17. Appendix E. Documentation of Hydrology Simulations for the Klamath Dam Removal Studies

Document	Description
Hydrologic Data Development And Management	Describes development of naturalized flows from historic data, an overview of synthetic hydrology, and an overview of data management system.
Climate Change Hydrology	Describes development of Climate Change Hydrology
BO 2010 Operations	BO2010 operation criteria and implementation in KPSIM without KDR adjustments. These are the operations assumed under No Action Alternative.
KBRA Operations	KBRA operation criteria and implementation in KPSIM without KDR adjustments. These are the operations assumed under the Dam Removal Alternative.
Operations Models	BO 2010 and KBRA operation criteria and implementation in KPSIM as implemented for KDR, daily operations model, and other operations specific to the KDR study.
Forecasts For Synthetic Flows and Dynamic Agricultural Demand	Detailed description of forecast generation for synthetic hydrology for UKL operations and KBRA demand computations.

17.1. Hydrologic Data Development and Management

Hydrologic Data Development and Management to support Klamath Dam Removal Study

David King
Bureau of Reclamation
02/24/2011

Introduction

The study to determine the feasibility of removing four dams on the Klamath River required development of historic hydrology to support hydrologic and other analyzes related to the study. Available historic USGS and PacifiCorp data were obtained for water years 1961 through 2009, extended to fill in missing periods, and used to compute hydrologic inflows to the basin. The primary developed data for the study are the historic gains, also known as accretions or local inflows. Historic data are used with the historic period for model development and for deconstruction scenarios. Historic data from water years 1961 through 2009 were used to develop three synthetic types of hydrology for dams-in and dams-out planning scenarios. The types of synthetic hydrology are:

1. Indexed sequential – A hydrograph created by repetition of historic hydrology.
2. Stochastic – Hydrographs created using statistical software reflecting statistics from historical hydrology.
3. Climate change – Hydrographs created using a watershed model forced with weather conditions consistent with several climate change scenarios.

Documentation of the stochastic and climate change data is available elsewhere. The stochastic data set was not actually used because it did not include temperature data needed by other modeling efforts. The indexed sequential traces use all 49 years of historic data as a starting year. All traces are processed through a monthly upstream WRIMS model (KPSIM) and a daily downstream RiverWare model (Klamath Dam Removal Model - KDRM). Because of the large amounts of data, the processes were automated to the extent possible. These pages document historic hydrologic data development and data management applications.

Data Inventory

Historic monthly data upstream of Iron Gate Reservoir are developed by the Klamath Basin Area Office (KBAO). These data are used as hydrologic input data to the KPSIM. The downstream model required development of daily data downstream of Keno Reservoir. USGS streamflow records are mostly complete. Availability of reservoir elevations and releases varies considerably. Table 1 is a summary of available historic data downstream of Keno Reservoir.

KDRM Hydrology Nodes

The KPSIM has existed for a number of years and no modifications to its nodes were made. The KDRM was created for this study. The KDRM include hydrology nodes, routing nodes, confluences, and for the dams-in operations, power plants and reservoirs. A list of the primary hydrologic nodes in the KDRM is listed in Table 2. Additional nodes exist between these nodes which correspond to SALMOD fisheries model nodes. These nodes correspond to additional tributary inflows. Note that the Hoopa to Klamath gains are all gains from the Trinity At Hoopa and Klamath At Orleans gages to the Klamath Near

Klamath gage. Primary gains developed from historic data are spatially disaggregated to the SALMOND

Data Item	Source	Available Data
Klamath Near Keno Flow	USGS	1961 – 2009
JC Boyle Pool Elevation	PacifiCorp	1961 – 2009 with a few missing days.
JC Boyle Reservoir Spill	PacifiCorp	1979 - 2009 with some missing periods.
JC Boyle PP Turbine Release	PacifiCorp	1979 - 1982 and 1988 – 2009
Klamath Below JC Boyle PP Flow	USGS	1961 – 2009
Copco 1 Monthly Pool Elevation	USGS	1968 – 2002
Copco 1 Daily Pool Elevation	PacifiCorp	1979 - 2009 with some missing periods.
Copco 1 Outflow	PacifiCorp	1979 - 2009 with some missing periods.
Iron Gate Monthly Pool Elevation	USGS	1968 – 2002
Iron Gate Daily Pool Elevation	PacifiCorp	1979 – 2009 with some missing periods.
Klamath Below Iron Gate Flow	USGS	1961 – 2009
Shasta Near Yreka Flow	USGS	1961 – 2009
Scott Near Ft Jones Flow	USGS	1961 – 2009
Klamath Near Seiad Valley Flow	USGS	1961 – 2009
Indian Creek Near Happy Camp Flow	USGS	1961 – 2009
Salmon River At Somes Bar Flow	USGS	1961 – 2009
Seiad to Orleans Gain Reach	USGS	1961 – 2009
Klamath At Orleans Flow	USGS	1961 – 2009
Trinity At Hoopa Flow	USGS	1961 – 2009
Klamath Near Klamath Flow	USGS	1961-1994 and 1998 – 2009

Table 1. Downstream Klamath River Hydrologic Data Inventory.

Klamath River Near Keno
Keno to Boyle Reservoir Gain
JC Boyle Reservoir
Boyle Reservoir To Boyle Gage Gain
Boyle Gage To Copco Gain
Copco 1 Reservoir
Copco 2 Reservoir
Copco To Iron Gate Gain
Iron Gate Reservoir
Iron Gate to Seiad Gain
Seiad to Orleans Gain
Scott Near Ft Jones
Salmon At Somes Bar
Indian Creek Near Happy Camp
Shasta Near Yreka
Hoopa to Klamath Gains
Trinity At Hoopa

Table 2. Primary Downstream Model Hydrology Nodes.

nodes. KDRM uses temporally disaggregated monthly flows produced by KPSIM for Keno Reservoir releases. The temporal disaggregation process is described in a later section.

Data Development

Because of the file sizes involved, individual workbooks were created for data in the reservoir reaches and data downstream of the reservoir reaches. The downstream workbook consists entirely of USGS streamflow data and is self contained. The reservoir reaches workbook consists of USGS and PacifiCorp data and is supported by several other workbooks. The reservoir reaches workbook includes USGS streamflow data, Boyle spills, Boyle power plant flows, and change in storage for Boyle, Copco 1, and Iron Gate reservoirs expressed as flow. The computation of change in storage and conversion to flow is done in a separate workbook that has all end-of-period data obtained for the study. These data include a mix of USGS and PacifiCorp daily and monthly data.

A Reclamation developed Excel Add-In called the Data Utilities Toolkit (DUT) was used to move data between workbooks, between workbooks and HEC Data Storage System (DSS) files, and other data stores. The DUT also includes temporal aggregation utilities. The DUT is available at:

ftp://ftp.usbr.gov/tsc/jrieker/warsmp/dmiutils/dutaddin.zip

A DUT data management interface (DMI) exists in both primary historic data workbooks to pull USGS streamflow data. Except for two missing days for Klamath Below JC Boyle PP and three missing years for Klamath Near Klamath, these data are complete. The two missing days for Klamath Below JC Boyle PP were linearly interpolated. The missing data for Klamath Near Klamath were filled using regressions of monthly data. For instance, if a January value was missing, the January regression was used to fill that value.

A number of regression combinations were investigated to fill the missing Klamath Near Klamath period. The most satisfactory combination was a regression of the Hoopa to Klamath gain to the sum of Trinity At Hoopa plus Klamath At Orleans flow. Although the R^2's range from 0.16 to 0.78, the filled data are believed to be sufficient for this study because these flows do not affect the reservoir reaches.

Because of temporal and data quality issues, gains computed using historic streamflow data often have unnatural spikes including negative values. While negative gains can exist, they would typically not include large spikes. A smoothing method was applied to all gains downstream of Iron Gate reservoir that consisted of applying the flow pattern of the next downstream gage to the monthly gain. This approach maintains continuity on a monthly basis while computing a more natural hydrograph on a daily basis.

As seen in Table 1, data availability was problematic in the reservoir reaches. The record for the total hydrologic gain from Keno to Iron Gate is complete, so the missing data only affects the estimation of the total natural gain and the distribution of those gains between Keno and Iron Gate. Evaporation and other losses were not computed because insufficient data on evaporation rates was available, because insufficient knowledge of future river profiles for the dams-out scenario exists, and because a sensitivity analysis showed that evaporation is an insignificant portion of the gain. The results of the sensitivity analysis are shown in Table 3. Because evaporation and other losses were not computed, the computed gains in the reservoir reaches should be described as pseudo natural gains or developed gains. Furthermore, the gains below the reservoirs do not account for historic diversions and reservoir storage. The basic equation to compute pseudo natural gains is:

Pseudo natural gain = hydrologic gain + change in storage

Estimated reservoir evaporation @ 5.0 feet/year using historic average areas.							
Reservoir	Average Pool Elevation (feet)	Average Surface Area (acres)	Evaporation Volume (acre-feet/year)	Evaporation Volume (cfs)	PacifiCorp Maximum Surface Area (acres)	Evaporation Volume (acre-feet/year)	Evaporation Volume (cfs)
JC Boyle	3791.20	197	985	1.360	220	1100	1.518
Copco 1	2603.84	935	4675	6.453	980	4900	6.764
Copco 2	N/A	6	30	0.041	6	30	0.041
Iron Gate	2326.61	921	4607	6.359	1000	5000	6.902
Total	N/A	2059	10296	14.212	2206	11030	15.225
Average Annual Gain Volume			418297			418297	
Percent of Average Ann Gain			2.46%			2.64%	
1/2 Average Annual Evaporation			5148			5515	
Percent of Average Annual Gain			1.23%			1.32%	

Table 3. Evaporation Sensitivity Analysis.

Boyle pool elevation data were obtained but not storage values. An area-capacity table for Boyle reservoir was developed from an area-capacity curve provided by PacifiCorp. Historic Copco 1 and Iron Gate data include USGS end-of-month pool elevations and contents from 1968 through 2002. These data were used with PacifiCorp area-capacity curves to develop area-capacity tables for Copco 1 and Iron Gate reservoirs.

Missing reservoir data were handled in a number of ways. Small periods of 1 to 4 days were linearly interpolated. Periods where monthly elevations existed but daily values did not, a straight line interpolation of the monthly storage values was used. Missing change in storage for longer periods for Copco 1 and Iron Gate were computed using monthly regressions to Boyle's change in storage. Although these regressions are poor, they only affect data before 1968. Since these estimates only affect pseudo natural gain computations before 1968 and those data are only used for the deconstruction scenarios and model development, it was decided that these estimates are sufficient for this study.

Three additional adjustments of the daily data were made. First, PacifiCorp has periodically measured the gain from spring inflows between Boyle Reservoir and the gage below the power plant. The average flow of 220 cfs was incorporated as the minimum gain in this reach, also known as the bypass reach. Second, the years that Copco reservoir releases are available were used to compute the average monthly spatial distribution of gains between the Klamath River Below JC Boyle Power Plant gage and Iron Gate reservoir upstream and downstream of Copco reservoir. These distributions were applied to total gain when the measured distribution was unavailable. The monthly spatial distribution pattern is shown in Table 4.

The third adjustment was to compute a provisional change in storage for the regressed and interpolated periods, then adjust the change in storage if it produced negative reservoir inflows. When negative inflows are computed, they were set to zero. Then the change in storage was recomputed using the adjusted inflow. This adjustment mostly affects computations before 1979. However, it can affect the distribution of gains between reservoirs on any day if bad recorded data exists.

Month	Fraction
January	0.240
February	0.208
March	0.144
April	0.093
May	0.144
June	0.175
July	0.303
August	0.349
September	0.292
October	0.178
November	0.165
December	0.067
Annual	0.183

Table 4. Klamath Below JC Boyle PP to Copco Gain To Total Gain Monthly Distribution.

The Trinity at Hoopa case is problematic in that this reach is highly regulated and is affected by transbasin operations which have changed over time. Therefore, historic flows for Trinity at Hoopa were noted used. Instead, the flows used for this study are based on CALSIM output for Trinity at Lewiston. CALSIM is a WRIMS model for the central valley of California. These data are available through 2003. CALSIM output for 2004 through 2009 was estimated by regressing CALSIM Trinity at Lewiston to CDEC natural flow for Trinity at Lewiston. The actual and estimated CALSIM flows were extended to Trinity at Hoopa by adding the historic hydrologic gain between the two gages.

The developed gains are consolidated in another workbook and posted to a DSS. The consolidated workbook computes daily to monthly ratios that support the disaggregations that are used by the KDRM. Monthly data from KPSIM and the synthetic monthly data traces are disaggregated to daily by the KDRM.

Synthetic Hydrology Development

Historic monthly data upstream of Iron Gate Reservoir are developed annually by the Klamath Basin Area Office (KBAO) in workbook MODSUM. Data from MODSUM are used as hydrologic input data to the KPSIM for planning studies using two primary operation scenarios:

BO – Current operations based on various biological opinions
KBRA – Klamath Basin Restoration Agreement

A 100-year repeated historic data set was created with 2012 as the starting year using 1961 through 2009 historic data for all hydrology nodes used by the KDRM and for Upper Klamath Lake (UKL) inflow and Keno to Iron Gate gain of the KPSIM. This trace was mostly intended for calibration purposes. It was intended that KDR analyzes use the indexed sequential, stochastic, or climate change scenarios. In actual implementation, it was not possible to use the stochastic data because it was problematic to compute stochastic climate data to support fisheries modeling.

Initially, the synthetic hydrologies were based upon historic 1977 through 2009 data based from a study by Dr. Tim Mayer of the U.S. Fish and Wildlife Service (Mayer, 2008)[1]. This study analyzed trends in hydrology for the Klamath basin. Subsequently, it was decided to base all hydrologies on the 1961 through 2009 historic record. It was decided that hydrologic variation was more important than hydrologic trends to the KDR analyzes.

Temporal Disaggregations

The KDRM requires daily data. Disaggregations of monthly to daily data are based on historic daily to monthly relations. As previously noted, the disaggregation fractions are computed using the filled historic daily data and equivalent monthly data. The disaggregations are computed by the KDRM. In addition to the disaggregation fractions, the KDRM needs rankings of the historic data by season. The rankings are computed in a workbook as a pre-process. Before a model run, synthetic monthly flows from the hydrologic traces are imported into the KDRM. At the beginning of each month, the disaggregation rules compute the seasonal volume, find the closest match to historic seasonal volume, and use the disaggregation fractions from the matched season to compute the daily flows for the month. Seasonal matching was used in lieu of monthly matching to reduce unnatural transitions between disaggregation periods.

The KDRM Keno daily flows are treated differently because those flows are regulated and because of the overlap with the KPSIM model. Both operating scenarios of the KPSIM attempt to meet an instream flow requirement (IFR) at Iron Gate[2]. Because Iron Gate is downstream of the beginning of the KDRM, Keno daily flow is computed as daily Iron Gate flow without the reservoirs less Keno to Iron Gate daily gain. The IFR is subtracted from the total KPSIM flow at Iron Gate and only the excess water is disaggregated. The daily flow at Iron Gate is the sum of the disaggregated excess water and the IFR. If the KPSIM flow for the month is less than the IFR, the average daily flow is used.

Gains between Keno and Iron Gate use the pattern of disaggregated Keno flow. This was done to enable the KDRM to better meet Iron Gate IFR's. In actual operations, additional water is released from UKL to meet Iron Gate IFR's. However, this not possible with the KDRM because it does not model UKL. Using Keno's daily pattern is a virtual emulation of supplemental releases of UKL.

Spatial Disaggregations

The temporally disaggregated data downstream of Iron Gate Dam are spatially disaggregated to a number of tributaries. The spatial distribution factors were estimated as a function of the drainage area at the tributary and the drainage area of the next downstream gage. This approach produces similarly shaped hydrographs for all the tributaries between gages but maintains mass balance with respect to the total daily gain of the reach.

Streamflow Routing

Hourly data from the gages downstream of Keno were used to estimate travel times between gages as a function of flow. These were used in the KDRM to lag flows down the river. More sophisticated routing methods require more data than were available for this study.

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[1] Mayer, T. F., 2008. Analysis of Trends and Changes in Upper Klamath Lake Hydroclimatology, U.S. Fish and Wildlife Service.

[2] The criteria for the Iron Gate IFR vary between the BO and KBRA operations.

Data Management

The data development and the numerous steps to generate model input and process model output require considerable data management. Most of the hydrologic workbooks used for the study include DMI's managed by the DUT. Each DMI requires a header worksheet which is basically a mapping of the workbook's data for one time-series worksheet to another data store. These DMI's are usually ran interactively using the DUT. Automated management of the multiple models, operating scenarios, and hydrologic traces was facilitated by creating Excel macro based workbook for managing the runs. Using user provided file specifications, number of years, number of traces, and other data, the runs manager runs appropriate DUT DMI's and the models in batch mode. The runs manager uses an input data workbook that includes the input DMI headers and templates for the spatial disaggregations. It also includes knowledge of how to adjust UKL inflows for the KBRA KPSIM operating scenario. All monthly model input data are retained in the input data workbook. A user manual for the data manager is available.

17.2. Climate Change Hydrology

Klamath Dam Removal Study
Climate Change Hydrology Development
David King, David Sutley, and David Raff
02/24/2011

Introduction

The Klamath Dam Removal (KDR) study used two hydrologic models to assist in analyzing several hydrologic scenarios. The two hydrologic models consist of an upstream monthly model and a downstream daily model. Output of the upstream model becomes part of the input to the downstream model. The upstream monthly timestep was sufficient to allocate water supplies in the upper basin and a reasonable estimate of Klamath River flows available to the downstream model. The daily timestep of the downstream model provided better computations of power production and streamflows in critical river reaches. To analyze a wide range of potential future hydrologic scenarios, three synthetic hydrologies were developed:

1. Indexed sequential – A hydrograph created by repetition of historic hydrology.
2. Stochastic – Hydrographs created using statistical software reflecting statistics from historical hydrology.
3. Climate change – Hydrographs created using a watershed model forced with weather conditions consistent with several climate change scenarios.

The following pages describe the definition of regional climate change scenarios in a larger process of identifying the potential impact of climate change on the water resources management of the Klamath Basin, the use of these data into a Sacramento Soil Moisture Accounting (SAC-SMA**)** watershed model, and the incorporation of the hydrology produced by the watershed model in the KDR models.

Climate Change Data Development

The regional climate change scenario selection described here builds upon two recent studies performed in support of the 2008 Central Valley Project/State Water Project Operations Criteria and Plan (Reclamation 2008) and the San Joaquin River Restoration Program Supplemental Hydrologic and Water Operations Analyses (Reclamation 2009), respectively. The selection criteria described here is similar to Reclamation 2008 and Reclamation 2009 in that the first four regional scenarios were chosen for how they bracket a range of possible regional climates. Similar to Reclamation 2009, a fifth scenario is chosen for how it represents a centrally projected climate change over the region. And similar to Reclamation 2008 and Reclamation 2009, the possible regional climates are defined by paired precipitation-temperature conditions. Projection information is surveyed for changes in these conditions given four selection factors:

1. Historical and future climate periods
2. Climate change metrics
3. Location of climate change
4. Change-range of interest.

The climate change information used throughout the selection procedure is through the Bureau of Reclamation (Reclamation) in cooperation with the Lawrence Livermore National Laboratories, Santa Clara University and The Institute for Research on Climate Change and its Societal Impacts have developed and host a downscaled climate projection archive:

http://gdodcp.ucllnl.org/downscaled_cmip3_projections/

Within that archive are housed 112 climate projections from 1950 through 2099. These represent three emissions paths, A1B, A2, and B1 (IPCC 2000) for sixteen general circulation models (GCMS) with different initial conditions for different model simulations. The GCMS represent various climate modeling groups coordinating through the World Climate Research Programme Working Group on Coupled Modeling through the CMIP3 effort (Meehl et al. 2007). The sixteen GCMs represent a spatial scale that is too coarse for most impact studies. Therefore, a downscaling methodology (Wood et al. 2004) has been applied to these projections to provide information at an1/8° resolution that can be used to study potential climate change impacts. In addition, GSM data require bias corrections to adjust the data to historic climate of a selected location. Therefore, data obtained from this archive have also been bias corrected.

Location of Climate Change

The Klamath Basin was divided into two regions for analysis of climate change. These regions were selected for consistency with the tools and methods that were used for the impact analyzes as well as to evaluate potential different climate change effects in the upper and lower basin, given the possibility of change different dynamics in these distinct geographic regions. The first region encompasses the Upper Klamath basin and roughly corresponds to the geographic extent (***Upper*** basin) of the upstream monthly WRIMS model (KPSIM). That is the Klamath Basin above Iron Gate.

The second region (***Lower*** basin) is located below Iron Gate and encompasses three regions that correspond to availability of National Weather Service forecast points on the Klamath River and their operational SAC-SMA hydrologic tool availability. These forecast points are Seiad, Klamath, and Orleans. The downstream daily RiverWare model (KDRM) covers this area plus the power reservoirs upstream of Iron Gate and therefore, overlaps the KPSIM.

These two regions were used to provide climate information for the ***Upper*** basin in order to evaluate operations and the ***Lower*** basin to provide intervening effects at Seiad, Klamath, and Orleans as shown on Figure 1.

Historical and Future Climate Periods and Climate Change Metrics

Temporally, the 75 projections were divided into two equal length periods, the base period defined as 1950 – 1999 and a lookahead period defined as 2020 – 2069. The lookahead period was chosen based on the analysis period defined for the KDR Study. A fifty year base and lookahead period were used to encompass the full time period of effects analysis that would lead to a single set of projections, desired for ease in evaluation. Using a shorter time period to define selection criteria could result in selection of different model projections for different lookahead horizons and some reconciliation would then have to take place. The 39 projections for each of the Upper and Lower portions of the Klamath Basin, as shown in Table 1, were averaged spatially and temporally. The result of this averaging is a single value of temperature and precipitation for each projection within the base period and the lookahead period for temperature and precipitation, respectively.

The three emissions scenarios within the downscaled archive 75 projections were extracted representing all of the projections following A1B and the A2 emissions paths. The A1B and A2 emissions paths are greater than the B1 emissions path. The B1 emissions path was not included because global emissions are already known to exceed all SRES scenarios to present and therefore the B1 projections were considered less likely future projections than the A1B and A2 paths (Figure 2). The metrics of climate change to be evaluated are changes in precipitation and temperature described as a net change from future to base for temperature and a ratio from future to base for precipitation. The rationale for these metrics is that ultimately it will be precipitation and temperature that will be used to drive the hydrologic tool and therefore the metrics evaluated should then define a range of hydrologic outputs.

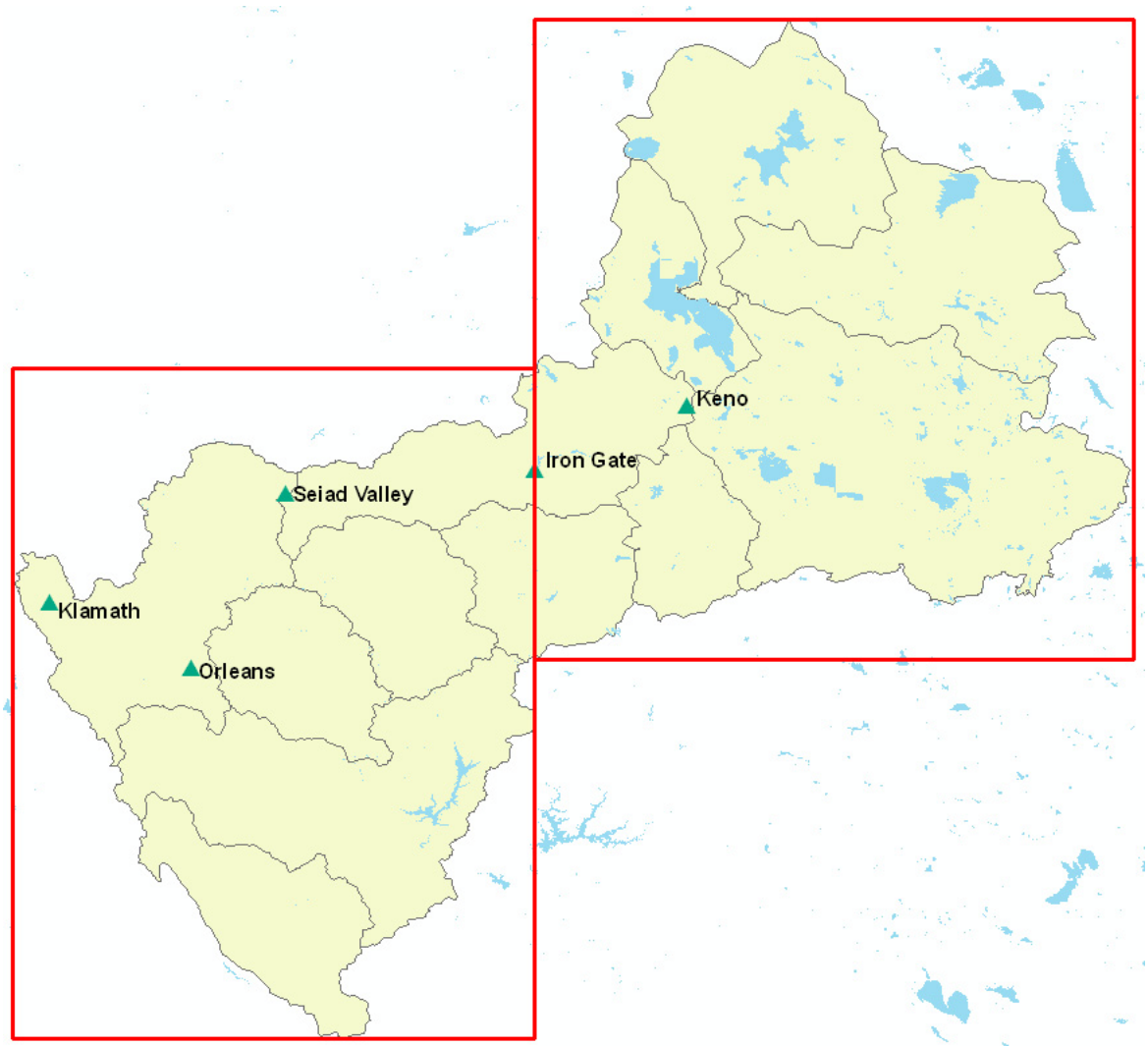


Figure 1. Klamath Basin downscaled climate projection data extraction regions.

Change-Range of Interest

The four bracketing climate scenarios were defined by the distribution of the climate change projection metrics. The climate change metrics (net change temp, ratio of precip) are evaluated by their Weibull plotting positions as shown on Figure 3. The bracketing criteria were set as the 25th and 75th quantiles of the empirical distributions of precipitation and temperature. These are then used to define a quantile plot for the joint distribution of the temperature and precipitation ratios as shown on Figure 4. The 25th and 75th quantiles are used because they represent a range about the central tendency that is assumed to describe climatic drift as opposed to interdecadal

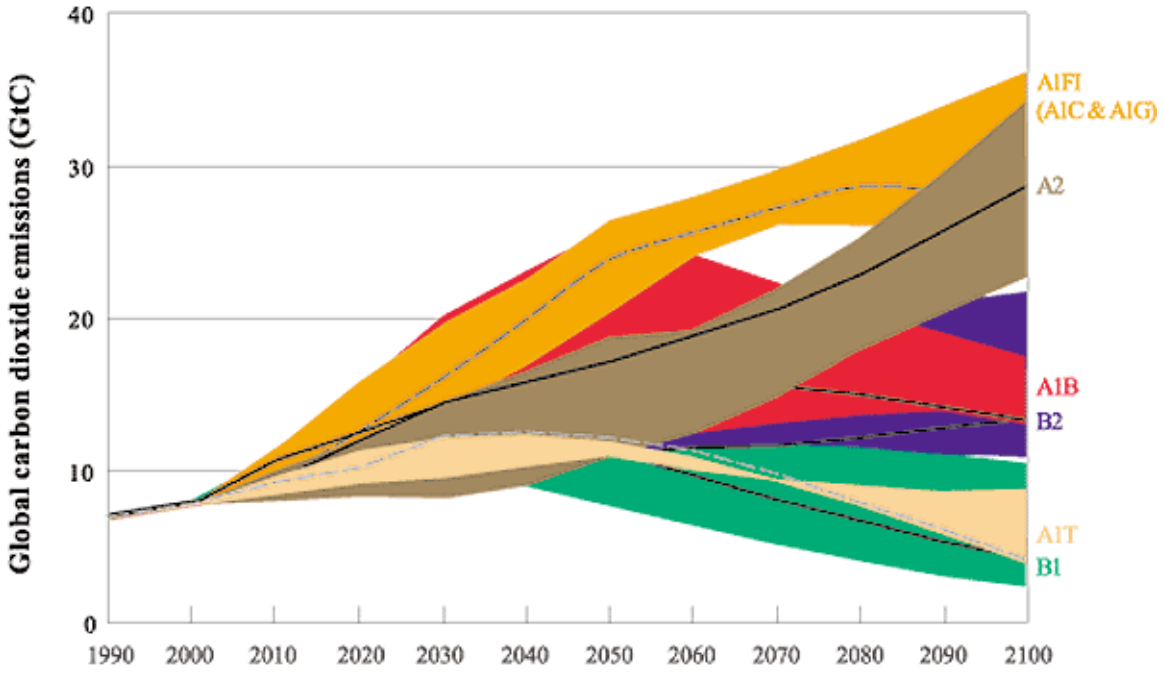


Figure 2. Emissions Paths. Paths A1B and A2 were used as selection criteria for data extraction.

variability that would be more described by 10th and 90th quantiles as learned through Reclamation 2009. The central tendency was defined as the mean of the climate change metrics. Therefore, on the joint distribution plot (Figure 4) the scenarios are defined as being nearest to the vertices:

- Vertice 1: 25th quantile Temperature paired with 25th quantile Precipitation
- Vertice 2: 25th quantile Temperature paired with 75th quantile Precipitation
- Vertice 3: 75th quantile Temperature paired with 25th quantile Precipitation
- Vertice 4: 75th quantile Temperature paired with 75th quantile Precipitation

and the centrally projected vertice

- Vertice 5: 50th quantile Temperature paired with the 50th quantile Precipitation

Each region are shown on Figure 4 as highlighted by the blue boxes. The selection criteria for the Upper and Lower basins are shown in Table 2, respectively. For consistency between the Upper and Lower basins it is desirable to use the same set of projections. Therefore the differences between Table 2a and Table 2b must be resolved. The resolution criteria employed here was to reevaluate the projection distances from each of the five vertices and determine the projections whose distance is shortest from both the Upper and Lower basins. These projections are shown in yellow in Figure 4 and are listed in Table 3.

Projection Index	Projection Name	Projection Index	Projection Name
1	bccr_bcm2_0.1.sresa1b	39	miub_echo_g.3.sresa2
2	bccr_bcm2_0.1.sresa2	40	mpi_echam5.1.sresa1b
3	cccma_cgcm3_1.1.sresa1b	41	mpi_echam5.2.sresa1b
4	cccma_cgcm3_1.2.sresa1b	42	mpi_echam5.3.sresa1b
5	cccma_cgcm3_1.3.sresa1b	43	mpi_echam5.1.sresa2
6	cccma_cgcm3_1.4.sresa1b	44	mpi_echam5.2.sresa2
7	cccma_cgcm3_1.5.sresa1b	45	mpi_echam5.3.sresa2
8	cccma_cgcm3_1.1.sresa2	46	mri_cgcm2_3_2a.1.sresa1b
9	cccma_cgcm3_1.2.sresa2	47	mri_cgcm2_3_2a.2.sresa1b
10	cccma_cgcm3_1.3.sresa2	48	mri_cgcm2_3_2a.3.sresa1b
11	cccma_cgcm3_1.4.sresa2	49	mri_cgcm2_3_2a.4.sresa1b
12	cccma_cgcm3_1.5.sresa2	50	mri_cgcm2_3_2a.5.sresa1b
13	cnrm_cm3.1.sresa1b	51	mri_cgcm2_3_2a.1.sresa2
14	cnrm_cm3.1.sresa2	52	mri_cgcm2_3_2a.2.sresa2
15	csiro_mk3_0.1.sresa1b	53	mri_cgcm2_3_2a.3.sresa2
16	csiro_mk3_0.1.sresa2	54	mri_cgcm2_3_2a.4.sresa2
17	gfdl_cm2_0.1.sresa1b	55	mri_cgcm2_3_2a.5.sresa2
18	gfdl_cm2_0.1.sresa2	56	ncar_ccsm3_0.1.sresa1b
19	gfdl_cm2_1.1.sresa1b	57	ncar_ccsm3_0.2.sresa1b
20	gfdl_cm2_1.1.sresa2	58	ncar_ccsm3_0.3.sresa1b
21	giss_model_e_r.2.sresa1b	59	ncar_ccsm3_0.5.sresa1b
22	giss_model_e_r.4.sresa1b	60	ncar_ccsm3_0.6.sresa1b
23	giss_model_e_r.1.sresa2	61	ncar_ccsm3_0.7.sresa1b
24	inmcm3_0.1.sresa1b	62	ncar_ccsm3_0.1.sresa2
25	inmcm3_0.1.sresa2	63	ncar_ccsm3_0.2.sresa2
26	ipsl_cm4.1.sresa1b	64	ncar_ccsm3_0.3.sresa2
27	ipsl_cm4.1.sresa2	65	ncar_ccsm3_0.4.sresa2
28	miroc3_2_medres.1.sresa1b	66	ncar_pcm1.1.sresa1b
29	miroc3_2_medres.2.sresa1b	67	ncar_pcm1.2.sresa1b
30	miroc3_2_medres.3.sresa1b	68	ncar_pcm1.3.sresa1b
31	miroc3_2_medres.1.sresa2	69	ncar_pcm1.4.sresa1b
32	miroc3_2_medres.2.sresa2	70	ncar_pcm1.1.sresa2
33	miroc3_2_medres.3.sresa2	71	ncar_pcm1.2.sresa2
34	miub_echo_g.1.sresa1b	72	ncar_pcm1.3.sresa2
35	miub_echo_g.2.sresa1b	73	ncar_pcm1.4.sresa2
36	miub_echo_g.3.sresa1b	74	ukmo_hadcm3.1.sresa1b
37	miub_echo_g.1.sresa2	75	ukmo_hadcm3.1.sresa2
38	miub_echo_g.2.sresa2		

Table 1. 39 projections analyzed for possible selection for climate change analysis. Numbers correspond to quartile scatter plot with Figure 4. The Projection naming convention is <model>.<run>.<path>.

Vertice	Projection Index	Projection Name
1	22	giss_model_e_r.4.sresa1b
2	48	mri_cgcm2_3_2a.3.sresa1b
3	39	miub_echo_g.3.sresa2
4	6	cccma_cgcm3_1.4.sresa1b
5	41	mpi_echam5.2.sresa1b

Table 2a. Upper Basin.

Vertice	Projection Index	Projection Name
1	14	cnrm_cm3.1.sresa2
2	48	mri_cgcm2_3_2a.3.sresa1b
3	36	miub_echo_g.3.sresa1b
4	6	cccma_cgcm3_1.4.sresa1b
5	43	mpi_echam5.1.sresa2

Table 2b. Lower Basin.

Table 2. Projections nearest to selection criteria vertices.

Vertice	Projection Index	Projection Name
1	70	ncar_pcm1.1.sresa2
2	48	mri_cgcm2_3_2a.3.sresa1b
3	36	miub_echo_g.3.sresa1b
4	6	cccma_cgcm3_1.4.sresa1b
5	18	gfdl_cm2_0.1.sresa2

Table 3. Projections nearest to vertices 1-5 for both Upper and Lower Basin.

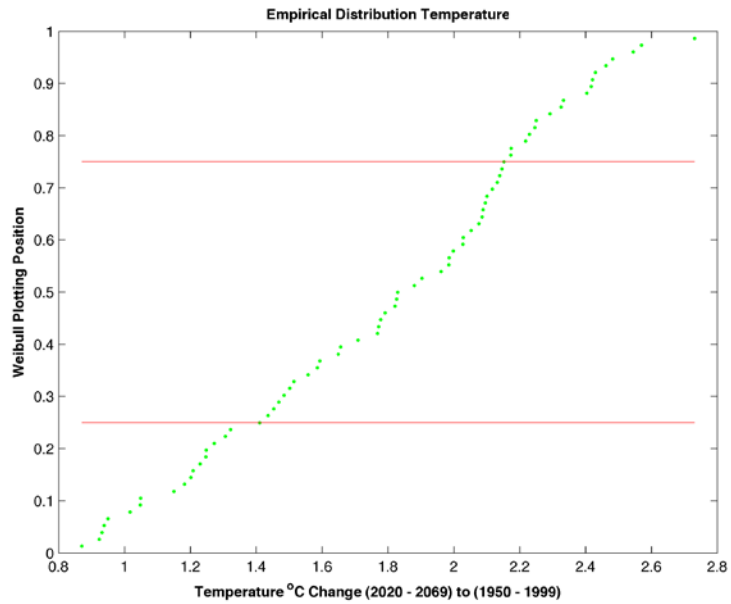
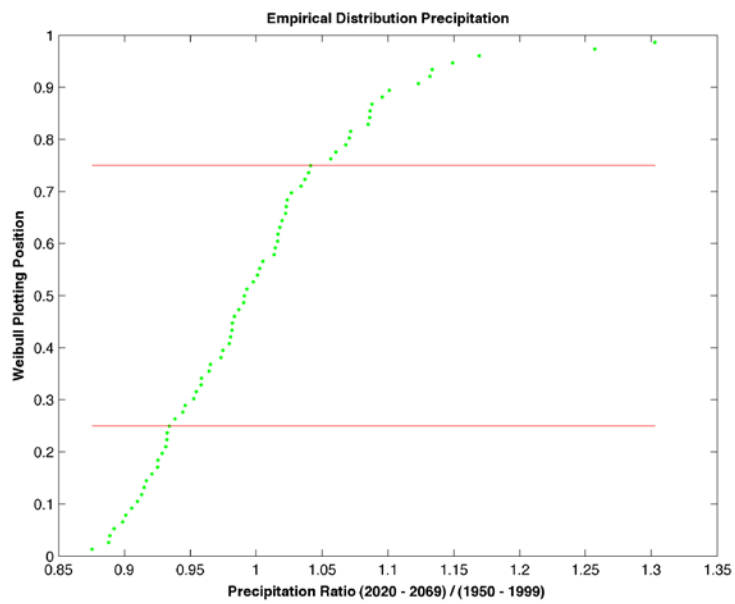
Temperature	
Precipitation	

Figure 3a. Upper Basin.

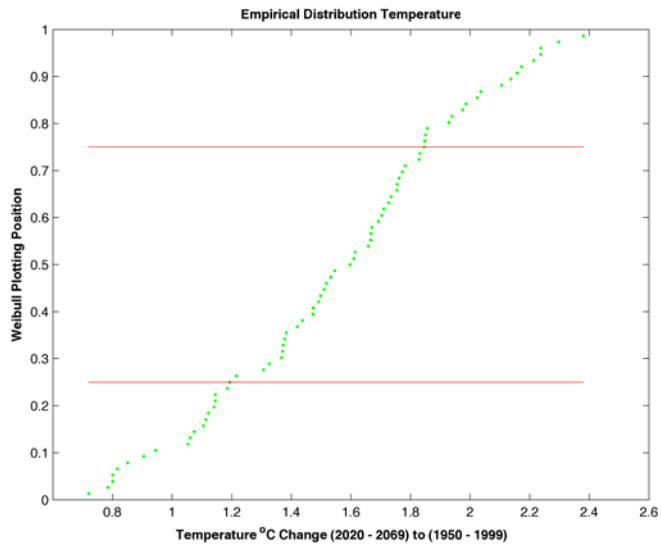
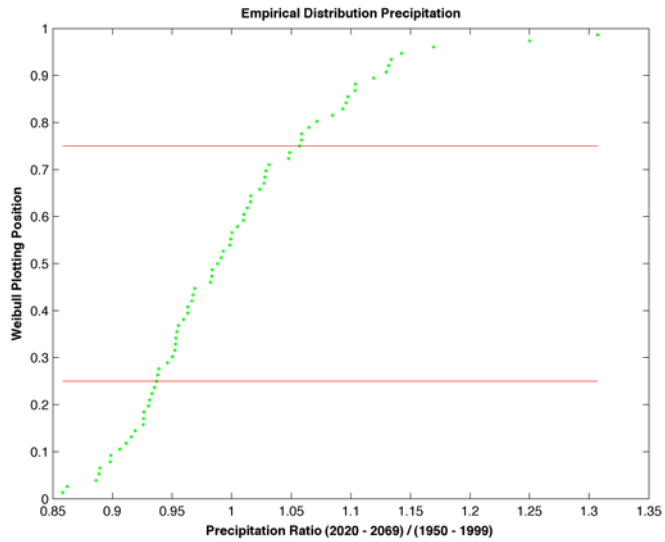
Temperature	
Precipitation	

Figure 3b. Lower Basin.

Figure 3. Weibull plotting positions for temperature and precipitation projections. Red horizontal lines represent 25th and 75th quantiles, respectively.

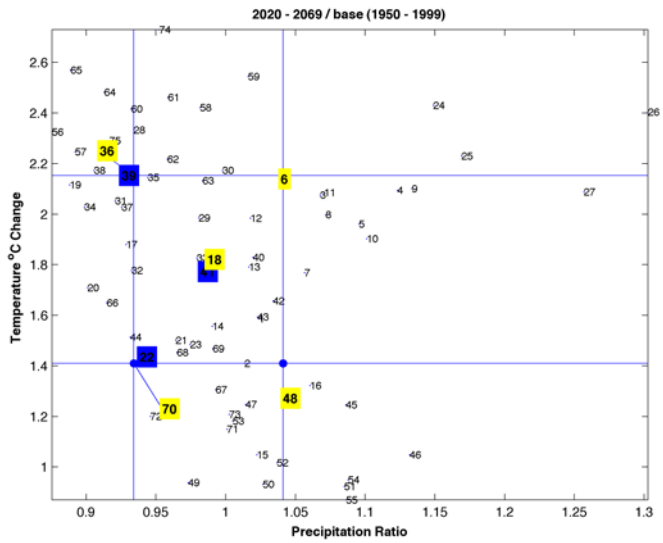
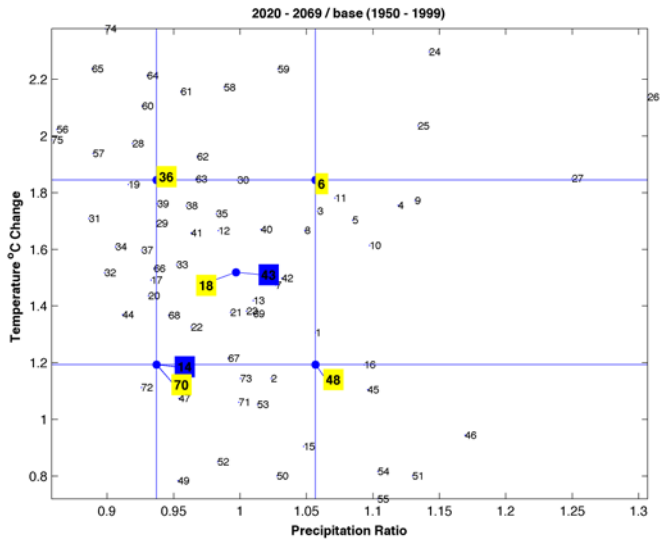
Upper Basin	
Lower Basin	

Figure 4. Quartile Maps of 39 projections. Projections selected for climate change analysis are those highlighted by blue box closest to quartile vertices.

Watershed Model

Climate change implications for hydrology were evaluated using the SacSMA/Snow17 hydrology model. A set of subbasin-specific SacSMA/Snow17 model-applications spanning the Klamath River Basin were obtained from the NOAA-NWS California Nevada River Forecast Center (CNRFC). The SAC-SMA/Snow17 hydrologic application were used to translate the regional climate change scenarios into hydrologic runoff scenarios to drive the WRIMs operational

tool for the Upper Klamath Basin and to define intervening flows at Seiad, Klamath, and Orleans (Figure 1).

As described in Reclamation 2009, the SAC-SMASnow17 is a coupling of the Sacramento Soil Moisture Accounting model (Burnash et al. 1973) coupled to the Snow17 snow accumulation and ablation model (Anderson 1973). SacSMA/Sno17 applications have been applied to support numerous studies on climate change implications (i.e. Miller et al. 2003, Brekke et al. 2004, Zhu et al. 2005, Reclamation 2008, Brekke et al. 2009). Structurally, SacSMA/ Snow 17 applications depict a water balance evolving through time, where accumulated precipitation eventually leaves the watershed as either runoff or evapotranspiration. SacSMA/Snow17 is driven by information of temperature and precipitation at 6-hourly time steps. The models are calibrated to reproduce historical runoff given historical streamflow and weather station observations (Brazil and Hudlow 1981, Burnash et al 1973, Burnash 1995, and Finnerty et al. 1997).

One issue of uncertainty is to what degree warming over the Klamath basin would increase actual and potential evapotranspiration (AET and PET) over the watershed. Conceivably, warmer air can hold more moisture, so it might be expected that PET could increase under warming, thus raising the limits on AET. Even without raising PET limits, AET should increase when summed over the water year if snow-covered fraction is reduced in area extent and in time.

SacSMA/Snow17 does not compute PET internally. However, it does feature input PET values to constrain AET. These input PET values reflect historical climatological (mean-monthly) PET and vary by month. These inputs were not adjusted for the SacSMA/Snow17 simultions under climate change. Thus, the simulated runoff estimates may be slightly greater than they would have been had some scheme been used to increase PET limits relative to the degree of warming in each climate change scenario. However, the omission of elevated PET with warming may be minor matter with the SacSMA/Snow17 applications in the Klamath basin, particularly if the basin behaves similarly to the Sacramento above Shasta or N.F. American. In the latter two basins, climate change impacts on runoff were found to be largely similar when simulated by a model featuring internally computed PET and increased PET for warming, and SacSMA/Snow17 applications also obtained from the California Nevada River Forecast Center (Maurer et al. 2010).

Decision Modeling

As previously noted, the KDR study used two hydrologic decision models to assist in analyzing the impacts of study alternatives and hydrologic scenarios, a monthly upstream model (KPSIM) and a daily downstream model (KDRM). Although 6-hour values were available from the watershed model, these data were not biased corrected and were not available for all nodes needed by the decision models. In addition, KDR study modelers did not have sufficient resources to use all 50 traces generated by the SAC-SMA. Based upon these considerations, the realization closest

to the median of the ten realizations per climate change model was used for each of the five climate change scenarios. This narrowed the used scenarios to the five listed in Table 4.

Model	Realization
cccma_cgcm3_1.4.sresa1b - Realization 7	7
gfdl_cm2_0.1.sresa2 - Realization 2	2
miub_echo_g.3.sresa1b - Realization 5	5
mri_cgcm2_3_2a.3.sresa1b - Realization 8	8
ncar_pcm1.1.sresa2 - Realization 6	6

Table 4. Climate change scenarios.

Bias correction of watershed model output is computationally intensive and would have required considerable time to implement. In addition, bias corrected flows would still have required spatial transformation into KDR nodes. Subsequently, it was decided to use a more direct approach to translate climate change scenario streamflows into equivalent flows for KDR analyzes.

For the five used scenarios, daily output of used SAC-SMA nodes were aggregated to monthly and used to perturbate historic hydrology for KPSIM and KDR nodes. The perturbation factors are the ratio of scenario's average monthly flows to the historic average monthly flows. These are multiplied by the historic monthly flows to compute the climate change flows as:

Decision model scenario flow = Decision model historic flow * SAC SMA monthly ratio

Subsequently, the climate change hydrologies used by the decision model have a dependency upon historic hydrology. Because the KPSIM input data includes precipitation, the SAC-SMA's precipitation upstream of UKL was also used to compute climate change precipitation for the KPSIM using the same approach. Example flow perturbation data are shown in Table 5.

The KPSIM model uses the monthly climate change data generated by this process directly. The downstream model uses a combination of those data and data from the KPSIM. All monthly values are disaggregated to daily in the KDRM using methods discussed elsewhere.

Average Monthly SAC SMA Scenario to Calibration Ratios For 39 years of calibration									
Month		Hoopa to Klamath Gains	Total Iron Gate to Seiad Gain	Total Seiad to Orleans Gain	Williamson Near Klamath Agency	Sprague Near Chiloquin	UKL Inflow	Trinity At Hoopa Flow	Upstream UKL Precipitation
January	1	0.7903	0.9767	0.8372	0.6109	0.6391	0.8329	0.7868	0.8594
February	2	0.8863	1.3559	0.8272	0.7244	0.9646	0.9757	1.0722	1.3120
March	3	0.9651	1.3998	0.8733	0.8811	1.2191	1.1793	1.1002	1.1970
April	4	0.7225	0.8037	0.5022	0.5622	0.9088	0.8853	0.6747	0.8665
May	5	0.7244	0.3882	0.3161	0.4469	0.6109	0.7185	0.4154	0.9412
June	6	0.7066	0.3377	0.3205	0.5066	0.6537	0.7242	0.4089	0.8878
July	7	0.7659	0.5283	0.5139	0.5770	0.6625	0.7696	0.6507	0.7237
August	8	0.8196	0.6548	0.7206	0.6264	0.5801	0.7862	0.7058	0.3973
September	9	0.7224	0.7918	0.7248	0.6895	0.7077	0.8633	0.7288	1.0469
October	10	0.9330	0.8744	0.6117	0.6937	0.7245	0.8689	0.7374	0.9282
November	11	0.6158	0.7559	0.4702	0.7118	0.8069	0.9097	0.5937	0.8198
December	12	0.6338	0.6579	0.5316	0.6112	0.5983	0.8008	0.5221	0.8849
Annual Total		0.7833	0.8787	0.6512	0.6355	0.7932	0.8758	0.7714	0.9398
Average Monthly SAC SMA Scenario Flows									
Month		Hoopa to Klamath Gain	Total Iron Gate to Seiad Gain	Total Seiad to Orleans Gain	Williamson Near Klamath Agency	Sprague Near Chiloquin	UKL Inflow	Trinity At Hoopa Flow	Upstream UKL Precipitation
January	1	451416	165636	452691	44732	11535	117216	596103	3.26
February	2	458846	229829	459152	58741	18987	142843	822618	3.55
March	3	498745	265707	513160	98641	36295	222623	925681	3.20
April	4	220549	122792	199999	66070	32333	161331	400465	1.51
May	5	109958	65806	101999	46712	24301	125717	192747	1.62
June	6	51814	31583	52612	32411	13997	88716	101328	1.20
July	7	22395	15747	30549	21279	6567	56823	56179	0.42
August	8	12627	9198	22639	19295	4158	48786	34406	0.33
September	9	8281	11072	18679	23316	5282	62600	26026	0.94
October	10	31762	22215	33886	28409	6867	76784	42477	1.71
November	11	154667	43278	110036	32016	8559	92668	139973	3.17
December	12	342028	87210	259880	38686	9750	107568	309716	3.61
Annual Total		2363089	1070073	2255280	510309	178632	1303675	3647720	24.54
Average Monthly SAC SMA Historic Flows									
Month		Hoopa to Klamath Gain	Total Iron Gate to Seiad Gain	Total Seiad to Orleans Gain	Williamson Near Klamath Agency	Sprague Near Chiloquin	UKL Inflow	Trinity At Hoopa Flow	Upstream UKL Precipitation
January	1	571232	169580	540704	73227	18048	140739	757607	3.79
February	2	517688	169507	555061	81091	19684	146401	767224	2.71
March	3	516775	189818	587610	111952	29771	188780	841402	2.67
April	4	305260	152777	398273	117527	35577	182233	593515	1.74
May	5	151783	169506	322661	104533	39776	174962	463947	1.72
June	6	73331	93515	164163	63973	21412	122503	247808	1.35
July	7	29239	29808	59445	36876	9911	73838	86335	0.58
August	8	15407	14048	31416	30805	7168	62057	48746	0.84
September	9	11462	13983	25771	33816	7464	72509	35709	0.90
October	10	34044	25407	55400	40951	9478	88373	57608	1.85
November	11	251170	57254	234017	44978	10608	101861	235777	3.87
December	12	539624	132560	488887	63298	16296	134325	593235	4.08
Annual Total		3017015	1217763	3463409	803026	225193	1488581	4728914	26.11
Average Monthly Historic Flows									
Month		Hoopa to Klamath Gain	Total Iron Gate to Seiad Gain	Total Seiad to Orleans Gain	Williamson Near Klamath Agency	Sprague Near Chiloquin	UKL Inflow	Trinity At Hoopa Flow	Upstream UKL Precipitation
January	1	539324	186139	580698	10507	39213	150716	625254	1.95
February	2	474214	157758	500242	12853	42488	146596	557031	1.25
March	3	490600	177892	520940	20811	62892	179463	593761	1.26
April	4	347098	149108	423154	21233	71382	163385	407886	0.93
May	5	221370	157636	389118	12351	70218	136523	326511	1.01
June	6	119578	92679	200394	5262	35942	74485	176509	0.70
July	7	51349	30606	76194	1659	16265	32946	80172	0.26
August	8	33274	12896	40405	467	11930	32493	47488	0.50
September	9	32041	12321	30412	411	13333	52317	40381	0.44
October	10	60020	23283	50131	1147	18462	79756	54168	0.98
November	11	233068	54363	190512	4450	21294	109057	162474	2.02
December	12	467861	134484	449100	9739	31528	141232	429981	2.18
Annual Total		3069797	1189164	3451300	100892	434948	1298968	3501616	13.51

Table 5. Example climate change flow perturbations.

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17.3. BO 2010 Operations

Upper Klamath Biological Opinion Operations

David King and Nancy Parker
Bureau of Reclamation
01/04/2011

Introduction

Several Section 7 Consultations and Biological Opinions (BO's) have governed operation of Upper Klamath Lake (UKL) and the Klamath Project (Project) since the late 1990's. The consultations involve the National Marine Fisheries Service (NMFS), also known as NOAA Fisheries, the U.S. Fish and Wildlife Service (FWS), and the Bureau of Reclamation (Reclamation). The latest FWS BO and the NMFS BO, dated March 15, 2010, are the basis of the operating criteria used by the Klamath Project Simulation Model (KPSIM) in the setup known as the "BO 2010" or "BO" operation. The following sections document the BO 2010 operation as implemented in the KPSIM.

Modeling Software

Modeling has been conducted using the Water Resources Integrated Modeling System (WRIMS) – general purpose river and reservoir planning and operations modeling software developed and maintained by the California Department of Water Resources Modeling Support Branch. The Klamath Project Simulation Model (KPSIM) was originally a spreadsheet model. Development of the WRIMS KPSIM model began in 2004 and by 2006 had replaced the KPSIM spreadsheet model as the analytical tool of choice to address increasingly complex water management scenarios and strategies in the basin.

WRIMS uses a mixed integer linear programming solver to route water through a network. Policies and priorities for water routing are implemented through user-defined weights applied to flow arcs and storage nodes in the network. System variables and the constraints on them are specified with a scripting language called the "water resources engineering simulation language" (wresl). Wresl code is developed in simple ascii text files. Time series input data and model results are stored in HEC-DSS files. Relational data (lookup tables) is stored in ascii text files.

Hydrology Data

Current representation of the Klamath Project uses a 49-year period of hydrology, encompassing water years 1961 through 2009. A full set of data is available from the USGS for key streamflow gages for this period, and it includes the dry period of record as well as some of the wettest years in the Upper Klamath Basin. Hydrologic input to the model includes historical records for net inflow to Upper Klamath Lake, Lost River Diversion Canal spills to the Klamath River, local gains between Link River and Keno Dam, runoff from agricultural lands above Lower Klamath Lake, gains between USGS gages at Keno and Iron Gate, and returns from the Klamath Straits Drain.

Each water year is divided into 17 timesteps – full months in August-February and half-months in March through July. This temporal scale is necessary to represent some operational requirements for lake elevation and flow.

System Description and Model Network

Figure 1 shows the schematic diagram of the model. Headwaters inflows are represented for Upper Klamath Lake, Gerber Reservoir, and Clear Lake. Local gains and other inflows are represented by Lake Ewauna gain, Lost River Diversion Channel Spill, Area A2 Winter Runoff, Klamath Straits Drain inflows, and Keno to Iron Gate Gain. Diversions to Project demands are represented at A Canal, Lost River Diversion Channel, North Canal, and Ady Canal. Although it is included in the model, the Lost River portion of the system is not germane to the outcome of the KPSIM runs. Lost River inflow and operations for Gerber Reservoir, Clear Lake, and Area C delivery are completely separate and have no hydrologic impact on Klamath River operations in the model.

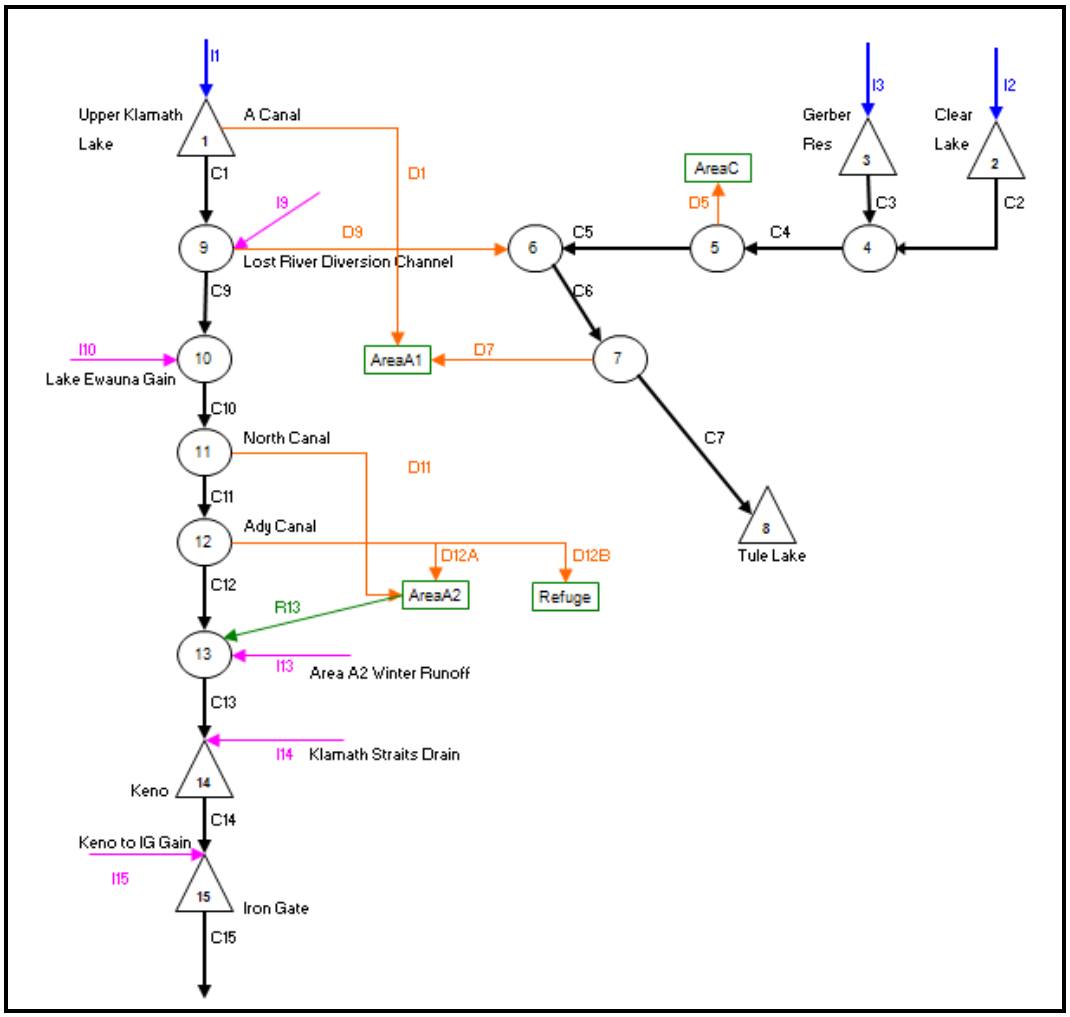

Figure 1. Schematic Network of the Klamath Project Planning Model,

Operations Criteria

Input data and operating rules for BO 2010 operation of the KPSIM are described below. Priorities for water use are:

- Meet Iron Gate base flows.
- Meet BO minimums for UKL elevations.
- Meet full RPA flow targets at Iron Gate Dam.
- Deliver water to Klamath Project irrigators.
- Deliver water to satisfy National Wildlife Refuge demands
- Meet UKL Refill Targets.

Target flows at Iron Gate are comprised of two parts – a base flow and an augmentation flow. Base flows were taken from the 95% exceedence level described by NMFS in the 2010 BO. The flow augmentation portion of the flow target is based on water supply conditions in the basin under the assumption that wetter conditions enable higher flows. In the fall and winter months, without an established forecast for upcoming inflows, the water supply index is based solely on the storage in Upper Klamath Lake. Water supply for spring and summer months is described by a combination of storage volume, forecasted April through September inflow, and desired end-of-September UKL carryover storage. Unique relationships were developed for each month or half-month timestep, implementing flow augmentation targets as a function of the water supply expression. The relationships were refined so that the model results achieved by their use produced a set of output flows whose probability distribution matched as closely as possible that described by NMFS in the 2010 BO.

Iron Gate base flows are shown in Table 1. Table 2 shows the definition of the water supply index as it is calculated for each timestep in the KPSIM. Tables 3A through 3C show the relationships between the water supply index and flow augmentation targets in thousands of acre-feet (TAF) for each timestep in the model. Interpolation is used to determine flow augmentation for values of the WSI that are not precisely represented by values in the table. In some months, no flow augmentation is targeted at the lowest WSI levels. If the flow augmentation target is zero, total target flow at Iron Gate is the base flow value. Flow augmentation targets are substantial at high WSI levels. No flow augmentation target exists in October.

Klamath Project demands for irrigation and refuge water users are based on precipitation indices that define annual demand and its monthly distribution. A1 deliveries include diversion from UKL to the A Canal and diversion from Lake Ewauna to the Lost River Diversion Channel. A2 deliveries include diversions from the Klamath River to irrigation uses through the North and Ady Canals. Refuge deliveries as modeled are the Ady Canal deliveries to the Lower Klamath Lake National Wildlife Refuge. Tule Lake National Wildlife Refuge, D-pump operations, and distribution of Lost River water is not explicitly represented in the model. Annual demands are based on precipitation conditions are shown in Table 4.

The BO operation includes criteria for minimum elevations in UKL per the FWS 2008 BO. Criteria used by the KPSIM are shown in Table 2.

UKL can be run with existing capacity or with existing capacity plus expanded storage capacity that includes Agency Lake, Barnes Ranch, Tulana Farms, and Goose Bay areas. Evaporation and changes to consumptive use for these new storage areas are represented specifically in the model.

Flood control rules are adjusted from the original Pacific Power and Light levels to reflect the same amount of available storage space given the modified storage capacity. Flood control targets are shown in Table 1.

KPSIM Timestep	Iron Gate Target Flow (cfs)	UKL BO Elevation Minimum (feet)	UKL Refill and Carryover Targets(Feet)	UKL Flood Control Rules (feet)
Oct	1300		4139.10	4141.80
Nov	1300		4139.90	4141.39
Dec	1260		4140.80	4141.70
Jan	1130		4141.70	4142.30
Feb	1300	4141.50	4142.50	4142.70
Mar 1-15	1275	4141.85	4143.00	4142.90
Mar 16-31	1275	4142.20		4143.15
Apr 1-15	1325	4142.20		4143.30
Apr 16-30	1325	4142.20		4143.30
May 1-15	1175	4141.90		4143.30
May 16-31	1175	4141.60		4143.30
JUN 1-15	1025	4141.05		4143.30
JUN 16-30	1025	4140.50		4143.30
JUL 1-15	805	4140.10		4143.30
JUL 16-31	805	4139.30		4143.30
Aug	942	4138.10		4143.30
Sep	1000	4137.50	4138.00	4143.05

Table 1. Iron Gate Base Flow and UKL Elevation Criteria.

November - February	Beginning of Month (End of Previous Month) UKL Storage Volume
March 1	(End of February UKL Storage) +(March 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
March 16	(March 15 UKL Storage) + (March 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
April 1	(End of March UKL Storage) + (April 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
April 16	(April 15 UKL Storage) + (April 1st April-September 50% UKL Inflow Forecast) –(End-of-September Carryover Storage Target)
May 1 - Sept	Use the index value computed for the previous April 16th

Table 2. Planning model definitions of Water Supply Index.

November		December		January		February	
Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation
0	0	0	0	0	0	0	0
104	0	132	0	176	0	246	0
117	0	143	2.46	210	7.07	273	0
124	0	175	2.46	222	10.45	293	0
133	0	187	2.46	254	10.45	312	0
147	0	195	2.46	275	10.45	314	0
150	0	210	2.46	286	10.45	328	0
152	0	216	2.46	312	10.45	349	1.28
160	0	269	2.46	323	11.01	373	32.21
180	0	277	5.23	326	32.34	377	65.15
190	0	289	9.22	333	38.18	383	70.92
213	0	302	29.08	340	54.6	398	79.31
238	0	307	35.48	348	68.37	416	100.24
260	0	315	50.36	351	87.25	430	122.46
265	7.97	320	74.46	377	89.03	488	129.51
270	17.26	335	101.33	404	92.05	508	140.06
290	31.6	345	106.8	421	109.32	522	147.73
320	44.03	356	111.78	454	145.6	550	161.61
379	66.35	362	124.2	488	166.32	555	165.78
416	69.02	463	130.66	545	175.85	556	176.33

Table 3A. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

March 1-15		March 16-31		April 1-15		April 16-30	
Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation
0	0	0	0	0	0	0	0
432	0	453	0	480	0	489	0
502	4.02	546	4.28	517	5.21	528	5.21
552	5.21	564	5.55	607	5.21	625	5.21
599	12.14	641	12.95	632	5.21	642	5.21
645	23.06	676	24.6	699	5.21	720	5.21
649	31.98	691	34.12	729	5.21	734	5.21
677	40.28	725	42.97	740	7.85	772	7.85
721	48.05	761	51.25	779	37.64	789	37.64
757	55.79	799	59.5	798	41.59	825	41.59
783	56.59	808	60.36	824	50.73	862	50.73
812	65.19	818	69.53	860	57.12	881	57.12
861	71.7	861	76.48	909	64.26	900	64.26
914	74.14	918	79.08	943	70.81	937	70.81
952	79.29	958	84.58	952	77.5	978	77.5
981	80.78	1004	86.16	986	81.52	1036	81.52
1053	85.83	1061	91.56	1043	86.43	1067	86.43
1075	89.55	1087	95.52	1142	92.23	1145	92.23
1115	91.64	1115	97.75	1177	96.99	1174	96.99
1199	94.76	1196	101.08	1243	103.09	1235	103.09

Table 3B. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

Water Supply Index	May 1-15	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	August	September
	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation
0	0	0	0	0	0	0	0	0
489	0	0	0	0	0	0	0	0
528	1.34	1.43	1.64	1.64	1.04	1.11	0.45	0
625	7.14	7.62	4.02	4.02	2.98	3.17	0.92	0
642	12.73	13.58	8.78	8.78	4.17	4.44	1.8	0.36
720	14.67	15.65	12.79	12.79	6.28	6.7	3.08	0.77
734	18.68	19.93	14.07	14.07	6.66	7.11	4.16	1.43
772	20.86	22.25	14.73	14.73	6.84	7.3	4.62	1.79
789	25.41	27.1	16.19	16.19	7.29	7.78	5.05	2.44
825	27.97	29.83	16.93	16.93	7.47	7.97	5.29	2.86
862	43.65	46.56	18.27	18.27	7.88	8.41	5.72	3.57
881	48.79	52.05	19.16	19.16	8.09	8.63	5.91	3.93
900	53.11	56.65	19.55	19.55	8.24	8.79	6.09	4.22
937	57.72	61.57	20.05	20.05	8.78	9.36	6.64	5.06
978	60.99	65.06	21.36	21.36	9.31	9.93	6.83	5.3
1036	65.9	70.29	50.64	50.64	9.88	10.54	7.14	5.77
1067	68.58	73.15	54.3	54.3	10.32	11.01	7.63	8.03
1145	72.6	77.43	58.02	58.02	12.44	13.27	9.29	9.64
1174	75.42	80.45	60.4	60.4	16.81	17.93	11.32	14.64
1235	79.44	84.73	64.26	64.26	18.6	19.83	12.61	16.72

Table 3C. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

Feb-Mar Precipitation Index (in)	A1 Demand Apr-Mar (TAF)	Refuge Demand Apr-Mar (TAF)	Oct-Jan Precipitation Index (in)	A2 Demand Apr-Mar (TAF)
0.00 - 1.999	340	30	0.00 - 3.99	105
2.00 - 2.749	310	25	4.00 - 6.99	95
2.75 - 3.299	300	20	7.00 - 9.99	90
>= 3.30	275	15	>= 10.00	80

Table 4. Project demand as a function of precipitation.

17.4. KBRA Operations

Upper Klamath KBRA Operations

David King and Nancy Parker
Bureau of Reclamation
01/03/2011

Introduction

The Klamath Basin Restoration Agreement (KBRA) among stakeholders in the Klamath River basin has the objective of restoring and sustaining fisheries while establishing reliable water and power supplies. The KBRA includes specific hydrologic criteria that were implemented using a version of the Klamath Project Simulation Model (KPSIM). This documentation describes the operating criteria and implementation in the KBRA version of the Klamath Project Simulation Model (KPSIM).

Modeling Software

Modeling has been conducted using the Water Resources Integrated Modeling System (WRIMS) – general purpose river and reservoir planning and operations modeling software developed and maintained by the California Department of Water Resources Modeling Support Branch. The Klamath Project Simulation Model (KPSIM) was originally a spreadsheet model. Development of the WRIMS KPSIM model began in 2004 and by 2006 had replaced the KPSIM spreadsheet model as the analytical tool of choice to address increasingly complex water management scenarios and strategies in the basin.

WRIMS uses a mixed integer linear programming solver to route water through a network. Policies and priorities for water routing are implemented through user-defined weights applied to flow arcs and storage nodes in the network. System variables and the constraints on them are specified with a scripting language called the "water resources engineering simulation language" (wresl). Wresl code is developed in simple ascii text files. Time series input data and model results are stored in HEC-DSS files. Relational data (lookup tables) is stored in ascii text files.

Hydrology Data

Current representation of the Klamath Project uses a 49-year period of hydrology, encompassing water years 1961 through 2009. A full set of data is available from the USGS for key streamflow gages for this period, and it includes the dry period of record as well as some of the wettest years in the Upper Klamath Basin. Hydrologic input to the model includes historical records for net inflow to Upper Klamath Lake, Lost River Diversion Canal spills to the Klamath River, local gains between Link River and Keno Dam, runoff from agricultural lands above Lower Klamath Lake, gains between USGS gages at Keno and Iron Gate, and returns from the Klamath Straits Drain.

Each water year is divided into 17 timesteps – full months in August-February and half-months in March through July. This temporal scale is necessary to represent some operational requirements for lake elevation and flow.

System Description and Model Network

Figure 1 shows the schematic diagram of the model. Headwaters inflows are represented for Upper Klamath Lake (UKL), Gerber Reservoir, and Clear Lake. Local gains and other inflows are represented by Lake Ewauna gain, Lost River Diversion Channel Spill, Area A2 Winter Runoff, Klamath Straits Drain inflows, and Keno to Iron Gate Gain. Diversions to Project demands are represented at A Canal, Lost River Diversion Channel, North Canal, and Ady Canal. Although it is included in the model, the Lost River portion of the system is not germane to the outcome of the KPSIM runs. Lost River inflow and operations for Gerber Reservoir, Clear Lake, and Area C delivery are completely separate and have no hydrologic impact on Klamath River operations in the model.

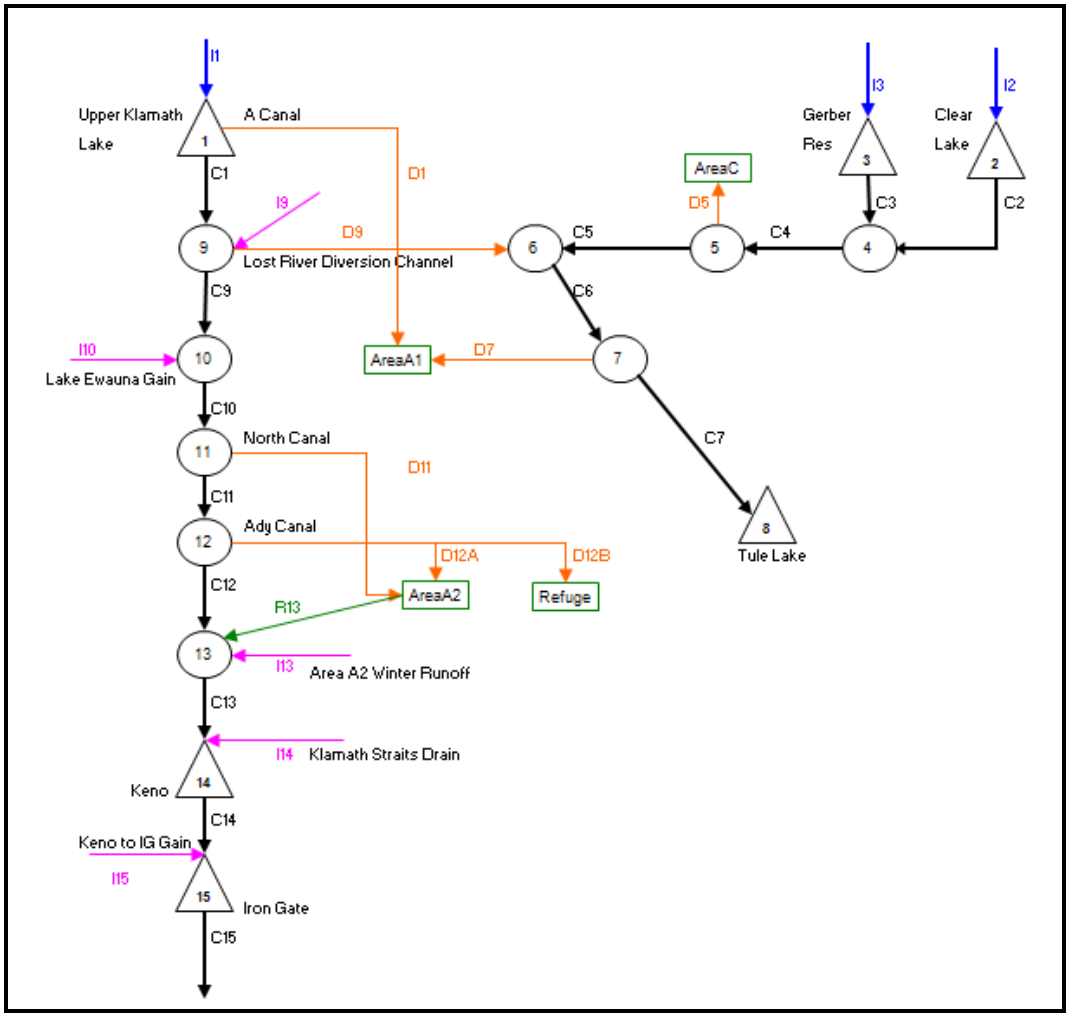

Figure 1. Schematic Network of the Klamath Project Planning Model.

Operations Criteria

Input data and operating rules for KBRA operation of the KPSIM are described below. The fundamental modeling approach is:

- Deliver Project Irrigation allocation and meet National Wildlife Refuge demands
- Balance Iron Gate Flow and UKL elevation conditions – set targets and balance any shortage or surplus

- If Iron Gate Flow or UKL elevation would fall short of an environmental baseline under the above operation, first reduce Refuge delivery to no more than 24,000 acre-feet (24 TAF) April-October and then decrease Irrigation deliveries.

The specific operating criteria are:

Net Inflow to UKL is augmented by 30,000 acre-feet (30 TAF) per year distributed between March and October.

March through October Project demand from UKL and Klamath River is computed as a function of inflow forecast using following criteria:

330 TAF when March 1 inflow forecast is <= 287 TAF
385 TAF when forecast is > 569 TAF
Linear interpolation between 330 TAF and 385 TAF for forecasts between 287 TAF and 569 TAF

November through February project demand is based on historic delivery.

March through October refuge demand from UKL and Klamath River is computed as a function of inflow forecast using the following criteria:

48 TAF when Mar 1 inflow forecast is <= 287 TAF
60 TAF when forecast is > 569 TAF
Linear interpolation between forecasts of 287 TAF and 567 TAF.

November through February refuge demand is based on historic delivery. Demand for diversions from the Klamath River are reduced by estimated D Plant pumping.

Target flows at Iron Gate are selected based on cumulative winter or summer inflows to UKL through the previous time step, using the Inflow Exceedence Index (IEI). Values are interpolated between exceedence levels. The targets used in the model are shown in Table 1.

UKL level targets are selected based on cumulative winter or summer inflows to UKL through the previous time step, using the Inflow Exceedence Index (IEI). Values are interpolated between exceedence levels. The targets used in the model are shown in Table 2.

During shortage years, irrigation and refuge supplies are redistributed to reflect KBRA language. KPSIM does adjustments on an annual basis as a post process. Monthly adjustments are done as a post process in a workbook.

UKL can be run with existing capacity or with existing capacity plus expanded storage capacity that includes Agency Lake, Barnes Ranch, Tulana Farms, Goose Bay, and Wood River areas. Evaporation and changes to consumptive use for these new storage areas are represented specifically in the model.

Flood control rules are adapted from the original Pacific Power and Light levels to reflect the same amount of available storage space given the modified storage capacity. Flood control targets are shown in Table 2.

Probability	100%	98%	97%	90%	70%	50%	30%	10%	0%
Oct	970	970	1000	1000	1100	1300	1300	1300	1300
Nov	1000	1000	1000	1000	1100	1300	1300	1300	1300
Dec	1000	1000	1000	1000	1100	1300	1300	1300	1300
Jan	1000	1000	1000	1000	1100	2024	2223	2421	2421
Feb	1000	1000	1000	1000	1100	2353	2592	2831	2831
Mar 1-15	1100	1175	1398	1398	2085	2721	2988	3224	3224
Mar 16-31	1200	1250	1446	1446	2149	2932	3220	3458	3458
Apr 1-15	1250	1325	1494	1494	2212	3030	3335	3620	3620
Apr 16-30	1250	1325	1542	1542	2276	3015	3334	3710	3710
May 1-15	1100	1175	1240	1240	2090	2739	3306	3728	3728
May 16-31	1100	1175	1182	1182	1936	2559	3063	3675	3675
Jun 1-15	1000	1022	1109	1109	1746	2315	2782	3147	3147
Jun 16-30	1000	1022	1022	1022	1522	2008	2463	2781	2781
Jul 1-15	700	700	840	840	1070	1330	1830	2140	2140
Jul 16-31	700	700	840	840	1070	1330	1830	2140	2140
Aug	880	880	1110	1110	1260	1305	1430	1545	1545
Sep	970	970	1110	1110	1260	1305	1430	1545	1545

Table 1. KBRA Iron Gate Flow Targets (cfs).

Probability	100%	98%	97%	90%	70%	25%	0%	Flood
Oct	4137.80	4137.80	4138.85	4138.90	4139.20	4139.95	4140.20	4141.80
Nov	4138.80	4138.80	4139.61	4139.74	4140.02	4140.65	4141.00	4141.70
Dec	4139.80	4139.80	4140.21	4140.33	4140.59	4141.15	4141.50	4141.90
Jan	4140.80	4140.80	4140.91	4141.01	4141.23	4141.73	4142.00	4142.30
Feb	4141.60	4141.60	4141.61	4141.69	4141.87	4142.28	4142.50	4142.70
Mar 1-15	4141.70	4141.70	4142.20	4142.44	4142.52	4142.70	4142.80	4142.90
Mar 16-31	4141.80	4141.80	4142.40	4142.72	4142.76	4142.85	4142.90	4143.00
Apr 1-15	4141.30	4141.50	4142.80	4142.82	4142.86	4142.95	4143.00	4143.00
Apr 16-30	4141.20	4141.50	4142.90	4142.92	4142.96	4143.05	4143.10	4143.10
May 1-15	4141.00	4141.30	4143.00	4143.02	4143.06	4143.15	4143.20	4143.20
May 16-31	4140.70	4141.10	4141.60	4142.40	4142.70	4143.10	4143.10	4143.20
Jun 1-15	4140.40	4140.60	4141.20	4142.00	4142.40	4142.85	4142.85	4143.30
Jun 16-30	4139.80	4140.10	4140.80	4141.55	4142.10	4142.60	4142.60	4143.30
Jul 1-15	4139.60	4139.60	4140.32	4141.02	4141.57	4142.02	4142.02	4143.30
Jul 16-31	4139.10	4139.10	4139.80	4140.40	4141.00	4141.40	4141.40	4143.30
Aug	4138.10	4138.10	4139.14	4139.65	4139.80	4140.84	4140.84	4143.30
Sep	4137.50	4137.50	4138.50	4139.00	4139.05	4139.60	4140.30	4143.30

Table 2. KBRA UKL Target and Flood Control Elevations (feet).

The KBRA process intends to develop a drought plan in which shortage criteria and minimum flows in the river are explicitly defined. However, at the time this document was complete, no such drought plan was available. The following assumptions were made in place of the drought plan:

1. Incorporation of a minimum flow of 100 cfs at Link River to provide adequate passage through the fish ladder and stream channel.

2. Incorporation of a minimum flow at Keno Dam of 300 cfs to provide adequate fish passage.

3. Minor adjustment of KBRA flow targets for use in the hydrology model for the time steps from July 1 through the end of September to improve flow conditions for adult migration and reduce the potential for fish die off. The changes that were implemented include reducing the target from 921 to 840 cfs for July 1 to 15, increasing the target from 806 to 840 cfs for July 16 to 31, increasing the target from 895 to 1110 cfs in August, and increasing the targets from 1010 to 1110 cfs in September.

4. Incorporation of minimum Ecological Base Flow levels during the periods from March 1 through June 30 and during the months of August and September. The EBF volumes would be represented by the Hardy Phase II 95% exceedence flow levels.

5. Minor adjustment to the flow targets for the month of March for water years represented by the 70% Exceedence. These adjustments include reductions in the targets from 2358 to 2085 cfs (March 1-15) and from 2343 to 2149 cfs (March 16-31). The change is consistent with rate of change for wetter water years.

6. Incorporation of minimum base flows of 800 cfs during the months of October through February. The minimum of 800 cfs is considered to be necessary to prevent adverse impacts to salmonids during the winter months.

7. Redistribution of irrigation and refuge supplies during shortage years to reflect KBRA language. KPSIM does adjustments on annual basis as a post process. Monthly adjustments are done as a post process in a workbook by the data manager which runs both models.

8. Minor adjustments were made to UKL elevation criteria in association with shortage adjustments.

17.5. Operations Models

Klamath Dam Removal - Hydrologic Operations

David King and Nancy Parker
Bureau of Reclamation
01/04/2011

Introduction

The Klamath Dam Removal (KDR) study used two hydrologic models to assist in analyzing several hydrologic scenarios and two basin operating criteria. The two basin operating criteria are the Biologic Opinion (BO) and Klamath Basin Restoration Agreement (KBRA). These operations correspond to the Dams In and Dams Out KDR scenarios, also known as the No Action and Dam Removal Alternative scenarios. The two hydrologic models consist of an upstream monthly model and a downstream daily model. Output of the upstream model becomes part of the input to the downstream model. The upstream monthly timestep was sufficient to allocate water supplies in the upper basin and a reasonable estimate of Klamath River flows available to the downstream model. The daily timestep of the downstream model provided better computations of power production and streamflows in critical river reaches. The following pages document the KDR hydrologic models.

Modeling Software

Recent upstream modeling has been conducted using the Water Resources Integrated Modeling System (WRIMS) – general purpose river and reservoir planning and operations modeling software developed and maintained by the California Department of Water Resources Modeling Support Branch. The Klamath Project Simulation Model (KPSIM) was originally a spreadsheet model. Development of the WRIMS KPSIM model began in 2004 and by 2006 had replaced the KPSIM spreadsheet model as the analytical tool of choice to address increasingly complex water management scenarios and strategies in the basin.

WRIMS uses a mixed integer linear programming solver to route water through a network. Policies and priorities for water routing are implemented through user-defined weights applied to flow arcs and storage nodes in the network. System variables and the constraints on them are specified with a scripting language called the "water resources engineering simulation language" (wresl). Wresl code is developed in simple ascii text files. Time series input data and model results are stored in HEC-DSS files. Relational data (lookup tables) is stored in ascii text files.

The downstream model, known as the Klamath Dam Removal Model (KDRM), was developed using RiverWare. RiverWare is a generic hydrologic modeling tool developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) located at the University of Colorado. Reclamation is a co-owner of RiverWare. RiverWare has several controllers - the KDRM uses the rule based simulation controller. Rules in RiverWare are written using RiverWare Policy Language (RPL), a user-friendly language that includes a debugger and other tools for implementing and troubleshooting operating criteria.

Hydrology Data

The KDR uses hydrology based on a 49-year period of historic hydrology, encompassing water years 1961 through 2009. A mostly full set of data is available from the USGS for key streamflow gages for this period which includes the dry period of record as well as some of the

wettest years in the Upper Klamath Basin. Hydrologic input to the KPSIM includes net inflow to Upper Klamath Lake, Lost River Diversion Canal spills to the Klamath River, local gains between Link River and Keno Dam, runoff from agricultural lands above Lower Klamath Lake, gains between USGS gages at Keno and Iron Gate, and returns from the Klamath Straits Drain. Input to the KDRM are monthly flow that includes output of the KPSIM at Keno and Iron Gate, four gains between Keno and Iron Gate, and major gains downstream of Iron Gate.

Historic data were developed from USGS daily streamflow records, USGS monthly reservoir records (partial record) and reservoir data obtained from PacifiCorp. Reservoir data were incomplete but were extended by interpolation and other methods. Additional documentation of downstream data development is available. The Klamath Basin Area Office (KBAO) develops data used by the KPSIM annually.

Historic data from water years 1961 through 2009 were used to develop three synthetic types of hydrology for dams-in and dams-out planning scenarios. The types of synthetic hydrology are:

1. Indexed sequential – A hydrograph created by repetition of historic hydrology.
2. Stochastic – Hydrographs created using statistical software from the historic hydrology.
3. Climate change – Hydrographs created using a watershed model with climate variation.

Development of synthetic hydrologies is discussed in detail in other documents. In the end, the stochastic data were not used because it was problematic to create climate data stochastically. In addition, the climate change traces used for KDR analyzes were reduced to five. All scenario runs use a simulation period starting date 10/1/2011, water year 2012 and are 51 water years to obtain 50 calendar years for the economic analyzes. The indexed sequential scenarios consist of 49 traces using every historic year as a starting year. The five climate change traces were run with three starting years representing median (1961), wet (1982), and dry (1990) periods of the historic record.

Each water year of the KPSIM is divided into 17 timesteps – full months in August-February and half-months in March through July. This temporal scale is necessary to represent some operational requirements for lake elevation and flow. The 17 timesteps of the upstream model are temporally aggregated for the monthly input data used by the KDRM. All monthly data are temporally disaggregated to daily by the KDRM as explained in more detailed in the KDRM operations section.

System Description and Model Network

Figure 1 shows the schematic diagram of the KPSIM. Headwaters inflows are represented for Upper Klamath Lake, Gerber Reservoir, and Clear Lake. Local gains and other inflows are represented by Lake Ewauna gain, Lost River Diversion Channel Spill, Area A2 Winter Runoff, Klamath Straits Drain inflows, and Keno to Iron Gate Gain. Diversions to Project demands are represented at A Canal, Lost River Diversion Channel, North Canal, and Ady Canal. Note that although the diagram shows Keno and Iron Gate reservoirs, the KPSIM does not explicitly model these reservoirs.

The KDRM model begins just downstream of Keno Reservoir and ends at the ocean as shown on Figure 2. A list of the primary hydrologic nodes in the KDRM is listed in Table 1. Additional nodes exist between these nodes which correspond to SALMOD fisheries model nodes. These nodes correspond to additional tributary inflows. Note that the Hoopa to Klamath gains are all gains from the Trinity At Hoopa and Klamath At Orleans gages to the Klamath Near Klamath

gage. Primary gains developed from historic data are spatially disaggregated to the SALMOD nodes.

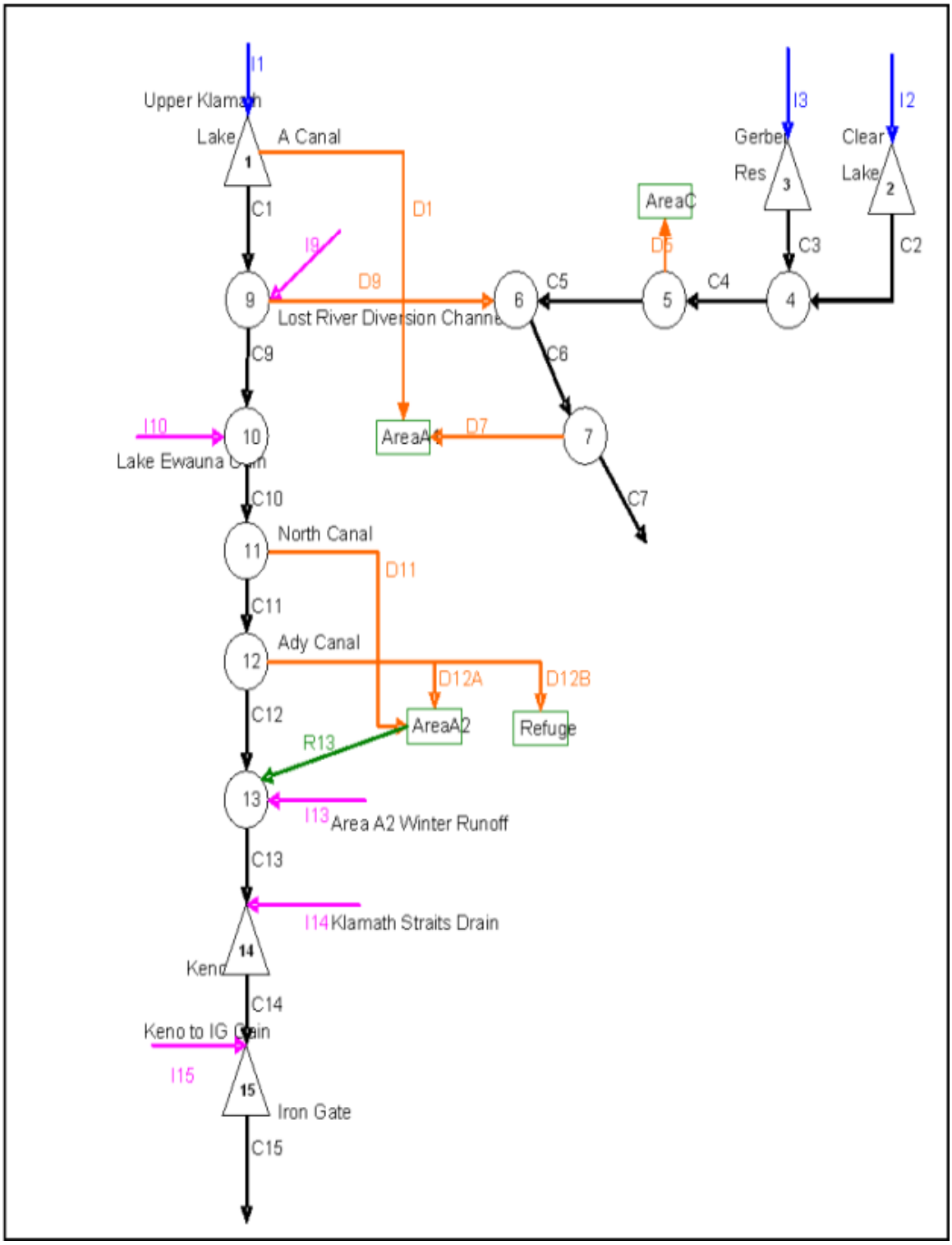

Figure 1. Schematic network of the upstream model.

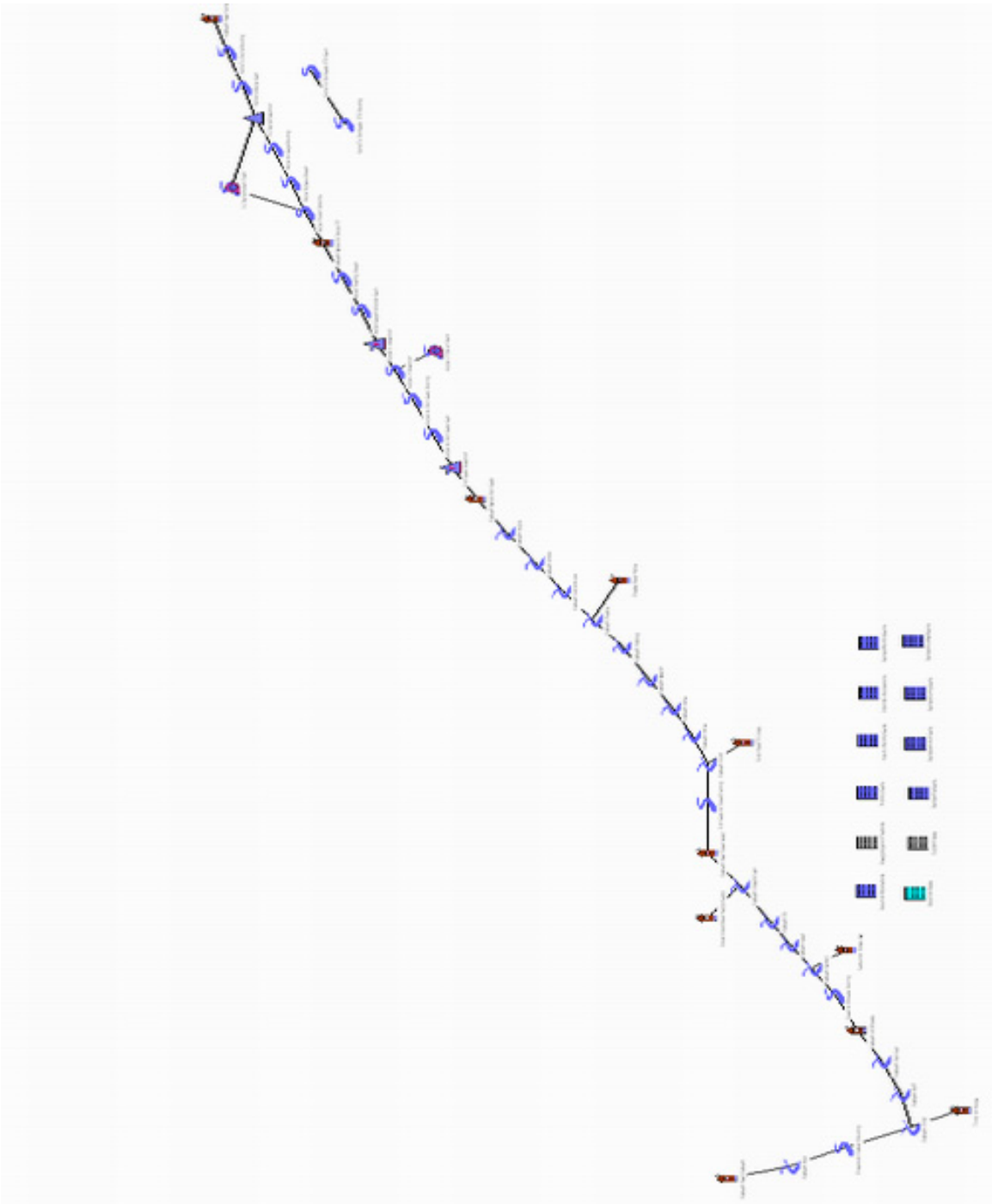

Figure 2. Schematic network of the downstream model.

Klamath River Near Keno
Keno to Boyle Reservoir Gain
JC Boyle Reservoir
Boyle Reservoir To Boyle Gage Gain
Boyle Gage To Copco Gain
Copco 1 Reservoir
Copco 2 Reservoir
Copco To Iron Gate Gain
Iron Gate Reservoir
Iron Gate to Seiad Gain
Seiad to Orleans Gain
Scott Near Ft Jones
Salmon At Somes Bar
Indian Creek Near Happy Camp
Shasta Near Yreka
Hoopa to Klamath Gains
Trinity At Hoopa

Table 1. Primary Downstream Model Hydrology Nodes.

KPSIM Biological Opinion Operations

Several Section 7 Consultations and Biological Opinions (BO's) have governed operation of Upper Klamath Lake (UKL) and the Klamath Project (Project) since the late 1990's. The consultations involve the National Marine Fisheries Service (NMFS), also known as NOAA Fisheries, the U.S. Fish and Wildlife Service (FWS), and the Bureau of Reclamation (Reclamation). The latest FWS BO and the NMFS BO, dated March 15, 2010, are the basis of the operating criteria used by the Klamath Project Simulation Model (KPSIM) in the setup known as the "BO 2010" or "BO" operation. The following sections document the BO 2010 operation as implemented in the KPSIM.

Input data and operating rules for BO 2010 operation of the KPSIM are described below. Priorities for water use are:

- Meet Iron Gate base flows.
- Meet BO minimums for UKL elevations.
- Meet full RPA flow targets at Iron Gate Dam.
- Deliver water to Klamath Project irrigators.
- Deliver water to satisfy National Wildlife Refuge demands
- Meet UKL Refill Targets.

Target flows at Iron Gate are comprised of two parts – a base flow and an augmentation flow. Base flows were taken from the 95% exceedence level described by NMFS in the 2010 BO. The flow augmentation portion of the flow target is based on water supply conditions in the basin under the assumption that wetter conditions enable higher flows. In the fall and winter months, without an established forecast for upcoming inflows, the water supply index is based solely on the storage in Upper Klamath Lake. Water supply for spring and summer months is described by a combination of storage volume, forecasted April through September inflow, and desired end-of-September UKL carryover storage. Unique relationships were developed for each month or half-

month timestep, implementing flow augmentation targets as a function of the water supply expression. The relationships were refined so that the model results achieved by their use produced a set of output flows whose probability distribution matched as closely as possible that described by NMFS in the 2010 BO.

Iron Gate base flows are shown in Table 2. Table 3 shows the definition of the water supply index as it is calculated for each timestep in the KPSIM. Tables 4A through 4C show the relationships between the water supply index and flow augmentation targets in thousands of acre-feet (TAF) for each timestep in the model. Interpolation is used to determine flow augmentation for values of the WSI that are not precisely represented by values in the table. In some months, no flow augmentation is targeted at the lowest WSI levels. If the flow augmentation target is zero, total target flow at Iron Gate is the base flow value. Flow augmentation targets are substantial at high WSI levels. No flow augmentation target exists in October.

KPSIM Timestep	Iron Gate Target Flow (cfs)	UKL BO Elevation Minimum (feet)	UKL Refill and Carryover Targets(Feet)	UKL Flood Control Rules (feet)
Oct	1300		4139.10	4141.80
Nov	1300		4139.90	4141.39
Dec	1260		4140.80	4141.70
Jan	1130		4141.70	4142.30
Feb	1300	4141.50	4142.50	4142.70
Mar 1-15	1275	4141.85	4143.00	4142.90
Mar 16-31	1275	4142.20		4143.15
Apr 1-15	1325	4142.20		4143.30
Apr 16-30	1325	4142.20		4143.30
May 1-15	1175	4141.90		4143.30
May 16-31	1175	4141.60		4143.30
JUN 1-15	1025	4141.05		4143.30
JUN 16-30	1025	4140.50		4143.30
JUL 1-15	805	4140.10		4143.30
JUL 16-31	805	4139.30		4143.30
Aug	942	4138.10		4143.30
Sep	1000	4137.50	4138.00	4143.05

Table 3. Iron Gate Base Flow and UKL Elevation Criteria.

November - February	Beginning of Month (End of Previous Month) UKL Storage Volume
March 1	(End of February UKL Storage) +(March 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
March 16	(March 15 UKL Storage) + (March 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
April 1	(End of March UKL Storage) + (April 1st April-September 50% UKL Inflow Forecast) – (End-of-September Carryover Storage Target)
April 16	(April 15 UKL Storage) + (April 1st April-September 50% UKL Inflow Forecast) –(End-of-September Carryover Storage Target)
May 1 – Sept	Use the index value computed for the previous April 16th

Table 3. Planning model definitions of Water Supply Index.

Klamath Project demands for irrigation and refuge water users are based on precipitation indices that define annual demand and its monthly distribution. A1 deliveries include diversion from UKL to the A Canal and diversion from Lake Ewauna to the Lost River Diversion Channel. A2 deliveries include diversions from the Klamath River to irrigation uses through the North and Ady Canals. Refuge deliveries as modeled are the Ady Canal deliveries to the Lower Klamath Lake National Wildlife Refuge. Tule Lake National Wildlife Refuge, D-pump operations, and distribution of Lost River water is not explicitly represented in the model. Annual demands are based on precipitation conditions are shown in Table 5.

The BO operation includes criteria for minimum elevations in UKL per the FWS 2008 BO. Criteria used by the KPSIM are shown in Table 2.

UKL can be run with existing capacity or with existing capacity plus expanded storage capacity that includes Agency Lake, Barnes Ranch, Tulana Farms, and Goose Bay areas. Evaporation and changes to consumptive use for these new storage areas are represented specifically in the model.

Flood control rules are adjusted from the original Pacific Power and Light levels to reflect the same amount of available storage space given the modified storage capacity. Flood control targets are shown in Table 2.

November		December		January		February	
Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation
0	0	0	0	0	0	0	0
104	0	132	0	176	0	246	0
117	0	143	2.46	210	7.07	273	0
124	0	175	2.46	222	10.45	293	0
133	0	187	2.46	254	10.45	312	0
147	0	195	2.46	275	10.45	314	0
150	0	210	2.46	286	10.45	328	0
152	0	216	2.46	312	10.45	349	1.28
160	0	269	2.46	323	11.01	373	32.21
180	0	277	5.23	326	32.34	377	65.15
190	0	289	9.22	333	38.18	383	70.92
213	0	302	29.08	340	54.6	398	79.31
238	0	307	35.48	348	68.37	416	100.24
260	0	315	50.36	351	87.25	430	122.46
265	7.97	320	74.46	377	89.03	488	129.51
270	17.26	335	101.33	404	92.05	508	140.06
290	31.6	345	106.8	421	109.32	522	147.73
320	44.03	356	111.78	454	145.6	550	161.61
379	66.35	362	124.2	488	166.32	555	165.78
416	69.02	463	130.66	545	175.85	556	176.33

Table 4A. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

March 1-15		March 16-31		April 1-15		April 16-30	
Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation	Water Supply Index	Flow Augmentation
0	0	0	0	0	0	0	0
432	0	453	0	480	0	489	0
502	4.02	546	4.28	517	5.21	528	5.21
552	5.21	564	5.55	607	5.21	625	5.21
599	12.14	641	12.95	632	5.21	642	5.21
645	23.06	676	24.6	699	5.21	720	5.21
649	31.98	691	34.12	729	5.21	734	5.21
677	40.28	725	42.97	740	7.85	772	7.85
721	48.05	761	51.25	779	37.64	789	37.64
757	55.79	799	59.5	798	41.59	825	41.59
783	56.59	808	60.36	824	50.73	862	50.73
812	65.19	818	69.53	860	57.12	881	57.12
861	71.7	861	76.48	909	64.26	900	64.26
914	74.14	918	79.08	943	70.81	937	70.81
952	79.29	958	84.58	952	77.5	978	77.5
981	80.78	1004	86.16	986	81.52	1036	81.52
1053	85.83	1061	91.56	1043	86.43	1067	86.43
1075	89.55	1087	95.52	1142	92.23	1145	92.23
1115	91.64	1115	97.75	1177	96.99	1174	96.99
1199	94.76	1196	101.08	1243	103.09	1235	103.09

Table 4B. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

Water Supply Index	May 1-15	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	August	September
	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation	Flow Augmentation
0	0	0	0	0	0	0	0	0
489	0	0	0	0	0	0	0	0
528	1.34	1.43	1.64	1.64	1.04	1.11	0.45	0
625	7.14	7.62	4.02	4.02	2.98	3.17	0.92	0
642	12.73	13.58	8.78	8.78	4.17	4.44	1.8	0.36
720	14.67	15.65	12.79	12.79	6.28	6.7	3.08	0.77
734	18.68	19.93	14.07	14.07	6.66	7.11	4.16	1.43
772	20.86	22.25	14.73	14.73	6.84	7.3	4.62	1.79
789	25.41	27.1	16.19	16.19	7.29	7.78	5.05	2.44
825	27.97	29.83	16.93	16.93	7.47	7.97	5.29	2.86
862	43.65	46.56	18.27	18.27	7.88	8.41	5.72	3.57
881	48.79	52.05	19.16	19.16	8.09	8.63	5.91	3.93
900	53.11	56.65	19.55	19.55	8.24	8.79	6.09	4.22
937	57.72	61.57	20.05	20.05	8.78	9.36	6.64	5.06
978	60.99	65.06	21.36	21.36	9.31	9.93	6.83	5.3
1036	65.9	70.29	50.64	50.64	9.88	10.54	7.14	5.77
1067	68.58	73.15	54.3	54.3	10.32	11.01	7.63	8.03
1145	72.6	77.43	58.02	58.02	12.44	13.27	9.29	9.64
1174	75.42	80.45	60.4	60.4	16.81	17.93	11.32	14.64
1235	79.44	84.73	64.26	64.26	18.6	19.83	12.61	16.72

Table 4C. Augmentation Flow Volumes in TAF as a function of WSI and timestep.

Feb-Mar Precipitation Index (in)	A1 Demand Apr-Mar (TAF)	Refuge Demand Apr-Mar (TAF)	Oct-Jan Precipitation Index (in)	A2 Demand Apr-Mar (TAF)
0.00 - 1.999	340	30	0.00 - 3.99	105
2.00 - 2.749	310	25	4.00 - 6.99	95
2.75 - 3.299	300	20	7.00 - 9.99	90
>= 3.30	275	15	>= 10.00	80

Table 5. Project demand as a function of precipitation.

KPSIM KBRA Operations

The Klamath Basin Restoration Agreement among stakeholders in the Klamath River basin with the objective of restoring and sustaining fisheries while establishing reliable water and power supplies. The KBRA includes specific hydrologic criteria that were implemented using a version of the Klamath Project Simulation Model (KPSIM). This documentation describes the operating criteria and implementation in the KBRA version of the Klamath Project Simulation Model (KPSIM).

Input data and operating rules for KBRA operation of the KPSIM are described below. Priorities for water use are:

- Deliver Project Irrigation allocation and meet National Wildlife Refuge demands
- Balance Iron Gate Flow and UKL elevation conditions – set targets and balance any shortage or surplus
- If Iron Gate Flow or UKL elevation would fall short of an environmental baseline under the above operation, first reduce Refuge delivery to no more than 24,000 acre-feet (24 TAF) April-October and then decrease Irrigation deliveries.

The specific operating criteria are:

Net Inflow to UKL is augmented by 30,000 acre-feet (30 TAF) per year distributed between March and October.

March through October Project demand from UKL and Klamath River is computed as a function of inflow forecast using following criteria:

330 TAF when March 1 inflow forecast is <= 287 TAF
385 TAF when forecast is > 569 TAF
Linear interpolation between 330 TAF and 385 TAF for forecasts between 287 TAF and 569 TAF

November through February project demand is based on historic delivery.

March through October refuge demand from UKL and Klamath River is computed as a function of inflow forecast using the following criteria:

48 TAF when Mar 1 inflow forecast is <= 287 TAF
60 TAF when forecast is > 569 TAF
Linear interpolation between forecasts of 287 TAF and 567 TAF.

November through February refuge demand is based on historic delivery. Demand for diversions from the Klamath River are reduced by estimated D Plant pumping.

Target flows at Iron Gate are selected based on cumulative winter or summer inflows to UKL through the previous time step, using the Inflow Exceedence Index (IEI). Values are interpolated between exceedence levels. The targets used in the model are shown in Table 6.

UKL level targets are selected based on cumulative winter or summer inflows to UKL through the previous time step, using the Inflow Exceedence Index (IEI). Values are interpolated between exceedence levels. The targets used in the model are shown in Table 7.

Probability	100%	98%	97%	90%	70%	50%	30%	10%	0%
Oct	970	970	1000	1000	1100	1300	1300	1300	1300
Nov	1000	1000	1000	1000	1100	1300	1300	1300	1300
Dec	1000	1000	1000	1000	1100	1300	1300	1300	1300
Jan	1000	1000	1000	1000	1100	2024	2223	2421	2421
Feb	1000	1000	1000	1000	1100	2353	2592	2831	2831
Mar 1-15	1100	1175	1398	1398	2085	2721	2988	3224	3224
Mar 16-31	1200	1250	1446	1446	2149	2932	3220	3458	3458
Apr 1-15	1250	1325	1494	1494	2212	3030	3335	3620	3620
Apr 16-30	1250	1325	1542	1542	2276	3015	3334	3710	3710
May 1-15	1100	1175	1240	1240	2090	2739	3306	3728	3728
May 16-31	1100	1175	1182	1182	1936	2559	3063	3675	3675
Jun 1-15	1000	1022	1109	1109	1746	2315	2782	3147	3147
Jun 16-30	1000	1022	1022	1022	1522	2008	2463	2781	2781
Jul 1-15	700	700	840	840	1070	1330	1830	2140	2140
Jul 16-31	700	700	840	840	1070	1330	1830	2140	2140
Aug	880	880	1110	1110	1260	1305	1430	1545	1545
Sep	970	970	1110	1110	1260	1305	1430	1545	1545

Table 6. KBRA Iron Gate Flow Targets (cfs).

Probability	100%	98%	97%	90%	70%	25%	0%	Flood
Oct	4137.80	4137.80	4138.85	4138.90	4139.20	4139.95	4140.20	4141.80
Nov	4138.80	4138.80	4139.61	4139.74	4140.02	4140.65	4141.00	4141.70
Dec	4139.80	4139.80	4140.21	4140.33	4140.59	4141.15	4141.50	4141.90
Jan	4140.80	4140.80	4140.91	4141.01	4141.23	4141.73	4142.00	4142.30
Feb	4141.60	4141.60	4141.61	4141.69	4141.87	4142.28	4142.50	4142.70
Mar 1-15	4141.70	4141.70	4142.20	4142.44	4142.52	4142.70	4142.80	4142.90
Mar 16-31	4141.80	4141.80	4142.40	4142.72	4142.76	4142.85	4142.90	4143.00
Apr 1-15	4141.30	4141.50	4142.80	4142.82	4142.86	4142.95	4143.00	4143.00
Apr 16-30	4141.20	4141.50	4142.90	4142.92	4142.96	4143.05	4143.10	4143.10
May 1-15	4141.00	4141.30	4143.00	4143.02	4143.06	4143.15	4143.20	4143.20
May 16-31	4140.70	4141.10	4141.60	4142.40	4142.70	4143.10	4143.10	4143.20
Jun 1-15	4140.40	4140.60	4141.20	4142.00	4142.40	4142.85	4142.85	4143.30
Jun 16-30	4139.80	4140.10	4140.80	4141.55	4142.10	4142.60	4142.60	4143.30
Jul 1-15	4139.60	4139.60	4140.32	4141.02	4141.57	4142.02	4142.02	4143.30
Jul 16-31	4139.10	4139.10	4139.80	4140.40	4141.00	4141.40	4141.40	4143.30
Aug	4138.10	4138.10	4139.14	4139.65	4139.80	4140.84	4140.84	4143.30
Sep	4137.50	4137.50	4138.50	4139.00	4139.05	4139.60	4140.30	4143.30

Table 7. KBRA UKL Target and Flood Control Elevations (feet).

During shortage years, irrigation and refuge supplies are redistributed to reflect KBRA language. KPSIM does adjustments on an annual basis as a post process. Monthly adjustments are done as a post process in a workbook. The KBRA process intends to develop a drought plan in which shortage criteria and minimum flows in the river are explicitly defined. However, at the time this document was complete, no such drought plan was available. The following assumptions were made in place of the drought plan:

1. Incorporation of a minimum flow of 100 cfs at Link River to provide adequate passage through the fish ladder and stream channel.

2. Incorporation of a minimum flow at Keno Dam of 300 cfs to provide adequate fish passage.

3. Minor adjustment of KBRA flow targets for use in the hydrology model for the time steps from July 1 through the end of September to improve flow conditions for adult migration and reduce the potential for fish die off. The changes that were implemented include reducing the target from 921 to 840 cfs for July 1 to 15, increasing the target from 806 to 840 cfs for July 16 to 31, increasing the target from 895 to 1110 cfs in August, and increasing the targets from 1010 to 1110 cfs in September.

4. Incorporation of minimum Ecological Base Flow levels during the periods from March 1 through June 30 and during the months of August and September. The EBF volumes would be represented by the Hardy Phase II 95% exceedence flow levels.

5. Minor adjustment to the flow targets for the month of March for water years represented by the 70% Exceedence. These adjustments include reductions in the targets from 2358 to 2085 cfs (March 1-15) and from 2343 to 2149 cfs (March 16-31). The change is consistent with rate of change for wetter water years.

6. Incorporation of minimum base flows of 800 cfs during the months of October through February. The minimum of 800 cfs is considered to be necessary to prevent adverse impacts to salmonids during the winter months.

7. Redistribution of irrigation and refuge supplies during shortage years to reflect KBRA language. KPSIM does adjustments on annual basis as a post process. Monthly adjustments are done as a post process in a workbook by the data manager which runs both models.

8. Minor adjustments were made to UKL elevation criteria in association with shortage adjustments.

UKL can be run with existing capacity or with existing capacity plus expanded storage capacity that includes Agency Lake, Barnes Ranch, Tulana Farms, Goose Bay, and Wood River areas. Evaporation and changes to consumptive use for these new storage areas are represented specifically in the model.

Flood control rules are adapted from the original Pacific Power and Light levels to reflect the same amount of available storage space given the modified storage capacity. Flood control targets are shown in Table 7.

KDRM Operations Criteria

The primary function of the KDRM is routing of flows from Keno Reservoir to the Klamath at Klamath gage. When the dams are removed, this is the KDRM's only function. When the dams exist, the KDRM also performs the following:

1. Compute power production
2. Sets target elevations for the reservoirs
3. Attempt to prevent spilling of reservoirs
4. Meet instream or target flow requirements
5. Create pulse flows when sufficient water exists

Target elevation is always set to the normal maximum elevation of the reservoir unless hydrologic conditions warrant a change. If the reservoir is spilling or a large event is occurring, the target elevation is set to the normal minimum elevations. If a spill is anticipated, additional releases are made in an attempt to prevent spilling. Table 8 lists the reservoir allocations.

Boyle Reservoir has a minimum release (bypass) requirement of 100 cfs. Total release is computed as a function of the inflow, previous storage, and target elevation and distributed to minimum release, power plant diversion, and additional spill. Power diversion is limited by power plant capacity. If power diversion and outlet works capacity limit the release, targeted release is constrained to available capacity.

Copco 1 has a minimum release (bypass) requirement of 5 cfs. Total release is computed as a function of the inflow, previous storage, and target elevation and distributed to minimum release, power plant release, and additional spill. Power plant release is limited by power plant capacity which is a function of rated capacity, head and tailwater. RiverWare iterates power computation to account for change in tailwater with change in release. If power plant release capacity and outlet works capacity limit the release, targeted release is constrained to available capacity. Copco 2 has no storage and total release is set to inflow. Power plant release is limited by power plant capacity which is a function of rated capacity, head and tailwater.

Iron Gate minimum release (bypass) requirement is determined by the upstream operating criteria and model. Total release is computed as a function of the inflow, previous storage, and target elevation and distributed to minimum release, power plant release, and additional spill. Power plant release is limited by power plant capacity which is a function of rated capacity, head and tailwater. If power plant release capacity and outlet works capacity limit the release, targeted release is constrained to available capacity. In addition, because Iron Gate's spillway is unregulated, the model releases water that has to be spilled. In those instances, total release could be higher than targeted release.

Boyle Capacity Allocations			
Pool	Elevation	Volume	Increment
Dead	3753.00	0.7	0.0
Inactive	3781.50	720.0	719.3
Normal Minimum	3788.00	1500.0	780.0
Normal Maximum	3793.00	2610.5	1110.5
Active	3793.50	2715.0	104.5

Copco Capacity Allocations			
Pool	Elevation	Volume	Increment
Dead	2588.50	29760.0	0.0
Inactive	2593.50	33895.7	4135.7
Normal Minimum	2601.00	40660.0	6764.3
Normal Maximum	2606.00	45390.0	4730.0
Active	2607.50	46867.0	1477.0

Iron Gate Capacity Allocations			
Pool	Elevation	Volume	Increment
Dead	2184.75	407.0	0.0
Inactive	2324.00	20000.0	19593.0
Normal Minimum	2324.00	55004.0	35004.0
Normal Maximum	2328.00	58794.0	3790.0
Active	2328.00	58794.0	0.0

Table 8. KDRM Reservoir Allocations.

In addition to the reservoir specific minimum releases, Boyle and Copco 1 attempt to meet any anticipated shortfall of minimum release at Iron Gate. If the anticipated unregulated flow at Iron Gate is less than the target flow, Boyle and Copco have to pass inflows up to release capacity. Note that this requirement was necessary in part because the upstream and downstream models are not coupled and have different timesteps. See the temporal disaggregation section below for additional detail.

Streamflow routing uses a variable time lag method that is a function of flow. Historic hourly flows were monitored in fall of 2009 and winter of 2010 to estimate lag times. Lag times in the reservoir reaches were approximated. Streamflow routing is an imperfect science but it is believed that the KDRM routes flows sufficiently well for the study analyzes.

The KDRM also estimates the distribution of power production by on-peak and off-peak. All Sunday releases are off-peak. Copco 1, Copco 2, and Iron Gate compute the other days as 0.6666 percent of the energy as on-peak. Boyle estimates the peak power volume and computes the on-peak energy as a function of peak power volume and total power volume.

The KDRM creates pulse flows (flushing flows) when sufficient water exists. The objective is to obtain a 4,500 cfs flow for three days every other year at Iron Gate to create habitat and reduce the disease vector. Sufficient water exists to creating a flushing release if the volume is greater than the volume of a specified hydrograph with ramping criteria that also meets the low flow requirements for the remainder of the month. Typically, the model was able to produce these hydrographs during medium years. Low flow years have insufficient volume to produce pulse flows and high flow years produce flows above the intended target regardless.

KDRM Temporal and Spatial Disaggregations

Monthly data are provided to the KDRM for a given hydrologic scenario for the same nodes that were used to develop natural flows. The KDRM requires daily data and a finer spatial resolution than the historic data nodes. The KDRM disaggregates monthly data temporally and daily data spatially to provide data at the desired spatial resolution.

Disaggregations of monthly to daily data are based on historic daily to monthly relations. Disaggregation fractions are computed using the filled historic daily data and equivalent monthly data. In addition to the disaggregation fractions, the KDRM needs rankings of the historic data by season. The rankings are computed in a workbook as a pre-process. Before a model run, synthetic monthly flows from the hydrologic traces are imported into the KDRM. At the beginning of each month, the disaggregation rules compute the seasonal volume, find the closest match to historic seasonal volume, and use the disaggregation fractions from the matched season to compute the daily flows for the month. Seasonal matching was used in lieu of monthly matching to reduce unnatural transitions between disaggregation periods.

The KDRM Keno daily flows are treated differently because those flows are regulated and because of the overlap with the KPSIM model. Both operating scenarios of the KPSIM attempt to meet target flows at Iron Gate. Because Iron Gate is downstream of the beginning of the KDRM, Keno daily flow is computed as daily Iron Gate flow without the reservoirs less Keno to Iron Gate daily gain. The target flow is subtracted from the total KPSIM flow at Iron Gate and only the excess water is disaggregated. The daily flow at Iron Gate is the sum of the disaggregated excess water and the target flow. If the KPSIM flow for the month is less than the IFR, the average daily flow is used.

Gains between Keno and Iron Gate use the pattern of disaggregated Keno flow. This was done to enable the KDRM to better meet Iron Gate IFR's. In actual operations, additional water is released from UKL to meet Iron Gate IFR's. However, this is not possible with the KDRM because it does not model UKL. Using Keno's daily pattern is a virtual emulation of supplemental releases of UKL.

The temporally disaggregated data downstream of Iron Gate Dam are spatially disaggregated to a number of tributaries. The spatial distribution factors were estimated as a function of the drainage area at the tributary and the drainage area of the next downstream gage. This approach produces similarly shaped hydrographs for all the tributaries between gages but maintains mass balance with respect to the total daily gain of the reach.

KDR Model Adjustments

Both the BO and KBRA operations of the KPSIM use historic forecasts to inform decisions. Furthermore, the KBRA uses UKL inflow exceedence data and has other historic dependencies in the computation of Project and Refuge water demand. Because the KDR is using synthetic hydrologies, both versions of the KPSIM were modified to accommodate these hydrologies. Detailed documentation of these modifications is available elsewhere. The following paragraphs are an overview of the modifications.

Forecast generation for both KPSIM operations are based on an index to 1977 through 2009 historic forecasts. It was observed that historic forecasts can be classified as dry or wet. The dry/wet threshold for historic inflows is 400 TAF. 400 TAF was used for BO forecast generation. The threshold for the KBRA operation was set at 430 TAF to account for the additional UKL inflow used by the KBRA. If a dry year, the latest index of the dry forecasts is used and the dry index is incremented. If a wet year, the latest index of the wet forecasts is used and the wet index is incremented.

Winter and summer inflow exceedences for the KBRA are computed as a pre-process for every hydrology. The pre-process is included in the functionality of the data and model manager (documentation available).

Under the terms of the KBRA, annual agricultural allocation is defined based on the March 50% forecast for April-September UKL Inflows. The same imperfect forecasts used for reservoir operations are used for allocation. An index of the historic relation between full use (385 TAF) and less use was used. In addition, distribution patterns as a function of the April through September forecasted UKL inflow were developed. A random number was used as the exceedence level to determine winter A2 deliveries. Refuge demands are adjusted for summer D Plant pumping which is estimated as a function of April through September UKL forecasted inflow.

Another adjustment made for dams out operations was to add an estimate of the net gain of evaporation and riparian evapotranspiration. It was necessary to use the estimated net gain because insufficient data existed to compute evaporation for the natural flow computations. In addition, although reservoir evaporation will be removed, riparian evapotranspiration will increase. Therefore, the net gain to the river is the reduction in evaporation minus the increase in evapotranspiration. The estimated annual gains by reservoir are shown in Table 9. The KPSIM uses a monthly distribution of the gains which is disaggregated to an average daily value in the KDRM.

Reservoir	Evaporation and Riparian ET Reduction Volume (acre-feet/year)	Evaporation and Riparian ET Reduction Volume (cfs)
JC Boyle	158	0.219
Copco 1	2990	4.129
Iron Gate	2980	4.117
Total	6153	8.499

Table 9. Estimated annual net gain in evaporation and riparian evapotranspiration.

17.6. Forecasts For Synthetic Flows and Dynamic Agricultural Demand

Klamath Dam Removal Study
Forecast Generation and Demand Representation in Upstream Operation Models

David King and Nancy Parker

02/24/2011

Introduction

Models of operations under current and assumed future conditions are being used to study the potential effects of Klamath Dam Removal (KDR) on flows and associated effects in the Klamath River. These models will be run under both current hydrological conditions and conditions indicating potential future climate change. Several hydrologies were developed as discussed below. All selected hydrologies are processed through a monthly upstream WRIMS model (KPSIM) and a daily downstream RiverWare model (KDR Model – KDRM). The KPSIM is operated with a current conditions operation and a proposed future operation. The No Action alternative, also known as current conditions or Dams In, uses the Biological Opinion's (BO's) under which the Klamath Project now operates and requires use of data for forecasted inflows. The other alternative, known as future conditions or Dams Out, uses the most recent criteria for the Klamath Basin Restoration Agreement (KBRA), which also uses inflow forecast data and implements project demands in a specific sequence tied to historical hydrology. Adaptations to data handling in both scenarios were necessary to accommodate the robust input hydrology that has been developed for the KDR Study.

Historic data from water years 1977 through 2009 were used to develop three synthetic types of hydrology for dams-in and dams-out planning scenarios. The types of synthetic hydrology are:

1. Indexed sequential – A hydrograph created by repetition of historic hydrology.
2. Stochastic – Hydrographs created using statistical software reflecting statistics from historical hydrology.
3. Climate change – Hydrographs created using a watershed model forced with weather conditions consistent with several climate change scenarios.

Documentation of the development of the three hydrologies is available elsewhere.

Previous studies using the KPSIM used a combination of historic forecasts or perfect knowledge of the forecasts. The BO operation uses forecasts to inform flow requirements and delivery cuts. KBRA uses forecasts to assess water supply and define refuge and project agricultural demands. Historical forecasts were not compatible with the synthetic KDR hydrology traces. Therefore, dynamic methods were developed to compute forecasts from the synthetic hydrologies and to apply those to the BO and KBRA operations. The following sections document these methods.

The BO operation uses the March and April 50% forecasts to inform operations criteria. The KBRA model uses the March 50% forecast as one factor to inform seasonal delivery targets, and then defines monthly demands using data keyed to the historical period of record. Methods were needed to define forecast values from synthetic inflows for both scenarios, and to define demands for the KBRA scenario.

This document will describe the methodologies for addressing each of these information needs for KPSIM operations.

Synthetic Forecast Generation

Hydrologic forecasts provide reservoir and river system operators a reasonable estimate of expected inflow into Upper Klamath Lake (UKL). Previous KPSIM operations used actual historic forecasts to emulate data available to operators. The KDR modeling effort required computation of forecasts relative to the synthetic hydrologic inputs that were consistent with historic forecasts in terms of forecasting skill. The quality of historical forecasts can be demonstrated by plotting the forecasts against actual inflows and fitting a linear trend line to the points. The key question is what period of historical data set to use as the basis for the variability that characterizes these relationships. The full available period of record is water years 1961-2009. However, because water year 1977-2009 data are being used as the basis for KDR hydrologies and because it is believed that forecasting skill has improved, the data was analyzed for three periods as shown on Figure 1 for the historic Natural Resources Conservation Service (NRCS) March 50% forecasts.

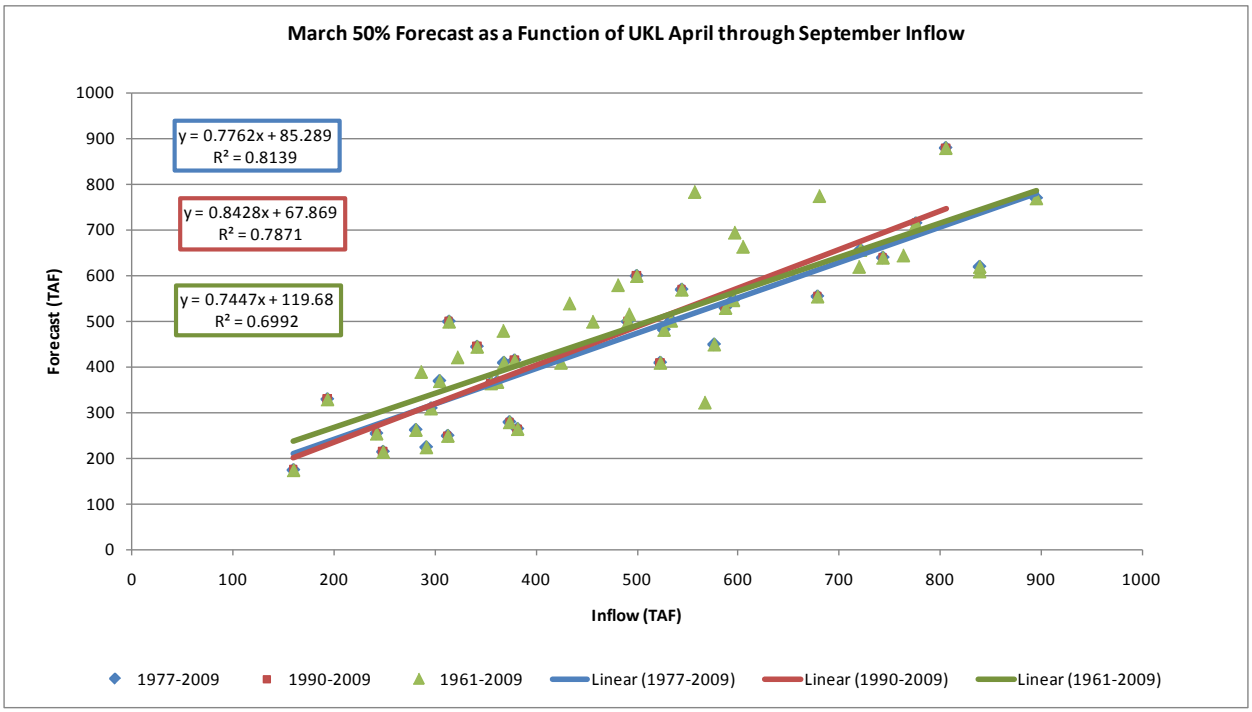

Figure 1. April through September Forecasts vs Actual Upper Klamath Lake Inflows.

The 1977-2009 data uniformly shows improved inflow/forecast relationships over those for 1961-2009 for all three forecasts, with all of the r-squared values improving significantly. Similar improvement however can not be seen by moving to the more recent 20-year period. For most cases, the r-squared values for the regression relationships are slightly worse for the 20-year period than for the 33-year period. Based on these observations, it was decided that methodology for developing forecasts from inflow values would be built upon data from the 1977-2009 period of record.

The regression equations seen on Figure 1 could be used to approximate forecast values from inflows, but if the resulting errors to actual historical errors are compared, they would have a much smaller range with

fewer extreme values. It was desired to capture the nature of actual errors that have occurred and apply this knowledge to the derivation of synthetic forecast values from synthetic hydrologies. An examination of forecast errors was made with the goal of identifying if patterns exist in the errors that track with the actual inflows. If positive errors are defined as inflows greater than the forecast and negative errors as inflows that fall short of the forecast, a vague trend can be seen that shows more negative errors in drier years and more and larger positive errors in wetter years as shown on Figure 2. However, no apparent statistically significant characterization of this trend exists.

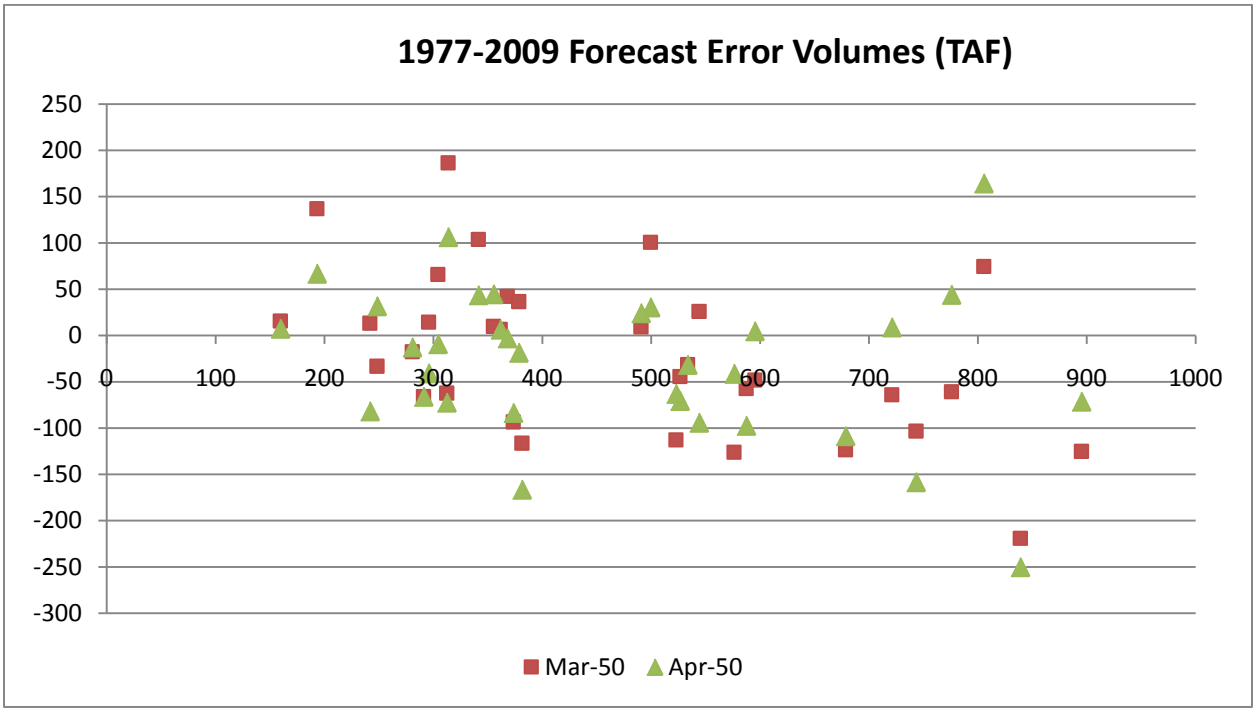

Figure 2. Forecast Error Relative to Actual April through September UKL Inflow.

It is clear that the forecast errors in wetter years have a larger range and have a greater chance of being positive (underestimating inflow) than in drier years. For the 33-year period hydrologic record, dividing the years into categories with April through September inflows above or below 400 thousand acre-feet (TAF) yielded two sets of 17 and 16 years respectively. The differences in forecast error volume in the two groups can be seen in Table 1. The drier year group has lower average errors which is a function of having both under forecasting and over forecasting cases. The range of errors is lower in the drier group for every type of forecast.

	Mar-50	Apr-50
Dry Average	14	-14
Dry Maximum	187	107
Dry Minimum	-116	-166
Wet Average	-57	-44
Wet Maximum	101	165
Wet Minimum	-219	-250

Table 1. Summary of historic forecast error volumes above and below 400 TAF.

Each set of years was ranked in chronological order so that the associated forecast errors for each year group represent the range of potential errors that would be encountered for years that were hydrologically similar. These forecast error volumes were put into an indexed table. At the beginning of any model run, indices to both the drier and wetter error tables are set to one. As the model run proceeds, each year is assessed to determine whether the total April through September inflow is above or below 400 TAF. The forecast error volume is selected from either the wetter table or the drier table, and an increment is made to the appropriate index. The forecast error is applied to the actual inflow to derive the forecast value and the model uses this value as the basis for forecast-dependent operations. KBRA operations include an additional 30 TAF per year of inflow to UKL. The indexing process was adjusted for the increased inflows by using a 430 TAF as the dry/wet threshold for KBRA operations.

Test results using this approach show forecasts error volumes and percents that are consist with historic as shown on Figure 3. This approach was used in KPSIM to include forecast error in reservoir operation decisions using all hydrologies.

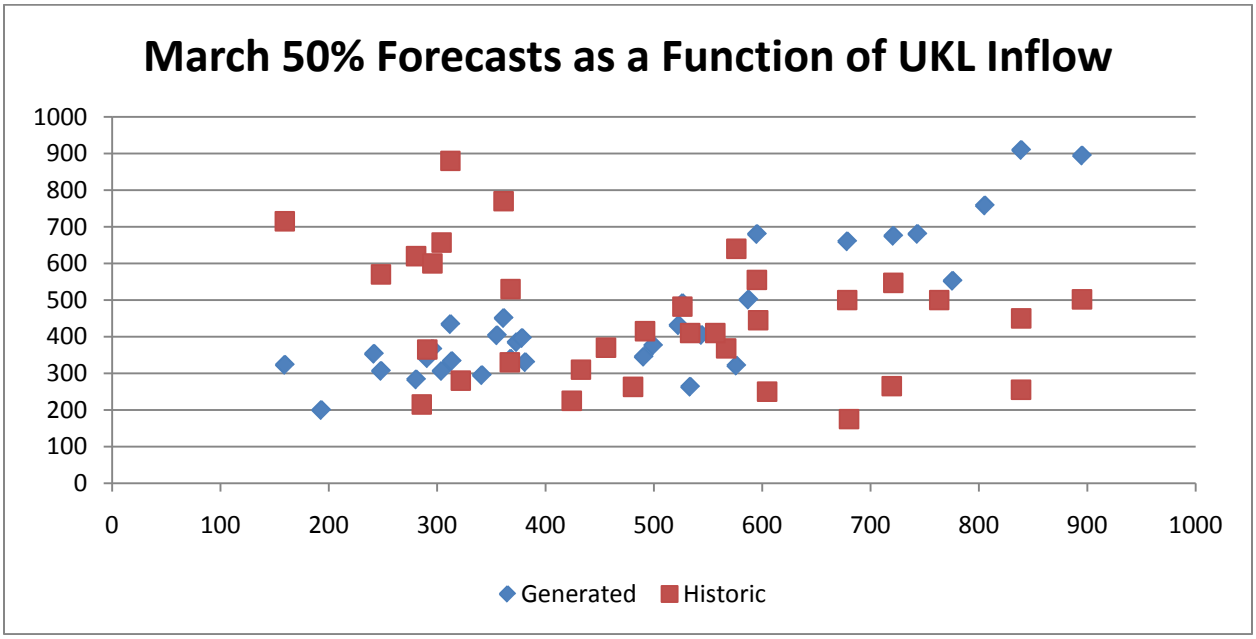

Figure 3. Generated to Historic Forecast Comparison.

Annual KBRA Agriculture Allocation

Under the terms of the Klamath Basin Restoration Agreement, an annual allocation of March-October water supply to agricultural purposes is defined based on the March 1st 50% forecast for April-September UKL Inflows as shown on Figure 4. For forecasts of 287 TAF or less, the allocation is 330 TAF. For forecasts of 567 TAF or greater, the allocation is 385 TAF. And for forecasts between 287 and 567 TAF, the allocation is interpolated between 330 and 365 TAF.

To support KBRA modeling done for the dam removal study, a time series of input demand data (target deliveries) was pre-processed based on the historical sequence of hydrology as detailed in the following steps. The annual allocation is determined from the historical inflow forecast and the allocation is distributed over the March-October period by following the observed historical delivery pattern for that year. If actual historical delivery is smaller than the computed distributed allocation for a particular

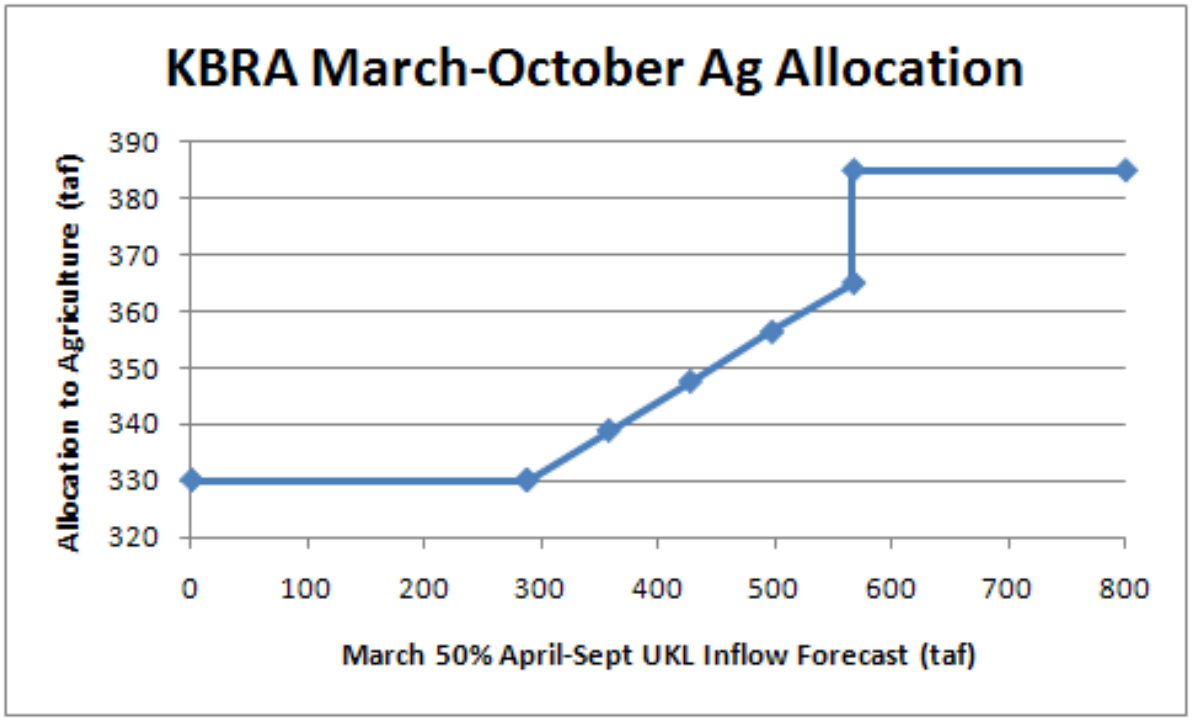

Figure 4. KBRA Agriculture Allocation.

timestep, the smaller value is used as the demand value by the model. This approach is intended to reflect observed historical project operations in which wetter year total March-October diversions often did not reach 385 TAF.

Because model runs for the KDR study do not use the historical sequence of hydrology, a new, dynamic approach was developed to accommodate the intent of this implementation. An examination of project agriculture deliveries from 1981-2009, not including 2001-2005 (when operations were impacted by the shutoff and water bank program), shows that all years in which allocations would have been 365 TAF or lower had water deliveries higher than the allocation, indicating that the allocation would be fully utilized under a KBRA scenario. There were ten years when the allocation would have been 385 TAF based on the March 1st inflow forecast. Of these ten years, water delivery in three years was very close to 385 TAF and seven years had deliveries lower than 385. Insufficient supply ranged from 46 to 81 TAF.

To avoid using perfect foresight in the modeling, lacking correlations between unused allocation and forecast or inflow, and without an agent-based model upon which to predicate potential farm management decisions under the KBRA, a method was developed that uses an indexed table of allocation reductions, similar to the method previously described for forecast errors. The goal was to maintain the same ratio of number of years with full use of a 385 TAF allocation to number of years with reduced use. The set of years where historical forecasts would have resulted in allocations of 385 TAF were put in year order, and the associated sequence of presumed allocation reductions (3 zeros and 7 values between 46 and 81) became the indexed values by which successive allocations of 385 in any model run would be reduced.

Allocation Distribution

The next aspect of the KBRA KPSIM implementation that needed to be modified for the KDR was the assumption that March through October demands, based on the allocation, would follow historical delivery distribution patterns. Since the input hydrology for KDR model runs are not guaranteed to follow the same historical sequence, a more general approach was developed to determine allocation distribution over the March through October delivery season. Again examining the 1981-2009 period (without 2001-2005), average distributions were computed for three categories based on April through September UKL inflow - 1.) < 500 TAF; 2.) 500-700 TAF; 3.) >700 TAF. This approach is believed to be compatible with the intentions of the original KBRA model in that is preserves some sense of distribution variance with general water supply conditions. Separate relationships were derived for Area A1 and Area A2 demands as shown on Figure 5.

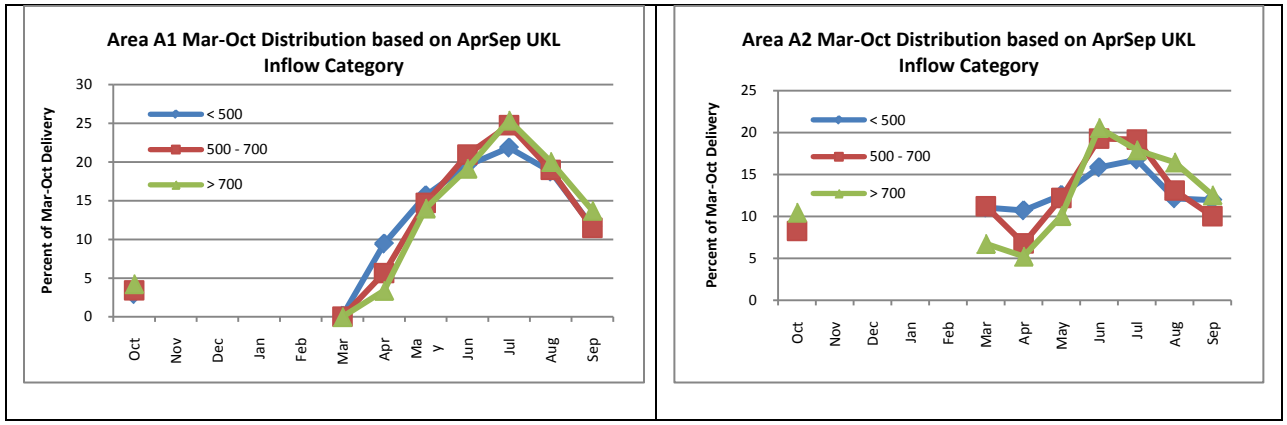

Figure 5. March through October Distributions of KBRA Agriculture Allocation.

Fall and Winter Area A2 Demands

Another aspect of KBRA KPSIM demands that had to be modified was the Area A2 demand in November through February. Historical deliveries to North and Ady canals in this fall and winter are difficult to characterize. No solid correlation can be found between precipitation or inflow data and diversions on either monthly or seasonal basis. It can be noted that in recent years (1995-2009), diversions have not shown the higher values that were seen in some earlier years. Total November-February diversions to the Ady and North Canals have varied between 20.2 and 43.5 TAF. If historic diversions are ranked as shown on Figure 6, a reasonably linear distribution is observable. It was suggested that a random number between zero and one be used in the equation shown in the plot to generate a seasonal demand which could be distributed on the average historical monthly pattern of Nov-.23, Dec-.26, Jan-.33, Feb-.18, based on 1995-2009 data.

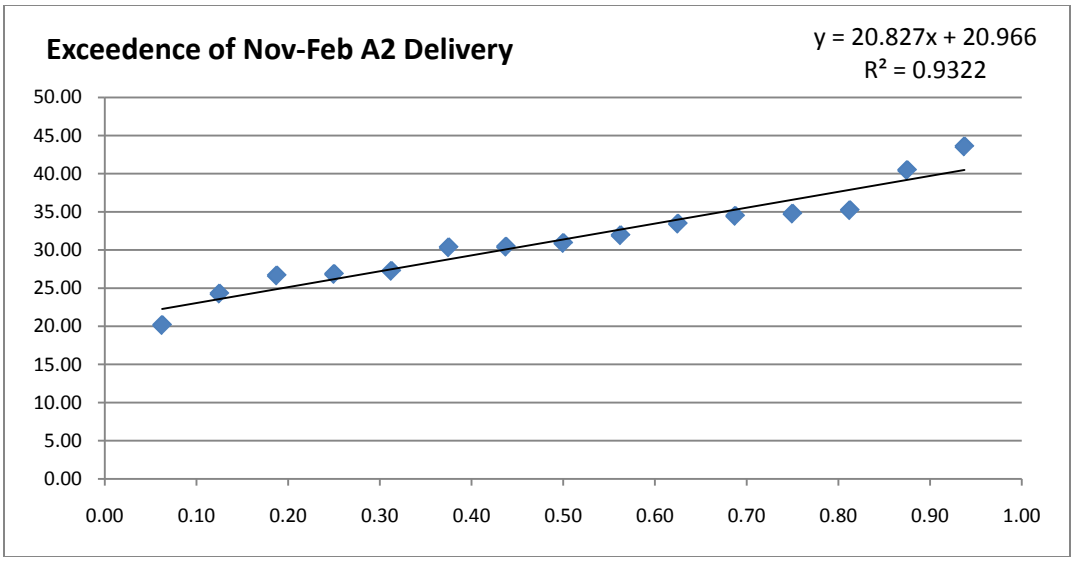

Figure 6. Ranked Fall and Winter Area A2 Historical Deliveries.

Refuge Demands

Refuge demands for the KBRA scenario were developed by the Fish and Wildlife Service (FWS). These are based on management assumptions and a set of historic input data elements, including repeating monthly values for overall demand and return flow operations and input time series data for UKL inflow and Tule Lake precipitation. For the KBRA scenario, the constant total annual refuge demand is 95.392 TAF, distributed by a 17-timestep pattern. Several additional considerations can affect the final demand for surface water delivery from the Klamath River which is discussed below.

April through October refuge demand may be reduced as a function of the March 1 forecast of April through September inflow to UKL. For forecasts of 263 TAF or less, demand is reduced by 20%. For forecasts over 580 TAF, no reduction occurs. For forecasts between 263 and 580 TAF, the reduction is linearly interpolated to be a value between 0% and 20% based on the value of the forecast.

D Plant pumping of water from Tule Lake to the Lower Klamath Lake area can also reduce the amount of water needed from the Klamath River, and there is specific logic for both winter and summer D Plant pumping. Winter is Nov-Mar, and it is assumed that D Plant pumping will be the total volume of the precipitation on the Tule Lake Sump area that happens in that period, distributed evenly through the 5 months. In order to apply this method to alternative hydrologies, it is necessary to define precipitation on the Tule Lake Sump. The Tule Lake area assumed for this study is 13,000 acres. Total winter Tule Lake precipitation for the historical record was computed by dividing the FWS values for the annual volumes by 13,000 TAF. Figure 7 shows a regression relationship between historical Klamath Falls precipitation for the November-March period and the derived Tule Lake Sump precipitation values. With an r-squared of .876, it was determined that a reasonable estimate of Tule Lake Sump precipitation could be defined as a function of model inputs for UKL precipitation.

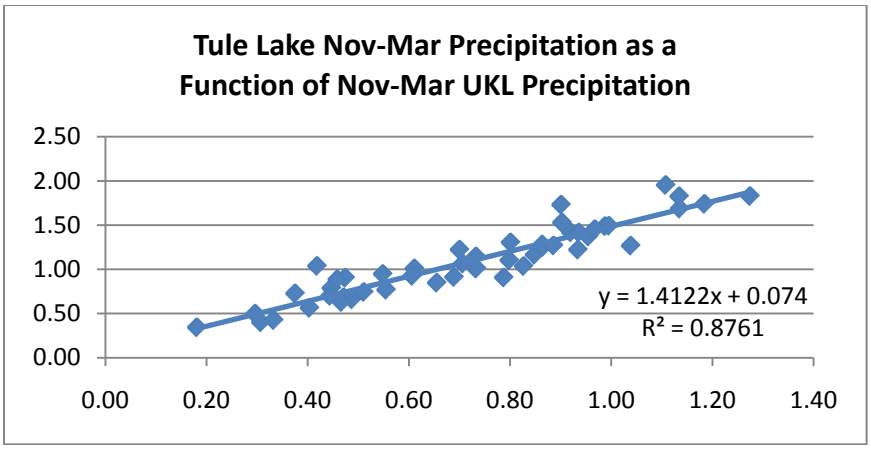

Figure 7. Tule Lake Precipitation to UKL Precipitation Relation.

Summer is April through October. The total volume of D Plant pumping in this period is a number between 0 and 20 TAF, distributed evenly by the exceedence value of the April through September UKL inflow. To adhere to this approach would require pre-processing all of the refuge demands. To use a dynamic approach, it is necessary to derive total pumping as a function of the inflow or inflow forecast. Plotting the FWS values for April through October D Plant Pumping against April through September UKL Inflow yields a linear relationship with an r-squared of .978, as shown on Figure 8. This approach to defining total April through October D Plant pumping can be used dynamically in the model. The monthly distribution of this total follows a constant pattern.

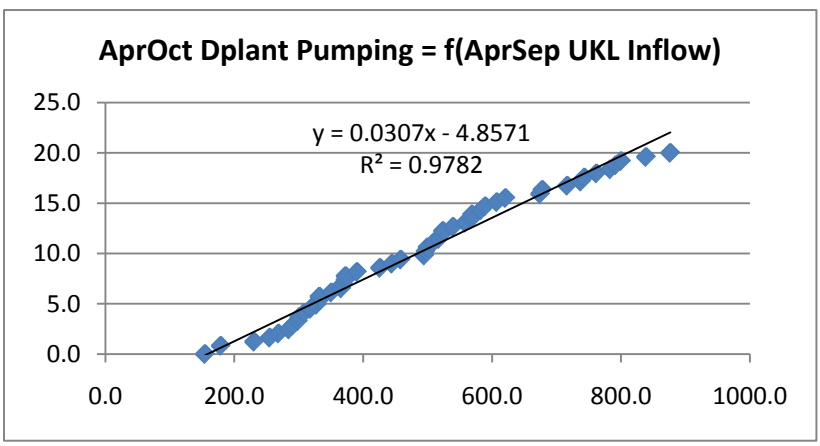

Figure 8. Determination of Summer D Plant Pumping.

Given data inputs developed as described above, actual demands for surface diversions of Klamath River water to the Refuge are determined as follows. Winter demand is calculated in November through March as the timestep distributed annual demand, potentially reduced by the amount of water coming from the D Plant. Summer demand is calculated in April through October, also as the timestep distributed annual demand, but potentially reduced by both the percentage reduction factor discussed above and the D Plant contribution.

Klamath Straits Drain (KSD) flows from the Refuge to the Klamath River were also determined by the FWS analysis. They are a repeating annual time series totaling 21.107 TAF. In April through October,

the KSD return is subject to the same level of reduction that is applied to the refuge demand. Also, in any time step when D Plant pumping provides more water than the refuge demand needs, over-supply is added to the KSD return.

All repeating time-series inputs have been retained in lookup tables as model input, and the regression relationships described above were coded in the KDR versions of the KBRA KPSIM model to create a fully dynamic representation of the agricultural and refuge demands. The effects of modifications to the KBRA version of the KPSIM for KDR operations are shown on Figure 9 and in Table 2.

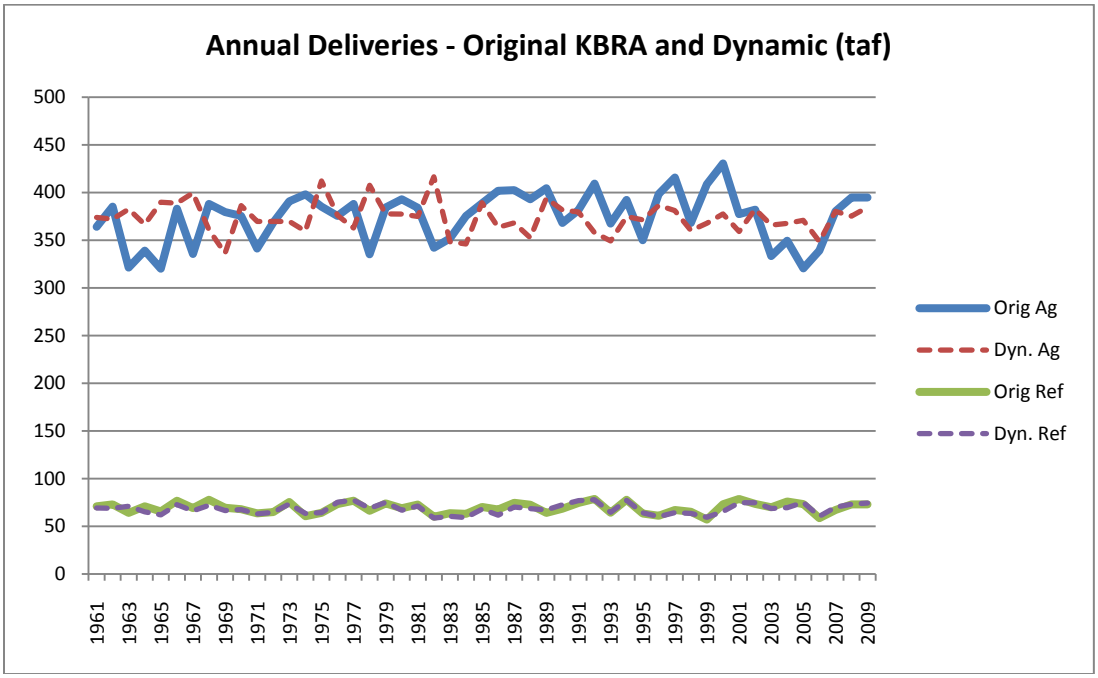

Figure 9. Comparison of Original and Dynamic KBRA Demand Implementations.

	Original KBRA	Dynamic KBRA
Oct-Sep Ag	375	374
Mar-Oct Ag	339	342
Nov-Feb Ag	35	32
Oct-Sep Ref	69	68

Table 2. Comparison of Original and Dynamic KBRA Delivery Totals in TAF.