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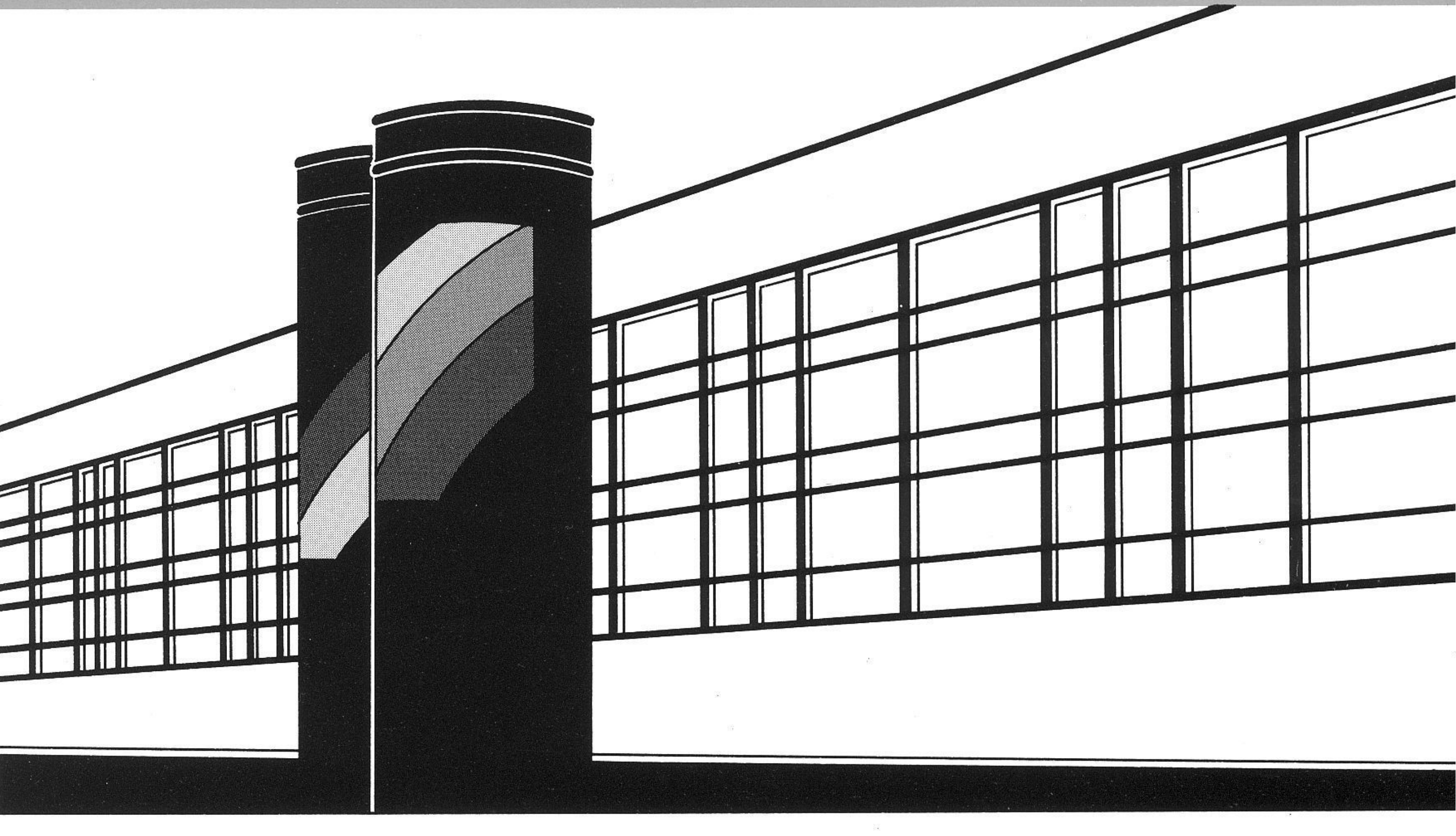

Heft 166

Beau James Freeman

Modernization Criteria Assessment for Water Resources Planning; Klamath Irrigation Project, U.S.

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Von der Fakultät Bau- und Umweltingenieurwissenschaften der
Universität Stuttgart zur Erlangung der Würde eines
Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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Tag der mündlichen Prüfung:	10 July 2008

Institut für Wasserbau der Universität Stuttgart
2008

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von
Dr.-Ing.
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Eigenverlag des Instituts für Wasserbau der Universität Stuttgart

D93 Modernization Criteria Assessment for Water Resources Planning; Klamath Irrigation Project, U.S.

Titelaufnahme der Deutschen Bibliothek

Freeman, Beau:
Modernization Criteria Assessment for Water Resources Planning; Klamath Irrigation Project, U.S. / von Beau Freeman. Institut für Wasserbau, Universität Stuttgart. Stuttgart: Inst. für Wasserbau, 2008

(Mitteilungen / Institut für Wasserbau, Universität Stuttgart: H. 166)
Zugl.: Stuttgart, Univ., Diss., 2008)
ISBN 3-933761-70-0
NE: Institut für Wasserbau <Stuttgart>: Mitteilungen

Herausgegeben 2008 vom Eigenverlag des Instituts für Wasserbau
Druck: druckcooperative, Karlsruhe

Abstract

Agricultural irrigation is the largest consumer of diverted surface water and groundwater resources in the world, with major regions becoming critically water deficit. Agriculture in the western United States (US) and elsewhere has reached the point where the demands from irrigators, domestic users, and various commercial interests for allocated quantities and qualities are beyond acceptable levels for environmental needs in many river basins. Despite decades of investment in irrigation projects by governments, foreign lending agencies, and development banks in numerous countries, irrigation performance remains unsatisfactorily low and in many places progress is being reversed due to water logging, salinization, over-drafting of aquifers, environmental degradation, and infrastructure deterioration. Maintaining current irrigation practices will lead to worsening environmental and economic consequences.

To restore healthy ecosystems and sustain irrigated agriculture, *irrigation modernization* should be promoted as a key component of basin-level water management to effectively balance competing water needs. Improvements in the technical and economic efficiency of irrigation water use through modernization increase the quantity and quality of freshwater available in a river basin. Significant public and private investments in modernization will be required to facilitate the precise control and monitoring of reallocated flows at different levels of irrigation systems, especially on a real-time basis, and thus provide excellent water delivery service to water districts, end-users, and other commercial and environmental stakeholders. This doctoral study investigates a specific problem that many irrigation professionals and water resources planners will face in the future: how to effectively analyze and make an assessment of irrigation modernization project-alternatives.

Selecting the best modernization strategy to pursue from potential project-alternatives in water resources planning is a complex decision-making process. Irrigation modernization alternatives and their impacts involve a variety of diverse stakeholders in the selection of preferred engineering solutions based on subjectively defined criteria (quantitative and qualitative). As a consequence, technical feasibility, environmental, social/community, institutional, political, and economic factors have to be properly assessed as part of water resources planning.

This research introduces a strategic decision analysis methodology for the definition, evaluation, ranking, and selection of appropriate modernization strategies in an engineering case study of the Klamath Irrigation Project (89,000 ha). In 2001 a combination of events occurred there that led to one of the most prominent conflicts over water supplies in the U.S. Due to stricter flow requirements put in place to protect fish species and a critical drought, irrigation water was unexpectedly withheld from the majority of farms in the Project, resulting in major economic losses, calling the basis for environmental restrictions into question, and generating intense political controversy.

The composite programming approach is applied to develop a project ranking index based on standardized indicators – effective for analyzing the trade-offs associated with balancing technical and water conservation considerations with eco-system health, economics, and risk. This modernization criteria assessment requires defining the management objectives according to the nature of the internal processes and agro-hydrological features of the system, selection of alternative engineering solutions, selection of appropriate decision criteria relevant to the specific water-related problems, and the assignment of desirable and critical threshold values pertinent to each criterion. Input data consist of hydrologic, agronomic, engineering, economic, and political/policy information.

Table of Contents

List of Figures

List of Tables

List of Acronyms, Abbreviations and Symbols

ρ_a	air density [kg m^{-3}]
α_r	albedo: radiation reflection coefficient of the crop
ASCE	American Society of Civil Engineering
CDWR	California Department of Water Resources
CFR	Code of Federal Regulations
cfs	cubic feet per second
CI	confidence interval
cms	cubic meters per second
CR	capillary rise [mm]
DD	drainage district
D_e	cumulative depletion from the evaporation zone [mm]
D_r	cumulative depletion of the root zone [mm]
DEQ	Department of Environmental Quality
DOQ	digital orthophoto quadrangle
DP	deep percolation from the root zone [mm d^{-1}]
DP_e	deep percolation from the evaporative layer [mm d^{-1}]
DU	distribution uniformity
e_a	actual vapor pressure [kPa]
e_s	saturated vapor pressure [kPa]
E_a	actual soil evaporation [mm d^{-1}]
$E_{empirical}$	evaporation according to an empirical equation [mm d^{-1}]
E_{max}	maximum evaporation according to Darcy's law [mm d^{-1}]
E_p	potential evaporation [mm d^{-1}]
ECe	soil salinity (saturated soil paste extract) [dS m^{-1}]
ET	evapotranspiration [mm d^{-1}]
ET_c	crop evapotranspiration [mm d^{-1}]
ET_f	evapotranspiration from fallow fields [mm d^{-1}]
ET_{iw}	evapotranspiration of irrigation water [mm d^{-1}]
ET_o	reference evapotranspiration [mm d^{-1}]
ET_p	potential evapotranspiration [mm d^{-1}]
f_{ew}	fraction of the soil that is exposed and wetted
f_{w}	fraction of the soil that is wetted
FAO	Food and Agriculture Organization
FERC	Federal Energy Regulatory Commission
G	soil heat flux [MJ m^{-2} d^{-1}]
h	mean crop height [m]
ID	irrigation district
IIMI	International Irrigation Management Institute
IWMI	International Water Management Institute
ITRC	Irrigation Training and Research Center
K_c	crop coefficient
K_{cb}	basal crop coefficient
K_e	soil evaporation coefficient
K_{eva}	soil evaporation coefficient (SWAP)
K_r	evaporation reduction coefficient
K_s	transpiration reduction coefficient
λ	latent heat of vaporization of water
LAI	leaf area index

List of Acronyms, Abbreviations and Symbols

LKNWR	Lower Klamath National Wildlife Refuge
MAD	management allowable depletion
MADM	multi-attribute decision-making
MCDA	multiple criteria decision analysis
mcm	million cubic meters
MODM	multi-objective decision-making
NDVI	normalized difference vegetative index
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NRCS	National Resources Conservation Service
OWRD	Oregon Water Resources Department
P	precipitation [mm]
r_a	aerodynamic resistance [$s\ m^{-1}$]
r_c	crop resistance [$s\ m^{-1}$]
RAP	Rapid Appraisal Process
RAW	readily available water in the root zone [mm]
REW	readily evaporable water [mm]
RH	relative humidity
RI	relative importance
RO	runoff from surface soil [$mm\ d^{-1}$]
RPA	reasonable and prudent alternative
R_n	net incoming radiation flux at the canopy surface [$MJ\ m^{-2}\ d^{-1}$]
R_s	solar radiation [$MJ\ m^{-2}\ d^{-1}$]
R_{so}	maximum solar radiation on a clear day [$MJ\ m^{-2}\ d^{-1}$]
S_a	root water extraction rate [$mm\ d^{-1}$]
SCADA	supervisory control and data acquisition
SC	soil cover fraction
SEE	standard error of estimate
θ_{FC}	water content at field capacity [$m^3\ m^{-3}$]
Θ_{WP}	water content at wilting point [$m^3\ m^{-3}$]
T	temperature [°C]
TP_a	actual transpiration [$mm\ d^{-1}$]
TP_p	potential transpiration [$mm\ d^{-1}$]
TEW	total evaporable water [mm]
TMDL	total maximum daily load
μ_2	wind speed at 2 m [$m\ s^{-1}$]
US	United States
USBR	U.S. Bureau of Reclamation
USC	United States Code
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
VFD	variable frequency drive
z	height above reference surface [mm]
Z_e	upper soil layer thickness [mm]
Z_r	rooting depth [mm]

Acknowledgements

I am indebted to many people for the successful completion of this doctoral dissertation. I am grateful for the generous support of my faculty advisor, Dr. rer .nat. Dr.-Ing. András Bárdossy, and my committee members, Dr.-Ing. Walter Marx and Dr. oec. Werner Doppler. I also extend special thanks to Dr. Charles Burt, Dr. Stuart Styles and Dan Howes, who have been with me throughout the years as mentors and colleagues.

I have been fortunate enough to know some exceptional people in my life whose qualities have had a lasting impact on my professional work. They exemplified the traits of high-performance expectations, integrity, honesty and a problem-solving attitude. These men include my grandfather James W. Baker and Professor John L. Merriam. Both were able to share important lessons before I could complete this adventure. My appreciation to them is a continuing effort to remember that all research and engineering should aim at being truly useful for humankind.

Finally, I owe my greatest debt to my family. Wonderful gratitude and love to my children, Luka, Frida and Flora, who remind me everyday about the real joys in life. And extra credit to both of my teacher parents – Gay Moessner and Flint Freeman – for this dissertation, my final and last school project. Most of all, I thank my beloved partner, Ariane, who shares my burdens and my joys. This work is equally her achievement because, for me, it is she who makes it all possible.

Zusammenfassung

Landwirtschaftliche Bewässerung zählt weltweit zu den größten Verbrauchern von Oberflächenwasser- und Grundwasservorkommen, wobei in ausgedehnten Regionen ein beträchtlicher Wassermangel herrscht. In vielen Flussgebieten im Westen der USA ist der Bedarf seitens Bewässerung, häuslichem Gebrauch und unterschiedlichen kommerziellen Nutzern hinsichtlich ökologischer Erfordernisse nicht mehr akzeptabel. Obwohl jahrzehntelang größere Investitionen in Bewässerungsprojekte durch Regierungen, internationale Kreditanstalten und Entwicklungsbanken in zahlreichen Ländern getätigt wurden, verharrte die Leistungsfähigkeit von Bewässerungssystemen auf geringem Niveau. Häufig ist eine Verschlechterung aufgrund von Vernässung, Versalzung, Übernutzung von Aquiferen, Umweltverschmutzung und Verfall der Infrastruktur eingetreten. Werden die gegenwärtigen Bewässerungspraktiken beibehalten, ist von zunehmenden wirtschaftlichen und die Umwelt betreffenden Schäden auszugehen.

Um Ökosysteme wiederherzustellen, die Bewässerungslandwirtschaft zu erhalten und konkurrierende Wasseransprüche zu vereinbaren, sollte der Modernisierung der Bewässerung eine Schlüsselrolle innerhalb der Wasserwirtschaft auf Flussgebietsebene zukommen. Verbesserungen der technischen und wirtschaftlichen Effizienz der Bewässerung im Zuge der Modernisierung erhöhen die Wassermenge und -qualität innerhalb eines Flussgebiets. Dabei sind erhebliche öffentliche und private Investitionen in die Modernisierung erforderlich, um eine präzise Kontrolle und ein Monitoring der umverteilten Ströme, möglichst in Echtzeit, auf unterschiedlichen Ebenen der Bewässerungssysteme zu ermöglichen. Diese Dissertation behandelt eine besondere Problemstellung, mit der zahlreiche Bewässerungsfachleute und Wasserwirtschaftler in Zukunft konfrontiert sein werden: Wie können verschiedene Optionen zur Modernisierung der Bewässerung effektiv analysiert und beurteilt werden?

Die Auswahl der besten Modernisierungsstrategie aus möglichen Alternativen ist ein komplexer Entscheidungsfindungsprozess bei der wasserwirtschaftlichen Planung. Die verschiedenen Alternativen zur Modernisierung der Bewässerung und deren Auswirkungen betreffen eine Vielzahl unterschiedlicher Akteure mit subjektiv definierten Kriterien (quantitativ und qualitativ). Daher müssen die technische Umsetzbarkeit sowie soziale, die Umwelt betreffende, behördliche, politische und wirtschaftliche Faktoren bei der wasser-wirtschaftlichen Planung sorgfältig bewertet werden.

Diese Untersuchung stellt eine Methodik zur Entscheidungsanalyse für die Definition, Bewertung, Einordnung und Auswahl der geeigneten Modernisierungsstrategie anhand einer technischen Fallstudie des Bewässerungsprojekts Klamath (89.000 ha) vor. Im Jahr 2001 kam es aufgrund des Zusammentreffens verschiedener Ereignisse zu einer der bedeutendsten Auseinandersetzung über die Wasserversorgung in den USA. Infolge von strengeren Vorgaben des Mindestdurchflusses zum Schutz der Fischarten und einer ausgeprägten Dürre wurde das Bewässerungswasser den meisten Farmen unerwartet vorenthalten, was zu größeren wirtschaftlichen Ausfällen und der Infragestellung der Umweltschutzvorgaben führte sowie eine heftige politische Debatte auslöste.

Der Ansatz des “composite programming” wird verwendet, um einen Projekt-Rangordnungs-Index zu entwickeln, der auf standardisierten Indikatoren basiert. Er stellt ein wirkungsvolles Instrument dar, um technische Belange, Maßnahmen zur Wassereinsparung mit Erfordernissen von Umweltschutz, Wirtschaft und mit Risikoabwägungen abzustimmen. Diese Bewertung anhand von Modernisierungs-Kriterien erfordert die Definition von Zielsetzungen bei der Betriebsführung, die Auswahl alternativer technischer Lösungsansätze, die Auswahl geeigneter Entscheidungskriterien sowie die Festlegung anzustrebender und kritischer Schwellenwerte zu jedem entsprechenden Kriterium. Die Eingangsdaten bestehen aus hydrologischen, agronomischen, technischen, wirtschaftlichen und politisch vorgegebenen Informationen.

UNTERSUCHUNGSKONZEPT UND METHODIK

Der Gegenstand dieser Untersuchung entstand aus Besorgnis über die zukünftige weltweite Entwicklung der Bewässerung und aus der Überlegung, wie diese Entwicklung beeinflusst werden sollte und kann. Die Untersuchung betrachtet die Rolle der Bewässerungsmodernisierung bei der Lösung von wasserwirtschaftlichen Multi-Kriterien- und Multi-Akteur-Problemstellungen durch die Anwendung eines Systems zur Entscheidungsunterstützung, um Projekt-Alternativen auf der Grundlage von Benchmark-Indikatoren einzuordnen. Dies ist mein Ansatz als wasserwirtschaftliche Fachkraft zur Beantwortung der folgenden Frage:

> *Wie können neue Investitionen zur Bewässerungsmodernisierung anhand von wirtschaftlichen und sozialen Erwägungen sowie anhand von Umweltgesichtspunkten begründet werden vor dem Hintergrund knapper Kassen in der Landwirtschaft, fortgesetzter Zerstörung der Umwelt durch unterschiedliche Kräfte, einschließlich der Bewässerung selbst, sowie einer nie da gewesenen öffentlichen Aufmerksamkeit für wasserwirtschaftliche Entscheidungen von Seiten unterschiedlichster, einflussreicher Interessenvertretungen?*

Zielsetzungen

Folgende Zielsetzungen wurden für die vorliegende Untersuchung festgelegt:

- Festlegung eines wissenschaftlichen, konzeptuellen Systems für Maßnahmen zur Bewässerungsmodernisierung
- Berechnung von umfassenden Wasserbilanzen für verschiedene hydrologische Ebenen, die alle Fließwege in das Bewässerungsprojektgebiet hinein und aus diesem heraus auf Monatsbasis quantifizieren, sowie Bewertung von relevanten Leistungsindikatoren für eine mehrjährige Zeitspanne
- Durchführung einer systematischen Untersuchung der internen Prozesse (Informations-Systeme, Entscheidungsfindung, Kommunikation, Infrastruktur von Kanälen und Pumpwerken, hydraulische Kontrollstrukturen, Rezirkulation etc.), ausgerichtet auf das Verhältnis zwischen der bisherigen Leistungsfähigkeit des Systems und dem realistischen Verbesserungspotential
- Aufbau von quantifizierbaren Zielsetzungen mit technisch umsetzbaren Empfehlungen für ausgewählte Fälle im Untersuchungsgebiet, die zukünftige wasserwirtschaftliche und landwirtschaftliche Herausforderungen erfüllen, die bei einer Vielzahl an Einflüssen entstehen, und Demonstration von State-of-the-Art-Techniken zur Modernisierung
- Anwendung von Multi-Kriterien-Analyse-Techniken zur Aufstellung von Bewertungsindikatoren für Wasserwirtschaftler und Interessensvertretungen für die Bewertung von alternativen, verbesserten Betriebskriterien und Modernisierungsprojekten innerhalb besonderer Einschränkungen bei der Betriebsführung des komplexen Systems

Aufbau der Arbeit

Die vorliegende Untersuchung ist in sieben Kapitel untergliedert. Kapitel 1 beschreibt das Untersuchungsgebiet und die Aufgabenstellung und gibt einen Überblick zu Zielstellungen und Untersuchungsmethoden. Kapitel 2 stellt grundlegende Konzepte zur Bewässerungsmodernisierung vor, auf denen der theoretische Rahmen der vorliegenden Arbeit basiert. Eine umfassende Analyse der agrar-hyrologischen Ressourcen innerhalb des Bewässerungs-projekts Klamath ist Gegenstand von Kapitel 3. Die Analyse beinhaltet detaillierte Wasserbilanzen der Bewässerung und eine Bewertung der konkurrierenden Wasseransprüche sowie alternative Verteilungsoptionen. In Kapitel 4 werden die besonderen wasser-wirtschaftlichen Herausforderungen des Projekts angesichts von gegenwärtigen und zukünftigen internen Einschränkungen diskutiert. Kapitel 5 stellt ein Multi-Kriterien-Analyse-System zur Entscheidungsfindung vor und definiert strategische Szenarios zur Bewertung. Diese zukünftigen wasserwirtschaftlichen Alternativen werden ausführlich anhand des Multi-Kriterien-Entscheidungsfindungs Tools („composite programming“) in Kapitel 6 bewertet. In Kapitel 7 werden schließlich die Folgerungen der Untersuchung zusammengestellt und Vorschläge für zukünftige Maßnahmen unterbreitet.

System zur Entscheidungs-Analyse

Das Bewässerungsprojekt Klamath wurde anhand eines Systems analysiert, das zwei Hauptkomponenten kombiniert; 1) die räumlich und zeitlich aufgelöste Hydrologie der Wasserressourcen mit Simulation der regionalen Evapotranspiration (*ET*) und der geplanten Struktur der Landnutzung und 2) interne Prozesse, um ein Werkzeug zur Entscheidungs-Analyse für künftige Entwicklungsstrategien mit einer speziellen Anwendung zur Einordnung von Alternativen zur Bewässerungsmodernisierung zu erstellen. Die Strategien wurden anhand von detaillierten Geländeerhebungen, der agrar-hydrologische Modellierung der unterschiedlichen Fließwege von Oberflächen- und Grundwasser, technischen Analysen von Sachverständigen sowie Beratungen mit Entscheidungsträgern und den ausführenden Stellen entwickelt. Bei der Evaluierung einer repräsentativen Palette von Projekten an einem strategischen Planungszeitpunkt wird eine Vielzahl an quantitativen und qualitativen Kriterien berücksichtigt, um verschiedene potentielle Ergebnisse zu vergleichen und einzuordnen.

Die Bedingungen, Sachverhalte und Ziele des Aufbaus von Infrastruktur, Betriebsregeln, Organisationsstrukturen und Betriebsführungs-Praktiken wurden in Echtzeit anhand des Tools „*Rapid Appraisal Process*“ (RAP) – einem innovativen, technischen Werkzeug zur Projektevaluierung – untersucht, um über eine bloße Beschreibung von Eigenschaften (z. B. Länge oder Abflussleistung eines Kanals) hinauszugehen und um so tatsächlich die Handlungsabläufe zu erfassen – auf welche Weise und aus welchem Grund Eingriffe vorgenommen werden, welche Einschränkungen der Bewässerungs-Distrikt aufweist, welche physikalische Infrastruktur verwendet wird etc. Die Untersuchung dieser internen Prozesse erleichtert es herauszufinden, welche speziellen Maßnahmen zur Verbesserung der Leistungsfähigkeit des Projektes ergriffen werden können.

Anhand von Wasserbilanzen, der Identifizierung und Quantifizierung von Risiken bei gleichzeitigem Verständnis für interne Prozesse kann das tatsächliche Potential abgeschätzt werden, ob die Zielsetzungen bei den unterschiedlichen Bewässerungs-Strategien erfüllt werden. Zudem können dadurch Schwerpunkte bei Investitionen – einschließlich Projektanlagen und On-Farm-Programmen – innerhalb des Systems gesetzt werden. Damit kann ermittelt werden, welche speziellen Maßnahmen ergriffen werden können. Gleichzeitig können die Auswirkungen auf die übrigen Bereiche des Bewässerungs- sowie Ökosystems mit berücksichtigt werden.

Sobald die möglichen Maßnahmen herausgearbeitet wurden, sind Wasserwirtschaftler und Ingenieure jedoch mit einem weiteren Fragenkatalog konfrontiert – *wie können die möglichen Auswirkungen der unterschiedlichen Modernisierungsvarianten, die unter Umständen auf verschiedene Bereiche des Systems ausgerichtet sind oder beträchtliche Differenzen in Bezug auf Kosten, Nutzen, Risiken, technische Komplexität etc. aufweisen, beurteilt werden?* Zudem gibt es in jedem Bewässerungsprojekt eine Vielzahl von internen und externen Interessens-vertretungen mit unterschiedlichen Anschauungen im Hinblick auf die Bedeutung verschiedenartiger Streitfragen (bedrohte Arten, Verantwortung gegenüber den Ureinwohnern, wirtschaftliche Umsetzbarkeit von bestimmten Arten der landwirtschaftlichen Produktion, Wiederherstellung von Lebensräumen etc.).

Wasserwirtschaftlicher Planungsansatz zur Umsetzung von Modernisierungsprojekten

Das System des empfohlenen wasserwirtschaftlichen Planungsprozesses bei der Bewässerungsmodernisierung wird in der folgenden Darstellung veranschaulicht.

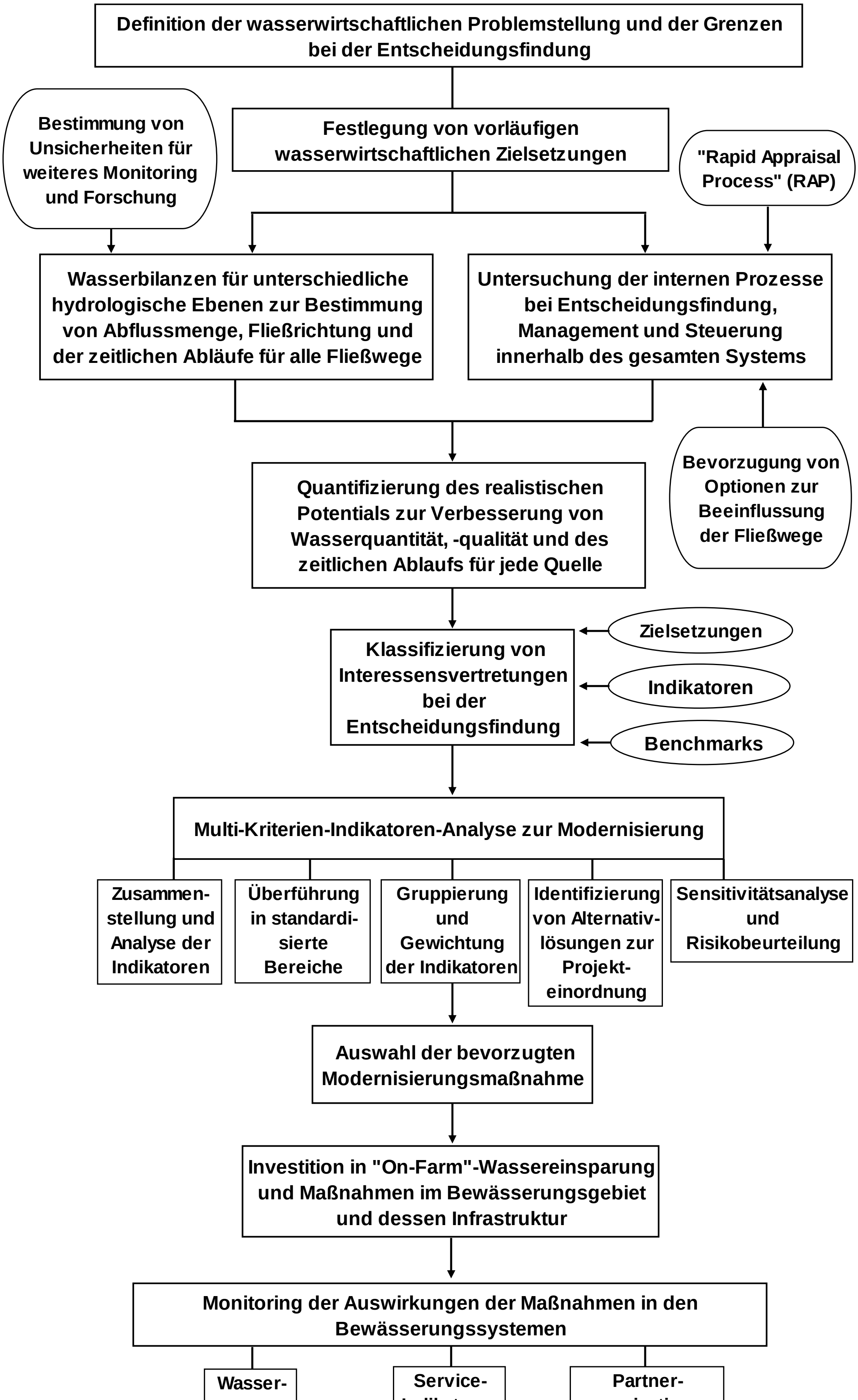
BEWÄSSERUNGSMODERNISIERUNG ALS GRUNDLEGENDES PRINZIP DER LANDWIRTSCHAFTLICHEN WASSERWIRTSCHAFT

Die Experten-Anhörung der FAO über Modernisierung von Bewässerungssystemen gelangte zu folgender Definition der Bewässerungsmodernisierung (Wolter und Burt, 1996):

> *Die Modernisierung stellt einen Vorgang der technischen und betrieblichen Qualitätsverbesserung (im Gegensatz zur bloßen Instandsetzung) von Bewässerungssystemen dar mit dem Ziel einer verbesserten Ressourcenverwertung (Arbeit, Wasser, Wirtschaftlichkeit, Umweltschutz) und Wasserversorgung der landwirtschaftlichen Betriebe.*

Ein Modernisierungsansatz lenkt die Projektumsetzung entsprechend modernen Methoden und Fachkompetenz aus Bauingenieurwesen, Pflanzenbauwissenschaft, Entwurf und Ausführung und wirtschaftliche Analyse zur Umsetzbarkeit. In dieser Hinsicht sind Fachkräfte, die für die Erstellung von speziellen, umsetzbaren Lösungen für existierende Problemstellungen zuständig sind, auf neuartige Werkzeuge zur Bewertung von Projekten angewiesen.

Die FAO prognostiziert für das Jahr 2030, dass weniger als 20% der benötigten Ertragsteigerungen aus der Ausdehnung der Anbauflächen resultieren werde (2002). Der restliche Zuwachs werde durch höhere Erträge zustande kommen. Es konnte jedoch vielfach nachgewiesen werden, dass der gegenwärtige Stand der Wasserversorgung in den meisten Projekten für die Einführung von modernen „On-farm“-Methoden zur Bewässerung nicht ausreichend ist (Burt and Styles, 1999; Burt, 2000; Burt, 2004). Plusquellec et al. (1994) und Burt and Plusquellec (2000) führen das mangelnde Augenmerk für die grundlegende Ausführung und die technischen Sachverhalte als Hauptgrund für die Beschränkung der landwirtschaftlichen Erträge an.



Empfohlener wasserwirtschaftlicher Planungsansatz zur Umsetzung von Modernisierungsprojekten

Im Gegensatz zu den geringen internationalen Anstrengungen wurden in den Bewässerungsdistrikten der USA in kurzer Zeit eine Modernisierung der Versorgungs- und Verteilungssysteme durchgeführt (Burt, 2000). Diese Anstrengungen zur Modernisierung richteten sich auf das Ausmaß an Flexibilität bei der Wasserversorgung im Zusammenhang mit dem landwirtschaftlichen Bedarf, auf eine Verbesserung der Bewässerungseffizienz (irrigation efficiency, *IE*) sowie eine Verringerung oder Beseitigung von Drainageabflüssen. Die rasche Ausbreitung von Methoden zur Tröpfel- und Mikrobewässerung war dabei eine Hauptantriebskraft der Modernisierung (Burt et al., 2000).

Der Hauptgrund für Bewässerungsprojekte sowie für neue Bewässerungsinvestitionen besteht darin, dass die Versorgung mit Wasser zur Bewässerung einen Service darstellt, mit dem die Abnehmer auf effiziente Weise Erlöse erzielen müssen. Um die benötigten Ertragsniveaus zukünftig erreichen zu können sowie um mit konkurrierenden wirtschaftlichen und ökologischen Themen vereinbar zu sein, müssen die Verfahren der Bewässerungs-landwirtschaft mehr im Stil von vergleichbaren Industrieprozessen ablaufen, die durch wiederholte Abfolgen, stabile Steuerung und messbare Ergebnisse charakterisiert sind. Industrielle Prozesse beinhalten eine komplexe Reihe von Schritten zur wirtschaftlichen Umsetzung der Produktion in großem Maßstab.

KONTEXT DES BEWÄSSERUNGSPROJEKTES KLAMATH (USA)

In einer technischen Fallstudien-Analyse des US-Innenministeriums, Bureau of Reclamation (USBR) wird das Bewässerungsprojekt Klamath herangezogen, um zu veranschaulichen, wie Modernisierungsmöglichkeiten abgeleitet und anschließend qualitativ und quantitativ durch Bewässerungsspezialisten und auch durch Interessensvertreter mit gegensätzlichen Präferenzen hinsichtlich zukünftiger wasserwirtschaftlicher Szenarios bewertet werden. Die primären wasserwirtschaftlichen Zielsetzungen im Flussgebiet Klamath bestehen aus einer Überarbeitung der Wasserzuteilung, aus dem Herausfinden der optimalen Modernisierungsstrategie und der Veranschaulichung der Abstimmung zwischen landwirtschaftlichen und ökologischen Interessen. Weder die Bewässernden noch Umweltschützer können jedoch alleine Entscheidungen zu Wassernutzung und Modernisierungsstrategien fällen.

Das Bewässerungsprojekt Klamath befindet sich in einer semi-ariden Region des Flussgebiets Klamath und erstreckt sich über Südoregon und Nordkalifornien. Das Projekt besteht aus einem System von Haupt- und Nebendämmen, Verteilungsstrukturen und Pumpstationen, die 500 Mio. m^3 Wasser für landwirtschaftliche Zwecke und Naturschutzgebiete speichern und abgeben. Im Flussgebiet Klamath kommen über 400 Vogel- und Fischarten vor (NRC, 2002). Die lokale Landwirtschaft erwirtschaftet jährlich etwa 300 Mio. US$, und viele Familien stammen von den ursprünglichen Grundbesitzern ab, die in dieses Gebiet kamen, nachdem Seen und Sümpfe kulturfähig gemacht waren und ein komplexes System von Kanälen und Gräben errichtet worden war (Braunworth et al., 2002).

Versuche, sowohl vertragliche Ansprüche auf Bewässerungsmengen einzuhalten als auch den Betriebskriterien, die aus der Umweltgesetzgebung stammen, nachzukommen, führten zu Streit zwischen unterschiedlichen Interessensvertretungen und einer intensiven politischen Debatte. Im April 2001 kam es aufgrund des Zusammentreffens verschiedener Ereignisse zu einer der bedeutendsten Auseinandersetzung über die Wasserversorgung in den USA. Aufgrund einer aktualisierten biologischen Studie der USBR forderten die Bundesumweltbehörden höhere Seewasserstände *und* die Durchsetzung von größeren Abflussmengen in den Flüssen, um Fischarten zu erhalten. Zu diesen Umweltschutzvorgaben kam eine heftige Dürre, die geringere Zuflüsse in den Oberen Klamathsee, dem Hauptspeicher, zur Folge hatte. Infolge der strengeren Vorgaben und der Dürre wurde das Bewässerungswasser den meisten Farmen unerwartet vorenthalten, was zu größeren wirtschaftlichen Ausfällen und dem Infragestellen der strengen Umweltschutzvorgaben führte.

REGIONALE MODELLIERUNG DER BEWÄSSERUNGSHYDROLOGIE ZUR BEWERTUNG VON LEISTUNGSFÄHIGKEIT UND VERFÜGBARKEIT VON LANDWIRTSCHAFTLICHEN WASSEREINSPARMAßNAHMEN

Mehrskalige hydrologische Wasserbilanzen

Eine umfassende Bilanzierung der Bewässerungsmengen ist erforderlich, um sinnvolle Entscheidungen in Bezug auf die regionale Wasserverteilung und –einsparung zu treffen (Bos et al., 2005). Für den Fünfjahreszeitraum 1999 – 2003 wurden mehrskalige Wasserbilanzmodelle auf Monats- und Jahresbasis entwickelt, die sämtliche Fließwege und Bewässerungsanlagen im Bewässerungsprojekt Klamath einbeziehen. Das anhand eines GIS' definierte Gebiet beinhaltete 134.920 ha und enthielt u.a. Angaben zu Bodeneigenschaften, Landnutzung, Feldbestand und Anbauweise, Herkunft des Wassers, Meteorologie. Jeder Fließweg von Oberflächen- und Grundwasser wurde festgelegt und entsprechend der additiven oder subtraktiven Wirkung auf subregionale Bilanzen definiert. Der mittlere Gesamtzustrom in das Modellgebiet belief sich auf etwa 961 Mio. m^3, während der Gesamtabstrom ca. 1.028 Mio. m^3 betrug. Unter Einbeziehung der mittleren jährlichen Speicheränderung von Oberflächenwasser (-12 Mio. m^3) und der mittleren Speicheränderung von Grundwasser (-30 Mio. m^3) resultierte ein lateraler Netto-Grundwasserzufluss in das Gebiet von etwa 22 Mio. m^3. Die Zuleitung über Kanäle und die Evapotranspiration des Bestandes ET_c stellten die größten Zu- bzw. Abstromkomponenten dar. Die Evapotranspiration des Bestandes ET_c bezieht sich dabei auf den Teil des Bewässerungswassers, der vom Bestand selbst verbraucht wird. Die ET_c von Ackerflächen und Feuchtgebieten belief sich mit 542 Mio. m^3 auf ca. 49% des Gesamtabstroms in den Jahren vor der Dürreperiode.

Modellierung des Bewässerungswassers

Durch die Anwendung eines tagesbasierten Modellsystems für den Verbrauch an Bewässerungswasser zusammen mit komplexen agrar-hydrologischen Datensätzen und detailliertem Wissen zu den lokalen wasserwirtschaftlichen Praktiken werden Schätzungen des Volumens von Bewässerungswasser, das eingespart werden kann, durchgeführt.

Die Wiederauffüllung der *ET* stellt den Hauptgrund zur Bewässerung dar, demnach ist die *ET* ein wichtiges Element bei der Bestimmung des Bedarfs an Bewässerungswasser und der Wasserverteilung in einem bewässerten Flussgebiet. Der Verbrauch wurde mit einem tagesbasierten Pflanze-Boden-Wasser-Modell nachgebildet, das den FAO-56 „dual crop coefficient approach“ (Allen et al., 1998) mit verschiedenen Schritten zu Organisation und Qualitätskontrolle der Datensätze heranzieht. Bei dieser Vorgehensweise wird die *ET* sowohl von landwirtschaftlich genutzten als auch ungenutzten (offene Wasserflächen, Feuchtgebiete etc.) Flächen auf Tages-, Monats- und Jahresbasis berechnet. Diese Methode wurde auf das Untersuchungsgebiet angewendet, um belastbare Informationen zu den Auswirkungen von möglichen kurzzeitigen Engpässen als auch von langfristigen Entwicklungen des Wasserverbrauchs zu gewinnen.

Möglichkeiten zur Einsparung von Bewässerungswasser

Eine wichtige Erkenntnis dieser mehrjährigen hydrologischen Analyse besteht darin, dass ein sinnvoller Referenzrahmen auf die Reduzierung des Verbrauchs von kaum ertragreichen Anbau- und Feuchtgebietsflächen abzielen sollte. Die Ergebnisse der Berechnungen zur Bewässerungseffizienz (irrigation efficiency, *IE*) auf Projekt-Ebene im fünfjährigen Untersuchungszeitraum (mittlere *IE*: 86%) zeigen, dass traditionelle Einsparmaßnahmen wie eine Effizienzverbesserung der Feldbewässerung und die Abdichtung von Kanälen nicht geeignet sind, um signifikante Mengen für andere Verbraucher zur Verfügung zu stellen.

Um das Potenzial für die Wassereinsparung von Anbauflächen quantifizieren zu können, wurde die Evapotranspiration von Bewässerungswasser (ET_{iw}) ausgiebig modelliert. Der Unterschied zwischen der ET_c eines bestimmten Bestands während der gesamten Anbauzeit und der geschätzten *ET* einer hypothetischen, vergleichbaren, brachliegenden Fläche stellt eine Approximation der Bewässerungskomponente der *ET* dar. Nach diesem Ansatz ergab sich für die ET_{iw} ein Jahresmittel von 393 Mio. m³ für die Fünfjahresperiode, wobei für das Jahr 2001 aufgrund der vorgeschriebenen Kürzungen des Bewässerungswassers eine Verringerung um über 40% eintrat. Aufgrund der Verhältnisse im Jahr 2001 fiel der Anteil von Bewässerungswasser an der gesamten ET_c von Ackerflächen im Jahr 2001 um 20% auf 55% im Vergleich mit dem Vierjahresmittel ohne Dürre von 76 %.

MULTI-KRITERIEN-ENTSCHEIDUNGS-ANALYSE: BEWERTUNGSPROZEDUREN ANHAND VON MODERNISIERUNGSKRITERIEN BEI DER EINORDNUNG VON PROJEKTALTERNATIVEN

Die wasserwirtschaftliche Planung von Modernisierungsmaßnahmen in Bewässerungsprojekten muss sich an potentiell konkurrierenden Zielsetzungen wie die Erhöhung der Wassernutzungseffizienz, der Verringerung der Umweltschäden, der Einhaltung von Sicherheitsstandards und arbeitsrechtlichen Vorgaben und der Erhöhung des Profits von Bewässernden ausrichten. Die Entwicklung eines Entscheidungs-Analyse-Systems zur Bewertung breit gefächerter technischer und sozioökonomischer Kriterien ist behilflich bei der Förderung von Bewässerungsmodernisierung und einer effektiven Nutzung von modernen Techniken zur Wassersteuerung und –messung.

Im Zuge einer Bewertung anhand von Modernisierungskriterien können die relevanten Zielsetzungen repräsentiert, ineffektive oder ineffiziente Alternativen ausgeschlossen und eine quantitative Evaluierung der Kompromisse zum Erreichen der Ziele von einer Vielzahl an Entscheidungsträgern erhalten werden. Bei der Anwendung des „composite programming "-Algorithmus können unterschiedliche Alternativen anhand einer stabilen logisch-mathematischen Prozedur mit einer quantifizierten Gruppierung von Indikatoren und subjektiven Einordnungen bewertet werden. Diese integrierte Technik evaluiert die prognostizierten Ergebnisse von alternativen Umsetzungsstrategien, die anhand von verschiedenen Kriterien entsprechend den benutzerdefinierten angestrebten und kritischen Schwellenwerten innerhalb eines Referenzbereichs erfasst werden.

Die Anwendung der "composite programming"-Methode zur Analyse von Bewässerungsmodernisierungsstrategien erfordert die Definition der Zielsetzungen bei der Betriebsführung, die Auswahl alternativer technischer Lösungsansätze, die Auswahl geeigneter Entscheidungskriterien sowie die Festlegung von zugehörigen Schwellenwerten. Die Eingangsdaten bestehen aus hydrologischen, agronomischen und wirtschaftlichen Informationen. Das Hauptziel besteht nicht darin, die „perfekte" Lösung herauszufinden (Klawitter, 2003). Bei der Anwendung des „composite programming" sollte vielmehr eine grundlegende Übereinkunft zwischen den unterschiedlichen Interessensvertretungen über die Bewertungskriterien entstehen, der Einfluss ihrer Präferenzen widergespiegelt und die Kompromisse bei den verschiedenen Stufen der Bewässerungsmodernisierung systematisch erklärt werden.

Entscheidungsebenen 1 bis 4

Diese Bewertung anhand von Modernisierungskriterien zur Ermittlung der Leistungsfähigkeit von Projektalternativen mit dem Ansatz "composite programming" wurde in eine Vier-Ebenen-Hierarchie zur Entscheidungs-Analyse gegliedert, die aus einer Vielzahl von speziellen Einordnungsindikatoren bestand. Die Festlegung der 4. Ebene bestand aus der Aufstellung von 30 separaten Schlüsselindikatoren zur Quantifizierung des Verhältnisses zwischen Bewässerungslandwirtschaft und Umwelt sowie von damit verbundenen politischen Vorgabe-Aspekten. Auf der 3. Ebene wurden die Entscheidungsattribute eines jeden Indikators in die folgenden relevanten Zielsetzungen integriert:

1. Möglichkeiten zur Wassereinsparung
2. Technische Umsetzbarkeit
3. Verbesserung des Umweltschutzes
4. Unsicherheiten/Risiken
5. Wirtschaftlichkeit
6. Recht/Fairness
7. Einhaltung gesetzlicher Vorgaben

Auf der 2. Ebene wurden die Modernisierungsalternativen im Hinblick auf drei Zielsetzungen analysiert: Bereitstellung einer Lösung, ökologische Nachhaltigkeit und Übereinstimmung mit behördlichen Vorgaben.

Unterschiedliche Modernisierungsvorhaben können zweckmäßig von Ingenieuren und Managern bewertet und empfohlen werden, um Baukosten, Finanzierung, Wasserrechtsverfahren, Wassertransfers etc. zu analysieren. Die quantitativen Analysen werden mit der systematischen Ermittlung, welche Projektalternative von einem oder mehreren Entscheidungsträgern bevorzugt wird und unter den Gesichtspunkten von Maßstab und Technik umsetzbar ist, kombiniert. Transparente Entscheidungsschritte ermöglichen eine ausführliche Analyse einer Vielzahl von technischen Aspekten der Bewässerungsmodernisierung.

Vorteile von standardisierten Bewertungindikatoren

Die Erfahrungen aus der technischen Fallstudie des Bewässerungsprojekts "Klamath" verdeutlichen, wie stark eine scheinbar unlösbare, kontroverse Thematik von einem wissenschaftlichen Rahmenkonzept profitieren kann, das standardisierte Bewertungsindikatoren auf der Basis einer Multi-Kriterien-Entscheidungsanalyse für unterschiedliche Interessensvertretungen einbezieht. Der Ansatz verfügt über das Potential, um weltweit Programme zur Modernisierung der Bewässerung von Flussgebieten voranzutreiben. Die Übertragung der Informationsbasis zu Bewässerungsmodernisierung – von der angemessenen Konzeptualisierung der Bewässerung als *Service* bis hin zu den hier verwandten komplexen Werkzeugen zur Analyse- und Entscheidungsfindung – in nicht-industrielle, landwirtschaftlich geprägte und industriell unterentwickelte Länder in Afrika und Asien würde einen besonders wichtigen Beitrag dieser Dissertation darstellen.

Die Verwendung der standardisierten Indikatoren, die in dieser Dissertation entwickelt wurden, zusammen mit empfohlenen Entscheidungskriterien hinsichtlich der Leistungsfähigkeit von Bewässerungssystemen, moderner Ausführung und Technologie und einer umweltgerechten Hydrologie hat viele potentielle Vorteile und Anwendungen:

- Ermittlung von Schlüsselinformationen im Zusammenhang mit zukünftigen wasserwirtschaftlichen Szenarios
- Monitoring der Auswirkungen von wasserwirtschaftlichen Entscheidungen
- Hervorhebung der Stärken und Schwächen von unterschiedlichen Modernisierungsmaßnahmen
- Unterstützung bei der Formulierung von Investitionsvorgaben
- Hilfestellung bei der Bewertung der Dringlichkeit von Bewässerungsinvestitionen, besonders in Konfliktfällen hinsichtlich der Wasserversorgung
- Aufstellung eines angemessenen Systems, um die wichtigsten Asymmetrien zwischen unterschiedlichen Projekt- oder Investitionsstufen zu bestimmen

Entscheidungsträger

Es wurden vier Hauptgruppen von Entscheidungsträgern bestimmt: (1) Diejenigen, die Bereitstellung einer technischen Lösung bevorzugen, (2) diejenigen, die ökologische Nachhaltigkeit bevorzugen, (3) diejenigen, die ökologische Nachhaltigkeit zusammen mit der Übereinstimmung mit behördlichen Vorgaben bevorzugen, (4) diejenigen, die technischen Lösungen, ökologischer Nachhaltigkeit und Übereinstimmung mit behördlichen Vorgaben gleiche Bedeutung beimessen. Der mehrdimensionale Entscheidungskontext der vorliegenden Studie geht davon aus, dass ein bestimmter Betrag an öffentlichen Geldern zur Verfügung gestellt werden muss, während anerkannt wird, dass manche Lösungen möglicherweise unabhängig von den Kosten zu bevorzugen sind, sofern sie die Umweltschutzziele erfüllen.

Zusammenstellung der Schlüssel-Indikator-Kriterien und Attribute zur Modernisierung

Modernisierungsindikator [4. Ebene]	**Wasserwirtschaftliche Zielsetzung [3. Ebene]**	**Planungs-Bewertungs-Gruppen [2. Ebene]**	**Projekt-Alternativen-Bewertung [1. Ebene]**
Verfügbare Wassermenge aus geringerer Bewässerungszufuhr oder höherer Effizienz	Möglichkeit zur Wassereinsparung	Bereitstellung einer Lösung	Gesamtbewertung
Grad der Abhängigkeit von Grundwasserressourcen			
Änderung des Grundwasserflurabstands über die Zeit			
Verringerung der Verfügbarkeit in Dürreperioden			
Netto-Verringerung der bewässerten Fläche (Jahresbasis)	Technische Umsetzbarkeit		
Effizienz des Wasserverbrauchs (prozentualer Zuwachs im Anschluss an Projekt)			
Erhaltungskosten			
Wasserversorgungsservice (zusammengesetzter Index)			
Anzahl der Jahre zum Abschluss des Projekts			
Bewährte Technologien moderner Wassersteuerung und –messung			
Verbesserung für Lebensraum gefährdeter oder bedrohter Arten	Verbesserung des Umweltschutzes	Ökologische Nachhaltigkeit	
Beitrag zu Fließverhältnissen in Flüssen			
Änderung der Wasserqualität von Drainagesystemen (Frachtreduzierung)			
Komplexität der technischen Ausführung und Technologie	Unsicherheiten/ Risiken		
Beständigkeit gegenüber Hochwasser- oder Dürreeinflüssen			
Erfordert Übernahme von Neuerungen durch eine beträchtliche Anzahl von Wasserverbrauchern			
Mögliche langfristige Anfälligkeit gegenüber unerwarteten Änderungen im Fließregime			
Baukosten	Wirtschaftlichkeit	Übereinstimmung mit behördlichen Vorgaben	
Kosten für 1 Mio. m³ eingespartes Wasser			
Netto-Zuwachs der Energiekosten			
Bedarf an Kostenteilung von Seiten des (der) Wasserdistrikts (-distrikte)			
Spürbare Fairness bei Umverteilung des Wassers	Recht/Fairness		
Erhalt existierender Wasserrechte			
Beteiligung verschiedener Wasserdistrikte (Anzahl der Projektpartner)			
Beschränkungen von Anbaufrüchten oder Zeitplänen			
Einhaltung von ESA- und sonstigen Umweltschutzgesetzen	Gesetzliche Konformität		
Grad, zu dem gegenwärtige behördliche Vorgaben zur Umsetzung geeignet sind			
Basis der Befolgung seitens der Verbraucher quantitativ oder qualitativ			
Neue Anstellungen erforderlich für Monitoring der Projektumsetzung und -auswirkungen			
Synergien mit anderen existierenden oder geplanten Vorhaben			

TECHNISCHE FALLSTUDIEN: BEWERTUNG VON VIER STRATEGISCHEN OPTIONEN

Eine Bewässerungsmodernisierung könnte ökologischen Zielsetzungen im Flussgebiet Klamath in vielerlei Hinsicht zugute kommen. Dies ist abhängig davon, inwieweit die am Bewässerungsprojekt Beteiligten und andere Interessensvertretungen – einschließlich der öffentlichen Agenturen, die voraussichtlich für den Großteil der öffentlichen Investitionen zu Planung, Entwurf und Umsetzung der technischen Projekte aufkommen müssen – bereit sind, den generellen Maßstab und die Art und Weise des Wasserverbrauchs zu verändern.

Als Ziel dieser Analyse gilt es Wege aufzuzeigen, wie Beschränkungen der Bewässerungswasserzufuhr und die Abflussmenge von Drainagen entschärft werden können, indem Modernisierungsprojekte unter dem Blickwinkel vorangetrieben werden, die Auswirkungen auf Umweltziele zu minimieren und gleichzeitig die Bewässerungslandwirtschaft auf einem nachhaltigen Niveau zu erhalten. Die Bewässerungslandwirtschaft war der Hauptgrund zur Entwicklung des Projekts und zur bisherigen wasserwirtschaftlichen Entscheidungsfindung innerhalb der Grenzen des Projekts. Dennoch kann es nicht weiterhin als Selbstzweck angesehen werden. Die wasserwirtschaftliche Entscheidungsfindung zur Umverteilung von Frischwasser sollte auf einem Verständnis der physikalischen und internen Prozesse beruhen, bei denen Wasser mit anderen natürlichen Komponenten wie Böden, Auenvegetation und Tierwelt in Wechselwirkung tritt und diese weitgehend kontrolliert.

Wasserwirtschaftliche Szenarios

1. Erhalt des Status quo – *Ablehnung von Umweltschutzforderungen*
2. Umsetzung eines Wasser-Bank-Programms zum Schutz der Umwelt, bei dem zu bestimmten Jahreszeiten zusätzliche Wasservorräte zur Verfügung gestellt werden, hauptsächlich durch Unterlassung von Bewässerung (Flächenleerstand) – *Erhaltung des generellen Maßstab und der Art und Weise des Wasserverbrauchs im Projekt bei gleichzeitiger Verringerung der Schädigung der Umwelt*
3. Ausführung des Wasser-Bank-Programms aus Nr. 2 und/oder Ergreifung von Maßnahmen zur Rückführung des gesamten Drainagewassers, welches das Projekt während der Bewässerungssaison verlässt – *Teilweise Veränderung des generellen Maßstabs und der Art und Weise des Wasserverbrauchs im Projekt bei gleichzeitiger Verringerung der Schädigung der Umwelt*
4. Ausführung eines projektweiten Modernisierungsprogramms – unter Einbeziehung einer Rangfolge – *tiefgreifende Veränderung des generellen Maßstabs und der Art und Weise des Wasserverbrauchs*

Wasser-Bank-Programms zum Schutz der Umwelt

Eine Wasserbank stellt einen institutionellen Mechanismus zur Ermittlung des Marktwerts von Wasserrechten dar. Der Wasserbanktyp, der Gegenstand der vorliegenden Untersuchung ist, ist eine Ausführung dessen, was unter einer Akquisitionsbank verstanden wird: Wasser wird von einem einzelnen Käufer (USBR) zu einem bestimmten Zweck (Erhöhung der Wasserführung von Flüssen) anhand von Verträgen mit Bewässernden erworben, durch die die Wasserrechte von Bewässernden für eine Saison übertragen werden. Anhand dieser Verträge würden die Bewässernden sich mit folgendem einverstanden zeigen bzw. kompensiert werden: (1) Verzicht auf Bewässerung insgesamt (Flächenleerstand) (2) Bewässerung ausschließlich mit Grundwasser (Grundwasser-Ersatz) (3) Förderung von Grundwasser und Einleitung in Bewässerungskanäle zum Gebrauch durch andere (Grundwasser-Förderung). Dadurch wird Wasser verfügbar für zusätzliche Freigaben vom Oberen Klamathsee während der kritischen Monate im Frühjahr und im Sommer.

Bezüglich der Programmumsetzung würde Wasser der Wasserbank während der gesamten Bewässerungssaison zufallen, indem ausgewählte Beteiligte auf Bewässerung durch Flächenstilllegung verzichten oder Ersatz durch Grundwasser vornehmen. Da das USBR verpflichtet wäre, Freigaben von Wasser aus der Wasserbank für Lachshabitate im Frühjahr zu tätigen, bevor eine ausrichtende Wassermenge in der Wasserbank aufgelaufen ist, müsste es Wasser von der Bank für kurzfristige Versorgungen leihen, das durch das Ausbleiben der Bewässerung während der Saison ersetzt werden würde. Durch den freiwilligen Verzicht auf einen Teil ihres gegenwärtigen Wasserverbrauchs könnten Bewässernde zudem eine Quelle zur Finanzierung der Modernisierung der Handlungsabläufe und der Betriebsführung im System auftun.

Rückführung von Drainagewasser auf Distriktebene

Um sich den künftigen Herausforderungen in Bezug auf Wasserversorgung und –qualität im Projekt zu stellen, ist ein sinnvoller Umgang mit öffentlichen und privaten Ressourcen erforderlich, der auf „win-win“-Projekte abzielt, die imstande sind, eine Vielzahl von Zielsetzungen einzubeziehen. Im vorliegenden Fall würde das vorgeschlagene Projekt zur Rückführung von Drainagewasser einen beträchtlichen Beitrag zur Steigerung der Bewässerungs-effizienz *IE* auf Distrikt-Ebene (in Subregion 3), zur Vereinfachung von Echtzeit-Handlungsabläufen und zur Verringerung der jährlichen Energiekosten für Pumpen liefern und darüber hinaus ein integraler Bestandteil der Strategie zur Erhöhung der Wasserqualität und –einsparung im Fluss Klamath werden.

Die Option, bei der eine Rückführung auf Distrikt-Ebene im Hauptbereich des Projekts vom Tule Lake Sumps bis zum J-Kanal vorgesehen ist, ermöglicht eine vollständige Belieferung von landwirtschaftlichen Verbrauchern, eine Einhaltung der umweltgesetzlichen Vorgaben und eine Verringerung des Abstroms von Drainagewasser von geringer Qualität in den Fluss Klamath. Dabei würde der generelle Maßstab und die Art und Weise des Wasserverbrauchs im Projekt beibehalten. Dieses Konzept würde die Betriebsspeicherung des Tule Lake Sumps verwenden und „on-demand“-Wassermengen zu dem Hauptversorgungskanalsystem anhand einer Reihe von automatisierten Niedrighub-Pumpstationen – im Vergleich zu einem angrenzenden Bewässerungskanal – in umgekehrter Richtung befördern. Dadurch könnte ein großes Hauptpumpwerk während kritischer Spitzenbedarfszeiten außer Betrieb genommen werden.

Unter Einbeziehung der Fläche, die von dieser 5,2 Mio. $ teuren Variante profitieren würde, werden die entsprechenden jährlichen Kosten pro Hektar auf etwa 11 $ geschätzt (52.000 ha in Subregion 3 und zudem die Flächen des Lower Klamath National Wildlife Refuge, LKNWR). Unter der Annahme, dass die jährliche Netto-Zufuhr um die gleich Menge wie die Wasserrückfuhr (20 Mio. m^3) verringert werden kann, entsprechen die Kosten pro Volumeneinheit Wasser etwa 30.000 $ für eine Million m^3.

Modernisierung auf System-Ebene

Bei dieser Projektvariante würde das gesamte Wasserverteilungssystem, das das Projekt beinhaltet, allmählich durch eine neue Infrastruktur, automatisierte Kanalstrukturen, einem umfangreichen SCADA-System, Rückführsysteme, verbesserte Messvorrichtungen und neue Leitungen modernisiert. Diese technischen Lösungsansätze wären alle gekennzeichnet durch die Konzentration auf eine Verbesserung der physikalischen Infrastruktur und der Betriebsführungs-Kapazität des Projektes, um präzise Fließraten und Volumina an bestimmten Punkten im gesamten Verteilungsnetz auch in Dürreperioden bereit stellen zu können. Diese würde zu einer besseren Wasserversorgung für Bewässernde führen, so dass diese ausreichend Gelegenheit hätten, das Wassermanagement auf Farm-Ebene zu verbessern, während gleichzeitig die negativen Auswirkungen auf das Ökosystem des Flussgebiets Klamath minimiert würden. Eine stabile Steuerung und gute Messtechnik würde dazu beitragen, dass die am Bewässerungsprojekt Beteiligten mit unterschiedlichsten künftigen Herausforderungen wie TMDLs und Steigerungen der Stromkosten umgehen könnten.

Diese Variante wurde in die folgenden Kategorien eingeteilt:

1. Integrierte Informations-Systeme
2. Verbesserung der Echtzeit-Kontrolle von Volumina und Fließraten
3. Veränderung der Landnutzung
4. Verbesserte “On-Farm”-Bewässerungseffizienz
5. Verbesserung der Pumpwerke
6. Speicherung außerhalb der Bewässerungsphase
7. Ersatz durch Grundwasser

Abschließende Einordnung der Projekt-Alternativen

Die Ergebnisse der Bewertung anhand von Modernisierungs-Kriterien liefern einen abschließenden Index, der eine Einordnung der Projekt-Alternativen unter Berücksichtigung einer Vielzahl von Modernisierungskriterien darstellt. Auf der Ebene der Gesamt-Projektbewertung (Ebene 1) bevorzugten sämtliche Entscheidungsträger-Gruppierungen die Umsetzung des Wasserbankprogramms (0,74 bei Umweltvertretern; 0,69 bei U.S. Fish and Wildlife Service (USFWS)/National Marine Fisheries Service (NMFS); 0,68 bei USBR), abgesehen von den Bewässernden, die eine Modernisierung auf System-Ebene am höchsten einordneten (0,62), dicht gefolgt vom Wasserbankprogramm an zweiter Stelle. Durch die Eingrenzung der Ergebnisse des „composite programming“ in dieser Hierarchiestruktur wurde die Rückführungsvariante auf Distrikt-Ebene von allen Entscheidungsträgern ausgeschlossen.

Indexwerte der Gesamtbewertung anhand von Modernisierungs-Kriterien

Gruppierung von Entscheidungsträgern	Keine Maßnahmen	Wasserbank-Programm	Rückführung auf Distrikt-Ebene	Modernisierung auf System-Ebene
Bewässernde	0.32	0.61	0.59	**0.62**
Umweltschützer	0.03	**0.74**	0.50	0.66
USFWS/NMFS	0.13	**0.69**	0.52	0.59
USBR	0.24	**0.68**	0.55	0.65

Die Nachweise dieser technischen Fallstudie tragen zu einem besseren Verständnis folgender Sachverhalte bei:

- Vorbedingungen für eine Bewässerungsmodernisierung
- Systematische Techniken zur Identifikation, Quantifizierung und Einordnung von Modernisierungsmöglichkeiten
- Technische Ausführung und Konzepte mit einer hohen Erfolgswahrscheinlichkeit
- Ansatz zur Analyse von Bewässerungsprojekten als Netzwerk von Ebenen
- Win-win-Situationen zum verbesserten Umweltschutz
- Rolle der wasserwirtschaftlichen Planer und Ingenieure bei der Förderung des Entscheidungsfindungsprozesses
- Kriterien zur Bewertung von modernen Ausführungen, von empfohlenen Strategien zur Verbesserung des Betriebs und von verschiedenskaligen Einflüssen

1 Introduction

1.1 Modernization Criteria Assessment Framework for Water Resources Planning

Agricultural irrigation is the largest consumer of diverted surface water and groundwater resources in the world, with many regions critically water deficit (United Nations, 2006). Rapid population growth, environmental degradation, competition from urban and industrial users and public perceptions of waste and pollution are forcing a revolution in the way those water resources devoted to irrigation are allocated and managed. The performance of many large irrigation systems has widely been reported as poor, with on-farm irrigation often the primary source of irrigation inefficiency, in addition to growing problems associated with nutrient leaching and salt loading. The *Comprehensive Assessment of Water Management in Agriculture* (Molden, 2007) findings suggest that the overuse of freshwater in many river basins worldwide is leading to serious environmental deterioration to the point that the basins can no longer support biodiversity, partly because the interdependencies of irrigation management and ecosystem conservation are improperly treated as separate issues. Effective water resources planning requires a comprehensive consideration of all related aspects. Thus, technical feasibility, environmental, social/community, institutional, political, and economic factors become prime potential assessment criteria in terms of assessing long-term integrated water management strategies.

This research examines the role of irrigation modernization in solving multi-criteria, multi-stakeholder water resources problems within the context of a new approach to agricultural water management. A case study analysis of the Klamath Irrigation Project (Oregon-California, U.S.) is used to illustrate how specific modernization opportunities are derived and then assessed qualitatively and quantitatively by both irrigation engineering specialists and various stakeholders with conflicting preferences over future water management scenarios. A decision support framework for ranking and selecting modernization project alternatives is applied with assessment criteria referenced against critical benchmarks within the constraints of a controversial planning process. The application of these new water resources planning tools for decision-support aiding the choice between alternative modernization solutions has great potential in hydraulic and environmental engineering projects.

Water conservation interventions and engineering projects cannot be implemented effectively without a broad, system-wide understanding of how water is presently being used, how reallocations would impact established water use patterns, and whether changes can be achieved that produce the desired results. More efficient use of water is not an end in itself. It is a means, potentially, of achieving other desired objectives. If a desired water management objective is worth the investment necessary to make the changes, irrigation modernization can be beneficial. Water is a limited resource shared by irrigators and many other users. To continue as a viable activity, irrigated agriculture must bring its practices more closely in line with comparable controlled industrial processes – characterized by a repeatable pattern of timely information, robust control, and measured results – to be compatible with contending ecological and commercial functions. The results of this study suggest that there *are* things that can be done, and many will be widely agreed to be for the better.

1.2 The Need for Modern Engineering and Public Choices in Water Management

1.2.1 Engineering Solutions for Meeting New Water Demands

Demands for good quality water for more people living in an increasingly urbanized world will greatly stress agricultural water supplies, especially in some river basins where the available systems are already over-allocated. In places like China and India, the problems are so serious they are expected to reduce overall GDP in future years as environmental catastrophes penalize their rapid industrialization (Molden, 2007). In turn, the public is demanding a more central role in decisions over how water is managed and allocated. Inefficient water use and decision-making that is not transparent are becoming less and less tolerable. New investments in U.S. irrigation projects and foreign loan-sponsored water sector projects must therefore be evaluated on multiple criteria with clear linkages to real solutions.

A modernization approach guides project implementation according to modern scientific practices and expertise from civil engineering, crop production, design and construction, and economic feasibility analysis. In this respect, engineering professionals who are responsible for coming up with specific and implemental project-alternatives for complex problems have to rely on new tools for project development and evaluation.

The definition of *irrigation modernization* arrived at during the FAO Expert Consultation on Modernization of Irrigation Schemes (Wolter and Burt, 1996) is the following:

> *Modernization is a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes with the objective to improve resource utilization (labor, water, economics, environmental) and water delivery service to farms.*

An expanded definition was proposed during another FAO workshop on the efficiency of irrigation water in large-scale schemes of North Africa in 1999:

> *Modernization is a process of rehabilitation of irrigation systems during which substantial modifications of the concept and design are made to take into consideration the changes in techniques and technology and to adapt the irrigation systems to the future requirements of operation and maintenance. Delivery of water should be as flexible as possible, with demand irrigation being the ideal solution.*

These two definitions differ slightly in their emphasis on *technical* aspects. The 1999 definition focuses on future needs in terms of operation and maintenance, while the earlier one from 1996 centers on the shift from a supply-oriented to service-oriented approach. However, both suggest the use of modern design and advanced engineering for improving performance. The 1996 definition incorporates institutional changes, including strong participation from water users themselves.

1.2.2 Guiding Principles of Modern Design

The paramount guiding principle of irrigation modernization is *change*. Irrigation modernization is about changing from a traditional supply-oriented mode of design and engineering to a service-based approach. But change by itself is not the goal. The prime justification for irrigation projects, along with new investments in modernization, is that the provision of irrigation water is a service by which farmers have to generate benefits in an efficient manner. The emerging vision articulated in this dissertation is that irrigation projects will progressively evolve to resemble *controlled industrial processes.* The ingredients of such a model process are characterized by a repeatable pattern of timely information, robust control, and measured results. Industrial processes are distinguished by a complex series of steps that make production economically feasible on a large scale.

Burt (1999b) outlines some principles of irrigation modernization by noting the differences from traditional rehabilitation efforts. Rehabilitation programs simply attempt to restore deteriorated irrigation projects to their original state, usually retaining the initial mode of operation ('simple' only in terms of the limited scope of objectives). The problem is that this typically only perpetuates a vicious (and expensive) cycle of rehabilitation, deterioration, rehabilitation, deterioration, etc. This is often done without considering that the deterioration may be a symptom of poor irrigation technical design.

By contrast, a modern design approach integrates concepts and knowledge from advanced hydraulic engineering, irrigation engineering, agronomy, and social science to select and implement a well-defined and realistic water management plan (Plusquellec et al., 1994; Plusquellec, 2002). The essence of modernization is the appropriate combination of technical, managerial, and institutional changes. According to Burt and Styles (1999) modern designs for upgrading irrigation systems start with defining the true objectives of both project authorities and clients (water users) such that some prioritized aspect(s) of irrigation performance are improved. As Plusquellec (2002) notes, the proper choice over specific hardware components, control logic, scheduling procedures, etc. must fit into an overall strategy for accomplishing those objectives.

Some guiding principles of modern design are summarized below (Plusquellec et al., 1994; Burt and Styles, 1999; Burt, 2000; Plusquellec, 2002):

- Irrigation projects are composed of a series of 'levels' with clearly defined hydraulic interfaces
- Each level is financially autonomous and hydraulically independent to the degree that is practical
- Each level is responsible for providing an agreed-upon quality of water delivery service in terms of equity, timeliness, reliability and flexibility in response to the needs of water users
- The design of hydraulic structures is created in conjunction with a well-defined operations plan
- At each level the specific configuration of control structures, measuring devices, communications, etc. are appropriately targeted towards valid objectives
- Enforcement of water rights and effective conflict mechanisms are in place
- Robust, simple and cost-effective solutions are preferred

1.3 Motivating Forces for Irrigation Districts to Modernize

The western U.S. states – notably California, Oregon, Washington, and Arizona – continue to grow and develop rapidly. Chronic water supply problems are one of the greatest challenges facing some of the fastest developing areas in the U.S. The Water 2025 initiative of the USBR and other similar conservation programs being promoted by federal and state agencies recognize that demands for water in many basins exceed available supplies leading to serious conflict, now and increasingly in the future (USBR, 2005a). Many farmers in the U.S. receive all or part of their annual irrigation supplies from irrigation districts, which generally operate as public agencies on behalf of individuals who hold water rights.

Modernization opportunities and potential efficiency improvements are present at all levels of irrigation water distribution and delivery systems (refer to **Figure 1**). The policy and technical challenge is to implement solutions for the sustainability of both agriculture and natural ecosystems.

In the early days of U.S. irrigation development beginning in the late 1800s all the way up to the 1980s, rotation schedules (reliable but inflexible) allowed farmers to achieve reasonably good crop yields while having efficiencies only in the range of 40 to 60% (Burt, 2000). These low efficiencies were justified primarily by considering the overall macro-scale aggregated losses in basin-level systems. Water stresses have forced a re-evaluation of this type of thinking, while economic pressures have compelled growers to seek every economic advantage possible. Thus, the water management situation that existed in the past focusing primarily on exploitation is no longer acceptable in much of the western U.S.

Keller (2000) has characterized the early stages of the water resources development sequence that began with the *exploitation era* and illustrates how many river basins in the U.S. have moved towards *closure* in which the depletion of water is approaching or equal to the available effective supply. Over this six-phase progression, river basins go from conditions of abundance to scarcity. According to this progression, the Klamath River Basin would be classified in Phase III of this sequence, which is characterized by demand reduction and increasing water use efficiency (refer to Figure 1 in Keller, 2000).

Skogerboe (2000) lists two major institutional measures evolved in the U.S. over the last 100-150 years that have established a success basis for irrigated agriculture: 1) water rights, and 2) locally managed irrigation districts. To achieve success in international modernization efforts presumably will require somewhat similar initiatives, but adapted to site-specific situations. A corollary message of the recent modernization of systems in the U.S. is that if a particular hardware or managerial innovation hasn’t been successfully adopted here – where environmental, economic, and societal pressures are as strong as any place in the world, and available resources are at a maximum – they are unlikely to be successful in less developed countries – where financial resources are very limited and societal problems are greater.

Major changes have been underway in U.S. irrigation districts in the last 10-15 years as, for example, farmers are rapidly switching to more efficient pressurized systems (drip and sprinkler), or attempting to improve their fertilizer and nutrient management compared to traditional surface irrigation methods. Motivating factors for modernization are both *internal* (locally driven by the irrigators themselves) and *external* (in response to regional pressures). Some of the typical internal benefits of modernization may include reduced O&M costs, the increased flexibility needed for new field irrigation technologies (e.g., drip/micro systems), and reduced operational losses in water stressed areas (Playan and Mateos, 2004; Keller, 2000).

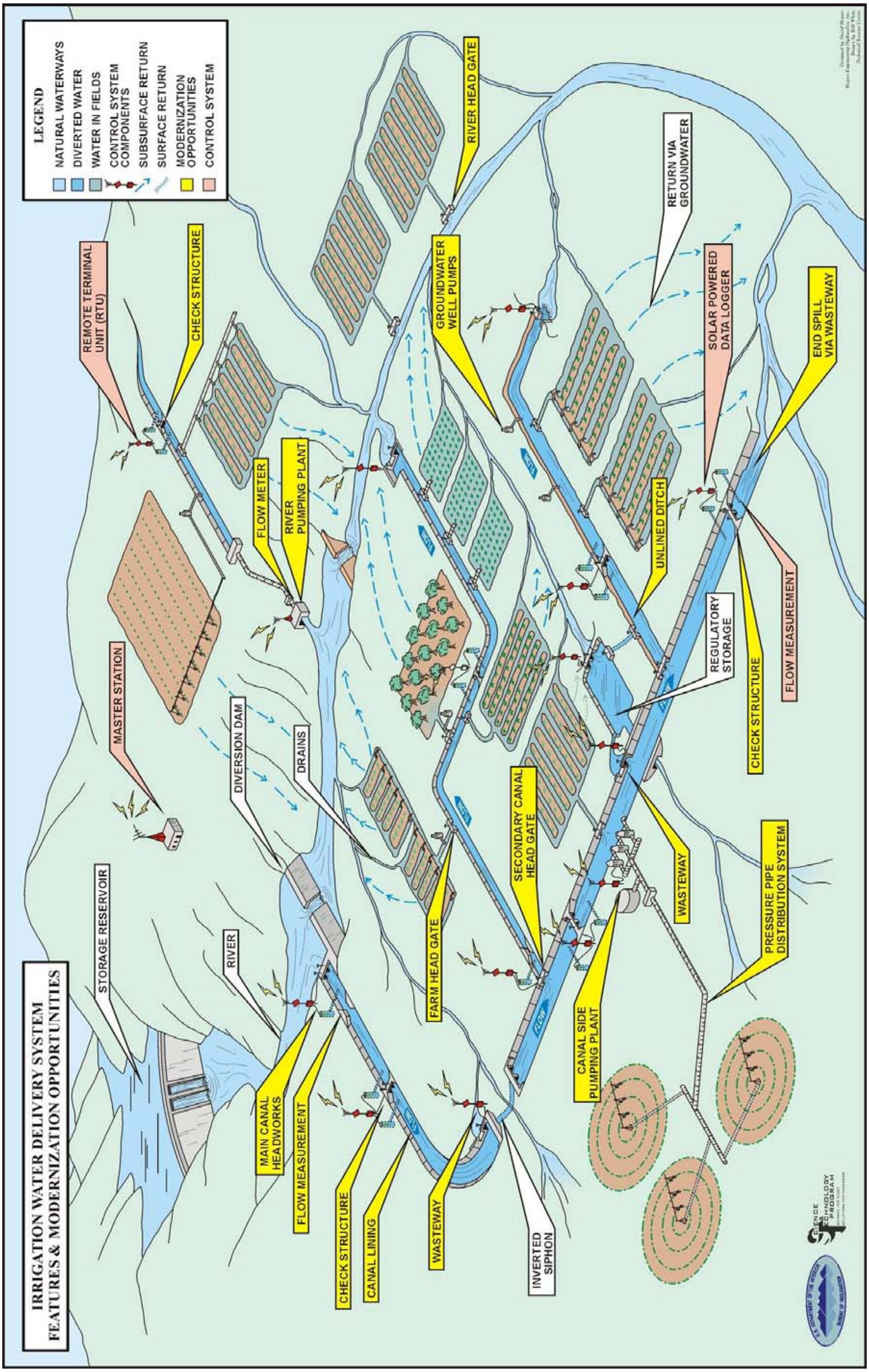


Figure 1. Irrigation water delivery system features and modernization opportunities
Source: USBR Water Management Planner

Burt (2004) and Merriam and Freeman (2007) offer evidence that the central element guiding the modernization process is responding to the water delivery service flexibility required for automated farm irrigation. However, Burt (2004) notes that very few farmers have the vision to articulate how investments in modernization are justified now in order to meet challenges that are 10 or 20 years in the future. Meanwhile issues such as the price of water, annual availability of water supplies, cost of electric power, etc. are hot topics among farmers and managers. Thus, external forces or pressures on irrigation districts can actually dominate, particularly in regards to conserving water so that it can be used for environmental restoration (Burt, 2004).

At the global level, Plusquellec (2002) identifies the key forces driving this change in the conceptualization of irrigation projects as follows:

- Population growth and demographic transition towards more urbanization
- Increased competition for fresh water supplies between agriculture and other users (urban households, industry, recreation, energy generation, environmental uses)
- Rising cost of developing new resources for irrigation
- Globalization of regional and national economies through trade agreements and modern information and communication technologies
- Public awareness of the need for environmental protection
- The diminishing role of government agencies due to policy changes towards decentralization
- Global climate changes, for example the increased occurrence of severe droughts

These driving forces to change the status quo are particularly pronounced in the western U.S. and are coalesced in the Klamath River Basin to a unique extent that means the likelihood for conflict is especially pronounced. Fish species, and other aquatic fauna, are endemic because the arid conditions and direct drainage to the Pacific Ocean create genetic isolation in many river systems (NRC, 2002). This aridity, in conjunction with the expansion of population centers in Los Angeles and other places in California, have resulted in extensive redistribution of water resources to support economic growth at the expense of traditional farming areas.

The potentially incompatible roles of federal agencies that on one hand have a contractual obligation to deliver water for irrigation (the USBR in the Department of the Interior) and on the other hand have a mandate to enforce environmental protection measures on behalf of endemic fish species (the U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS), also in the Department of the Interior), have added to the current conflicts. Finally, the use of water for irrigation has occurred within the larger context of the historical displacement of Native American Tribes.

Thus, for inter-connected bio-geographic, hydrologic and socio-economic reasons the Klamath Irrigation Project encapsulates many aspects of the wider conflict in the western U.S. over historical uses of freshwater resources for irrigation and the legal requirements for the protection of threatened or endangered species.

1.3.1 Conflicts over Water Resources: Tradeoffs between Agricultural Irrigation and Environmental Water Demands

Agriculture, as the largest user of freshwater resources, has increasingly become an appealing target for obtaining water supplies that could be put to other environmental and economic uses. Water conservation projects are widely seen as one of the preferred methods of reducing agricultural diversions, although the amount of savings from specific projects has rarely been quantified or documented (Clemmens and Allen, 2005). Depending on the hydrologic settings, reducing diversions for irrigation may not in fact reduce the overall net consumption of water in a river basin, since any “surplus” diverted water may re-enter the system for re-use downstream.

Irrigation scientists and professional engineers have essential roles in developing sustainable technical-scientific solutions. With recognition of freshwater availability as a common constraint to sustainable agriculture and environmental restoration, the case of the Klamath Irrigation Project offers lessons for managing competing uses in other river basins. This research examines the inter-relationships between irrigation water uses and the ecosystem in the Klamath River Basin, and explores the role of “win-win” investments in irrigation modernization.

The question of who pays for these solutions and their long-term impact on current beneficiaries is highly controversial. Even determining what the proper evaluation criteria are raises contentious issues. A new conceptual framework has been developed for this study that engages multiple stakeholders in the real work of figuring out what the best engineering solutions are for proposed water management changes in order to avoid endless expensive studies and inconclusive, all-or-nothing negotiations. The usefulness of this approach is reinforced by implementable examples of new design concepts and innovative applications of advanced technologies.

1.4 Defining Research Benchmarks and Indicators

The international irrigation community, including water users in the Klamath Irrigation Project, faces critical future challenges, which the existing management capacities and physical infrastructure of many irrigation projects are incapable of dealing with successfully. Significant irrigation modernization will be required to improve the precise control and monitoring of water flows at different levels of the physical distribution and delivery systems, especially on a real-time basis, and thus provide excellent water delivery service to individual irrigation agencies and water users.

Even though in recent years *modernization* is starting to appear more and more as a general theme of technical conferences and engineering seminars, and is showing up prominently in places like World Bank project preparation documents, as well as slowly becoming an explicit funding priority of water conservation programs, only a small number of excellent examples of sustainable irrigation district modernization efforts actually exist and the reasons for their success have not been well studied (Burt, 2000). Many attempts at modernization, particularly in non-industrialized countries using funding from international donors, have been initiated, but continue to struggle with complex technical and engineering problems in implementation.

The subject of this research – an assessment framework for irrigation modernization opportunities and performance in the Klamath Irrigation Project – arose from a core concern about the future path of irrigation development worldwide, and how it should be changed. As a water resources professional and proponent of the transformation of irrigation projects into controlled industrial processes, this is my attempt to explore the following question:

> **How can new investments for irrigation modernization be justified on economic, environmental, and social grounds given the financial pressure on agriculture, continuing environmental degradation stemming from a variety of forces (including irrigation itself), and unprecedented public scrutiny of water resources decisions by a wide range of powerful stakeholders and interest groups?**

The following research objectives were formulated for this study:

- To develop a scientific conceptual framework for irrigation modernization interventions
- To compute comprehensive water balances and models at different hydrologic levels that quantify all flow paths of water on a monthly time-step and to assess relevant performance indicators for a multi-year time period
- To conduct a systematic examination of the internal processes (information management systems, decision-making, communications, canal and pumping infrastructure design, hydraulic control structures, recirculation, etc.) focusing on inter-relationships between project performance, benefits and constraints
- To synthesize quantifiable objectives with feasible engineering recommendations for selected cases in the research area that will meet future water and agricultural-related challenges arising from multiple arenas
- To utilize multi-criteria analysis techniques for formulating assessment indicators for water resource managers and stakeholders to use in appraising enhanced operational criteria and multiple engineering project-alternatives

1.5 Research Methods

The researcher was in the position to conduct this research through his association as a Senior Water Resources Engineer with the Irrigation Training and Research Center (ITRC) of California Polytechnic State University, San Luis Obispo, California. The ITRC had a multi-year technical assistance agreement with the U.S. Department of Interior under the Mid-Pacific Region of the USBR, including the Klamath Basin Area Office (in Klamath Falls, Oregon) operating the Klamath Irrigation Project. Access to primary data, investigative trips to the study area, and general support for activities carried out under this research investigation was facilitated by this arrangement.

The analyses in this dissertation deal with the management of water resources in complex agricultural and wildlife refuge systems, referring to a multi-criteria assessment under varying conditions of water availability and quality resulting from different modernization scenarios. Water resources management for irrigation in the Klamath River Basin is part of an inter-related and dynamic system involving competing demands from commercial fishing interests, native communities, and society as a whole (as taxpayers, recreational users, etc.). While it was recognized as important to analyze the Basin's water resources within this wider perspective, the research methods of this study placed special emphasis on the irrigation components within the defined study area of the Klamath Irrigation Project.

The Klamath Irrigation Project was analyzed as a case study in a framework that combines two major components – 1) spatially and temporally distributed water resources hydrology with simulated regional evapotranspiration (*ET*) modeling and planned land use patterns, and 2) internal processes – to develop a robust decision-making tool for assessing future development strategies with specific application to ranking irrigation modernization alternatives. The strategies were developed through detailed field investigations, agro-hydrological modeling, expert engineering analyses, and consultations with decision-makers/managers and implementing agencies. Multiple quantitative and qualitative criteria are incorporated into the evaluation of a representative range of projects at a strategic planning level by comparing and ranking different potential outcomes.

1.5.1 Ranking Water Management Alternatives

A synthesis of the detailed water balance accounting, recognizing and quantifying uncertainties, with an understanding of the internal processes, allows one to assess the realistic potential for meeting resource objectives from different irrigation water management strategies, in addition to prioritizing investments at different levels in the system, including project facilities and on-farm programs. Once these potential opportunities have been identified, however, resource managers and engineers face another set of questions – *how does one properly assess the potential outcomes of different modernization efforts that may focus on different parts of the system or have considerable differences in costs, benefits, risk, technical complexity, etc.?* Further, in every irrigation project there are multiple internal and external stakeholders who have different philosophical opinions on various issues (endangered species, tribal responsibilities, economic feasibility of certain types of agricultural production, habitat restoration, etc.) that must be integrated into the decision-making process.

To address this need for new comprehensive scientific approaches and decision-making tools in analyzing irrigation modernization, this research develops and utilizes a set of multi-criteria assessment indicators, both quantitative and qualitative, that can be used to represent the preferences of different stakeholders in assessing potential modernization opportunities through composite programming (Bardossy et al., 1985; Bardossy, 1988).

The conceptual approach has three components, which are inter-related and follow a logical order. This research attempts to answer the following set of questions:

- *What water is potentially available to meet a quantifiable objective?* What are the water quantities, and timing of surface and subsurface flow paths at different hydrologic levels in the irrigation project?
- *Can the available water be manipulated and, if so, how?* What are the most feasible and cost-effective engineering options for changing the current physical regulation and management systems that control the water as it moves through the system in order to meet a selected quantifiable objective?
- *What will be the impact of making "x" change at "y" location at "z" time?* What is the potential impact of a particular water conservation activity or change in operations, in terms of the relative water quantity, quality, and timing of the various flow paths in the surface and groundwater hydrology of the system?

This research emphasizes a unique conceptual approach, incorporating state-of-the-art technical aspects of modern irrigation science and engineering, as well as an evaluation tool for multi-criteria decision analysis, in order to rank and select accompanying irrigation engineering project-alternatives. The framework of the recommended water resources planning process for irrigation modernization is illustrated in **Figure 2**.

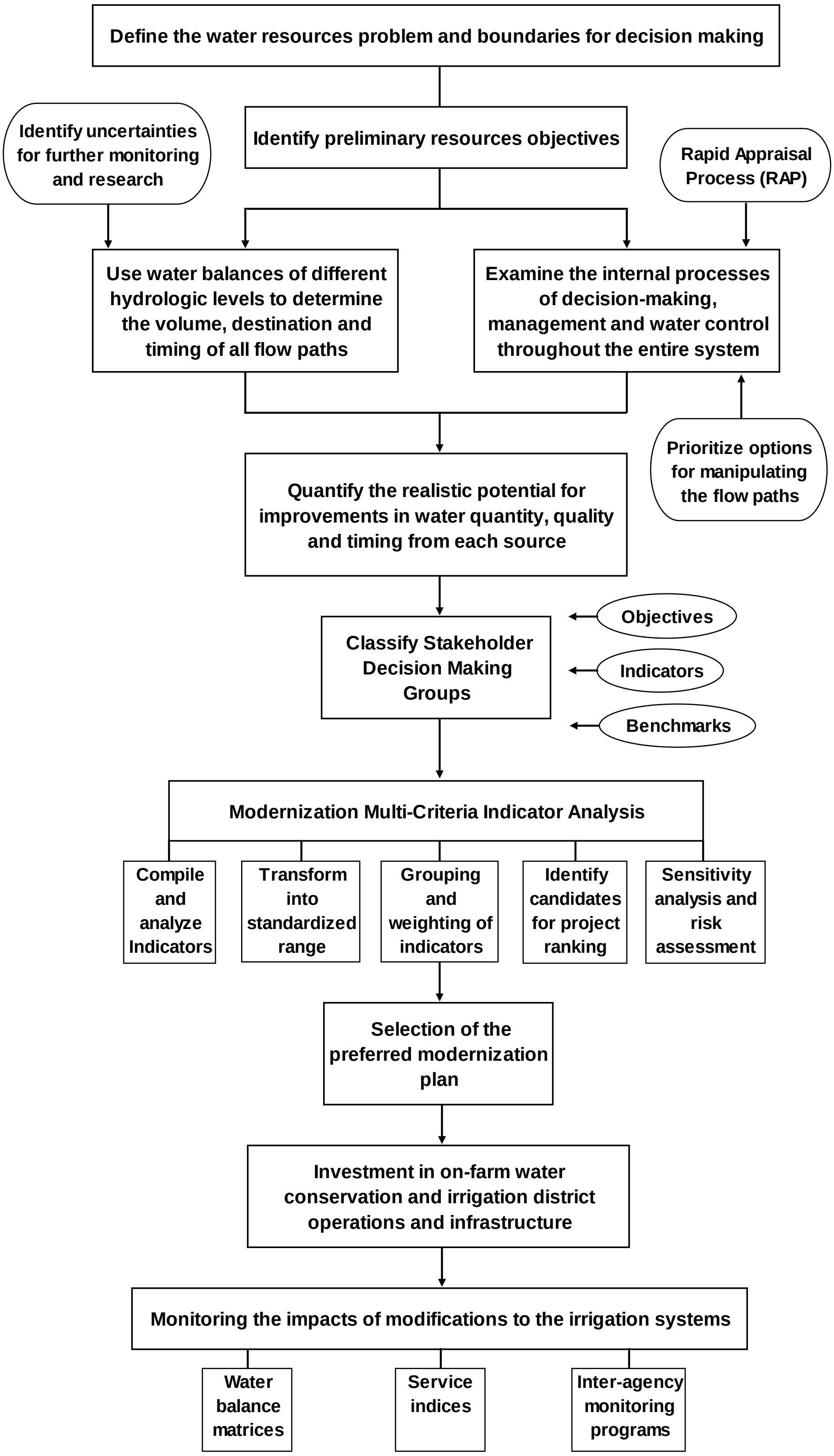


Figure 2. Water resources planning approach to implementing irrigation modernization alternatives

1.6 About this Report

This study is organized into seven chapters. Chapter 1 presents the water resources planning approach for irrigation modernization and the research problem, and outlines the objectives and research methods. Chapter 2 introduces the Case Study area – the Klamath Irrigation Project (U.S.) – and through an analysis of internal processes as they are influenced by various elements. A comprehensive analysis of the agro-hydrological resources in the Project is the subject of Chapter 3. The analyses include detailed irrigation water balances and an assessment of competing water demands and alternative allocation options. Chapter 4 presents a multi-criteria analysis framework for policy decision-making and defines strategic scenarios to be evaluated. These future water management alternatives are assessed in-depth through the application of the multi-criteria decision-making tool (composite programming) to water management scenarios involving modernization project-alternatives in Chapter 5. Finally, Chapter 6 summarizes the conclusions from the study and offers recommendations for future policy consideration.

2 Klamath Irrigation Project

2.1 Description of the Case Study Area – Klamath River Basin

The U.S. Department of Interior, Bureau of Reclamation's (USBR) Klamath Irrigation Project (refer to **Figure 3**) is located in a semi-arid region of the Klamath River Basin spanning the borders of southern Oregon and northern California. The Project provides irrigation water to over 89,000 ha (220,000 acres) of productive farmland, as well as year-round water supplies for important national wildlife refuges and wetlands. The Klamath River Basin supports over 400 species of birds and wildlife (NRC, 2002). The local agricultural economy generates about \$300 million annually and many families are descendents of original homesteaders that moved to the area after local lakes and marshlands were reclaimed and the elaborate system of canals and drains was constructed (Braunworth et al., 2002). Initiated in 1905, the Project is the second-oldest federal irrigation system in the western U.S.

The availability of good quality water for stakeholders in the Klamath River Basin is directly related to the management of the Klamath Irrigation Project. Project operations largely determine the amount of water flowing in the Klamath River, which passes through several hydroelectric generating dams before discharging to the Pacific Ocean. The Project is a complex system of main-stem and tributary dams, diversion structures, open channels, and pumping stations that store and deliver water for agricultural water users and national wildlife refuges. On average, about 1,850 mcm (1.5 million acre-feet) of water passes along the Klamath River from the Upper Basin to the Lower Basin annually. The Project diverts an average of 500 mcm (405,000 acre-feet) annually for irrigation in the semi-arid high desert in the Upper Basin. Extensive recirculation of the diverted irrigation water is a key design and operational feature.

In the Klamath Irrigation Project, attempts to meet contractual obligations for irrigation water and to simultaneously satisfy environmental operating criteria arising from the Endangered Species Act of 1973 (ESA) have led to resource conflict among competing stakeholder groups and have generated intense political controversy. On a larger scale, vast interventions in the natural water resources of the arid western U.S., through water resources engineering endeavors like the Klamath Irrigation Project, have resulted in extensive re-distribution and degradation of available freshwater supplies to support economic growth – for a population that continues to grow rapidly, putting further stress on resources. Native fish species in the western U.S. have experienced profound impacts from unrestricted river development; in the last century more than 20 species have gone extinct and at least one hundred more are considered threatened, endangered or of special concern (Minckley, 1997).

The Upper Klamath Lake is a large natural freshwater lake, although a small dam built as part of the construction of the Klamath Irrigation Project allows the elevation of the lake to be varied to facilitate water diversion for irrigation and releases for hydroelectric power generation in the Klamath River. The primary diversion from the Upper Klamath Lake is for irrigated agriculture in the Project, supplying about 85% of fields in the service area. Lake levels fluctuate seasonally and interannually depending on inflows from the Sprague, Williamson, and Wood Rivers and agricultural diversions. The Upper Klamath Lake suffers from over-appropriation and hypereutrophic water quality problems from excessive nutrient loading. The water supply available for irrigation depends on the snow pack that develops during the previous winter months, along with groundwater discharges to perennial streams, and controlled lake elevations.

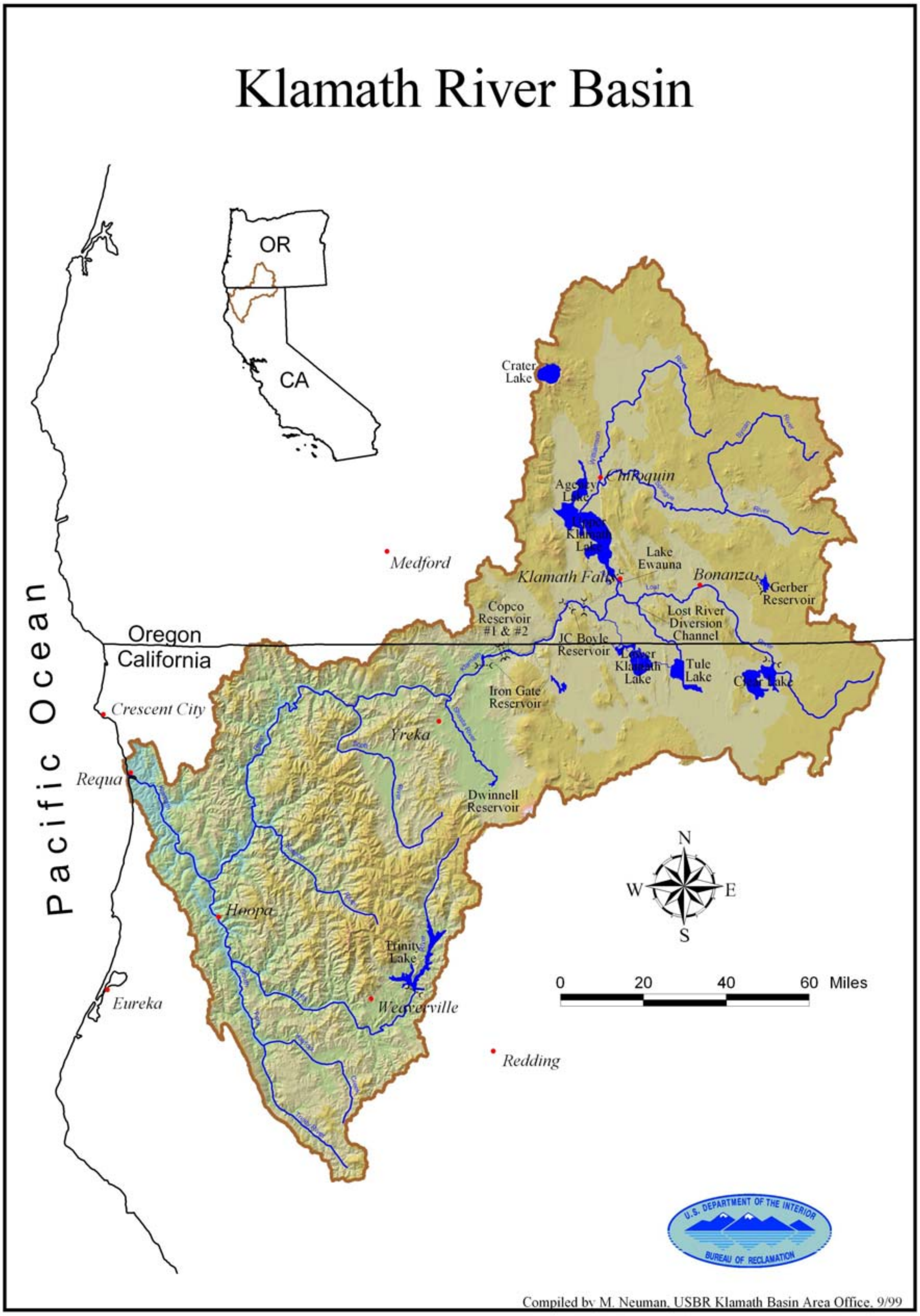


Figure 3. The Klamath River Basin

The Klamath Irrigation Project, authorized by the U.S. Congress at the beginning of the 20th century, was originally designed to serve only irrigators within the established boundaries of public irrigation districts[1] holding various types of water rights.[2] National wildlife refuges, used by almost 90% of all migrating western North American waterfowl along the Pacific Flyway, are equally dependent on the same water resources, but are legally subservient to agricultural needs because they were established later (USBR, 2000). Prior to the establishment of the Project, the Upper Klamath Basin was dominated by shallow lakes and freshwater marshes. In 1905 the USBR began to drain these widespread wetlands and the reclaimed land was opened to agricultural development and settlement.

For nearly nine decades operation and maintenance of the main supply reservoirs, including the Upper Klamath Lake, Gerber Reservoir, and Clear Lake, was managed foremost according to the needs of irrigated agriculture and flood protection. However, while the primary issues at the moment are the protection or delisting of endangered species in the Klamath River system, the irrigation community faces significant future challenges that the existing internal processes and physical infrastructure of the Project are incapable of successfully dealing with. Example future issues that have already arisen in other irrigation projects, and that can have profound impacts include:

a. Water quality regulations for disposal of drainage in rivers, streams, and wetlands
b. Proposed electricity rate hikes. Current electricity rates in the Klamath Irrigation Project are among the lowest in the U.S.
c. The ability to increase crop yields and crop qualities
d. Efficiency of farm fertilizer practices
e. Possible changes in water law that would require verified deliveries of specified volumes of water per ha, equitably distributed to users within districts
f. Possible changes in water law and rights that would allocate specific volumes and flows to each irrigation district or individual water user, with penalties for excess diversions.

2.1.1 Summary of Historical Operations

Water management in the Klamath Irrigation Project involves decisions on reservoir storage, hydropower releases, agricultural water deliveries, and downstream flow regimes (refer to the schematic drawing in **Figure 4**). The quantity and timing of flows that are available for irrigation diversions at a particular point in the system are the result of inter-related hydrological factors and management strategies, which have differed historically for irrigators depending primarily on the irrigation districts' geographic position in the system and their access to buffer supplies and storage areas for return flows.

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[1] *Irrigation districts* are cooperative, self-governing public corporations set up as a sub-division of state government, with definite geographic boundaries, and having taxing power to obtain and distribute water for irrigation of lands within the district.

[2] Water rights in the Klamath River Basin have been defined in terms of federal treaties, interstate compacts, and congressional enactments, in addition to the numerous and on-going court decisions. However, pre-1909 historic water rights claims based on "prior appropriation doctrine", including the Project, have not been *adjudicated*, meaning that the priority date of the claims, the rate of diversion, and the total amount of water that may be used for each claim is still unresolved.

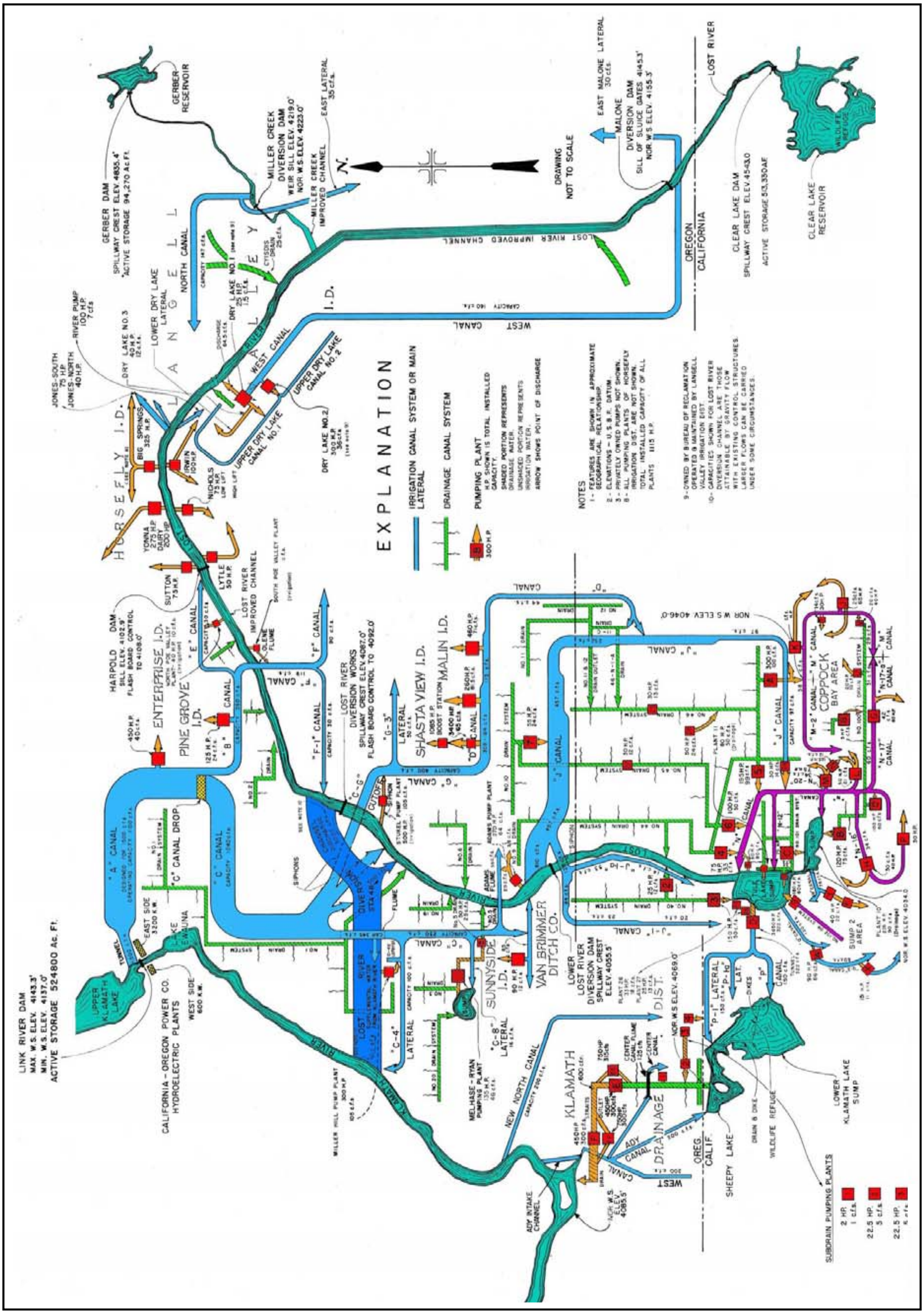

Figure 4. Schematic diagram of Klamath Irrigation Project pumping plants, water supply distribution canals, and drainage systems

Irrigation water for the Klamath Irrigation Project is stored in the Upper Klamath Lake, Clear Lake, and Gerber Reservoir. The main diversion points are the following:

- Malone and Miller Diversion Dams – divert water to the North Canal, West Canal, and East Canal in the Langell Valley
- Lost River Diversion Dam and Channel – diverts water between the Lost River and the Klamath River or allows water to flow in the reverse direction from the Klamath River to serve the Tulelake area
- A Canal – diverts water from the Upper Klamath Lake to Klamath ID, in addition to six other adjacent irrigation districts in the Lost River watershed, Poe Valley, and the Tulelake area
- Anderson-Rose Diversion Dam – diverts water to Tulelake ID and Tulelake NWR, mainly through the J Canal
- Ady Canal and North Canal – divert water from the Klamath River to Klamath DD and Lower Klamath NWR

The delivery of water stored in the Upper Klamath Lake for irrigation and wildlife refuges continues year-round. In March or early April, irrigation diversions begin from the A Canal, Malone and Miller Diversion Dams, and Anderson-Rose Diversion Dam. The irrigation season typically continues into October. Drainage water from the irrigation districts in subregions 1 and 2 returns to the Klamath River via the Lost River Diversion Channel or directly to the natural Lost River system for reuse by other downstream districts.

Return flows collect in the Tule Lake sumps, where they are reused by Tulelake ID or delivered to the Tulelake NWR. Pumping Plant D lifts the remaining water from the Tule Lake sumps to the P Canal system and the Lower Klamath NWR. This water is used to maintain permanent wetlands and fall flood-up requirements, in addition to deliveries to adjacent farmland.

The North Canal and Ady Canal in the Klamath DD (subregion 4) are operated throughout the year for agricultural deliveries and refuge use. Unlike most areas in other subregions, lands in the Klamath DD have been traditionally flooded in the fall for irrigation purposes with excess ponded water being drained off fields in early spring before germination.

2.1.2 Competing Demands for Water

As water demands for agriculture and environmental demands change over time – because of policy and technological changes, among other factors – the relationship between irrigation water use and the environment needs to be continually reviewed and adapted. The water management framework of the Klamath Irrigation Project is illustrated in **Figure 5**. It is important to note that obstacles, alongside the productive inter-relationships, currently exist to hinder the implementation of Project-wide water management alternatives involving the reallocation of irrigation water. For example, the willingness of irrigators to participate in cooperative solutions rests with the long-term capability of irrigation districts to be economically self-sustaining, irrespective of the amount of water to be reallocated. On the other hand, large-scale fish die-offs in recent years since the 2001 drought have hardened attitudes among those representing environmental and fishing interests (NRC, 2004).

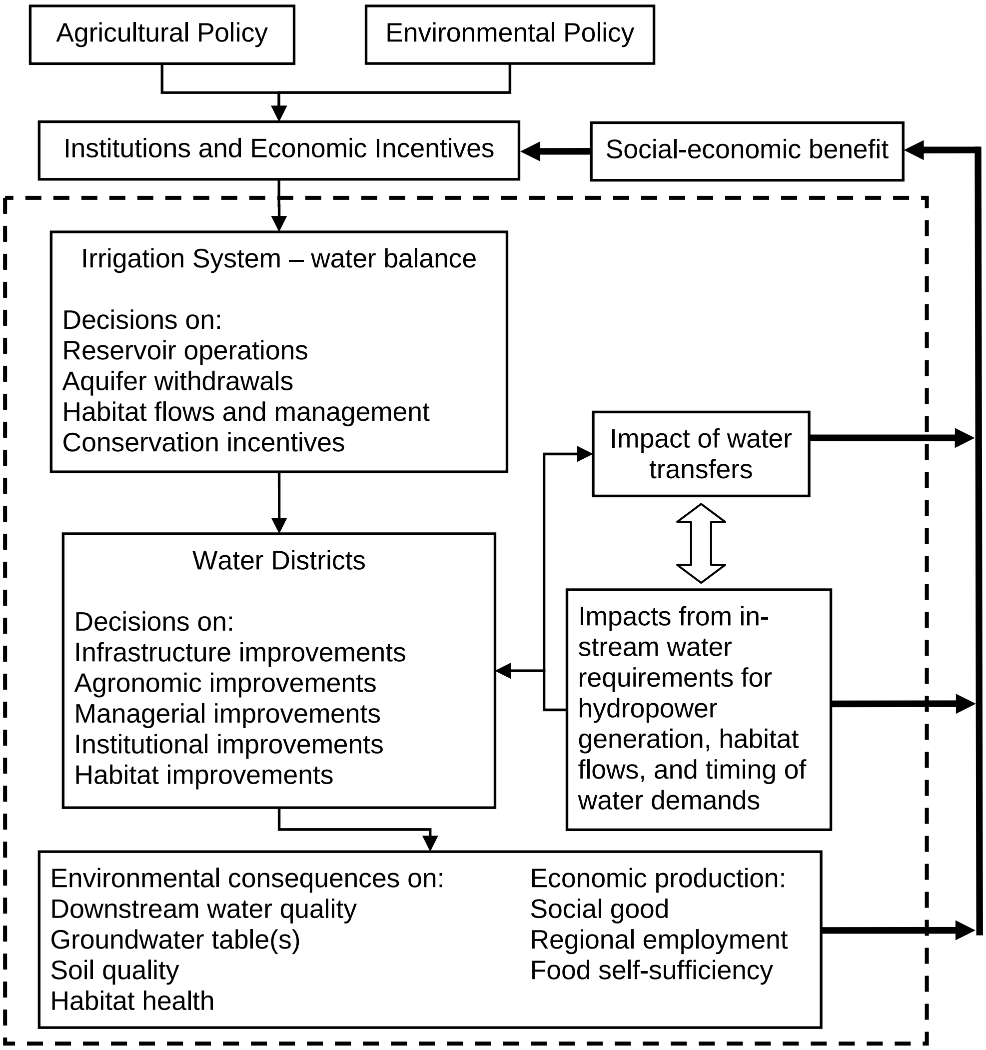

Figure 5. Water management framework for existing water policies in the Klamath Irrigation Project

2.1.2.1 Project-Level Water Management Strategies

The current strategy of water allocation and control for irrigation water in the Klamath Irrigation Project has been an effective one for the historical constraints faced during average or wet years. This is a less effective strategy during times when the water supply is constrained, such as was the case in 1992, 1994 and 2001. One of the key lessons learned from the aftermath of the irrigation curtailment in 2001 is that future alternatives for allocating specific *quantities* of scarce water available for agricultural and non-agricultural uses must address the technical and institutional mechanisms for managing reduced water supplies, particularly as related to the physical infrastructure in place and the likely reduction in return flows.

For most of the history of the Project, the USBR and irrigation districts had an effective strategy that took the best advantage of the Basin's hydrologic features and the Project's layout of canals and drains. The strategy did not require knowing the total amount of water. Rather, the strategy was one of dealing with errors – *is the inflow into a certain part of the system roughly matching the demand from that part of the system*? However, this means that the error can be the same with different amounts of water in the system. The districts have "indicators" to tell them the direction of the error, either increasing or decreasing, and can make the proper adjustments using rules-of-thumb the operators have developed for specific portions of the system.

This simple management strategy has been possible because the irrigation districts in the Project generally have two things:

1. A buffer supply
2. A buffer source for return flows

Due to the constraints related to the irrigation districts' ability to actually measure and control water within the system, the districts are not able to guarantee equity among water users in the situation of reduced allocation. The districts have no means of easily and effectively rationing a certain percentage allocation to each turnout. Because water flows from one district to the next as a combination of wheeled water and return flows, each district would also have no way to know what to do if it received a reduced percentage allocation or even be able to accurately verify what percentage it was receiving. This would require the adoption of measures during drought years that are easily verifiable and that do not require the splitting of flow rates. This is a "yes or no" type of measure to each individual turnout. In other words, water is simply not delivered to some districts or turnouts if there is a shortage.

Underlying the districts' operational constraints is the lack of quantified water rights in the Project and the long history of adequate water supplies (with a few notable exceptions in 1992, 1994 and 2001) has resulted in a management strategy that can be stated simply as either ON or OFF. As demonstrated clearly by the water allocation decision in 2001, the strategy to cope with reduced water supplies in the past has been to curtail irrigation deliveries. Previous drought allocations have given consideration to prioritization of water rights within the Project by date of contract and type of contract (A, B, and C contractors).

2.1.2.2 Technical and Institutional Considerations

In targeting irrigation modernization in the Project's irrigation districts, the design and implementation of projects have to address the following considerations:

1. There will probably be reductions in flows to the irrigation districts.
2. The districts will have to equitably distribute the scarcity.
3. Districts are presently unable to physically distribute a restricted volume of water equitably to the farm turnouts with reasonable flexibility. They lack:
    - Procedures and policies
    - Water control structures
    - Good flow measurements at heads of laterals and at turnouts
    - Canal controls that minimize lost spill
4. At present, the only options available to irrigation districts to deal with less water flowing into the Project at the moment are:
    - Fallowing
    - Pumping from wells – which can be extremely expensive
    - Less outflow through Straits Drain by recirculating more flows in the Lower Klamath NWR, which then impacts Klamath DD
5. Considerable opportunities to modernize exist in terms of both management and infrastructure.

2.1.2.3 U.S. Bureau of Reclamation

The USBR operates the Klamath Irrigation Project under a complex combination of technical, physical, financial, and institutional constraints. In addition, the federal agency is charged with simultaneously meeting competing obligations such as:

- Protecting threatened and endangered species including the Lost River and shortnose sucker, Coho salmon, and Bald Eagle
- Meeting tribal water rights and trust responsibilities for Klamath Indian Tribes
- Providing water for irrigated agricultural production
- Providing water to National Wildlife Refuges

Historically, the USBR and irrigation districts operated the Project to deliver irrigation water to farms, provide water to the wildlife refuges adjacent to or within the service area, and serve as a system for local flood control. Until the 1990s there were no formalized operations plans, as such, prescribing minimum lake levels or downstream flow regimes. Instead, the operation of the Project was based primarily on the demands from irrigators. The droughts in 1992 and 1994, and related environmental decisions for fish protection, began to transform the conditions under which the Project was designed and operated.

One initial result was the release of the Project's 1995 Operations Plan for public access, which specified the operational criteria and procedures for the management of storage and conveyance facilities to meet competing demands for water. The consequences of new scientific and technical information regarding endangered species compiled during the 1990s, as well as various political processes and a severe lack of snowfall, culminated in the events of 2001.

In addition to the institutional constraints associated with the legislated responsibility of the USBR as a federal agency under the ESA, there are physical and technical limitations purely related to the volume of irrigation water that can be stored and diverted by the USBR with the existing Project storage facilities. The Upper Klamath Lake, the principal storage feature of the Project, only has an active storage capacity of 600 mcm (487,000 acre-feet), even though the mean inflow is about 16,000 mcm (1.3 million acre-feet) (USBR, 2000). There is minimal carry-over storage from one year to the next, making each year's water allocation dependent on the accumulated and forecasted inflows during each spring.

This close relationship between storage in Upper Klamath Lake and annual irrigation diversions from the lake and downstream from the Klamath River is illustrated in **Figure 6**. The graph shows monthly lake storage between 1999 and 2003 (excluding the 2001 drought year) and the cumulative irrigation diversions to the A Canal, North Canal, Ady Canal, Station 48, and the Miller Hill Pumping Plant. The summation of these irrigation diversions shown in the graph takes into account the net contribution from the Lost River Diversion Channel to the Klamath River.

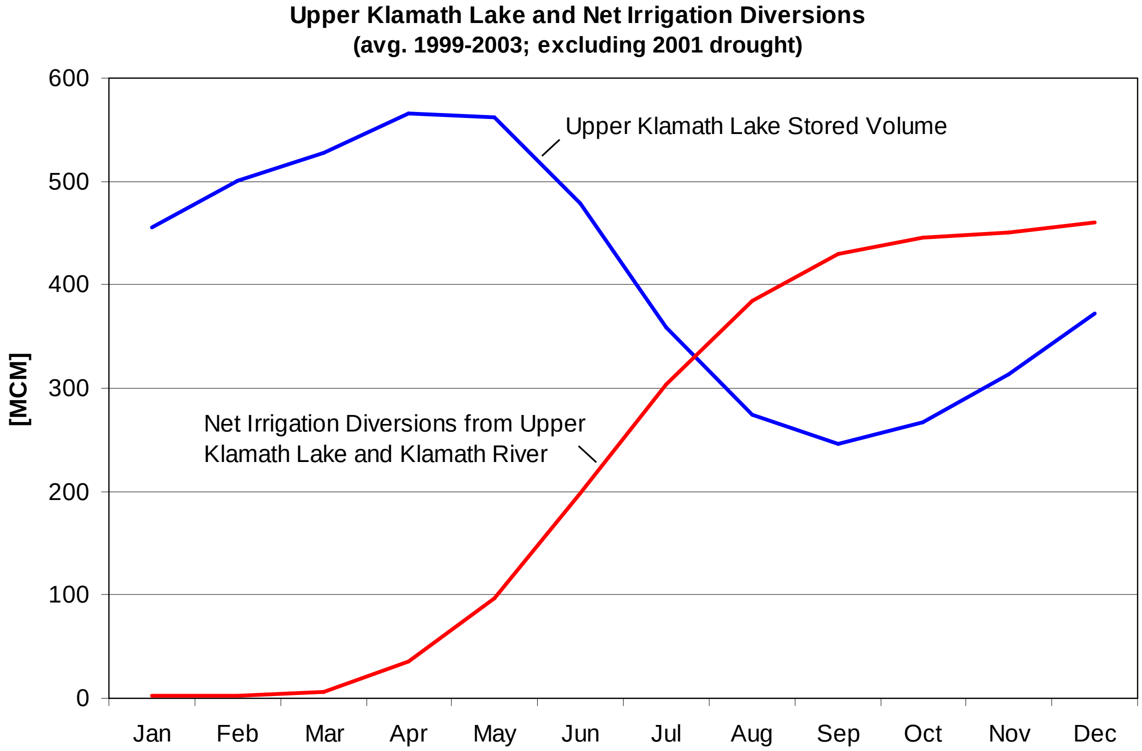

Figure 6. Upper Klamath Lake annual storage and irrigation diversions, mcm

Water Rights

The USBR, through over 250 contracts for water service,[3] provides water for irrigation and national wildlife refuges in the Project. Under federal law the USBR has to obtain water rights for authorized purposes in its projects in accordance with Section 8 of the Reclamation Act of 1902.[4] The 1902 Act authorized the USBR, then called the Reclamation Service, to build and operate facilities only for the purpose of supplying irrigation water by contract. However, state laws generally govern the control, appropriation, use and distribution of water used in irrigation (generally termed 'water rights'). The USBR claims 1905 (priority date) appropriative water rights for all the Project lands regardless of the contract type the users may have (USBR, 2000). In addition, projects administered by the USBR must be operated in a manner that does not impair senior or prior water rights. The doctrine of beneficial use in Oregon and California water law, which is consistent with federal law concerning USBR projects, requires that the acquired water right "shall be appurtenant to the land irrigated, and *beneficial use* shall be the basis, measure, and limit of the right."[5] In the Project, this beneficial interest is held by the water users who put irrigation water to beneficial use (USBR, 2002).

Four wildlife refuges are located within or adjacent to the Project. Refuges receive their water supplies from the Project under federally reserved rights for the water necessary to satisfy the refuges' primary purposes of supporting many fish and wildlife species. The Lower Klamath NWR and Tulelake NWR were created by Executive Orders in 1908 and 1928, respectively, the priority dates for their reserved unappropriated water rights. Portions of the refuges are used for agricultural crop production on leased lands. Refuges receive delivered water when in priority and when water is available, in addition to the return flows that are put to beneficial use (USBR, 2000).

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[3] USBR contracts commonly specify a land amount to be covered – not a specific water amount to be delivered
[4] 32 Stat. 388
[5] 43 USC §372

In 1950 federal government supervision of the Klamath Indian Reservation terminated. Subsequently, many tribal members sold their assets and withdrew completely from the 730,000 ha (1.8 million acres) reservation. However, when the U.S. Congress passed the Klamath Termination Act,[6] the tribal water rights (dated time immemorial) were not abrogated and continue to be held in trust by the U.S. Federal Government.[7] With respect to water rights, the USBR, similar to all federal agencies, has a trust responsibility, held for the benefit of the Tribes, to protect water resources in fulfillment of obligations guaranteed in the treaty (USBR, 2000; USBR, 2007). This trust responsibility requires the USBR to ensure that Project operations do not interfere with the Tribes' senior water rights to support fishing, hunting and food gathering. Tribal water rights have been explicitly acknowledged and confirmed by the state and federal governments in the Klamath Basin Compact (Article X), various court decisions,[8] and the Klamath Restoration Act (1986).

2.1.2.4 Operations Planning Process

Water managers in the Upper Klamath Basin use forecasts of spring and summer streamflows and other planning tools to make decisions regarding the optimal allocation of limited water supplies. The USBR examines the current and expected hydrologic conditions and formulates on a yearly basis an operations plan providing an estimated water supply for the following demands: (1) maintaining required flows for fish in the Lower Klamath River, (2) water deliveries for irrigation of about 81,000 ha (200,000 acres), (3) retention of water in the Upper Klamath Lake to protect water-quality habitat for fish, (4) hydroelectric power production, and (5) water deliveries for national wildlife refuges. The operations plan released in early April serves as the main planning aid for agricultural water users and other interested stakeholders.

NRCS Inflow Forecast for Upper Klamath Lake

Precipitation occurring in the Upper Klamath Basin develops a snow pack that provides most of the water available for the Klamath Irrigation Project when it melts in the spring. A portion of this runoff is stored in the Upper Klamath Lake and Klamath River, along with other reservoirs that also supply irrigation water for the Project including Clear Lake and Gerber Reservoir, which feed the Lost River system. Beginning in January, the NRCS develops forecasts for the estimated streamflow volumes to the Upper Klamath Lake, and four other locations in the Upper Klamath Basin.[9] Water supply forecasts, in thousands of acre-feet (equivalent to 1.233 mcm), are issued bi-monthly beginning in January and ending in June for 5%, 30%, 50%, 70% and 95% exceedance thresholds. The cumulative flow forecasts are for the 6-month period of April to September. The exceedance thresholds provide confidence limits on the forecasts so water resources managers can assess risk.

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[6] U.S. P.L. 587

[7] 25 USC §564m

[8] See Klamath Water Users Association v. Patterson, 15 F. Supp. 2d 990, 996 (D. Or. 1998), 204 F.3d 1206 (9 Cir. 2000) and Kandra v. United States, Civ. No 01-6124-AA, Opinion and Order of April 30, 2001 (D. Or.).

[9] In addition to the sites in the Upper Klamath Basin, the NRCS provides similar forecasts for hundreds of other locations in the irrigated areas in the western U.S.

The forecasted streamflow volumes are determined by NRCS from a combination of multiple regression models, collected snowpack and streamflow data, and subjective judgment, in coordination with the National Weather Service (NWS) California-Nevada River Forecast Center. The primary data source for the NRCS forecast is the SNOTEL network, which consists of 19 remote sites that collect hourly precipitation, snowpack water content, snow depth, and temperature data. Hydrologic data is also manually collected from four aerial markers (poles that indicate snow depth) and six snow courses. Additional forecast points within the Basin are located at long-term stream gauges that provide streamflow data (USBR and USGS stations). The data collection network stations are shown in **Figure 7**.

Accurate water supply forecasts are essential because the intense demands for water and planning time frames of agricultural users require decisions early in the season. Many of these decisions, particularly in water-short years, have serious economic implications.

The NRCS forecasts (on April 1st) for predicted inflow to the Upper Klamath Lake during the 5-year study period are shown in **Figure 8**. (Note: the April 1st forecast is the last one released before the USBR releases its operations plan.) Net inflow forecasts were about 22 to 25% above actual inflow conditions for 2 years (at the 50% exceedance level) and 11 to 31% below actual inflow for 3 years. In some years, the error in the predicted inflow was up to several hundred mcm or roughly the equivalent of 20 to 40% of the net surface diversions to the Project.

Improving the forecasting methodology and accuracy of supply predictions would involve narrowing the confidence limits of early season forecasts through more accurate and sophisticated modeling, better communication to stakeholders and managers about the range of uncertainty in possible streamflow outcomes, and better understanding of long-term climate variability (Risley et al., 2005). Partly due to limited knowledge about regional groundwater flow interactions, flow forecasts for the Upper Klamath Basin have larger uncertainties – a standard error of 20% for inflow to the Upper Klamath Lake – than other irrigated basins in the western U.S. (Risley et al., 2005). Until recently the NRCS flow forecasts did not incorporate any input variables to represent antecedent conditions from the preceding years or long-term climate trends.

Water Year Type

Based on the April 1st forecast of snowpack and runoff, USBR classifies each year according a *water year type*. Beginning in early January an initial classification is made (for information purposes) and subsequent revisions are made in February, March and April as new NRCS flow forecasts are available. Water year types for operations planning are defined by historic inflow conditions (USBR, 2007). The water year type is defined by the forecasted inflow between April 1st and September 30th. The estimate of predicted inflows for lake elevation planning uses the 50% exceedance value.[10] The forecast volume associated with a 50% exceedance probability has a 50% chance of receiving more than the forecast volume (and likewise a 50% chance of receiving less than the forecast volume). **Figure 9** shows the April-September annual inflows and associated water year types for Upper Klamath Lake.

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[10] In accordance with the requirements of the 2002 USFWS Biological Opinion.

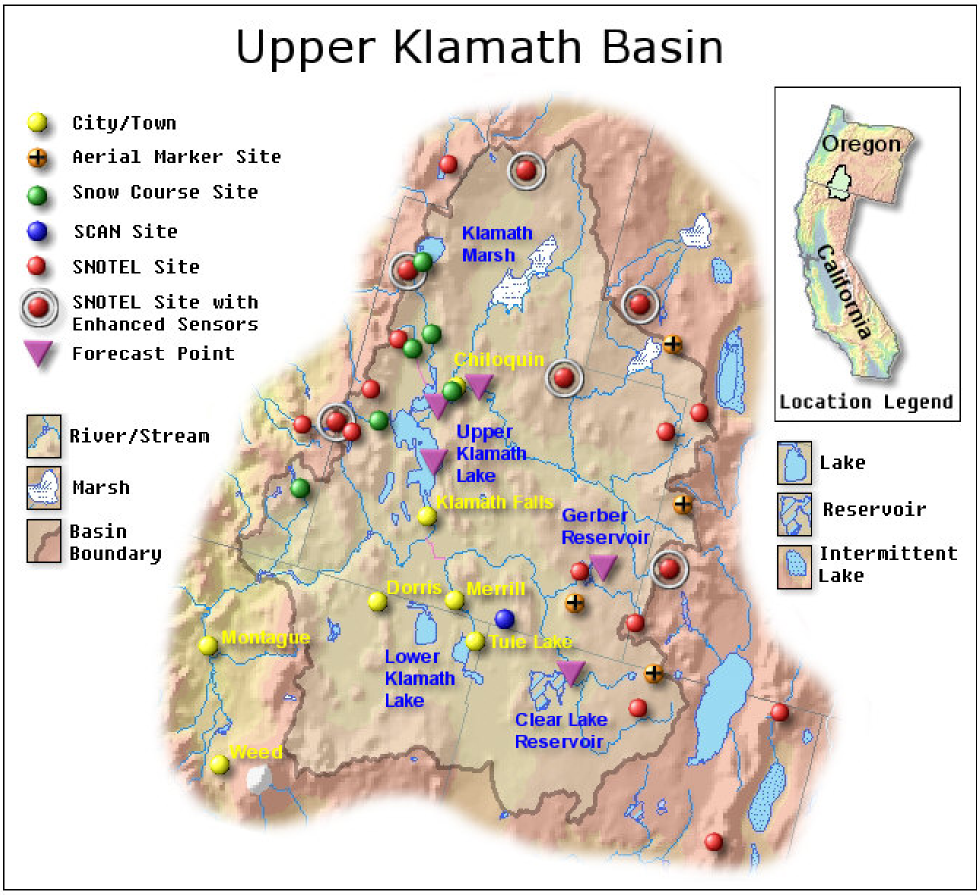

Figure 7. Upper Klamath Basin Hydromet Network water supply forecast points (Source: NRCS)

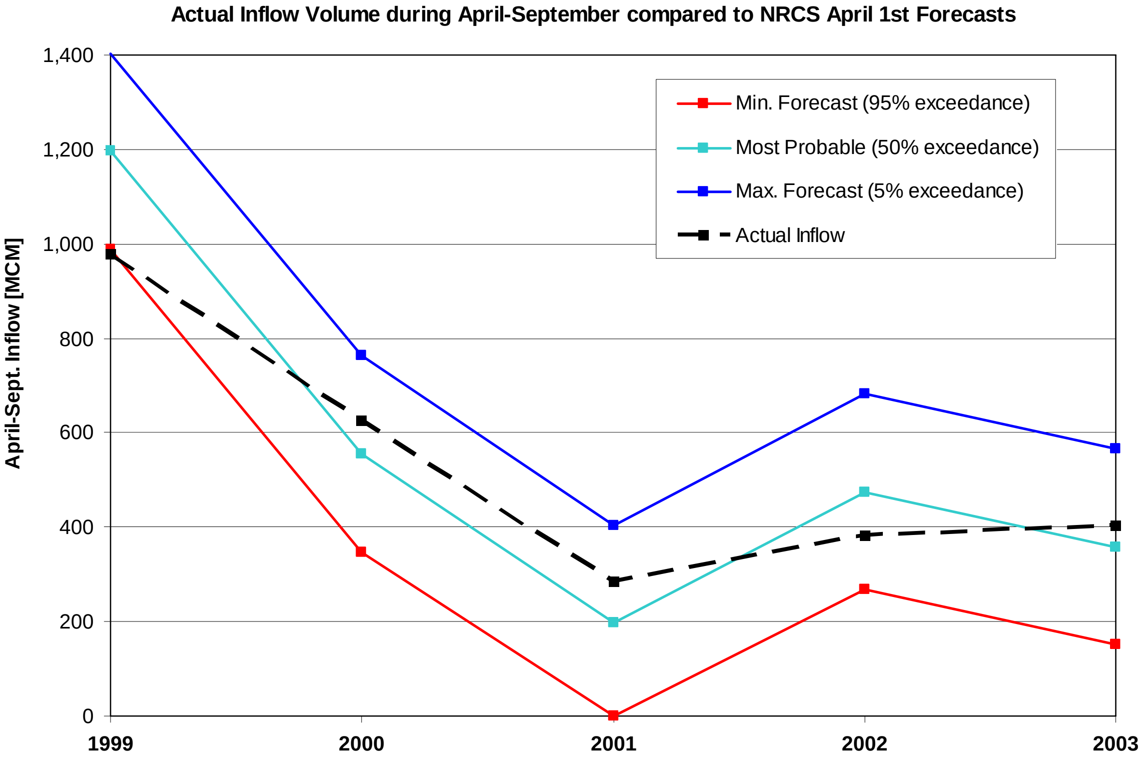

Figure 8. Upper Klamath Lake inflow forecasts and actual April-September inflow (1999-2003)

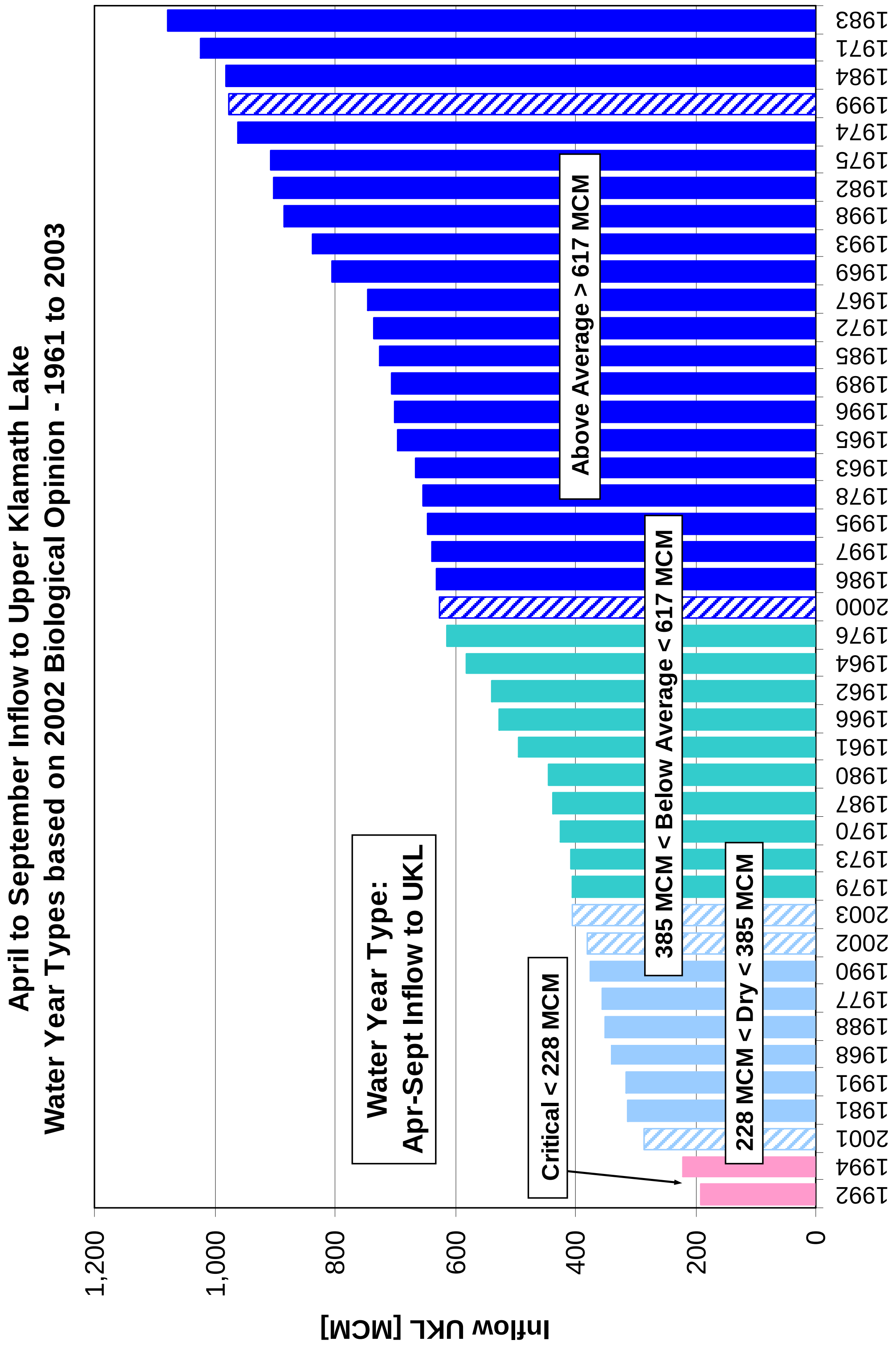

Figure 9. Inflow to Upper Klamath Lake sorted by water year type [1961-2003]

2.1.2.5 The Endangered Species Act

The Endangered Species Act (ESA) was passed in 1973 by the U.S. Congress and soon after signed into law by President Richard Nixon. The ESA has been cited as the most powerful environmental legislation in the world (Stanford, 2001; James, 2004). The act gives priority to the needs of threatened and endangered species and their habitat, and sets a framework for future water management (NRC, 2004). The Upper Klamath Lake is the primary habitat for the shortnose sucker (*Chasmistes brevirostris*) and Lost River sucker (*Deltistes luxatus*), both listed as endangered species in 1988. Specifically, this means in the case of the Klamath Irrigation Project that the implementing agencies of the ESA may direct that the USBR, as manager of water resources in the Project, must augment water supplies for fish needs, even if this means reducing the amount for irrigation (Adams and Cho, 1998; NRC, 2002).

The USBR's compliance with ESA lake level restrictions for Upper Klamath Lake reduces average water supplies available for irrigation, in addition to the lake's ability to stabilize during drought cycles (USBR, 2007). It is documented (Adams and Cho, 1998) that on the basis of historical lake levels, the ESA restrictions could not have been met for 45 of the last 73 years without reducing irrigation diversions to the Klamath Irrigation Project. The ESA has impacted water operations in other irrigation projects including the Central Utah Project (Breitenbach, 2004; Swanson, 2004), and the Colorado River Storage Project in the Upper Colorado River Basin (James, 2004).

Biological Opinions by the USFWS and NMFS

In 1988, the USFWS used provisions of the ESA to protect two fish species – the Lost River and shortnose suckers – by setting monthly minimum elevations in the Upper Klamath Lake when they were classified as endangered (USFWS, 1988). The group of coho salmon endemic to the Klamath River Basin and tributaries was classified as federally threatened under the ESA in 1997 (NMFS, 1997) and corresponding minimum flows were set. These listings required the USBR to assess potential impairments to the species or their habitat in the Basin.

Under Section 7(a)(2) of the ESA legislation, before the USBR can initiate a proposed action related to the operations of the Klamath Irrigation Project the agency must prepare a biological assessment [16 USC §1536(c)(1)] for consultation with the appropriate agencies (USBR, 2002). In response to these endangered and threatened listings, the USBR prepared biological assessments in 2001 regarding the effects of Project's operations (USBR, 2001a; USBR, 2001b; NRC, 2004). The purpose of the biological assessments was to describe and analyze Project features and operations in order to justify specific water levels and river flows based on historical conditions. In both assessments, the USBR concluded that operation of the Project would be harmful to the listed fish without specific constraints on water levels in the Upper Klamath Lake and minimum flows in the main stem of the Klamath River (NRC, 2004).

Determination of whether or not the USBR's proposed actions in the Project would jeopardize the listed species or adversely affect its critical habitat was determined by an analysis of relevant literature and field data contained in a report called a biological opinion prepared by the relevant expert agency. In response to the 2001 USBR biological assessments of the endangered and threatened species, the USFWS and NMFS issued separate biological opinions that differed sharply in terms of the corresponding lake levels and river flows that were to be maintained (NRC, 2002). Both biological opinions identified multiple "reasonable and prudent alternatives" (RPAs) for long-term operation of the Project (USFWS, 2001; NMFS, 2001) under authority provided for in 16 USC §1536(b)(3)(A).

Final 2001 Biological Assessment by the USBR

During the severe drought in 2001, the U.S. Department of Interior, which is the parent agency of the USBR and the USFWS, ruled that the more stringent environment restrictions in the biological RPAs would have to prevail. As a result, nearly all the irrigation water that would have gone to agricultural water users in the Klamath Irrigation Project was used instead to meet the requirements in the two RPAs. Severe economic consequences and political tensions from this drastic shift in water management led to the formation of a special committee under the National Research Council (NRC) with the mandate to independently review the technical and scientific validity of the USBR assessment and biological opinions (NRC, 2002; NRC, 2004).

The NRC committee released their interim report in February 2002, which contained two conclusions that led to the USBR re-formulating the annual operations plan for the Project (NRC, 2002). The interim report of the *Committee on Endangered and Threatened Fishes in the Klamath River Basin* concluded:

1. Regarding Upper Klamath Lake Elevations: "*The present scientific record is consistent with use of operational principles in effect between 1990 and 2000.*"
2. Regarding Klamath River flows: "*There is no convincing scientific justification at present for deviating from flows derived from operational practices in place between 1990 and 2000.*"

Thus, the NRC concluded that there was no substantial scientific basis for changing the operation of the Klamath Irrigation Project to maintain higher lake elevations or higher minimum flows for the listed species. This finding was confirmed in the final report by the NRC (2004) which placed emphasis on an ecosystem approach to restore healthy fish species, but left in place the basis for operations planning using the flow regimes of the 1990s. The 2001 biological assessment is still in force.

2.1.2.6 Operational Criteria

Operational criteria regulate, on a monthly basis, minimum lake elevations for the Upper Klamath Lake and minimum in-stream flows in the Klamath River. The USBR has established the current and future operating criteria for the Klamath Irrigation Project in the *Final Biological Assessment - the Effects of Proposed Actions related to Klamath Project Operation (April 1, 2002 - March 31, 2012) on Federally-Listed Threatened and Endangered Species* (USBR, 2002). The 10-year plan for the Project is based on maintaining operations that are consistent with the observed values for lake levels and river flows from water year 1990 through water year 1999 (10 yrs). Namely, the USBR proposed to operate the Project in a manner such that lake levels and river flows do not go below the minimums that resulted during the selected 10-year time period. During this time period the Klamath Basin experienced annual hydrologic conditions ranging from drought to flood. Water years with similar hydrologic conditions were grouped into four official categories for lake elevations and five official categories for minimum main stem flows.

Upper Klamath Lake Levels

Table 1 summarizes the operating criteria for the Upper Klamath Lake based on water year type. The annual operations plans specify end-of-the-month elevations that shall be met for the corresponding water year type. The elevation of the Upper Klamath Lake is to be controlled within well-defined limits ranging from 1,261.0 to 1,262.9 m (4,137.0-4,143.3 ft).

Table 1. Lake elevation operational criteria for the Upper Klamath Lake, m

	Water Year Type			
	Above Average	**Below Average**	**Dry**	**Critical Dry**
March 31	1262.6	1262.7	1262.4	1262.5
April 30	1262.8	1262.7	1262.5	1262.5
May 31	1262.8	1262.7	1262.6	1262.3
June 30	1262.7	1262.5	1262.3	1261.9
July 31	1262.3	1262.1	1262.0	1261.5
August 31	1262.0	1261.8	1261.6	1261.1
September 30	1261.8	1261.5	1261.3	1261.0
October 31	1261.8	1261.5	1261.3	1261.0
November 30	1262.0	1261.6	1261.6	1261.3
December 31	1262.2	1261.5	1261.8	1261.5
January 31	1262.3	1261.7	1262.0	1261.9
February 28	1262.5	1262.4	1262.0	1262.2

Klamath River Flows below Iron Gate Dam

Table 2 summarizes the operating criteria for the Klamath River flows at Iron Gate Dam based on water year type. The criteria for flow in the Klamath River below Iron Gate Dam means releases have to be controlled between 28.32 and 85.66 cms (1,000-3,025 cfs) depending on the month and water year type (USBR, 2007).

Table 2. Klamath River operational criteria for flows at Iron Gate Dam, cms

	Water Year Type				
	Wet	**Above Average**	**Average**	**Below Average**	**Dry**
April	58.05	76.46	80.70	44.60	42.48
May	73.62	85.66	85.66	29.56	42.48
June	82.12	84.95	42.48	43.18	39.64
July	28.32	28.32	28.32	28.32	28.32
August	28.32	28.32	28.32	28.32	28.32
September	28.32	28.32	28.32	28.32	28.32
October	36.81	36.81	36.81	36.81	36.81
November	36.81	36.81	36.81	36.81	36.81
December	36.81	36.81	36.81	36.81	36.81
January	36.81	36.81	36.81	36.81	36.81
February	36.81	36.81	36.81	36.81	36.81
March	65.13	71.50	77.87	48.85	41.06

2.1.2.7 Irrigation Districts – Organization, Functions, and Programs

California and Oregon Water Law govern the function of public water agencies (irrigation districts) in the Klamath Irrigation Project. There are 18 districts in the Project ranging in size from several hundred ha to over 20,000 ha. Irrigation districts are political sub-divisions of state government. Irrigation districts are a special category of state water districts, out of hundreds of different kinds, formed by a petition of landowners to the local County Board of Supervisors and organized under an elected Board of Directors for the defined purpose of furnishing water to irrigable lands. Fees and assessments may be collected on designated lands within the boundaries of the service area (land tax). Districts can also raise funds through public revenue bonds. The Wright Act passed in California in 1887 formed irrigation districts and served as a model for future legislation in western states (Teilmann, 1963).

In general terms, irrigation districts are responsible for the day-to-day operation of distribution and delivery systems, in addition to representing the interest of its water users. Many districts are multi-purpose, providing electric power, recreation facilities, and reclamation. Generally, the districts are the "owners" of the water rights on behalf of members. They have personnel devoted to administration, billing, O&M activities, and some larger districts may have professionally-licensed staff engineers who handle design and construction-related projects. Most district staff usually have long tenures; many people in senior management have risen through the ranks over time. Districts, particularly those in the western U.S., also have extensive legal representation from firms who specialize in water law. Managers serve at the pleasure of the Board of Directors and can be removed at any time. Burt (2004) points out that the legal structure and local nature of irrigation districts stimulates a "can do" attitude.

Water rights in the U.S. are primarily based on the concept of "prior appropriation", which roughly translates into "first in time is first in right." This law tradition began during the time of the California "gold rush," when settlers would lay claim to stretches of rivers/streams for gold prospecting. Later these self-made property rights of "first come, first serve" were formalized by courts and legislatures as settlement grew rapidly (Teilmann, 1963). Riparian water rights, based on English common law principles, are also present in various districts and it is not uncommon for a district to have water rights held in several different categories. Most states allow for the sale, lease and exchange of appropriated rights. As a result of active water markets, whereby districts can sell or trade a portion of their water supply, these rights have become extremely valuable. State water laws and related regulations in the western U.S. generally require that irrigation diversions must be put to "reasonable and beneficial uses."[11] Beneficial uses include irrigation used for crop *ET*, salt removal, soil preparation or climate control. Reasonableness considers the economics, weather uncertainties, and physical limitations involved with the system.

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[11] §100, Water Code, State of California: "It is hereby declared that because of the conditions prevailing in this State the general welfare requires that the water resources of the State be put to *beneficial* use to the fullest extent of which they are capable, and that the waste or unreasonable use or unreasonable method of use of water be prevented, and that the conservation of such water is to be exercised with a view to the *reasonable and beneficial use* thereof in the interest of the people and for the public welfare."

The irrigation districts that comprise the Klamath Irrigation Project face their own sets of operational constraints, while being reliant on the water allocation established each season by the USBR. The timing and volumes of irrigation water available to irrigation districts have historically been reliable and sufficient to meet the needs of local water users. For most of the history of the Project, the available storage in the Upper Klamath Lake was enough to provide full allocations for both farmland and the wildlife refuges. Having only experienced drought conditions in the relatively recent past, there has previously been no strong incentive to invest in the operational strategies and physical infrastructure required to cope with reduced allocations. Indeed, the previous droughts in 1992, 1994 and 2001 were initially viewed as anomalies and not, understandably, as an appropriate basis for policy making.

The convergence of several factors, resulting in severe uncertainty about future water supplies, makes it necessary to address the operational constraints under which the Project's irrigation districts are presently operating. Unfortunately, the barrage of litigation in recent years has further limited their abilities, management energy, and internal funding resources available to proactively implement solutions to improve operations. In addition, water districts are often aware that their operations have a potential to improve, but they may lack the sufficient knowledge or expertise with modern water control and measurement technologies to reach higher potentials.

In general, the ability to control water within the Project at present is very simplistic. This is not meant as a negative criticism of the irrigation districts; the simple operation scheme was ideally suited for historical conditions. Operational procedures followed by the districts are influenced by the lack of flow measurement devices (at heads of laterals, at farmer turnouts), accurate volumetric accounting procedures, or good flow control structures. The basic argument that overall irrigation water use within the Project is highly efficient is true due to the extensive reuse of return flows, which has been facilitated by the relatively low electric power rates available for agricultural pumping. The Project's infrastructure, much of which was constructed more than 75 years ago, has not undergone widespread upgrading of the control structures, communications equipment, or monitoring systems except at a few locations.

The lack of accurate internal flow measurement at key control points is indicative of a strategy of "moving water around" rather than the type of rigorous management needed to deal with reduced allocations that must be equitably spread among uses throughout the Basin.

Besides not having accurate flow measurement devices to measure the flow rate and volume of internal Project deliveries, the existing infrastructure for controlling water as it moves from one irrigation district to the next one downstream is not adequate to meet future operational scenarios envisioned as a controlled industrial process (repeatable pattern of timely information, robust control, and measured results). Because water flows from one district to the next as a combination of wheeled water and return flows, each district would also have no way to know what to do if it received a reduced percentage allocation or even be able to accurately verify what percentage it was receiving.

2.1.3 Sources of Water Resources Conflicts in the Klamath River Basin

The situation in the Klamath Irrigation Project is not unique, but the dramatic events there represent the potential opportunities and challenges for assessing future integrated management scenarios that will result elsewhere from the global competition for water. To summarize, the water resources conflict in the Klamath River Basin can be traced to several roots:

- Official decisions by state and federal agencies made over a long period of time under varying regulatory and hydrological circumstances have created a legal basis for conflicting claims to a limited water resource, mainly by four interests – irrigators, Native Americans, at-risk fish species, and wildlife refuges.
- As society's priorities have evolved over time, the relative influences of interest groups have also changed, altering how various agencies with regulatory jurisdiction respond to water resources conflicts.
- Unadjudicated water rights in the Klamath River Basin – determining who has what rights to how much water – have limited the ability of irrigators and other water users to effectively plan and deal with droughts.
- The habitat of declining populations of endemic fishes with extensive genetic isolation in rivers in arid areas of the west that drain directly to the Pacific Ocean, has deteriorated significantly.
- Government agencies and employees, sometimes within the same overall department/bureau, have different and overlapping – or even conflicting – missions and motivations.
- Managers of water resources projects often lack definitive data (uncertainty) about the water balance/efficiency and internal processes of their systems that would form the basis of assessing different modifications (e.g., modernization improvements). This is especially apparent in the Klamath Irrigation Project, even though only an understanding of the internal processes can identify what specific investments must be targeted for improved performance.
- The antiquated and time-worn infrastructure in the Klamath Irrigation Project has not undergone systematic upgrading, and which in many places consist of out-dated technology. An example is the 100-year old, heavy steel, manual regulating structures and measuring devices. The system has very few modern control structures.

2.2 Rapid Appraisal Process (RAP)

2.2.1 A Knowledge-Based Toolkit

Determining the correct course for modernization in irrigation projects is a major challenge for engineers. The recommended first step in a modernization program is an in-depth diagnostic assessment of the current performance of the project (Plusquellec, 2002; Burt and Styles, 2004, Bos et al., 2005). The diagnostic assessment of an irrigation project should complement routine performance monitoring and evaluations carried out by agency staff and others (Bos et al., 2005). Rapid diagnostic techniques for assessing and understanding irrigation performance have been developed by a number of groups and applied to many projects (Chambers and Carruthers, 1986; Harvey et al., 1987; Pradhan et al., 1988; Groenfeldt, 1989; Burt and Styles, 1999; Burt and Styles, 2004).

Burt and Styles (1999) introduced the formal Rapid Appraisal Process (RAP) diagnostic technique as part of a benchmarking effort of 16 international irrigation projects. The RAP is a knowledge-based toolkit that allows trained professionals to systematically diagnose system performance at disaggregated hydraulic levels. The basic objective of the RAP diagnosis is to identify the best approach to solving problems as part of developing a strategic master plan with well-defined objectives. Selecting the components of a modernization strategy depends on a number of physical, social, managerial, and financial considerations that can be time-consuming and expensive to assess (Bos et al., 2005).

The RAP for irrigation projects is a 1-2 week process of collection and analysis of data both in the office and in the field (Burt and Styles, 2004). The process examines external inputs such as water supplies, and outputs such as water destinations (crop evapotranspiration, surface runoff, etc.). It provides a focused examination of the hardware and management processes used to store, divert, convey and distribute water internally to all levels within the project (from the source to the fields).

The RAP is designed in general to:

- Identify specific and immediate actions that could be easily taken, with a minimum of investment, to improve system operation and water management
- Quickly critique options that have been proposed for major future investment
- Provide a fresh look at the whole system, with the goal of being able to provide suggestions for new ways to improve the overall irrigation distribution system

External indicators and internal indicators are developed to provide: (i) a baseline of information for comparison against future performance after modernization, (ii) benchmarking for comparison against other irrigation projects, and (iii) a basis for making specific recommendations for modernization and improvement of water delivery service. Physical infrastructure and internal processes are examined starting with the main canal system, along with representative lateral canals or pipelines, pumping plants, regulation reservoirs, etc. During the field portion of the visit, relevant measurements and photographs are taken of control structures, flow measurement devices, reservoirs, pumps, etc. Other areas of emphasis investigated included communications, flow measurement devices, drainage recirculation, energy usage, changing cropping patterns, urbanization, SCADA,[12] and water quality trends.

The RAP has only recently been used for widespread diagnosis of irrigation projects, although variations of the RAP have been used since 1989 by the ITRC on dozens of irrigation modernization projects throughout the western U.S. (Burt and Styles, 2000). Since the RAP diagnostic evaluation of irrigation projects was introduced in the joint IPTRID/FAO/World Bank publication *Water Reports 19* (Burt and Styles, 1999), the international project-level techniques have been recently updated (Burt and Styles, 2004).

Traditional diagnostic procedures and research tend to examine isolated *portions* of an irrigation project, whether, for example, they are the development of water user associations (WUAs) or the fluctuation of flow rates in a single canal. Those research projects typically require the collection of substantial field data over extended periods of time. In contrast, a systems-based approach, such as the RAP, recognizes the complex influences and interactions of the human, physical and socio-economic conditions in a project (Bos et al., 2005).

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[12] SCADA stands for Supervisory Control and Data Acquisition. Many irrigation districts in the western U.S. have put in radio telemetry, electronic sensors, flow meters, automatic gates and valves, etc. that are generally referred to as SCADA systems.

2.2.2 Irrigation Systems and Internal Processes

The terms, circumstances, and purposes of physical infrastructure design, operation rules, organizational structures, and management practices followed in the real-time operation of the Project were investigated to go beyond merely describing its characteristics (e.g., length or capacity of a particular canal) and actually understand why things are done in a particular way – how and why the water is being manipulated, what types of constraints the district has, what hardware is being used, etc. Scrutinizing these types of internal processes helps to identify what specific actions can be taken to improve project performance and what opportunities for improved operations or water conservation might exist (refer to **Figure 10**). The primary reason for examining the internal processes used to store, convey, and deliver irrigation water is the realization that, in the future, conditions in the Klamath Basin are certainly going to be different – more restrictive for irrigators – than in the past. This aids in identifying constraints that might impede accomplishing the desired objectives.

2.2.2.1 Water Delivery Service

Water delivery service is commonly characterized by the following (Burt, 2000):

- Adequacy
- Equity
- Reliability
- Flexibility

Adequacy is a measure of how closely the water delivery meets crop water demands, either at specific growth stages or seasonally. *Equity* describes how well the water deliveries are fairly distributed to meet the needs of all users in a system. *Reliability* refers to the system's capability for delivering the expected amount of water (either in terms of flow rate or volume) at the times expected. *Flexibility* refers to capability for adjusting the timing, flow rate, and frequency of water deliveries. Achieving reasonable levels of adequacy, equity, and reliability are prerequisites for improving the flexibility of water deliveries (Burt, 2000). Including flexibility as a service criterion recognizes the requirement that for farmers to achieve the highest level of performance, the water delivery must be sufficiently flexible in terms of flow rate and time adjustments (Merriam and Freeman, 2007).

Burt and Styles (1999) formalized ranking indicators for characterizing the quality of water delivery service that is provided by an irrigation project. Key indicators are specified for different levels of the system – individual field, most downstream point operated by a paid employee, second level canals and main canals. The water delivery service index is a composite of assigned ratings (on a 0 to 4 scale) for flexibility, reliability, equity, and other parameters such as the measurement of volumes and control of flow rates, depending on the level of the system being analyzed. Weighting factors are applied to each sub-indicator rating to reflect their relative importance in the degree of service within each indicator group.

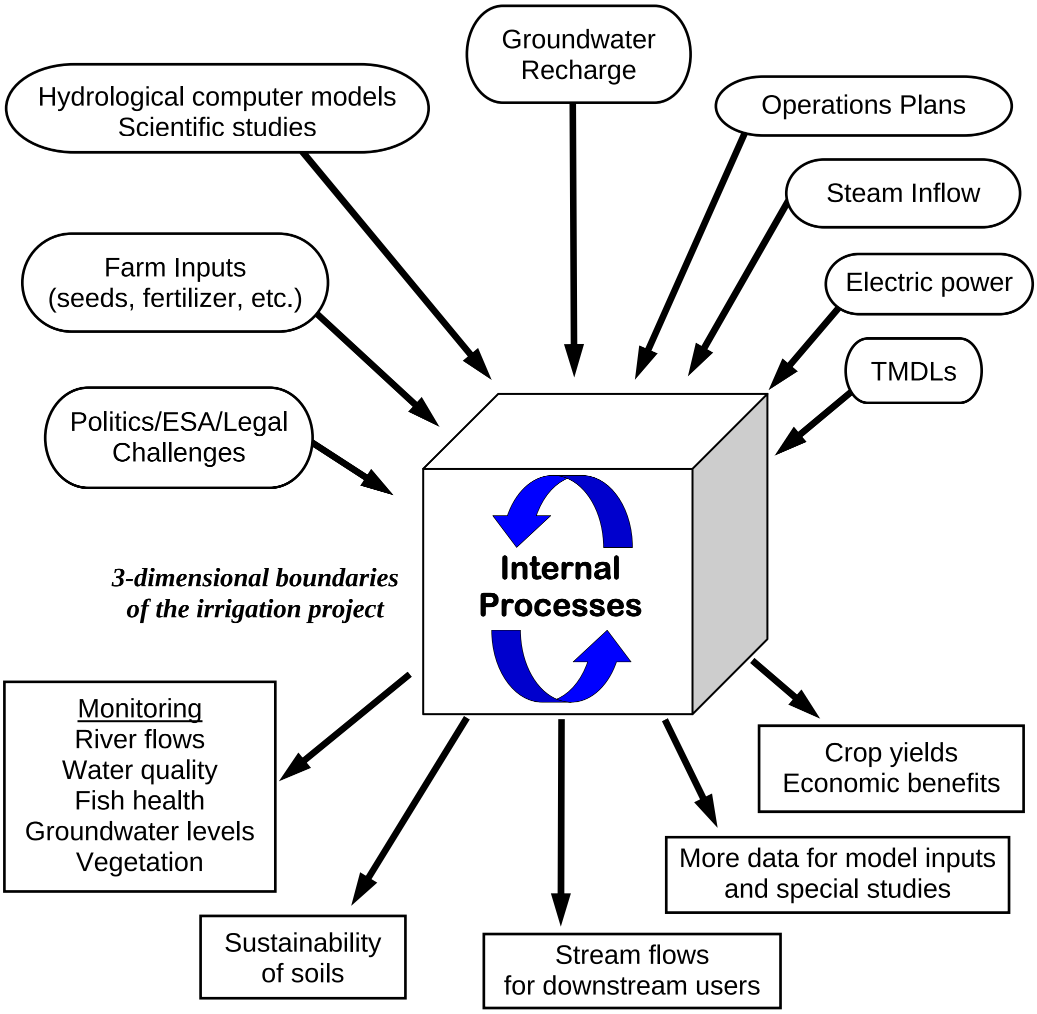


Figure 10. Internal processes in an irrigation project affecting and being affected by external pressures

As discussed previously, one of the primary goals of irrigation modernization is to improve water delivery services to farms (Wolter and Burt, 1996). Bautista et al. (1999) list four ways that the quality of service can impact farm irrigation management: (1) crop area and selection; (2) selection, design, and management of irrigation system hardware; (3) water and soil management; and (4) irrigation costs and farm profitability. From a grower's standpoint, the quality of service depends on the rules governing the delivery of water that take into account expected water demands, supply characteristics, water rights, the capabilities of measurement, and control infrastructure (Bautista et al., 1999). When farmers can't get water deliveries when they are needed to match crop water requirements (inflexible deliveries), yields may decline due to deficient or excessive water applications, partly due to plant stress in critical growth periods or to water logging, lack of aeration, etc.

While efficiencies attained with rotation schedules in the U.S. (on deep-rooted crops) were believed to be acceptable in the past, recent surveys have shown that more flexible arranged schedules have been near universally adopted by irrigation districts in California. Burt et al. (2000) found in a study of 61 districts in the Mid-Pacific Region of the USBR that only one still retained a rotation schedule.

Rotation methods still practiced in many parts of the world (e.g., *warabandi* or *shejpali* schedules in South Asian countries), though less and less in the U.S. and other irrigated areas with high value crop production, can *theoretically* attain high levels of equity and reliability (Plusquellec et al., 1994; Bautista et al., 1999; Merriam and Freeman, 2007). However, the reality is that a substantial portion of irrigation projects with rotational delivery schedules suffer from tailender inequities due to poor design of the control infrastructure, unrealistic operational assumptions, lack of proper consideration for water requirements for different crops, an inability to adjust to climatic variations, etc. (Sakthivadivel et al., 1999; Plusquellec, 2002). Plusquellec (2002) provides figures that show overall project efficiencies for rotational schemes were limited to about 38% for surface methods and 43% for sprinkler methods based on an ICID survey of international projects in 1974. Dismal results have also been reported for projects with rotation schedules in such diverse conditions as Nepal, the Philippines, Thailand, India, and Vietnam (Burt and Styles, 1999; Plusquellec, 2002). Indeed, as Burt and Styles (1999) note, there is no point in talking to farmers about on-farm irrigation scheduling, crop diversification or measurement of water deliveries and soil moisture, when they receive irrigation water deliveries on a rotational basis.

Flexibility in Water Supply

To operate an irrigation project for optimum crop production and effective water use, water must be applied to a crop when it is needed (flexible frequency); at a flow rate to match the soil intake rate and area (flexible rate); and for a duration to match the needed infiltration depth to avoid waste (flexible duration) (Merriam, 1987; Merriam, 1991; Bautista, 1999; Cross, 2000; Merriam and Freeman, 2007). Flexible on-farm management of an irrigation water supply is essential for the farm manager to obtain optimum use of land, water, crops, weather and labor resources.

In systems where water deliveries are used for surface irrigation methods, canals account for over 90% of the global irrigated area (Van Bentum and Smout, 1994; Bautista, 1999). While pressurized methods (sprinkler, drip, micro-spray) require a certain degree of delivery flexibility in order to operate, surface methods that do not incorporate on-farm reservoirs or groundwater pumps require enough flexibility in the canal system that the delivery of irrigation water will correspond with soil intake rates, labor availability and convenience, and other parameters related to the avoidance of high water tables and salinity (Merriam and Freeman, 2007). The ASCE publication *Selection of On-Farm Irrigation Methods* (Burt et al., 1999) provides specific selection criteria for the different irrigation methods based on the degree of water delivery flexibility that is available from the delivery system.

Flexibility (Merriam, 1987) is a measure of the empowerment of individual farmers to control irrigation deliveries to their field in terms of flow rate, duration, and frequency. In terms of on-farm irrigation deliveries flexibility has the subcomponents of frequency (how often – measured in days or weeks), flow rate (how much – lps or other standard flow unit) and duration (how long – hrs or days).

Embedded within the concept of flexibility are issues about the amount of advance time needed to order water, whether a farmer can receive or stop deliveries at odd hours and without agency staff being present, and whether the delivery flow rate can be adjusted. The essence of a flexible water supply is to provide farmers with management control of the flow rate, duration, and frequency of irrigation so that they can manage their entire farm program as one integral unit without the restraints created by the usual rigid, rotational water supply system (Merriam, 1987; Merriam, 1991; Cross, 2000; Merriam and Freeman, 2007).

Index of Flexibility

One of the first steps in developing a modernization plan for irrigation districts is the characterization of service that they provide using standardized indicators (Burt et al., 2000; Burt and Styles, 2004). Burt and Styles (2000) developed a *Flexibility Index* (refer to **Table 3**) with ranking indicators to characterize the level of water delivery flexibility provided by irrigation districts in the western U.S. Flexibility was the primary criteria because equity and reliability are not serious concerns in most California districts. Their study found a high-degree of flexibility (**Table 4**: average score of 11.7 out of 15). This information was used to help develop modernization strategies for the districts to improve water delivery service and district-level *IE*.

Table 3. Criteria for ranking a *Flexibility Index* to farms (after Burt and Styles, 2000)

Frequency	
1	Always a fixed rotation
2	Fixed rotation with trading, or limited frequency, or fixed rotation during the peak season only
3	24 hrs or more advance notice required before the delivery is made
4	Less than 24 hrs advance notice required before the delivery
5	Farmer does not need to notify district before delivery
Rate	
1	Same flow must always be delivered
2	Several flow rates are allowed during the season
3	A different flow rate is available each irrigation cycle, with up to 2 changes per event allowed
4	Flow rate change can be made any time, provided advanced notice is given to the district
5	Flow rates can be different and changed by the farmer without giving advance notice to the district
Duration	
1	District assigns a fixed duration of irrigation
2	District assigns a fixed duration, but allows some flexibility
3	Farmers must select a duration with a 24-hr increment
4	Farmers can choose any duration, but must give notice before changing
5	Farmers can have any duration

Table 4. Average flexibility results for 61 irrigation districts in the USBR Mid-Pacific Region (after Burt and Styles, 2000)

Flexibility Parameter	Ranking
Frequency	3.3
Rate	4.4
Duration	4.0
Average Flexibility	**11.7**
Index: 3 min., 15 max.	

2.2.3 RAP Evaluation of the Klamath Irrigation District

The RAP evaluations and resulting development of the specific modernization and engineering recommendations focus on the two largest water agencies in the Main Division of the Klamath Irrigation Project: the Klamath Irrigation District (ID) and Tulelake ID, which together account for over 40,000 ha (100,000 acres) or about 50% of the total irrigated area in the Project. The specific modernization project-alternatives formulated for future water management planning scenarios in the case studies using the multi-criteria analysis are the result of findings from the RAPs and follow-up site visits carried out in these districts.

Klamath ID is the largest irrigation district in the Project (approximately 22,000 ha) and the one that diverts directly from the Upper Klamath Lake (via the A Canal). The district operates and maintains the A, B, C, D, E, F, and G Canals in the Main Division of the Project, in addition to the associated drainage system and pumping plants. The 2001 water year showed what the effect on district operations can be when inflow to the A Canal is reduced. It became difficult, if not impossible, to equitably distribute a reduced volume within the district.

A RAP diagnostic evaluation was carried out in the district's service area to determine possible justifications for modernization based on the present constraints affecting water management. The RAP involved traveling throughout the water distribution and delivery systems over a 1-week period accompanied by engineering and operations staff. Interviews were conducted with both management and operations staff. A set of standardized data and measurements were taken at each of the key control structures including hydraulic headloss, structural dimensions, GPS coordinates, minimum and maximum flow rates, and operational targets, along with detailed site photographs. Historical records for parameters such as water deliveries and cropping patterns were also obtained for representative years and reviewed with district staff.

The main crops grown in the district include alfalfa, pasture, potatoes, and cereal grains. About one-third of the farms served by the district are 8 to 16 ha (20-40 acre) parcels located in and around the city of Klamath Falls. The majority of the district is sprinkler irrigated. Most of the irrigated lands are relatively flat, but the district is surrounded by hills on its western and eastern boundaries with the Lost River traversing Poe Valley and southeast through the service area. A system of drainage channels conveys the district's return flows to the Lost River, where they are either recycled by the district or are passed downstream to Tulelake ID.

Klamath ID does have some physical characteristics that make modernization more expensive and difficult than may typically be the case for other irrigation districts. Key challenges include:

- The district has some very long canals.
- The canals are fairly old, often without good year-round access for operators.
- The district has almost no modern control structures.
- The canals typically wind around to follow the contours, rather than being laid out in a simple rectangular grid.
- Many of the fields have irregular shapes and are relatively small.
- Using the Flexibility Index criteria in **Table 3**, the district scored only 9 out of a possible total of 15.
- The water delivery service indicator (refer to **Table 47)** for the Klamath ID was only 2.6 out of a possible total of 4.0.

A key feature of the present management is that one canal operator "passes" a flow rate from one section of a main canal to another operator who is responsible for a downstream section of the same canal. One of the first steps in modernization of water districts has typically been to discard this form of management, and have all requests by operators go through the central office.

Figure 11 shows the present operational logic of the main canal system starting with flow control at the A Canal headworks on the Upper Klamath Lake to meet the projected downstream demand. Flow rate control is used at division points for one of the downstream branches, with the other branch used for maintaining an upstream water level. Thus any "error" is passed down the canal that does not have flow rate control. Error is defined as an excess or deficit of water passed through the system in order to maintain the upstream water level at a bifurcation. When the error reaches the end of the canal system, it is spilled into drainage ditches or, at the end of main canals, into the Lost River. Mismatches between supply and demand are a normal occurrence in a dynamically-operated (changes in flow requirements) canal delivery system with multiple off-takes. Effective canal management strives to minimize the error. However, one must realize that it cannot be, nor should it be, eliminated entirely in open channel flow systems. In fact, a certain amount of error is necessary for *flexible* and *reliable* service to the end user. Flexible and reliable service to the end user will almost certainly result in the highest beneficial use of the total water used by the district because it permits enhanced farm management.

This type of district-level flow routing analysis provides the basis for developing modified control strategies including new infrastructure and management objectives.

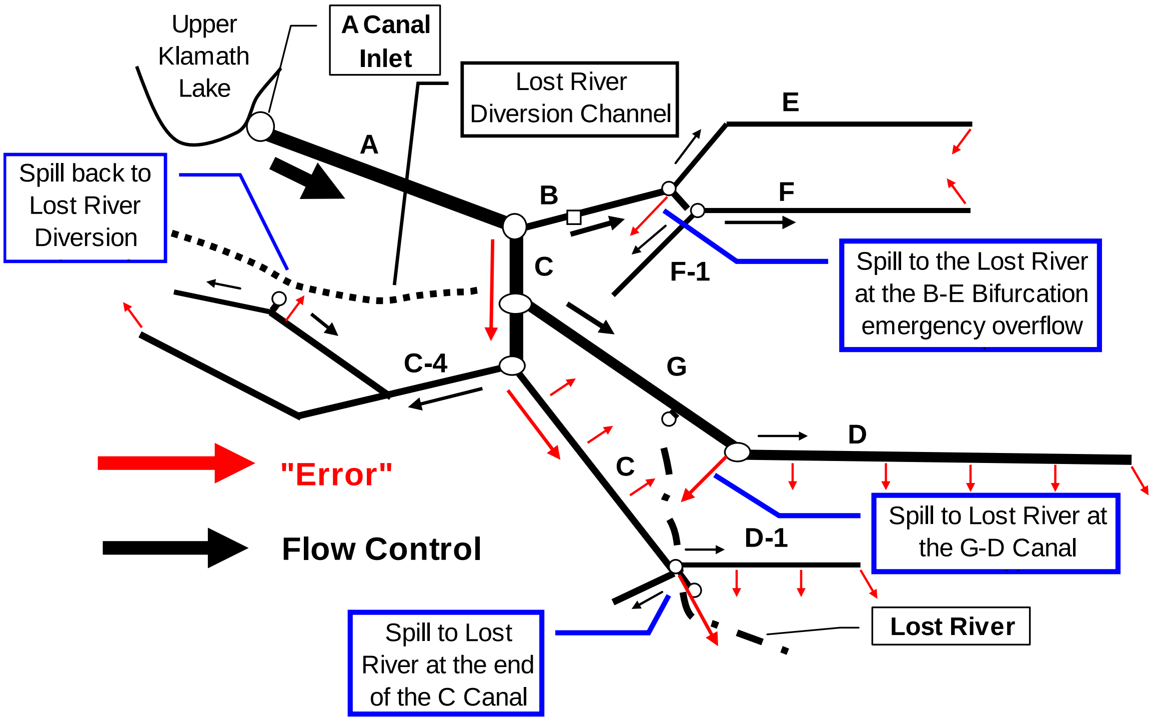


Figure 11. Schematic of existing control logic for canal operation in the Klamath ID. (The direction of "error" is shown in red.)

In summary, the operational plans and physical infrastructure required to control and measure reduced water allocations simply do not exist in the Project at the moment. Future alternatives for allocating specific *quantities* of scarce water available for agricultural and non-agricultural uses must address both technical and institutional mechanisms for managing reduced water supplies, particularly as related to the physical infrastructure in place and the likely reduction in return flows. Furthermore, the lack of good real-time information and reliable historical records means that it is difficult to evaluate the impact of various allocation strategies for individual irrigation districts, even if they could control their inflows and return flows.

Klamath ID diverts about twice the amount of supply water it needs for its internal consumptive use (ET_{iw}) from the Upper Klamath Lake and the Klamath River (refer to **Figure 12**). This diversion total includes water delivered to other districts, water for filling the water table that eventually becomes available to downstream users as drainage water, and operational spills that are used by other districts downstream.

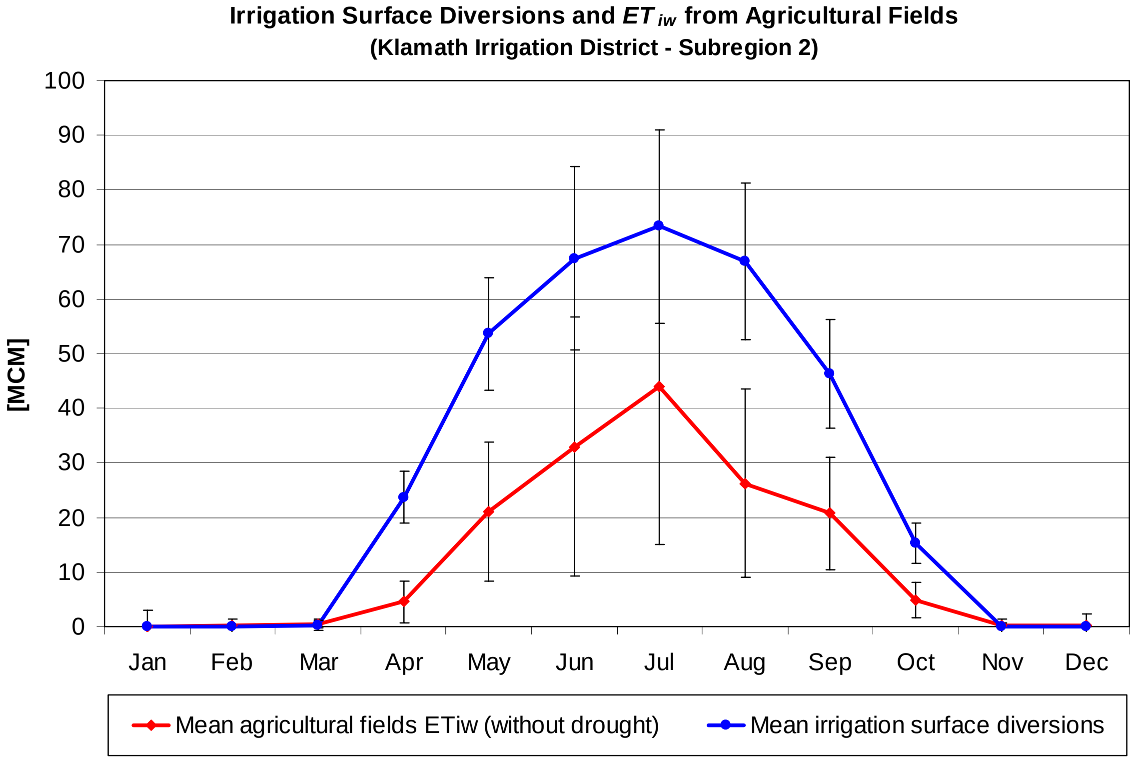


Figure 12. Net surface diversions into the Klamath ID compared to consumptive use (ET_{iw})

This further highlights that in most cases the irrigation district boundaries in the Project are mainly political rather than hydrologic boundaries. Perhaps the present irrigation district boundaries will need to be consolidated and re-organized more along hydrological lines if the existing boundaries become problematic from strictly a regulation standpoint.

One of the factors in attaining high efficiencies in the Project is the low electric power rate paid for pumping return flows. The extensive reuse of drainage flows within the Project has permitted upstream (upslope) districts to operate with minimal control over their return flows. These return flows are a substantial, though haphazard, water supply for downstream districts, particularly Tulelake ID. Obviously, districts are now re-examining this strategy in light of the expected large increases in power costs in the next several years.

3 Conceptualizing Limitations on Resources Availability for Water Conservation

> "Over the years since 1900, water and land-use patterns in the Upper Klamath River Basin have developed piecemeal. Investigations have not been made to develop facts on which local people, the two States, and several Secretaries of the Interior could base long-range plans for use of the water and public land resources of the area."
>
> *– Report of the Regional Director, Clyde H. Spencer*
> *Upper Klamath River Basin*
> *A Comprehensive Departmental Report on the*
> *Development of Water and Related Resources*
> *June 1954*

Increasing demand for water in the semi-arid Upper Klamath Basin for irrigation, power generation, and wildlife habitat restoration has resulted in the need to accurately quantify water availability and use. A recent report by the Government Accountability Office (GAO) to the U.S. Congress recommended that the USBR "provide stakeholders with systematic and clear information" concerning the rationale and effects of water management decisions (GAO, 2005). The purpose of this section is to present the results of a comprehensive assessment of project-level and subregional inflows, outflows, consumptive use, and changes in storage, and to provide an approximation of the error associated with each of the water balance components. Using a daily crop water use modeling framework with complex agro-hydrological data sets and detailed knowledge of local water management practices, estimates of the volume of irrigation of water available for water conservation objectives are quantified.

A comprehensive irrigation water balance of an irrigation project is necessary for making wise decisions regarding regional water allocation and conservation (Bos et al., 2005). Accurate estimates of physical quantities and destinations of water are a prerequisite of computing any irrigation performance measures. Different water balance frameworks have been developed with varying combinations of common elements for surface water, consumptive uses, operational losses, groundwater, drainage recycling, rainfall and other destinations at different levels of spatial and temporal disaggregation (Smith, 1992; Perry, 1996; Molden and Sakthivadivel, 1999; Burt 1999b; Droogers and Bastiaanssen, 2002). Burt (1999b) defines an irrigation water balance of a system as an accounting of *all* water volumes entering and leaving a specified three-dimensional boundary during a specified time period. This accounting includes any changes in internal water storage. Irrigation water balances can be conducted for a single field, for a farm, for a water district or even for a hydrologic basin. It is critical to clearly define the spatial boundaries of the water balance to avoid confusion over the potential for water conservation (Allen et al., 1997; Burt et al., 1997).

An "irrigation water balance" is a sub-category of a "water balance" recognizing that to properly define irrigation performance measures, the specific portion of crop water use and the leaching requirement that originated as irrigation water (as opposed to natural sources such as rain water) have to be estimated. A further partitioning of irrigation water destinations is required to compute the terms *IE* and irrigation sagacity (*IS*) (Burt et al., 1997; Burt 1999b).
Figure 13 illustrates a standard water balance structure for an irrigation district showing the inter-relationships between the district (distribution, delivery and drainage systems) and farm levels (USBR, 2005b).

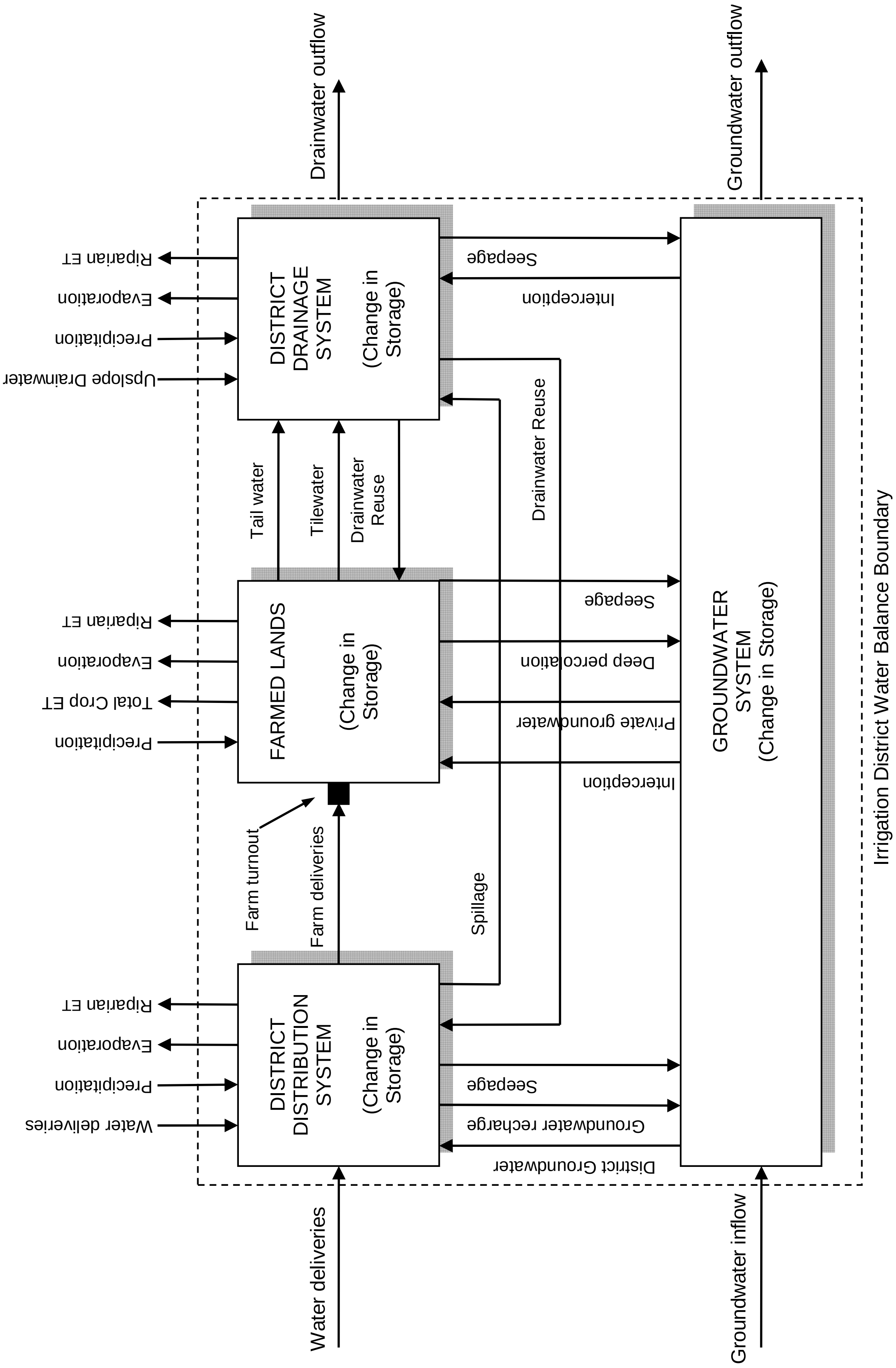


Figure 13. Standard water balance structure for an irrigation district (after the USBR Water Management Planner, Oct. 2005)

For example, on-farm water management (i.e., *IE*) may or may not have a real impact on project-level efficiencies. For larger scale systems water may be recirculated within the boundaries of the system; over-application in one field, resulting in deep percolation to the ground water aquifer, may in fact be the supply for other users. Internal recycling of irrigation water, as extensively practiced in the Klamath Irrigation Project, is often incorrectly counted in a project water balance as a projected savings for water conservation. Thus, in irrigation projects with high overall efficiencies there may be some justification for water users' arguments over the (un)reasonableness of water conservation regulations (Davids Engineering Inc., 1998). However, there may be other reasons for improving the efficiencies of first-time use related to water quality and the timing of in-stream flows.

Temporal boundaries must also be properly defined because useful performance measures are based on specified periods of time, rather than observations of single events. Every value in a hydrologic water balance (rain, irrigation supply, antecedent soil moisture, etc.) changes from one time period to another (day, month, year, etc.). It may be difficult on certain time scales to discernibly measure some types of water balance-related data. Burt 1999b recommends, therefore, that project-level irrigation water balances be carried out over multi-year periods for determining "average" computations that take into account situations with drought years, wet years, etc.

3.1 Irrigation Water Balance Indicators and Benchmarks

The fundamental hydrologic relationship of water balances is that the volume of water (surface water and groundwater) entering an area with defined 3-dimensional boundaries is equal to the volume of water leaving the same boundaries, plus any change in storage (refer to the conceptual sketch in **Figure 14**). Water enters the Klamath Irrigation Project by several pathways, which include precipitation, natural stream runoff, groundwater lateral flows, and irrigation diversion canals. Water leaves the Project through evaporation, *ET* (from agricultural fields, wetlands, open water, and misc. developed areas), drainage channels, and groundwater fluxes. The water balance framework in this section represents an extensive "state of knowledge" of water operations and hydrology in the Project.

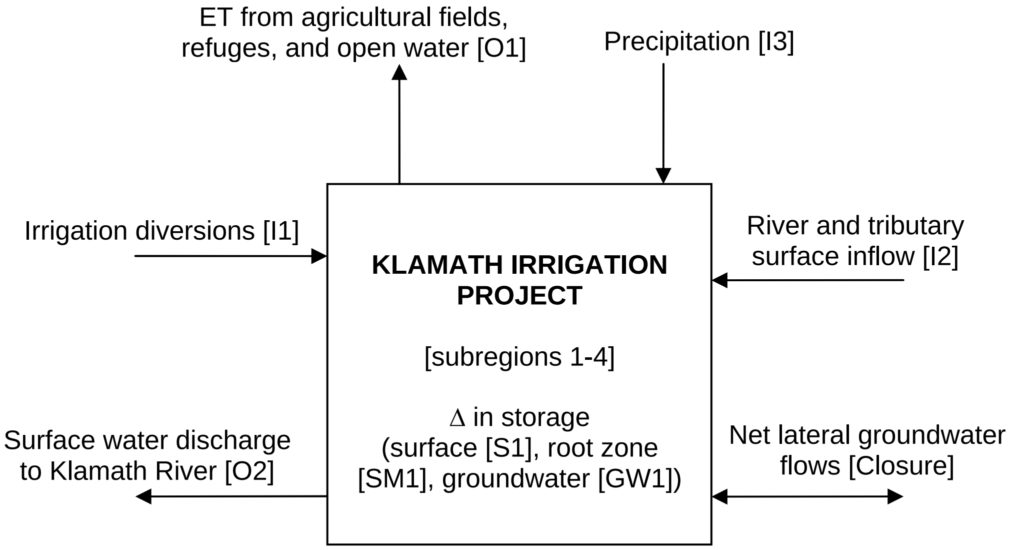


Figure 14. Schematic of the major flow paths entering and exiting the Klamath Irrigation Project

To increase the spatial resolution of the water balance and to better account for hydrological inter-actions between adjacent subregions within the Klamath Irrigation Project, the study area was divided into four subregions (refer to Section 3.3 – *Land Use Areas*). Thus, the subregional water balances and the overall water balance for the Project (encompassing subregions 1-4) were computed according to:

Inflows = Outflows + Change in Storage

Inflows

+ Surface water diversions (I1)

+ River and tributary flows (I2)

+ Precipitation and snowfall (I3)

+ Groundwater inflow discharged at Bonanza Springs (I4)

Outflows

– Total consumptive use (O1)

– Surface water discharge (O2)

Change in Storage

– Change in surface water storage (S1)

– Change in root zone storage (SM1)

– Change in groundwater storage (GS1)

= **Net lateral groundwater inflow/outflow** (closure term)

The water balance closure term used in this hydrologic assessment was the net lateral groundwater inflow/outflow to the boundaries. A positive (+) closure term indicates net lateral outflow of groundwater leaving the area of investigation. A negative (-) value means that there is a net lateral groundwater inflow into the boundaries. However, because of the uncertainty associated with individual water balance components, the sign (+ or -) of the final closure term does not necessarily indicate the net contribution (direction) of external lateral groundwater flow depending on the value of the final closure *CIs*.

3.1.1 Uncertainty and Quality of Measurements and Data

The water balances that were computed in this investigation were heavily dependent upon data provided by the USBR Klamath Basin Area Office and individual irrigation districts, in addition to information obtained from other entities such as the National Climatic Data Center (NCDC), PacifiCorp, OWRD, USFWS, and the California Irrigation Management Information System (CIMIS) network. Even though previous reports (Davids Engineering Inc., 1998; Kaffka and Dhawan, 2002; NRC, 2002; GAO, 2005; Gannett et al., 2007) have recognized the fact that uncertainty does indeed exist, there have been no previous attempts to quantify the magnitude (and therefore, relative importance) of the specific uncertainties associated with different water flow paths in the Klamath Irrigation Project. In cases of missing or incomplete data for some inflow and outflow components, estimates were made based on experience with water balance studies and assumptions about the general hydrologic features of the area. Weather data from the agricultural metrological stations were screened using integrity assessment techniques described by Allen et al. (1998).

There is always some degree of uncertainty associated with all the values used in water balance computations and related hydrological analyses. For example, even the best instantaneous surface flow rate measurements will typically only be plus or minus 2 to 4% accurate – if one fully considers all the factors related to the equipment calibration, construction, measurement errors, resolution of the instruments, and theoretical assumptions. In some cases, there may be large inherent uncertainties in relatively small contributions to the water balance, and vice versa. This can lead to the misconception that more or less water is actually available, and more importantly it may mean time and effort is wasted on relatively minor parts of the water balance, which in the end will have only minimal impacts.

Burt et al. (1997), Burt (1999b), and Clemmens and Burt (1997) discuss many of the difficulties in making accurate estimates of crop consumptive use (*ET*). In particular, deep percolation and shallow groundwater lateral flow into or out of a defined boundary of an irrigation project are very difficult to measure accurately. Other hydrologic variables dealing with regional groundwater can be especially difficult to predict from limited datasets (Gannett et al., 2007). This research recognizes that associated with all values of measured or estimated water volumes and fluxes are elements of uncertainty. Confidence intervals (*CI*) at the 95% level, representing ±2 standard deviations are standard statistical tools for describing the uncertainty correlated to measured water values. The 95% *CI* is commonly used to represent the range over which one is 95% certain that the true value lies. For example, a *CI* of "10%" indicates that one is 95% certain that the correct value lies between plus or minus 10% of the stated value. A *CI* of "0%" would indicate that there is no uncertainty in the value – an impossibility when dealing with water studies.

CIs expressed as a percent (Clemmens and Burt, 1997) can be estimated from an expert evaluation of the methods and instruments in use. Potential errors to be considered in assigning an estimated *CI* include device calibration, frequency of measurements (sample size), and systematic installation errors (Clemmens and Burt, 1997). To account for the impacts of measurement inaccuracies in the hydrological analysis of the Klamath Irrigation Project, *CI* estimates are assigned to all water balance terms and performance parameters.

The use of *CIs* in this water balance is particularly important because it identified which individual components (both sources and destinations) have the greatest impact on the overall estimates of inflows and outflows. If a value is not known when a water balance is computed, it is more incorrect to ignore it or to assume it has a value of zero than to make an initial estimate of its value; therefore, estimates were made for any missing data (Burt, 1999a). The *CIs* reported in this study reflect the author's best judgments about the accuracy of the available information and should be considered a starting point when determining the priorities for future studies and data collection efforts. The *CIs* assigned to individual water balance components are an indication of the inexact knowledge of the inflows and outflows that cross the boundaries of the service areas of the irrigation districts in the Project.

3.2 Boundary Conditions and Spatio-Temporal Constraints

An irrigation water balance has both spatial and temporal boundaries that must be clearly defined in order for the analysis to be useful in making decisions regarding water management and the potential for water conservation. The key concepts associated with boundary conditions and components of water balances are identified and described in detail by Burt (1999b). The boundaries of the Klamath Irrigation Project, delineated by irrigation district service areas, are the basis of the water balance in this analysis. This quantitative investigation provides an accounting of all water volumes that entered or left the defined boundaries on a monthly and annual basis over the selected 5-year time period of 1999 to 2003.

The Klamath Irrigation Project was sub-divided into five separate but adjoining subregions. Subregion 5 was not included in water balance computations. Each of the surface and subsurface flow paths was defined and positioned according to its relative additive or subtractive effect on each of the subregional water balances. In most cases, a surface flow path was assigned to be consistent with records that are collected at major diversion points within the Project. Similarly, the partitioning of the geographic subregions used in this study generally follows the breakdown used in previous water balances and hydrologic investigations done in the Klamath River Basin.

3.3 Land Use Areas

3.3.1 GIS Spatial Analysis Categories

The geographic boundaries of the water balance correspond to a delineation of four subregions in the Klamath Irrigation Project (out of a total of five subregions). The area of investigation was divided into separate subregions to facilitate a more accurate assessment of the hydrologic records/data and internal water control processes. The boundaries of the five subregions encompass a total area of 134,920 ha (333,383 acres). The irrigation districts and geographical area included in each subregion are summarized in **Table 5**. The crops and land use area types within each subregion were determined from a geographic information system (GIS) database.

Table 5. Irrigation districts and geographical area in each subregion (Klamath Irrigation Project)

Subregion 1 Langell	Subregion 2 Upper Klamath	Subregion 3 Tulelake	Subregion 4 Lower Klamath	Subregion 5 Westside
Langell Valley ID Horsefly ID Lost R. contracts Bowne land	Klamath ID Van Brimmer DC Enterprise ID Pine Grove ID Sunnyside ID Shasta View ID Malin ID Poe Valley ID Klamath B. Impr. D	Tulelake ID Tulelake NWR Westside Impr. D J & D ind. contracts TID misc. contracts	Lower Klamath NWR Klamath DD P Canal contracts Midland DIC Area K	Plevna DIC Pioneer DIC UKL contracts Ady DIC Klamath R. contracts
23,047 ha	**34,884 ha**	**39,644 ha**	**29,818 ha**	**7,527 ha**

Figure 15 shows the geographic locations of the hydrologic subregions' boundaries and key features of the Klamath Irrigation Project.

The water balance computations focused on subregions 1-4. Surface water diversion and crop data were not available for subregion 5 (not shown). Even though the irrigated lands in subregion 5 are officially part of the Klamath Irrigation Project, water is diverted from the Klamath River at numerous, unmetered points by private landowners and small irrigation districts. In addition, the boundaries of the irrigated fields are not contiguous and in some places not well-defined, which is not the case with subregions 1-4. To simplify calculations and analyses this smallest geographically-separate subregion 5 was not included in the water balance.

(1) *Langell*: subregion 1 includes the service areas of the Langell Valley ID and Horsefly ID. The subregion consists of approximately 23,050 ha (56,950 acres). In hydrologic terms, the subregion extends from the Miller Diversion Dam and Malone Diversion Dam to Harpold Dam on the Lost River.

(2) *Upper Klamath*: subregion 2 extends from downstream of Harpold Dam to the Anderson-Rose Dam. It encompasses the irrigated land in the Lost River Basin lying east of the Klamath River and north and east of the Klamath Hills, in addition to Poe Valley. The subregion includes approximately 34,880 ha (86,200 acres). Irrigation districts in the subregion include Klamath ID, Enterprise ID, Pine Grove ID, Sunnyside ID, Shasta View ID, Malin ID, and Van Brimmer Ditch Company. The southern boundary of the subregion is defined as the J Canal to the junction with the D Canal in the Tulelake ID. This greatly simplified the hydrologic analyses of historical records and corresponds to operational procedures followed by the adjoining districts.

(3) *Tulelake*: subregion 3 encompasses the irrigated areas and refuge wetlands downstream of Anderson-Rose Dam. The subregion includes approximately 39,640 ha (97,960 acres). The subregion is mainly defined by the Tulelake ID, except for the small portion of the district served by the D Canal. The Tulelake National Wildlife Refuge, including the Tule Lake sumps and federal lease lands, lie within the boundaries of this subregion.

(4) *Lower Klamath*: subregion 4 covers approximately 29,820 ha (73,680 acres) of irrigated land and wildlife refuge lying generally to the east of Highway 97 and west of the Klamath Hills. The subregion includes the Klamath DD and the Lower Klamath National Wildlife Refuge.

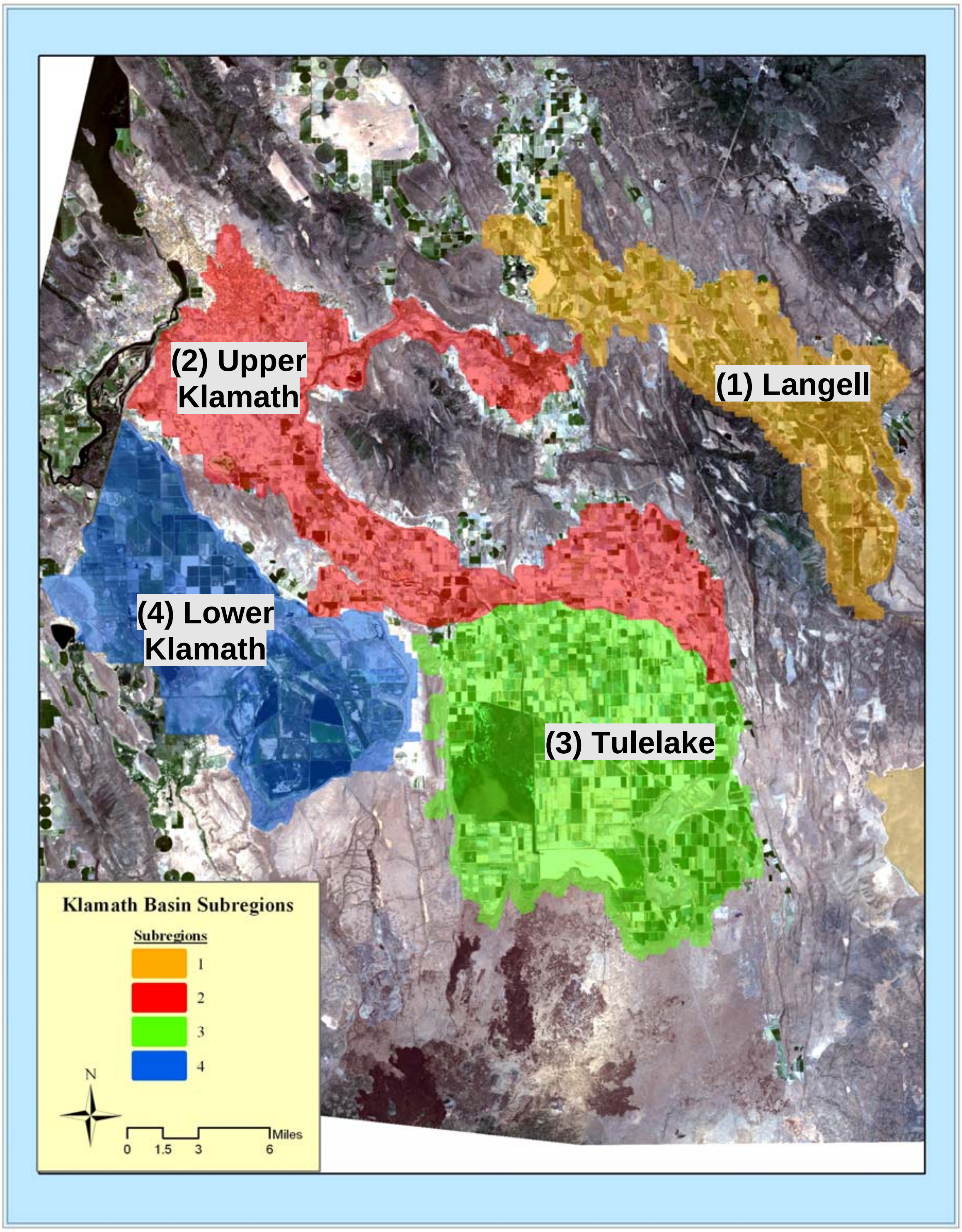


Figure 15. Geographic location of the hydrologic subregion boundaries

3.3.2 Soil Resources

A GIS database (ArcInfo® platform) was developed for geo-processing of the individual subregions delineated in the water balance. Soil surveys done by the Natural Resources Conservation Service (NRCS) for Southern Klamath County (map ID# OR640; NRCS, 1985) and the Tulelake region (map ID# CA684; NRCS, 1994) in digital format were integrated to the GIS program. Digital soil maps summarize soil types and general characteristics in terms of slope, depth, drainage and other features that affect their management. The principal landscape features in the Klamath Irrigation Project region are agricultural basins about 5 to 40 km (3-25 miles) in length bounded by steep ridges on at least 2 sides (NRCS, 1985).

Soils are classified by the NRCS based on their suitability for growing field crops in Capability Classes from I to VIII, representing progressively greater limitations. Class I soils have few limitations, and generally fields preferred for irrigated agriculture lie within Class I-III (termed "prime farmland"). Specific limitations identified for some agricultural soils in the Project are related to erosion susceptibility, poor drainage (shallow water tables), and low fertility (NRCS, 1985). There are no designated Class I soils in the Project due to the regular occurrence of frost and high-altitude limitations on crop growing season length; however, properly irrigated and drained fields can be considered prime farmland (Chapter 7 in Braunworth et al., 2002).

There are significant differences in the predominant soil types, and therefore water holding capacities and other characteristics related to irrigation management, in the four subregions (Oregon State Water Res. Board, 1969). For example, the soils in subregion 2 are predominately loam, sandy loam, and loamy fine sand. Without irrigation, the stored soil moisture in these fields in Klamath ID would not be sufficient for grain crops, and pasture and alfalfa fields would experience severe stress during at least part of the growing season. In contrast, the soils in subregion 4 in the Lower Klamath Lake area, an old lakebed, are much heavier consisting of mainly silt loams and able to sustain small grain crops with stored soil moisture from winter irrigations. Subregion 3, containing the Tulelake ID, is dominated by mucky silt loams with high-organic matter (NRCS, 1997).

There are over 100 series, complexes, and associations of soils found in irrigated fields in the Klamath Irrigation Project. This diverse set of soils was categorized into four major soil types: sand, loam, silt loam, and clay loam. *ET* for each major crop type was modeled with the four different soil types as summarized in **Table 6**. Digital soil survey data were utilized to determine the weighted average evapotranspiration in each subregion based on the extent of each major soil type.

Table 6. Percentage of soil types in subregions 1-4 (Klamath Irrigation Project), %

Soil Type	1	2	3	4
Sand	9.9%	40.4%	9.3%	1.8%
Loam	64.3%	51.9%	19.4%	3.7%
Silt Loam	3.7%	0.3%	19.7%	91.8%
Clay Loam	22.2%	7.3%	51.6%	2.7%

Source: USDA-NRCS Soil Survey Division (1997).
National SSURGO Database.

The soil parameters in **Table 7** were assigned to the four major soil types based on information in the NRCS soil surveys, experience with modeling results in other similar projects, and guidelines in Table 19 in FAO 56 (Allen et al., 1998). When the soil is wetted, evaporation occurs, primarily from the exposed fraction, at a maximum rate limited by the amount of energy available at the soil surface layer for *ET*. This period is referred to as Stage 1 drying (energy limiting stage) and can occur for several days. The exposed fraction of soil (f_{ew}) refers to the portion that is not covered by vegetation and is wetted by irrigation or precipitation. During Stage 1, when the soil surface remains wet, evaporation continues until the hydraulic properties of the topsoil layer become limiting because water cannot be transported to the surface at a rate that can supply the potential demand. The cumulative depth (D_e) at the end of Stage 1 is termed *REW*, which is the maximum depth of water that can be evaporated from the topsoil layer without restriction during Stage 1 (Allen et al., 1998). The total amount of water that can be depleted from the top 10-15 cm of the top soil layer (*TEW*) is assumed to be at a point that is halfway between oven dry (no water left) and wilting point (*WP*).

Table 7. Hydraulic parameters and soil-water characteristics for daily soil water balance modeling

Soil Type	Field capacity [mm/m]	PWP[1] [mm/m]	W[2] [mm/m]	REW[3] [mm]	TEW[4] [mm]
Sand	150	60	90	6	18
Loam	245	120	125	8.5	28
Silt Loam	300	150	150	9.5	34
Clay Loam	360	190	170	10.5	40

[1] Permanent wilting point
[2] Water content
[3] Readily evaporable water (evaporation layer depth=15 cm)
[4] Total evaporable water (evaporation layer depth=15 cm)

3.3.3 Annual Land Use

The Klamath Irrigation Project is located in two hydraulically linked, adjoining river basins in southern Oregon and northern California: the Upper Klamath River Basin above Iron Gate Dam, and the Lost River Basin. The developed land use areas in the four subregions are principally irrigated cropland and wildlife refuge lands. The entire Project area (with subregion 5) includes approximately 97,000 ha (240,000 acres) of arable land of which about 81,000 ha (200,000 acres) are irrigated annually, plus about 11,000 ha (28,000 acres) of irrigated refuge lands.

The geographic boundaries of the water balance investigation encompass all cropland and refuge land receiving project water deliveries. The Tulelake National Wildlife Refuge and the Lower Klamath National Wildlife Refuge are managed wetlands that receive project water for irrigation and habitat maintenance. Interspersed within the water balance boundaries are urban areas, wetlands, forested areas, reservoirs and lakes, and farmsteads.

Table 8 summarizes the annual land use areas within the assigned water balance boundaries. An accurate and full accounting of the land use areas in 1999 to 2003 was an important requirement of the water balance. *Annual Crop Reports* provided by the USBR and irrigation districts were used to determine crop areas in 1999, 2000, 2002, and 2003. To assess the extent and condition of crop areas in 2001, a vegetative index was developed using satellite remotely-sensed electromagnetic radiation data, in addition to limited crop reports. A GIS spatial analysis provided estimates of the land use areas identified as canals, drains, urban areas, and roads.

Table 8. Annual land use areas and irrigated area, ha

Item	1999	2000	2001	2002	2003	Mean
Crop area, irrigated[1]	75,664	76,278	55,706	73,479	70,462	**70,318**
Fallow or idle	3,046	1,887	21,863[4]	4,886	7,963	**7,929**
Refuge wetlands[2]	11,638	11,517	11,376	11,517	11,517	**11,513**
Canals and drains	1,385	1,385	1,385	1,385	1,385	**1,385**
Reservoirs/rivers/streams[3]	6,698	6,698	6,698	6,698	6,698	**6,698**
Urban areas and roads	3,303	3,303	3,303	3,303	3,303	**3,303**
Undeveloped land[5]	25,660	26,326	27,063	26,125	26,066	**26,248**
Total	**127,393**	**127,393**	**127,393**	**127,393**	**127,393**	**127,393**

[1] USBR *Annual Crop Reports* and cooperatively farmed area in the Lower Klamath NWR and Tulelake NWR.
[2] The refuge areas in the Lower Klamath NWR and Tulelake NWR reported as permanent wetlands, seasonal wetlands and upland areas.
[3] Includes the Tule Lake sumps in the Tulelake NWR.
[4] Includes areas planted with an emergency cover crop that was not irrigated, usually barley.
[5] A closure term of "undeveloped land" was computed for the area that was not specifically categorized as irrigated cropland, wildlife refuges, surface water bodies, canals, drains, or urban areas within the overall boundaries of the four subregions.

3.3.3.1 Assessing the Impact of the 2001 Drought

The cessation of irrigation deliveries in 2001 resulted in a substantial reduction in crop area and major temporary shifts in cropping patterns. The true-color satellites image (taken June 17, 2001) in **Figure 16** shows the effect of the 2001 drought and subsequent water delivery reallocation on the agricultural landscape in the Upper Klamath Basin. In 2001, irrigated agricultural area in the Klamath Irrigation Project was reduced by about 27% (refer to **Table 8**), as evidenced by the large extent of brown (bare) fields, mainly between Upper Klamath Lake and Tulelake (subregion 2). In a normal season irrigated farmland with actively growing crops would be visible as green fields.

In 2001 many irrigation districts did not complete regular annual crop reports. Therefore, it was necessary to utilize an approach based on a combination of sources, including Klamath County Annual Crop Reports (cited in Braunworth et al., 2002) and a vegetative index to determine the extent of irrigated area. A Normalized Difference Vegetative Index (*NDVI*) was developed using remotely-sensed electromagnetic radiation data from a satellite image of the Upper Klamath Basin.

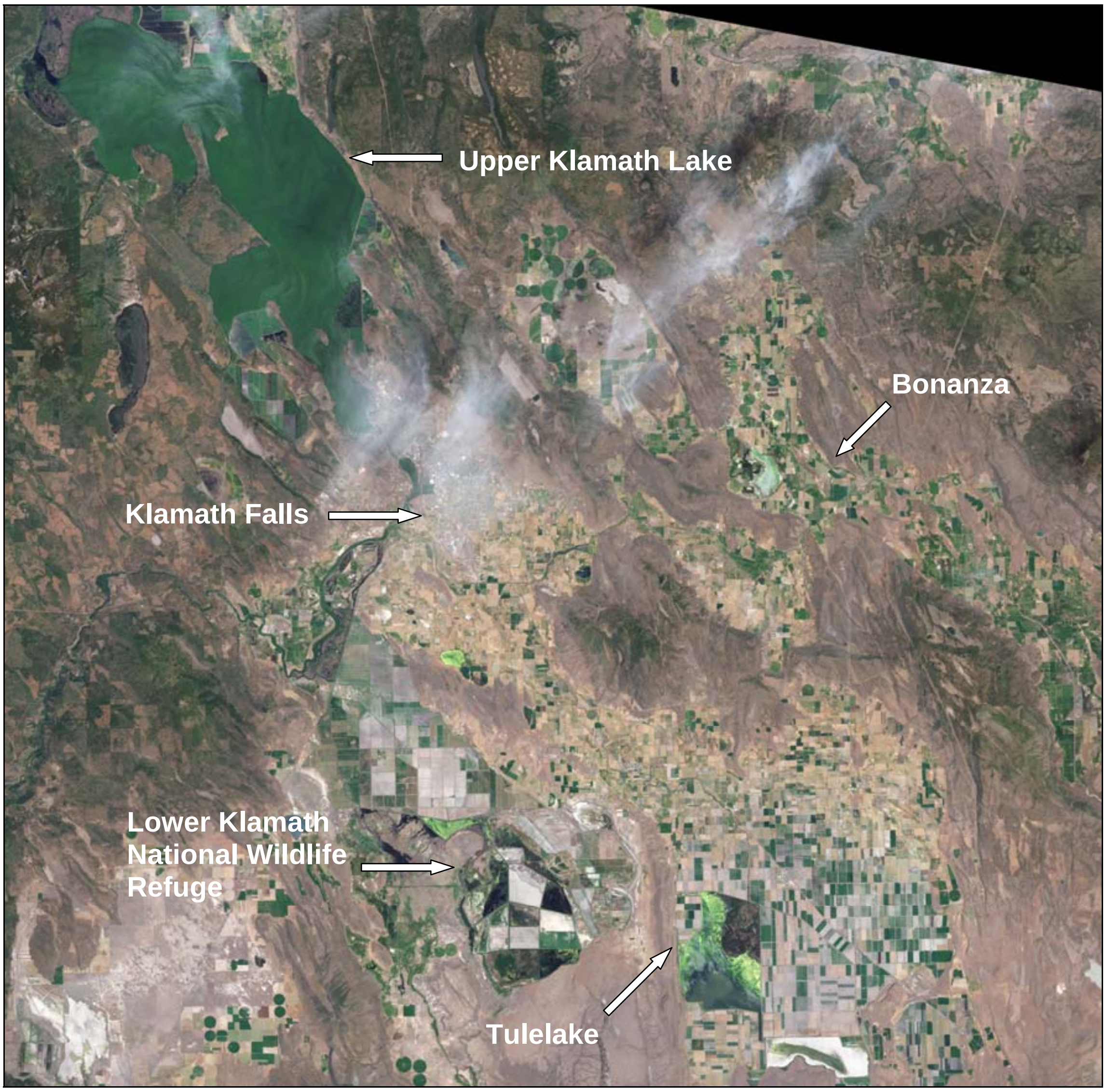


Figure 16. 2001 drought effects on the agricultural landscape in the Upper Klamath Basin

Figure 17 shows the *NDVI* developed for the agricultural fields in the Klamath Irrigation Project. This *NDVI* was used to assess the extent of irrigated areas in the project rather than to determine seasonal *ET*, which requires further SEBAL (Surface Energy Balance Algorithm for Land) processing of six to eight satellite images (Bastiaanssen et al., 2005). LandSAT 7 images have eight bands of data available for each image. Each pixel of the image is quantified in terms of the wavelength in eight predetermined bands (or ranges) of wavelengths. The first three bands are in the visible light spectrum and the fourth band is in the near-infrared spectrum (*NIR*). The third band is in the red range (Red) of the visible light spectrum. For the vegetative index, one is interested in the third and fourth bands. The most commonly used vegetative index is the *NDVI*. The *NDVI* is used to determine the density and relative health of vegetation. It is calculated from the ratio between measured reflectivity in the red and near infrared portions of the electromagnetic spectrum:

$$NDVI = (\text{Band } 4 - \text{Band } 3)/(\text{Band } 4 + \text{Band } 3) = (NIR - \text{Red})/(NIR + \text{Red})$$

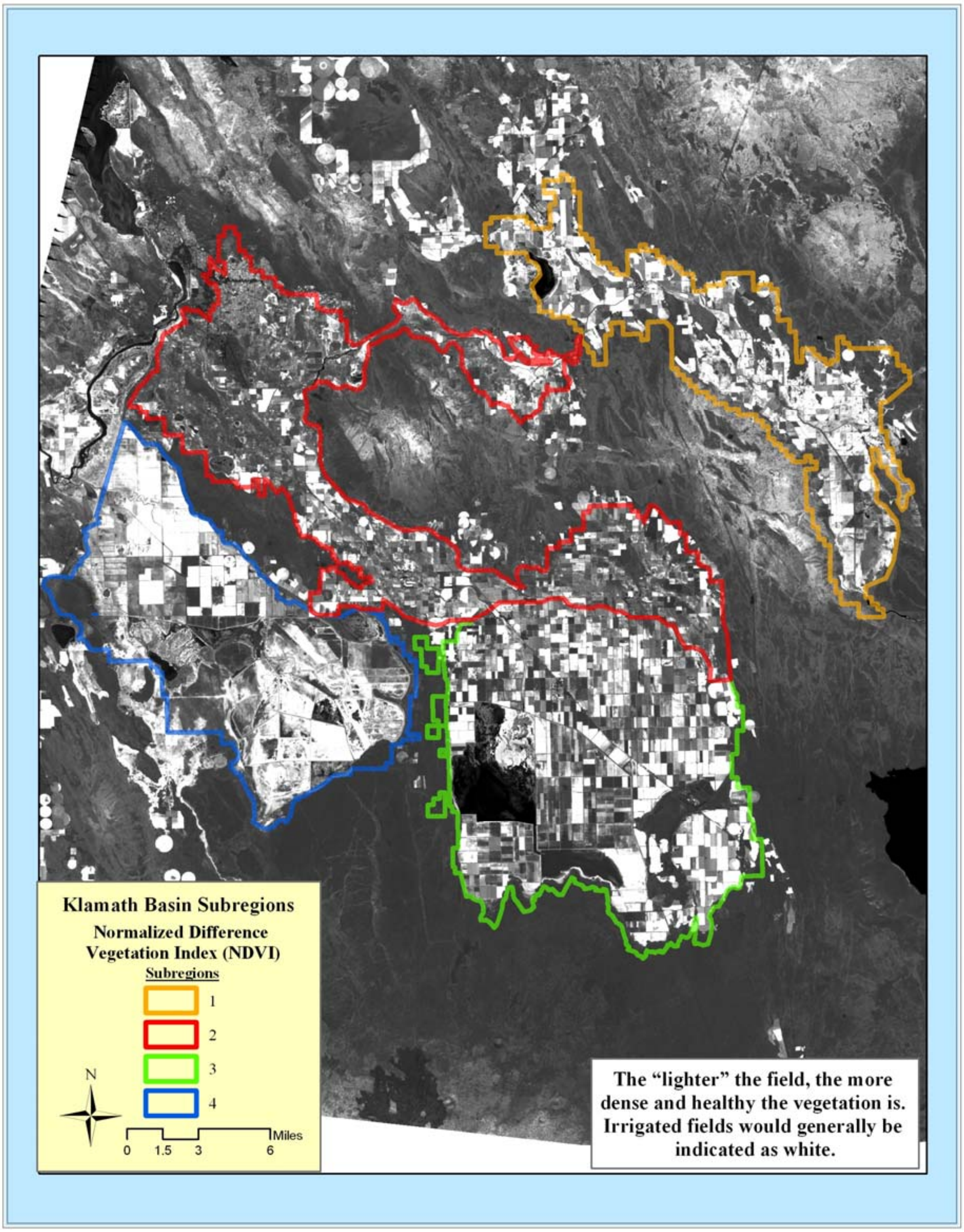
The LandSAT 7 1G image in **Figure 17** (acquired using the Enhanced Thematic Mapper Plus sensors aboard the LandSAT 7 satellite) was taken on July 28, 2001, before the emergency release of irrigation water that occurred in August. The lighter the pixel, the more dense and healthier the vegetation. Using ArcView 3.2a and ArcView Image Analyst, the *NDVI* for the entire area of investigation was calculated for the LandSAT 7 1G image. The result was a grayscale image that had pixel values corresponding to the *NDVI*. Using the Image Analyst tool, the *NDVI* output was categorized into eight groupings. Then, the number of pixels in each group and within each field boundary was summed together for each of the four subregions. Since each pixel covers a known and constant unit, the area was then calculated for each group in each subregion. Comparing the natural color image to the *NVDI*, it was determined that groupings 6-8 were healthy irrigated crops and the remaining groups indicated bare soil through senescing crops.

As the time of data acquisition was during severe water stress in many non-irrigated fields, the spectral signature of many pasture and alfalfa fields may be similar to senescing crops. Both the image and the *NDVI* results show that the impact of the 2001 irrigation curtailment was much different among the subregions, depending on their primary source of water (i.e., Upper Klamath Lake or the Lost River System), among other factors.

Due to the timing at which the LandSAT image was taken, the image does not take into account the impacts of the emergency release of irrigation water in August. During the early part of the irrigation season, growers used water transferred from the Lost River system, privately owned wells, and purchases of groundwater from adjacent areas. Thus, it was nearly impossible to determine exactly which fields may have received late season irrigation or in what amounts. It was assumed that the reported area for crops such as potatoes, onions, and peppermint reflected situations where the grower had secured a full season's water supply without relying on the unpredicted August deliveries. Therefore, it was assumed that much of the irrigation water delivered in August went to maintain existing pastures and alfalfa fields.

In subregions 2 and 4, the irrigated areas determined from the vegetative index were compared to the preliminary Klamath County crop reports. There is a significant difference in the predominant soil types, and therefore water holding capacity, in the two subregions. In subregion 4, the soils are much heavier and may have been able to sustain grain crops and pasture through July when the satellite image was taken. The overall estimate of irrigated area for subregion 4 in 2001 is close to historic averages based on 1999 and 2000, with an expected increase in the number of fallow fields. Complicating the analysis of subregion 4 is the change in water management practices in the Lower Klamath NWR and adjacent P Canal area.

It was more problematic to estimate the crop area in subregion 2 during 2001 for several reasons. The largest district in the subregion, Klamath ID, did not prepare annual crop reports on account of the irrigation curtailment. However, the majority of the area has traditionally been alfalfa and pasture, which growers would not likely have plowed under to plant cover crops. The soils in subregion 2 are predominately loam, sandy loam, and loamy fine sand. Without irrigation, the stored soil moisture in these fields was not sufficient for grain crops, and pasture and alfalfa fields would have experienced severe stress during at least part of the growing season. The satellite image in late July and the resulting vegetative index may therefore reflect areas of pasture and cover crops that were indistinguishable from fallow, weedy fields.



The “lighter” the field, the more dense and healthy the vegetation is. Irrigated fields would generally be indicated as white.

Figure 17. Normalized difference vegetative index (*NDVI*) of the Klamath Irrigation Project, (July 28, 2001)

3.3.4 Irrigated Crop Area

Agricultural cropland is the predominant land use within the Klamath Irrigation Project, dominated by pastures, hay, and cereals. The principal crops produced in the Project include alfalfa, irrigated pasture, small grains (barley, oats, rye, wheat), potatoes, onions, and sugar beets. The agricultural fields within the approximately 1,400 private farms in the Project area average about 81,000 ha each year (200,000 acres/yr). The average of the total irrigated crop area from 1999 to 2003 excluding fallow lands was 70,300 ha (173,800 acres), which is consistent with long-term, historical averages.

The total combined hay crops, including alfalfa, grass/meadow hay, grain hay, and grain/legume hay comprise the largest area in the project, followed by grain crops. Hay crops represented an average of 33% of the total crop area during the five-year period. Barley is the leading cereal crop, comprising an average of 15% of the total crop area (excluding 2001 when planting was reduced from historical patterns due to the drought). Hay production increased by 30% during the 1990s, while total grain area declined by about 25%. Potato production has also declined because of unfavorable market conditions (Smith and Rykbost, 2000). Potatoes comprised an average of 7% of the total crop area during the study period (excluding 2001).

Annual Crop Reports prepared by the USBR provide the best available information on crop area figures and shifts in cropping patterns. Crop data for the Project are fairly accurate due to the USBR's requirement that each irrigation district must submit annual reports of all irrigated area and crops grown. These crop reports were analyzed to determine the crop types and areas within each subregion. There were some slight differences in the reporting formats used each year that somewhat affected the classification of minor crops.

The withholding of irrigation water in 2001 affected different crop types in different areas of the project to varying extents (refer to **Figure 18** and the discussion in Section 3.6.1 – *Crop Irrigation Water Requirements*). While the combined area of alfalfa and other hay crops declined slightly, the areas of other crops such as potatoes, onions, and wheat were dramatically reduced. The resulting increase in fallow fields or fields planted with emergency cover crops was over ten-fold from the previous year. In 2001, the area of sugar beets was removed completely due to the closure of sugar refineries. The impact of the irrigation curtailment on growers' decisions regarding crop rotations and the relative per-acre yields they received depended on many factors including the large variability in soil types between subregions, access to other sources of irrigation water such as private wells, the timing of planting dates to coincide with localized rainfall events, and the residual soil moisture conditions depending on the previous crop.

A completely accurate assessment of crop area in 2001 is further problematic because some large districts did not compile annual crop reports, while others did but may not have been able to verify which fields actually produced a crop. Braunworth et al. (2002) estimate about 35% of the total irrigated area in the Upper Klamath Basin did not receive irrigation water in 2001, but the effects were more acute for water users whose normal supply is Upper Klamath Lake. Without a systematic, project-wide appraisal of the magnitude of crop area reductions, the figures for 2001 must be considered only approximately indicative of changes in cropping patterns and relative amount of irrigated areas. This increased uncertainty is reflected in the provision of greater *CIs* for the estimate of evapotranspiration in 2001.

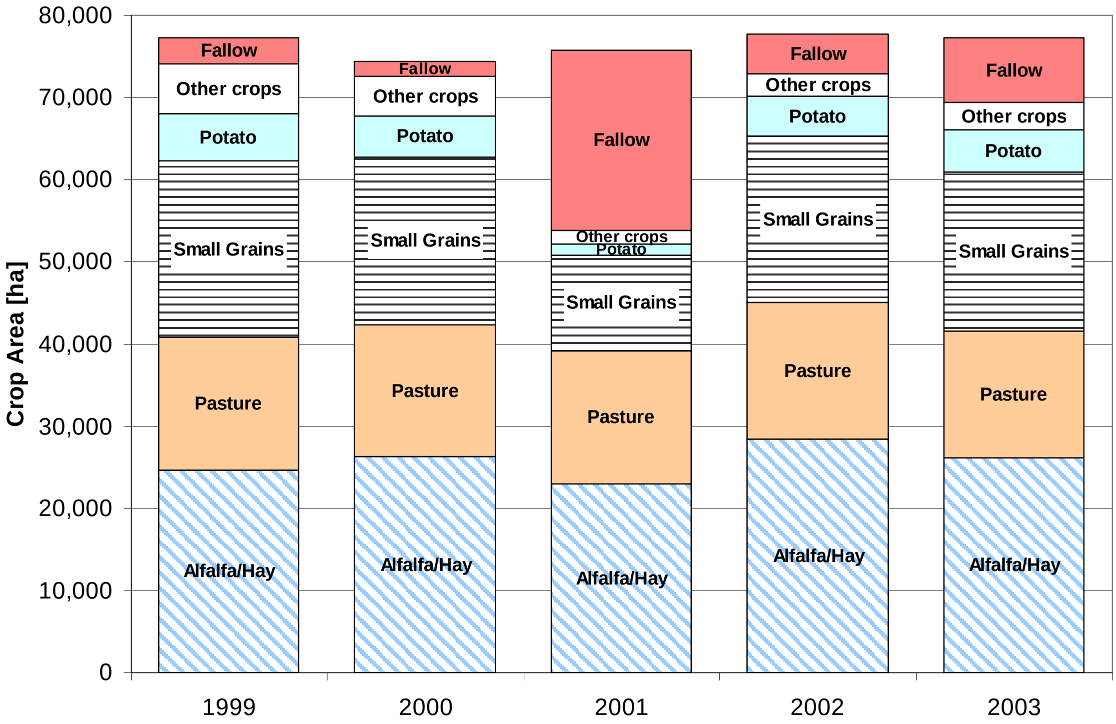


Figure 18. Annual crop areas in the Klamath Irrigation Project (1999-2003)

The reported crop areas for each crop type in 1999, 2000, 2002 and 2003 and the estimated crop areas during 2001 are shown in **Table 9**.

Table 9. Crop areas in the Klamath Irrigation Project (subregions 1-4), ha

Crop type	1999	2000	2001	2002	2003	Mean
Alfalfa	19,214	20,625	17,142	21,240	20,498	**19,744**
Barley	12,141	13,171	9,417	12,144	10,278	**11,430**
Berries	136	92	0	124	219	**114**
Gardens	395	0	0	0	0	**79**
Hay	5,458	5,738	5,859	7,146	5,616	**5,963**
Misc. crops	333	401	336	364	363	**359**
Oats	1,949	1,628	959	2,256	2,419	**1,842**
Onions	1,554	1,201	315	879	768	**943**
Other grains	176	163	0	123	225	**137**
Pasture	16,146	15,915	16,156	16,725	15,483	**16,085**
Peas	4	92	245	86	114	**108**
Peppermint	607	965	547	773	969	**772**
Potato	5,717	5,095	1,352	4,920	5,041	**4,425**
Rye	71	0	42	0	0	**23**
Silage	158	454	241	351	877	**416**
Sugar beets	2,960	1,549	0	63	0	**914**
Vegetables	2	2	0	0	0	**1**
Wheat	7,145	5,453	1,248	5,641	6,480	**5,193**
Fallow, not irrigated	3,046	1,887	21,863[2]	4,886	7,963	**7,929**
Unharvested, irrigated[1]	1,499	3,733	1,847	645	1,114	**1,768**
Total	**78,711**	**78,164**	**77,569**	**78,366**	**78,427**	**78,245**

[1] Includes reported totals for the P Canal area, but not the cooperative grain area in the Lower Klamath NWR shown in **Table 8**.

[2] Includes crop area that was planted with emergency cover crops, usually barley, as part of the NRCS's Emergency Watershed Protection program.

3.3.5 Wildlife Refuge Land Use

The Upper Klamath Basin is the location of five national wildlife refuges: the Lower Klamath, Upper Klamath, Tulelake, Clear Lake, and Klamath Forest. The Lower Klamath and Tulelake NWRs are within the boundaries of the water balance and receive their water supplies from the Klamath Irrigation Project. Both the Tulelake and Lower Klamath NWR complexes provide feeding and resting grounds for the largest concentration of migratory waterfowl in North America. These refuges receive project water under federally reserved water rights and return flows from irrigated lands.

Lower Klamath NWR consists of 43 separately diked wetlands or fields with a total surface area of approximately 13,000 ha (32,000 acres), in addition to approximately 2,400 ha (6,000 acres) of federal lease lands for agricultural production (referred to as Area K). Each refuge unit is operated annually under one of four habitat management strategies: permanently flooded wetlands (flooded year-round), seasonally flooded wetlands (typically flooded in October, and in some years November), farmed units (winter-irrigated grain), and upland habitat (flooded with precipitation and runoff). Habitat management plans are completed each year that specify the intended habitat type and flood cycle for each unit in the refuge. The refuge generally maintains:

- Permanent wetlands – 3,400 to 3,600 ha
- Seasonal wetlands – 5,700 to 7,200 ha
- Farmed units – 1,400 to 1,600 ha

The land area of each habitat management type for 1999-2003 is summarized in **Table 10**. Between 1999 and 2001 the area of seasonally flooded wetlands averaged about 5,580 ha (13,800 acres), with a substantial reduction in 2001. Due to the reduction in available water in 2001, the area of upland habitat increased over three-fold. After 2001, the area of seasonal wetlands went back up beyond previous levels, mainly due to a reduction in grain fields managed by the refuge.

Table 10. Refuge wetlands area in the Lower Klamath National Wildlife Refuge, ha

Habitat type[1]	1999	2000	2001	2002	2003
Permanent	3,428	3,591	2,466	3,567	3,510
Seasonal	6,132	5,706	2,153	6,687	7,240
Upland	1,907	1,846	6,383	2,172	1,975
Grain[2]	1,382	1,705	1,847	423	123
Total	**12,848**	**12,848**	**12,848**	**12,848**	**12,848**

[1] Habitat management plan data from USFWS.

[2] Area K lease lands are included as cropped areas in **Table 8**.

Tulelake NWR consists of the shallow Tule Lake sumps (1A and 1B), seasonal wetlands outside the sumps, and approximately 7,000 ha (17,000 acres) leased for farming (refer to **Table 11**). The total service area is 15,830 ha (39,120 acres).

Table 11. Refuge wetlands area in the Tulelake National Wildlife Refuge, ha

Habitat type	1999	2000	2001	2002	2003
Seasonal	171	374	374	374	374
Upland	3,300	3,100	3,100	3,100	3,100
Lease Lands	7,000	7,000	7,000	7,000	7,000
Sumps 1A and 1B[1]	5,358	5,358	5,358	5,358	5,358
Total	**15,830**	**15,830**	**15,830**	**15,830**	**15,830**

[1] The surface area of the Tule Lake sumps (open water) in the Tulelake NWR is accounted for in **Table 8**.

3.4 Climate Conditions & Natural Resources in the Upper Klamath River Basin

The Upper Klamath Basin is an arid high desert region with considerable variation in storm patterns within its geographic boundaries. Long-term mean annual precipitation in the Klamath Irrigation Project is about 330 mm (13 in), ranging from less than 200 mm in drought years to more than 500 mm in extremely wet years (8-20 in). During the time period of the study (1999-2003), the 5-year mean precipitation in the Klamath Irrigation Project was below average at 252 mm (9.9 in) (refer to **Table 13**). This amount of rainfall is insufficient for agricultural crops, and generally occurs outside of the growing season, so irrigation is necessary.

In addition, the timing of precipitation events varies substantially from month to month as the irrigation season progresses, with most rainfall coming at times when crops are not planted. Most of the annual precipitation in the Basin occurs from November to March (about 70-75%), and mainly comes as snowfall at higher elevations in areas to the north of the Klamath Irrigation Project. However, localized thunderstorms in summer months can produce several inches of rainfall in confined areas, and frost is a year-round occurrence.

The Klamath Basin is a large watershed with a wide diversity of topography. Consequently, there is no single rainfall dataset that is representative of the entire study area. Long-term local climate information is summarized in the *Annual Reports of the Klamath Experiment Station* and other studies with long-term historical climatological records (CDWR, 1964; Oregon State Water Res. Board, 1971; Davids Engineering Inc., 1998, Brownell and Rinallo, 1995; USGS, 1996). Each subregion has unique characteristics affecting not only the amount or timing of precipitation, but the eventual destinations of surface runoff, stored soil moisture, and groundwater recharge are influenced by a diverse range of localized factors. A comprehensive hydrologic assessment of precipitation is further complicated by the lack of long-term records in some places.

3.4.1 Agricultural Weather Station Networks

Climatological datasets were retrieved for relevant water balance parameters from automated agricultural weather stations located in the Upper Klamath Basin including the AgriMet[13] network and the California Irrigation Management Information System (CIMIS). [14] Historical databases for precipitation (P), temperature (T), solar radiation (R_s), relative humidity (RH), wind speed (u_2), and reference evapotranspiration (ET_o) were compiled for use in computing crop water use. It was important that the stations represented the same microclimate as the area of interest; therefore, multiple stations were selected corresponding to their locations in the subregions and based on a quality control analysis of the available records. Each network has standardized site conditions and instrumentation specifications are generally identical.

The automated weather stations collect data on a minute-by-minute basis, calculate hourly and daily values, and store them in on-site dataloggers. Data is transmitted to central computer networks, whose configuration depends on the network, analyzed for quality, and compiled for storage and retrieval. Registered users of the weather station networks can obtain various hourly, daily, and monthly agro-hydrological datasets.

Agricultural weather stations used in this study are summarized in **Table 12** showing the irrigation district in which they are located and the year data collection began. Climatological datasets were obtained for the study area for the period of record January 1, 1999 to December 31, 2003. During the time period of the study, some weather stations became inactive, while other new stations were added. New weather stations in Lorella (Langell Valley) and Worden (Lower Klamath Lake area) will help in the future to provide more localized rainfall data and crop water use information for these subregions (1 and 4, respectively).

Table 12. Automated agricultural weather stations in the Upper Klamath River Basin

Station Name (Agency)	Irrigation District	Installation Date
Lorella (AgriMet; LORO)	Langell Valley ID	2001
Klamath Falls (AgriMet; KES)	Klamath ID	1999
Klamath Falls (NOAA; 35-4511-7)	Klamath ID	1996
PacifiCorp (NOAA; 35-4506)	Klamath ID	1948
Tulelake (CIMIS; 91)	Tulelake ID	1989
Tulelake Irrig. Dist. (NOAA; 04-9053-1)	Tulelake ID	1948
Worden (AgriMet; WRDO)	Klamath DD	2000

---

[13] AgriMet, a conjunction of the words "agricultural" and "meteorology", is a satellite-based network of automated agricultural weather stations operated and maintained by the USBR. The stations are located in irrigated agricultural areas throughout the Pacific Northwest and are dedicated to regional crop water use modeling, agricultural research, frost monitoring, and integrated pest and fertility management (Palmer, 1999).

[14] CIMIS is a program of the Office of Water Use Efficiency (OWUE), CDWR that manages a network of over 120 automated weather stations in the state of California. CIMIS was developed in 1982 by DWR and the Univ. of California, Davis to assist irrigators in managing their water resources efficiently.

The approximate locations of the agricultural weather stations in the Klamath Irrigation Project are shown in **Figure 19**.

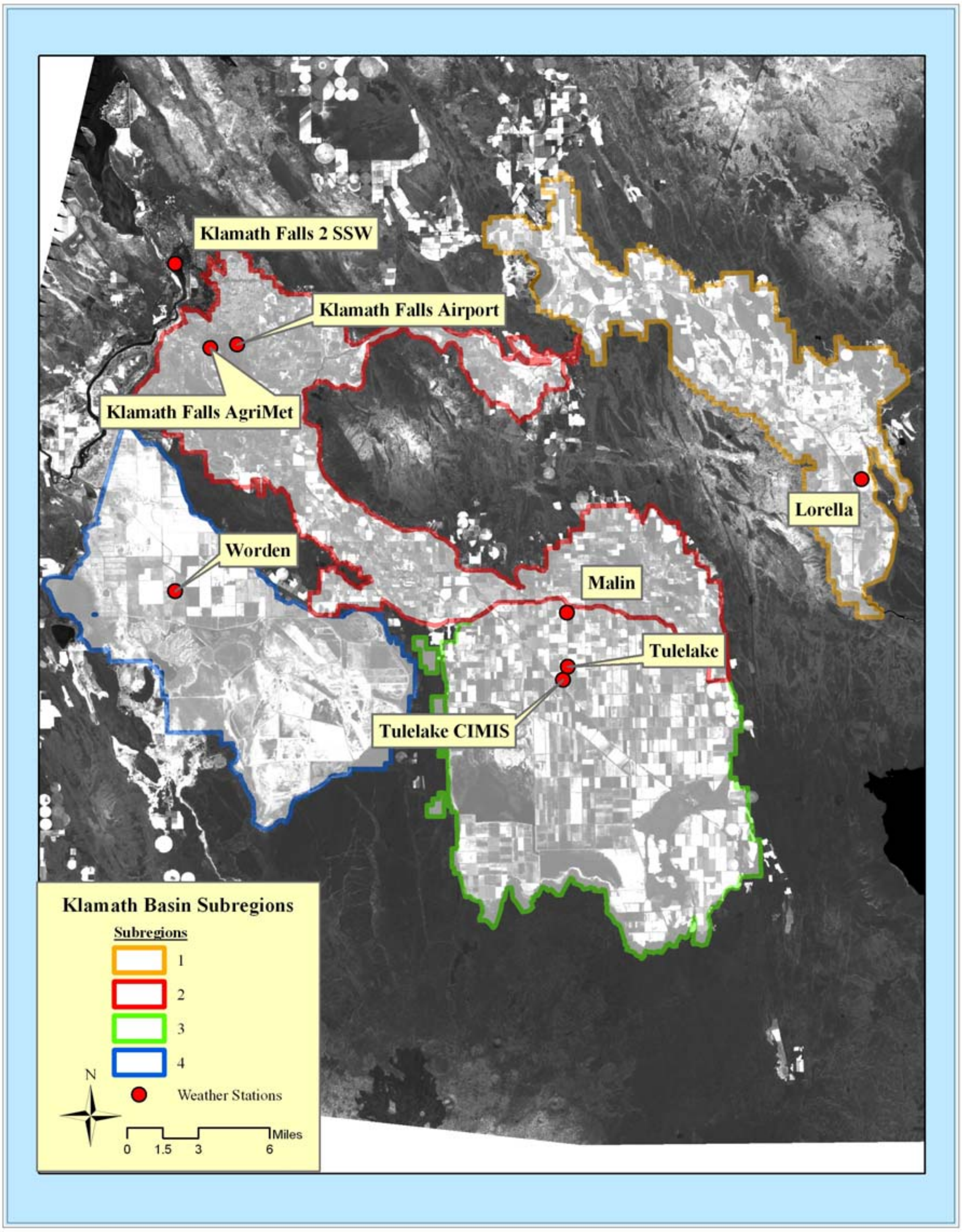


Figure 19. Agricultural weather stations in the Klamath Irrigation Project

3.4.2 Precipitation

The annual precipitation amounts measured at seven different weather stations in the Klamath Irrigation Project are summarized in **Table 13**. The locations of each station relative to the Project's water balance boundaries are shown on the previous page in **Figure 19**. The stations with the longest period of continuous record are at agricultural experiment stations in Klamath Falls and Tulelake, which generally represent conditions in the majority of farmland in the study area.

Only about one-third of rainfall in the Project usually occurs during the growing season; almost half of annual rainfall occurs in the three month period from November to February. Measured precipitation ranged from approximately 200 mm per year in 1999 (in Tulelake; subregion 3) to nearly 360 mm in 2000 (in Klamath Falls; subregion 2).

Table 13. Annual rainfall measured at weather stations in the Klamath Irrigation Project, mm

Station Name (Agency)	1999	2000	2001	2002	2003
Lorella (AgriMet; LORO)	---	---	198[1]	169	264
Klamath Falls (AgriMet; KES)	286	269	246	230	307
Klamath Falls (NOAA; 35-4511-7)	290	292	255	230	300
PacifiCorp (NOAA; 35-4506)	295	358	91[2]	---	---
Tulelake (CIMIS; 91)	198	304	204	175	239
Tulelake Irrig. Dist. (NOAA; 04-9053-1)	229	306	206[3]	187	260
Worden (AgriMet; WRDO)	---	99[4]	206	185	251

[1] The Lorella AgriMet station was installed on March 31, 2001.
[2] No data is available for the PacifiCorp NOAA weather station after May 31, 2001.
[3] Rainfall data is unavailable for the Tulelake NOAA weather station during May 2001.
[4] The Worden AgriMet station was installed on April 19, 2000.

Precipitation in the Project is a function of many topographical land features as well as geographical locations. Geostatistical methods and stepwise regression modeling were used to improve estimations of mean annual precipitation amounts in the spatial coverage of the subregional water balances. Because of limited and non-uniform distribution of weather stations in the Project, spatial interpolation techniques were employed to model precipitation fields by incorporating information about elevation, slope, and geographical coordinates as predictor variables in the GIS database of the Project.

Previous studies of modeling regional-level precipitation variability have shown significant benefits of employing geostatistical analyses (Karnieli, 1990; Kravchenko et al., 1996; Comrie and Broyles, 2002). Interpolation algorithms in the Spatial Analyst extension of the ArcGIS software system (ver. 9.2) mapped regression relationships and model residual values in order to predict precipitation in each grid cell in the different subregions (at 30 m × 30 m resolution). Final modeled datasets of mean precipitation were verified by comparing the independent station data (cross-validation) to modeled precipitation.

While there is some annual variation in precipitation as an inflow to the Project boundaries, as evident in the cumulative totals in **Table 13**, water shortages such as the 2001 drought are due primarily to reductions in stream flows in the Upper Basin. This has significant advantages for agricultural water users because streamflows can be forecast with considerably greater accuracy than seasonal rainfall. This means that water supply drought conditions should be considered on a regional basis, and are not directly based on local precipitation.

Digital database files of daily rainfall values were obtained for each station and checked for quality control flags, completeness and reasonableness, and then summed on a monthly and annual basis for initial analyses. The most complete weather information was usually available for subregions 2 and 3. Each of these subregions has multiple meteorological stations and long-term records were accessible. In subregion 2, four weather stations had datasets available for all or part of the period of record. The 24-hr rainfall records for the AgriMet and NOAA stations cover different time periods during the day; starting times are not synchronous. The Lorella station in subregion 1 became operational in March 2001. The Worden AgriMet station in subregion 4 was installed and made operational in April 2000.

Previous studies have mainly used data from the Klamath Falls NOAA weather station that had been operated by PacifiCorp. An evaluation of the rainfall data from this station indicated it was consistently higher than the other Klamath Falls stations. This may be due in part to its close proximity to the Klamath River. The station was abandoned by PacifiCorp in May 2001.

As a further quality control initial step, rainfall records from multiple stations were examined to determine the extent of spatial rainfall variability. There was significant variation observed in the monthly and annual totals measured at the different weather stations inside and surrounding the study area. Differences in daily precipitation of 10-20 mm were not uncommon. In some cases this can be partially explained by localized geographically influenced weather patterns, but in other instances even stations that are in close proximity to each other recorded large differences, particularly on a daily basis.

Weather data from public sources such as NCDC and CIMIS may be flagged for quality control purposes for a variety of reasons. Any flagged data was examined and evaluated individually based on comparable records at other stations during the same time period. For example, on Feb. 9, 1999 the CIMIS rainfall record was flagged with an "H," meaning "missing hourly data" and the daily total was 0 mm (0.0 in), while the nearby NOAA station recorded 34 mm (1.32 in). Over the 2-day period between Feb. 9 and 10, the total rainfall measured by the NOAA and CIMIS stations were 35 mm and 8 mm (1.39 and 0.31 in), respectively. To account for these apparent errors and missing data, which were only a few cases, absent daily totals were estimated by regression analyses.

Using the GIS project file, a set of terrain variables including latitude and longitude coordinates, elevation and slope were calculated for each grid cell for use as predictor variables. The methodology used to develop the precipitation model is outlined in **Figure 20**. Using stepwise linear multiple linear regression, the predictor variables were used in the model to compute the predicted mean precipitation across all the subregions in the Project. Data from the weather stations in each subregion were used to identify any bias inherent in the model by comparing to their predicted values. Differences between predicted data from the regression analysis and station data were calculated (residuals). Some areas of under-prediction were apparent in adjacent mountainous areas, but the effects were outside the delineated boundaries of the Project. The result was a time series of datasets of precipitation at a regional scale resolution.

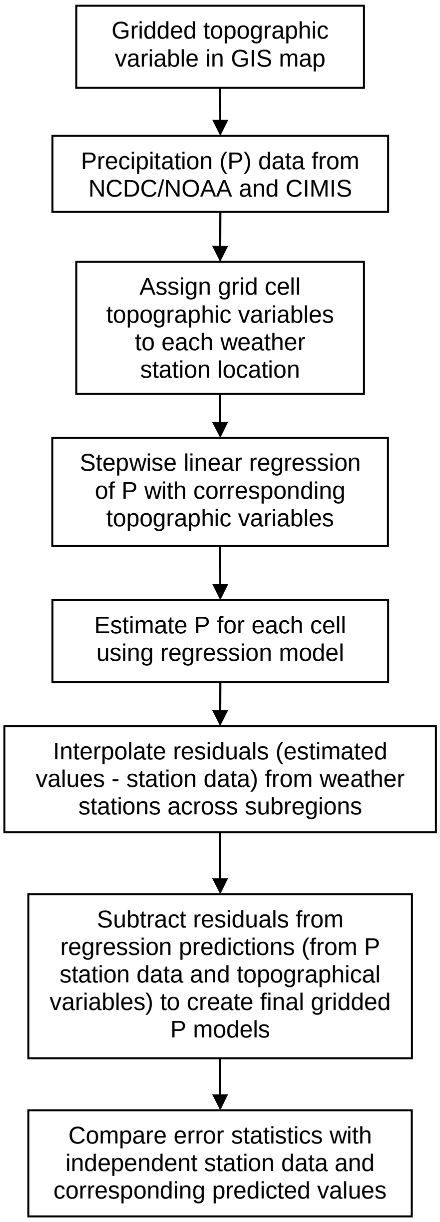


Figure 20. Flow chart illustrating methodology used to create regression-based model of precipitation

To interpolate the calculated residual values in the final modeled maps of precipitation, geostatistical techniques were utilized in the Spatial Analyst extension following a procedure from Brown and Comrie (2002). Using the *kriging* method, spatial modeling of the residual data was generated by a spherical semivariogram function and then predictions were made for all unmeasured locations. Kriging assumes the distance (or direction) between points with station data reflects a spatial correlation according to a weighting function based on the selected variogram model. The kriging estimator is expressed as follows:

$$Z(s_o) = \sum_{i=1}^{N} \lambda_i Z(s_i)$$

where	$Z(s_o)$	estimated value of Z at location s_o
	λ_i	weight of the measured value Z at the location s_i
	N	number of observations

The weights, λ_i, were determined by the model fit results from the spherical semivariogram, where the empirical semivariogram graph is derived from the formula:

$$\gamma(h) = \frac{1}{2}\sum_{i=1}^{N}\left[Z(s_i + h) - Z(s_i)\right]^2$$

for measured values Z at locations s_i and s_i + h that are separated by a distance h.

The regression with both geographical location (coordinates) and elevation, plus the kriging using residual values, generally gave acceptably good correlations (adjusted $R^2>0.65$) for most instances in the Project involving monthly datasets. However, a basin-level precipitation relationship was more difficult to create given the limited number of stations available outside the Project boundaries and the short time period of the study (5 years). An improved topographical regression model for precipitation may potentially alleviate some of the observed error by taking into account major features such the distance and direction to Upper Klamath Lake and mountains in the kriging interpolations. Separate predictions of estimated mean precipitation calculated directly with the kriging interpolation of measured precipitation did not yield useful information given the small sample set.

The annual rainfall amounts used in the water balance computations for each subregion are summarized in **Table 14**.

Table 14. Annual rainfall by subregion in the study area, mm

Subregion	1999	2000	2001	2002	2003
1	305	290	273	184	260
2	291	268	250	234	312
3	194	300	195	170	241
4	276	270	198	180	245
Mean	266	282	229	192	264

Several improvements to the modeling analysis are potentially possible in future studies, such as extending the data coverage, sub-domain level regression, further dividing into temporal subsets, and introducing additional predictor values into stepwise linear regression methodologies (for instance the distance and direction to the nearest large water source). To account for the evident uncertainty in the values used to determine the quantity of precipitation, a *CI* of 20% was assigned to the precipitation volumes used in the water balance computations.

3.4.3 Temperature

Air temperature is one of the principle data components in the calculation of ET_o. Thermistors measure the minimum and maximum temperatures that occur at a height of 1.5 m over a 24-hr period beginning at midnight. Of concern for computing ET_o is the air temperature near the level of the crop canopy (Allen et al., 1998). The daily maximum and minimum temperature (T_{max} and T_{min}) data were compiled for each subregion based on weather station datasets from the Klamath Falls AgriMet and Tulelake CIMIS stations according to the same representative geographical assignments as described previously for precipitation data.

For standardization purposes in the FAO-56 Penman-Monteith equation, the mean daily temperature (T_{mean}) is defined as the mean of the daily maximum and minimum temperatures rather than as the average of the hourly temperature measurements (Allen et al., 1998).

$$T_{mean} = \frac{T_{\max} + T_{\min}}{2}$$

The mean monthly temperatures occurring during each month over the 5-year study period in each subregion are summarized in **Table 15**. The Klamath Irrigation Project experiences relatively moderate air temperatures which seldom exceed 32°C (90°F) for highs or -18°C (0°F) for lows. However, the difference between daytime highs and nighttime lows is frequently over 4 Celsius degrees (40 Fahrenheit degrees). During the time period 1999 to 2003, mean monthly temperatures ranged from approximately 0 to 18°C (32-64°F). Maximum daily temperatures typically occur in July, while minimum daily temperatures usually occur in December or January.

Table 15. Mean monthly temperature (T_{mean}) by subregion (1999-2003), °C

Month	1[1]	2[1]	3	4	Mean
Jan	0.5	0.3	0.1	0.2	0.3
Feb	0.1	0.0	-0.3	-0.1	-0.1
Mar	3.4	3.4	3.0	3.2	3.3
Apr	5.7	5.9	5.6	5.8	5.8
May	10.4	10.7	10.6	10.7	10.6
June	14.8	15.0	14.6	14.8	14.8
July	18.4	18.7	17.5	18.1	18.2
Aug	17.5	18.0	16.6	17.3	17.4
Sep	14.2	14.8	13.5	14.1	14.2
Oct	8.4	9.0	8.1	8.6	8.5
Nov	2.5	2.5	2.2	2.4	2.4
Dec	0.3	0.0	-0.2	-0.1	0.0

[1] Temperature data for Klamath Falls (i.e., subregions 1 and 2) between January to March 1999 is from NOAA 35-4511-7.

3.4.4 Solar Radiation

Net solar radiation (R_n) is the primary climatic factor controlling *ET* when soil water supplies are not limited (Jensen et al., 1990). Therefore, it was critical to ensure that accurate radiation data were used in the ET_o computations. R_n data are derived from the (average) shortwave radiation (R_s) that reaches the Earth's surface and is available for vaporizing water and heating the soil profile. R_s data from agricultural weather stations used in the study were obtained via pyranometer, a type of actinometer used to measure radiant energy. An initial quality control check was conducted on the hourly R_s data from all weather stations listed in **Table 12** in preparation for re-computing ET_o on an hourly time-step.

It was determined from the quality control analysis that the solar radiation readings at the Klamath Falls AgriMet and Tulelake CIMIS stations had some evident errors during the period of study. Pyranometers have to be cleaned and calibrated regularly to ensure correct readings. Visual inspection of the pyranometers indicated only minimal maintenance (cleaning) and the one at Klamath Falls was pointed slightly off vertical level, which presumably contributed to errors of an undeterminable degree.

Solar radiation data from the Klamath Falls and Tulelake stations selected were checked further by comparing against the "clear sky maximum solar radiation" (R_{so}). Theoretical R_{so} can be calculated based on the weather station's elevation, latitude, and the day of the year. On a completely clear day, the R_s data should be approximately equal to the R_{so} value for that day (R_{so} computational procedure can be found in Annex 5 of Allen et al., 1998).

R_{so} computed with the following equation plots as an (theoretical) upper envelope of measured R_s for the purpose of checking the calibration of pyranometers:

$$R_{so} = K_T \times R_a$$

where		
	R_{so}	short wave radiation expected to occur under a clear sky
	K_T	"clearness" or transmission index
	R_a	extraterrestrial radiation

Where significant differences between R_s and R_{so} values were observed for a significant period of time or where the measured R_s was greater than R_{so}, a correction multiplier was used to increase or decrease the R_s values so they more closely followed, but did not exceed, the R_{so} curve (theoretical maximum).

The R_s data from the Tulelake CIMIS station had relatively few visible discrepancies. Portions of the datasets in 1999, 2001 and 2002 were corrected to account for the fact that the original values were above the maximum possible solar radiation on a clear day. In 2003, selected portions of the measured R_s data were adjusted upwards to account for an evident trend below the potential R_{so} threshold.

The R_s data from the AgriMet station had more visible discrepancies in the plotted graphs. Data from mid-1999 through about two-thirds of 2000 were significantly below the R_{so} curves. In 2001 and 2002, the measured R_s values were above the R_{so} curve during the summer; these data were adjusted downwards so the maximum R_s values matched the R_{so} curve. **Figure 21** shows the resulting R_s and R_{so} curves for 2001. The lighter **pink** line indicates the corrected R_s.

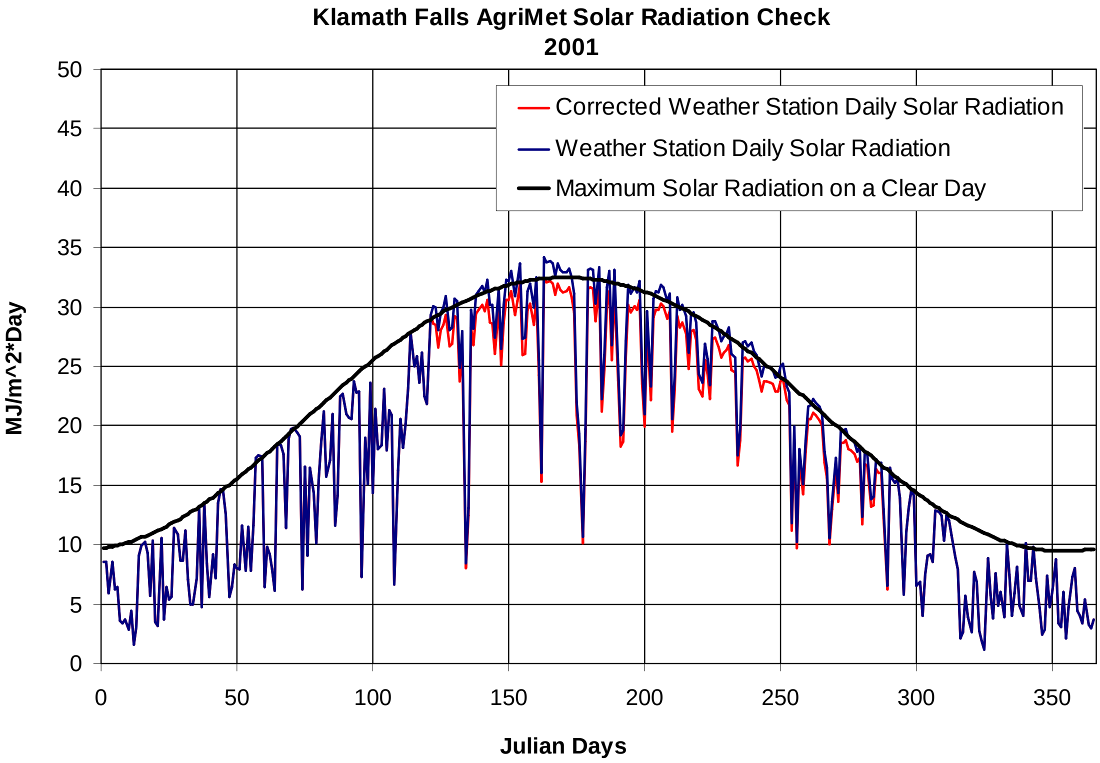


Figure 21. Klamath AgriMet R_s (weather station daily solar radiation), R_{so} (maximum solar radiation on clear days), and corrected R_s (corrected weather station daily solar radiation) for 2001

Table 16 summarizes average monthly measured and corrected R_s data for the Klamath Falls AgriMet and Tulelake CIMIS stations. The applied adjustment factor based on the R_{so} analysis resulted in a percentage change for both stations ranging from approximately -3% to +2% (over a 5-year period). On an individual month-to-month basis, however, the percentage change was considerably higher. For the Klamath Falls AgriMet station the percent difference between the raw and corrected R_s varied from -10.6% (September 2002) up to +11.7% (December 1999). At the Tulelake CIMIS station the range in percent difference of R_s values was slightly better: -2.2% to +7.1% in July 1999 and August 2003, respectively.

Table 16. Corrected and uncorrected average monthly solar radiation (R_s) for the Klamath AgriMet and Tulelake CIMIS stations (1999-2003), MJ m^{-2}

	Klamath Falls AgriMet			Tulelake CIMIS		
Month	**Uncorrected**	**Corrected**	**% change**	**Uncorrected**	**Corrected**	**% change**
Jan	205	203	-0.6%	211	210	-0.3%
Feb	298	294	-1.4%	285	283	-0.5%
Mar	485	473	-2.5%	468	467	-0.1%
Apr	588	580	-1.4%	576	583	1.2%
May	798	774	-2.9%	783	786	0.4%
June	884	865	-2.2%	864	864	0.0%
July	884	865	-2.2%	874	882	0.9%
Aug	767	754	-1.6%	769	774	0.7%
Sep	608	587	-3.4%	594	603	1.5%
Oct	433	421	-2.7%	428	427	-0.4%
Nov	220	219	-0.3%	224	225	0.6%
Dec	170	173	2.0%	179	179	0.0%

3.4.5 Wind Speed

Wind speed (u_2) is measured at the weather stations in the Klamath Irrigation Project with anemometers (propeller type) placed at a height of 2 m, conforming to FAO-56 instrumentation requirements (Allen et al., 1998). Wind speed affects the rate of *ET* by bringing heat energy into an area and by replacing of drier air over the evaporating surface (Allen et al., 1998). Due to the effect of topography, wind speed in the Project is highly variable, and these spatial differences may result in calculated ET_o. Schulz et al. (1997) demonstrate a technique using a digital elevation model to extrapolate wind speed data from a meteorological station over an agricultural catchment area that has potential to improve the prediction of *ET* in the Project.

Table 17 summarizes average monthly wind speed data for the Klamath Falls AgriMet and Tulelake CIMIS stations. Wind speed generally peaks in April and May and then decreases through the crop growing season, with minimum average winds occurring in the fall. Average wind speed data showed high temporal variability on a daily basis – up to nearly +700% (max.) variation from day-to-day. In terms of spatial variation, mean daily wind speeds were about 30% higher as measured by the Tulelake CIMIS station (subregion 3) compared to the Klamath AgriMet station (subregion 2). Maximum and minimum mean daily wind speeds from 1999 to 2003 ranged from 0.89 mps (19 mph) to 0.03 mps (0.6 mph), respectively.

Table 17. Mean monthly wind speed (u_2) by subregion (1999-2003), m/s

Month	1[1]	2[2]	3	4[1]	Mean
Jan	0.16	0.16	0.21	0.18	0.18
Feb	0.20	0.20	0.25	0.22	0.22
Mar	0.21	0.21	0.26	0.24	0.23
Apr	0.22	0.22	0.31	0.26	0.25
May	0.21	0.21	0.29	0.25	0.24
June	0.20	0.20	0.26	0.23	0.22
July	0.15	0.15	0.20	0.18	0.17
Aug	0.15	0.15	0.19	0.17	0.17
Sep	0.14	0.14	0.18	0.16	0.16
Oct	0.14	0.14	0.19	0.16	0.16
Nov	0.15	0.15	0.20	0.18	0.17
Dec	0.16	0.16	0.21	0.18	0.18

[1] Poor site conditions with observed interference at the Lorella and Worden AgriMet stations prevented use of wind speed data during the study period.

[2] Wind speed data for Klamath Falls (i.e., subregions 1 and 2) between January and March 1999 is from NOAA 35-4511-7.

3.5 Surface Water Resources

3.5.1 Upper Klamath Lake and Surface Water Resources

The Upper Klamath Lake, the main hydrologic feature in the Upper Klamath River Basin, is hypereutrophic. It is a large shallow reservoir covering a surface area of 28,000 ha (70,000 acres) that concentrates enormous blue-green algae blooms in the summer, dominantly *Aphanizomenon*. The lake has a storage capacity of about 600 mcm with an annual mean inflow of approximately 16,000 mcm (1961 to 2004). High nutrient loading – mainly phosphorous and nitrogen – promotes correspondingly high production of algae (Oregon DEQ, 2002). The large blooms of algae modify the chemical and physical water quality conditions in the Upper Klamath Lake, affecting the ESA-listed fishes, chiefly through the removal of large amounts of oxygen (decomposition) and increases in pH (CO_2 respiration). As the pH rises, a shift in chemical composition takes place and ammonia is made, which is extremely toxic to fish. In addition, the blooms of *Aphanizomenon* are able to fix nitrogen out of the air so that they actually recruit more of the algae into an already hypereutrophic river system. The results have been periodic fish kills, which number in the many thousands of fish each occurrence.

Phosphorous loading into the Upper Klamath Lake is now the subject of a Total Maximum Daily Load (TMDL)[15] program, meaning the drainage water that flows into the lake from farms and wetlands in the upstream watershed is restricted. The TMDL process has been around since the passage of the Clean Water Act of 1972. The Clean Water Act, section 303, established water quality standards and TMDL programs, but until recently they had not been a major factor in water management in the western U.S. Enforcement was delayed due to technical complexities and court challenges, but also a lack of impetus from water quality regulators. Now, what was once seen as an arcane piece of the Clean Water Act is rapidly becoming the number one challenge for agricultural water agencies. This is evident if one takes a look at the urgent declarations at major technical conferences such as “Helping Irrigated Agriculture Adjust to TMDLs” held by the U.S. Committee on Irrigation and Drainage in October 2002 at Sacramento, California.

The pesticides, sediments, salts and other pollutants in agricultural runoff are a significant cause of water pollution in many water bodies in the western U.S. and internationally, including sections of the Klamath River and Lost River. For water quality standards to be met then requires discharge restrictions to some degree and control of the disposal of agricultural drain water. At some point in the near future, if events elsewhere are an indication of what’s coming to the Klamath Irrigation Project, irrigators will be facing an extensive drainage problem that is no less serious or challenging than the previously discussed water supply issues.

3.5.2 Irrigation Water Diversions

Irrigation water diversions to the canal distribution system comprise the largest proportion of the surface inflows to the study area, approximately 50% on average of the total inflows between 1999 and 2003. **Table 18** summarizes hydrologic data for irrigation diversions at irrigation district boundaries in the Klamath Irrigation Project in of terms annual volumetric totals. Tabulated monthly data for each diversion point are included in **Appendix 1**.

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[15] A *Total Maximum Daily Load* is a calculation of the maximum amount of a pollutant that a body of water can receive and still meet water quality standards, and an allocation of that amount to the pollutant's sources.

Total surface water diversions into the area of investigation were down over 60% in 2001 compared to the previous year. In particular, the A Canal diversions in 2001 were only 15% of those in 2000. Irrigated farms served by the Gerber Reservoir and Clear Lake (subregion 1) were not subject to the imposed cut-off arising from the 2001 ESA restrictions, so irrigation diversions during that year were at normal levels.

Table 18. Annual irrigation surface water diversions, mcm per year

Source[1]	Diversion	1999	2000	2001	2002	2003	Mean
Upper Klamath Lake	Link River[2]	1,676	1,294	882	848	910	**1,122**
	A Canal	348	336	51	347	263	**269**
Klamath River Dams	Keno	2,174	1,397	903	788	976	**1,248**
	Iron Gate	2,533	1,787	1,217	1,162	1,313	**1,602**
Gerber Reservoir and Clear Lake	North Canal[3]	45	44	44	46	40	**44**
	West Canal	25	39	38	40	37	**36**
	East Canal	3	5	5	6	5	**5**
Lost River Diversion Channel and Return Flows	Station 48	85	101	25	128	77	**83**
	Miller Hill[4]	23	26	6	31	14	**20**
	J Canal	168	163	41	165	130	**133**
	D Pumps	123	92	35	84	73	**81**
Klamath River Diversions	Ady Canal	112	112	51	123	97	**99**
	Ady Canal at LKNWR	24	33	13	59	36	**33**
	North Canal	45	51	19	62	38	**43**

[1] The "source" of irrigation diversions corresponds to the general point of measurement (e.g., the Lost River Diversion Channel is supplied by the Upper Klamath Lake and the Lost River system).
[2] Includes flows measured in the Link River at a gauge station downstream of the Eastside power station plus flow from the Westside power station, which enters below the gauge.
[3] North Canal diversion data is based on the Gerber Reservoir releases during the irrigation season and accounts for minor downstream releases from Miller Diversion Dam.
[4] The reported pumping volumes in this table are not adjusted for spill back to the Lost River Diversion Channel, since some of the spill may be canal spill from the adjacent C4 Canal system. The total measured amount of spill was used in determining the net flows in the Lost River Diversion Channel.

A separate *CI* was assigned to each surface diversion component based on the estimated accuracy of the reported measurement over the time period of the study (which in turn was based on the accuracy of the techniques being followed and the condition of the equipment). The *CI* values applied in the water balance computations reflect not only the inherent accuracy of the instruments, but also issues such as the quality control procedures followed in archiving the datasets.

The *CIs* assigned to the surface water diversions and pumping plants ranged from 5% for rated sites with good entrance conditions and continuous recording devices (e.g., A Canal) to 70% for poor measurement sites such as the North Canal and Ady Canal in Klamath DD. Properly designed, installed, and maintained flow monitoring sites will greatly improve the measurement accuracy of flows diverted from the Klamath River.

3.6 Consumptive Use in the Klamath Irrigation Project

Water diversions are consumed in the Klamath Irrigation Project primarily through the processes of evapotranspiration (*ET*) from agricultural fields and wildlife refuges, in addition to some evaporation from drains, urban and undeveloped areas, and open water surfaces (reservoirs, rivers, lakes, etc.). The rate of *ET* is primarily a function of being water limited, as this region is not considerably energy limited. To avoid crop water stress, irrigation water must be sufficient to meet the crop's *ET* requirement, and thus, the amount of irrigation water available limits the crop area that can be successfully developed each season. In addition, the gross irrigation requirement to be diverted and delivered through the irrigation system includes water applied for leaching of salts, freeze protection, crop cooling, and other management practices. It is essential that irrigation water requirements and consumptive uses be known with as much precision as practical, for water resources planners to evaluate water needs and alternatives of development.

There are several commonly used methods to estimate crop consumptive use. The dual crop coefficient method of calculating *ET* was modeled in this study (referred to here as the FAO-56 procedure) with local climatic data and soil characteristics, along with individualized management parameters for different crops in each subregion. Although significant efforts were made to adapt the FAO-56 procedures for application to the Klamath Irrigation Project based on available input data and extensive quality control techniques, there is a still an appreciable range of uncertainty. Some of this uncertainty is related to the quality of the model input data and localized variability in the subregions, but other issues are related to the method itself and its sensitivity to various conditions.

3.6.1 Crop Irrigation Water Requirements

3.6.1.1 Crop Consumptive Use and Growth Modeling

Estimates of the actual consumptive use by irrigated crops are necessary to understand the links between land use, water allocation, and irrigation use. Growing plants take up soil water at their roots and transmit it to leaves as liquid water, where if the stomata are open, it then moves as a vapor to be dispersed in the atmosphere in a dynamic process termed *transpiration* (*TP*) (Penman et al., 1967). The combined consumptive process of water movement from the soil surface by *evaporation* and by the crop as transpiration is referred to as *evapotranspiration* (*ET*). *ET* is normally expressed in terms of depth (mm) per unit time (hour, day, month or year). The rate of *ET* expresses the amount of water lost (or consumed) by a crop in units of water depth over an extensive surface. Many factors affect *ET* fluxes of irrigated crops including weather parameters such as solar radiation, air temperature, humidity and wind speed; crop characteristics such as crop type, density and stage of growth; management, and environmental aspects such as soil type, nutrient availability, salinity, aeration of the root zone, etc. (Allen et al., 1998).

Energy, provided by direct solar radiation and to a lesser extent the ambient air temperature, is required to change water from liquid to vapor (vaporization). As water is evaporated from the soil and wet leaves of plants it causes the surrounding air to become gradually more saturated, the rate of which depends on the movement of drier air to replace it (wind speed). Hence, the principal weather factors to consider in the analysis of *ET* are solar radiation, air temperature, humidity and wind speed (Allen et al., 1998; Allen et al., 2005a).

ET can be predicted using a variety of equations and models. Accurate determination of *ET* is not straightforward due to heterogeneity of agroecosystems and the complexity of hydrological processes. A large number of empirical methods have been developed for estimating *ET* under various data situations, including for example, pan evaporation techniques, lysimeters, and various theoretical *ET* equations proposed by Hargreaves, Blaney-Criddle, and Penman. Recent development of satellite remote sensing methods has enabled accurate prediction of *ET* at catchment scales that integrates spatio-temporal variations due to crop varieties, soil types, irrigation methods, field management, etc. for large numbers of individual fields (Bastiaanssen et al., 2005). Modeling the consumptive use of irrigation water has many useful applications, particularly in investigations calculating water balance and performance indicators. A theoretical modeling approach is necessary because, as Burt et al. (1997) and Clemmens and Burt (1997) point out, there is considerable difficulty associated with accurately determining *ET* as the residual from water balance computations.

Replenishment of *ET* is the primary purpose of irrigation, and thus *ET* is a major element in determining crop water requirements and diversions in an irrigated basin. The irrigation requirement for crop production is the amount of water, in addition to rainfall, that must be applied to meet a crop's *ET* needs without significant reduction in yield. *ET* represents the component of irrigation diversions that undergoes a physical phase change from liquid to vapor form. A common approach in irrigation projects for quantifying crop water requirement volumes is the K_c ET_o-based procedure, where the volume of *ET* is computed from the following equation:

$$ET = (K_c \times ET_o/1{,}000) \times \text{area of land use}$$

where		
	ET	volume of evapotranspiration [ha m]
	ET_o	(corrected) reference evapotranspiration [mm]
	K_c	crop coefficient [dimensionless]
	area	land use category [ha]

The procedure involves computing the *ET* from a reference crop such as grass or alfalfa (termed ET_o and ET_r, respectively) and then multiplying this value by an empirical crop coefficient for a specific crop (K_c) to produce an estimate of consumptive use on a daily, monthly or annual basis.

The framework developed in this study for determining total consumptive use and irrigation water requirements is illustrated by the flow chart in **Figure 22**. Consumptive use was calculated by daily plant-soil-water modeling using the dual crop coefficient approach with localized crop, weather, and soil information. The procedure computes *ET* from agricultural fields and non-agricultural lands (open water, wetlands, etc.) on a daily, monthly and annual basis. The method was applied to the study area to properly capture information about the impacts of both in-season and off-season irrigation and precipitation events on water consumption.

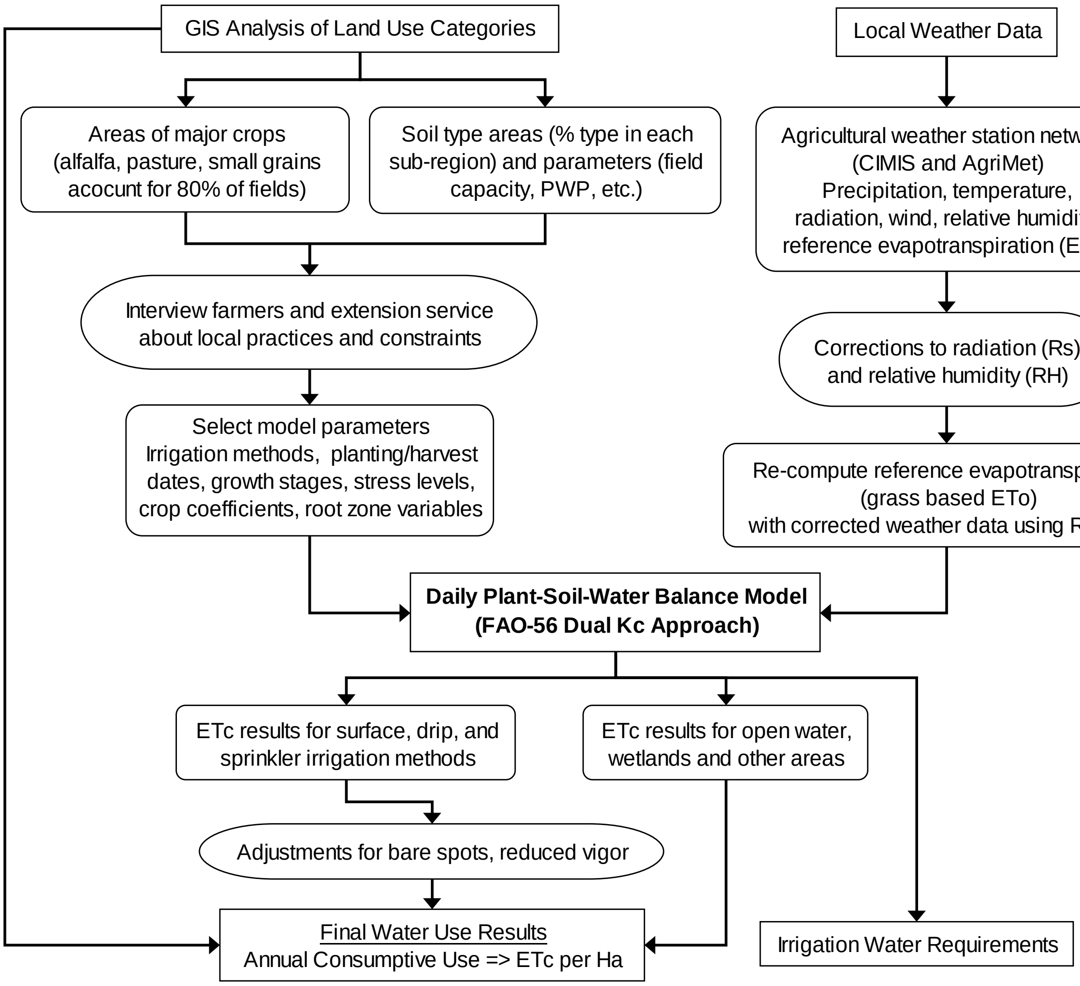


Figure 22. Conceptual flow chart for computing annual consumptive use of irrigated crops in the Klamath Irrigation Project

Given their major contribution to the overall irrigation water balance and estimations of the amount of water available for water conservation objectives, the accuracy of the *ET* computations are particularly significant as explained in the following sections.

The accuracy of the computations of *ET* depends in turn upon the accuracy of the following components (Clemmens and Burt, 1997; Allen et al., 2005b):

- Area of each land use section (irrigated field, wetland, lakes, etc.)
- Growing season duration
- ET_o. This "reference evapotranspiration" value was initially obtained from the AgriMet or CIMIS weather station network on a daily basis and then re-computed with the REF-ET program using corrected data. The accuracy of raw ET_o data depends on the location, maintenance, and accuracy of the weather station instruments. Furthermore, the equation that converts the meteorological data into daily ET_o values has its own inherent inaccuracies.
- Crop coefficients (K_c). These must be estimated for each "crop" for each month. The K_c value depends upon local management factors such as how frequently the "crop" receives water, irrigation method, stress levels, etc.

In addition, there are uncertainties associated with local agronomic factors such as planting dates, growth stage, and harvest dates, along with uncertainty about the precise health and crop vigor of different fields (Allen et al., 2005b). Combined with the uncertainties associated with the effectiveness of precipitation and irrigation events in meeting crop water demands, ET estimates derived with the K_c method may contain some degree of unavoidable inaccuracies even though the overall procedure has been used with acceptable levels of accuracy to quantify consumptive use under field conditions.

Allen (2005b) examined the project-wide accuracy of the FAO-56 dual crop coefficient method for the Imperial Irrigation District (200,000 ha) and found that the standard error of estimate (SEE) for annual ET_c for the entire project was only 3.4% compared to water balance derived values. For a basin-scale irrigation project such as the Klamath Irrigation Project it is probably realistically impossible to reduce the CI for ET_c estimates below 8%. Utilizing remote sensing satellite technologies (Bastiaanssen et al., 2005), conducting extensive grower interviews, and performing rigorous quality control checks of weather stations and their data are recommended methods for reducing the uncertainties in ET estimates.

3.6.1.2 Reference Evapotranspiration

Reference evapotranspiration (ET_o) expresses the evaporative rate of a hypothetical reference crop with specific characteristics (fixed surface resistance, height, albedo, etc.). The concept of using a reference crop was developed in order to separate the climatic parameters of a specific location independent from crop type, management practices, and growth stage. Thus, the ET_o value reflects the local climate based on measured meteorological parameters.

Penman-Monteith Method

The most commonly used approach in irrigation science for estimating the consumptive use of irrigated crops under actual real-world conditions is the crop coefficient-reference evapotranspiration ($K_c\,ET_o$) procedure. Reference evapotranspiration (ET_o) is first computed for a reference crop using a standardized equation and is then multiplied by an empirical crop coefficient (K_c) to estimate crop evapotranspiration (Jensen et al., 1971; Doorenbos and Pruitt, 1977; Wright, 1981, 1982; Allen et al., 1998). The hypothetical reference crop is an extensive surface of green grass of uniform height – 8 to 15 cm tall – actively growing, completely shading the ground, and with no water stress (Jensen et al., 1990; Smith et al., 1991). Because ET_o represents nearly all weather effects this concept allows the study of water demand independently of crop type, crop development, and management practices. The K_c values under standard conditions vary depending on crop characteristics. This technique has been refined through the use of computer simulation models to predict accurate estimates of ET_c integrated over study areas with multiple crop and soil types (Allen et al., 2005b).

$$ET = K_c \times ET_o$$

The Penman-Monteith method refers to the use of an equation for computing ET_o that combines an energy balance and an aerodynamic formula. Penman (1948) initially defined relationships for evaporation from bare wet soil or grass as fractions of open water evaporation. Monteith (1965) built upon Penman's equation and derived empirical functions with a thermodynamic basis for computing evaporation from vegetated surfaces. The Penman-Monteith equation has been widely applied by many researchers and extended in engineering usage for well-defined reference crops.

The combined Penman-Monteith equation for calculating the ET of a reference crop is generally expressed as (Monteith, 1965; Monteith, 1980):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \dfrac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \dfrac{r_s}{r_a}\right)}$$

where	λET	latent heat flux density [MJ m^{-2} s^{-1}]
	R_n	net radiation at the crop surface [MJ m^{-2}]
	G	soil heat flux density [MJ m^{-2}]
	ρ_a	mean air density at constant pressure [kg m^{-3}]
	c_p	specific heat of air [°C]
	$(e_s\text{-}e_a)$	vapor pressure deficit of the air [kPa]
	r_a	aerodynamic resistance [s m^{-1}]
	r_s	bulk surface resistance of the canopy [s m^{-1}]
	Δ	slope of the vapor pressure temperature curve [kPa $°C^{-1}$]
	γ	a psychrometric constant [kPa $°C^{-1}$]

The FAO (Allen et al., 1998) proposed using a revised version of the Penman-Monteith equation as the standard method for estimating ET_o. Crop water requirements determined using the FAO Penman-Monteith method (applied daily) have shown acceptable project-level accuracy on a monthly time step (ASCE, 2002; Allen et al., 2005b). Allen et al. (2005b) found annual estimates of actual crop evapotranspiration (ET_c) computed using the Penman-Monteith equation as part of the FAO-56 dual crop coefficient approach were consistently accurate to within ±6% at the 95% confidence level, but cautioned that the use of planting and harvesting dates specific to the local area improved estimates.

The actual ET_c under non-standard conditions where water is limited depends on management and environmental aspects. Allen et al. (1998) demonstrate how factors such as salinity, poor fertility, plant diseases, etc. may reduce potential evapotranspiration (ET_p) and limit crop development compared to standard conditions. The FAO-56 dual crop coefficient method accounts for the occurrence of soil water stress under non-ideal growing conditions by including the effects of various environmental and agronomic stresses (Allen et al., 2005a). A separate coefficient, K_e, is calculated depending on the soil moisture content of the upper portion of the root zone, exposed soil fraction, and the amount of energy (radiation) available. To adjust ET_c for a decrease in soil water potential, a water stress coefficient, K_s, is applied to account for the effect on crop transpiration.

The complete form of the FAO-56 equation for computing the actual ET_c in water-stressed conditions from agricultural crops is:

$$ET_{c\ adj} = (K_s\, K_{cb} + K_e)\, ET_o$$

where	$ET_{c\ adj}$	adjusted ET_c under non-standard conditions [mm d^{-1}]
	ET_o	reference evapotranspiration [mm d^{-1}]
	K_{cb}	basal crop coefficient
	K_s	water stress coefficient
	K_e	soil evaporation coefficient

The FAO-56 dual crop coefficient procedures provide the opportunity for precise estimations of crop consumptive use. A major improvement over previous methods is the calculation of evaporation (*E*) from precipitation and irrigation events separately from *ET* computed for crops, which enables one to account for effects from different irrigation methods and management variables (Allen et al., 2005b). The use of validated, well-documented crop coefficients in the FAO-56 approach, along with readily-attainable local information about crop schedules and water management practices and public domain weather data, to compute accurate estimates of consumptive use affords modernization practitioners a practical and reliable tool that can be applied within the relatively short timescale of most investment programs. An adapted FAO-56 modeling technique was utilized in this study to estimate crop water use and irrigation requirements as part of a project-scale water balance.

SWAP, CROPWAT, WOFOST – Agro-Hydrological Field-Scale Models

Computer modeling of crop water use and growth and has been widely used for the prediction of various agro-hydrological variables. Better knowledge of these variables leads to the opportunity for better water management. Such agro-hydrological models can simulate processes that are difficult or expensive to measure directly (e.g., crop *ET*) or have complex temporal and/or spatial interactions between natural systems and anthropogenic activities. Reliable simulation of water balance parameters in agricultural settings, including ET_c, has been done with various models such as CROPWAT (Smith, 1992), WOFOST (Van Diepen et al., 1989), and SWAP (Kroes and Van Dam, 2003), among others. Various conceptual techniques and integrated modeling techniques have also been used to bridge the gaps between one-dimensional field-scale models such as SWAP and basin-wide models such as SLURP or advanced remote-sensing algorithms (Kite and Droogers, 2000b; Bastiaanssen et al., 2005).

The use of dynamic crop-weather models in which *ET* and transpiration are computed as part of full hydrological cycle calculations have advantages in understanding alternative water management scenarios at different scales. At the smallest scale of analysis in an irrigated basin – the individual field – crop water models can show the relationships between water quantity, water quality and crop yields (Van Dam et al., 1997). The SWAP computer model (ver. 3.0.3) is designed for the simulation of vertical water flow, solute transport and plant growth in the soil-water-atmosphere-plant environment with variably saturated, cultivated soils (Van Dam et al., 1997; Kroes et al., 2000; Kroes and Van Dam, 2003). The SWAP model also includes detailed modules for simulating irrigation applications and crop yields.

The SWAP model has a wide range of uses for evaluating water management options. Van Dam (2000) cites various case study examples where SWAP has been used for interdisciplinary analyses including:

- Field scale water and salinity management
- Irrigation scheduling
- Transient drainage conditions
- Plant growth affected by water and salinity
- Pesticide leaching to ground water and surface water
- Regional drainage from top soils towards different surface water systems
- Optimization of surface water management
- Effects of soil heterogeneity

In inter-comparisons of hydrological models with field-data methods, the results of crop models showed a significant range of uncertainty and highlighted their advantages and disadvantages relative to different techniques in terms of complexity, field data/measurement requirements, spatial and temporal resolution, and variety of output. Kite and Droogers (2000a) weren't able to discern clear trends in predicted ET observed among field methods, crop models (including SWAP), and remote sensing methods for a common dataset in western Turkey.

The SWAP model uses crop specific data/parameters to compute the potential evapotranspiration for a crop directly with the Penman-Monteith equation. A two-step approach is followed in SWAP for calculating actual ET_c (Van Der Tol, 2000; Kroes and Van Dam, 2003). First, potential evapotranspiration (ET_p) is calculated with the Penman-Monteith equation using the minimum value of the canopy resistance (r_c) and the actual air resistance (r_a). In the second step, actual ET_c is calculated accounting for root water uptake reduction (α_{rw}) due to water and/or salinity stress and evaporation. SWAP calculates separate quantities with the Penman-Monteith equation for three different conditions by varying values for crop resistance, crop height, and albedo selected for particular crops: potential evapotranspiration for wet canopies (ET_{w0}), dry canopies (ET_{p0}), and a wet bare soil (E_{p0}).

SWAP also permits the use of a reference potential rate that is calculated by:

$$ET_{p0} = k_c \, ET_{ref}$$

where ET_{ref} is the input reference evapotranspiration (from one of the major methods) and k_c is a crop factor that is specific for the crop type (and method employed to obtain ET_{ref}), but held constant from emergence to maturity. [Note: the k_c crop factor used in the SWAP model is not the same as the K_c crop coefficient term used in the FAO-56 procedure applied in this study. The methods differ in their means of estimating actual ET_c.]

FAO-56 Penman-Monteith Standard Reference Equation

ET_o computed using the FAO-56 Penman-Monteith equation is the recommended standard method when meteorological data is available because of observed deviations and global variability in other methods such as the Blaney-Criddle, pan evaporation, and radiation methods (Smith et al., 1991; Allen et al., 1998; Allen et al., 2005b). The FAO-56 Penman-Monteith method requires solar radiation (R_s), air temperature (T), air humidity (RH), and wind speed data (u).

An *FAO Expert Consultation on Revision of FAO Methodologies for Crop Water Requirements* (May 1990) defined the reference surface to be used with the Penman-Monteith approach as "a hypothetical reference crop with an assumed crop height (h_c) of 0.12 m, a fixed surface resistance (r_c) of 70 s m^{-1} and an albedo (α) of 0.23" (Allen et al., 1998, p. 23). This reference crop closely resembles an extensive area of actively growing grass with adequate water and uniform height. For this reason the siting criteria for agricultural weather stations generally require placement in the center of a large well-watered pasture. Bare soil conditions at the site where the weather station is located can affect net radiation severely, which will in turn adversely affect the ET_o calculations.

The FAO-56 version of the Penman-Monteith equation used in this study to estimate ET_o is:

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\dfrac{900}{T + 273}\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

where	ET_o	reference evapotranspiration [mm day^{-1}]
	R_n	net radiation at the crop surface [MJ m^{-2} day^{-1}]
	G	soil heat flux density [MJ m^{-2} day^{-1}]
	T	mean daily air temperature at 2 m height [°C]
	u_2	wind speed at 2 m height [m s^{-1}]
	e_s	saturation vapor pressure [kPa]
	e_a	actual vapor pressure [kPa]
	e_s-e_a	saturation vapor pressure deficit [kPa]
	Δ	slope vapor pressure curve [kPa °C^{-1}]
	γ	psychrometric constant [kPa °C^{-1}]

The FAO-56 Penman-Monteith method is limited to situations where measurements are taken at 2 m above the 0.12 m tall grass; however, this condition was met at the weather stations in the Klamath Irrigation Project. Allen et al. (1989) also provide a "full" version of the Penman-Monteith equation that uses resistance terms computed from the actual height of the reference crop.

The quality control analysis of meteorological data and published ET_o data from both the AgriMet and CIMIS stations indicated that daily ET_o should be re-calculated to improve the accuracy of water balance values and to have a standard approach for all subregions. The REF-ET software program (ver. 2.0) provides standardized calculations for ET_o and other micro-meteorological parameters including the FAO-56 and ASCE standardized versions of the Penman-Monteith equations, among others (Allen, 2000). The program is designed to read weather data, either on an hourly or daily basis, with supplementary site information including the heights of the anemometer and temperature sensors, elevation, geographical coordinates, etc.

Using the corrected radiation and relative humidity data, along with datasets for precipitation, temperature, and wind speed, ET_o was re-computed on a daily basis for the Klamath and Tulelake subregions. **Table 19** summarizes annual ET_o calculated for the Klamath Irrigation Project. Annual ET_o ranged from approximately 1,000 mm to 1,150 mm (39-45 in) between 1999 and 2003. On average the corrected ET_o was about 5% higher in the Tulelake subregion than in Klamath Falls subregion.

Table 19. Annual reference evapotranspiration (ET_o) by subregion (1999-2003), mm

Subregion	1999	2000	2001	2002	2003
1	1,050	1,070	1,119	1,021	991
2	1,050	1,070	1,119	1,021	991
3	1,124	1,106	1,179	1,093	1,034
4	1,087	1,088	1,149	1,057	1,012
Mean	1,078	1,084	1,142	1,048	1,007

The potential impact on water management planning of using the corrected ET_o procedure is illustrated by a comparison with raw reported ET_o values from the CIMIS weather station network as shown in **Figure 23**. In 2002, the corrected ET_o used in this water balance was 13% lower than the reported values (average of 8% in 1999-2003). This is equivalent to a water volume of over 100 mcm (over the irrigated cropland) in 2002 or roughly 15% of total irrigation diversions that year.

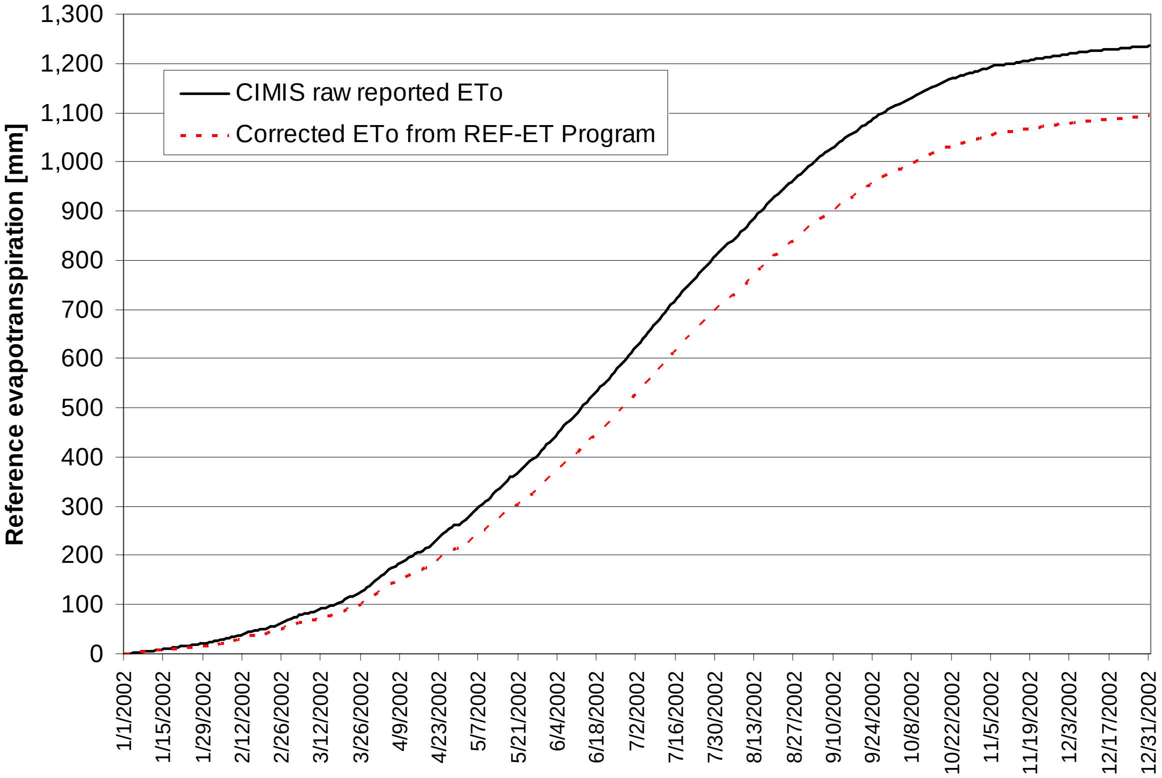


Figure 23. Comparison of cumulative reference evapotranspiration (ET_o) reported by CIMIS weather station network and values re-computed with corrected weather data and FAO-56 Penman-Monteith (13% difference)

3.6.1.3 Evapotranspiration of Irrigation Water from Agricultural Fields

Evapotranspiration from agricultural fields (ET_c) is the largest single outflow component from the water balance boundaries, but also one of the most difficult to measure or estimate precisely. To be as precise as possible in predicting water consumption from irrigated fields in the Klamath Irrigation Project, a modeling approach (refer to **Figure 22** in the previous pages) was applied on a daily basis to compute evaporation from precipitation and irrigation events separately from ET_c computed for individual crops for complete 12-month periods (growing season and non-growing season) using specific local datasets for soil type coverage, precipitation, and corrected ET_o. Information about various crop parameters and common irrigation practices in the Upper Klamath Basin was obtained from interviews with extension agents and farm advisors, researchers, growers, and irrigation district personnel.

Crop Water Use Modeling with FAO-56 Procedures

Calculation of ET_c with the FAO-56 dual K_c procedures involved computation of a daily water balance of the full crop root zone to account for E from the upper wet soil layer in conjunction with T from the lower root zone layer, considering separately the contributions of precipitation and applied irrigation water. A flow chart of the computational steps for the FAO-56 crop water model is provided in **Figure 24**. This model predicted ET_c and related variables on a daily basis.

The daily soil water balance equation of the *upper soil surface layer* is:

$$D_{e,i} = D_{e,i-1} - (P_i - RO_i) - \frac{I_i}{f_w} + \frac{E_i}{f_{ew}} + TP_{ew,i} + DP_{e,i}$$

where	$D_{e,i}$, $D_{e,i-1}$	cumulative evaporation at the end of days i and i-1 [mm]
	P_i	precipitation [mm]
	RO_i	runoff from soil surface [mm]
	I_i	irrigation depth that infiltrates the soil [mm]
	E_i	evaporation [mm]
	$TP_{ew,i}$	transpiration from the exposed and wetted soil layer [mm]
	$DP_{e,i}$	drainage from the topsoil layer [mm]
	f_w	fraction of soil surface wetted by irrigation [0.01-1]
	f_{ew}	exposed and wetted soil fraction [0.01-1]

and	$0 \leq D_{e,i} \leq TEW$	
	TEW	total evaporable water [mm]
	$TEW = 1000\ [FC - 0.5\ WP]\ Z_e$	
	FC	field capacity [mm]
	WP	wilting point [mm]
	Z_e	upper soil layer thickness [10-15 cm]
	E_i	$K_e \times ET_o$ [mm]
	K_e	$K_r\ [K_{c\ max} - K_{cb}] \leq f_{ew}\ K_{c\ max}$
	K_r	factor for reduction of soil evaporation, [1 when $D_{e,i-1} \leq REW$]
	K_r	$[TEW - D_{e,i-1}]\ /\ [TEW - REW]$ for $D_{e,i-1} > REW$

Calculation of the daily water balance of the *lower root zone layer*, including the ET_c term is given by the following:

$$D_{r,i} = D_{r,i-1} - DP_{e,i} - CR_i + ET_{c,i} + DP_i$$

where	$D_{r,i}$, $D_{r,i-1}$	soil water content at the end of days i and i-1 [mm]
	CR_i	capillary rise [mm]
	$ET_{c,i}$	evapotranspiration [mm]
	$DP_{e,i}$	drainage from upper surface layer [mm]
	DP_i	deep percolation downward [mm]

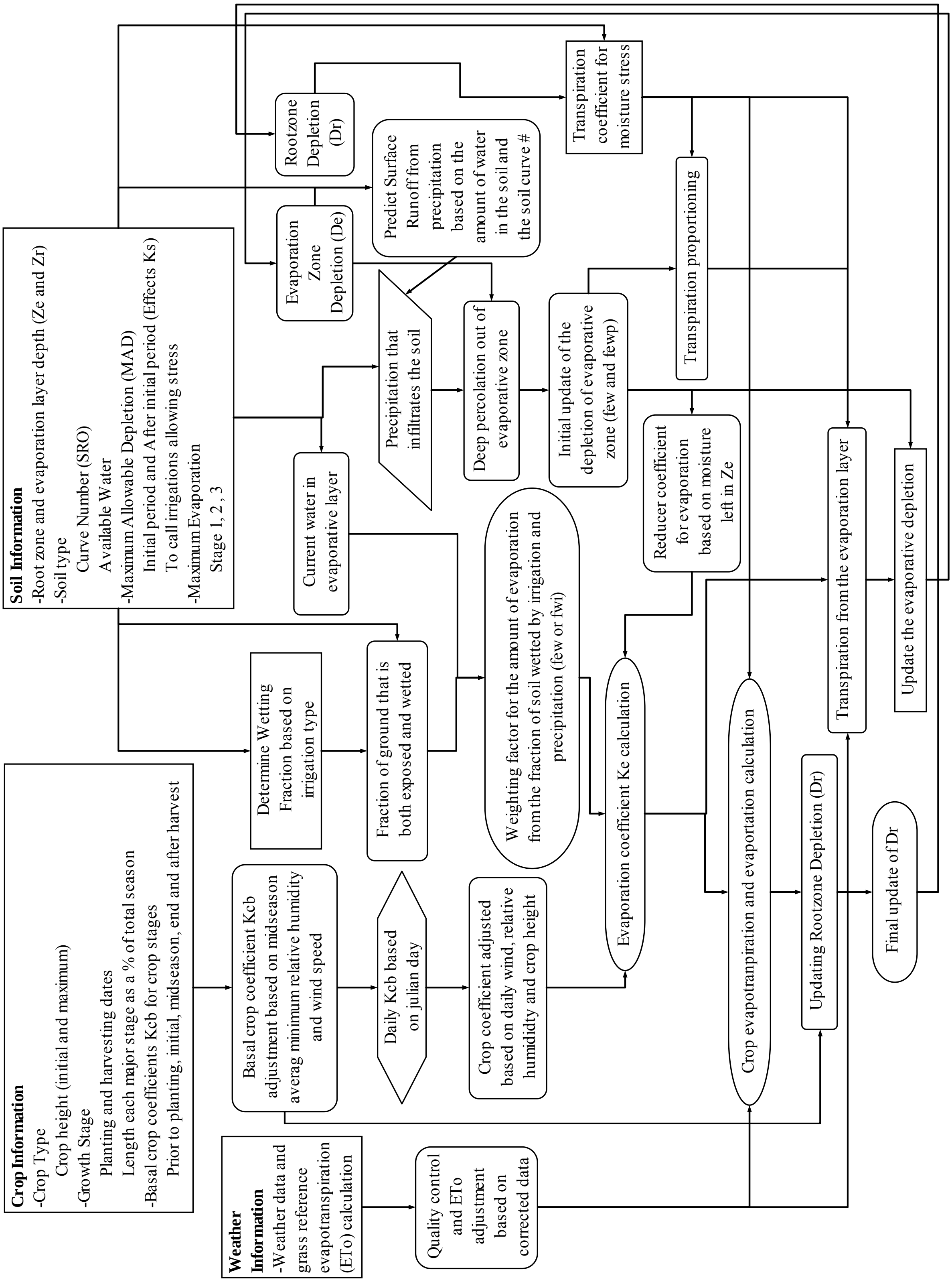


Figure 24. Flow chart of FAO-56 model application methodology

ET Model Input Parameters

Table 20 summarizes the input parameters used in the crop water model. In addition to four agricultural crops (alfalfa, grain, pasture, potato) and a "misc. field crop," phreatophytes and open water categories were analyzed. The primary methods of field irrigation in the Klamath Irrigation Project are flood and sprinkler. Sprinkler irrigation has steadily increased since the 1990s (mainly for high-value crops such as potatoes and onions), as water users took steps to conserve water with funding from the NRCS, which in turn has affected their overall farm management.

Irrigations in the model were scheduled based on the concept of Management Allowable Depletion (*MAD*) according to the stress indicators (% depletion) defined in the table for each crop. *MAD* represents the degree to which the volume of water in the soil is allowed to be depleted before the next irrigation is applied and is very crop-specific. Refer to the following sections for additional information about the specific irrigation schedules, crop coefficients, and agronomic practices used in the model analysis.

Table 20. Mean crop input parameters for dual K_c model calculations of ET_c

Crop	Height [m]		Root Zone [m]		% Depletion		Wetted Fraction
	Initial	Max.	Initial	Max.	Start Stress	Schedule Irrigation	
Alfalfa/hay	0.10	0.7	1.2	1.2	50	65	0.9
Grain	0.05	1.0	0.2	1.0	55	65	0.9
Misc. field crops	0.05	0.8	0.2	1.0	50	60	0.6
Pasture	0.10	0.5	0.2	1.0	50	65	0.9
Potato	0.05	0.8	0.2	0.8	50	60	0.6
Wetlands vegetation	0.05	0.5	0.2	1.0	---	---	1.0
Wetlands open water	0.05	0.5	0.2	1.0	---	---	1.0
Non-irrigated grass	0.10	0.5	0.4	0.4	60	---	---

Planting Dates and Localized Irrigation Schedules

The specification of local irrigation dates was important for accurately estimating the ET_c from agricultural fields. Irrigation dates were scheduled for each crop according to the daily soil water balance and assumed *MAD* values (**Table 20**) and soil characteristics (**Table 7**). The modeled irrigation schedules were specific to each crop and each year. Irrigations were terminated prior to a specified time before harvest to follow local cultural practices. Alfalfa irrigations were scheduled manually with the stipulation that events didn't occur 5 days before or after scheduled cutting events.

Planting and harvest dates, along with information about irrigation schedules, were obtained from interviews with agricultural specialists and farmers to determine specific input parameters for estimating crop water use for major crops in the study area. Due to the large number of farms in the Klamath Irrigation Project and lack of knowledge of precise irrigation dates it was not possible to simulate irrigation events for individual fields.

Tables 21 to **23** summarize specific local information about the water management practices obtained during this study relevant to crop water use modeling in the Klamath Irrigation Project. On-farm water management planning varies to an extent depending on local soil and climate conditions, but also largely follows localized preferences for the main crops that have evolved along with the water delivery schedules within irrigation districts (Kaffka and Dhawan, 2002).

Table 21. Local agronomic and irrigation practices for alfalfa

Item	Description	Source
Pre-Irrigation	Farmers pre-irrigate grass and alfalfa. February for alfalfa. Some farmers will flood a grass field for 30 days to warm up the soil temperature as opposed to irrigating for a short period of time.	Klamath DD
First Irrigation	Early to mid-May (In some years 1st cutting can be put up before irrigating)	Oregon State Univ. Experiment Station
	Sometime in April	Univ. of Calif. Farm Advisor
	Late April/early May (typically one irrigation before 1st cutting and one irrigation between cuttings)	Tulelake ID
	May (typically 2 irrigations per cutting)	Klamath DD
	Early April to Early May. Typically 10 days to 14 days between irrigations.	NRCS, Tulelake
Last Irrigation (3 cuttings)	End of August, beginning of September	Tulelake ID
	End of August	Univ. of Calif. Farm Advisor
	End of August, beginning of September	Klamath DD
	September	NRCS, Tulelake
Last Irrigation (4 cuttings) approx. 20%	Mid-Sept. to the end of September	Tulelake ID
	First part of September	Univ. of Calif. Farm Advisor

Table 22. Local agronomic and irrigation practices for potatoes

Item	Description	Source
Irrigation Practices	Start irrigating in late May, early June 1 to 2 irrigations per week Shut off water in September Harvest about 2 weeks after shutting water off	Klamath DD
Irrigation Practices	Start water in April or May. Early in the season farmers will have frequent irrigations, short sets. Frost protection is important. They try to avoid having the soil too wet or too dry. Wet soil may cause rot and increase the probability of frost damage. Irrigate right up until harvest, which is in October and November.	NRCS, Tulelake

Table 23. Local agronomic and irrigation practices for grain crops

Item	Description	Source
Planting Date	Starts April 10th (only a few hardy varieties are planted earlier)	Univ. of Calif. Farm Advisor
	End of April, beginning of May	Klamath ID
	Late April, early May	Tulelake ID
	April and May	Klamath DD
	April: Finished planting by April 30th	NRCS, Tulelake
First Irrigation	End of May: typically not pre-irrigated	Klamath ID
	Middle of May: some farmers pre-irrigate in early April or the in the fall	Tulelake ID
	It is common to pre-irrigate in KDD. KDD runs water all year. Some farmers don't irrigate after the pre-irrigation. Others start the water in May.	Klamath DD
	Farmers pre-irrigate spring grains.	NRCS, Tulelake
Harvest	Early to mid-August	Univ. of Calif. Farm Advisor
	End of August, early September	Oregon State Univ. Experiment Station
	Start the 1st part of August and finish at the end of August	Tulelake ID
	Start in September through the end of October	Klamath DD
	Begin September, finish in October	NRCS, Tulelake
Timing of Last Irrigation	Heavy soils: 3rd or 4th week in July or 3 to 4 weeks before harvest. Sandy soils: water is shut off about 2 to 3 weeks before harvest Rule of thumb: have 30% to 50% of the AWHC in the effective RZ (2' to 2.5').	Univ. of Calif. Farm Advisor
	Irrigate until the grain heads begin to fill: this is typically in early to mid-August. Last irrigation is 2 to 3 weeks before harvest depending on soil type.	Oregon State Univ. Experiment Station
	Late June or early July (heavy soil) Grain becomes too tall to move wheel lines through the field (4 or 5 weeks before harvest)	Tulelake ID
	End of June, 1st part of July (8 weeks before harvest)	Klamath DD
	Sometime in August: about 3 weeks before harvest	NRCS, Tulelake
Number of Irrigations	Depends on soil type: varies from 1 irrigation to grow the crop up to 5-6	Univ. of Calif. Farm Advisor
	Sprinkler: 2 Flood: 1 (Heavy soils in TID area)	Tulelake ID
	Depends on the farmer/soil. Some farmers pre-irrigate only, others will irrigate up to 3 times with sprinklers.	Klamath DD

Application of local management preferences in the Project to the crop water use model is complex, with many different crop-soil-water factors involved, as illustrated by the responses regarding specific irrigation practices. However, an analysis of the compiled information from interviews and field observations showed similar trends in field water management for the major crops. **Table 24** presents the mean cropping dates used in the calculation of ET_c.

Table 24. Mean planting and harvest dates for major crops for the daily soil water balance model

Crop	Planting Date	Harvest Date	Last Irrigation (days before harvest)
Alfalfa/hay	April 10	Nov 5	30
Grain	April 25	Sept 10	20
Misc. field crops	May 15	Aug 20	10
Pasture	April 1	Oct 15	20
Potato	May 15	Oct 5	10
Wetlands vegetation	April 15	Sept 30	---
Wetlands open water	Jan 1	Dec 31	---
Non-irrigated grass	April 1	Aug 1	---

Crop Coefficients

The crop coefficient (K_c) is an integration of specific crop characteristics that distinguish field crops (alfalfa, wheat, potato, etc.) from the grass reference including primarily height, albedo, canopy resistance, and evaporation from the soil (Allen et al., 1998). The actual modeled K_c in the dual crop coefficient method is calculated on a daily basis depending on crop water stress (K_s) and the evaporative rate from the upper soil profile at irrigation and rainfall events (K_e).

$$K_c = (K_s \times K_{cb}) + K_e$$

The calculation steps for the estimation of the actual K_c for each crop and soil type (by subregion) consists of (Allen et al., 1998):

1. Identifying the lengths of the crop growth stages, and plant and harvest dates
2. Selecting corresponding K_{cb} values
3. Adjusting K_{cb} values for local climatic conditions
4. Computing daily K_s values for crop water stress based on available soil moisture relative to management tolerated depletions
5. Computing daily K_e values for surface evaporation

The basal crop coefficient (K_{cb}) is the component that describes plant transpiration and represents the baseline potential K_c for a dry soil surface layer. The K_{cb} value varies corresponding to different stages of crop growth divided into the periods of initial, crop development, mid-season and late season. K_{cb} occurs when the plant is not under water stress; therefore, water is not limiting transpiration.

The FAO-56 report (Table 17, Allen et al., 1998) recommends K_{cb} values for most agricultural crops. However, the published values represent K_{cb} for sub-humid climates with moderate wind speeds, and therefore, specific adjustment for the local climatic conditions in the Klamath Irrigation Project was required. This adjustment was made to account for local relative humidity and wind speed conditions using the following equation (Equation 70, Allen et al., 1998):

$$K_{cb} = K_{cb(Tab)} + \left[0.04(u_2 - 2) - 0.004(RH_{\min} - 45)\right] \left(\frac{h}{3}\right)^{0.3}$$

where $K_{cb(Tab)}$ value for $K_{cb\ mid}$ or $K_{cb\ end}$ (if ≥ 0.45) taken from table

u_2 mean value for daily wind speed at 2 m height over grass during the mid or late season growth stage [m s^{-1}] for $1 \text{ m s}^{-1} \leq u2 \leq 6 \text{ m s}^{-1}$

h mean plant height during the mid or late season stage [m]

Adjusted K_{cb} values for the major crops used in the daily soil water balance computations for each crop growth stage are presented in **Table 25**. In **Table 25** K_{cb} values are also provided for periods preceding and following harvest of crops. For field crops these values were set to zero to allow the soil surface to dry to zero ET_c during long periods with no wetting. The relative lengths for the four growth stages – initial, development, mid-season and late season – were derived from FAO-56 and adjusted based on information about local crop dates (refer to **Table 24**).

Table 25. Basal crop coefficients (K_{cb}) and crop development stages for major crops in the Klamath Irrigation Project

	Basal crop coefficients (K_{cb})					% of Season			
Crop	K_{cb} prior to planting	K_{cb} ini	K_{cb} mid	K_{cb} end	K_{cb} after harvest	ini	dev	mid	late
Alfalfa/hay	0.00	0.30	1.15	1.10	0.00	20	45	25	10
Grain	0.00	0.15	1.10	0.15	0.00	15	20	40	25
Misc. field crops	0.00	0.15	0.90	0.65	0.00	20	25	25	30
Pasture	0.00	0.30	0.90	0.70	0.00	10	20	50	20
Potato	0.00	0.15	1.10	0.50	0.00	15	25	50	10
Wetlands vegetation	0.30	0.30	1.20	0.30	0.30	10	20	55	15
Wetlands open water	1.00	1.00	1.05	1.05	1.00	5	20	60	15
Non-irrigated grass	0.00	0.30	0.90	0.70	0.00	10	20	50	20

The effects of water stress were accounted for by reducing the K_{cb} values using a stress reduction coefficient (K_s) when the available root zone moisture content was low enough to limit transpiration. The estimation of K_s requires a daily water balance computation of the root zone. Water content in the root zone relative to field capacity is expressed in the model in terms of root zone depletion according to the management allowed depletion.

K_s is computed on a daily time step according to the amount of root zone water available to the plant:

$$K_s = \frac{TAW - D_r}{TAW - RAW}$$

where	K_s	transpiration reduction factor dependent on available soil water
	TAW	total available water in the root zone [mm] $TAW = 1000(\theta_{FC} - \theta_{WP})\, Z_r$
	θ_{FC}	water content at field capacity [$m^3\ m^{-3}$]
	θ_{WP}	water content at wilting point [$m^3\ m^{-3}$]
	Z_r	rooting depth [m]
	D_r	previous day's root zone depletion [mm]
	RAW	readily available water in the root zone [mm] $RAW = TAW \times MAD$
	MAD	Management Allowable Depletion

Note: *TAW* is the total amount of water available in the soil reservoir (root zone), while *TEW* refers to the total evaporable water in the soil surface layer (15 cm depth).

The daily soil water balance model also kept track of evaporation from the wet soil surface during and after a rainfall or irrigation event. When the soil is wet, evaporation occurs in proportion to the amount of water remaining in the surface soil layer. When the surface layer dries out a reduction in evaporation occurs in proportion to the amount of water remaining. Using information about rainfall events, soil drying properties, cropping patterns, growth stages, and irrigation methods the amount of evaporation was estimated from the soil surface layer (Z_e) throughout the year on a daily basis.

$$K_e = K_r\ (K_{c\,\max} - K_{cb}) \leq f_{ew}\, K_{c\,\max}$$

where	K_e	soil evaporation coefficient
	K_{cb}	basal crop coefficient
	$K_{c\,max}$	maximum value of Kc following rain or irrigation
	Kr	evaporation reduction coefficient dependent on the cumulative depth of water depleted from the surface layer Z_e
	f_{ew}	fraction of soil that is both exposed and wetted

A graphical analysis of the crop coefficient curves illustrates the effect of rainfall and irrigation events on the actual K_c values for misc. field crops and alfalfa in subregion 2 as shown in **Figures 25** and **26**, respectively. After rain or irrigation, when soil moisture is replenished, the crop coefficient increases above the K_{cb} curve (depending on the antecedent conditions) due to evaporation from the soil surface. The curves also show the differences in K_{cb} between the two different crop types.

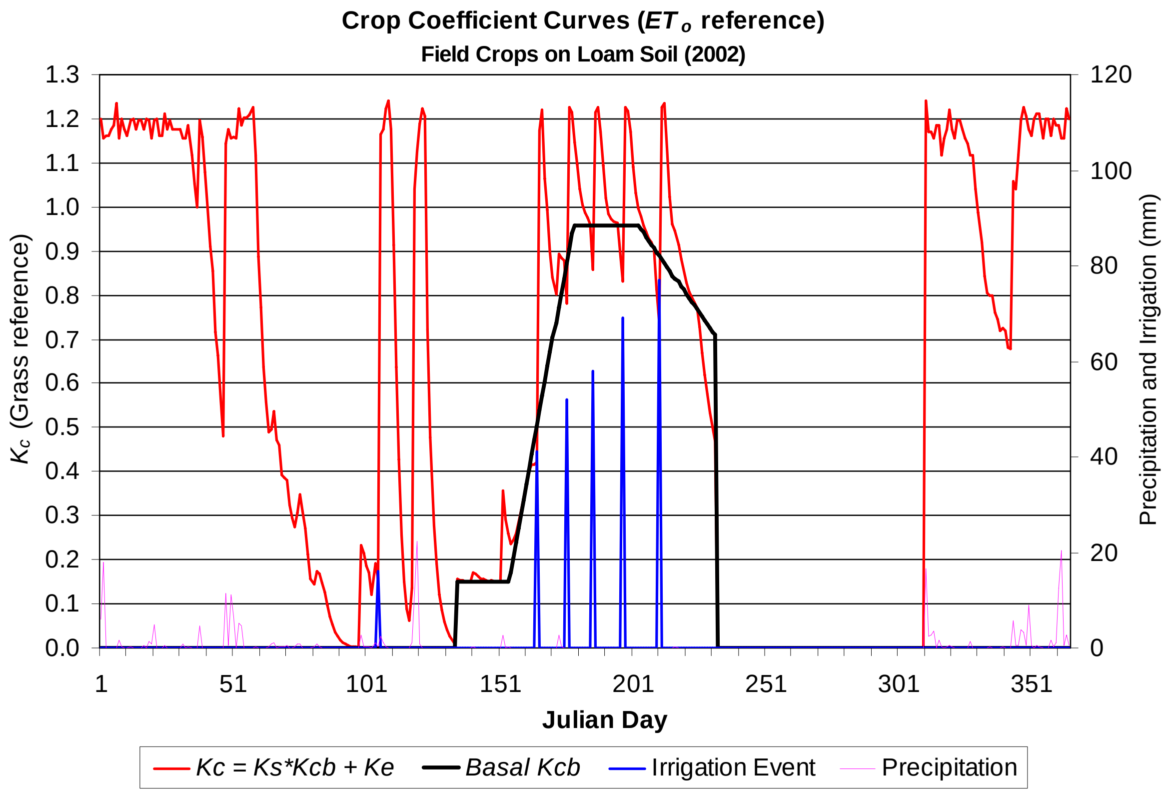


Figure 25. Daily crop coefficients for misc. field crops on loam soil (subregion 2; 2002)

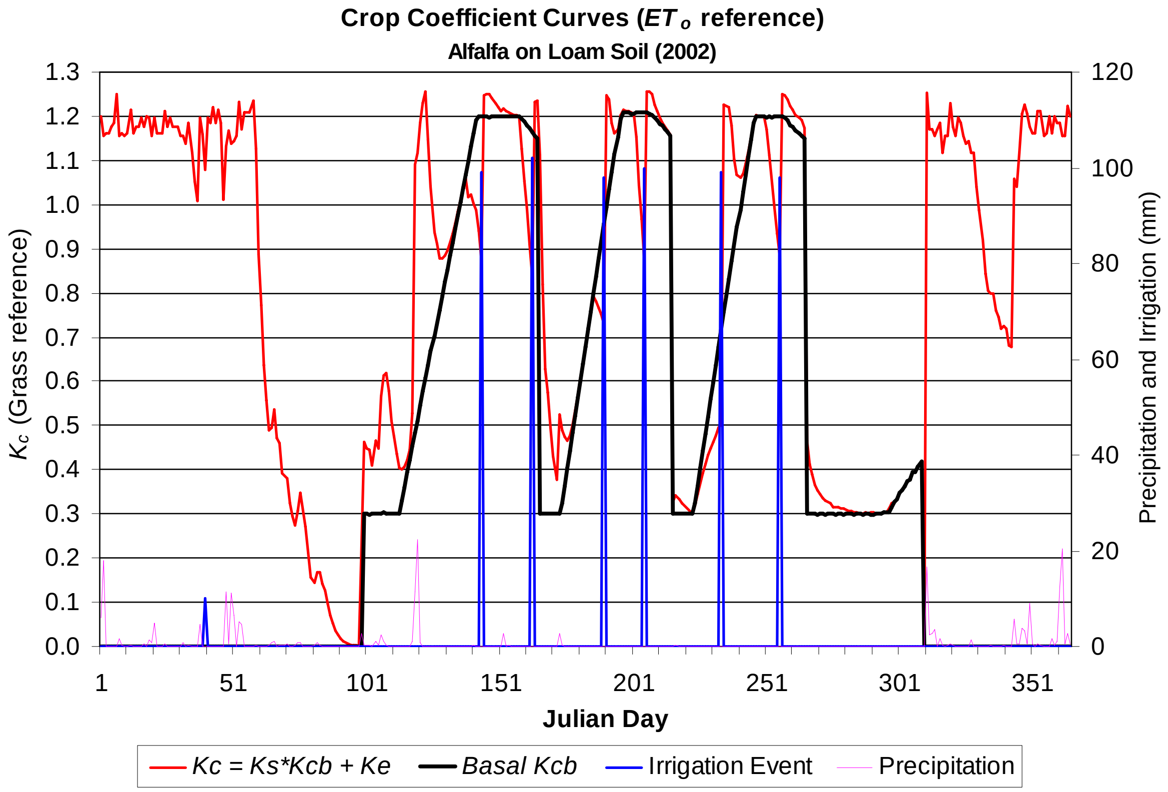


Figure 26. Daily crop coefficients for alfalfa on loam soil (subregion 2; 2002)

Reduction in ET due to Bare Spots and Reduced Vigor

A pristine crop has none of the bare spots or reductions in plant vigor and vegetative mass that generally occurs in real-world cropping situations and which was evident in fields in the Klamath Irrigation Project. A manual visual rating of field appearances was made using aerial photographs and field inspections to note the presence of brown spots and visible areas of low plant densities. An adjustment factor was then applied to computed ET_c values to account for observed suboptimal agronomic conditions, which appeared to be distributed over all crop types.

Digital orthophoto quadrangles (DOQs) prepared in 1994 were obtained from the Oregon Spatial Data Clearinghouse. A dozen samples of enlarged scale (about 10 to 20 fields per image) were taken at random throughout the Project for further analysis. Square grids were overlaid on the aerials and the visible areas of bare spots were counted for each field. The overlay assessment indicated that the percent of bare ground per field ranged from 1% to over 20% in extreme cases, with an overall average for the fields sampled of 8%.

The extent of ET_c reduction due to the effects of salinity, irrigation and fertilizer distribution uniformity (*DU*), crop damage caused by machinery (including the building of levees for flood irrigation), pest and disease damage, soil variability, high water table, poor initial crop stand, etc. ranges from 7-8% based on previous unpublished studies cited by the ITRC (2003) and water balance results for a large irrigation project in Allen et al. (2005b). The impact of bare spots and reduced vigor (as opposed to pristine conditions) on the volume of water actually consumed as *ET* is a time-integrated process. The reduction factor assigned for the Klamath Irrigation Project was equivalent to a constant 9% reduction in monthly ET_c from agricultural fields during summer months because of the higher expected incidence during high *ET* months.

3.6.1.4 FAO-56 Crop Water Model Results

Crop ET_c for a 5-year period (1999-2003) was evaluated for four different soil types according their areal extent in each subregion (refer to **Table 6**). *ET* flux was also predicted for fallowed land (receiving precipitation only). The annual mean results from the FAO-56 dual K_c method for the ET_c of agricultural crops are presented in **Table 26**. These modeled results are generally consistent with a major state-wide study of crop water use and irrigation water requirements in Oregon (Cuenca, 1992; Cuenca et al., 1993). Estimates of ET_c during the growing season for major crops (alfalfa, grain, pasture) from the model were generally within 4-7% of Cuenca's published values for the Klamath region.

The annual depth of ET_c [mm] for each crop was multiplied by the respective land use areas in **Table 9** to compute volumes of *ET* in each subregion. The summary of annual ET_c volume by crop is presented in **Table 27**.

A *CI* of 20% was assigned to ET_c estimates due to uncertainties in the predicted irrigation schedules, crop area identification in reporting, representativeness of K_c values for crop varieties grown in the project, and variability in the lengths of growing periods, planting dates and harvest dates. In 2001, the *CI* was increased to 30% to reflect the lack of crop reports and uncertainties associated with the estimations of irrigated areas using the NDVI procedure.

Table 26. Mean annual agricultural crop evapotranspiration (ET_c) by subregion (1999-2003), mm

Crop type	1	2	3	4	Mean
Alfalfa	826	759	799	771	789
Barley	724	711	722	703	715
Berries	561	546	563	547	554
Gardens	561	546	563	547	554
Hay	826	759	799	771	789
Misc. crops	561	546	563	547	554
Oats	724	711	749	703	722
Onions	561	546	563	547	554
Other grains	724	711	722	703	715
Pasture	873	739	767	760	785
Peas	561	546	563	547	554
Peppermint	561	546	563	547	554
Potato	752	742	773	751	755
Rye	724	711	722	703	715
Silage	873	739	767	760	785
Sugar beets	752	742	773	751	755
Vegetables	561	546	563	547	554
Wheat	724	711	722	703	715

Table 27. Annual agricultural crop evapotranspiration volume, mcm

Crop type	1999	2000	2001	2002	2003	Mean
Alfalfa	158	169	119	165	166	155
Barley	84	103	66	81	74	82
Berries	1	1	0	1	1	1
Gardens	2	0	0	0	0	0
Hay	45	47	43	56	45	47
Misc. crops	2	2	2	2	2	2
Oats	14	13	7	16	17	13
Onions	9	7	2	4	4	5
Other grains	1	1	0	1	2	1
Pasture	137	142	80	139	131	126
Peas	0	1	1	0	1	1
Peppermint	3	6	3	4	6	4
Potato	43	41	10	35	39	34
Rye	0	0	0	0	0	0
Silage	1	4	2	3	8	4
Sugar beets	22	13	0	0	0	7
Vegetables	0	0	0	0	0	0
Wheat	49	43	9	38	47	37
Fallow, not irrigated	5	4	52	7	17	17
Unharvested, irrigated	1	15	0	4	8	6
Total	**577**	**613**	**397**	**556**	**569**	**542**

3.6.2 Evapotranspiration from Refuge Wetlands

The evapotranspiration amounts for the different habitat types in the Lower Klamath NWR and Tulelake NWR were estimated using the daily crop and soil *ET* model. Two categories – emergent vegetation and open water – were modeled based on wetlands coefficients reported in FAO-56 and information obtained from the USFWS about habitat management strategies involving deliberate dry down periods. Evaporation from the Tule Lake sumps was accounted for in the model using the corrected reference evapotranspiration data for subregion 3 (corrected Tulelake CIMIS) and coefficients for open water with less than a 2 m depth.

The 43 separate diked wetlands or fields in the Lower Klamath NWR include units varying in size from about 20 to 2,000 ha (50-5,000 acres). Each of the refuge units is operated under one of four habitat management strategies with different corresponding *ET* fluxes (refer to **Figure 27**: from the 2002 Habitat Plan).

Site-specific information on the areas of emergent vegetation and open water was not available for each of the seasonal and permanent wetlands units in the Lower Klamath NWR, and detailed mapping of the refuges was beyond the scope of this investigation. The modeled evapotranspiration estimates for a representative wetlands vegetation were applied assuming a 50-50 percent delineation of vegetation and open water for the permanent and seasonal units (except during the summer months, when the seasonal units are drained). This spatial partitioning was verified though field observations. The modeled representative "grain" crop was used for estimating the evapotranspiration of the cooperatively farmed areas (lease lands).

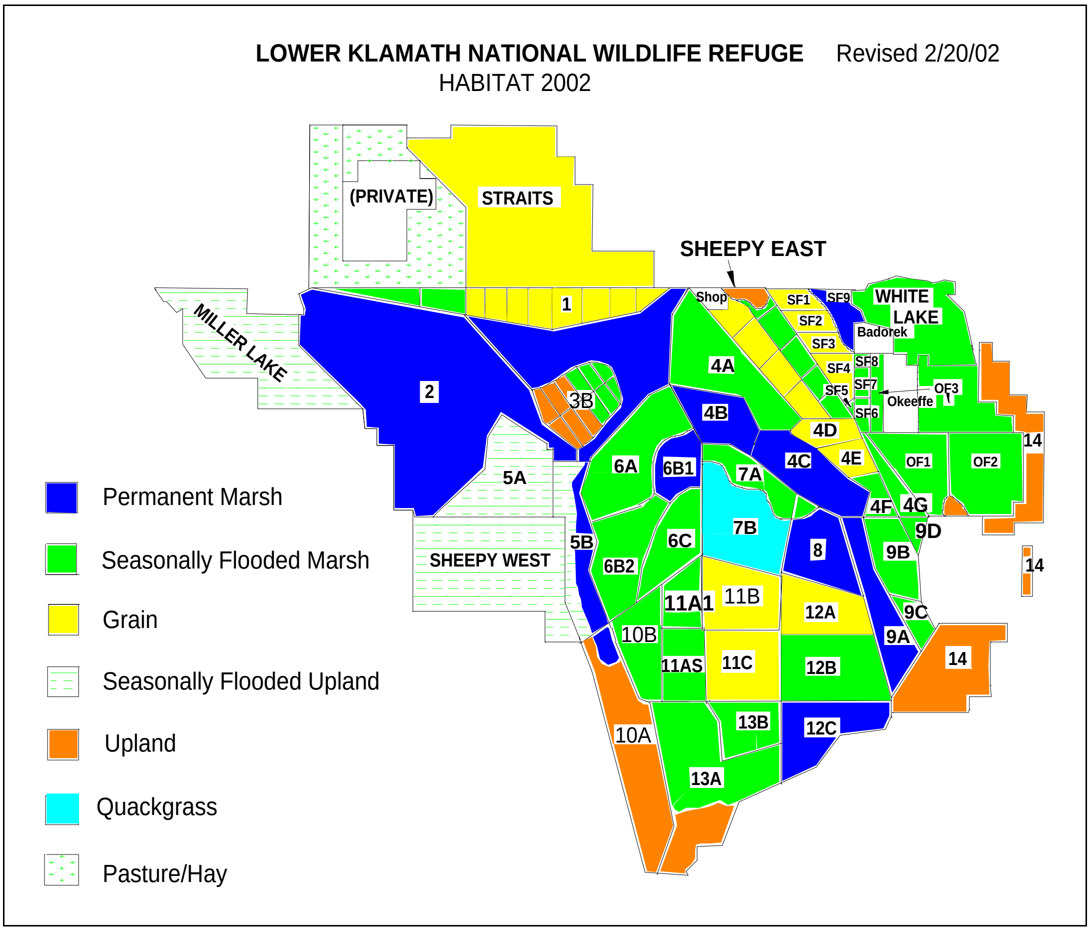


Figure 27. Lower Klamath National Wildlife Refuge showing the 2002 habitat plan

Overall, the average depth of annual *ET* from the seasonal and permanent wetland units in the Lower Klamath NWR (i.e., not including public areas, roads, equipment yards, etc.) in non-drought years was 814 mm, with a reduction of approximately 10% in 2001. Note: this does not include water required for the fall flood-up of seasonal units. The *E* from the Tule Lake Sumps 1A and 1B accounted for an average of about 37% of total refuge *ET* (both Lower Klamath NWR and Tulelake NWR) in non-drought years (1999, 2000, 2002 and 2003) (not including the federal lease lands in Tulelake).

Table 28 summarizes the annual evapotranspiration from the wetlands units in the Lower Klamath NWR and Tulelake NWR. The *ET* from dirt roads, service areas, and other parts of the refuge complexes are included in the "undeveloped land" categories in each subregion, respectively. A *CI* of 20% was assigned to these *ET* values to account for the uncertainty in estimating the surface areas, evaporation rates, and assumptions about vegetative cover during different time periods in the year.

Table 28. Wetlands evapotranspiration in the Lower Klamath NWR and Tulelake NWR, mm

Refuge	1999	2000	2001	2002	2003
Lower Klamath NWR[1]	812	838	744	777	781
Tulelake NWR[2]	1,239	1,152	1,217	1,261	1,074

[1] Mean depth for permanent and seasonal wetlands, upland areas and grain
[2] Includes evaporation from Tule Lake Sumps 1A and 1B (5,356 ha), but does not include the federal lease lands (refer to **Table 6**)

3.6.3 Evapotranspiration from Canals and Drains

Evaporation from the canals and drains within the boundaries of the water balance was estimated using the modeled coefficients for open water and phreatophytes (wetlands vegetation), respectively, along with the corrected ET_o datasets for each subregion. The surface areas of the canal and drain systems were determined from an analysis of GIS information. The total surface area of the canals and drains within the water balance boundaries is approximately 1,430 ha (3,540 acres). An average width was assumed for each main canal based on its flow rate capacity, ranging in size from 5 to 20 m across (20-60 ft). An average width of 4.5 m (15 ft) was assumed for the approximately 1,100 km (680 miles) of lateral channels in the project. Similarly, an average width of 4.5 (15 ft) was assumed for the approximately 1,170 km (728 miles) of drains.

The lengths of canals and drains within the Klamath Irrigation Project are reported in several publications including the report *Klamath Project Historic Operation* (USBR, 2000) and the technical memorandum *System Facilities associated with the Klamath Project* (CH2M Hill, 1996). The lengths of main canals from the GIS database generally matched the reported values. A use factor was assigned on a monthly basis to the canals and drains based on the timing of surface water diversions during the year in each subregion. In 2001, a reduction in the use factors for subregions 1-4 was applied to account for the irrigation curtailment.

Table 29 summarizes the annual *E* amounts from the canals and drains in the water balance boundaries of subregions 1-4. A *CI* of 20% was assigned to these values to account for the uncertainty in estimating the surface areas and evaporation rates.

Table 29. Evaporation (*E*) from canals and drains in the Klamath Irrigation Project water balance boundaries for subregions 1-4, mm

Item	1999	2000	2001	2002	2003
Canals	1,014	1,022	552	965	944
Drains	989	1,045	1,038	971	1,009

3.6.4 Evaporation from Urban Areas

Evapotranspiration from urban areas within the boundaries of the water balance was estimated using the corrected ET_o datasets and a monthly coefficient of 0.50 to reflect the combination of urban landscapes and residential property. The amount of urban area in each subregion was determined from an analysis of GIS information. The total surface area of the urban areas within the water balance boundaries is approximately 2,130 ha (5,266 acres). **Table 30** summarizes the annual *ET* from urban areas in subregions 1-4. A *CI* of 20% was assigned to these values to account for the uncertainty in estimating the surface areas and evaporation rates.

Table 30. Evapotranspiration from urban areas, mm

Item	1999	2000	2001	2002	2003
Urban areas	527	536	561	512	497

3.6.5 Evaporation from Undeveloped Areas

Undeveloped land was designated as the closure term in the quantification of various land use areas in this GIS investigation. This land use category included farmsteads, forestland, open rangeland, unpaved roads, and other miscellaneous areas. In terms of the entire area within the boundaries of the water balance, undeveloped land represented about 22% of the total area. Evapotranspiration from undeveloped lands within the boundaries of the water balance was estimated using modeled coefficients for an early maturing, non-irrigated grass vegetation and the corrected ET_o datasets for each subregion. **Table 31** summarizes the annual *ET* from undeveloped land areas in subregions 1-4. A *CI* of 20% was assigned to these values to account for the uncertainty in estimating the surface areas and evaporation rates.

Table 31. Evapotranspiration from undeveloped areas, mm

Item	1999	2000	2001	2002	2003
Undeveloped areas	208	242	152	181	253

3.6.6 Evaporation from Reservoirs, Lakes, Rivers, and Streams

Evaporation from the reservoirs, lakes, rivers, and streams within the boundaries of the water balance was estimated using the modeled coefficients for open water and the corrected ET_o datasets for each subregion. The surface areas of these open bodies of water were determined from an analysis of GIS information. The total surface area of the reservoirs, lakes, rivers, and streams within the water balance boundaries is approximately 1,340 ha (3,310 acres).

Table 32 summarizes the annual evaporation amounts from these open bodies of water in subregions 1-4. A *CI* of 20% was assigned to these values to account for the uncertainty in estimating the surface areas and evaporation rates.

Table 32. Evaporation from reservoirs, lakes, rivers, and streams, mm

Item	1999	2000	2001	2002	2003
Lakes/reservoirs	1,197	1,215	1,271	1,160	1,132
Rivers/streams	1,202	1,218	1,275	1,166	1,134

3.7 Change in Storage of Reservoirs, Lakes and Refuges

The change in storage of surface water bodies on approximately 34,700 ha (85,700 acres) within the boundaries of the Upper Klamath Basin water balance was determined on a monthly and annual basis for the reservoirs, lakes and refuge units. The surface area of all significant water bodies was estimated based on USBR GIS datasets and aerial photographs as summarized in **Table 33**.

Table 33. Surface water area for major water bodies in the Klamath Irrigation Project, ha

Item	Surface Area
Alkali Lake	290
Channel at Lost River Dam	290
Clear Lake Reservoir	9,470
Gerber Reservoir	1,720
Indian Tom Lake	180
Long Lake	410
Lost River	850
Lower Klamath Lake	6,820
Nuss Lake	70
Round Lake	720
Spring Lake	170
Swan Lake	330
Tulelake Sump A	3,900
Tulelake Sump B	1,460
Upper Klamath Lake	7,430
Willow Valley Reservoir	300
Wilson Reservoir/Lost River	80
Other	290
Total	**34,690**

3.7.1 Lower Klamath National Wildlife Refuge Units

The 43 separate units in the Lower Klamath National Wildlife Refuge (NWR) cover a total surface area of 12,850 ha (31,750 acres). Irrigation water is delivered during the fall flood-up period in the Lower Klamath NWR from September to November in an attempt to fill the seasonal wetland units to a water depth specified in the annual *Habitat Management Plan*. The refuge practices moist soil management, requiring dewatering of the wetlands units during the spring and early summer and re-flooding of these wetlands in the fall. Once the seasonal wetlands reach their objective level (target water surface elevation within ±30 mm), usually by October 31st, irrigation water is delivered to farmed units. Upland units are flooded and maintained by precipitation and tributary inflows. The seasonally flooded wetlands, farmed units, and upland habitat units are drained through a prolonged drawdown in the spring (March to May). The monthly volumes of surface water stored in the wetlands units of the refuge between 1999 and 2003 are provided in **Figure 28**.

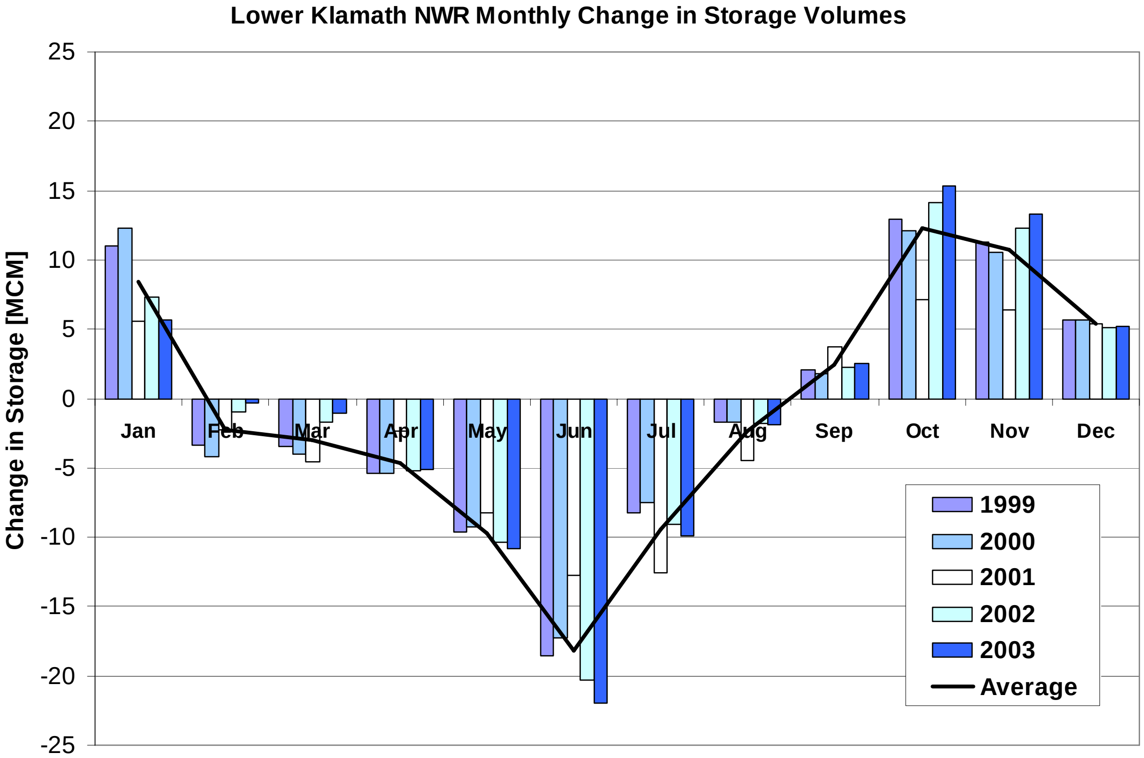


Figure 28. Volume of surface water stored in wetlands units in the Lower Klamath National Wildlife Refuge, 1999-2003

The USFWS has conducted detailed studies on the fall water requirements for seasonal wetlands. Mayer and Thomasson (2003) conducted a study using site measurements and modeled estimates for the fall water requirements for selected units in the Lower Klamath NWR. They concluded that a modeling approach using an "average inflow rate" (ha m per ha during flood-up), based on site-specific information from three monitored wetlands, was a good approximation compared to actual delivery records.

Average monthly water levels, based on staff gauge readings taken at various times during each month, were available for most of the refuge units in 1999-2003. Some months had frequent readings (about 10 to 15 total readings), whereas other months had only one water level reading. Data collected as part of the USFWS effort and information provided by refuge staff were analyzed to determine average water depth in each unit at the end of the month during 2000-2003.

The annual change in surface water storage for the Lower Klamath NWR is summarized in **Table 34**. Variations in the relative volume of water required for each unit are related to differences in the volumetric capacity, target water depth, topography, groundwater depth and other factors. A *CI* of 5% was assumed for the change in surface water storage in the Lower Klamath NWR based on the water elevations in the wetlands units, in addition to uncertainties in the precise surface area and volumetric capacities of the units.

Table 34. Change in surface water storage in the Lower Klamath NWR, mcm

Month	1999	2000	2001	2002	2003	Mean
Jan	11	12	6	7	6	8
Feb	-3	-4	-2	-1	0	-2
Mar	-3	-4	-5	-2	-1	-3
April	-5	-5	-2	-5	-5	-5
May	-10	-9	-8	-10	-11	-10
June	-19	-17	-13	-20	-22	-18
July	-8	-7	-13	-9	-10	-9
Aug	-2	-2	-4	-2	-2	-2
Sept	2	2	4	2	3	3
Oct	13	12	7	14	15	12
Nov	11	11	6	12	13	11
Dec	6	6	5	5	5	6
Annual	**-7**	**-7**	**-19**	**-8**	**-9**	**-10**

3.7.2 Tule Lake National Wildlife Refuge (Tule Lake Sumps)

The Tule Lake sumps intercept and store drainage return flows through the Lost River system and directly from project drains from Tulelake ID and Klamath ID, providing flood control, protection of wildlife, and re-cycled water for irrigation. The sumps are located within the boundary of Tulelake ID (subregion 3). Water levels in the sumps are controlled primarily by Pumping Plant D, where the water is lifted approximately 20 m and conveyed via gravity through a concrete tunnel to the Lower Klamath NWR. In 1999, sump 1B was drained to begin a seasonal wetlands management program, which has continued since 2000. The combined surface area of sumps 1A and 1B is 5,360 ha (13,240 acres) (refer to **Table 11**).

The USBR maintains a table of area-capacity data for sumps 1A and 1B based on state topographic maps 12-D-983 and 984 (produced in 1986). The area-elevation data is provided to the nearest tenth of a foot. USBR records of the daily water elevation in sump 1A are provided to the nearest hundredths of a foot, so the approximate daily sump storage was estimated using a linear interpolation analysis. The change in storage (mcm) for sump 1A was determined by computing the difference in storage on the last day of each previous month.

Tulelake ID provided corrected water level elevation records for sump 1B based on the “East” staff gauge. Some months had frequent readings recorded, while others had only a few readings per month. The lowest gauge reading is 10.09 m (33.10 ft) – no records are kept below this level. The change in storage (on a volumetric basis) for sump 1B was determined by computing the difference in storage on the last day of each previous month based on measured water elevations. The annual change in surface water storage for the Tulelake NWR is summarized in **Table 35**.

Table 35. Change in surface water storage in the Tulelake NWR, mcm

Month	1999	2000	2001	2002	2003	Mean
Jan	0.6	0.9	2.0	0.7	1.1	1.1
Feb	0.7	5.1	0.4	2.9	2.3	2.3
Mar	2.5	1.4	1.1	1.9	1.7	1.7
April	1.6	1.1	1.6	1.3	1.4	1.4
May	-0.8	-2.3	-4.8	-1.5	-2.3	-2.3
June	0.2	-5.6	-1.4	-2.7	-2.4	-2.4
July	1.0	-3.2	0.6	-1.1	-0.7	-0.7
Aug	-0.4	0.8	8.4	0.2	2.3	2.3
Sept	-0.9	-0.5	4.2	-0.7	0.5	0.5
Oct	0.1	3.4	-7.2	1.8	-0.5	-0.5
Nov	-8.1	-3.8	1.2	-6.0	-4.2	-4.2
Dec	0.6	0.9	-4.6	0.8	-0.6	-0.6
Annual	**-2.9**	**-1.8**	**1.6**	**-2.3**	**-1.4**	**-1.4**

3.8 Reservoirs and Lakes

In addition to the wildlife refuge areas that are filled and drained in coordination with the USFWS and USBR, there are approximately 18,200 ha (45,000 acres) of various small reservoirs and lakes used by irrigation districts and private landowners to store water within the boundaries of the Project. The change in surface water storage in these reservoirs, including Nuss Lake, Spring Lake, and Wilson Reservoir was determined on annual basis as shown in **Table 36**. An overall *CI* of 3% was assigned to the change in surface water storage in the reservoirs and lakes based on the uncertainties associated with the measurements of monthly water elevations and the inexact approximations of the surface areas and volumetric capacities.

3.8.1 Clear Lake

Clear Lake is used to store seasonal runoff for irrigation deliveries to the Klamath Irrigation Project, principally for Langell Valley ID and Horsefly ID (subregion 1), and to control high flood flows to the Tulelake area. The estimated surface area of the lake at normal operating level is approximately 9,500 ha (23,400 acres).

3.8.2 Gerber Reservoir

Gerber Reservoir is used to store seasonal runoff for irrigation deliveries to the Klamath Irrigation Project (principally Langell Valley ID), and to control high flood flows to the Tulelake area. The estimated surface area of the reservoir at normal operating level is approximately 1,700 ha (4,200 acres). Daily records of water level elevations and storage were obtained from the USBR for 1999 to 2003. End of the month storage volumes changed by up to ±10-12 mcm (8,000-10,000 acre-feet) when releases were being made for irrigation.

3.8.3 Wilson Reservoir

Wilson Reservoir is situated on the Lost River at the Wilson Diversion Dam. The reservoir is located within the service area of Klamath ID (subregion 2). The estimated surface area of the reservoir is 80 ha (200 acres). During the summer months, the reservoir stores about 3 mcm (2,300 acre-feet) of water that can be released to either the LRDC or back to the Lost River. The USBR operates the reservoir to maintain the surface elevation within ±15 cm (0.5 ft) during the irrigation season. The USBR provided water surface elevations for the end of each month between 1999 and 2003 as measured automatically by a pressure transducer that is transmitted to the USBR office in Klamath Falls. The change in the amount of water stored in the reservoir at the end of each month was determined based on a derived storage capacity table and the daily measured water level elevation.

3.8.4 Nuss Lake and Spring Lake

Nuss Lake is located within the service area of Klamath ID (subregion 2). It serves as a small reservoir that stores approximately 1.2 mcm (1,000 acre-feet) during the summer irrigation season. The typical change in water level elevation over the summer is about 30 cm (1 ft). The estimated surface area is 70 ha (170 acres). The change in monthly storage was determined based on a drop in water elevation of equal increments between June and September (irrigation season). It was assumed that the lake is re-filled each spring during February and March.

Spring Lake is located within the service area of Klamath ID (subregion 2). It is a shallow lake that stores return flows from divisions 1, 3, and 4 of the district. The estimated surface area is 170 ha (410 acres). The Melhase Ryan Pump station is used to maintain the lake level at a target gauge level of about 30 cm (1 ft). The typical operating range on this gauge is ±15 cm (0.5-1.0 ft). The surface elevation is always kept below 45 cm (1.5 ft) because of the potential for flooding out adjacent farmland. During the winter, Klamath ID usually maintains the lake level around 15 cm (0.5 ft).

Table 36. Change in surface water storage in reservoirs and lakes, mcm

Month	1999	2000	2001	2002	2003	Mean
Jan	-0.17	0.01	-0.07	-0.03	-0.06	-0.06
Feb	0.91	0.18	0.20	0.19	0.42	0.38
Mar	-0.36	0.22	0.20	0.21	0.02	0.06
April	0.58	0.60	-0.01	0.29	0.49	0.39
May	0.04	0.02	0.06	0.04	0.03	0.04
June	-0.09	-0.12	0.00	-0.06	-0.09	-0.07
July	-0.13	-0.12	0.10	-0.01	-0.08	-0.05
Aug	-0.12	-0.03	-0.07	-0.05	-0.07	-0.07
Sept	-0.07	0.05	-0.06	-0.01	-0.01	-0.02
Oct	-0.61	-0.24	0.10	-0.07	-0.31	-0.23
Nov	-0.03	-0.38	0.06	-0.16	-0.19	-0.14
Dec	0.01	-0.09	-0.28	-0.19	-0.09	-0.13
Annual	**-0.03**	**0.09**	**0.21**	**0.15**	**0.07**	**0.10**

3.9 Groundwater Resources

The groundwater system in the Upper Klamath Basin has been an important resource in past drought years to augment the available surface water supplies, although the quantitative potential for long-term, sustainable groundwater withdrawals is still mostly unknown (Gannett et al., 2007). Historically groundwater use in the Klamath Irrigation Project for irrigation has been relatively minor (CDWR, 2004). To address the need for information on the groundwater hydrology and future development of large-scale pumping, the U.S. Geological Survey (USGS) and the CDWR initiated ongoing long-term studies to characterize and quantify the groundwater flows in the major hydro-geologic units in the Basin (Gannett et al., 2007). Future efforts will lead to updating basin-wide groundwater management plans to better address the impact of increased groundwater withdrawals on groundwater elevations and stream flows.

The movement of groundwater from upland recharge areas toward discharge areas in valleys and lowland areas has been identified throughout the Upper Klamath Basin (Newcomb and Hart, 1958; Leonard and Harris, 1974; Illian, 1970). However, the lack of detailed information about the source and quantities of lateral groundwater inflow precludes an accurate accounting of all the contributions from external recharge areas that are discharged through perennial springs, such as those in the Lost River system, and by *ET* from associated marshy areas.

The principal aquifer in the basin occurs in the highly permeable deep basalt zone, which in turn is hydraulically connected to the sedimentary layer and intermediate zone. The source of groundwater is primarily infiltrated precipitation. Illian (1970) described the salient features of a three-part groundwater system divided into local, intermediate, and regional flow systems. Notably, the regional flow system identified by Illian (1970) receives recharge from the highest water table elevations in the basin and moves large distances and at great depths (over 3,000 m) before it is discharged in vicinity of Lower Klamath Lake (and presumably also at Tule Lake sumps, which are also at the lowest basin elevations). Leonard and Harris (1974), CDWR (2004), and Gannett et al. (2007) concluded a large part of the infiltrated precipitation seeps downward to the lower aquifer zones and moves as lateral flow beneath the lowlands areas until it is intersected by streams or rivers. When this occurs, such as at the Bonanza Big Springs in the Horsefly ID, the amount of discharge can be considerable.

It is anticipated that the development of new irrigation wells may expand under an environmental water bank program that utilizes groundwater substitution for farms with private pumping facilities. With an expansion in the amount of groundwater being pumped there will likely be localized consequences in the Project and surrounding watersheds (e.g., Butte Valley). However, this study was inconclusive in quantifying the amount of groundwater recharge and the related safe yield, beyond acknowledging that groundwater resources are obviously limited and respond to complex micro-climatic conditions, topography, and hydro-geologic features of the region.

It should be noted that water destination such as “canal seepage” and “irrigation water deep percolation” are not included in the water balance. This is because these destinations are *internal* to the boundaries of interest. Only water paths passing into and out of the boundaries of the defined region are included in the analysis.

3.9.1 Change in Root Zone Moisture Storage

The change in root zone moisture storage and the related change in groundwater storage were estimated on an annual basis based on results from the daily crop and soil evapotranspiration model. The amount of stored soil water at the end of the irrigation season and at the end of the calendar year varies according to climatic conditions, soil classification properties, and agronomic parameters assigned to each modeled crop type. As such, the daily model kept track of the soil root zone depletion amount on a daily basis throughout both the growing season and non-growing season.

The amount and intensity of precipitation in the fall months (October to December) has a major bearing on the relative level of soil moisture present at the end of the year (depending on soil type, crop rotation, vegetative cover, irrigation practices, etc). Therefore, the trends reflected in the change in soil moisture storage largely reflect variations in precipitation during the fall. The amount of fall precipitation dropped sharply in 1999 from the previous year and then increased again in 2000, and then rose substantially again at the end of 2001. The corresponding annual change in root zone depletion in 1999 went from approximately -25 mm to -55 mm (-1 to -2 inches) depending on the crop and soil type, to 40 mm to 75 mm (1.5-3 inches) at the end of 2001. In 2002 and 2003, the amount of fall precipitation dropped by approximately 22% and 12% respectively from the previous year, reflected by the trend downward in root zone moisture storage in those years.

Table 37 summarizes the annual change in root zone moisture storage for agricultural fields within the boundaries of subregions 1-4. A *CI* of 20% was assigned to the change in soil moisture storage to account for the uncertainties associated with modeled estimates of irrigation practices and agronomic parameters, and the true representation of subregional precipitation amounts in localized zones.

Table 37. Annual change in soil moisture in the root zone of irrigated crop areas in subregions 1-4, mcm

Subregion	1999	2000	2001	2002	2003
1	-4	0	6	-3	2
2	-8	-1	12	-4	0
3	-12	5	9	-7	-6
4	-3	-2	6	-2	-3
Total 1-4	**-27**	**3**	**33**	**-15**	**-7**

3.9.2 Change in Groundwater Storage

The annual change in groundwater storage was estimated based on well elevation datasets obtained from the USGS and the CDWR. The fall readings (last measurement of the year available) were plotted in the GIS map sets for all the wells within the boundaries of the water balance. While many observation wells have been installed in recent years and the measurement frequency has increased (especially in 2001), there was a limited number of wells that had consecutive fall readings from 1998 to 2003.

The specific yield approach was used to estimate the change in groundwater storage in each subregion. Specific yield is defined as the volume of water released from a known volume of saturated soil under the force of gravity and inherent soil tensions. It is expressed as a percent of total volume of saturated soil. In an unconfined aquifer, the specific yield is equivalent to the coefficient of storage, which is the volume of water taken into or out of storage per unit of area per unit change in head. Values of the storage coefficient for unconfined aquifers range from 0.01 to 0.30 (dimensionless).

The annual change in groundwater storage was computed as the product of the specific yield and the average groundwater elevation change and the area of each subregion. In the absence of detailed information about the porosity of the tops of the water-bearing formations comprising the primary stratigraphic zones among the occurrence of the water table, a representative value of 10% was selected for the specific yield (Table 5.2, Driscoll, 1986). At any given location, the specific yield will vary due to changes in the thickness of the saturated zone (fluctuations in water table elevation) and hydro-geologic variations in the aquifer structure.

The change in groundwater storage for each subregion was calculated as follows:

$$\text{Change in Volume (ha m)} = \text{Specific Yield (\%)} \times \text{Area (ha)} \times \text{Change in Elevation (m)}$$

3.9.2.1 Groundwater Elevations

There are a large number of observation wells in the study area maintained by the OWRD, the USGS, and others. Each of the subregions was divided into sub-areas to account for localized groundwater influences as reflected by the inventory of well measurements that were collected without interruption during the study period. Representative wells were selected based on information in previous groundwater studies (Leonard and Harris, 1974; Gorman, 1994; Vestra, 2002) and interviews with staff from the OWRD and the USGS who have undertaken a major groundwater study of the entire Upper Klamath Basin (USGS, 2002; Gannett et al., 2007).

Groundwater elevation information in subregion 1 (Langell Valley) was based on data from well KLAM 51922, located near Bonanza Big Springs. The groundwater levels measured at this well appear to be similar to fluctuations measured at other wells in Eastern Lost River Basin and Yonna Valley (Grondin, 2001; Grondin, 2004). For example, the annual fluctuation in groundwater elevation at KLAM 51922 from 2000 to 2001 was -0.94 m (-3.07 ft) (refer to **Table 38**), and at other wells the changes were -0.88 m (-2.88 ft) (KLAM 13353, NW Bonanza), 1.06 m (-3.47 ft) (KLAM 13400, east of Bonanza), and -0.98 m (-3.21 ft) (KLAM 51920).

Table 38. Groundwater elevation change in subregion 1 (well KLAM 51922), m [Land surface elevation = 1,253.78 m]

Item	1998	1999	2000	2001	2002	2003
Groundwater elevation	1252.86	1252.75	1252.58	1251.64	1251.82	1251.78
Year-to-year change	---	-0.11	-0.17	-0.94	0.18	-0.03

Subregion 2 was divided into three sub-areas: a) Poe Valley area, b) Klamath Falls area to the Anderson-Rose area, and c) the area directly north of subregion 3 in the Klamath ID, Shasta View ID, and Malin ID. The partitioning of subregion 3 into 5 sub-areas corresponded to the sub-division used in the *Groundwater Inventory and Preliminary Water Budget* prepared by Vestra Resources (2002). Only 2 monitoring wells are located in subregion 4.

3.9.2.2 Annual Change in Groundwater Storage Volume

Table 39 summarizes the annual change in groundwater storage for subregions 1-4. The annual change in stored groundwater was most significant in 2001 when private pumping for irrigation was substantially increased, and an additional 10 large-capacity irrigation wells were installed along the Stateline in the northern part of Tulelake ID (CDWR, 2004). On average, groundwater elevations declined approximately 3 m (10 ft), although some wells dropped by over 10 m (30 ft) before partially recovering in 2002 and 2003. Gannett et al. (2007) report that in some areas of the Project groundwater levels have fallen by about 4.5 m (15 ft) in years since the 2001 drought.

Table 39. Annual change in groundwater storage in subregions 1-4, mcm

Subregion	1999	2000	2001	2002	2003
1	-3	-4	-22	4	-1
2	20	-4	-67	-10	4
3	-2	3	-34	5	-8
4	2	-11	-24	7	-8
Total 1-4	**17**	**-16**	**-147**	**6**	**-13**

A discrepancy between the groundwater elevations of adjacent wells was noted in a number of cases. The variation in groundwater elevations of adjacent wells may be explained by factors such as the distance, depth, and the presence of different geologic materials in the hydro-geologic zones that the water must flow through. A *CI* of 25% was assigned to these values to account for the uncertainty in estimating the specific yields of particular hydro-geologic units and the approximations of the average elevation changes associated with using a limited number of wells.

3.10 Water Balance Results

A comprehensive water balance was computed for the Klamath Irrigation Project for the years 1999 to 2003. The irrigation water balance provides an accounting of all surface and groundwater volumes that entered or left the boundaries of subregions 1-4 on a monthly and annual basis. The quantitative assessment presented in this research study incorporates detailed information developed for the surface hydrology, climate, irrigation district operations, water measurement, hydro-geology, and farming practices of the Klamath River Basin. The final annual hydrologic quantification in **Table 40** is composed of over 30 separate components, each with an assigned *CI* to reflect the estimated accuracy of the reported values.

3.10.1 Klamath Irrigation Project

The 5-year irrigation water balance framework provides a benchmark description of Klamath Irrigation Project operations in the future. **Table 40** presents the overall water balance results for the Klamath Irrigation Project. The water balance summary table includes the volume of water for each flow path between 1999 and 2003, the 5-year average, the *CI*, and the relative importance of the accuracy of each component as a measure of the relative contribution to the total variance. The monthly water balance summary tables are included in **Appendix 2**.

Total average inflow into the boundaries was approximately 961 mcm (779,000 acre-feet), while total outflow was approximately 1,028 mcm (833,000 acre-feet). Taking into account the mean annual change in surface water storage (-12 mcm; -9,500 acre-feet) and the mean change in groundwater storage (-30 mcm; -25,000 acre-feet), the apparent 5-year average net lateral groundwater inflow to the area was about 23 mcm (18,000 acre-feet). Canal diversions and crop ET_c from agricultural fields are the largest single inflow and outflow components, respectively.

The key points from the Project-level water balance results include:

- There was more than 200% uncertainty in the closure term of net lateral groundwater inflow/outflow, as evidenced by the closure *CI* values. The magnitude of the closure term's *CI* range was approximately 300 to 400 mcm (245,000-319,000 acre-feet), depending on the year.
- The value of the closure term for each year (94 mcm inflow to 47 mcm outflow; -76,000 to 38,000 acre-feet) was within the estimated margin of error of ±20% for just the ET_c from agricultural fields, and nearly within the margin of error of some other individual inflow and outflow components. This is illustrated by **Figure 29**, which shows the estimated annual net lateral groundwater inflow/outflow relative to the mean margin of error in the ET_c from agricultural fields.
- The most important source of uncertainty in terms of the accuracy of the final values was the volume of ET_c from agricultural fields (542 mcm; 440,000 acre-feet) and refuge wetlands (167 mcm; 136,000 acre-feet). Refer to Section 3.11 – *Priorities for Reducing Hydrologic Uncertainty – Relative Importance (RI) of Water Balance Volumes* for an analysis of the relative importance of the accuracy of the water balance components.
- Greater *CI* values were applied to the estimates of evapotranspiration in 2001 (30% vs. 20%, not shown in the table) to reflect the increased uncertainties associated with the use of remotely-sensed satellite imagery to approximate the amount and location of irrigated area in the project. This resulted in a significant increase in the total outflow *CI* in 2001 (18% vs. an average of 12% in the other 4 yrs).

Table 40. Annual water balance of the Klamath Irrigation Project (subregions 1-4), mcm

	Flow Path Component	1999	2000	2001	2002	2003	Avg	*CI*	*RI*
Inflows	Surface Water Diversions	614.21	643.94	237.12	695.20	514.83	541.06	14%	24%
	River and Tributary Flows	241.81	42.70	78.49	40.27	34.19	87.49	15%	1%
	Precipitation	330.90	359.91	286.43	245.24	338.71	312.24	15%	8%
	Groundwater from External Sources	22.33	20.99	20.57	13.37	21.39	19.73	50%	**
	Total	**1,209.25**	**1,067.53**	**622.61**	**994.08**	**909.13**	**960.52**		
	(*CI*)	(9%)	(10%)	(9%)	(11%)	(10%)			
Outflows	ET from Agricultural Fields	577.27	612.83	396.66	556.42	569.27	542.49	20%	52%
	ET from Wildlife Refuges	172.90	171.39	162.86	169.58	159.75	167.30	20%	4%
	ET from Canals	8.91	8.99	4.86	8.49	8.30	7.91	20%	**
	ET from Drains	5.49	5.79	5.76	5.38	5.60	5.60	20%	**
	Evaporation from Open Water	16.07	16.29	17.05	15.58	15.18	16.04	20%	**
	ET from Urban Areas	11.23	11.42	11.96	10.92	10.58	11.22	20%	**
	ET from Undeveloped Areas	53.25	63.80	41.16	47.35	66.05	54.32	20%	1%
	Flow to the Klamath River	478.11	255.63	65.99	156.62	159.54	223.18	23%	11%
	Total	**1,323.22**	**1,146.14**	**706.29**	**970.35**	**994.26**	**1,028.05**		
	(*CI*)	(12%)	(12%)	(18%)	(13%)	(13%)			
Storage	Change in Surface Water	-10.28	-9.08	-17.80	-10.88	-10.58	-11.72	4%	**
	Change in Soil Moisture	-27.04	2.62	33.32	-15.43	-7.18	-2.74	20%	**
	Change in Groundwater	17.34	-15.90	-146.50	6.35	-12.88	-30.32	25%	**
Closure	**Net Lateral Groundwater Inflow/Outflow (‘-’ *is net inflow*)**	**-93.99**	**-56.25**	**47.31**	**43.70**	**-54.50**	**-22.75**		
	(*CI* ±range)	**(-291 to 103)**	**(-233 to 121)**	**(198 to -104)**	**(206 to -119)**	**(-209 to 100)**			

** *RI* < 1%

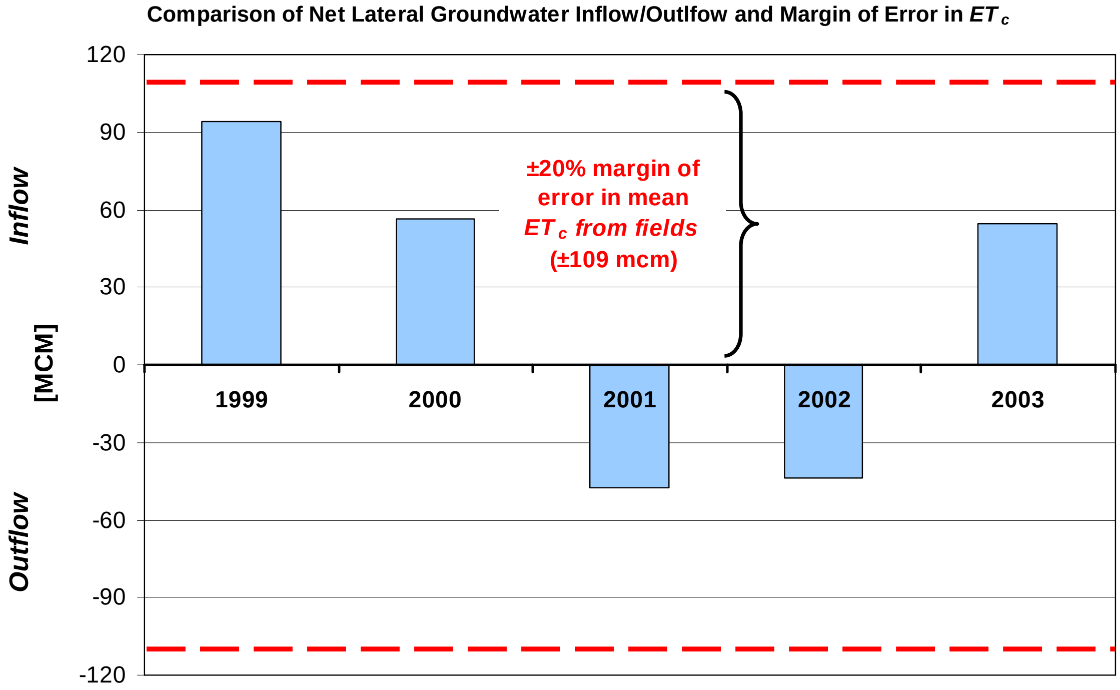


Figure 29. The closure term of net lateral groundwater inflow/outflow is less than the magnitude of the margin of error in the calculation of mean ET_c from agricultural fields.

- The inflow *CI* values ranged from 9% to 11%, which is equivalent to a margin of error of about ±83 mcm (±67,000 acre-feet) on average.
- River and tributary inflows to the study area, not including the Lost River system at the Malone Diversion Dam, contributed only about 5% on average of the total surface inflows. While this assessment attempted to account for all surface flows into the Klamath Irrigation Project, a complete field survey wasn't conducted of all the minor tributaries, particularly those in subregions 2 and 3.
- The outflow *CI* values ranged from 12% to 18%, which is equivalent to a margin of error of about ±137 mcm (±111,000 acre-feet) on average.
- ET_c from agricultural fields was the largest single water balance component in all years, averaging approximately 542 mcm (440,000 acre-feet) between 1999 and 2003.
- ET_c from agricultural fields and wetlands accounted for about 49% of the total outflows in the years before the drought. This value increased to over 56% in 2001 and subsequent years as the volume of surface water leaving the boundaries of the Klamath Irrigation Project dropped substantially.
- The net Lost River Diversion Channel flow to the Klamath River contributed about 20%, or about 250 mcm (203,000 acre-feet), of the total surface outflows in 1999 and 2000, primarily occurring from September to March. In 2001 and afterwards, the average annual outflow contribution dropped to 7%. During the irrigation season, the average net inflow to the Lost River Diversion Channel (from the Klamath River and Upper Klamath Lake) between 1999 and 2005 was approximately 46 mcm (37,000 acre-feet).

- The relatively large change in soil moisture storage in 2001 is explained by several factors. Precipitation in November and December of 2001 was over 100% greater than the same winter time period in 2000. In addition, the dramatic reduction in cropped area (600% more fallowed fields compared to 2000) resulted in substantially less consumptive use (*ET*). (Note: the water shortage in 2001 resulted from crisis-level surface water supplies and was not due to a localized precipitation drought; refer to Section 3.4.2 – *Precipitation*).
- The results of the annual water balances apparently indicate that in 1999 and 2000 there was an average net lateral groundwater inflow of about 75 mcm (61,000 acre-feet) to the study area. In 2001, the drought year, there was a net lateral groundwater outflow of approximately 47 mcm (35,000 acre-feet). This trend continued in 2002 (44 mcm; 34,000 acre-feet) before reversing to a net lateral inflow in 2003 (55 mcm; 44,000 acre-feet). However, the magnitudes of the *CI* values of the closure terms mean that the actual net recharge or discharge contribution of lateral groundwater flow was uncertain.

3.10.2 Subregional Water Balances

The subregional water balances provide an accounting of all surface water and groundwater volumes that entered or left the boundaries of subregions 1-4 on an annual basis. The annual water balances for each subregion are included in **Appendix 3**. The water balance tables include the volume of water for each flow path between 1999 and 2003, the 5-year average, the *CI* for each component, and the relative importance of the accuracy of each component as a measure of the relative contribution to the total variance.

The key points from the subregional water balances include:

- There is over 100% uncertainty in the closure terms for all subregions for all five years.
- In most instances, the closure term *CIs* of the subregional water balances are greater than the corresponding closure term *CIs* in the overall water balance for the Klamath Irrigation Project. This indicates that the measurements taken at monitoring stations as inter-boundary sites between irrigation districts are not as accurate as those on the external boundaries of the project.
- With the exception of subregion 1, the total inflow *CIs* are much greater than those in the overall Project water balance, ranging from 6% to 49%. This is primarily due to the large uncertainties associated with the measurement of surface water diversions and return flows that occur between irrigation districts (flows that are internal to the overall Project water balances – see previous point).
- Unlike in the overall Project water balance, the volume of ET_c from agricultural fields is not always the single largest water balance component. The only exception is subregion 3.
- In all cases, the total outflow *CI* values are substantially greater than those in the overall Project water balance, ranging from 12% to 35%. This is equivalent to a margin of error of about ±48 to ±149 mcm (±39,000-120,000 acre-feet), respectively.
- The water balance components with the largest margin of error were the following: i) the upstream drain flows from Klamath ID to Tulelake ID (up to ±199 mcm; ±162,000 acre-feet), the Lost River flow at Harpold Dam (up to ±147 mcm; ±119,000 acre-feet), and iii) the Lost River Diversion Channel outflows to the Klamath River (up to ±112 mcm; ±91,000 acre-feet).

3.11 Priorities for Reducing Hydrologic Uncertainty – Relative Importance (*RI*) of Water Balance Volumes

The relative importance (*RI*) of the accuracy of each water balance component was ranked to determine the recommended priorities for improving future water balances and hydrologic investigations. A variance analysis of the annual water balance volumes provides a useful indication of the relative influence of the accuracy of each component on the accuracy of the overall closure values. The estimated accuracies of each water balance quantity are expressed in terms of the assigned *CI* values summarized in **Table 40**. Computed multi-parameter *CI* values for the total inflow and total outflow sums are shown as percentages, and for the closure term, the equivalent *CI* values are summarized in the bottom row of the water balance tables in terms of the range of (±) values around the annual mean.

The *RI* of the accuracy of each flow path component, as it relates to the final water balance, is computed as:

$$\text{Relative Importance} = \frac{100 \times \text{Variance of the Component}}{\text{Sum of all Component Variances}}$$

where

$$\text{Variance of a component} = \left[\frac{\text{CI}}{2} \times (\text{Average m}_\text{i})\right]^2$$

Average m_i = the average of the annual values of a water balance component

Table 41 shows the Klamath Irrigation Project water balance components with a *RI* of uncertainty of more than 0.5%. The combination of the ET_c volumes from agricultural fields and refuge wetlands together accounted for about 60% of the total variance.

Table 41. Ranking of the relative importance (*RI*) of the uncertainty of various Project-level water balance components (above 0.5%) as a percentage of the overall variance

Water Balance Component	Relative Importance
Agricultural fields ET_c	52%
Ady Canal	19%
Precipitation	8%
Lost River Diversion Channel (inflow/outflow)	8%
Refuge wetlands *ET*	4%
North Canal	4%
Straits Drain	3%
A Canal	1%
ET from undeveloped land	0.5%

Figure 30 shows the variance components for the Klamath Irrigation Project water balance with the *RI* of the accuracy of the various mean water balance quantities.

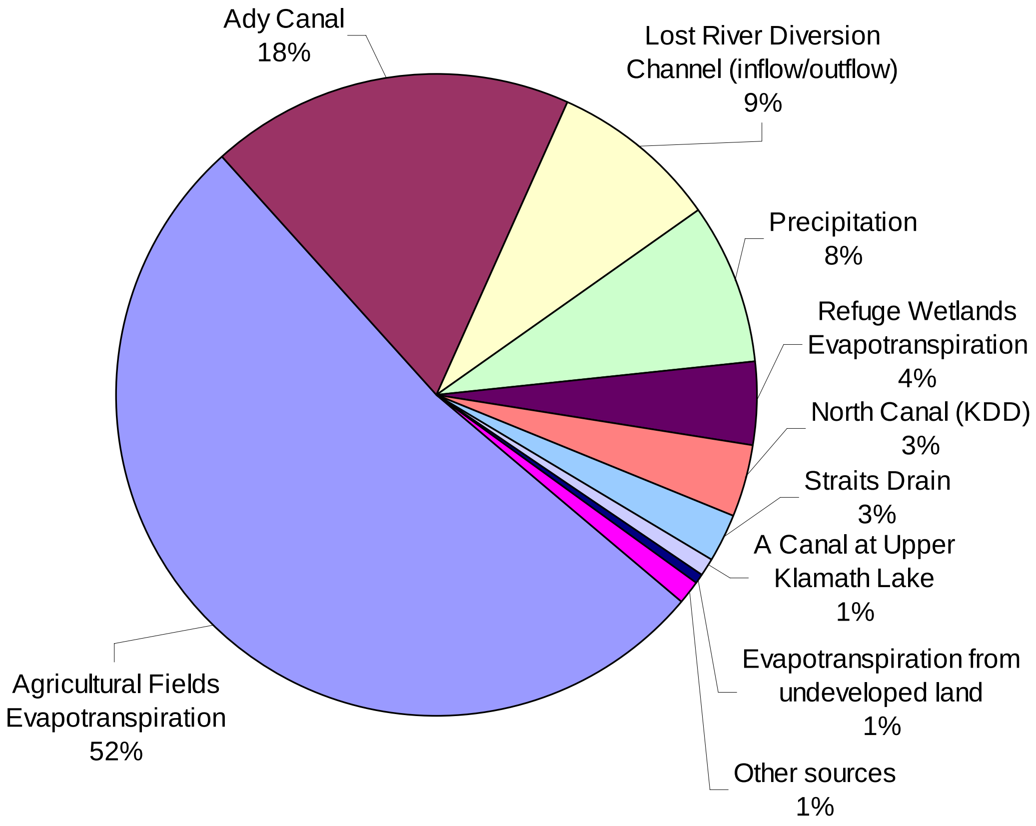


Figure 30. Variance components (*RI*%) for the annual water balance parameters

The *RI* gives an indication where further investment is recommended to improve the accuracy of a water balance. One cannot evaluate the significance of the known accuracy of a single water balance component based solely on the assigned *CI*.

Take, for example, the estimate of the annual change in groundwater storage in **Table 40**. This had an assigned *CI* of 25%, meaning that the change in groundwater storage was only known within ±25%. However, the change in groundwater storage only had a 0.2% impact on the accuracy of the final values in the water balance, thus accounting for a very small fraction of the overall variance. This may be considered almost negligible when compared to the overall accuracy of the Project-level water balance computations. This further indicates that additional investment would be more beneficially directed towards improving the accuracy of other water balance components with a higher *RI* (e.g., better *ET* estimates from upgraded and expanded weather station networks and more accurate information on irrigation practices and crop factors).

$$\mathrm{RI}_{\text{groundwater storage}} = \frac{\left[\left(\frac{0.25}{2} \times (30.32) \right)^2 \right]}{6,471} \times 100\% = 0.2\%$$

3.12 Availability of Irrigation Water for Conservation

The estimated Klamath Irrigation Project water supply for irrigation and wildlife refuges is provided by the USBR in their Operations Plan and through pre-season consultations with irrigation district managers and stakeholders. As the largest diverter of freshwater in the Upper Klamath Basin, the irrigators in the Project are in the position of being able to possibly contribute substantial amounts of water to regional water conservation goals. A question inherent in the prospect of reducing irrigation diversions to the Project are the impacts to irrigated agriculture that may result (Davids Engineering Inc., 1998; Braunworth et al., 2002). The scope of any negative consequences depends in large part on the magnitudes and timing of inefficiencies in water use, if any exist.

The results of Project-level irrigation efficiency calculations for the 5-year study period indicate that traditional water conservation activities such as improved field irrigation efficiencies and canal lining would not make significant amounts of water available for other uses (refer to **Table 43**). This assessment that integrated water use patterns within the various subregions of the Klamath Project over a range of hydrologic conditions concludes that almost all district conveyance and on-farm inefficiencies are recycled internally within the system. The resulting performance indicators that occur in individual subregions show distinct patterns of irrigation diversions and consumption; however, the hydraulic nature of the system corrects for subregional reductions in efficiency because of the extensive ability to reuse return flows.

The main finding of this multi-year hydrologic analysis is that the proper frame of reference for water conservation goals should aim at reducing *ET* through targeted decreases of under-performing agricultural areas and marginal units in wildlife refuges. There are several mechanisms available for Project water users to increase flows to the Klamath River during critical late summer months in order to meet mandated ESA requirements and to contribute to broader ecosystem restoration. These mechanisms primarily include the establishment of a Project-level water bank involving land idling through forbearance of surface water deliveries or groundwater substitution. *Quantifying* accurately the potential water conservation benefits of irrigated lands in terms of ET_{iw} – the net amount of diverted water that is consumed on agricultural fields – is therefore necessary as the first step for assessing the real potential of a water bank's impact on water availability and use in the Klamath River Basin.

3.12.1 Reducing the Evapotranspiration of Irrigation Water (ET_{iw}) - Agricultural Fields

To quantitatively assess the potential for water conservation from agricultural fields in the Klamath Irrigation Project, the evapotranspiration of irrigation water (ET_{iw}) was estimated based on an analysis of the crop water modeling results. The difference between the full-season ET_c (refer to **Table 26**) for the reported cropped areas (refer to **Table 7**), and the estimated *ET* from a hypothetical comparable area of fallow fields represents an approximation of the irrigation water component of *ET*.

$$ET_{iw} = ET_c - \left(ET_f \times \text{Crop Area}\right)$$

where the ET_c is the total volume of evapotranspiration from the irrigated fields (all crop types) (mcm); ET_f is the modeled depth of evapotranspiration from a bare soil field that receives no irrigation water (m); and crop area is the amount of hypothetical fallowed fields, in this case the entire annual irrigated area in the Project.

Using this approach, the annual ET_{iw} averaged 393 mcm (318,000 acre-feet) for the 5-year period, with over a 40% reduction in 2001 due to the imposed irrigation curtailment. As a result of conditions in 2001, the ratio of total ET_c from agricultural fields that came from irrigation water dropped about 20% in 2001 to 0.55, compared to a 4-yr non-drought mean of 0.76. Some protective irrigations were applied to pasture and grain fields in 2001 to maintain viable cover crops, but yields were minimal, except on soils with very high water-holding capacities (Braunworth et al., 2002).

Several factors combine to determine the relative per hectare consumption of irrigation water on individual fields including the soil type, the presence of residual soil moisture, the timing of localized rainfall relative to crop growth stage, crop characteristics, and irrigation method. On a Project-wide basis, the annual ET_{iw} was about 0.56 ha m per ha (1.8 acre-feet/acre). Irrigated fields with alfalfa and pasture, the predominant crop types, averaged an ET_{iw} in non-drought years of approximately 0.62 and 0.66 ha m per ha (2.03 and 2.15 acre-feet/acre), respectively. Field crops (e.g., peppermint, horseradish, vegetables) had a mean non-drought ET_{iw} that was about 40 % lower (0.38 ha m per ha; 1.25 acre-feet/acre) than alfalfa and pasture. Variations in ET_{iw} of about 10% were also evident between the different subregions, which represents the combined impacts of localized rainfall variations, soil types, and differences in farm management practices.

Figure 31 shows mean irrigation surface diversions in non-drought years compared to the estimated ET_{iw} on a monthly basis. The two curves – representing the volumes of beneficial consumptive use and surface water supplies – track very closely for most of the year, even overlapping when the *CIs* in the data were considered. As indicated by the graph, surface diversions increase beyond consumptive use in the fall period when the wildlife refuges take water to fill seasonal wetlands units. The figure also shows the impact on ET_{iw}, of the irrigation cut-off in 2001 including the midseason emergency release of 49 mcm (40,000 acre-feet) to the Main Division as shown by the inflow spike in August.

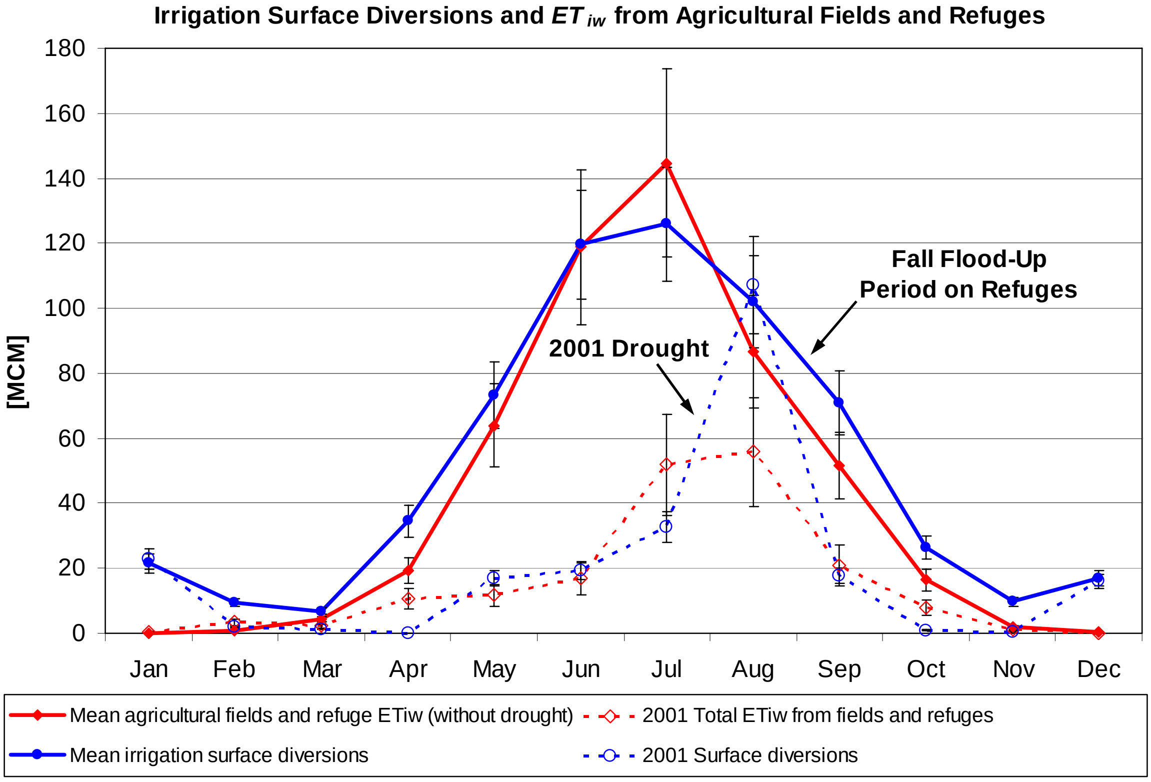


Figure 31. Net irrigation surface diversions and the ET_{iw} of agricultural fields and wildlife refuges

Table 42 summarizes the estimated ET_{iw} between 1999 and 2003. In below-average to above-average water year types during this time period, irrigation water contributed over 75% of total ET_c. The analysis indicates that in drought years effective precipitation contributes overall between 40 and 50% of the total ET_c, although on a field-by-field basis the contribution of rainfall varies widely depending on the number, if any, and scale of applied irrigations. The crop water use model kept track of antecedent soil moisture conditions at the beginning of the season – presumably an important contributor to the *ET* from fields that would be fallowed in the initial year of an extended drought.

Table 42. Evapotranspiration of irrigation water (ET_{iw}) from agricultural fields in the Klamath Irrigation Project (subregions 1-4), mcm

Subregion	1999	2000	2001	2002	2003	Mean
1	76.30	79.55	79.81	76.93	71.89	76.90
2	159.97	165.04	48.48	163.54	134.76	134.36
3	143.33	141.91	66.31	139.79	130.36	124.34
4	64.95	69.96	24.70	64.31	61.59	57.10
Total	444.55	456.45	219.30	444.56	398.61	392.69
ET_{iw}/ET_c	**0.77**	**0.75**	**0.55**	**0.80**	**0.70**	**0.72**
ET_{iw}/ha [m]	**0.59**	**0.60**	**0.39**	**0.61**	**0.57**	**0.56**

3.12.2 Irrigation Performance Indicators

3.12.2.1 Project-Level Irrigation Efficiency (*IE*) and Irrigation Sagacity (*IS*)

The fundamental engineering definition of "efficiency" is an output divided by an input. The definition of irrigation efficiency (Burt et al., 1997) is:

$$IE = \frac{\text{volume of irrigation water beneficially used}}{\text{volume of irrigation water applied - }\Delta\text{ storage of irrigation water}} \times 100$$

The *IE* denominator represents the total volume of irrigation water (beneficial and non-beneficial) that flows <u>into</u> the defined boundaries (outflow = applied - Δ storage). The boundaries may be defined as a field, farm, irrigation district, project or river basin. Burt et al. (1997) provide the basic definition of "beneficial" use as one that supports the production of crops, but caution that a common source of error is confusion over "actual" vs. "theoretical" beneficial uses. The "irrigation water" term in the *IE* equation excludes precipitation. The *IE* varies with each water application event throughout the growing season, and with location, soil type, and application system.

While the computation of *IE* for an irrigation project is a useful measure of the performance of the system, it is incomplete in relation to water rights granted on the basis of beneficial *and* reasonable use (Solomon and Burt, 1999). Further benefits that are not adequately captured strictly by a comparative analysis of *IE* may be derived from the applied irrigation water (for example, to support riparian habitat). A complementary term *irrigation sagacity*, with "sagacious" meaning wise or prudent, has been introduced (Solomon, 1993) to account for reasonable uses that may not be strictly beneficial (crop evapotranspiration, leaching, etc.) but are justified under particular conditions (Burt et al., 1997; Solomon and Burt, 1999).

Irrigation sagacity (Burt et al., 1997) is defined as:

$$IS = \frac{\text{volume of irrigation water beneficially and/or reasonably used}}{\text{volume of irrigation water applied - }\Delta\text{ storage of irrigation water}} \times 100$$

Implicit in the consideration of *IS* is the awareness that a perfect efficiency (*IE*=100%) is neither possible nor reasonable due to the economics, weather variability and uncertainty, physical limitations of irrigation systems, and scheduling uncertainties associated with even the best techniques for deciding when and how much to irrigate.

To judge the performance of the Project from an efficiency standpoint, the fraction of irrigation water used for crop production in a specified time period has to be estimated as described in the previous section. The water balance quantities and destinations define the inter-relationships of reasonable and beneficial uses at the Project-level and subregional-level. The standard definition of *IE* represents the ratio of the volume of irrigation water consumed by crops – a beneficial use – to the volume of irrigation water diverted into the water balance boundaries. An estimation of the Project-level efficiency as a performance criterion expressing the overall effectiveness of the Project and its management is provided by:

$$IE = \frac{ETiw}{\text{Project Surface Diversions}} \times 100$$

The mean *IE* computed on an annual basis for the service area covered by subregions 1-4 over the 5-year study period was approximately 86% with a calculated *CI* of ±25%. The range of annual *IE* values was 75 to 100%. **Table 43** summarizes the annual *IE* estimates integrated over subregions 1-4 between 1999 and 2003. The mean overall *IE* for the study period was relatively high compared to many irrigation systems, although this is largely a function of the reuse of return flows internally within the irrigation districts. If one includes other non-beneficial but reasonable uses of diverted irrigated water – canal and drain evaporation, a portion of surface discharge, etc. – the mean Project-level *IS* increases to 90-95%. The *IS* term is a measure of prudent water use considering beneficial and reasonable uses of irrigation water as justified under prevailing conditions (Solomon and Burt, 1999).

Table 43. Annual irrigation efficiency (*IE*) on a Project-level basis, %

Year	*IE* [%]
1999	84%
2000	83%
2001	100%
2002	75%
2003	91%
Mean	86%

In a study of long-term Project efficiencies, Davids Engineering (1998) demonstrated that during wet years *IE* values tended to decline as diversions increased more than consumptive use. In contrast, in dryer water years, efficiencies tend to be higher in the Project. The situation in 2001 confirmed this to be the case. Several reasons for the *IE* of 100% in 2001, and other previous water-short years, include irrigators temporarily adopting water-conserving strategies at the farm-level and the increased use of groundwater as a substitute for replacing surface supplies. In severe droughts, like the one in 2001, besides the increase in groundwater pumping there is extensive use of soil moisture carried over from the previous year.

The use of *IE* as an indicator of performance at the subregional level has significant limitations. In subregion 1, the diversion points – North Canal, West Canal and East Canal – are clearly defined. However, the computation of *IE* for subregion 1 in isolation would not capture the consumption of reused irrigation water (a beneficial use at a Project-scale) that returns to the Lost River system and is pumped by downstream irrigators in subregions 2 and 3. This is also the case with the relatively disproportionate diversions by Klamath ID (subregion 1), compared to the amount of consumptive use within its service area, even though this is a key operational aspect of the management of its canal system. Variations in the pattern of Project-level *IE* can also be observed on a monthly basis when in the early part of the season the percentage of diversions is relatively high, compared to *ET*, because water is being used to replenish soil moisture.

3.13 Impact of Agricultural Water Conservation on Water Availability

Water demands in the Upper Klamath Basin for irrigation, species conservation and habitat protection, commercial fishing, recreation, and tribal rights exceed available supplies, even in relatively wet years. The water resources available for irrigators and wildlife refuges in the Project depend on stream flows from melting snows upstream of the Project's boundaries and the annual recharge of groundwater. Even in wet years, the water resources of the Basin are stretched and all the committed allocations cannot be met. The water balance prepared in the previous sections presents a comprehensive analysis of flow destinations and quantities from multiple sources used for the irrigation of agricultural crops and ecological services (wetlands). Reduced demand for irrigation water would translate into a reduced volume of diverted water equivalent in a conceptual sense to the amount of ET_{iw} – the reduction in the water supply required to irrigate the fields can be transferred as a reduced demand to the Basin up to the amount of consumptive use.

On average, approximately 617 mcm (500,200 acre-feet) of irrigation water was diverted into the Klamath Irrigation Project in non-drought years between 1999 and 2003, which is consistent with long-term operations (Davids Engineering Inc., 1998; USBR, 2000). During the same time period, approximately 739 mcm (599,400 acre-feet) was consumed by *ET* from farmland and wetlands, in addition to the evaporation from the Project's extensive network of canals, drains, and storage reservoirs. Domestic and municipal use of surface water in the Project is negligible.

Although the achievements of irrigation in the Project have been impressive in terms of agricultural production and rural welfare, the traditional measures of irrigation performance such as *IE* or other efficiency terms are insufficient by themselves to capture the basis for water conservation or water quality improvements. Maintaining current irrigation practices in the Project will lead to worsening environmental and economic consequences. A sustainable and cost-effective solution, or set of solutions, involving reallocations of water resources will place a strong emphasis on conserving water either through growing crops with less irrigation water through improved farming practices or fallowing of less-productive farmland. However, the volume of water to be gained by improving farm-level efficiencies is relatively small as indicated by the high Project-level *IE* values, although water quality enhancements would result from reducing deteriorated return flows to the Klamath River. Such conservation efforts will require informed cooperation among irrigators, the Tribes, environmental stakeholders, and fishing interests.

The purpose of this detailed agro-hydrological investigation was to analyze the quantitative basis for possible alternative modernization solutions. Accurate estimates of crop water use, irrigation water use, and other water balance parameters aid in the decision analysis for water resources planning. Hydrologic relationships provide a physical basis to evaluate water availability conditions. The water balance analysis has provided benchmarks for the formulation of strategic management scenarios in the multi-criteria analysis that aim to ensure the environment is restored while agricultural production continues in the future at a sustainable level.

The results of this comprehensive analytical framework are encapsulated in **Figure 32**. The graph shows the equivalent area of the major crop types grown in the Project that would have to be idled (or served with substituted groundwater) in order to meet future water conservation targets ranging from roughly 10 to 140 mcm per year (10,000-110,000 acre-feet/yr), from all sources based on proposed benchmarks in the biological opinions (NRC, 2004). Nevertheless, the expansion of fallowed areas has physical and managerial limits. At present, annual field crops such as vegetables and potatoes represent less than 10% of the cropped area. The water balance assessment indicates that in theory if half of the crop areas that have the biggest relative consumptive use (ET_{iw}), pasture and alfalfa, were idled it would provide about 135 mcm (110,000 acre-feet). However, this is probably an unrealistic scenario, without also considering other possible sources of contributions, because it's very unlikely that the irrigation districts would be able to continue operating if half of their major crops were no longer supplied with Project water.

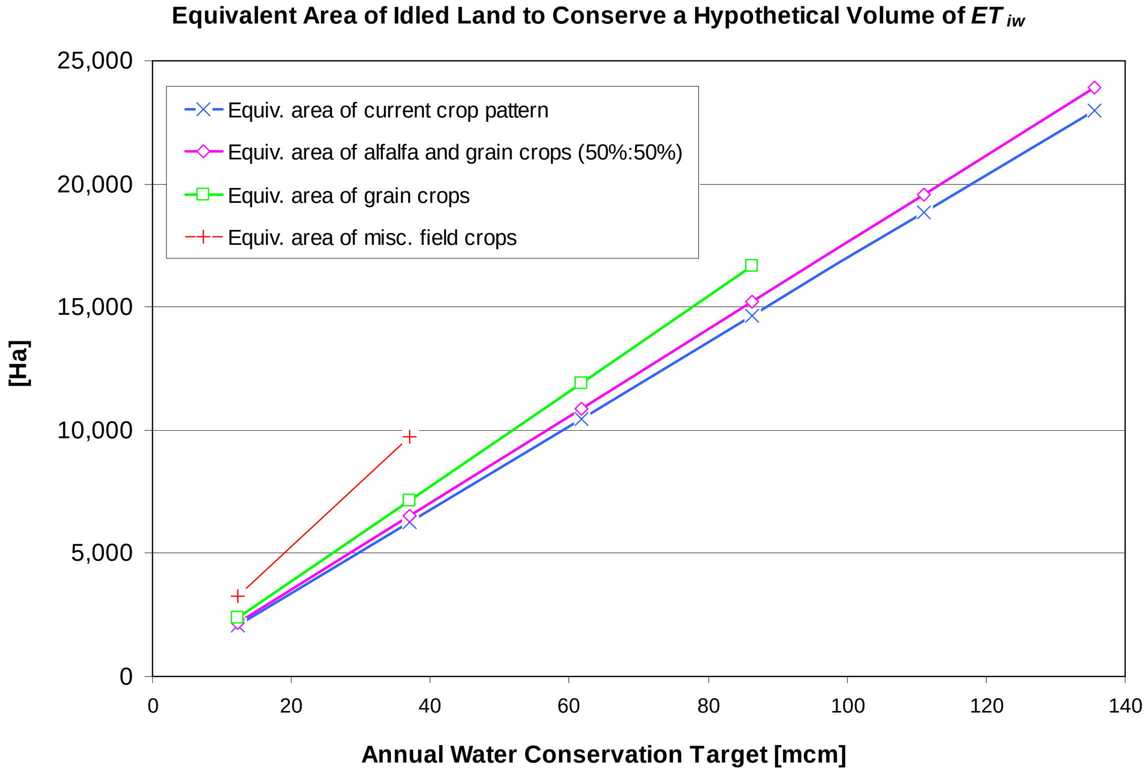


Figure 32. Water conservation targets met through a reduction in the area of irrigated fields

The main argument of this chapter is that relatively limited gains for water conservation objectives are possible solely from water management improvements, even though it was recognized that the Project has significant return flows that impact water quality in the Klamath River. Water available for reallocation may be obtained from irrigated fields in the amount of ET_{iw} only because unrecoverable losses are comparatively small. Additional water available for reallocation would meet urgent water needs in the Klamath River Basin.

4 The Multi-Criteria Model in a Technical Modernization Project Context

In irrigation engineering, designers and planners are often faced with decisions involving conflicting objectives and tradeoffs. Decision-makers in irrigation projects may be confronted with opposing needs and overwhelming, but uncertain, supporting information when faced with having to decide how to best use limited resources. A driving force of modernization projects is the attempt to model the abstraction and delivery of water in large-scale canal systems on *controlled industrial processes* (Burt, 2000). This recently conceptualized perspective integrates the environmental concerns of various members of society with the economic concerns of farmers and producers, placing rigorous demands on engineers whose expertise may have been limited to conventional technical methods. Water resources planning for modernization interventions in irrigation projects may have to address potentially conflicting objectives such as increasing water use efficiency, decreasing ecological harm, enforcing safety standards and labor laws, and improving economic returns to irrigators. The development of a decision analysis framework for assessing wide-ranging technical and socio-economic criteria will assist in promoting irrigation modernization and the effective use of modern water control and measurement technologies.

The ranking of alternative modernization strategies is challenging because there is no single criterion that captures the true impact of each project and there is no single decision-maker. Irrigation modernization projects (alternatives) also have to be designed and engineered for the specific hydrological characteristics, existing infrastructure, and management capabilities in the project area. Robust technical analysis of alternatives thus requires scientific methodologies and suitable tools to support multiple decision criteria involving a variety of stakeholders.

4.1 Modernization Criteria Assessment and Project Ranking: A Strategic Approach

Modernization criteria were developed in this study as a tool to aid decision-makers in assessing the most appropriate strategy among alternative modernization projects. The purpose of this modernization criteria assessment was to generate potential engineering solutions to satisfy conflicting objectives in the case study of the Klamath Irrigation Project, which was selected as a representative example of future water conflicts in the western U.S. and elsewhere. Due to the fact that both environmental and agricultural concerns are affected by the diversion and utilization of water resources in the Project, a compromise must be achieved to resolve the conflict. This strategic approach considered a real application of project selection methodology in terms of predicted performance in regard to water conservation goals. This methodology is a specific application of *multiple criteria decision analysis* (MCDA).

MCDA is the general field of management science and decision analysis that involves decision-making in the presence of two or more conflicting objectives and/or involving processes with two or more attributes in a structured and systematic manner (Tecle and Duckstein, 1994). The general objective is to assist decision-makers in selecting the best alternative from a range of alternates in a multi-dimensional environment. MCDA methods differ in the way multiple criteria are assessed, the application and computation of weights, the mathematical algorithms utilized, how preferences are operationalized, the level of uncertainty in the dataset, and the ability of stakeholders to participate in the decision-making process (De Montis et al., 2000). Effective use of any MCDA method in the proper analytical context requires an understanding of the assumptions and inherent limitations of the selected approach (Roman et al., 2004).

Applied to the problem of ranking alternative modernization strategies, the process incorporates the following key basic steps:

- Structuring decision-making in terms of explicitly defined evaluation hierarchies of modernization indicators (decision criteria)
- Evaluation of project-alternatives in terms of the extent to which they satisfy each of the identified decision criteria
- Aggregation across decision criteria to generate a measure of the extent to which each modernization project-alternative satisfies the overall goals represented by the decision criteria

Input data consists of hydrologic, agronomic, and economic information. While the principal aim is not to find a "perfect" solution (Klawitter, 2003), the process of applying a distance-based procedure called "composite programming" (Bardossy et al., 1985) should create basic agreement between different stakeholders on the evaluation criteria, properly reflect the influence of their preferences, and systematically explain the tradeoffs associated with varying degrees of irrigation modernization.

4.1.1 Decision Analysis in Water Resources Planning

A large number of multi-criteria decision-making approaches have been developed and applied for different policy purposes in diverse contexts. According to Roman et al. (2004) there are over 70 multi-criteria decision-making methods that have thus far been proposed in the literature. MCDA has hundreds of applications in natural resources management (for a review of agricultural resources management applications see Hayashi, 2000). Different multi-criteria analysis techniques have been applied to a range of water resources planning issues: water allocation conflict (Bella et al., 1996); optimal cropping patterns to preserve groundwater aquifer sustainability (Salazar et al., 2005); evaluation of urban surface drainage options (Scholes et al., 2004), pollution control (Giupponi and Rosato, 2002); project ranking of hydropower investments (Buchanan et al., 1999); selection of wastewater management alternatives (Tecle et al., 1988); assessment of urban water pricing (Klawitter, 2003); management of groundwater (Pietersen, 2006); and appraisal of large dam projects (Petersson and Giupponi, 2004).

There are many MCDA methods that could be used for any given water resources problem. MCDA techniques approach the analysis of multi-objective problems in a variety of ways (Őzelkan and Duckstein, 1996; De Montis et al., 2000; Roman et al., 2004). Each MCDA method has inherent strengths and limitations depending on the specific problem situation and parameters such as the type of data allowed, the cost and time intensity involved, and the possibility for facilitating communication in group decision-making, among many other factors; therefore, an assessment of the appropriate method as a decision tool should be based on quality criteria (De Montis, 2000; Roman et al., 2004).

Some desirable characteristics (quality criteria) in the context of modernization decision analysis for water resources planning include:

- Extended participation of stakeholders in the decision process
- Transparency and openness
- Allowance for the interdependence of criteria
- Capacity to consider both societal and technical problems
- Ability to consider uncertainty

4.1.2 Compromise and Composite Programming

Compromise programming is a distance-based technique that attempts to find a feasible solution from a set of alternative solutions by the closest measure of distance to an ideal (infeasible) solution (Prodanovic and Simonovic, 2003). Compromise programming has been extensively documented and studied in water resources literature including the work of Őzelkan and Duckstein (1996), Bella et al. (1996), Bender and Simonovic (2000), Raju et al. (2001), and Salazar et al. (2005).

In application, the technique obtains a compromise solution that is as close as practically possible to the maximum obtainable solution given the features of the problem through ranking alternatives by resolving decision criteria into a commensurable, unitless, distance metric valid for the selected weights (Bender and Simonovic, 2000). In mathematical terms the distance metric can be presented as:

$$L_z = \left[\sum_{i=1}^{t} \left\{ \omega_i^p \left(\frac{f_i^* - f_i}{f_i^* - f_i^-} \right)^p \right\} \right]^{\frac{1}{p}}$$

where	L_z	distance metric of alternative z
	i	1, 2, 3…t and represents t criteria
	f_i	actual value of criterion i
	f_i^*	best value for criterion i
	f_i^-	worst value for criterion i
	ω_i	corresponds to a weight of a particular criteria, indicating relative importance of a criterion
	p	exponent parameter ($p = 1, 2, \infty$)

The parameter ω_i captures preferences concerning the relative important of criterion i, reflecting differences in viewpoints of the decision-makers.

The parameter p represents the degree of compensability of the criteria in terms of the importance of the deviation from the ideal point. Varying the value of p from 1 to infinity allows the decision-maker(s) to move from perfect compensation among the criteria ($p = 1$) to no compensation, in which case alternatives are ranked lower when one or more criteria have extremely low degrees of achievement. In general, the greater the conflict there is among the multiple stakeholders (decision-makers), the smaller the allowable compensation becomes.

Bardossy et al. (1985) and Bardossy (1988) formulated composite programming as a hierarchical extension of compromise programming. In the proposed hierarchy, the main objective resides at the highest level, with the lower levels containing groupings of sub-criteria (degree of achievement) of the parent or previous levels. In ranking alternative projects, for each level a compromise solution is solved for the maximum or minimum criteria value, which is then used as an input to the next level.

The composite programming approach permits comparison between alternatives on different levels, either based on the total composite value that the alternative can achieve or by comparing the values of the grouped indicators. The advantage of the composite technique lies in the fact that it makes clear for decision-makers the relative tradeoffs between major indicators. Each group of sub-criteria (or indicators) are assigned a weight (ω) by technical or preferential grounds and compensation factor (p) defining the degree to which individual groupings or indicators can compensate for each other. The ranking of composite indicator achievement in cascading groups for different alternatives is determined according to:

$$I_k = 1 - \left[\sum_{j=1}^{J} \left\{ \alpha_k \left(1 - n_{kj}\right)^{p_k} \right\} \right]^{\frac{1}{p_k}}$$

where I_k indicator ranking for the criteria in group k
n_{kj} value of indicator j normalized between 0 and 1
α weighting factor for the criteria j in group k
p compensation within group k

The final index value based on the composite programming analyses at each successive level yields an overall ranking of alternative scenarios.

4.1.3 Decision-Making Context

Although irrigated agriculture remains a key component of the economy of places as varied as California and India, large financial resources are required to maintain existing infrastructure and construct new infrastructure to comply with environmental needs in both industrialized and rural societies (Keller, 2000; Postel, 2000; Molden, 2007). Irrigation modernization projects, including those designed explicitly to conserve water for environmental purposes, are likely not possible if no extra public resources are made available, particularly in competitive agricultural markets, because necessary changes have significant costs associated with them. Thus, public policy involves weighing different levels of investment with achievable outcomes.

These public investment resources probably won't be made available if there have not been sustained technical and scientific studies demonstrating the existence and impacts of the water resources problem(s). For example, although increasing water efficiency is frequently promoted, its real outcome may or may not benefit long-term ecological restoration. The quantitative analyses in Chapter 3 – *Conceptualizing Limitations on Resources Availability for Water Conservation* provided baseline information about project-level irrigation efficiencies and the related achievable water conservation quantities. Local agencies (e.g., water districts) may apply for public funding (e.g., water conservation grants) by presenting suitable projects, particularly those with detailed engineering justification that the project is technically feasible and the results can be quantified. So in addition to demonstrating that a problem exists, the engineering analysis of modernization projects has to establish how implementation will contribute to regional goals. The multi-dimensional decision context in the present study acknowledges that a given amount of public funds will need to be made available, all the while recognizing that some solutions may be preferred if they meet environmental goals regardless of costs.

The multi-functional nature of irrigated agriculture in large river basins poses particular planning problems because irrigation operations are complex and may positively or negatively affect water resources objectives differently at varying spatial scales. Potential solutions may also be constrained by the local water district's willingness or ability to invest in new projects, which in turn affects farmers' selection of irrigation methods and farm-level water management practices. As Burt (2004) notes, the innovativeness of individual farmers has a large impact on whether or not they will move towards new technologies.

Four groups of decision-makers were identified for the evaluation of irrigation modernization project-alternatives in the Klamath Irrigation Project, namely: (1) those who prioritize technical solution delivery, (2) those who prioritize ecological sustainability, (3) those who prioritize ecological sustainability and conformance with strategic mission, and (4) those who give technical solutions, ecological sustainability, and conformance with strategic mission equal importance (refer to **Table 44** in Section 4.3.1 – *Selection of Evaluation Objectives*). These distinct opinions are reflected by the three sets of criterion weights (refer to Section 4.3.4 – *Formulating the Stakeholder Preference Structure).*

4.2 Strategic Scenarios for Coping with Growing Ecological Demands for Water

A wide range of options exists regarding irrigation modernization efforts to meet growing ecological demands for water from the Klamath Irrigation Project. To illustrate how a collaborative decision-making approach could be used to assess modernization options, alternative scenarios were generated to satisfy these competing demands. In the first place, one option is to do nothing and maintain the status quo. However, maintaining current water management practices in the Project will lead to worsening environmental and economic consequences. It is therefore reasonable to expect that some changes will be made to water allocations and some investments will be made to modernize the irrigation system for river flow augmentation. Nevertheless, past responses to drought crises in the early 1990s and experiences with ESA-mandated water objectives in other places (Swanson, 2004) support the idea that irrigation modernization may not happen for a long time, or never, in place of permanently retiring a large area of irrigated Project land.

It is already clear from the analysis of the Project's agro-hydrology and internal processes that the *opportunity* for irrigation modernization exists. On one hand the question is primarily one of scale (and cost) and the resulting contribution(s) to water resources objectives. However, regardless of which strategy is selected, a choice always faces irrigation engineers about which project-alternatives should be put forward for implementation. In some cases there may be a variety of project designs that would fully or partially meet an objective. Through the application of the composite programming technique to analyze modernization project-alternatives for meeting the goals of multiple decision-makers, the relevant objectives can be represented, ineffective or inefficient alternatives can be screened out, and a quantitative evaluation of the trade-offs inherent in the selection among alternatives can be assessed.

4.2.1 Selection of Alternative Modernization Strategies

The following four general approaches are useful for defining a set of alternative strategies that could determine the outcome of policies devised for future water resources planning in irrigation projects:

I. Resist ecological demands
II. Develop new sources of water or new storage-infrastructure
III. Retain general scale and water use patterns, but reduce environmental harm
IV. Change the general scale and pattern of water use

Of primary consequence, an acceptable modernization project-alternative for each strategy has to be designed in such a way that the amount of water (re)allocated from the Klamath Irrigation Project would not eliminate agricultural production (below sustainable levels) and at the same time the remaining flows in the Klamath River system should be as large as possible to minimize adverse environmental impacts.

The discussion of the major strategic options in the Project in these terms is intended to offer insights into the tradeoffs among the implementation of irrigation modernization at gradually increasing scales of magnitude, including the option of those with existing water rights trying to block ecological demands. It is natural to expect that those with secure legal basis for diverting and using freshwater resources for irrigation would initially resist new requests for limited supplies of water that may cause them economic harm. However, there is the risk that resisting environmental reallocations in the face of intensifying challenges will become less and less acceptable.

There are different degrees to which irrigation modernization may benefit ecological goals in the Klamath River Basin, depending on the extent to which the irrigation community and other interested stakeholders – including those public agencies who will likely have to provide the majority of public investments necessary for the planning, design, and implementation of engineering projects – are willing to change the general scale and pattern of water use. To provide information about the real-world application of the alternative strategies in the case study area, an example modernization project-alternative was developed for each scenario.

4.3 Multi-Criteria Analysis Framework

Conflicting objectives have been identified and the opportunity for irrigation modernization has been demonstrated in the Klamath Irrigation Project. An MCA evaluation framework was developed to rank the performance of decision options (i.e., modernization project-alternatives for the different strategies outlined in Section 4.2.1 – *Selection of Alternative Strategies*) against multiple objectives measured in different units. The general structure of the MCA framework based on the composite programming technique consists of the following basic steps:

a. Identify the alternatives to be compared
b. Identify a set of objectives for comparing the alternatives
c. Define performance indicators (criteria) as quantitative measures
d. Define the benchmarks (threshold values) for each criterion
e. Distinguish the relative importance of each criterion (weighting)
f. Score the alternatives against each criterion
g. Multiply the score by the weighting for the criterion
h. Aggregate the criteria characterizing each objective
i. Sum scores for a given alternative and rank the alternatives by their total score

Figure 33 summarizes the strategic approach applied to the ranking of modernization project-alternatives.

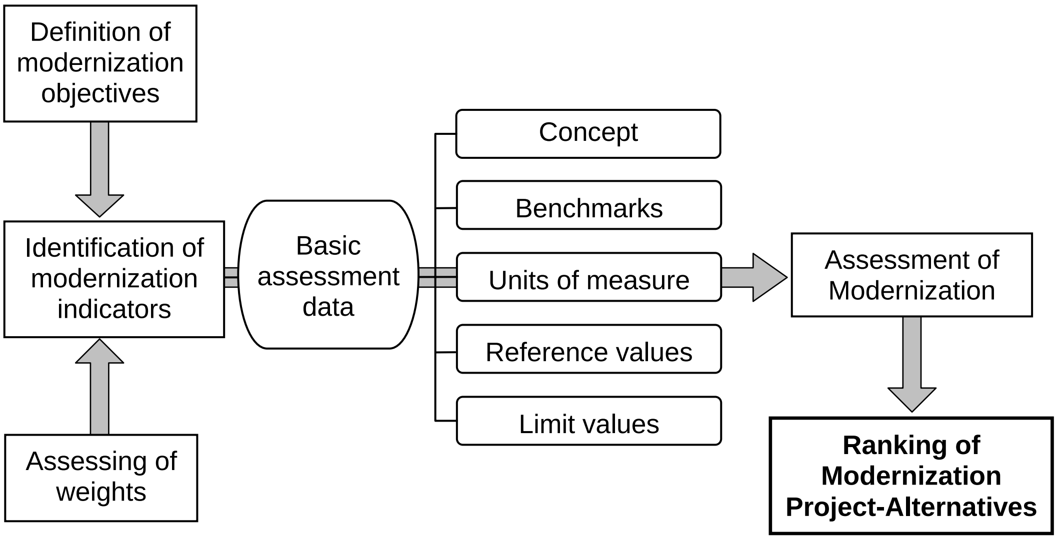


Figure 33. MCA strategic approach for the assessment of modernization project-alternatives

The assessment of irrigation modernization through the definition of objectives and conceptualization of performance indicators leading to a project-ranking of alternatives cannot be done without taking into account the contextual information of the irrigation project, as well as characteristics of the resource problem to be addressed.

4.3.1 Selection of Evaluation Objectives

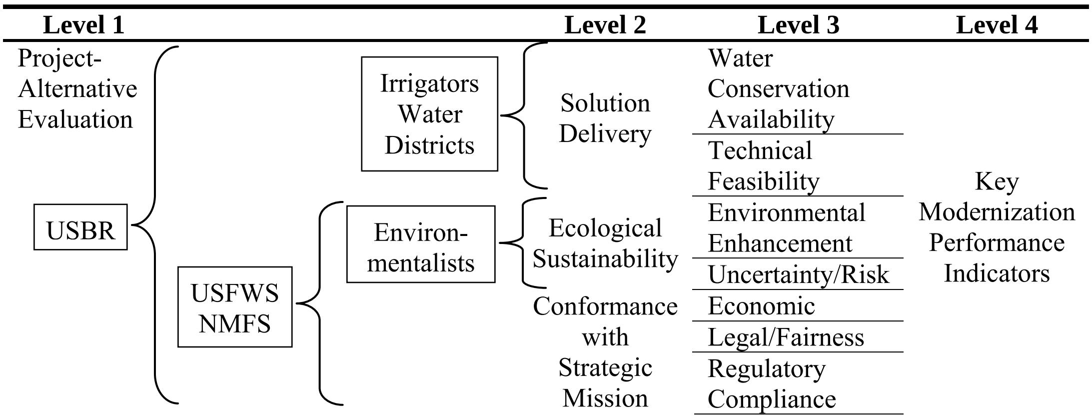
In a real-world decision-making context, the selection of evaluation objectives is a complicated subjective exercise, where water or irrigation issues are rarely if ever defined solely in terms of technical achievements or environmental impacts (Adams and Cho, 1998; Giupponi and Rosato, 2002; James, 2004; Breitenbach, 2004; Pietersen, 2006). In this case, the objectives, which correspond to the decision support of the technical project planning type, were aimed at describing how the different modernization project-alternatives, and combinations between different options, contribute towards determining a scale of preference with respect to specially-defined performance indicators. The objectives correspond to an appropriate 5-year planning time period.

Following this approach, the minimum elements of a modernization criteria assessment have been identified to meet the challenges of future water resources planning:

1. Water Conservation Availability
2. Technical Feasibility
3. Environmental Enhancement
4. Uncertainty/Risk
5. Economic
6. Legal/Fairness
7. Regulatory Compliance

These objectives describe partly competing irrigation policy goals. To facilitate a strategic approach for decision-making applied to other than purely technical irrigation issues, by different stakeholder groups, the defined objectives were grouped into broader classifications. The overall indicator system for the project-alternatives incorporates three thematic groups of aggregated indicators: *Solution Delivery*, *Ecological Sustainability*, and *Conformance with Strategic Mission*. The relationship between the hierarchical structure of the indicators and the major priorities of the designated decision-makers is illustrated in **Table 44**.

Table 44. Hierarchy of indicators for irrigation modernization project-alternatives prioritized for different decision-maker groups (macro-criteria of primary emphasis)



In the project-alternative decision hierarchy, Level 1 provides a general overview of the proposed project's effectiveness and suitability (final results). Level 2 in this structure provides a broad classification of themes for considering and evaluating the main points of the classic irrigation vs. environmental dispute, while taking into account the critical role of resource and regulatory agencies. The third level, Level 3, contains the evaluation objectives related to water management for conservation, hydraulic engineering, environmental impacts, uncertainty, and attributes associated with legal and economic issues. The key performance indicators and sub-criteria for particular aspects of each objective are in Level 4. This framework permits the different decision-makers to consider the importance and inter-relationship of various attributes associated with various decision alternatives.

4.3.2 Key Indicators, Benchmarks, and Reference Values

Key indicators were developed to provide a quantitative measure for evaluating the objectives of the project-alternatives in relation to assigned benchmarks and reference values. MAF (1997, p. 9) defines an indicator in the context of irrigated agriculture as "a measure of the state of a system that enables us to evaluate the effect of our actions on resources and adjust our actions to meet specified goals." There are no clear independent guidelines that can provide unambiguous agreement on which parameters regarding irrigation modernization might be optimal or should be prioritized. However, various forms of performance indicators have been used by researchers for the monitoring and evaluation of irrigation projects, including for the development of system improvement recommendations (MAF, 1997; Molden et al., 1998; Kloezen and Garces-Restrepo, 1998; Burt and Styles, 1999; Burt et al., 2000; Burt and Styles, 2000; Bos et al., 2005).

There are important differences in the indicators used to assess modernization project-alternatives and the *outcome* of the modernization implementation itself. The concept of a traditional performance indicator to measure some aspect of the efforts of irrigation and its related terminology are illustrated by **Figure 34** (adapted from Bos et al., 2005).

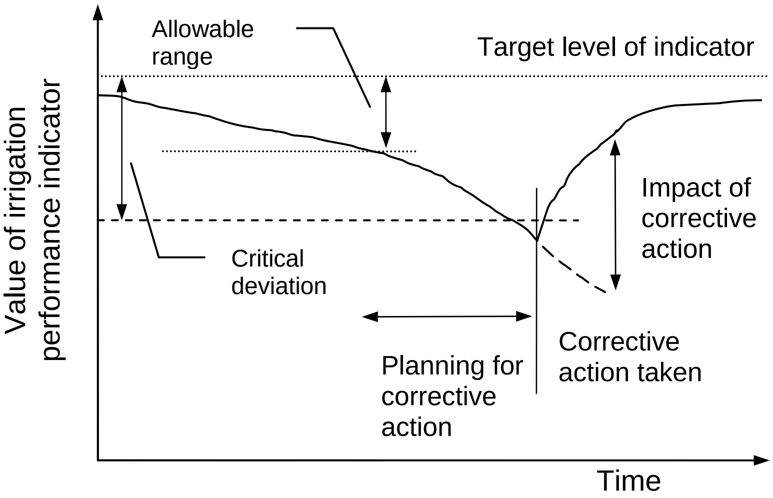


Figure 34. Use of a dimensionless irrigation performance indicator (adapted from Bos et al., 2005)

The purpose of modernization indicators as they are developed in the following sections is to manage and improve system performance, not to measure it. How far a project-alternative goes towards achieving the benefits of investment in system upgrades depends on what the measured objectives are. In determining the most satisfying of the different project-alternatives for modernization, predicting their outcomes across a series of hierarchal criteria is a useful decision analysis tool. The choice over implementation can be weighed against various criteria with varying levels of fulfillment. The values for each indicator define a solution-set for the project-alternatives according to parameters such as expanding irrigated area and protecting fish (refer to **Figure 35**). The preferences of a wide range of stakeholders are represented by the importance of each distance metric from the ideal solution.

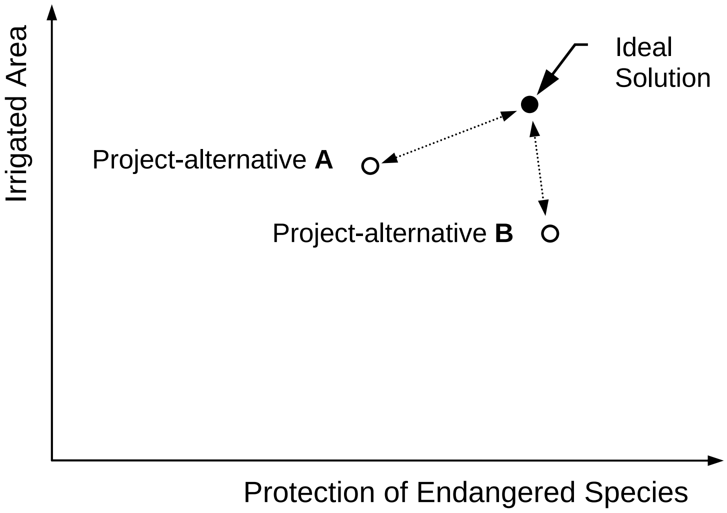


Figure 35. Analysis of different project-alternatives achievement towards an ideal solution for two modernization indicators (irrigated area vs. protection of endangered species)

Klawitter (2003) identifies some important potential benefits of applying indicators to the assessment of sustainable water pricing policies that also have application to this study of modernization criteria:

- Provision of key information related to future water scenarios
- Monitoring the effects of water management decisions
- Highlighting strengths and weaknesses of modernization alternatives and support for the formulation of investment policies
- Assistance in assessing investment priorities, project selection and follow-up
- Providing an appropriate framework for identifying the main asymmetries between different project or investment levels

Modernization indicators at Level 4 in the decision hierarchy should be viewed as leading indicators of the expected beneficial outcomes from implementation of the project-alternatives. To be useful, indicators need to refer to a well-defined time period and geographical area (Klawitter, 2003). In this case, as already mentioned, the planning horizon was selected as an arbitrary 5-yr time period. This is a practical amount of time for the design, installation, and break-in of modernization enhancements based on previous experience in other irrigation districts (Styles et al., 1999a; Styles et al., 1999b; Schantz et al., 2002). While the area considered in this analysis was the boundaries of the Klamath Irrigation Project, the same approach could be used at broader geographic scales to compare outcomes in the larger regions of Klamath River Basin, or in different-sized irrigation projects elsewhere.

The indicators reflect different types of benefits, including environmental and irrigation system performance, but they are based on the assumption that the primary purpose of modernization spending is to achieve specific water conservation benefits. As Burt et al. (2000) note this is a common situation in irrigation districts in large areas of the western U.S. where irrigation engineering projects have to respond to external pressures related to various aspects of environmental enhancements (see **Figure 24**).

The following sections present the modernization indicators that are used for assessing each evaluation objective, along with the associated desirable and critical values compiled for this study. These values are the result of the author's research on modernization and analysis of case studies, collected from various entities but primarily from the ITRC, and several years of technical project experience in the Klamath area. It should be noted that the desirable and critical values reported here may have to be re-evaluated for other applications with special circumstances, particularly those found in non-industrialized countries, which present a challenging environment for many reasons not directly related to the irrigation systems themselves (e.g., lack of social cohesion, lack legal enforcement, little capital available for infrastructure investment, etc.). However, one is also cautioned that if a modernization project-alternative would likely fail in regard to the assessment based on these criteria values as presented here, it may be even less likely to succeed in situations in developing countries for those very same reasons.

4.3.3 Definition of Modernization Indicators

This section defines the indicators used for the assessment of modernization project-alternatives. To describe each indicator the following characteristics are defined:

- The concept of the indicator with a concise meaning and unique interpretation
- The unit of measure
- The reference value to define a desirable threshold by meaning that, if the indicator reaches or exceeds the value, then the indicator is met, accounting for the potentially wide range of values for different projects (termed desirable value)
- The critical value to mark a limit of the least acceptable value
- Basic assessment data including the indicator as a function of time and its spatial distribution

To assess a useful range of possible project-alternatives, the modernization indicators were developed to overcome three potential challenges:

1. *General acceptance*: the indicators should extend beyond purely physical measures of project outcomes to illustrate the benefits from a variety of perspectives. Although challenging, the indicators should be particularly sensible from a water planner's point of view, and also make sense to other stakeholders.
2. *Practical*: the indicators should be usable where spending decisions are made under tight time and budget constraints. The assessment of modernization alternatives, in line with the nature of *modernization* and the *Rapid Appraisal Process*, should not be a multi-year, exhaustive effort requiring months and months of data analyses.
3. *Flexible*: the indicators should be flexible enough to distinguish between different systems and areas and be capable of reflecting tradeoffs among different types of environmental benefits measured at different scales.

For each of the evaluation objectives, several key indicators have been developed. While some of the indicators have particular relevance to the Klamath Irrigation Project, the indicators and their assessment guidelines are designed to be generally applicable. More indicators can certainly be justified depending on the specific conditions where different modernization projects are being considered for possible implementation. For example, this case study has not looked at issues dealing with urbanization, but in many regions of the western U.S., particularly in California and Arizona, this is a major challenge facing agricultural water districts. The number of criteria selected for each objective ranges from 3 to 6. It is important to recognize that in evaluating feasible project-alternatives, engineers and water resources planners would have already at this point had to integrate extensive knowledge of the hydrological water balance and internal process (physical and legal constraints, management capacity, operation rules, etc.) in order to develop reasonably acceptable candidates for evaluation.

Preliminary values have been assigned for the desirable and threshold elements of each indicator based on an assessment of the particular circumstances in the Project. Refer to the explanations in the following sections.

4.3.3.1 Water Conservation Availability

Water conservation may or may not be an objective of an irrigation modernization program and, depending on the particular hydro-geologic conditions of the system, traditional efficiency improvements may or may not make water available for other non-agricultural uses. However, in the western U.S. water conservation efforts are frequently geared towards obtaining a reallocation of irrigation water through modernization efforts that may involve direct reductions in consumption, infrastructure enhancements, management improvements, or some other technique (Howell, 2000; Keller, 2000; Burt, 2004; Clemmens and Allen, 2005). In the case study of the Klamath Irrigation Project, a key justification – and an important funding mechanism for any modernization projects with public financial resources – is making irrigation water available for water conservation goals (refer to Section 3.12 – *Availability of Irrigation Water for Conservation*).

With this being the case in the Klamath Irrigation Project, a primary concern for decision-makers is assessing the varying *amounts* of water that will result from different project-alternatives, along with other related assessment criteria to characterize the impact or reliance on groundwater resources. The key indicators developed for evaluating the Water Conservation Availability objective are summarized in **Table 45**.

The 2002 biological assessment prepared by the USBR includes a provision for the establishment of a "water bank" through which additional water supplies shall be made available for fish and wildlife. This was a requirement of the final biological opinion by NMFS (2002). The purpose of the water bank is to provide water during critical spring and summer months for meeting ESA-mandated in-stream flows. The size of the water bank is expected to reach 123 mcm annually depending on water year type (100,000 acre-feet/year). This volume of set-aside water is expected to come from a variety of sources including compensated idling of farmland, groundwater substitution, and new off-stream storage.

A water bank would be considered an alternative under the second strategic scenario of "developing new sources of water or new storage-infrastructure." Thus, a water bank was one of the project-alternatives evaluated using the modernization criteria assessment (refer to Chapter 5 – *Assessing Future Modernization Alternatives*). For the purposes of this case study, 123 mcm is considered the desirable volume of water for conservation goals through the implementation of a modernization project-alternative. The threshold for a project-alternative is estimated to be approximately 12 mcm (10,000 acre-feet) in order to even be included for further consideration in a basin planning context.

One of the obvious alternatives for replacing surface water diversions for irrigation so that they can be transferred to other stakeholders is substitution with pumped groundwater. Indeed, this is being done in many irrigated basins throughout the world, often causing serious problems with over-reliance on dwindling aquifers (Postel, 2000). When conjunctive use is an intentional water management strategy to help balance water demands with the timing of natural surface water runoff, groundwater pumping can help minimize undesirable effects of surface reservoirs (sedimentation, evaporation losses, etc.). But the potential impacts of a shift towards more groundwater use should be properly and thoroughly considered when formulating water resources plans involving modernization project-alternatives that rely on more pumping. As discussed in Section 3.9 – *Groundwater Resources*, some areas in the Project are already experiencing declines in the water table as irrigators and water districts have installed more pumps to deal with drought conditions.

Groundwater has been used for irrigation at various places in the Klamath River Basin for at least the last 50 years (CDWR, 2004). As reported in a major USGS study of the groundwater hydrology in the Basin by Gannett et al. (2007), until recently pumping volumes and water table elevations have remained fairly stable. There were drought-related impacts in the past, but no chronic year-to-year declines in pumping elevations, as groundwater levels have always returned to normal over multi-year periods. However, after the drought in 2001, groundwater elevations in several places in the Basin noticeably declined as much as 1.5 to 3 m the following year (5-10 ft) in response to a several-fold increase in pumping due to both private use and government programs. Well monitoring by the USGS (2005) found widespread continuing seasonal declines in the aquifer underlying the Project of 0.15 to 1 m per year (1-3 ft/year).

Table 45. Component attributes for the Water Conservation Availability objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Amount of water available from a reduction in irrigation diversions or efficiency improvements	123 mcm	12 mcm	123 mcm is the size of the annual water bank to be established for the Klamath Irrigation Project for enhancing or augmenting in-stream flows in the Klamath River
Degree of reliance on groundwater resources	3	1	0 – Depletion of the aquifer in all water year types 1 – Depletion that takes 3 or more years to recover; little monitoring 2 – Sustainable conjunctive use; in drought years more pumping allowed but with extensive monitoring 3 - Minor substitution of groundwater in critical dry years only
Change in groundwater depth over time	0 m/yr	2 m/yr	
Reduction of availability in drought years	3	1	0 – Does not provide conservation water in critical dry or drought years 1 – Only 25-50% of targeted conservation water would be available in a drought year 2 – Less than a 25% decrease in the availability of water 3 – Little or no drought-related influences on the amount of water that can be reallocated

4.3.3.2 Technical Feasibility

Irrigation projects exist to serve farmers. Of course, there are many other benefits that arise from irrigation development – human civilizations have risen and fallen according to their success with irrigation. However, it is always the growing of crops and overall agricultural production that generates the economic revenue in an irrigation project; as Merriam and Freeman (2007) point out "the farm and the project are one financial unit." Therefore, any reduction in agricultural production, either in terms of less land being irrigated or changes in the types of crops being grown, has a major impact on the financial health and sustainability of an irrigation project. The indicator for the amount of net reduction in irrigated land reflects the fact that the income of a water district is generally based on farmers paying for volumes of water or assessments for the amount of land served. If fields are taken out of production, the income for a water district decreases. If this decrease reaches a critical point, the water district may no longer be able to be self-sufficient. Related to this is the sustainability of the support industries that depend on local agriculture (firms that sell fertilizers, seeds, and tractors, or post-harvest processing, etc.). In addition, irrigation systems operate as an inter-connected hydraulic network and there is a point at which removing pieces of the network would render it unmanageable.

As a consequence, the technical feasibility of a modernization project-alternative depends in part on how much irrigated land, if any, is either permanently retired or temporarily idled, which can be assessed either in percentage terms or the net area affected (refer to **Table 46**). The three largest water districts in the Klamath Irrigation Project each cover an average irrigated area of approximately 19,000 ha (47,000 acres). In this case, the districts have no other significant sources of income besides water-related charges, but in other basins districts may receive money from other activities such as land rentals, hydropower generation, etc. that contribute to their operating budget. On the other hand, as has been demonstrated by the quantitative hydrologic assessment in Chapter 3, the primary means of water conservation available in the Project is reducing consumptive uses (ET_{iw}) because most recoverable "losses" are already recycled internally. As a consequence, some aspect of land idling is likely to be part of any successful initiative to reduce net diversions.

The analysis in Section 3.13 – *Impact of Agricultural Water Conservation on Water Availability* determined that the equivalent area of idled land required to meet present water conservation targets ranges from about 2,100 to 23,000 ha (5,200-57,000 acres). Assuming that the main water districts could only absorb a net reduction associated with about 25% of their irrigated lands and still remain viable, this is equivalent to an average of 4,800 ha (12,000 acres) per district or a project-wide total of 14,400 ha (36,000 acres). Ideally, from the water districts' point of view the amount of land idled annually would be the minimal amount necessary to meet conservation targets, and other steps would be taken to provide freshwater for in-stream flow requirements. It is necessary to recognize that a combination of modernization projects and other solutions elsewhere in the Klamath River Basin will have to be implemented to restore the habitat of native fish species, so evaluation of individual project-alternatives should consider their *relative* contributions.

Table 46. Component attributes for the Technical Feasibility objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Net reduction in the amount of land irrigated (annual basis)	1,000 ha (5%)	4,800 ha (25%)	On an individual water district basis. Assuming no direct offset subsidies to water district, except direct payments to farmers/landowners.
Efficiency of water use (post-project percentage)	90%	80%	The threshold value should be close to the representative (multi-year) *IE* value.
Annual O&M costs	$0	$100,000	In addition to present maintenance budgets for existing infrastructure.
Water Delivery Service (composite index)	4	2.6	Applied at the level of individual fields or ownership units with weighting factors after Burt and Styles (1999): 0-4: Measurement of volumes to individual units 0-4: Flexibility 0-4: Reliability 0-4: Apparent Equity
Number of years for project completion	1	5	Longer implementation periods increase risk and uncertainty.
Proven technologies of modern water control and measurement	2	1	0 – Ineffective, technically-limited designs or non-transferable knowledge. 1 – Some modern technologies are utilized but they may not fit into an overall strategic plan. 2 – Excellent use of leveraging modern technologies to improve water management and save money.

A related issue is how efficiently water use is before and after implementation of a project-alternative. The *IE* of an irrigation project is an oft-cited statistic that has broad symbolic meaning. Obviously, project-level efficiency should increase or remain the same in order for the project-alternative to gain the necessary widespread support among environmentalists and other stakeholders. During the time period of this case study analysis (1999-2003), the mean *IE* of the Klamath Irrigation Project was approximately 86% (refer to **Table 43**). Previous historical studies of the Project have indicated long-term *IE* is above 90% (Davids Engineering, 1998).

The recurring cost for operation and maintenance of any project-alternative is another important consideration because this expenditure becomes part of the annual budget for the USBR and water districts. The presence of extensive deferred maintenance and the lack of substantial investments in recent decades in upgrading physical infrastructure in the Project means any additional costs would have a large bearing on the attractiveness and feasibility of each project-alternative. The minimization of annual costs where possible should therefore be considered in the development of modernization scenarios and the selection of technology.

Water delivery service can be measured by a composite index of ratings assigned to the relative degree of the flexibility, reliability, and equity of irrigation water deliveries provided by the water district(s). Applying the rating criteria developed by Burt and Styles (1999) and Burt and Styles (2000) to the scale of individual farms, one can evaluate the impact of project-alternatives on water delivery service, which in turn affects how efficiently and economically farmers can irrigate their crops. The quality of water delivery service determines the selection of irrigation methods available for farmers (Burt et al., 1999). Bautista et al. (1999) discuss the relationship between irrigation delivery performance and farm irrigation.

Baseline information was developed during the analysis of internal processes (refer to Section 2.2 – *Rapid Appraisal Process*) to determine the present quality of water delivery service being offered by water districts in the Project. **Table 47** summarizes an assessment of the current water delivery service (0 to 4 scale). The indicator results show that irrigation districts in the Project provide a relatively good level of service (2.6 out of 4.0) at present. However, there are opportunities for improving service in terms of equity and reliability, in addition to increasing flexibility of water deliveries.

The amount of time that it takes to implement a project-alternative relates to its effectiveness in addressing high-priority water issues. Major engineering projects typically take several years for planning, design, and construction. In the biological opinions (NMFS, 2002; Lewis, 2002) there are prescribed actions and conservation targets that are supposed to occur over time periods of several years. Water districts typically prepare their budgets on an annual basis, so the minimum implementation time period for investing in modernization is probably at least 1 year. Project-alternatives taking longer than 4 years would presumably face growing uncertainty as litigation, lawsuits, or changes in the political environment can affect the underlying rationale and funding availability before the project could be completed.

A core concept of modernization is the appropriate application of modern water control and measurement technologies. No control strategy, technology, or design is ideal for all situations found in irrigation projects to be modernized (Plusquellec, 2002). Modernization does not necessarily imply that expensive computerized programs or automated structures always have to be utilized. Often simple hydraulic structures with proven track records in the field can provide reasonable performance with little risk. The goal should be to promote ease of use – simplified, straight-forward operations rules are more likely to be followed – that may involve sophisticated design and engineering. Engineers and water resources planners have to select technologies and designs according to the particular situation, but state-of-the-art irrigation science relies on well-tested principles and concepts.

Table 47. Current water delivery service indicators for irrigation districts in the Klamath Irrigation Project at the level of individual fields (after Burt and Styles, 1999)

Key Indicator	Ranking Criteria	Assigned Value	Weighting Factor
Measurement of Volumes	4 – Excellent measurement and control devices, properly operated and recorded. 3 – Reasonable measurement and control devices, average operation. 2 – Useful but poor measurement of volumes and flow rates. 1 – Reasonable measurement of flow rates, but not of volumes. 0 – No measurement of volumes or flows.	3	1
Flexibility	4 – Unlimited frequency, rate, and duration, but arranged by users within a few days. 3 – Fixed frequency, rate, or duration, but arranged. 2 – Dictated rotation, but it approximately matches the crop needs. 1 – Rotation deliveries, but on a somewhat uncertain schedule. 0 – No established rules.	3	2
Reliability	4 – Water always arrives with the frequency, rate, and duration promised. Volume is known. 3 – Very reliable in rate and duration, but occasionally there are a few days of delay. Volume is known. 2 – Water arrives about when it is needed and in the correct amounts. Volume is unknown. 1 – Volume is unknown, and deliveries are fairly unreliable, but less than 50% of the time. 0 – Unreliable frequency, rate, duration, more than 50% of the time, and volume delivered is unknown.	3	4
Apparent Equity	4 – All fields throughout the project and within tertiary units receive the same type of water delivery service. 3 – Areas of the project receive the same amounts of water, but within an area the service is somewhat inequitable. 2 – Areas of the project receive somewhat different amounts (unintentionally), but within an area it is equitable. 1 – There are medium inequities both between areas and within areas. 0 – There are differences of more than 50% throughout the project on a fairly widespread basis.	2	4
Water Delivery Service (composite rating)		**2.6**	

4.3.3.3 Environmental Enhancement

As discussed previously, environmental enhancement is often a major part of the justification(s) for implementing irrigation modernization projects, as well as a potential funding mechanism. In this case study of the Klamath Irrigation Project, ESA-listed fish species are the primary motivation for irrigators to adopt different management practices and to fund new infrastructure upgrades.

Flows in the Klamath River downstream of Iron Gate Dam are strongly affected by operations (storage and diversions) of the Klamath Irrigation Project. Construction of the Project facilities has reduced average flows in summer months and altered natural seasonal variations of flows in the river (USBR, 2000). Less in-stream flows in the river reduces the amount of suitable habitat available to threatened coho salmon. The USBR (2002) developed a hydrologic baseline representing minimum and average multi-year conditions between 1961 and 1997. **Table 2** summarizes the long-term operational criteria for Klamath River flows determined by the USBR. For example, in June of a below-average water year, the flow requirement as measured downstream of Iron Gate Dam is 43.18 cms (1,525 cfs).

To determine appropriate conservation planning targets that would result in river flows staying within the historical range during the 10-year reference period (1990-1999) without letting the mean decline over time, NMFS (2002) calculated the mean monthly flows that would occur if the USBR were to meet the river targets in the biological assessment during the same time period. In June the estimated difference was 17.6 cms (620 cfs), which increased up to nearly 45.3 cms (1,600 cfs) in March. During the critical 4-month spring time period the average monthly discrepancy between the desirable conservation target and the operational criteria was 29.2 cms (1,030 cfs). This is a conservative estimate and well above the minimum conditions that the USBR proposes to achieve (minimum monthly flows). An analysis of historical flow records reported by the USGS (2005) at Iron Gate Dam indicates that during the irrigation season months of May and June the deficit between observed flows and predicted flows (based on USBR's implementation of the operating criteria in the biological assessment) ranges from approximately 17 cms (610 cfs) to 11 cms (380 cfs) in dry and below average years, respectively.

Elevated nutrient levels from agricultural runoff adversely affect the aquatic environment in the Klamath River system (NMFS, 2002). Combined with the removal of riparian vegetation resulting in elevated water temperatures, high nutrient levels stimulate the growth of aquatic plants and algae. As the aquatic plants and algae decompose, the level of dissolved oxygen may decrease to levels that are lethal to some fish species. Oregon's water quality objective for dissolved oxygen is 7.0 mg/L. As of 2007, TMDLs are still being developed for the river that will set numeric targets to maintain desired water quality standards, including temperature, nutrients, and dissolved oxygen. The drainage reduction indicator included in the assessment was quantified in terms of a percentage reduction of flows leaving the Project during the critical summer months. This indicator can be modified at a later date based on the final TMDL targets.

Table 48. Component attributes for the Environmental Enhancement objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Endangered or threatened species will benefit	3	1	0 – No benefit for listed species. 1 – Some benefits in terms of habitat preservation, but limited in scope and amount of area affected. 2 – Significant contributions to meeting environmental goals. 3 – Major contributions to environmental restoration and conservation goals sufficiently met over time to de-list species.
Contribution to in-stream flow conditions	17 cms	3 cms	Augmented flows in the Klamath River in excess of the specific base flow of water at Iron Gate Dam. Depends on water year type. Values shown are mean monthly flows during the critical months.
Change in water quality of drainage (load reductions)	100%	20%	Percent reduction of agricultural return flows to the Klamath River during critical summer months.

4.3.3.4 Uncertainty/Risk

The evaluation of modernization project-alternatives must address risk and uncertainty (refer to **Table 49**). As the complexity of engineering designs and technology increases, the risks associated with implementation and management also increases. On the other hand, the degree of risk that a water district will fail with modernization for technical reasons also has to do with how much technology they have already successfully incorporated into their operations. For example, if a water district is small, uses relatively old infrastructure, and the staff aren’t comfortable with computers, trying to introduce a system with extensive utilization of complex hydraulic automation probably has a high likelihood of failure.

Another area of risk is to what extent the proposed project-alternatives are expected to be affected by drought or long-term changes to water supplies and flow regimes. Since the modernization scenarios for the Klamath Irrigation Project are required the most in times of drought when conservation savings or reallocations are critical for in-stream flows, several indicators are used to predict how project-alternatives would be potentially affected in these conditions.

There is also some risk associated with the particular quantity of water users (or other stakeholders) that have to participate in the project-alternative or program in order for it to be successful. The idea is that enough people need to be involved in the proposed project for it to have sufficient scale, but if too many participants are required then the threshold may be unreasonably high.

Table 49. Component attributes for the Uncertainty/Risk objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Complexity of engineering design and technology	Medium	High	Low – only limited use of advanced technologies and simple construction techniques. Medium – complex design and engineering, but robust designs are used. High – the technologies require multi-level simulation, complicated numerical analysis techniques, or complex engineering/construction.
Resistance to flood or drought influences	High	Medium	Low – the project will be severely interrupted in times of droughts or water shortages. Medium – some impacts on the function of the project in major droughts but its benefits will still be available in all but severe water shortages. High – it is expected that there will be few or no drought effects.
Requires adoption of innovation(s) by a significant number of water users	50%	75%	Percent of water users who have to participate in or pay for the project. Higher participation becomes increasingly harder to achieve without substantial financial incentives.
Possibly vulnerable to unexpected change(s) in flow regime over the long-term	None	Medium	None – the project is not vulnerable to future unexpected changes to the flow regime. Medium – there is some expected reduction in project effectiveness if flow conditions change significantly, but little impact under foreseeable conditions. High – the project is highly vulnerable to changes in the flow regime as compared to current conditions, or costly modifications will be required.

Burt (2000) outlines some factors that almost guarantee failure based on his extensive experience with modernization programs worldwide in a variety of conditions. His list of related factors is intended for computerized modernization programs, but almost all are still generally applicable for most modernization projects:

- A large gap exists between what managers say is occurring versus what actually exists in the project.
- An inadequate budget for maintenance, spare parts, and long-term support
- No local "hero" who makes sure that things work out
- The lack of a "service mentality" at all levels within the project
- A plan that focuses only on computers and automation, and does not put a substantial percentage of the budget into simpler structures and recirculation systems
- Unmotivated staff that cannot be fired for poor performance and lack concern for details, as indicated by dirty facilities and many broken items.

4.3.3.5 Economic

The economic indicators in **Table 50** provide an assessment of the resources needed to achieve the benefits from implementing the modernization project-alternative. Overall construction costs are frequently one of the first-line criteria debated among water districts and stakeholders for obvious practical reasons. Depending on a variety of factors, modernization can be very expensive and often represents a significant portion of budget revenues for several years while the system is being upgraded. Recently in the last 5-10 years, construction and materials costs have soared in the western U.S. Heavy construction elements like reservoir excavation, pipeline installation, canal earthwork, pumping plants, etc. usually have to be done by outside private contractors and not by the districts themselves. Costs on these items can vary widely depending upon challenges with rights-of-way, agreements with farmers, decisions about who does the work, unanticipated drainage problems, prevailing wages, etc. Under certain types of contracting procedures and requirements, costs can easily double from what "can be done," especially if the work is all done with contractors using prevailing wages.

Two different construction cost indicators were used in the analysis of the economic evaluation objective. The first one was a planning-level estimate of equivalent annual costs[16] on a per-area basis for the area(s) in water district boundaries that will receive meaningful benefits from the proposed project-alternative. This was done to reflect differences between relatively expensive projects, such as mechanical fish screens, that would only benefit a single district versus broad-scale modernization that would address water issues for multiple districts. Modernization would ideally also have to include components to solve a variety of localized operational issues, besides meeting strictly environmentally-focused goals (the win-win solutions). Another cost-related indicator is the project-alternative equivalent annual cost per volume of water conserved. This is particularly important from the point of view of regulatory agencies that must typically adhere to a cost-benefit analysis seeking the lowest-cost alternative when allocating public sector funds.

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[16] Equivalent annual cost is the expected average cost per year, considering both capital and operating costs, over the life of the project. A discount rate of 10% was used in the economic analysis of project-alternatives.

Table 50. Component attributes for the Economic objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Equivalent annual cost per hectare	$0/ha	$150/ha	Annualized cost for planning, design, engineering, permitting, construction, management, inspection, etc. on a per-ha basis for areas in the water districts that receive meaningful benefits.
Equivalent annual cost per MCM of water conserved	$0/mcm	$120,000/mcm	Total implementation costs per unit of water conserved or made available for in-stream environmental flow requirements.
Net increase in energy costs per hectare	$0/yr	$10/yr	Annual additional cost for power requirements for project-alternative components.
Cost sharing required by water district(s)	50%	25%	The amount of total costs that are paid by the water district(s).

Upper Klamath Lake level restrictions have a profound effect on the water available for irrigation, and therefore on the planning by irrigators and their farm management decisions (due to the risk of water supply reductions). Adams and Cho (1998) provide quantitative estimates of the potential trade-offs between Upper Klamath Lake levels mandated by the ESA and net profits from irrigated farms in the Klamath Irrigation Project. The aggregated results from their farm models estimated the reduced profitably of maintaining ESA-mandated lake levels to be about 8% of the estimated annual profit arising from the entire Project with a base-case water supply. However, the authors estimate that observing the ESA restrictions on lake levels in severe drought years could account for an opportunity cost of almost 60% of average annual profits ($15 million).

Carlson and Todd (2002) examined the shifts and reductions in crop areas in the Project due to the water allocation restrictions during the 2001 drought when the USBR severely limited water available for irrigation. The regional economic consequences from the reduction in production value (farm-gate sales) were estimated to be nearly $50 million caused by a major shift in the amount of land idled. Precise irrigation records from the USBR for 2001 were not available for the analysis in Carlson and Todd (2002), but crop reports indicated that the largest irrigation district in the Project showed a 1,200% increase in idle acres. Detailed water balance data compiled for this dissertation provide a more complete picture of the water management practices and resulting outcomes in 2001.

Since pumped recirculation or new re-regulation (buffer) reservoirs are typical elements in modernization programs for irrigation districts, total energy usage could increase substantially after a project-alternative is implemented (if energy efficiency is not a core element of the design objective or management strategy). Electrical energy costs are already a major issue in the Klamath Irrigation Project, so an indicator is necessary to assess any net increase in power requirements. According to figures for agricultural energy consumption cited by Jaeger (2004c), total energy costs – including the costs incurred by irrigation districts for centralized pumping stations – was approximately $12 per hectare ($5/acre) in 2002. When the proposed rate hikes take full effect, energy costs for sprinkler irrigated fields could rise to $100-125 per hectare ($40-50/acre).

The USBR conducts a challenge grant program – *Water 2025: Preventing Crises and Conflict in the West* – that was initially developed in response to the 2001 drought in the Klamath Irrigation Project. The Water 2025 program is similar to other state and federal collaborative grant programs that require water districts to cost share a portion of the project's cost. In the Water 2025 program, a minimum 50/50 cost-share basis is required. Given the major investment required, and the non-agricultural environmental enhancement objectives to restore habitat conditions, it is anticipated that other agencies may subsidize part of the project-alternatives to reduce the cost for districts.

4.3.3.6 Legal/Fairness

Irrigators' water rights in the western U.S. are codified into law in various ways that may change over time. The details of current water rights in the Klamath Irrigation Project were discussed in Section 2.1.2 – *Competing Demands for Water*. Interests are held by irrigators, Tribes, fishermen, and the environment in the Klamath River Basin. Even though irrigators have third place in the order of Project priority after ESA requirements and the Tribes, the farming community is a vocal majority with a strong political base. Therefore, it is unlikely that any sustainable long-term solution could be implemented unless it has the willing consent of a substantial number of irrigators. As analyzed in Chapter 3 – *Conceptualizing Limitations on Resources Availability for Water Conservation*, there is little water to be gained from efficiency improvements alone, setting aside for the moment potential water quality enhancements. As a result there would have to be reallocations in the Project's overall water supplies, which could affect in varying degrees all 18 different water agencies. All irrigators have a justifiable basis for attaining a high degree of equity in the reallocations, or receiving compensation.

Besides looking for ways to achieve equity in terms of irrigation reductions, an attractive mechanism for persuading the irrigators to become active participants in water conservation programs for the purpose of habitat restoration – so the listed fishes can be taken off official ESA protection – is to preserve their legal water rights. As a result the project-alternatives are assessed in terms of the extent to which they preserve, or at least are not detrimental to, the existing water rights structure. The perception of fairness in how historical water rights are handled is especially important among the farming community in the face of any water reallocations that could have significant carry-over socio-economic effects into the whole community.

One indicator for how fairly (or equitably) the modernization project-alternatives would impact irrigators is the number of water districts to be involved. Given the hydraulic interconnectedness and adjoining service area boundaries of the water districts in the Project, including primarily the conveyance and reuse of return flows, it would be difficult to implement meaningful upgrades involving only one or two individual districts that could have a major impact on in-stream flows. Although two or three irrigation districts together contain a majority of the Project's service area, they each have smaller improvement districts as customers and neighbors.

Related to the notion of the fairness of modernization investments, management requirements, or water reallocations is whether some (or all) irrigators would have to abide by restrictions on the types of crops they would be permitted to grow. The Upper Klamath Basin is a semi-arid, high desert with a short growing season that does not support many high-value crops. In addition, irrigators have strong cultural ties and considerable business investments associated with growing particular crops. Preferably, irrigators would have sufficient knowledge and reasonable certainty about water supplies so that they could be allowed to continue making farm management and business decisions based on market conditions and historical preferences. Setting up a monitoring regime that gets into the details of irrigators' field-level decisions about acceptable crops or planting/harvest dates would introduce undesirable bureaucratic complexity and costs to the verification of water conservation.

Table 51. Component attributes for the Legal/Fairness objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Perceived equity of water reallocation	High	Medium	Low – Major inequities in how reallocations take water from individual irrigators or districts. Medium – Inequities are minimized among customers within a water district, but exist between different districts. High – All irrigators (and districts) share water reallocations.
Preservation of existing water rights	3	1	0 – Water rights are forcibly taken from irrigators without any monetary compensation. 1 – Water districts and individual irrigators retain water rights, but only on a year-to-year basis. 2 – Except in critical dry years the water rights for Class A and B districts are preserved. 3 – Existing water rights for the federal contractors are reinforced with long-term certainty over water contracts.
Involving multiple water districts (number of project partners)	8	2	The number of water districts who participate in the project
Restrictions on crop types or calendars	Low	High	Low – No restrictions on planting dates or crop types. Medium – Only restrictions on crop types during drought years. High – Strict regulations governing what types of crops can be grown and enforcement of cropping schedules.

4.3.3.7 Regulatory Compliance

The regulatory compliance evaluation objective assesses the degree to which modernization project-alternatives comply with the ESA, other laws, and various public policies. The USBR and irrigation districts are public agencies that are legally bound to follow existing laws and statutes. When the 2001 drought occurred, if project management staff of the USBR had not ceased irrigation deliveries in order to protect listed fish species as required by the ESA, as individuals they could have been put in jail. Historical conditions, including legally-sanctioned water rights, dictate that project-alternatives have to be judged in part on whether or not they are in compliance with relevant regulatory authorities, unless some specially mandated deviation is explicitly recognized by the courts or a large majority of stakeholders.

Compliance with the ESA is a fundamental requirement for any project-alternatives in the Klamath Irrigation Project, but the circumstances in other irrigation systems depend on the presence and scope of designated habitat under the ESA. All the significant waterways in the Project – Klamath River, Lost River, and the Lost River Diversion Channel – are subject to fish listings under the ESA. Many questions remain about the intersection of state water law, federal water contracts (water rights), and the ESA, including whether and to what extent water users may be entitled to compensation in the event enforcement affects water rights (Stanford, 2001). Braunworth et al. (2002) cite over 15 court cases related to water allocation in the Upper Klamath Basin. Until issues related to enforcement of the ESA and compensation are answered, any modernization action that deviates from established interpretations will carry a high potential for lengthy and expensive litigation (Braunworth et al., 2002; James, 2004; Swanson, 2004).

Assuming that the project-alternatives to be evaluated on their face do comply with the ESA and other environmental laws, a related issue is the capacity of the relevant resources agencies to implement the project and then adequately verify compliance. It is recommended that compliance be based on quantitative metrics when possible. Qualitative assessments are open to endless interpretations and administrative hassles. Quantitative assessments, including those that can ideally be verified on the basis of either "yes/no" or "on/off", are more straightforward to monitor and easier for non-technical stakeholders to understand and accept.

Verification of water conservation programs is important in order to develop confidence in savings achievements among all parties, although verification in irrigation projects can often be an expensive and time-consuming process (GAO, 2005; USGS, 2005). The Imperial ID in California (200,000 ha) received $109 million from a coalition of urban water providers to save 123 mcm of water annually (100,000 acre-feet/year), which was then leased for a 40-year period. Approximately 16% of the total budget was spent on conservation verification, which by itself saves no water. One relevant indicator is how many new employees would be required for monitoring and verification because this is an indirect cost associated with the different project-alternatives.

The likelihood for long-term success and acceptance by irrigators, regulatory agencies, and other stakeholders will presumably be greater if project-alternatives have some synergy with other conservation initiatives. The challenge for water resources planners is to seek and promote conservation synergies in the selection of project-alternatives so that irrigation modernization can advance other positive initiatives. Ideally, successful modernization should make conservation goals easier and more cost-effective to achieve, while complementing existing initiatives.

Table 52. Component attributes for the Regulatory Compliance objective

Key Indicator	Desirable Value	Threshold Value	Ranking Criteria or Guidelines
Legal compliance with ESA and other environmental laws	yes	yes	All project-alternatives should be in compliance with the ESA for final consideration.
Degree to which the current mandates of agencies are adequate for implementation	2	1	0 – The implementing agencies do not have recognized authority to fund or implement the project, and no remedies are available. 1 – Limited or partial authority exists, but legal or legislative options are available to address an expansion of the necessary authority. 2 – Legally enforceable mandates are vested with the agencies.
Basis of user compliance is quantitative or qualitative	3	1	0 – Conservation can only be assessed in terms of qualitative estimations or subjective valuations. 1 – Major new investments for monitoring networks are required. Some assessment parameters are open to conflicting interpretations. 2 – Existing monitoring stations to be upgraded to properly address measurement uncertainties. 3 – Water savings can be verified with easily understood metrics using readily available data. Little investment in new monitoring stations or databases.
New positions required for monitoring project implementation and outcomes	0	10	Number of new employees whose major responsibilities are related to monitoring and verification of modernization outcomes.
Synergy with other existing or planned initiatives	1	0	0 – Little or no synergy with other conservation initiatives. 1 – Some synergies are expected. At a minimum, the proposed project will not interfere with or adversely impact other conservation initiatives. 2 – Augments to a significant degree existing or planned initiatives making them more effective and less expensive.

4.3.4 Formulating the Stakeholder's Preference Structure

To illustrate the benefits of the selected composite programming technique involving multiple stakeholders, four different decision-making groups were considered: (1) irrigators/water districts, (2) environmentalists, (3) the USFWS/NMFS, and (4) the USBR. Weights (α) were assigned to each evaluation indicator in proportion to their (hypothetical) perceived importance to each decision-making group. Different viewpoints concerning the important criteria for ranking irrigation modernization project-alternatives are reflected by the different weights. To evaluate how varying degrees of achievement for particular indicators in each level affect overall preference for project-alternatives, appropriate compensation factors were formulated for each decision-making group.

4.3.4.1 Assigning Weight Sets

The weighting factors for Levels 4, 3, and 2 in the framework are summarized in **Tables 53**, **54** and **55**, respectively. The modernization indicators and evaluation objectives developed for this study (refer to Section 4.3.3 – *Definition of Modernization Indicators*) are primarily intended for practical use by water resources planners with experience in implementing engineering projects in irrigated agriculture. The ranking criteria are specific and require a certain level of expertise. However, the nature of the indicators themselves is intended to be general enough that one could solicit input regarding their importance from non-technical stakeholders. For example, a biologist working on restoring native fish populations does not have to know, or care about, the details of the quality of water delivery service to be provided to irrigators under a particular project-alternative in order to express an opinion about its relative importance compared to other indicators.

In the examined case of the Klamath Irrigation Project, the preferred outcomes of the irrigators (and the broader farming community dependent on the Project) and those of the various environmentally-oriented groups are essentially opposing in terms of the weighting for some criteria. Irrigators basically utilize irrigation water to stay in business and need a certain portion of the status quo to remain in place in order to be viably active farmers. Some measure of environmental protection is accepted by the vast majority of the irrigation community, although there are wide divergences in the conception of what constitutes "the environment" worth preserving and who should pay for it (Braunworth et al., 2002). Environmentalists, at least some of those putting extreme pressure on politicians to take action, want above all else to restore fish habitat, even it means dramatic reductions in, or even elimination of, agriculture in the basin. In between these two extremes are the resource agencies who manage water for the benefit of irrigators, the Tribes, and wildlife, while expending public funds.

A range of other concerns guided the determination of the weighting vector for each group, including for example:

- Irrigators, through their representative agencies the water districts, would have to pay for at least some portion of the implementation costs for the project-alternatives.
- The USBR, and other government agencies, have a legal requirement to enforce existing environmental regulations, without cost being a primary consideration (under ESA directives).
- External issue groups such as the broadly-defined "environmentalists" category of decision-makers are not directly influenced by some hydrological consequences of various proposals because either they are not based in the local area or not involved with related activities (e.g., declining groundwater levels).

- Irrigators are less tolerant of risk and uncertainty (than other external parties) as they have to make substantial private investment in farming each year, largely through lines of short-term credit.
- Implementing agencies such as the USBR have to give adequate consideration to their technical capacity and manpower for executing and monitoring any project-alternative.
- The USBR has to carefully straddle its unique position as enforcer of ESA mandates on behalf of society at large and as executor of water rights on behalf of the Project's irrigators.
- Environmentalists as private individuals do not necessarily have to worry about the direct costs for maintaining project-alternatives or monitoring their outcomes (except through their taxes).
- All other things being equal, irrigators and water districts would prefer projects that also result in some improvements to water delivery service and ease of operation, while addressing environmental needs.
- Irrigators would strongly prefer solutions that let them preserve their water rights, so that in event of eventual fish recovery they do not lose a legal basis for continued farming.

4.3.4.2 Assigning Compensation Factors

The parameter p in the composite programming analysis is used to determine to what extent the poor performance of a project-alternative in one indicator can be compensated by the good performance according to another indicator(s). As a balancing factor, p represents the expressed importance of the deviation from the ideal solution. If $p = 1$, (perfect compensation) all deviations are weighted equally. Values of p greater than 1 account for progressively lower degrees of compensability of the criteria, until at $p = \infty$ there is no compensation. In most cases, some degree of partial compensation was allowable; however, certainly stringent attitudes exist regarding the desirability of specific criteria by some groups, which are reflected in the assigned p values.

Table 53. Level 2 weights and compensation factors for different decision-maker groups

Ind.	Irrigators		Environmentalists		USFWS/NMFS		USBR	
	α	*p*	α	*p*	α	*p*	α	*p*
Solution Delivery	0.50	3	0.20	3	0.25	3	0.33	3
Ecological Sustainability	0.20		0.75		0.50		0.33	
Strategic Mission	0.30		0.10		0.35		0.33	

Table 54. Level 3 weights and compensation factors for different decision-maker groups

Ind.	Irrigators		Environmentalists		USFWS/NMFS		USBR	
	α	*p*	α	*p*	α	*p*	α	*p*
Solution Delivery								
Water Conservation Availability	0.40	2	0.80	4	0.70	4	0.60	2
Technical Feasibility	0.60		0.20		0.30		0.40	
Ecological Sustainability								
Environmental Enhancement	0.25	3	0.90	2	0.75	2	0.60	3
Uncertainty/ Risk	0.75		0.10		0.25		0.40	
Conformance with Strategic Mission								
Economic	0.45	2	0.05	2	0.10	4	0.20	4
Legal/Fairness	0.36		0.05		0.10		0.30	
Regulatory Compliance	0.18		0.90		0.80		0.50	

Table 55. Level 4 weights and compensation factors for different decision-maker groups

Ind.	Irrigators		Environmentalists		USFWS/NMFS		USBR	
	α	*p*	α	*p*	α	*p*	α	*p*
Water Conservation Availability								
1	0.35	4	0.45	2	0.45	3	0.47	3
2	0.26		0.09		0.09		0.13	
3	0.22		0.09		0.18		0.13	
4	0.17		0.36		0.27		0.27	
Technical Feasibility								
5	0.12	3	0.07	1	0.12	2	0.22	4
6	0.12		0.21		0.18		0.17	
7	0.29		0.14		0.18		0.22	
8	0.24		0.14		0.12		0.11	
9	0.06		0.29		0.24		0.17	
10	0.18		0.14		0.18		0.11	
Environmental Enhancement								
11	0.25	1	0.42	4	0.30	3	0.36	2
12	0.25		0.33		0.40		0.27	
13	0.50		0.25		0.30		0.36	
Uncertainty/Risk								
14	0.29	3	0.10	1	0.18	2	0.25	3
15	0.21		0.40		0.36		0.25	
16	0.36		0.20		0.18		0.17	
17	0.14		0.30		0.27		0.33	
Economic								
18	0.29	3	0.25	1	0.25	2	0.27	4
19	0.24		0.42		0.38		0.27	
20	0.19		0.25		0.25		0.09	
21	0.29		0.08		0.13		0.36	
Legal/Fairness								
22	0.28	3	0.14	1	0.30	2	0.15	2
23	0.39		0.57		0.40		0.46	
24	0.11		0.14		0.20		0.23	
25	0.22		0.14		0.10		0.15	
Regulatory Compliance								
26	0.18	1	0.40	1	0.33	3	0.33	3
27	0.09		0.13		0.22		0.22	
28	0.18		0.13		0.06		0.11	
29	0.27		0.07		0.17		0.17	
30	0.27		0.27		0.22		0.17	

4.3.5 Summary of Indicator Attributes

Table 56 is an ordered list of modernization and hydro-ecological criteria summarizing the decision elements at each level in the indicator hierarchy. At Level 1, the project-alternatives are analyzed and ranked by the results of relative indices for *Solution Delivery*, *Ecological Sustainability*, and *Conformance with the Strategic Mission*. At Level 2, the modernization indicators for seven evaluation objectives are assessed in terms of a series of inter-related criteria (Level 3) based on the modernization indicators (Level 1). The involvement of multiple decision-makers in a water resources conflict situation is facilitated by incorporating each group's relative preferences and areas of emphasis in terms of criteria weights.

4.4 Modernization plan assessment

Applying the methods outlined in this chapter to water resources planning establishes a ranking of project-alternative rating indices useful for decision analysis. Different modernization plans can be practically assessed and recommended by engineers for prioritizing future design and analysis of construction costs, financing, water rights negotiations, water transfers, etc. The leading-edge water balance and internal processes analyses techniques are integrated with the systematic determination of which project-alternatives are preferred by one or more decision-makers and implementable from the standpoints of scale and technology. Transparent decision steps facilitate an in-depth analysis of many technical features of irrigation modernization.

The key characteristics in the ranking of project-alternatives to serve as decision analysis tools have been defined for a series of criteria that measure some aspect of irrigation modernization. Using the composite programming algorithm different alternatives can be assessed through a robust logical-mathematical procedure with quantified groupings of indicators and subjective ratings. This integrated technique evaluates the predicted results from alternative implementation strategies as measured by various criteria that fall within a reference value range, according to user-defined desirable and critical threshold values. The decision model used in a real-world, long-term water allocation problem can be modified with different weights or used with different estimates of achievement according to the particular conditions. Once the procedure has been performed for different project-alternatives, an ordering is given for each thematic group. Standout compromise alternatives are identified by high ratings in the measure of long-range goals; fields of needful activity or further analysis are clarified by low ratings. The best scenarios from the economic and environmental point of view have common tendencies that can be illustrated by case study examples.

Table 56. Summary of key modernization indicator criteria and attributes

Modernization Indicator [Level 4]	Water Management Objective [Level 3]	Planning Assessment Groups [Level 2]	Project-Alternative Evaluation [Level 1]
Amount of water available from a reduction in irrigation diversions or efficiency improvements	Water Conservation Availability	Solution Delivery	Total Evaluation
Degree of reliance on groundwater resources			
Change in groundwater depth over time			
Reduction of availability in drought years			
Net reduction in the amount of land irrigated (annual basis)	Technical Feasibility		
Efficiency of water use (post-project percent increase)			
Maintenance cost			
Water Delivery Service (composite index)			
Number of years for project completion			
Proven technologies of modern water control and measurement			
Endangered or threatened species habitat will benefit	Environmental Enhancement	Ecological Sustainability	
Contribution to in-stream flow conditions			
Change in water quality of drainage (load reductions)			
Complexity of engineering design and technology	Uncertainty/ Risk		
Resistance to flood or drought influences			
Requires adoption of innovative by a significant number of water users			
Possibly vulnerable to unexpected change(s) in flow regime over the long-term			
Construction costs	Economic	Conformance with Strategic Mission	
Amount of project cost per MCM of water conserved			
Net increase in energy costs			
Cost sharing required by water district(s)			
Perceived equity of water reallocation	Legal/Fairness		
Preservation of existing water rights			
Involving multiple water districts (number of project partners)			
Restrictions on crop types or calendars			
Compliance with ESA and other environmental laws	Regulatory Compliance		
Degree to which the current mandates of agencies are adequate for implementation			
Basis of user compliance is quantitative or qualitative			
New positions required for monitoring project implementation and outcomes			
Synergy with other existing or planned initiatives			

5 Assessing Future Modernization Alternatives: Application to Engineering Case Studies in the Klamath Irrigation Project

> "Don't limit the future by what is built now."
>
> *– John L. Merriam*
> *Professor Emeritus*
> *California Polytechnic State University*
> *2000*

Case studies can provide insight into how the real world of water management works. In this chapter, applications of the modernization criteria assessment are illustrated for strategic scenarios with varying impacts on the general scale and pattern of water use in the Klamath Irrigation Project. Irrigators and other parties with an interest in resolving water conflicts in the Upper Klamath Basin have several options. Some of these entail risking continuation of the status quo to leave competing interests to battle it out in the courts and media in a winner-take-all contest. There are, however, some win-win opportunities available to achieve and reinforce both environmental goals and sustainable irrigated agriculture. The irrigation modernization alternatives evaluated in the following sections illustrate the complexities of analyzing theoretical, but technically feasible, engineering solutions. Multi-criteria decision-making through the modernization criteria assessment decision analysis tools developed in this study yield important benefits.

5.1 A Water Bank Program for Additional Environmental Water Supplies

With the ability to further develop new water supplies increasingly limited in places such as the Klamath River Basin, some 'already developed' and used water must meet growing demands for environmental-protection measures. One potential strategy, tested in California in the drought years of the 1990s (Postel, 2000), falls under the general heading of *water banking*. Water banks have been created in many water deficit areas of the western U.S. for a variety of reasons (MacDonnell et al., 1994). In simple terms, a water bank is a water exchange market operated to assist the voluntary transfer of water rights to other authorized uses. A water bank could provide irrigators, now focused nearly exclusively on protecting their water rights, with the opportunity for improving the certainty of future water supplies and supporting a viable agricultural economy. By voluntarily relinquishing use of a portion of the water they now use, irrigators could also provide a source of funding for modernizing system operations and management.

Water banking represents a means for developing additional supplies during the irrigation season so that this water could be used for augmenting Klamath River flows for the benefit of threatened coho salmon. However, the Klamath water bank would not be a physical reservoir of stored water but an administrative mechanism through which the USBR could contract with irrigators to purchase their water entitlement for a season. Through these contracts irrigators would agree and be compensated to either: (1) forego irrigation altogether (crop idling); (2) irrigate only with well water (groundwater substitution); or (3) pump their well water into irrigation canals for others to use (groundwater pumping), thus making water available to supplement releases from Upper Klamath Lake during critical spring and summer months.

A water bank is an institutional mechanism for the market valuation of water rights. The type of water bank assessed for this study is one type of what is referred to as an acquisition bank, in which water is purchased by a single buyer (USBR) for a specific use (augmenting river flows). The objective of the water bank would be to provide a more flexible and cost-effective water allocation strategy in times of water shortages. Even though some guidelines are already outlined in the biological assessment presently in force (USBR, 2002), the water bank approach in this scenario highlights possible programmatic opportunities that would enhance the process.

The willingness of irrigators to participate in a water banking program would depend on the difference between the price paid for the water and the net revenue a farmer would expect to earn by irrigating. However, besides many hydrological and environmental-related concerns, culture and tradition also play an important role in the acceptance and feasibility of such a market-based framework. Many irrigators rightly perceive that their most economically valuable resource is their irrigation water right and recognize that their future and present livelihoods are directly linked to keeping appropriated water within the Project. Clearly, significant institutional obstacles face the introduction of a new water marketing approach in the Klamath River Basin – including state water laws, third-party impacts, and restrictions on transfers between federal and state jurisdictions.

Currently, the institutions for water banking in the Project are incomplete (Braunworth et al., 2002; Jaeger, 2004a). Unadjudicated water rights and the lack of precise water measurement at some locations would further complicate implementation. However, Huffaker et al. (1993) have judged these types of issues to be surmountable, given that enough financial resources are available, and that augmenting in-stream flows for the protection of fish habitat through water banking has been evaluated as a cost-effective policy in some areas (Willis and Whittlesey, 1998; Willis et al., 1998). Oregon water law[17] does allow for water rights transfers from agricultural diversions for in-stream flows, both temporarily and permanently, but the OWRD must certify that no adverse third-party effects will be created. Still, it is predictable a water bank would ultimately be challenged in the courts by at least some groups, regardless of its final make-up.

The present analysis assesses water banking as a modernization strategy for developing new supplies for in-stream environmental flows in the context of the Klamath Irrigation Project. Given the interdependencies involved not only with the allocation of irrigation water, but also the maintenance of canals and other infrastructure, collection of fees for service, and the need to coordinate among multiple irrigation districts, it is presumed in this scenario that the water bank would be operated and managed by the USBR with well-defined rules for participation and pricing.

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[17] Instream Water Right Act (1987), SB140.

5.1.1 Determining the Required Size of the Water Bank

The 2002 USBR biological assessment included a provision for establishment of an annual water bank as an RPA[18] through which additional water supplies would be made available for fish and wildlife purposes and to enhance tribal trust obligations (USBR, 2002). It was envisioned that the size of the water bank would gradually increase each year according to a schedule contained in the NMFS biological opinion to avoid a jeopardy finding (NMFS, 2001). The size of the annual water bank would increase from 37 to 123 mcm through four steps (30,000-100,000 acre-feet) to be released during spring and summer months.

The scale and impact of the water bank can be understood by assessing an example of dry water year type conditions (2002) compared to the prescribed operational flow criteria at the Iron Gate Dam in the Klamath River. **Figure 36** illustrates a river flow regime augmented by a water bank consisting of approximately 89 mcm of spring and summer releases. Average daily augmented flows would have had to be about 8 cms. (Note: The relatively high river flows in February and March represent spill conditions from Upper Klamath Lake.)

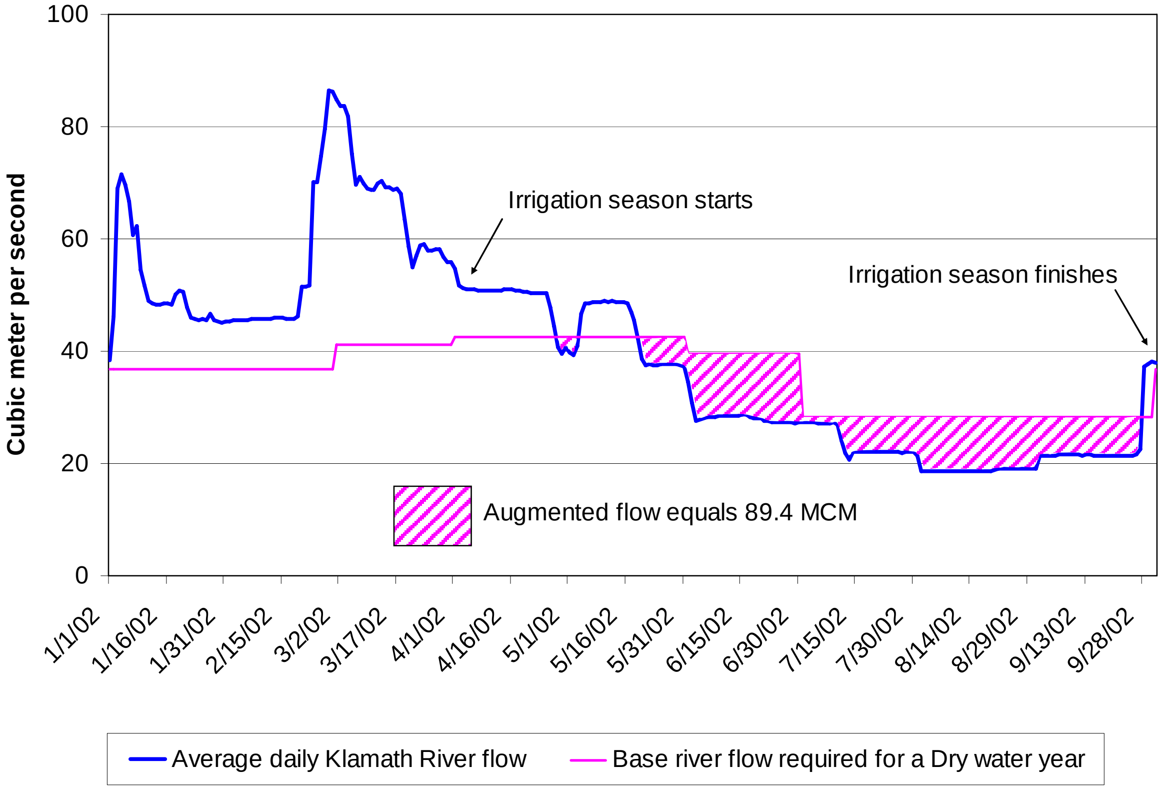

Figure 36. Prospective augmented Klamath River flows from a water bank based on dry water year type conditions in 2002

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[18] The intent of an RPA (Reasonable and Prudent Alternative) is to outline an alternative action to be implemented by the USBR that is judged by the NMFS to be economically and technically feasible, within the agency's authority, consistent with the original intent and purpose of the Klamath Irrigation Project, and that would avoid jeopardy of the listed species or adverse modification of critical habitat.

In terms of implementation, water would accrue to the water bank over the course of the entire irrigation season as water bank participants forego irrigating by fallowing fields or substituting with groundwater. As such, because the USBR is required to make the releases of "banked" water for the benefit of salmon habitat in the spring before sufficient water has accrued to the water bank, it would have to borrow water from the bank for short-term supplies, to be replaced by foregone irrigation over the course of the season.

Although the area of crop land idled (measured by sign-ups in a program) is a useful indication of a water bank's impact, it alone does not provide a reliable estimate of the true extent to which irrigation water would be made available for river flows. The precise impact of a water bank cannot be determined before the fact because of year-to-year variations in irrigation demands and determining factors such as temperature, precipitation and crop types. Due to the factors such as different weather conditions and variable groundwater contributions tied to long-term climatic trends, and different fields (soil types) that are planted, it is impossible to have a program that will guarantee exactly "X%" reduction in net diversions when compared to the previous year.

As explained in Section 3.12 – *Availability of Irrigation Water for Conservation*, the amount of water obtained for the water bank per hectare of land is roughly equivalent to about 600 mm (ET_{iw}); the actual value varies depending on crop type (350-700 mm). Assuming that a significant portion of the bank is acquired from the idling of highest water-use crops, it would still require a considerable portion of the irrigated area in the Project to be fallowed – about 30% of the average area currently irrigated. Furthermore, because crop idling would provide little water from April to June, such fallowing by itself would not provide sufficient water to meet spring river flow requirements under the biological opinion unless some groundwater substation (groundwater pumping) were part of the program as well.

5.1.2 Potential Future Benefits

There are a number of important advantages to a water bank program from the general viewpoint of the irrigation community. One is that with a well-structured and well-defined program, transferable water would be identified (quantified) and questions about future supply certainties could be resolved within the procedure. The water bank would serve as a means for meeting regulatory compliance with the USBR acting as the entity legally authorized to manage the program in a similar way to it current's role of overall water resources manager in the Project. Irrigators would know in advance the rules governing the purchase of water from the bank. Prices would be allowed to adjust to the supply and demand for the portion voluntarily placed into the bank by water rights holders. Further, irrigators could find in some cases that they may earn more money by selling a portion of their water through the bank.

As already mentioned, some of the funds received for banked water could be used potentially for system improvements (modernization). The water bank could also serve as a vehicle for irrigation districts to commence internal discussions, supported by their members, about procedures and conditions under which service fees for historically diverted water can be offset. If the board of directors of a district is not able to agree on acceptable terms, they could direct their members not to participate.

Irrigators need not permanently sell or transfer their rights, nor do they need to stop irrigating all their lands. However, such a dire outcome is one possible risk if conflicting parties continue with litigation. A water bank is a positive step towards habitat restoration and fish protection and should reduce resistance to the concept of agricultural-environmental water transfers. From the perspective of the USBR and other regulatory agencies (within and outside of the Department of Interior), a water bank program should have lower implementation and verification costs than other options to develop new surface supplies (i.e., building new off-stream reservoirs).

5.1.3 Management Concepts

The implementation of a water banking program as a water reallocation alternative for fish protection and long-term water supply certainty for irrigators would benefit from due consideration of program management and verification issues. Although the biological opinion recommended a water bank as an RPA, little specific guidance regarding the structure, management or operation was proposed. Provided there is public support and the institutional capacity needed to carry out a water bank approach, the following recommendations and guidelines are offered:

- It is evident that the configuration of the water bank program must take advantage of multiple management options. For example, groundwater pumping could provide water for increased spring time river flows, whereas other options such as crop idling are really applicable only when consumptive use is reduced in late spring and through the summer.
- Flexibility in obtaining the desired river flows without undue penalty to the Project's irrigators in severe drought conditions would be enhanced by expanding the water bank to the entire Upper River Basin above Iron Gate Dam. Irrigated lands in the Project account for approximately 57% of the total amount in the Upper Klamath Basin.
- Estimates of ET_{iw} (from modeled crop water use) would form the basis for the USBR to quantify the impact of idling specific areas of land.
- Variability in the climate of the basin, where runoff from the winter snowpack provides stream inflow for the Project, imposes the greatest hydrologic influence on river flow volumes and, therefore, water bank requirements. During prolonged dry periods, some adjustments to the water bank requirements should be made to take this variability into account instead of rigid monthly targets based solely on water year type (calendar year). For example, the annual water year type designation could be adjusted after the water season finishes in October based on current hydrologic conditions and precipitation in order to minimize the possibility of shortages in the following spring because of higher requirements that result from unmet forecasts in the previous spring.
- A key question regarding verification is whether the total fallowed area in a water banking year is the same as previous years. The water balance analysis in Chapter 3 indicated that the average fallowed area was close to 6% of total cropped area (1999-2003). Perhaps (rough approximation) half of this was permanently fallowed on a historical basis. That means 3% was "annual" fallow – about 2,350 ha (5,800 acres). There are two possible basic approaches for verification: (1) ignore the details and active field verification, and just de-rate the price per area, or (2) become involved in a fairly detailed administrative (and possibly adversarial relationship) procedure to verify new fallowed acres.

- If it is decided to only pay for “new, expanded fallowed area” then a possible administrative scenario is as follows: (1) USBR can use satellite photos to estimate the fallow area per irrigation district for several “historical” years, to use as a benchmark; (2) the irrigation districts can be brought into the selection procedure (see discussion below); (3) the irrigation districts can make the final selection of approved lands, but the irrigation districts must verify that only the fallowed area in excess of historical numbers be paid for; (4) the payment should be made to the irrigation district, which will disburse the funds to the participating farmers; and (5) a portion of the payment to the districts will be withheld by USBR until final verification of compliance.
- The impact of a payment scheme that only reimburses the irrigation districts for excess fallowing will be that the effective payment may only be one-third to one-half (per field) of payments otherwise. This may dramatically decrease the response to this particular program. But the other option is to pay for fields that would have been fallowed in any case. It is therefore recommended to let the districts decide exactly how the payments will be disbursed.
- Accurate verification of the water bank’s impact on river diversions would require a robust monitoring network and the installation of new measurement stations to reduce uncertainty associated with surface flow data. The assigned *CIs* for surface diversions in this study ranged from 5% to 70%. Although diversion and return flow data have known errors, these data provide the best method to directly measure the program’s benefits.
- The requirements for augmenting river flows should be linked to targets that are hydrologically attainable and based on historic stream flow data from a time period longer than the 10-yr planning period in the biological assessment. Flow data is available for periods of 20, 30 and 40 years.
- Establish criteria to give higher priority to idled fields at the ends of laterals, especially “stub” laterals. If this is done, there will be no spill or other conveyance losses along a whole section of canal.
- There is presently no written requirement for flow meters on groundwater wells, but the reimbursement would be for volumes of pumped water (cubic meters). The USBR should require independent recording of the totalizer at the beginning and end of the season.

5.1.4 Water Bank Benchmarking and Transformation Results (Level 3)

The results of the water bank assessment for the key modernization criteria in Level 3 are summarized in **Table 57**. The modernization criteria assessment ranked the water bank project-alternative relatively high for all decision-making groups in terms of water conservation and uncertainty/risk. However, the water bank project-alternative did less well in the indexed values for economic indicators. The individual Level 4 performance indicator values and transformed values (0 to 1 scale) are presented in **Appendix 4**.

In the Klamath Irrigation Project, net revenues (and hence the value of water) differ across location, soil class, and crop, which are reflected by differences in agricultural land prices. Jaeger (2004b) estimated that net returns for each acre normally irrigated in the Project ranges from approximately \$125 per ha for Class V lands to as high as \$1,000 per ha for Class II lands in the Tule Lake area (\$100-\$2,600 per acre).[19] In the same study, the marginal value of applied irrigation water in the entire Upper Klamath Basin ranged from approximately \$22 to \$300 per ha, with the weighted average being approximately \$60 per ha (assuming a 6% discount rate). These estimates of the annualized value of irrigation water reflect information on crop rotations and historic market fluctuations useful for approximating characteristics about the economics of irrigated agriculture in the Project. Adams and Cho (1998), using a farm-level economic model, estimated the marginal value of water (per unit volume) as \$18 per m^3 for a representative farm with low-value crops up to \$64 per m^3 for farms with a high percentage of high-value crops, such as onions and potatoes [assuming a base delivered water supply of 0.82 m per ha (2.7 acre-feet/acre)].

Based on these economic studies and the expenditures the USBR incurred for the emergency groundwater pumping during the 2001 drought, it is estimated that a water bank program could potentially cost about \$8 million annually. For a conservation target of 123 mcm per year, this represents a program cost of approximately \$66,000 per mcm. This equivalent annual cost would include a \$1,000,000 start-up cost and the USBR's annual administrative costs for payroll and overhead to administer the contracts, as well as other incurred costs related to the operation of the water bank, such as water quality analyses, contract compliance monitoring, and separate contracts for external agency support from the USGS, OWRD, etc.

Table 57. Index values for the Klamath Irrigation Project water bank (Level 3)

Modernization Indicator	Irrigators	Environmentalists	USFWS/NMFS	USBR
Water Conservation Availability	0.98	0.95	0.97	0.97
Technical Feasibility	0.47	0.57	0.57	0.55
Environmental Enhancement	0.46	0.75	0.70	0.63
Uncertainty/Risk	1.00	1.00	1.00	1.00
Economic	0.59	0.41	0.61	0.57
Legal/Fairness	0.67	0.52	0.58	0.71
Regulatory Compliance	0.62	0.71	0.71	0.66

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[19] The major source of heterogeneity is variations in soil productivity, ranging from Class II to Class VI with higher class numbers indicating progressively greater limitations on what crops can be grown (refer to Section 3.3.2 – *Soil Resources*).

5.2 Integrated Drain Water Recirculation and Disposal

Providing full deliveries to agricultural water users, meeting environmental flow obligations under the biological opinions, and reducing the outflow of poor quality drain water to the Klamath River are possible through a project-alternative involving district-level recirculation, while still retaining the general scale and pattern of water use in the Klamath Irrigation Project. This section describes an irrigation modernization project-alternative that was identified during the RAP evaluation of current water operations in the Tulelake ID. The *Tule Lake Sump – J-1 Lateral Recirculation Project* would integrate real-time operations of project-wide irrigation facilities including the Tule Lake Sumps, the D Pumping Plant, and the J Canal, along with providing new water supplies for the LKNWR.

5.2.1 Potential Future Benefits

An innovative solution was developed as part of this dissertation to recirculate water in the Main Division of the Project from the Tule Lake Sumps to the J Canal. The design concept would utilize the operational storage of the sumps and move water on-demand to the J Canal through a series of VFD (Variable Frequency Drive) automated low-lift pump stations in the reverse direction of an adjoining irrigation lateral (J-1 Lateral), thereby idling the D Pumping Plant [3,650 HP; 8,500 lps (300 CFS)] during critical peak demand times.

Meeting future challenges over water supplies and water quality in the Project requires a judicious use of resources aimed at win-win projects that are capable of addressing multiple objectives. In this case, the proposed recirculation project would make significant contributions towards increasing district *IE*, simplifying operations, reducing annual power costs for pumping, and in addition, become an integral part of the strategy to improve water quality and conservation in the Klamath River.

This project-alternative would utilize part of the water that is currently being pumped from the sumps at the D Pumping Plant as a flexible on-demand source of irrigation water to supplement demands in the J-1 Lateral, and thereby allow more water to remain in the J Canal on an as-needed basis. In addition, the design of the proposed infrastructure would allow operators to supply water to the J Canal from the sumps via the J-1 Lateral as a supplemental water supply. Further, as farmers upgrade their on-farm management to improve efficiencies there will be a requirement for more flexible operation of the J Canal, which is a central feature of this project.

The potential future benefits of this recirculation system include the following:

- Water conservation through a reduction of diversions from the Klamath River/Upper Klamath Lake to Tulelake ID, because more of its original deliveries will be recirculated within Tulelake ID
- Enhanced water quality in the Klamath River through basin-wide water management
- Greater operational flexibility in water diversions to Tulelake ID, near its source
- Augmenting water supplies to Tulelake ID through more use of drainage flows
- Reduced reliance by Tulelake ID on expensive groundwater pumping
- Reduced power consumption that is presently required to pump large volumes of water through the D Pumping Plant
- Better control of water deliveries to the LKNWR
- Simplified operations for field operations staff

In addition to the benefits of the flexible operations that this project-alternative would provide to local growers, it would also mean a substantial reduction in power costs for pumping. Pending the upcoming FERC re-licensing of the Klamath Hydroelectric Project (151 MW) there will be substantial increases in electricity rates for farmers and irrigation districts. When the current hydropower deal that has given Klamath farmers some of the lowest rates in the nation runs out in 2010, pumping costs may soar by 10-15 times.

A major justification for this approach is based on the fact that the total pumping lift (water elevation difference between the sump and the J Canal) is about 4 m (13 ft), compared to over 18 m (60 ft) of pumping lift for the D Pumping Plant. This represents a potentially large project-level financial benefit. Tulelake ID has estimated that without the recirculation project-alternative, annual pumping bills could rise dramatically from $40,000 to about $1 million based historical conditions.

5.2.2 Background

The J-1 Lateral is located in the northwestern section of the Tulelake ID as shown in **Figure 37**. It is an unlined channel approximately 10.5 km long (6.5 miles). There are a total of ten (10) existing check structures in the canal, which consist of different arrangements of automated and manual sluice gates with side overflow weirs. The lateral system serves approximately 2,800 ha (7,000 acres) of alfalfa, onions, potatoes, peppermint, and small grains in Class A areas of the Project. It is the first lateral canal to offtake from the J Canal. The supply canal serves the J-1-a, J-1-b, J-1-c, and J-1-d sub-laterals as well as 38 direct turnouts. Most of the adjacent fields served by the system are irrigated with pressurized systems; farmers pump from small turnout boxes supplied by the network of lateral and sub-laterals.

The J-1 Lateral is served by the J Canal, which is the main canal conveying irrigation water to Tulelake ID from the diversion at the Anderson Rose Dam. At certain times during the growing season, irrigators along the J Canal may suffer water shortages as a result of operational difficulties in reconciling the nature of variable demands in the system (e.g., frost protection, weekends, etc.), and the long travel times and variable drain water inflows from upslope irrigation districts. In a typical year, Tulelake ID diverts about 150 to 175 mcm (120,000-140,000 acre-feet) of water at Anderson-Rose Dam; however, the district actually delivers over 250 mcm (200,000 acre-feet) of water due to internal recirculation (refer to Section 3.10.2 – *Subregional Water Balances*).

Upslope return flows from the Lost River system and drain water generated internally within Tulelake ID flow to the Tule Lake Sumps (units 1A and 1B) where it is stored until some is pumped at the D Pumping Plant to the LKNWR. (Return flows are applied irrigation water that is unused by crops and recaptured in drains for re-application elsewhere.) Surface and sub-surface drainage water and recharge is recirculated at numerous points within the district. The D Pumping Plant is primarily used to maintain water elevations in the sump based on prescribed targets in the biological opinions and prescribed operations rules. While the sump currently provides some buffer storage for return flows, the existing infrastructure does not permit *district-level* recirculation.

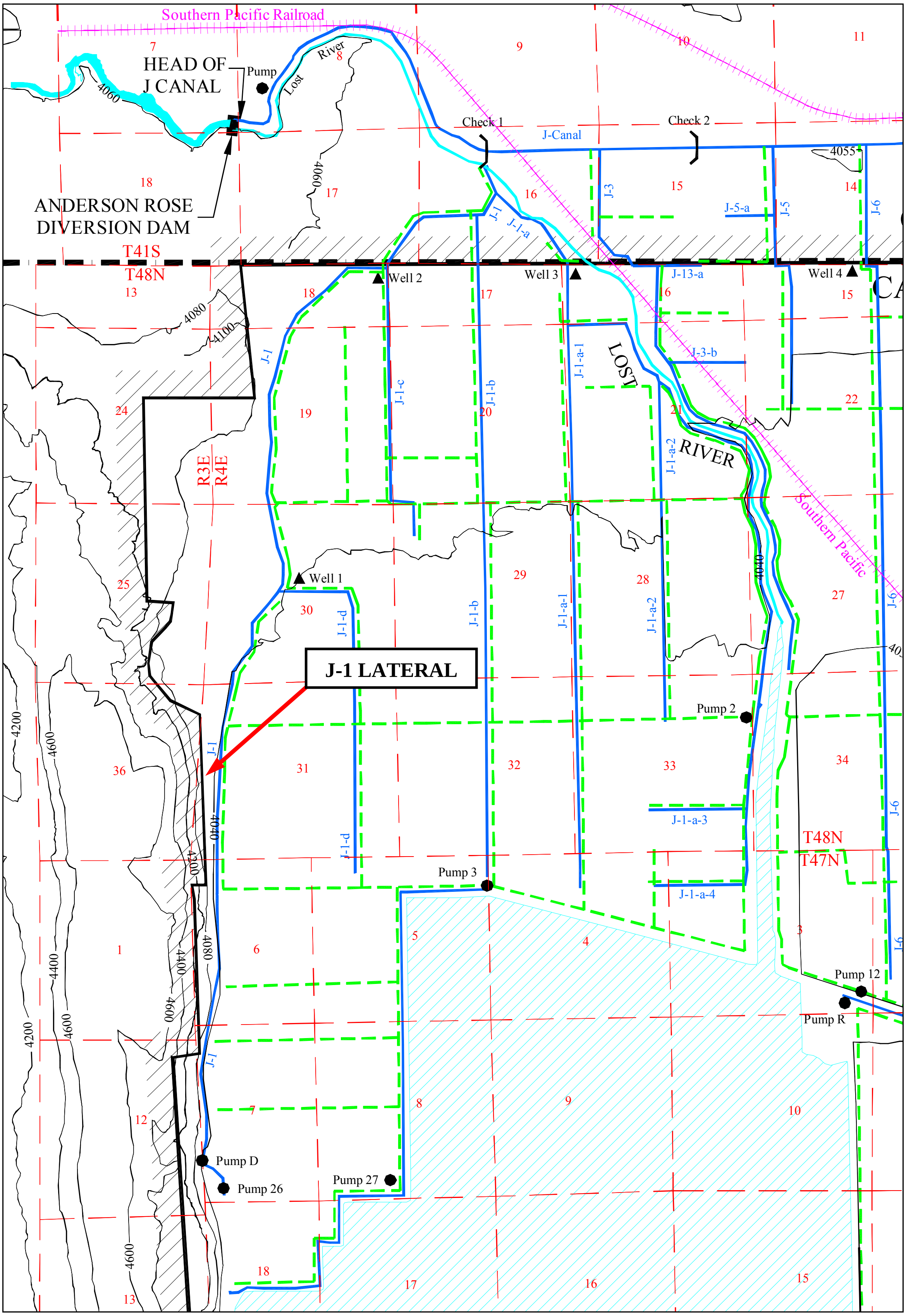


Figure 37. Location map for the *Tule Lake Sump – J-1 Lateral Recirculation Project* modernization project-alternative

5.2.3 Conceptual Design Features for Modernization

A number of innovative physical infrastructure modifications would be required to recirculate water from the sumps to the headworks at the J Canal. In addition, the implementation of the proposed recirculation project would require modifications to the operational strategy and infrastructure within the LKNWR and Straits Drain to provide an alternate water supply to the refuge complex, while curtailing discharge of drain water to the Klamath River. Preliminary design information and conceptual sketches are presented in this section to summarize the basic functions of the system in terms of daily operation and the linkages to environmental goals.

The proposed recirculation project would consist of:

- A remodeled, concrete or geomembrane-lined canal that will replace the existing J-1 Lateral. The estimated design capacity of the new lined canal is 5 cms (180 cfs) at both ends.
- Six VFD-equipped low-lift pump stations between the sumps and the J Canal, automated using downstream control algorithms
- Four (4) new sluice gate headworks for the lateral canals being served by the main lateral with automatic flow control.
- Two PLC-automated upstream water level control gates
- A SCADA system for monitoring and control in the J-1 Lateral system that would be integrated into the district's existing telemetry system.

5.2.3.1 Advanced Canal Automation Techniques

To contribute to the district-level water management objectives, the proposed recirculation system would combine elements of both state-of-the-art upstream and downstream automatic canal and pump control. Advanced control algorithms and hydraulic network model simulation techniques would be required to automate the pump stations along with the check gates in the irrigation canals and reservoirs for quick response to irrigators desired start-up and shut-down times.

Three basic modes of operation would be possible with the new system:

1. All water in the J-1 Lateral system is supplied by the J Canal, with no pumped recirculation.
2. All water in the J-1 Lateral is supplied by pumping from the Tule Lake Sump, making more water available in the J Canal for needs downstream. Extra water could also provide a flexible and supplemental supply to the J Canal.
3. Water for the J-1 Lateral is supplied by a combination of gravity flows from the J Canal and pumped water from the Tule Lake Sump. This is the scenario that is expected to occur most frequently.

The amount of water being pumped to satisfy irrigation demands in the J-1 system would depend on: a) the number and flow rate of turnout deliveries, and b) the flow rate turned into the head of the lateral. Operators could choose to manually reduce or increase the flow at the headworks in order to meet demands further downstream in the system. One of the pumps at each check structure/pump station would be equipped with a VFD controller in order to be able to fine-tune the pumped flow rate to precisely maintain the water level in the upstream pool. Control would be done with a PLC using proven control algorithms tuned specifically for this canal. The situation is similar if an irrigator or canal operator wants to reduce the delivery or shut-off a turnout – the pumps would automatically reduce the inflow to the system accordingly.

The new headworks of the sub-laterals would be automated for flow control. The motorized headgates would automatically maintain a target flow rate using PLCs and sensors reading new measurement structures. The headworks would therefore be able to maintain a constant target flow rate into the laterals regardless of which direction the water is flowing in the J-1 system.

The proposed project would not affect the ability to pump water from the sump via existing facilities to the refuge. This project-alternative would therefore comply with the existing biological opinions and TMDLs for the sumps and refuge areas, meeting target sump elevations for different times of year.

5.2.4 Water Quality Analysis (Salinity)

In order to assess whether more recirculation would cause long-term harm to irrigators because of an increase in salt loading, water quality data was analyzed. The J-1 Lateral service area has three water sources:

1. Water that originates from the Lost River (station 48 on the LRDC) and return flows from Klamath ID and other upslope districts, that is distributed through the J Canal
2. Groundwater pumped by well pumps designated “TID1” and “TID2”
3. Tule Lake Sump water

Approximate salinities of these three water sources, using USBR-supplied data for the months of June-September, are shown in **Table 58**.

Table 58. Mean water quality of water sources in the J-1 Lateral service area (2004)

Water Source	Description	Salinity, dS/m
Groundwater	Well (TID1)	0.61
Groundwater	Well (TID2)	0.26
Surface supply	J Canal	0.22
Tule Lake Sump	Pumped from D Plant	0.50

Assuming a salt-sensitive crop that has a salinity threshold EC_e of 2.0 dS/m, the required leaching requirement for the J Canal water is about 2.3%, whereas the leaching requirement for the Tule Lake Sump water is about 5%. This is a difference of about 2 cm (0.7 inches) of irrigation water requirement per year for the leaching requirement, for the sensitive crops and typical climate conditions in the local area. In practical terms, this is insignificant and the required deep percolation for salt control can realistically be expected to occur with normal non-uniformity that occurs with irrigation.

What is particularly interesting is that the sump water is apparently of better quality than the TID1 (groundwater well) water. Depending upon the particular usage of water during a year, the water quality in some areas of the J-1 Lateral service area may actually increase if the sump water is used, rather than the TID1 well water.

A legitimate question from irrigators is: Will the sump water salinity increase if more of the water is recirculated rather than discharged through the D Pumping Plant? The answer is: *Yes*, but there will still be significant pumping and flushing of the sump from the D Pumping Plant during non-summer months. Therefore, it is not expected that the sump salinity would increase to a detrimental level. However, it is always prudent to continually evaluate salinity because irrigation practices and pumping policies can change with time. In summary, the soil and water salinities do not indicate that a salinity problem will develop if the project-alternative is implemented.

5.2.5 Impact on the Lower Klamath National Wildlife Refuge

The D Pumping Plant lifts water from the Tule Lake Sump to the P Canal System and the LKNWR. The refuge complex receives water from both the D Pumping Plant and the Ady Canal. Drain water leaves the refuge complex via the Klamath Straits Drain. The flow in the drain, depending on the time of year, is a combination of drainage from the LKNWR, return flows received from the Tule Lake area via D Pumping Plant, and drainage from the adjacent Klamath DD and other private lands. Under the project-alternative, the amount of surplus sump water being pumped from the D Pumping Plant to the P Canal system for use in the refuge area would be reduced significantly or eliminated during the irrigation season. Instead, water from the sumps would be recirculated within the Tulelake ID; LKNWR deliveries would therefore have to be replaced with recirculated drain water from the Straits Drain and increased deliveries from the Ady Canal.

The water being pumped from the D Pumping Plant is a major source of the water currently reaching the Straits Drain (via the P Canal system). Refer to **Figure 38** for a schematic layout showing the locations of the main features of the Straits Drain. To reach the Klamath River, water in the drain that runs off nearby fields or is discharged by the refuge is lifted twice; first, near the mid-point at the E&EE Pumping Plant and again near the boundary of the Klamath DD where it crosses the Ady Canal at the F&FF Pumping Plant. The recommended mechanism for supplying the refuge with recirculated drainage water from the Straits Drain would be reversing the flow in the drain beginning at the E&EE Pumping Plant and then lifting the water again from one or more points along the drain network that runs parallel to Highway 161.

Mean diversion data for the surface inflows and outflows of the LKNWR are summarized in **Figure 39** and **Table 59**. The net inflow from both the Ady Canal and D Pumping Plant sources to the refuge during the 3-month summer period (July-September) was approximately 23 mcm (18,000 acre-feet). The volume of recirculated drain water potentially available to the refuge with a pumping plant to lift water from Straits Drain is equivalent to the amount of water that is pumped to the Klamath River from the F&FF Pumping Plant, less any flow in the drain at the boundary. In 1999-2003, the net mean inflow to the LKNWR from recirculation via the Straits Drain was 10 mcm (8,100 acre-feet).

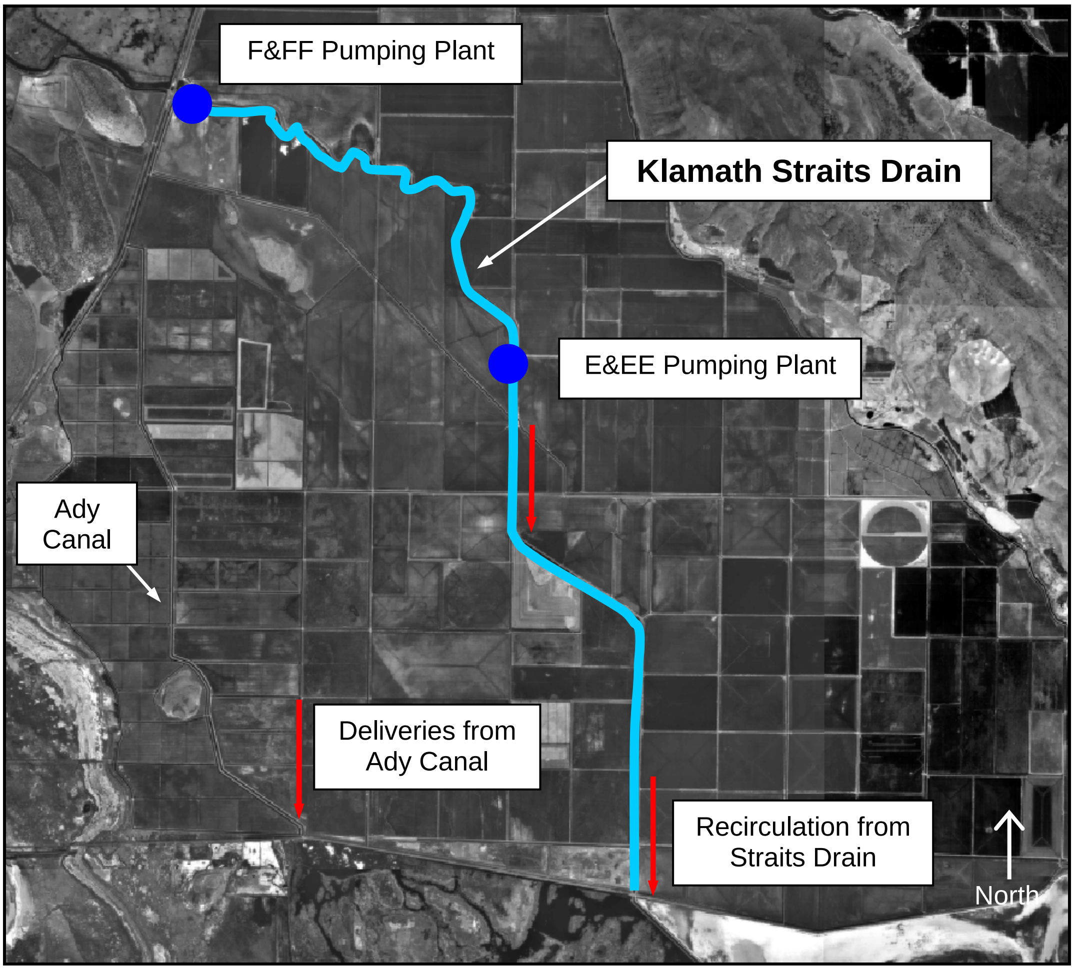


Figure 38. Schematic layout of the Straits Drain showing features of the proposed operation for recirculation to the LKNWR

Historically, refuge operations in the LKNWR have required a base flow rate of 3 cms (100 cfs), when water supplies were available. Assuming a minimum base flow to the refuge of 3 cms is desired during the 3-month summer time period, some additional inflows would have been required during July and September with the proposed 100% recirculation option. Therefore, to provide the desired 3 cms base flow, with a minimum 0.7 cms historical observed flow from the Ady Canal, the additional flow necessary from the Ady Canal would have been about 0.3 to 0.9 cms (10-30 cfs). If the time period of analysis is expanded to a 10-yr period (1990-2000), then it appears additional flows from the Ady Canal would have been required about 40% of the time (monthly basis) with the extra requirement usually about 0.6 cms (20 cfs). Therefore, based on having to provide an extra 3 mcm (2,400 acre-feet) via the Ady Canal to maintain the same net inflow to the LKNWR, and assuming the offset pumping from the D Plant replaces an equivalent in net diversions to subregion 3, the amount of water conservation from this project-alternative is about 20 mcm per year.

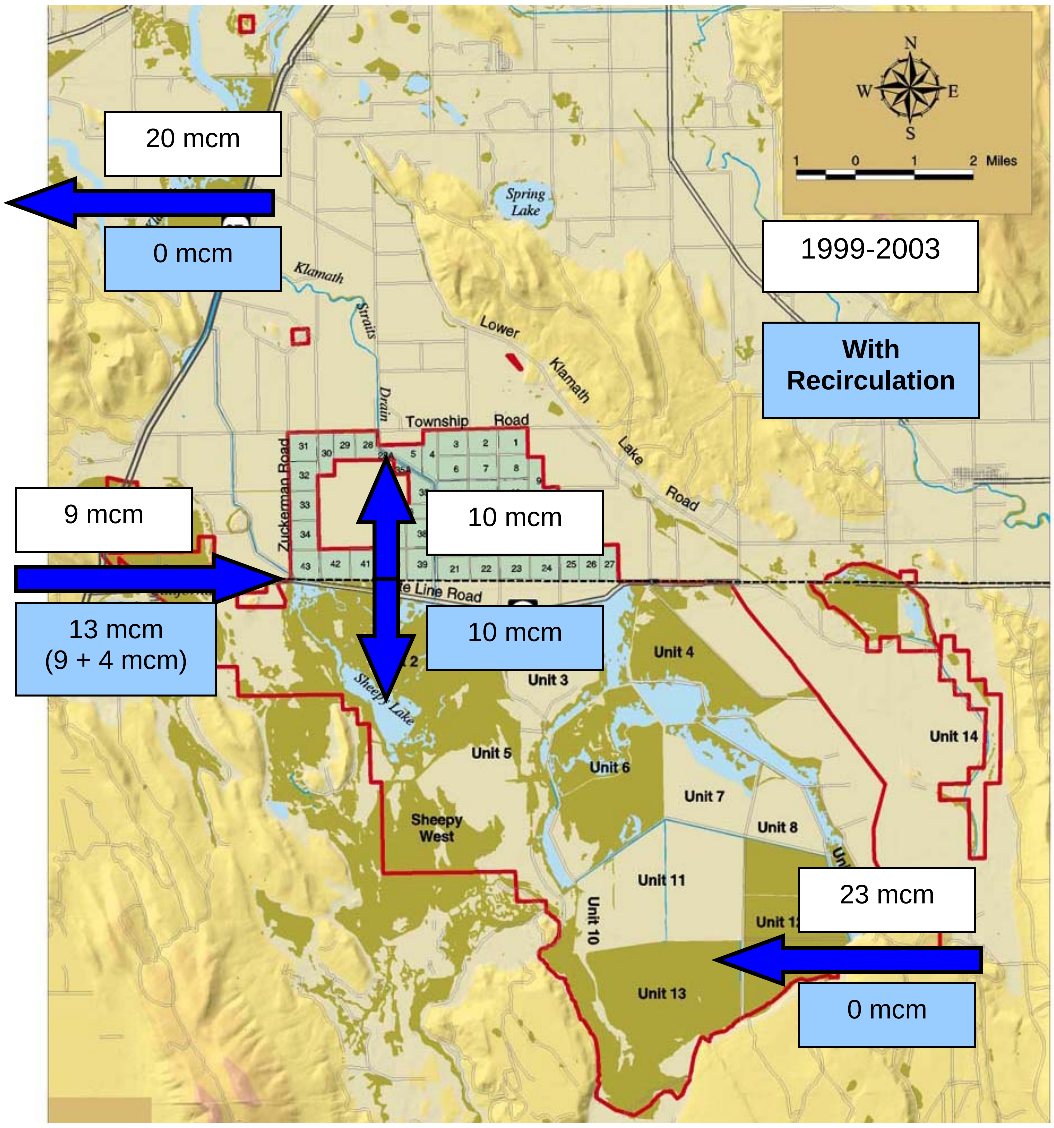


Figure 39. Flow diagram of the LKNWR under historical operation and proposed recirculation

Table 59. Comparison of net monthly inflow to the LKNWR under historical operation and under future condition with no pumping from D Pumping Plant during July to September

Scenario	Measurement Point	July	August	Sept	Total
Net Inflow to refuge under historical conditions	D Pumping Plant	4	8	11	23
	Ady Canal Delivery	3	3	3	9
	Straits Drain (net outflow)	*2*	*5*	*2*	*10*
	Total	**5**	**7**	**11**	**23**
Net Inflow to refuge with 100% recirculation from Straits Drain	*D Pumping Plant*	*0*	*0*	*0*	*0*
	Ady Canal Delivery	5	5	4	13
	F&FF Pumping Plant	6	9	5	20
	Straits Drain (net outflow)	*2*	*5*	*2*	*10*
	Total	**8**	**8**	**7**	**23**

5.2.6 Recirculation Project Cost Summary

Table 60 is a preliminary summary of the implementation and annual costs associated with the planning, design, construction, controller programming, purchase of equipment, etc. for the recirculation project-alternative. The total project-alternative estimated fixed construction cost for the recirculation system is approximately $5.2 million with an annualized cost of about $480,000. Not specifically included in these estimates are any costs associated with permit fees, rights-of-way, or any on-farm modifications to farm ditches and turnout boxes, or any environmental impact studies.

Table 60. Summary of system fixed and annual costs for the recirculation alternative

Item	Construction Costs	Annual Costs[1]
Pump stations and civil works[2]	$850,000	$75,000
Check structure control gates	$130,000	$9,000
SCADA system	$240,000	$25,000
Automation for flow control of lateral headgates	$270,000	$28,000
Flow Meter Installation at D Pumping Plant	$26,000	$3,000
Electric power	$60,000	$69,000
Surveying and soil testing	$15,000	$1,000
Earthwork and excavation	$534,000	$34,000
Canal construction and concrete lining	$2,560,000	$163,000
Engineering and design	$450,000	$29,000
Modeling, verification and field testing	$100,000	$7,000
Annual operation and maintenance	---	$41,000
Total	**$5,235,000**	**$479,000**

[1] Interest rate = 6%. Assumed service lives of 15, 20, and 50 years for SCADA, pumps and electrical, and canals and pipelines, respectively.

[2] Pump station sub-total includes pumps, piping and hardware, electric motors, VFD controllers, platform, building enclosures for pump panels and SCADA equipment.

Taking into account the approximately 52,500 ha that would benefit from this project-alternative (subregion 3 plus the wildlife areas in the LKNWR), the equivalent annual cost on a per hectare basis is estimated to be about $11 ($4.50/acre). Similarly, assuming that annual net diversions are reduced equivalent to the recirculated volume of water, 20 mcm (16,000 acre-feet), the equivalent cost per unit volume of water is estimated to be approximately $30,000 per mcm ($37/acre-foot).

5.2.6.1 Comparison of Pumping Costs *With* and *Without* the Recirculation Project-Alternative

For almost 100 years, PacifiCorp has provided discounted power for the drainage and irrigation of land in the Klamath River Basin. PacifiCorp provides electrical service to approximately 1,400 irrigators in the Project. In exchange, the power company has received the right to regulate flows in the Klamath River for their seven hydroelectric facilities, in accordance with specified elevations for irrigation purposes. This mutually beneficial relationship ended with the expiration of the 50-year FERC license and a gradual transition to cost-based rates was renegotiated.

An analysis was done to estimate the annual power cost savings that would potentially occur if the proposed recirculation project-alternative was implemented. If the project were to be implemented, the D Pumping Plant could be idled for 7 months during the irrigation season. A review of the annual pumping costs for Tulelake ID indicated that the D Pumping Plant is the single largest user of electricity in the district (out of 37 pumping plants) consuming over 8 million kW-hr for pumping in a typical year. The historical electric rate on average has been about $0.004 per kW-hr. Assuming an average volume pumped during the irrigation season of 32 mcm, the power cost for pumping during the irrigation season is estimated to have been about $35,000 (or about $45,000 per year).

Assuming the anticipated increase in the electric rate of 15× the current level is put in place (a tariff rate of $0.08/kW-hr, plus standby charges), the annual pumping bill for the D Pumping Plant (*without* the project) would grow dramatically to over $1 million per year. This estimate assumes no other changes occur in the Project, such as shifts in the timing or volume of inflows and outflows from the LKNWR, or an increase in internal recirculation within Klamath DD and refuge from other projects, or future reductions in the volume of upslope drain water entering the Tule Lake Sumps. In comparison, an analysis of the expected pumping volumes for the series of recirculation pumps in the J-1 Lateral indicates that the annual power bill for the whole system would be about $69,000 for the proposed facilities (refer to **Table 60**). Thus, over $950,000 is estimated to be the possible reduction in annual power costs for district-level recirculation (including the offset from the F&FF and E&EE pumping plants).

5.2.7 Tule Lake Sump Recirculation Evaluation Results (Level 3)

The results of the recirculation project-alternative assessment for the key modernization criteria in Level 3 are summarized in **Table 61**. The individual performance indicator values and transformed values (0 to 1 scale) are presented in **Appendix 4**. The modernization criteria assessment highlighted significant differences between the decision-making groups regarding the attributes of uncertainty/risk and legal/fairness involved with the recirculation project-alternative, particularly for the case where the environmental attributes were considered more important. This project-alternative ranked comparatively low in terms of water conservation availability by all decision-makers. This level of performance was due to the fact that the amount of water to be potentially conserved with this project-alternative was in the lower part of the desirable range and was judged to be vulnerable in drought years, which was an important environmentally-related attribute. The relatively high Level 3 results for the overall economic attributes reflected significant reductions in the pumping costs associated with the district-level recirculation system.

Table 61. Index values for the Tule Lake recirculation project (Level 3)

Modernization Indicator	Irrigators	Environmentalists	USFWS/NMFS	USBR
Water Conservation Availability	0.34	0.14	0.26	0.23
Technical Feasibility	0.72	0.63	0.72	0.85
Environmental Enhancement	0.60	0.79	0.71	0.70
Uncertainty/Risk	0.77	0.45	0.57	0.71
Economic	1.00	0.87	0.97	1.00
Legal/Fairness	0.61	0.45	0.46	0.57
Regulatory Compliance	0.74	0.78	0.77	0.76

5.3 A Project-Scale Plan for System Improvements

This project-alternative entails major changes in the approach to agricultural water management throughout the Klamath Irrigation Project – shifting the scale and pattern of water allocation and use in the Project. Under this project-alternative, the entire water conveyance and delivery system comprising the Project would be modernized with new civil works, automated canal structures, an extensive SCADA system, recirculation schemes, upgraded measurement devices, and new pipelines.

The engineering solutions contained in this modernization project-alternative all have in common a focus on upgrading the physical infrastructure and enhancing the management capacity of the Project to enable irrigation districts to deliver precise flow rates and volumes to known points throughout the complex canal and pumping plant distribution network, even in drought conditions. This would result in better water delivery service to irrigators so they have sufficient opportunity to improve farm-level water management, while minimizing negative consequences to the Klamath River ecosystem. Robust control and good measurement will help make it possible for the irrigation community in the Project to deal with a wide range of future challenges such as TMDLs and increases in electric power rates.

5.3.1 Summary of System Improvements

Table 62 provides a framework for identifying what specific actions can be taken to improve Project-level performance and what opportunities for improved operations or water conservation exist. The summary table is an outline of conceptual items in the project-alternative showing their inter-relationship with various outcomes. One can, thus, recognize how each component would fit into an overall strategy for meeting the objectives of the USBR, irrigators, and stakeholders.

Seven distinct programmatic elements were developed for this comprehensive strategy based on the extensive knowledge and analyses that this study represents. These actions encompass a range of reasonable things available to the USBR and irrigation districts in response to the land use, regulatory, and environmental-driven issues presented in previous sections of this dissertation. The term *programmatic* is used to emphasize that the discussion of the components in this project-alternative evaluated with the modernization criteria assessment tools are broad-based and strategic, and represent many underlying policy-level issues for further consideration and engineering analysis. The system improvements project-alternative was organized by the following categories:

1. Integrated information managements systems
2. Improved real-time control of water volumes and flow rates
3. Changing land use
4. Improved on-farm irrigation efficiency
5. Upgraded pumping plants
6. Off-season storage
7. Groundwater substitution

Table 62. Summary of Project-level system improvements (project-alternative)

Modernization Action Opportunities	Volumetric Allocation	Improved district operation and water delivery service	Improved basic data for water balances and long-term planning	Reduction in pumping costs	Maintain In-Stream Flows in the Lost River	Reduction of Evapotranspiration	Increased surface storage	Substitution of water sources
Integrated Information Management Systems								
Project-wide SCADA system (USBR)	√	√	√	√				
Irrigation district SCADA systems	√	√	√	√				
Rigorous quality control program for data management		√	√					
Flow measurement devices at district inlets/outlets	√	√	√	√				
Weather station maintenance, expansion and positioning			√					
Groundwater basin monitoring program		√						
Improved Real-Time Control of Water Volumes and Flow Rates within Irrigation Districts								
Measuring devices at farmer turnouts and pumps	√	√	√	√				
Improved water level control in irrigation district canals	√	√	√	√				
Flow rate control at key division points	√	√	√	√				
GIS irrigation scheduling and water ordering software	√	√	√	√				
Regulating reservoirs	√	√	√	√	√			
Changing Land Use								
Land acquisition of marginal irrigated fields						√		
Consolidation of wetland areas						√		
Land idling (water banking)						√		
Improved On-Farm Irrigation Efficiency								
On-farm irrigation system evaluation program			√	√	√			
Investment in improved irrigation and drainage hardware				√	√			
Upgraded Pumping Plants								
Variable frequency drive (VFD) installations		√		√				
Pump efficiency testing and pump repairs/retrofits			√	√				
Off-Season Storage								
Modification of Tulelake sumps (raising banks)							√	
Purchase and modification of farm land for reservoirs							√	
Groundwater Substitution								
Increased groundwater pumping								√

5.3.2 General Survey of the Plan’s Components

The complexity of water issues in the Klamath River Basin may eventually require a regional-scale strategic plan for addressing irrigation system improvements through modern water control technology and new operational strategies in order to make the most efficient use of scarce water supplies. The components in this project-alternative are described in the following sections.

5.3.2.1 Integrated Information Management Systems

The first specific type of SCADA system needed by the USBR is one that would remotely monitor key flow rates and water levels. Furthermore, it would archive and organize important information so that it could be examined later. The SCADA system would be managed from the KBAO headquarters. Reasons for this investment include:

- This study found that there was very limited data of high quality available.
- Existing project data that is required for good planning decisions are scattered between and within agencies.
- The USBR has funded (with cost-sharing) pieces of SCADA systems for various irrigation districts. Irrigation districts and others such as PacifiCorp also fund their own measurement devices. There is some redundancy at sites, and there has been minimal effort to ensure that multiple parties needing the same information have equipment that can communicate with the other party's equipment and software.
- The need for sharing data among agencies and stakeholders will increase with time.

Irrigation districts perform the real-time control of flows, water levels, and water distribution throughout the Project. Therefore, the irrigation districts require SCADA systems that perform a wider variety of functions than does the USBR. The district-level SCADA systems must not only provide monitoring of key sites (inflows, outflows, key water levels), but they must also enable the districts to have distributed control (automation or remote manual control) of key structures within their boundaries. Klamath ID and Tulelake ID have some limited remote monitoring capability, but modern SCADA systems are much more useful, have many more user features, and have faster responses than the existing district systems in the Project. Modern SCADA systems have been widely adopted by many irrigation districts over the past ten years, and have proven to be tremendous assets to improved water management.

Most of the many flow measurement sites visited during this study were very inaccurate or even non-functional, but the data is typically being dutifully reported and archived. Good measurement at these points was the exception rather than the rule. Furthermore, the present operation lacks a systematic, effective quality control program by the USBR and individual irrigation districts to ensure proper precision and resolution of measurements at the existing sites, maintenance of equipment and sites, etc. Because the irrigation districts operate their canals under upstream control, efficient diversions require excellent real-time knowledge of inflows and outflows. The magnitude of outflows (return flows) provides an instantaneous indication of how well the inflows match the deliveries (plus seepage) to farmers.

The largest single component of water outflows in the Klamath Irrigation Project water balance is *ET*. Accurate estimation of *ET* and regular computation of water balances requires access to detailed, representative, and accurate weather data. In the future, there will undoubtedly be more adoption of weather-based irrigation scheduling by farmers. Successful scheduling of this type will require reliable hourly weather data.

Extensive groundwater studies have been conducted by various agencies in different parts of the Klamath River Basin (CDWR, 2004; Gannett et al., 2007). These studies have shown that the basin groundwater hydrology is complicated both vertically and horizontally. It is now fairly apparent where water comes from and flows toward, but there are inconclusive values for the quantities of these flows.

Therefore, there are legitimate uncertainties regarding the sustainability of large groundwater pumping programs (or even medium-level efforts envisioned as part of the water banking program, and how they will affect water tables within the Project and outside Project boundaries. A systematic and extensive monitoring program that tracks water levels throughout the Project (and in some areas outside of the Project boundaries), as well as the timing and volumes of groundwater pumping, is needed. The data must also be properly organized and archived in a manner that makes it usable and accessible.

5.3.2.2 Improved Real-Time Control of Water Volumes and Flow Rates

The present system of allocating water during times of scarcity is “On or Off”. That is, there is no effective way of distributing a scarce supply of water equitably to all fields because individual field turnouts do not typically have accurate flow measurement devices. The lack of good flow measurement devices at farmer turnouts also limits the ability of farmers to develop good historical records of irrigation water delivered – which makes it difficult, if not impossible, to accurately estimate field *IE* values. Volumetric deliveries and volumetric charging for water are impossible without farm-level flow measurement devices.

Good farm-level flow measurement is also important for proper management of canal systems. Upstream controlled canals work on a simple principle – a volume of water is released into the head of the canal to meet the deliveries. The same principle applies to the headings of laterals along a main canal. If the operators cannot accurately measure the deliveries, it is very difficult to properly match the inflow. Under the current system of operation, which requires large diversions and then spill of the excess amounts, this is not a problem. But if diversions are reduced to maintain in-stream environmental flows, flow measurement at farm turnouts will become very important for matching the inflows and desired outflows.

The previous point was that the quality of flow measurements at both the farm turnouts and at lateral headings can be improved. But if canal water levels fluctuate with time, the flow rates through turnouts will also constantly fluctuate. Turnouts to laterals or farms with little head differential are also adversely affected when the canal water level varies, causing undesirable drops or peaks in flow. Relatively inexpensive volumetric measurement can be achieved with simple flow measurement equipment, plus knowing the duration of an irrigation...*if* the turnout flow rate stays constant with time. This in turn requires constant canal water levels.

A wide range of technologies exists to maintain constant water levels in canals. The present method of water level control in the canal system is done by adding/removing flashboards, which is time-consuming and results in water level fluctuations, as operators cannot always be there to make adjustments. Long-crested weirs potentially have wide application in the local irrigation districts to improve water level control. The hydraulic concept of a long-crested weir is simple – the additional (longer) weir length makes it possible to pass a variety of flow rates through the canal with only a small change in the elevation of the water surface. From an operations point of view this means that compared to shorter weir check structures, large changes in flow rate over the long-crested weir will result in smaller changes in head, leading to minimal changes in the flow out of turnouts and into the upstream laterals. Long-crested weirs are recommended for the Project (as opposed to computerized canal gates) because they are simple, reliable, and easy to construct. In addition, long-crested weirs are an integral component of the strategy to utilize future regulating reservoirs.

Given the large number of check structures in the system to potentially be upgraded (+200), the component of this project-alternative to design and install long-crested weirs would occur over multiple years. Therefore, site selection has to be prioritized. As a general guide, the priority of each check structures would be determined according to the following criteria:

a. Head available for the lateral canal or turnout immediately upstream of the check structure ("*low*" receives priority)
b. Lateral canal or turnout capacity in the upstream pool and area served (*large*)
c. The percentage change in canal flow rate through the check structure (*high*)
d. Narrow check structures (*such structures are more sensitive than wide ones*)

Klamath ID and Tulelake ID have long canal systems with considerable lag times between when water is put into the heads of canals and when that flow rate change reaches downstream users. For upstream controlled canals, and even downstream controlled canals with capacity limitations, regulating reservoirs located about two-thirds of the distance from the headworks are ideal for reducing lag time, providing flexibility, picking up discrepancies between expected and actual deliveries, etc. Regulating reservoirs would be included in the system improvements plan because of these advantages.

5.3.2.3 Changing Land Use

If the volume of ET_{iw} is to be reduced for water conservation goals, the irrigated area in the Project, including both agricultural fields and potentially wildlife preserve area, must be reduced. One strategy assessed in this chapter involves a water bank program (refer to Section 5.1 – *A Water Bank Program for Additional Environmental Water Supplies).* A limited version of the water bank program would also be included in the system improvements plan, but the area of land involved would be reduced in favor of other investments as outlined in this section. Some external environmental and fishing interests have argued that a water banking program to pay irrigators on a year-to-year basis to stop farming represents an unsustainable and unfair bureaucratic subsidy. The permanent transfer of water dedicated to augmenting environmental flows by purchasing water rights, rather than leasing them, may represent a better option from public relations and economic points of view.

From a purely agronomic and yield point of view, there is a logic argument in favor of first retiring the least productive farmlands and maintaining the most productive lands. The crop *ET* per unit area is similar on both types of land. It is envisioned that in addition to or as a substitution for the annual water banking program, the USBR or another agency would identify, purchase, and then permanently retire marginal fields. It is estimated that between approximately 5 and 15% of fields could be removed from production with manageable impacts on the districts. Permanently retiring fields would have the benefit of avoiding the transaction costs associated with perpetual leasing programs, a system where a new application, bid, price, contract and exchange must take place annually.

5.3.2.4 Improved On-Farm Irrigation Efficiency

Rapid field evaluations of farm-level irrigation performance has been successful in numerous irrigation projects as a means of informing irrigators about how to improve their practices, improving awareness of weaknesses in local irrigation system design and management, and improving crop yields and fertilizer efficiencies. Assessing the performance of on-farm irrigation systems is a first step to eventually reducing pumping costs, both at the farm and district levels.

A "Mobile Lab Program" would be initiated in the Klamath Irrigation Project to evaluate irrigation systems that represent the variety of conditions found throughout the various districts. These on-farm evaluations incorporate site-specific data about the soil, crop, and system hardware to identify problems with system design, operation and/or scheduling. Trained specialists can perform standardized field tests to measure the *DU* of an irrigation system and provide practical recommendations to increase uniformity and efficient scheduling. In addition to providing valuable information to irrigators, the datasets from these evaluations would be important for benchmarking future studies and long-term planning

5.3.2.5 Upgraded Pumping Plants

There is limited use of VFD installations in the Klamath Irrigation Project. VFDs are not required on large canal pools that have a significant amount of storage; the existing on/off pumping controls are sufficient. But for smaller canals, VFDs allow operators to either manually or automatically provide exactly the flow rate that is required in the canal. All other options to control the pumped flow rate into smaller canals (recycling water, or partially closing the control valves) waste energy. VFDs are becoming common features in irrigation districts in the western U.S. for the dual purposes of providing good water level (or flow rate) control as well as saving energy.

A pump testing program would provide irrigation districts with valuable benchmark data on pump performance. That data would enable them to decide which pumps should be operated first, which pumps need rebuilding, and whether pump performances change with time.

5.3.2.6 Off-Season Storage

Even during dry years, some flows exit the Klamath Irrigation Project via the Lost River Diversion Channel. At the same time, water levels in the Tulelake Sumps must be maintained low in order to be able to store unexpected flood flows that cannot safely pass through the downstream reaches of the diversion channel. It appears that the sump dikes could be raised (perhaps 2 m, to store about 60 additional mcm), and the sump could be managed tighter – filling it up to capacity without having to worry about maintaining capacity for possible flood flows. This could be accomplished if several bottlenecks were removed in the diversion channel. However, because the D Pumping Plant sits fairly close to the present high water level in the sumps, this project would have to involve refurbishing the plant. A related issue involves getting water into the elevated sump elevation by gravity; filling the highest portion of a raised sump may require pumps.

5.3.2.7 Groundwater Substitution

Tulelake ID embarked on an expanded groundwater pumping program during the 2001 drought (pumping well water into the canal system). Groundwater pumping has apparently received support by numerous parties as a potential reasonable alternative to surface water use from the canal system – up to a point. The primary disadvantage to using groundwater on an individual basis for irrigators is the substantial cost – of drilling the well, casing it, installing a pump, and paying for the power. It appears that there is some groundwater that leaves the service area, apparently towards the southeast (but the results are uncertain as indicated in **Table 40**). Exactly where that water goes and who uses it is unclear – but undoubtedly any groundwater extraction in the Klamath Irrigation Project will have an impact on downstream users of that water. Because of the uncertainties of the consequences of additional groundwater pumping, an extensive multi-year monitoring program would be done prior to implementation of any significant groundwater pumping program.

5.3.3 Technical Scope of System-Level Modernization Projects

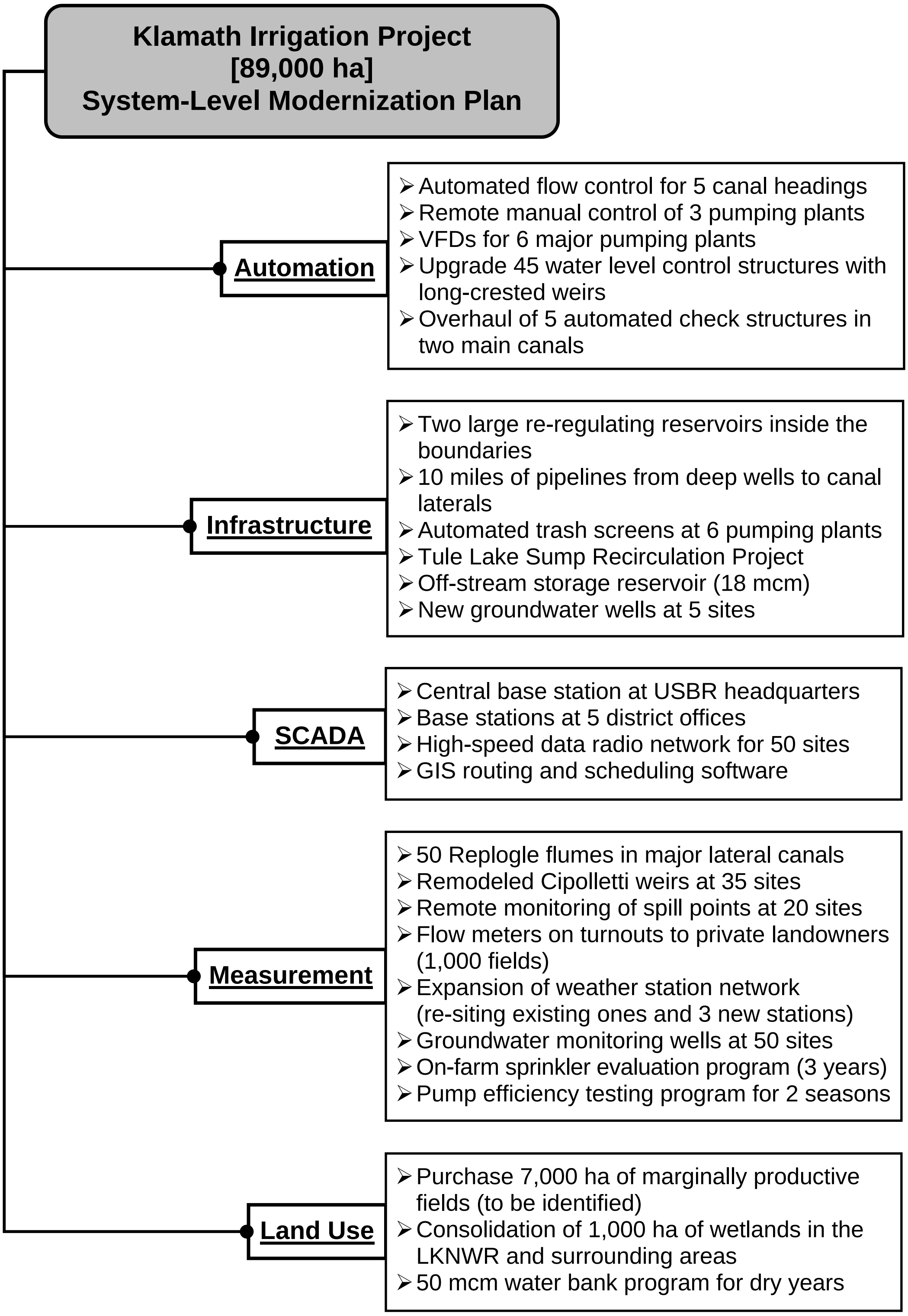
To quantify indicator values for the project-scale modernization plan, definite estimates of the components and quantities were developed for each of the pertinent categories in this project-alternative as illustrated in **Figure 40**. Taken altogether these elements of a Project-scale have an estimated planning-level budget of roughly $1,000 per hectare or about $89 million total. This modernization cost estimate is consistent with other major engineering efforts in large irrigation projects.

5.3.4 Assessing the Indicator Results for System-Level Modernization (Level 3)

The results of the modernization criteria assessment of the system-level project-alternative for each criteria in Level 3 are summarized in **Table 63**. The individual performance indicator values and transformed values (0 to 1 scale) are presented in **Appendix 4**. While as a whole the tendency of the decision-making groups uniformly reflected high indexed rankings for Level 3 attributes such as water conservation and legal/fairness, strong differences were apparent in the importance placed on economic attributes. Taking into account the significance placed on criteria such as the cost per unit of water conserved and the cost sharing that would be required by water users, the environmentalists decision-making group ranked the economic category quite low. In fact, the system-level modernization project-alternative performed well across most criteria, although obviously the estimated high cost of $89 million affected the indexed economic rankings. Full achievement occurred in the indexed rankings for the legal/fairness objective, but this is not surprising given that such large-scale investment would be occurring to provide conserved water at the same time existing water rights are being preserved. In other words, this analysis suggests that if enough money can be allocated towards system-level improvements, the assessment rankings across a range of multiple criteria would be acceptable to diverse decision-makers.

Table 63. Index values for a project-scale plan for system improvements (Level 3)

Modernization Indicator	Irrigators	Environmentalists	USFWS/NMFS	USBR
Water Conservation Availability	0.98	0.88	0.95	0.95
Technical Feasibility	0.70	0.69	0.76	0.77
Environmental Enhancement	0.27	0.68	0.55	0.49
Uncertainty/Risk	0.43	0.40	0.45	0.58
Economic	0.42	0.16	0.30	0.48
Legal/Fairness	1.00	1.00	1.00	1.00
Regulatory Compliance	0.65	0.83	0.91	0.85



Klamath Irrigation Project
[89,000 ha]
System-Level Modernization Plan

Automation

- Automated flow control for 5 canal headings
- Remote manual control of 3 pumping plants
- VFDs for 6 major pumping plants
- Upgrade 45 water level control structures with long-crested weirs
- Overhaul of 5 automated check structures in two main canals

Infrastructure

- Two large re-regulating reservoirs inside the boundaries
- 10 miles of pipelines from deep wells to canal laterals
- Automated trash screens at 6 pumping plants
- Tule Lake Sump Recirculation Project
- Off-stream storage reservoir (18 mcm)
- New groundwater wells at 5 sites

SCADA

- Central base station at USBR headquarters
- Base stations at 5 district offices
- High-speed data radio network for 50 sites
- GIS routing and scheduling software

Measurement

- 50 Replogle flumes in major lateral canals
- Remodeled Cipolletti weirs at 35 sites
- Remote monitoring of spill points at 20 sites
- Flow meters on turnouts to private landowners (1,000 fields)
- Expansion of weather station network (re-siting existing ones and 3 new stations)
- Groundwater monitoring wells at 50 sites
- On-farm sprinkler evaluation program (3 years)
- Pump efficiency testing program for 2 seasons

Land Use

- Purchase 7,000 ha of marginally productive fields (to be identified)
- Consolidation of 1,000 ha of wetlands in the LKNWR and surrounding areas
- 50 mcm water bank program for dry years

Figure 40. Physical infrastructure improvements, SCADA, measurement and farm-level elements in the system modernization plan

5.4 Results

5.4.1 Final Modernization Criteria Assessment Results

A multi-criteria expert decision-making problem was addressed in the Klamath Irrigation Project by analyzing four irrigation modernization project-alternatives through a ranking procedure based on composite programming. The modernization criteria assessment used to measure the performance of the project-alternatives was ordered into a four-level decision analysis hierarchy consisting of a number of specialized ranking indicators. Defining Level 4 of the analysis were 30 separate key indicators to quantify the inter-relationships between irrigated agriculture and the environment, as well as related policy aspects. At Level 3 decision attributes were integrated into relevant objectives for water conservation, technical feasibility, the environment, uncertainty/risk, economics, legal/fairness, and regulatory compliance using composite programming. At Level 2 the modernization project-alternatives were analyzed in terms of water-related issues for three simultaneous objectives: Solution Delivery, Ecological Sustainability, and Strategic Mission. The indicator results at each level reflect the preferences and opinions of a diverse group of decision-makers, namely, irrigators, environmentalists, government environmental protection agencies (USFWS/NMFS), and the government agency that manages water resources in the Project (USBR).

Irrigators, state and federal resource agencies, and other agricultural and environmental stakeholders have no false illusions about the prospects for continuing with the status quo in the Project or elsewhere. Critical issues confront irrigated agriculture throughout the western U.S. and globally. The underlying basis for each of the many challenges facing the Project have been investigated in previous chapters of this study. It is evident that the current situation is unsustainable. This is reflected by the assessment results for the “No Action” project-alternative that would essentially involve carrying on with existing conditions in the foreseeable future. For example, a do-nothing approach was ranked very low in terms of actual Solution Delivery by all decision-making groups (Level 2 in the decision analysis) as shown in **Figure 41**.

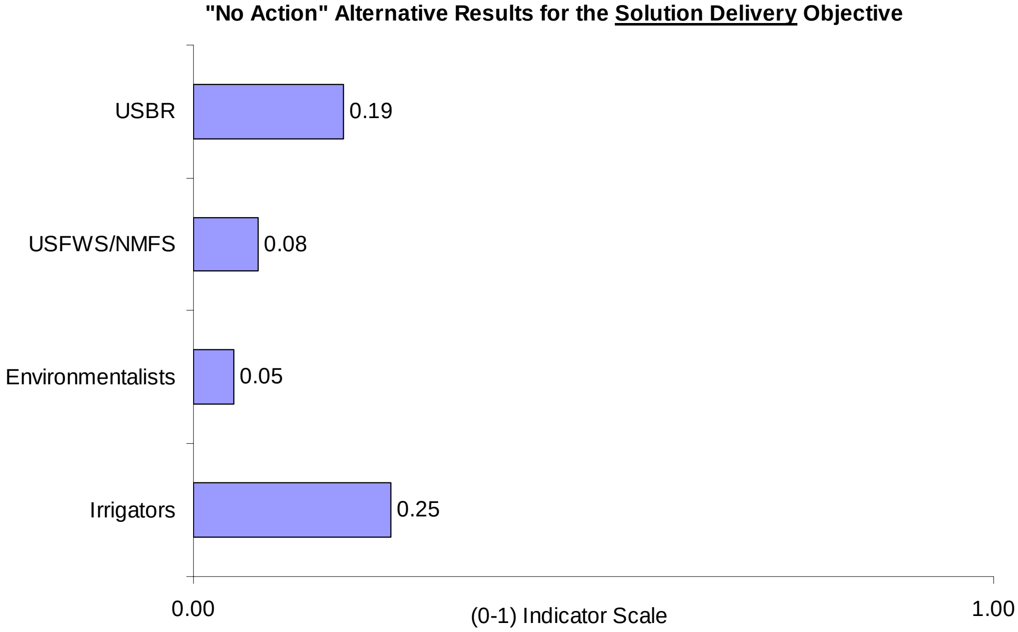


Figure 41. Indexed rankings for Solution Delivery (Level 2) for the No Action project-alternative

The final Level 2 results for the three potentially implementable project-alternatives – the water bank program, district-level recirculation using the Tule Lake Sump, and system-level modernization – are summarized in **Table 64**. The combined results of the considered options reflect the assigned weights and compensation factors for each decision-making group presented in Section 4.3.4 – *Formulating the Stakeholder's Preference Structure*.

In contrast to the no action alternative, the assessment of the indexed rankings of Solution Delivery for the water bank, district-level recirculation, and system-level modernization project-alternatives showed a significantly higher degree of achievement with results that ranged from 0.19 to 0.85 as shown in **Figure 42** (versus results of 0.19 to 0.25 for the no action alternative). For all decision-making groups, system-level modernization ranked highest for the Solution Delivery objective. However, a different picture emerged when the Ecological Sustainability objective was analyzed. **Figure 43** shows that for the environmentally-centered decision criteria, the system-level modernization project-alternative consistently lagged behind the water bank program and district-level recirculation, although neither one had a clearly expressed consensus among all decision-makers in regards to this objective. A similar mixed picture applied to the Strategic Mission objective. Thus, the inherent value of the composite programming technique is illustrated by its capability to handle multiple levels of relative trade-offs in an overall standardized analysis.

Table 64. Index values for all decision-making groups at Level 2 in the modernization criteria assessment

Objective	Irrigators	Environmentalists	USFWS/NMFS	USBR
Water Bank Program				
Solution Delivery	0.59	0.71	0.68	0.72
Ecological Sustainability	0.66	0.76	0.74	0.69
Strategic Mission	0.62	0.67	0.68	0.64
District-Level Recirculation (Tule Lake Sump)				
Solution Delivery	0.53	0.19	0.32	0.39
Ecological Sustainability	0.71	0.74	0.67	0.71
Strategic Mission	0.74	0.76	0.68	0.67
System-Level Modernization				
Solution Delivery	0.77	0.79	0.82	0.85
Ecological Sustainability	0.38	0.64	0.53	0.52
Strategic Mission	0.59	0.75	0.60	0.65

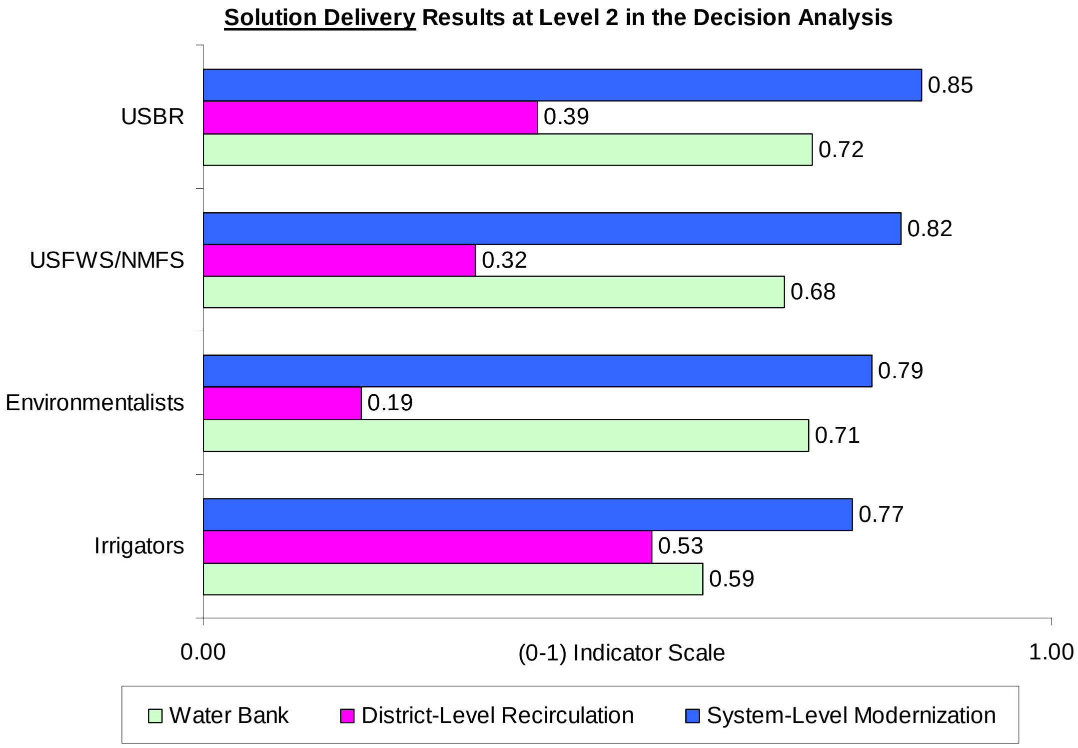


Figure 42. Indexed rankings for Solution Delivery (Level 2) for implementable project-alternatives by each decision-making group

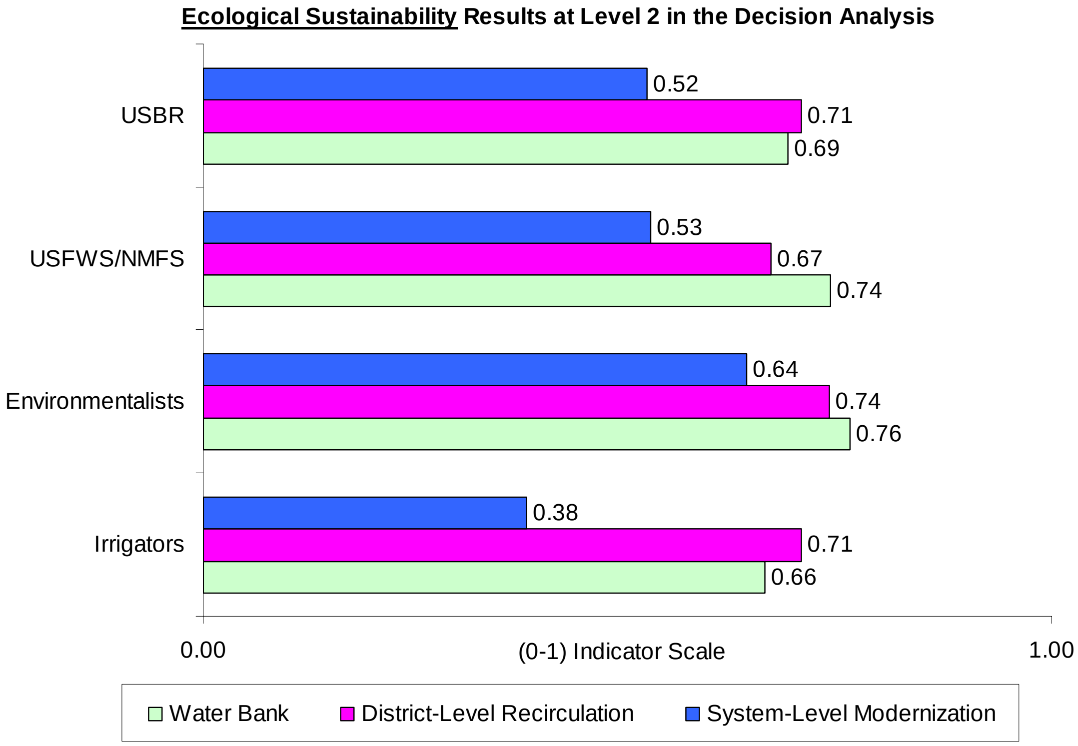


Figure 43. Indexed rankings for Ecological Sustainability (Level 2) for implementable project-alternatives by each decision-making group

To determine the "best" solution among the modernization project-alternatives, a final ranking index was developed at Level 1 in the decision analysis (refer to **Table 65**). The final-indexed results express a ranking of the project-alternatives with respect to wide-ranging modernization criteria. At the level of overall project-alternative evaluation, all the decision-making groups preferred implementation of the water bank program (0.74 for environmentalists; 0.69 for USFWS/NMFS; 0.68 for USBR) except for irrigators who ranked system-level modernization highest (0.62). Irrigators showed a slight preference for system-level modernization, but the water bank program was a very close second-choice. Narrowing the composite programming results in this hierarchy structure eliminated the district-level recirculation project-alternative for all decision-makers, even though it had by far the lowest equivalent annual cost (by a factor of over 10).

Table 65. Overall modernization criteria assessment index values

Decision-Making Group	No Action	Water Bank Program	District-Level Recirculation	System-Level Modernization
Irrigators	0.32	0.61	0.59	**0.62**
Environmentalists	0.03	**0.74**	0.50	0.66
USFWS/NMFS	0.13	**0.69**	0.52	0.59
USBR	0.24	**0.68**	0.55	0.65

5.4.2 Discussion of the Case Study Results

Decisions about different strategies to reallocate water resources involve multiple decision-makers that must take into account careful technical analyses of various decision criteria. Without the modernization criteria assessment, the correct and full interpretation of the relative preferences or judgments of conflicting decision-makers about different project-alternatives would be practically impossible. In the case study of the Klamath Irrigation Project, it was possible to differentially weight specially-developed indicators for four groups, while allowing for expressed compensation between different objectives. Good applications of multi-dimensional decision-making are simply procedures that enable those underlying preferences to be reflected most effectively in the final decision, in a way that is as inclusive and transparent as practical.

Disentangling candidate irrigation modernization solutions worth pursuing is an especially difficult task for water resources planners. Four water management strategies – ranging from keeping the status quo to a system-level overhaul of infrastructure and management – were conceptualized and fully analyzed. The main features, measurable results, and tradeoffs of each strategy were well-illustrated by the modernization criteria assessment. The project-alternative representing each strategy increases the knowledge base about the complex underlying inter-relationships of irrigation water use and environmental enhancement. Creating a water resources planning framework to implement irrigation modernization is already a useful accomplishment, but certainly not enough to make stable policy for balanced development. Meaningful pursuit of solutions requires changes in behavior and an excellent understanding of the agro-hydrological conditions and environmental possibilities in the Klamath River Basin.

The assessment results for the water bank program indicate a clear preference for this as a modernization solution by three of the four decision-making groups. However, from the viewpoint of the irrigation community a water bank falls short in several important respects, including the amount of farmland taken out of production and impacts on the existing water rights regime, especially when Project water supplies are reduced in drought years. Additionally, negligible improvements in the water quality of the drain water discharged to the Klamath River would be expected from a water bank, which would leave irrigators vulnerable to having to make further investments in solutions to meet TMDL targets and even potentially more lawsuits by fish interests. A water bank program also entails a fair increase in the net energy costs for two reasons: (1) more groundwater pumping, and (2) the lack of a mechanism in such a program for offsetting the high energy costs associated with the main system pumping plants.

Therefore, prospects for the future include applying the modernization criteria to further analytical evaluation by quantifying estimates of water and energy flows for different additional scenarios. The few examples presented here to illustrate the framework are far from exhaustive. They also do not suggest overall conclusive options and do not make specific quantifications of potential water savings since these are extremely implementation-specific.

The project-alternatives require additional planning details, systems engineering, environmental analysis, and/or design before proceeding to construction. Additional research will be required over the next few years to fully assess the quantitative effects of irrigation modernization on basin-level water use. The impacts on the socio-economic sustainability of the agricultural community in the Klamath Irrigation Project will also need to be evaluated so that proper analyses of the trade-offs of improving infrastructure and management can be developed beyond the planning-level estimates provided herein. To this end, the USBR and irrigators should:

- Continue to engage the irrigators, stakeholders, resource management agencies, and technical community in the planning and design process.
- Continue working to enhance the dialogue and provide up-to-date information.
- Use the modernization criteria assessment as the guiding framework for prioritizing and budgeting needed future system improvements.

6 Summary and Conclusions

6.1 Water, the Environment and Modern Irrigation Design

The subject of this research doctoral dissertation – a *Modernization Criteria Assessment for Water Resources Planning* – arose from a core concern about the future path of irrigation development worldwide, and how it can and should be changed. The urgent decline of ecological habitat conditions in many river basins associated with water withdrawals for agriculture will require long-term public and private investment in modernizing irrigation systems according to a variety of situations. This monumental engineering effort in irrigation modernization is necessary in order to meet international demands for affordable, nutritious, and safe farm products. Water resources planning for modernization benefits from the systematic evaluation and decision-making approaches developed herein considering the complexity of large-scale canal systems and their inter-relationships with physical constraints and economic and socio-political pressures, including balancing the attention paid to the proper engineering and workable strategies. The planning framework and key modernization principles presented in this dissertation are useful for analyzing and understanding the underlying mechanisms of technologies and management that can either enhance or limit irrigation system performance.

Irrigated agriculture is essential for global food security. However, despite decades of major investment in irrigation projects by foreign lending agencies and development banks in numerous countries, irrigation performance remains unsatisfactorily low and in many places progress is being reversed due to water logging, salinization, over-drafting of aquifers, environmental degradation, and infrastructure deterioration (Burt and Styles, 1999; Plusquellec, 2002). Ominously, a recent editorial in the American Society of Civil Engineering (ASCE) *Journal of Irrigation and Drainage Engineering* declared starkly that the "Age of Water Development" was over (Allison, 2003). This startlingly conclusion was based on an analysis of past trends in water development statistics indicating the world is running out of opportunities for new water sources that can be developed economically. Solutions for future food security must therefore be found elsewhere.

Admittedly, when it comes to potential agricultural production, social problems, lack of reliability, urban encroachment, conflicts between farmers, poor cost recovery, etc. severely hamper efforts to deal with future challenges of food security and fiber production under water scarcity conditions. But the crisis in irrigation must be resolved through an appropriate understanding of the role of technical aspects in terms of the resulting service to farms. This dissertation contributes to the emerging view that new concepts in design and modern technology are essential to a *service* orientation. Irrigation modernization is necessary to overcome the present challenges of water scarcity and to meet the food security needs for an expanding world population in a sustainable manner.

To restore healthy ecosystems and sustain agriculture, irrigation modernization should be promoted as a key planning concept in basin-level water management to effectively balance competing water needs. However, selecting the best modernization strategy from potential project-alternatives in water resources planning is a complex decision-making process. A modernization approach guides project implementation according to modern practices and expertise from civil engineering, crop science, design and construction, and economic feasibility analysis. In this respect, engineering professionals who are responsible for coming up with specific and implemental solutions to real problems have to rely on new tools for project evaluation.

The objectives of the present research were to develop an approach that provides decision analysis tools for planning different modernization strategies in river basins where irrigation is competing with other uses, particularly environmental flow demands. The modernization criteria assessment formulated in this research study defines a new strategic decision-making methodology with indicators combining water supply, irrigation demands, technical feasibility, uncertainty/risk, environmental enhancement, legal and regulatory compliance, and stakeholder participation. Decision-making in water management to achieve a reallocation of freshwater should be based on a proper understanding of the hydrology and internal processes within the system where water interacts with and, to a large degree, controls the extent of other natural components in the landscape such as soils, riparian vegetation, and wildlife.

6.2 An Engineering Case Study of the Klamath Irrigation Project

An engineering case study analysis of the Klamath Irrigation Project (89,000 ha) was used to illustrate how irrigation modernization opportunities are derived and then assessed qualitatively and quantitatively by water resources engineering specialists, as well as by stakeholders with conflicting preferences over future water management scenarios. Increasing knowledge about the concepts and application of irrigation modernization through a case study analysis will hopefully lead to the progressive adoption of decisions closer to realistic and achievable objectives.

Irrigated agriculture was the primary justification for development of the Klamath Irrigation Project in the early part of the last century. Attempts by the Project to meet contractual obligations for irrigation water and to simultaneously satisfy operating criteria arising from environmental laws have led to competition among diverse stakeholder groups and generated intense political controversy. In April 2001 a combination of events occurred that led to one of the most prominent conflicts over water supplies in the U.S. Due to stricter flow requirements to protect fish species and a critical drought, irrigation water was unexpectedly withheld from the majority of farms in the Project, resulting in major economic losses and calling the basis for further environmental restrictions into question. The primary water management objectives in the Klamath River Basin at present are to address the water allocation problem, find an optimum modernization strategy, and illustrate tradeoffs between agricultural and ecological interests.

One aim of this analysis was to identify ways in which restrictions on irrigation diversions and the discharges of drain water in the Klamath Irrigation Project could be mitigated by promoting modernization projects from a perspective that minimizes the consequences to ecological goals but maintains irrigated agriculture at a sustainable level. A main finding of this multi-year hydrologic analysis is that the proper frame of reference should aim at reducing non-beneficial consumptive use through targeted decreases of underperforming cropped and wetlands areas. The results of Project-level irrigation efficiency calculations for the 5-year study period (mean annual IE=86%) indicate that traditional water conservation activities such as improved field irrigation efficiencies and canal lining would not make significant amounts of water available for other environmental uses.

To quantitatively assess the realistic potential for water conservation from agricultural fields in the Project, ET_{iw} was extensively modeled. Replenishment of ET is the primary purpose of irrigation, and thus ET is a major element in determining crop water requirements and diversions in an irrigated basin. Modeling the processes determining agricultural water demands through a crop water balance model, of which consumptive uses are the highest in an irrigated river basin, provides a scientific context for reallocation of scarce water supplies. Consumptive use was modeled by a daily plant-soil-water model routine using the FAO-56 dual crop coefficient approach (Allen et al., 1998) with various steps to organize and quality control the datasets. The procedure computes ET from agricultural fields and non-agricultural lands (open water, wetlands, etc.) on a daily, monthly and annual basis. The method was applied to the study area to properly capture information about the impacts of potential short-term critical thresholds to the system, as well as long-term trends in water consumption.

The terms, circumstances, and purposes of physical infrastructure design, operation rules, organizational structures, and management practices followed in the real-time operation of the Project were investigated with the Rapid Appraisal Process (RAP) – an innovative technical project evaluation tool – to go beyond merely describing its characteristics (e.g., length or capacity of a particular canal) and actually understand why things are done in a particular way – how and why the water is being manipulated, what types of constraints the district has, what hardware is being used, etc. Scrutinizing these types of internal processes helped to identify what specific actions could be taken to improve project performance and what opportunities for improved operations or water conservation might exist.

Through a synthesis of the water balance technique, which recognized and quantified uncertainties in the main hydrologic inputs and outputs of a volumetric balance, with a comprehensive understanding of the Project's internal processes, three different implementable project-alternatives were developed, including focused priorities on project infrastructure facilities and on-farm programs. By applying the modernization criteria assessment – a project ranking index based on composite programming – a decision analysis methodology was formulated for evaluating the trade-offs associated with meeting the goals of different stakeholders. The composite programming method for analyzing modernization strategies required defining the management objectives according to the nature of the internal processes and agro-hydrological features of the system, selection of alternative engineering solutions, selection of appropriate decision criteria relevant to the specific water-related problems, and the assignment of desirable and critical threshold values pertinent to each criteria. Input data consisted of hydrologic, agronomic, engineering, economic, and political/policy information.

The main features, measurable results, and tradeoffs of each strategy were well-illustrated by the modernization criteria assessment. The assessment results indicated that none of the four selected decision-making groups – irrigators, environmentalists, government environmental agencies, and the government water resources agency responsible for the Project – desire to maintain the status quo, which would definitely lead to worsening environmental and economic consequences. Instead, the final indexed-ranking of project-alternatives showed that at the level of overall evaluation, the decision-making groups clearly prefer implementation of an environmental water banking program, except for the irrigators who ranked a system-level modernization program highest. However, even though irrigators had problems with the water bank program, because of the amount of farmland to be taken out of production, its negligible impact on the water quality of drainage to the Klamath River, and the resulting higher energy costs, it ranked a close second. Thus, the inherent value of the composite programming technique was illustrated by its capability to handle multiple levels of relative trade-offs in an overall standardized analysis.

6.3 The Way Forward

This study investigated a specific problem that will face many irrigation engineers and water resources planners in the future: how to effectively analyze and make an assessment of irrigation modernization project-alternatives. The experience with the engineering case study of the Klamath Irrigation Project illustrates how a seemingly intractable controversy may benefit significantly from the scientific conceptual framework incorporating standardized assessment indicators based on multiple criteria for diverse stakeholder decision analysis. The approach has the potential to help move forward irrigation modernization programs in irrigated basins worldwide. Transferring the knowledge base covering irrigation modernization – from proper conceptualization of irrigation as a *service* to the complex analytical and decision-making tools used here – to non-industrial, agrarian, and economically under-developed countries in Africa and Asia would be a particularly important contribution of this dissertation.

This case study evidence contributes to a better understanding of:

- The pre-conditions necessary for irrigation modernization
- Systematic techniques for identifying, quantifying, and prioritizing modernization opportunities
- Technical design and engineering concepts with a high likelihood of success
- The approach of analyzing irrigation projects as networked layers
- Win-win situations for environmental enhancement
- The role of water resources planners and engineers in facilitating the decision-making process
- Criteria for assessing modern designs, proposed strategies for upgrading operations, and multi-scale impacts

The use of the standardized indicators developed in this dissertation with proposed decision criteria about irrigation system performance, modern design and technology, and environmental hydrology has many potential benefits and uses:

- Providing key information related to future water management scenarios
- Monitoring the effects of water management decisions
- Highlighting strengths and weaknesses of different modernization opportunities
- Supporting the formulation of investment policies
- Assistance in assessing irrigation investment priorities, particularly in conflicting water supply situations
- Providing an appropriate framework for identifying the main asymmetries between different project or investment levels

Finally, in conclusion, further research and recommendations could improve the modernization criteria assessment developed in this dissertation. For example:

1. Empirical research in irrigation systems of different scales and typologies may highlight ways to reduce unnecessary complexity in the analytical framework(s).
2. The selection of key performance indicators could be extended to explicitly handle different situations where diverse issues such as wastewater recycling, urbanization, salinization, poverty alleviation, etc. are a central concern(s).

3. Methodologies to simplify the benchmarking process of threshold and desirable values – for example by using more descriptive sub-indicators instead of project-specific numeric quantities – may help broaden usage in instances where only limited data are readily available.
4. Integration of the modernization criteria assessment, or appropriate parts of it, into a suitable GIS platform may enhance usability, particularly in terms of generating interfaces that are designed specifically for different groups of end-users and/or organizing spatially-distributed datasets.
5. Incorporating conflict analysis into the overall planning framework for modernization would complement the modernization decision analysis framework.
6. Modeling the criteria in a fuzzy environment (i.e., merging composite programming with group decision-making under fuzziness algorithms) would help ensure that as much as possible of the relevant information is used.
7. Additional work with sensitivity analyses is needed to determine how the weights of the criteria and compensation factors affect the ranking pattern.
8. More case study examples would help determine what generally-applicable criteria could be used without being coupled together to specific project-alternatives.
9. The modernization criteria were intentionally narrowly focused primarily on irrigation-related aspects of basin hydrology, but more general criteria types could be incorporated into future assessment, as applicable.

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Appendix 1: Hydrological Datasets

Irrigation Canals and Pumping Plants [MCM/Year]

Monitoring Station	1999	2000	2001	2002	2003	Mean
A Canal	347.77	336.27	51.28	346.84	262.79	268.99
Ady Canal	111.75	111.86	50.53	122.96	97.00	98.82
Ady Canal (LKNWR)	23.71	33.22	13.33	59.00	36.49	33.15
D Pumping Plant	122.72	91.65	35.45	83.60	73.49	81.38
East Canal	3.23	4.51	5.12	6.43	5.37	4.93
E&EE Pumping Plant	66.86	47.90	10.29	91.86	80.65	59.51
F&FF Pumping Plant	138.16	95.69	22.76	98.49	79.67	86.96
J Canal	168.41	162.61	41.01	164.95	129.77	133.35
North Canal (Miller Creek)	45.34	43.55	44.01	46.06	40.48	43.89
North Canal (Klamath River)	44.57	51.17	19.14	61.93	38.17	43.00
Miller Hill Pumping Plant	22.88	26.00	5.86	30.71	13.55	19.80
Miller Hill Spill	3.42	3.79	0.88	4.94	4.75	3.55
Station 48	84.66	100.70	25.18	128.01	77.18	83.15
West Canal	25.40	38.71	37.91	39.74	37.03	35.76

Rivers and Streams [MCM/Year]

Monitoring Station	1999	2000	2001	2002	2003	Mean
Buck Creek	16.98	10.50	6.24	7.13	8.15	9.80
Cottonwood Creek	4.25	4.25	4.25	4.25	4.25	4.25
Klamath River (Keno Dam)	2174.13	1397.41	902.89	788.37	975.82	1247.72
Klamath River (Iron Gate Dam)	2532.77	1787.22	1216.53	1162.44	1313.36	1602.46
Link River (Upper Klamath Lake)	1676.00	1293.53	882.47	847.86	909.55	1121.88
Lost River (Malone Dam)	134.73	12.33	52.13	13.47	6.67	43.87
Lost River (Harpold Dam)	294.41	63.29	78.84	52.36	64.83	110.75
Lost River (Anderson Rose Dam)	31.99	33.40	68.09	39.53	25.34	39.67
Lost River Diversion Channel (Lost River)	339.95	159.94	43.23	58.13	79.86	136.22
Lost River Diversion Channel (Klamath River)	36.14	57.86	29.14	71.24	33.99	45.67
Miller Creek	72.17	1.93	2.18	1.74	1.44	15.89
Sheepy Creek	13.69	13.69	13.69	13.69	13.69	13.69

Appendix 2: Monthly Water Balance Volumes

Surface Water Diversions [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	17.35	22.28	22.78	30.99	15.45	21.77
Feb	4.44	10.82	1.80	9.35	13.35	7.95
Mar	4.44	7.01	1.36	7.91	7.70	5.68
Apr	26.40	33.49	0.06	56.32	21.75	27.60
May	77.67	86.58	16.99	88.77	40.15	62.03
June	110.31	130.83	19.37	123.34	113.95	99.56
July	139.74	127.75	32.65	133.39	102.71	107.25
Aug	99.22	120.43	107.11	107.99	80.44	103.04
Sept	83.73	58.76	17.72	73.53	67.54	60.26
Oct	34.60	23.88	0.91	24.12	22.98	21.30
Nov	10.41	3.37	0.31	16.30	8.65	7.81
Dec	5.90	18.74	16.05	23.19	20.17	16.81
Total	614.21	643.94	237.12	695.20	514.83	541.06

River and Tributary Flows [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	7.43	4.16	3.63	10.70	3.84	5.95
Feb	30.72	6.12	3.41	4.21	3.86	9.66
Mar	114.72	8.73	4.26	5.69	4.55	27.59
Apr	68.76	5.55	3.96	3.86	5.48	17.52
May	4.21	3.07	8.57	2.79	3.52	4.43
June	1.89	1.43	13.13	1.20	1.25	3.78
July	1.62	1.40	13.37	1.19	1.23	3.76
Aug	1.57	1.36	17.34	1.16	1.20	4.53
Sept	1.20	1.06	0.93	0.93	0.95	1.02
Oct	1.90	2.08	1.10	1.06	0.77	1.38
Nov	3.76	3.74	3.65	3.65	3.67	3.70
Dec	4.03	3.98	5.14	3.86	3.88	4.18
Total	241.81	42.70	78.49	40.27	34.19	87.49

Precipitation [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	73.00	117.09	7.50	35.60	57.81	73.00
Feb	81.43	36.06	13.02	38.43	16.05	81.43
Mar	11.27	30.05	30.15	7.90	49.43	11.27
Apr	19.03	46.75	28.74	45.75	52.48	19.03
May	10.72	15.34	13.72	1.66	28.74	10.72
June	7.02	2.90	7.32	5.22	0.40	7.02
July	2.68	13.93	11.54	0.40	5.37	2.68
Aug	65.82	0.22	3.61	0.70	17.22	65.82
Sept	2.89	28.20	25.71	1.27	14.62	2.89
Oct	14.35	32.97	9.40	0.13	1.08	14.35
Nov	25.95	15.48	69.16	31.70	44.62	25.95
Dec	16.74	20.92	66.55	76.46	50.89	16.74
Total	330.90	359.91	286.43	245.24	338.71	330.90

Consumptive Use [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	22.83	17.53	16.48	23.77	25.49	21.22
Feb	29.44	37.63	21.11	45.20	40.48	34.77
Mar	41.52	55.92	39.35	30.77	51.40	43.79
Apr	60.29	74.53	55.90	52.00	67.46	62.04
May	97.50	98.74	94.55	111.27	115.79	103.57
June	138.27	154.79	104.50	135.47	142.28	135.06
July	180.81	169.81	105.05	167.26	157.65	156.11
Aug	126.74	128.90	92.58	107.85	102.64	111.74
Sept	78.35	76.54	63.43	68.78	70.01	71.42
Oct	32.24	39.73	25.97	24.85	22.82	29.12
Nov	17.51	16.33	13.64	26.68	17.35	18.30
Dec	19.61	20.07	7.74	19.82	21.35	17.72
Total	845.11	890.51	640.30	813.72	834.73	804.87

Surface Water Flow to Klamath River [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	30.87	30.70	12.07	27.39	22.39	24.68
Feb	68.93	34.79	11.67	20.60	20.76	31.35
Mar	166.64	38.45	19.52	17.99	15.78	51.68
Apr	96.18	17.06	6.62	8.74	19.87	29.69
May	13.47	17.82	0.26	10.05	18.14	11.95
June	7.33	10.34	0.00	8.59	9.71	7.19
July	8.14	9.37	0.00	7.64	4.72	5.97
Aug	17.87	6.05	2.93	15.05	8.59	10.10
Sept	24.22	55.81	0.96	14.59	17.30	22.58
Oct	20.25	11.90	0.13	9.74	7.82	9.97
Nov	9.92	10.72	0.42	4.46	4.63	6.03
Dec	14.29	12.62	11.41	11.79	9.83	11.99
Total	478.11	255.63	65.99	156.62	159.54	223.18

Change in Surface Water Storage [MCM/Month]

Month	1999	2000	2001	2002	2003	Mean
Jan	11.50	13.22	7.45	8.05	6.88	9.42
Feb	-1.81	1.13	-1.99	2.09	2.46	0.38
Mar	-1.30	-2.46	-3.48	0.43	0.44	-1.27
Apr	-3.33	-3.94	-0.76	-4.06	-3.63	-3.15
May	-10.66	-12.08	-12.99	-12.12	-13.97	-12.37
June	-18.63	-23.30	-14.09	-23.29	-25.42	-20.95
July	-7.35	-10.81	-11.90	-10.25	-11.25	-10.31
Aug	-2.20	-0.94	3.92	-1.71	1.17	0.05
Sept	1.12	1.41	7.83	1.53	3.50	3.08
Oct	12.74	15.57	0.05	16.10	14.60	11.81
Nov	3.36	6.61	7.65	6.44	10.48	6.91
Dec	6.30	6.51	0.51	5.89	4.15	4.67
Total	-10.28	-9.08	-17.80	-10.88	-10.58	-11.72

Appendix 3: Subregional Water Balance Tables

Annual water balance of Subregion 1 – Langell, mcm

Flow Path Component		**1999**	**2000**	**2001**	**2002**	**2003**	**Avg**	***CI***	***RI***
Inflows	Surface Water Diversions	73.97	86.77	87.03	92.23	82.88	84.58	5%	**
	River and Tributary Flows	223.88	24.76	60.55	22.34	16.26	69.56	15%	3%
	Precipitation	70.31	66.86	62.83	42.41	61.49	60.78	14%	2%
	Groundwater from External Sources	22.33	20.99	20.57	13.37	21.39	19.73	50%	3%
	Total	**390.49**	**199.39**	**230.98**	**170.34**	**182.02**	**234.64**		
	(*CI*)	(10%)	(8%)	(7%)	(6%)	(8%)			
Outflows	ET from Agricultural Fields	97.66	101.39	100.06	94.92	99.86	98.78	20%	10%
	ET from Wildlife Refuges	0.00	0.00	0.00	0.00	0.00	0.00	20%	**
	ET from Canals	0.92	0.96	1.01	0.88	0.89	0.93	20%	**
	ET from Drains	0.77	0.82	0.83	0.76	0.80	0.80	20%	**
	Evaporation from Open Water	7.01	7.12	7.47	6.80	6.63	7.01	20%	1%
	ET from Urban Areas	1.11	1.14	1.19	1.08	1.05	1.11	20%	**
	ET from Undeveloped Areas	21.54	22.98	18.15	19.34	26.09	21.62	20%	1%
	Flow to the Lost River	294.41	63.29	78.84	52.36	64.83	110.75	50%	81%
	Total	**423.43**	**197.69**	**207.55**	**176.15**	**200.16**	**241.00**		
	(*CI*)	(35%)	(19%)	(24%)	(22%)	(23%)			
Storage	Change in Surface Water	0.00	0.00	0.00	0.00	0.00	0.00	---	**
	Change in Soil Moisture	-4.21	0.22	6.15	-2.74	1.77	0.24	20%	**
	Change in Groundwater	-2.53	-4.00	-21.57	4.07	-0.77	-4.96	25%	**
Closure	**Net Lateral Groundwater Inflow/Outflow ('-' *is net inflow*)**	**-26.20**	**5.48**	**38.85**	**-7.14**	**-19.14**	**-1.63**		
	(*CI* ±range)	**(-179 to 127)**	**(46 to -35)**	**(92 to -14)**	**(-48 to 34)**	**(-67 to 29)**			

** *RI* < 1%

Annual water balance of Subregion 2 – Upper Klamath, mcm

Flow Path Component		1999	2000	2001	2002	2003	Avg	*CI*	*RI*
Inflows	Surface Water Diversions	678.32	457.42	159.26	470.44	361.62	425.41	14%	13%
	River and Tributary Flows	0.00	0.00	0.00	0.00	0.00	0.00	---	**
	Precipitation	101.50	93.66	87.04	81.60	108.72	94.50	16%	1%
	Total	**779.82**	**551.08**	**246.31**	**552.04**	**470.34**	**519.92**		
	(*CI*)	(12%)	(12%)	(11%)	(12%)	(11%)			
Outflows	ET from Agricultural Fields	206.75	213.43	106.31	204.93	195.97	185.48	20%	6%
	ET from Wildlife Refuges	0.00	0.00	0.00	0.00	0.00	0.00	---	**
	ET from Canals	2.72	2.80	1.74	2.59	2.59	2.49	20%	**
	ET from Drains	1.79	1.90	1.90	1.77	1.86	1.84	20%	**
	Evaporation from Open Water	8.06	8.18	8.54	7.81	7.62	8.04	20%	**
	ET from Urban Areas	9.53	9.71	10.16	9.27	9.00	9.53	20%	**
	ET from Undeveloped Areas	8.81	10.32	9.18	8.08	11.35	9.55	20%	**
	Flow to the Klamath River	339.95	159.94	43.23	58.13	79.86	136.22	33%	7%
	Flow to the Lost River	200.40	196.01	109.10	204.47	155.11	173.02	9%	1%
	Uncontrolled Drain Flows Downslope	68.86	105.63	28.34	87.25	72.52	72.52	192%	72%
	Total	**846.87**	**707.93**	**318.49**	**584.31**	**535.88**	**598.70**		
	(*CI*)	(21%)	(30%)	(21%)	(31%)	(28%)			
Storage	Change in Surface Water	-0.03	0.09	0.21	0.01	-0.14	0.03	3%	**
	Change in Soil Moisture	-8.39	-1.32	12.15	-3.62	0.05	-0.23	20%	**
	Change in Groundwater	19.54	-3.86	-66.94	-10.38	3.74	-11.58	25%	**
Closure	**Net Lateral Groundwater Inflow/Outflow (‘-’ *is net inflow*)**	**-78.17**	**-151.76**	**-17.60**	**-18.28**	**-69.19**	**-67.00**		
	(*CI* ±range)	**(-281 to 125)**	**(-376 to 73)**	**(-92 to 57)**	**(-209 to 172)**	**(-230 to 92)**			

** *RI* < 1%

Annual water balance of Subregion 3 – Tulelake, mcm

Flow Path Component		1999	2000	2001	2002	2003	Avg	*CI*	*RI*
Inflows	Surface Water Diversions	168.41	162.61	41.01	164.95	129.77	133.35	10%	1%
	River and Tributary Flows	31.99	33.40	68.09	39.53	25.34	39.67	20%	**
	Precipitation	76.84	118.78	77.39	67.46	95.52	87.20	15%	1%
	Uncontrolled Drain Flows Upslope	68.86	105.63	28.34	87.25	72.52	72.52	192%	89%
	Total	**346.11**	**420.42**	**214.82**	**359.18**	**323.15**	**332.74**		
	(*CI*)	(39%)	(49%)	(27%)	(47%)	(44%)			
Outflows	ET from Agricultural Fields	184.56	202.80	132.67	173.80	183.72	175.51	20%	6%
	ET from Wildlife Refuges	68.52	63.72	67.27	69.72	59.40	65.73	20%	1%
	ET from Canals	3.70	3.66	1.38	3.50	3.35	3.12	20%	**
	ET from Drains	1.78	1.86	1.83	1.74	1.78	1.80	20%	**
	Evaporation from Open Water	0.91	0.90	0.95	0.88	0.84	0.89	20%	**
	ET from Urban Areas	0.58	0.57	0.61	0.56	0.53	0.57	20%	**
	ET from Undeveloped Areas	14.73	19.98	8.21	12.53	18.07	14.71	20%	1%
	D Pumps to the P Canal	122.72	91.65	35.45	83.60	73.49	81.38	25%	2%
	Total	**397.50**	**385.15**	**240.15**	**333.79**	**323.10**	**335.94**		
	(*CI*)	(13%)	(12%)	(18%)	(17%)	(17%)			
Storage	Change in Surface Water	-2.86	-2.36	0.97	-2.61	-1.33	-1.64	5%	**
	Change in Soil Moisture	-11.93	5.45	8.54	-7.17	-5.94	-2.21	20%	**
	Change in Groundwater	-1.94	3.32	-33.91	5.38	-8.12	-7.05	25%	**
Closure	**Net Lateral Groundwater Inflow/Outflow (‘-’ *is net inflow*)**	**-34.67**	**28.86**	**-0.94**	**29.78**	**15.44**	**7.69**		
	(*CI* ±range)	**(-178 to 108)**	**(239 to -181)**	**(-74 to 72)**	**(208 to -148)**	**(167 to -136)**			

** *RI* < 1%

Annual water balance of Subregion 4 – Lower Klamath, mcm

Flow Path Component		1999	2000	2001	2002	2003	Avg	*CI*	*RI*
Inflows	Surface Water Diversions	279.04	254.68	105.13	268.49	208.65	223.20	35%	79%
	River and Tributary Flows	17.94	17.94	17.94	17.94	17.94	17.94	40%	1%
	Precipitation	82.24	80.61	59.18	53.77	72.97	69.75	14%	1%
	Total	**379.22**	**353.23**	**182.24**	**340.19**	**299.56**	**310.89**		
	(*CI*)	(26%)	(26%)	(21%)	(28%)	(25%)			
Outflows	ET from Agricultural Fields	88.29	95.21	57.62	82.76	89.72	82.72	20%	4%
	ET from Wildlife Refuges	104.37	107.66	95.59	99.87	100.35	101.57	20%	6%
	ET from Canals	1.57	1.57	0.73	1.51	1.46	1.37	20%	**
	ET from Drains	1.15	1.21	1.19	1.12	1.16	1.17	20%	**
	Evaporation from Open Water	0.09	0.09	0.10	0.09	0.09	0.09	20%	**
	ET from Urban Areas	0.00	0.00	0.00	0.00	0.00	0.00	20%	**
	ET from Undeveloped Areas	8.17	10.52	5.61	7.39	10.53	8.45	20%	**
	Flow to the Klamath River	138.16	95.69	22.76	98.49	79.67	86.96	30%	9%
	Total	**341.81**	**311.95**	**183.62**	**291.24**	**282.98**	**282.32**		
	(*CI*)	(15%)	(13%)	(19%)	(17%)	(17%)			
Storage	Change in Surface Water	-7.39	-6.81	-18.98	-8.29	-9.11	-10.12	5%	**
	Change in Soil Moisture	-2.51	-1.73	6.48	-1.90	-3.05	-0.54	20%	**
	Change in Groundwater	2.27	-11.36	-24.08	7.27	-7.72	-6.73	25%	**
Closure	**Net Lateral Groundwater Inflow/Outflow (‘-’ *is net inflow*)**	**45.05**	**61.17**	**35.21**	**51.87**	**36.47**	**45.95**		
	(*CI* ±range)	**(155 to -65)**	**(160 to -38)**	**(87 to -17)**	**(159 to -55)**	**(125 to -52)**			

** *RI* < 1%

Subregional water balance components with the highest relative importance in terms of the accuracy of the annual flow volumes

Subregion	Water Balance Component	Relative Importance
1- Langell	Lost River at Harpold Dam (outflow)	81%
	Agricultural fields ET_c	10%
2- Upper Klamath	Drain flows to Tulelake Irrigation District at J Canal	72%
	Lost River at Harpold Dam (inflow)	11%
	Lost River Diversion Channel (outflow)	7%
	Agricultural fields ET_c	6%
3- Tulelake	Drain flows from Klamath Irrigation District	89%
	Agricultural fields ET_c	6%
	Pumping Plant D in the Tule Lake Sumps	2%
4- Lower Klamath	Ady Canal	62%
	North Canal	12%
	Straits Drain	9%
	Refuge wetlands ET	6%
	Pumping Plant D from Tule Lake Sumps	5%
	Agricultural fields ET_c	4%

Appendix 4: Modernization Project Assessment Indicators – *Benchmarking and Transformation*

Key Indicator Values (Level 4)

No.	No Action	Water Bank	Recirculation	System-Level	Best	Worst
1	0	123	23	123	123	12
2	0	2	1	2	3	1
3	2	1	1.25	0.5	0	2
4	0	3	1	2	3	1
5	0	4,800	0	0	1,000	4,800
6	0.8	0.95	0.93	0.98	0.9	0.8
7	0	0	41,000	100,000	0	100,000
8	2.6	2.6	3	3.75	4	2.6
9	1	2	2	3	1	5
10	0	1	1	2	2	1
11	1	3	2	2.5	3	1
12	0	15	5	6	17	3
13	0	0.15	0.9	0.25	1	0.2
14	0	1	2	2	1	0
15	0	2	1	1	2	1
16	0	0.3	0.2	0.8	0.5	0.75
17	1	0	1	0	0	2
18	$0	$91	$12	$127	0	$150
19	$0	$65,903	$30,886	$113,050	0	$120,000
20	$0	$8	$0	$10	$0	$15
21	0	0	0.5	0.3	0.5	0.25
22	2	1	1	2	2	1
23	3	2	2	3	3	1
24	0	6	3	10	8	2
25	0	0	0	0	0	2
26	0	1	1	1	1	0
27	2	1	0	2	2	1
28	0	1	2	1	3	1
29	0	4	3	6	0	10
30	0	1.5	1	2	1	0

Transformed Indicator Values (0-1)

No.	No Action	Water Bank	Recirculation	System-Level
1	0.00	1.00	0.10	1.00
2	0.00	0.50	0.00	0.50
3	0.00	0.50	0.38	0.75
4	0.00	1.00	0.00	0.50
5	1.00	0.00	1.00	1.00
6	0.00	1.00	1.00	1.00
7	1.00	1.00	0.59	0.00
8	0.00	0.00	0.29	0.82
9	1.00	0.75	0.75	0.50
10	0.00	0.00	0.00	1.00
11	0.00	1.00	0.50	0.75
12	0.00	0.86	0.14	0.21
13	0.00	0.00	0.88	0.06
14	0.00	1.00	1.00	1.00
15	0.00	1.00	0.00	0.00
16	1.00	1.00	1.00	0.00
17	0.50	1.00	0.50	1.00
18	1.00	0.39	0.92	0.15
19	1.00	0.45	0.74	0.06
20	1.00	0.50	1.00	0.33
21	0.00	0.00	1.00	0.20
22	1.00	0.00	0.00	1.00
23	1.00	0.50	0.50	1.00
24	0.00	0.67	0.17	1.00
25	1.00	1.00	1.00	1.00
26	0.00	1.00	1.00	1.00
27	1.00	0.00	0.00	1.00
28	0.00	0.00	0.50	0.00
29	1.00	0.60	0.70	0.40
30	0.00	1.00	1.00	1.00

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