, Reclamation might have been able to adjust the anticipated water availability for the season and thus allow the majority of acres to remain in production. We use the model to address how additional the additional pumping capacity available today would have affected farm losses observed in 2001.

The model allows a limited monthly amount of groundwater that can be pumped. We recognized that zero additional groundwater is unrealistically low, but we considered this scenario in order to represent how the system would respond in the absence of any additional pumping. It is also unrealistically high to assume that 40,000 acre-feet could be pumped each month, as the necessary hourly pumping rate over that month would require a pumping infrastructure likely not available in the near future. For perspective, during 2001, a small number of 6700 gallon per minute (gpm) groundwater wells were drilled along the Oregon-California border. To sustain 20,000 acre-feet of groundwater pumping per month, roughly 23 of these 6700 gpm wells would need to be operable throughout the basin.

It is unlikely that 40,000 acre-feet per month could be maintained without declines in aquifer levels and impacts on springs. Indeed, the USGS indicated that 2003 and 2004 water bank pumping had both acute impacts such as the dewatering of shallow wells and longer-term impacts (i.e., over multiple years) on regional groundwater levels. Although long-term increases in pumping would eventually result in a new dynamic groundwater equilibrium (i.e., a lower level that is maintained over time), the increase in pumping may result in decreased discharge to surface water systems (MacFarland et al. 2005). Note that pumping rates have been high in

recent years largely to meet Reclamation water bank requirements; absent these annual water bank requirements, pumping would be reduced considerably in wet years.

We assume therefore that a maximum of 20,000 acre-feet of groundwater can be pumped each month (or a total of 160,000 acre-feet per year). Under post-2006 ESA requirements, this amount of groundwater would have reduced 2001 losses from \$18.2 million to \$12.8 million. The model predicts that for conditions observed between 1962 and 2002, an average of only 15,000 acre-feet would be used during 36 of the 41 years. During the remaining five years, an average of roughly 110,000 acre-feet of water would be used annually (the 160,000 acre-foot constraint was binding in 1992 and 1994 only). As noted above, there is currently a significant level of existing pumping capacity. The merits of constructing additional pumping capacity to meet excess demands during drought years would involve comparing the cost of additional pumping capacity to the expected reduction in losses each year. The fixed cost to install each large diameter is about \$265,000. When the costs of 11 such wells (to provide 10,000 acre-feet of monthly capacity) are annualized at a 4 percent discount rate including depreciation, the annual cost is estimated to be approximately \$250,000. With current pumping capacity sufficient for supplementation in most of the year-types based on historical data, it would be difficult to justify this level of additional annual cost for infrequent use (e.g., one year in 10 or 20). However, to the extent that climate change has increased the frequency of very dry years, such an investment could be a reasonable insurance strategy.

Higher energy prices will make the economics of occasional supplemental groundwater pumping less attractive if wells cannot be located where water is available at shallow depths. For every 100 feet of lift, energy price increases could add \$56 per acre to the cost of irrigation. Since supplemental irrigation can be understood to make it possible to irrigate marginal lands

that currently generate about \$56 per acre in net revenues, the variable costs alone for pumping from these wells would bring net revenues for these lands down to zero or negative values.

Although groundwater pumping may exceed sustainable levels in dry years (Gannett et al. 2007), natural recharge in wet years may be sufficient to sustain aquifer levels. If not, groundwater systems could be recharged more rapidly through effective conjunctive use following dry years where aquifers were heavily taxed. Such approaches may include installing groundwater injection wells, constructing recharge basins, or converting groundwater-irrigated acres to surface water during wet years.

6.4 Water Markets

Now we turn to the question of water markets as a way to mitigate the costs of water scarcity among irrigators. What effect would water trading have on the losses associated with these different scenarios? We replicate alternative scenarios under conditions with and without water trading. These simulations are intended to provide an assessment of what might occur as a result of a water market (since 2001 Reclamation has engaged in water acquisition and water supply enhancement activities aimed at maintaining environmental flows. These “water bank” efforts involved contracts whereby Reclamation paid irrigators to idle land or pump groundwater).

We evaluate the gains from flexible water trading by allowing the model to move available water to more valuable uses within the physical constraints (e.g., irrigating potatoes in the project instead of pasture in the Upper Basins). Our findings suggest that although the absolute gains from trading depend heavily on the scenarios and parameters specified, these gains are fairly consistent on a relative basis. Allowing trading under 2001 basin inflows and post-2006 ESA requirements is estimated to reduce losses from \$18.2 million to \$8.5 million (53

percent). Under the same conditions but provided 20,000 acre-feet per month of groundwater pumping, trading reduces losses from \$12.4 million to \$4.7 million (62 percent). Jaeger (2004) estimates a gain from water trading of 75 percent. Generally speaking, if little or no water is available in the system, gains from trade are limited by the amount of water that is available to trade. As additional water becomes available through lower ESA requirements and increased groundwater pumping, more beneficial trades are possible. It also follows, however, that further reductions in environmental flow requirements coupled with increased groundwater pumping should, at some level, also lower the potential gains from trade with water markets: when water is abundant there would be few potential buyers.

As a related question, we investigate how trading occurs spatially across the basin. Not surprisingly, we find that water is transferred from acres in the Upper Basins, which generally grow lower value, higher water consumption crops (e.g., pasture, alfalfa), to acres in the Reclamation project where higher value and lower water crops are grown (e.g., potatoes).

These results for the gains from water markets assume essentially ‘frictionless’ market transactions that move water to its highest value use. In reality water markets involve significant planning, coordination and transaction costs that will reduce both the level of transactions and the net benefits achieved. The benefits estimates here, however, are large enough that the inclusion of transaction costs in the analysis would be unlikely to reverse the conclusion that significant gains from trade are possible. Indeed, in the scenario for 2001, the reduction in losses of \$9.7 million, even if representing transfers of 300,000 acre-feet of water, would represent an average gain from trade of \$32 per acre-foot of transferred water.

Table 1 summarizes these observations. Our model estimates that \$19.8 million—or 96 percent of the \$20.7 million in total net revenues—were lost in 2001. We find that moving to

post-2006 ESA requirements – by itself – has relatively minimal effect on 2001 losses (8 percent reduction); but providing 20,000 acre-feet of monthly groundwater reduces 2001 losses by 37 percent. Post-2006 ESA requirements coupled with trading – but no additional groundwater pumping – reduces losses to \$8.5 million (57 percent from 2001 losses), and providing 20,000 acre-feet of groundwater given flexible trading reduces losses from \$19.8 million to just \$4.7 million (76 percent reduction in 2001 losses). Under these conditions (i.e., post-2006 ESA requirements, 20,000 acre-feet of additional monthly groundwater availability, and flexible trading), losses in net revenue would have occurred in less than 10 percent of the years 1962-2002.

TABLE 1 here

6.5 Marginal Water Values

In years where limited water availability constrains agricultural production, our model allows us to evaluate the marginal value of water (shadow prices) as they vary across scenarios, sub-basins, months, and years. Because our model assumes perfect foresight within growing seasons, non-zero marginal water values will frequently be uniform across multiple months when storage makes substitutions possible, and across farm use areas when downstream irrigated areas that can be sources for either upstream sub-basin make it possible to indirectly substitute between separate upstream sub-basins that are not hydrologically connected.

With costless transfer of water, the optimization model will equate marginal water values to maximize profits. Within a given year, the marginal water value can vary between sub-basins (i.e., northern sub-basin, Lost River sub-basin, and Project) for specific months when a) insufficient water is available to fully irrigate all acres, and b) water cannot be substituted by

storage or transfers to the water-scarce sub-basin in a particular month. In some situations, water in early season months will have a zero marginal value when it cannot be stored due to limited storage capacity. Surplus water in late-season months will generally have zero marginal value when the limiting water constraint has occurred during an earlier month. During periods when intra-seasonal transfers of water are not possible, the marginal value of water in surplus periods will be zero.

Because water from the upper sub-basins can be substituted in the larger sub-basin downstream (the Project), the marginal water values will not generally vary spatially for the model. Under some circumstances observed in our scenarios, however, water was constraining in May and June in the Lost River sub-basin even though there was ample water available in the other basins and in all basins for later months.

Under some conditions for our scenarios, we see non-zero marginal water values in only one month (June). In other years non-zero marginal water values are spread over 2-6 months (March-August). The marginal values are highest when water in only one month is binding. Intuitively this is because additional water in that constraining month will allow the model to make productive use of not only that water, but of surplus water available in other months as well. In years when water is binding across a six-month period, for example, an additional acre-foot of water in any given month will tend to have a lower marginal value than in years when water is binding only in one month (e.g., \$214 for June in 1975 versus \$48 for March-August in 1977).

An additional factor affecting marginal water values is the overall scarcity of water in a particular year. In years when water is extremely scarce overall, production will be limited to the most-profitable high value lands. In these situations the marginal value of water will be higher

the greater is the profitability of the marginal acre of land that will be brought into production as a result of the incremental water made available.

As expected, we find that the marginal value of water varies widely across years, scenarios, and months. The maximum observed marginal value of water is \$274 per acre-foot, and occurs during June of 1982 under both the 2001 and 2006 ESA requirements scenarios with no groundwater. The average of nonzero marginal values across all years is \$111 and \$73 for the 2001 and 2006 ESA scenarios, respectively. The maximum marginal values for each month across the 1962 to 2002 period also vary widely, as indicated in Table 2. Note that marginal water value peaks in June and that water is never constrained in October.

TABLE 2 here

7 Concluding comments

Water managers and irrigators have been concerned that water shortages similar to those experienced in 2001 will become typical in future years absent substantial improvements to water management within the basin. These concerns have generated enormous conflict and controversy over water management in the basin, and have prompted tens of millions of dollars of Federal and State transfers and investments since 2001.

To understand the economics of these conflicts, and evaluate options to reduce or mitigate conflicts, we constructed a mathematical programming model in order to simulate past and future conditions in the Upper Klamath Basin. We reach three primary conclusions based on our analysis. First, the dire situation in 2001 was caused by a combination of a) extremely low basin inflows, b) ESA in-stream flow and lake level requirements that collectively reduced water

availability to agriculture by over 200,000 acre-feet, and c) by an allocation of water allowing low productivity lands to continue to be irrigated while the most productive lands were shut off, and left with no mechanism (such as a market) to move water from low value uses to higher value uses.

Second, we find that modest increases in groundwater use coupled with the current, less stringent post-2006 ESA requirements would greatly reduce the likelihood of large economic impacts even for hydrological conditions like those experienced in 2001. Since 2001, pumping capacity necessary to provide this additional supply during dry years has largely been installed. And third, if the current ESA requirements and additional groundwater pumping capacity were combined with the introduction of water markets, losses could be greatly reduced during dry years.

Between 2002 and 2006, the groundwater system in the basin has shown promising resilience in response to substantial water bank pumping, and the USGS has indicated that if these higher pumping levels are maintained, the groundwater system will eventually reach a new state of dynamic equilibrium (although the resulting effects to streams are unknown; Gannett et al. 2007). Absent the water bank requirements, our model suggests that the farm economy may only occasionally demand large volumes of groundwater, resulting in aggregate long-term demands that may be sustainable without substantially affecting regional groundwater levels. Furthermore, it may be possible to enhance groundwater recharge during wet years by moving groundwater-dependent irrigators into the surface water network, although this would require additional infrastructure development. If groundwater levels decline below acceptable levels during a given year, a short-term market mechanism could be used to efficiently redistribute

water to its highest value uses (largely from the upper basins to the project), minimizing regional economic impacts.

Establishing a water market with many buyers and sellers would necessitate completion of the ongoing water rights adjudication process in the basin, as well as water-metering infrastructure to track and quantify trades. Although it is uncertain when adjudication in the Upper Klamath Basin will be complete (the process has been ongoing since the 1980s), water-metering infrastructure that allows trading and tracking of water use could be beneficial if opportunities for gains from trade become frequent in the future. Although our analysis suggests that economic impacts during future dry years are unlikely to match those of 2001, it also indicates that future efforts should be directed toward improving groundwater management and establishing water markets. Taking these steps could reduce the need for publicly funded supply augmentation, such as those undertaken by Reclamation in recent years, or investments in additional surface water storage. To the extent that the pattern and timing of basin inflows in future years differs from those in the past, conjunctive use and contingent groundwater markets may become even more valuable as tools for efficient water allocation. The current study, of course, is unable to consider changes in water levels and variability that may occur in future years due to climate change or other factors.

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Table Captions

Table 1: Net Revenue Estimates for Varied Flow, ESA Requirements, Groundwater Availability, and Trading Flexibility

Table 2. Maximum Monthly Marginal Value of Water 1962 – 2002

Figure Captions

Figure 1: Klamath Basin

Figure 2: Klamath Model Schematic

Figure 3: 2001 and Post-2006 FWS and NOAA “Dry Year” Monthly Water Requirements

Figure 4: Frequency of simulated 1962-2002 losses under post-2006 versus 2001 ESA requirements; no additional groundwater pumping and no water trading.

Tables

Table 1: Net Revenue Estimates for Varied Flow, ESA Requirements, Groundwater Availability, and Trading Flexibility

Basin Inflows	ESA Requirements	Additional Monthly Groundwater Availability	Trading Flexibility	Modeled Losses in Improvement Net Revenues (millions)	over 2001 losses
2001	2001	None	None	\$19.8	0%
	Post 2006	None	None	\$18.2	8%
		20,000	None	\$12.4	37%
		None	Flexible	\$8.5	57%
		20,000	Flexible	\$4.7	76%
Result in more than 90% of years evaluated	Post 2006	20,000	Flexible	\$0	100%

Table 2. Maximum Monthly Marginal Value of Water 1962 – 2002

Month	Marginal water value (\$/acre-foot)	
	2001 ESA Requirements	2006 ESA Requirements
March	\$142	\$70
April	\$142	\$70
May	\$268	\$97
June	\$274	\$274
July	\$142	\$70
August	\$70	\$70
September	\$42	\$42
October	\$0	\$0

Figures

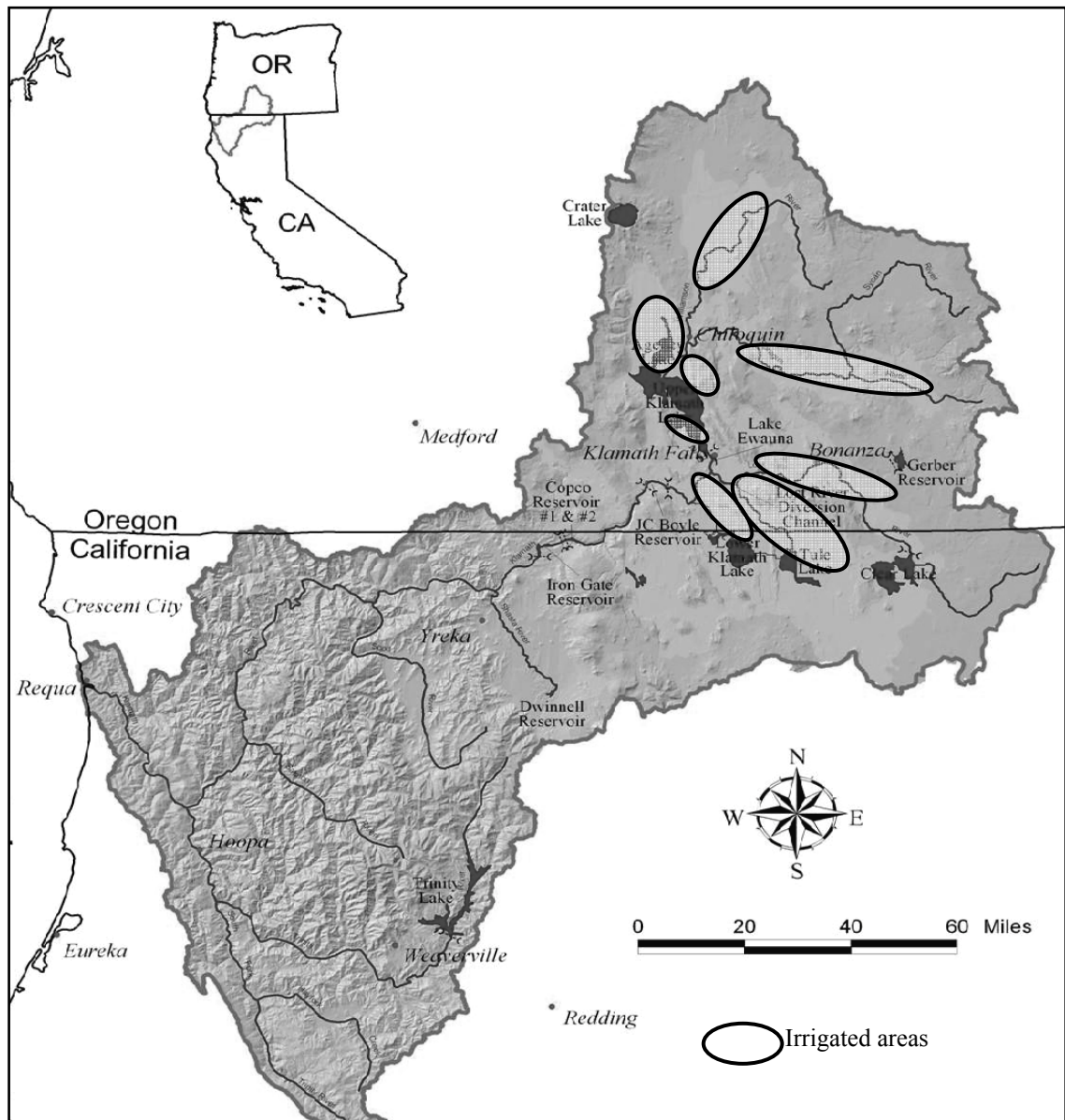


Figure 1: Klamath Basin

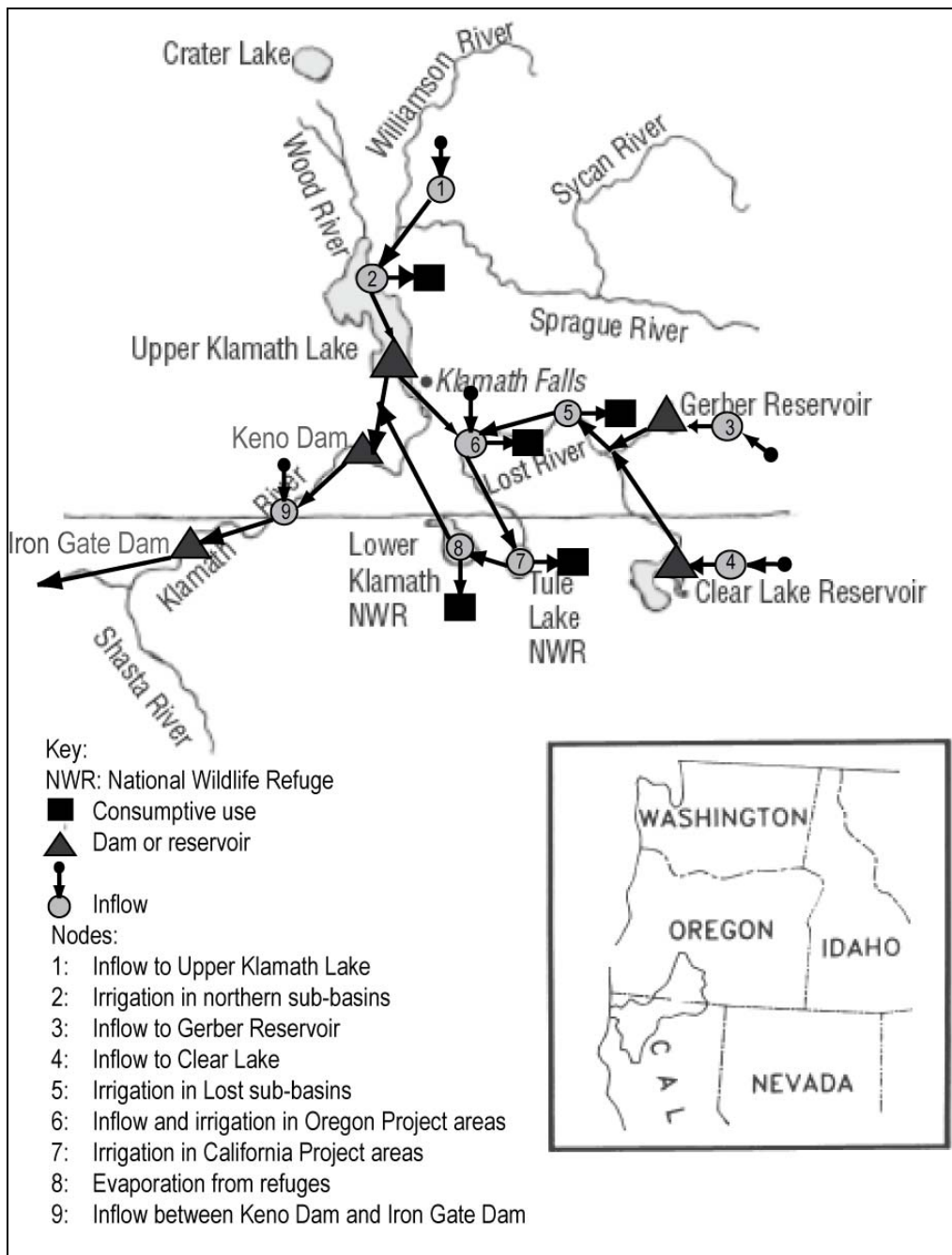


Figure 2: Klamath Model Schematic

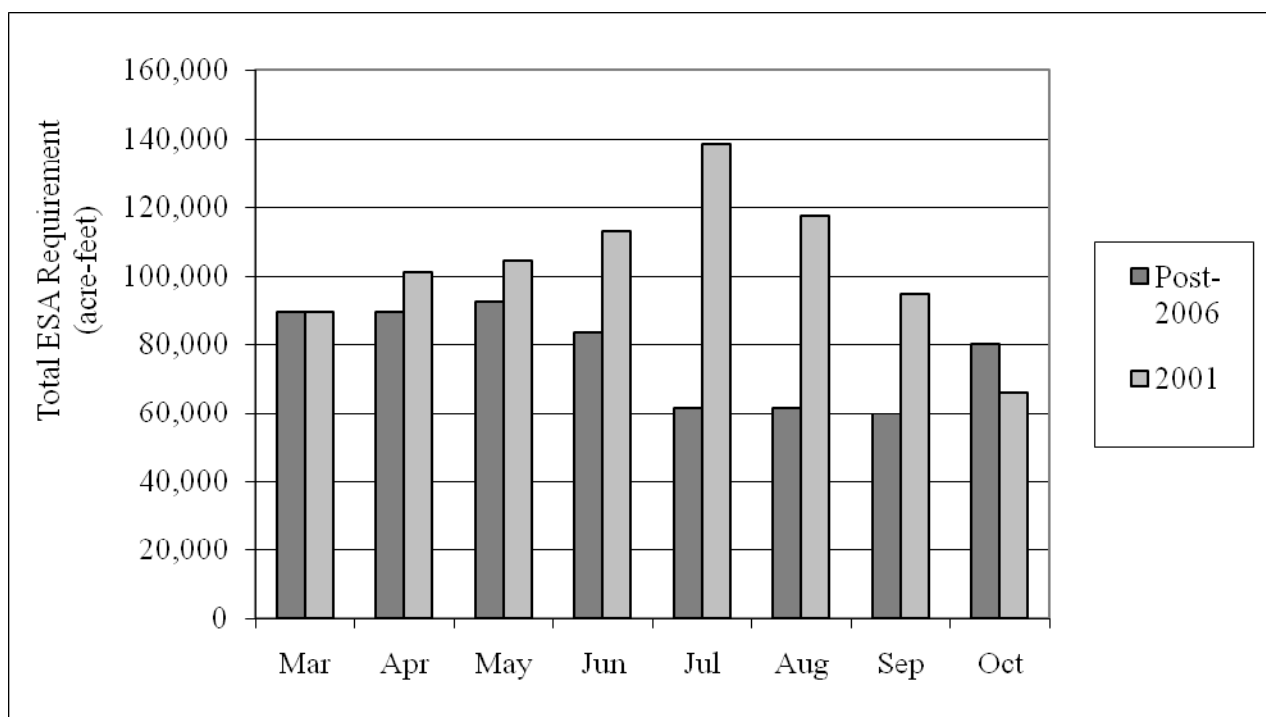


Figure 3: 2001 and Post-2006 FWS and NOAA “Dry Year” Monthly Water Requirements

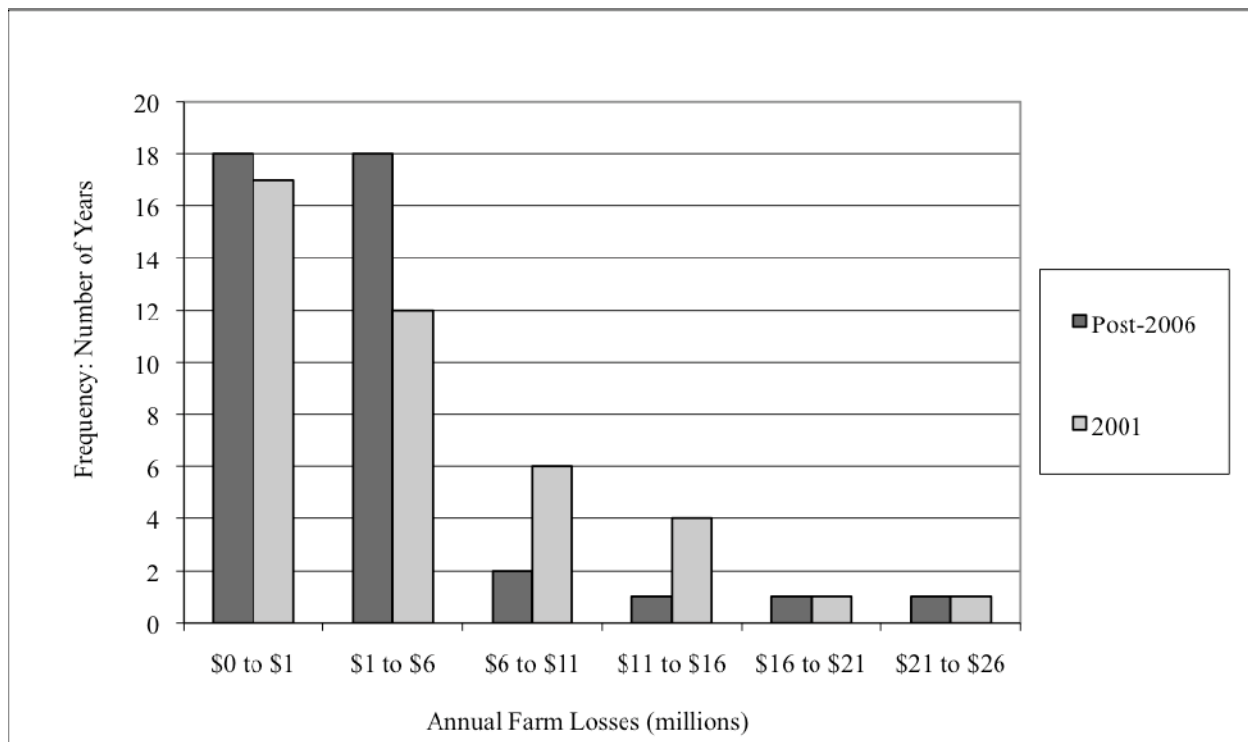


Figure 4: Frequency of simulated 1962-2002 losses under post-2006 versus 2001 ESA requirements; no additional groundwater pumping and no water trading.