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Preliminary Study of the Effect of the Proposed Long Lake Valley Project Operation on the Transport of Larval Suckers in Upper Klamath Lake, Oregon

By Tamara M. Wood

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Conversion Factors and Datums

Multiply	By	To obtain
acre-foot (acre-ft)	1,233	cubic meter (m^3)
meter (m)	3.281	foot (ft)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Vertical coordinate information is referenced to the Upper Klamath Lake Vertical Datum (UKLVD), which is used by the Bureau of Reclamation for reporting the elevation of Upper Klamath Lake.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

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By Tamara M. Wood

Abstract

A hydrodynamic model of Upper Klamath and Agency Lakes, Oregon, was used to explore the effects of the operation of proposed offstream storage at Long Lake Valley on transport of larval suckers through the Upper Klamath and Agency Lakes system during May and June, when larval fish leave spawning sites in the Williamson River and springs along the eastern shoreline and become entrained in lake currents. A range in hydrologic conditions was considered, including historically high and low outflows and inflows, lake elevations, and the operation of pumps between Upper Klamath Lake and storage in Long Lake Valley. Two wind-forcing scenarios were considered: one dominated by moderate prevailing winds and another dominated by a strong reversal of winds from the prevailing direction.

On the basis of 24 model simulations that used all combinations of hydrology and wind forcing, as well as With Project and No Action scenarios, it was determined that the biggest effect of project operations on larval transport was the result of alterations in project management of the elevation in Upper Klamath Lake and the outflow at the Link River and A Canal, rather than the result of pumping operations. This was because, during the spring time period of interest, the amount of water pumped between Upper Klamath Lake and Long Lake Valley was generally small. The dominant effect was that an increase in lake elevation would result in more larvae in the Williamson River delta and in Agency Lake, an effect that was enhanced under conditions of wind reversal. A decrease in lake elevation accompanied by an increase in the outflow at the Link River had the opposite effect on larval concentration and residence time.

Introduction

Long Lake Valley, a dry lakebed in the Upper Klamath Lake basin (fig. 1), is being studied by the Bureau of Reclamation as an offstream storage reservoir to augment water supplies in the Klamath River basin in dry years. Because moving water to and from the proposed Long Lake Valley (LLV) offstream storage would affect how water moves through Upper Klamath Lake (UKL), and because the existence of the LLV storage has the potential to change how UKL is managed in terms of the elevation of the lake and the outflows at Link River and the A Canal, it is unknown whether or how the construction of the LLV storage could affect the pathways and travel time of endangered Lost River and shortnose sucker larvae that enter UKL after spring spawning. Larval retention in shoreline areas of Upper Klamath Lake, where emergent vegetation provides cover from predators, is preferable for survival of the species to emigration from the lake (and therefore loss to the population) by way of passive transport in wind-driven currents (Cooperman and Markle, 2004; Markle and others, 2009). The reconnection of the Williamson River delta in October 2007 will likely result in much additional high-quality rearing habitat for larval suckers spawned in the Williamson River. Therefore, any alteration of

Klamath Project operations that has the potential to either increase or decrease the concentration of larval suckers and their residence time in high-quality habitat in UKL and Agency Lake system, and thereby diminish or enhance their chances of survival, is of interest.

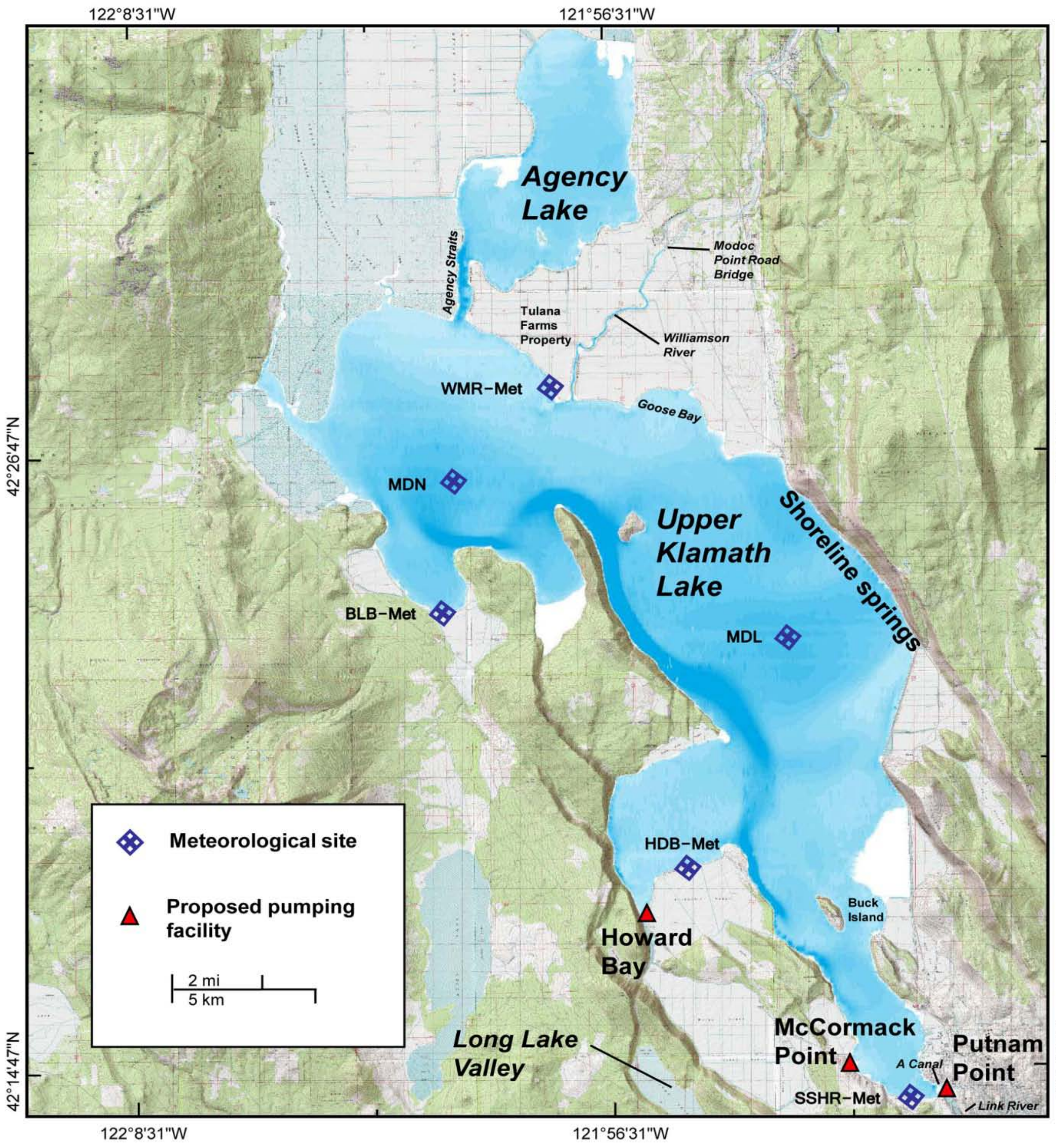

Figure 1. Map of Upper Klamath and Agency Lakes, Oregon, showing meteorological stations and proposed locations of Long Lake Valley pumping facilities. As a result of wetland restoration efforts, much of what is shown here as dry land in the Williamson River delta is now inundated.

The Bureau of Reclamation used the Water Resources Integrated Modeling System (WRIMS) to simulate project operations from 1961 through 2006 on a monthly (August–February) and twice monthly (March–July) basis (Nancy Parker, Bureau of Reclamation, written commun., 2009). This work has provided a simulated history of lake elevation and outflow at the Link River and A Canal, both with and without the Long Lake Valley storage in place, under the assumption that the project was managed according to the Proposed Action as described in the 2008 Biological Assessment (Bureau of Reclamation, 2008). Because project operations prior to 2008 were managed according to different rules from those in the 2008 Biological Assessment, the WRIMS simulation of lake outflow and elevation without the Long Lake Valley storage (denoted the No Action scenario in this report) differs from the actual gauged measurements during those years.

The U.S. Geological Survey (USGS) developed a hydrodynamic and heat transport model of UKL for the purposes of understanding the hydrodynamics of the lake and how the hydrodynamics affect water quality (Wood and others, 2008). This model can be used to explore, through experimentation with numerical tracers, passive transport through the lake under varying conditions of wind speed and direction, and varying inflows, outflows, and lake elevation. It is possible, therefore, to use this model to explore how the transport of sucker larvae might be affected by the construction of the LLV offstream storage, under the assumption that the larvae are transported passively through the system.

Purpose and Scope

This report describes a set of numerical experiments that are designed to explore the possibility that the LLV storage could affect the retention of larval fish in UKL. The results are exploratory in the sense that they are designed to determine, for a reasonable range of conditions, whether it is likely that the project will have a large effect on larval sucker transport and, if so, whether further, more rigorous study of the problem is warranted. This study has not attempted to consider all the possible extremes in conditions, but rather a manageable range in both wind forcing and basin hydrology as described below.

The appraisal study of LLV identified three possible locations for pumping facilities. In the model runs presented here, only the location in Howard Bay (fig. 1) is considered. Because all of the proposed sites are located in the southern end of the lake, the differences in the results would be small except for locations in Howard Bay and south of Buck Island, so it was considered more important for this exploratory work, and given the time constraints of this study, to use the model runs to determine possible differences in outcome based on a range in basin hydrology and wind forcing. The appraisal study also evaluated several scenarios for the amount of storage in LLV and the maximum capacity of the pumps. The model simulations discussed in this report used only the WRIMS results for the scenario in which it was assumed that the storage in LLV would be 500,000 acre-ft (6.2 x 10^8 m^3), and the maximum pump capacity would be 2,000 ft^3/s (57 m^3/s).The scope of this work is limited to the assumption that the sucker larvae travel passively in the current and that there are no other loss terms.

Design of Numerical Experiments

A 1-layer version of the UnTRIM hydrodynamic model of the lake described in Wood and others (2008) was used in order to speed computation time. The use of a 1-layer model removes the effects of water temperature (and therefore density) on the flow. These effects are important for understanding the transport of some water quality constituents, particularly dissolved oxygen and buoyant cyanobacteria (Wood and others, 2006; Wood and others, 2008). In this case, because it is assumed that larvae are transported passively, and that thermal stratification of the water column would not affect their vertical distribution, the benefit of being able to run many more simulations in the available time outweighs the loss of accuracy that occurs by using a 1-layer model.

The numerical grid has been further modified from that described in Wood and others (2008) to represent the Tulana Farms portion of the Williamson River delta that was reconnected to the lake when the levees around the delta were breached in October 2007 (fig. 1). Thus the configuration of the Upper Klamath Lake and Agency system in the hydrodynamic model reflects current rather than past conditions, but it is based on design elevations at the remaining levees around the delta. In the process of implementing the reconnection of the delta, those remaining levees were lowered even though the design of the project had called for them to remain unaltered. There is some inaccuracy, therefore, in the simulation of the connection between the Williamson River, the delta, and Agency Lake at elevations above approximately 4,140.5 ft, as that is the nominal elevation of the remaining levees (Heather Hendrixson, The Nature Conservancy, written commun., 2009).

A challenge of this study was to be able to run the hydrodynamic model of Upper Klamath Lake under past conditions of inflow, outflow, and lake elevation as simulated by the WRIMS model during years for which the wind data needed to force the model are not available. Early spring wind data to force the model have been collected around the lake since 2006, but the basin hydrology as simulated by the WRIMS model for the Long Lake Valley appraisal study considered years dating back to 1961. All of the years that were of most interest in terms of the effects of installing the project on the basin hydrology were prior to 2005. In order to deal with this mismatch between the availability of wind data to force the model and the basin hydrology, a strategy was adopted to decouple the wind forcing from the basin hydrology; that is, the wind data used to force the model was taken from the data available since 2006, and the basin hydrology (Williamson River inflow, Link River and A Canal outflow, and lake elevation) was taken from the WRIMS modeling effort. Six scenarios of basin hydrology and two scenarios of wind forcing were selected. In all cases, the time period of the model runs was between May 8 and June 30, in order to capture the period during which larval suckers are expected to enter the lake (Ellsworth and others, 2008; Ellsworth and others, 2009).

Numerical tracers were used to simulate the passive drift of the larvae. These numerical tracers are the numerical analogue of a dye tracer experiment. They are "injected" into the modeled system at the Williamson River boundary and at locations representing springs where spawning takes place along the eastern shoreline. The numerical tracers used in these simulations represent passive (no behavior) and conservative (no sources or sinks) drift. The transport of these tracers through the system also depends on the boundary conditions. Because of the limitations inherent in assuming passive and conservative drift, and because the determination of how many larvae are actually entering the system (a boundary condition) is inexact, the results of the simulations are expressed in relative terms rather than in terms of actual numbers of larvae.

Wind-Forcing Scenarios

The wind-forcing functions for the model were constructed from data collected between May 8 and June 30 of 2006 and 2007. The wind over the lake is interpolated from the values at six meteorological stations on and around the lake (fig. 1) as described in Wood and others (2008). Data have been collected from these six stations since 2005, but are available for early May only since 2006. Because the time constraints of the study limited the number of model runs, the number of unique wind-forcing scenarios was limited to two. These 2 years had contrasting conditions: there was a strong reversal of winds from their prevailing direction for several days during May 20–24 and June 2–4 of 2006, whereas May and June of 2007 were characterized by moderate winds primarily from the northwest (fig. 2).

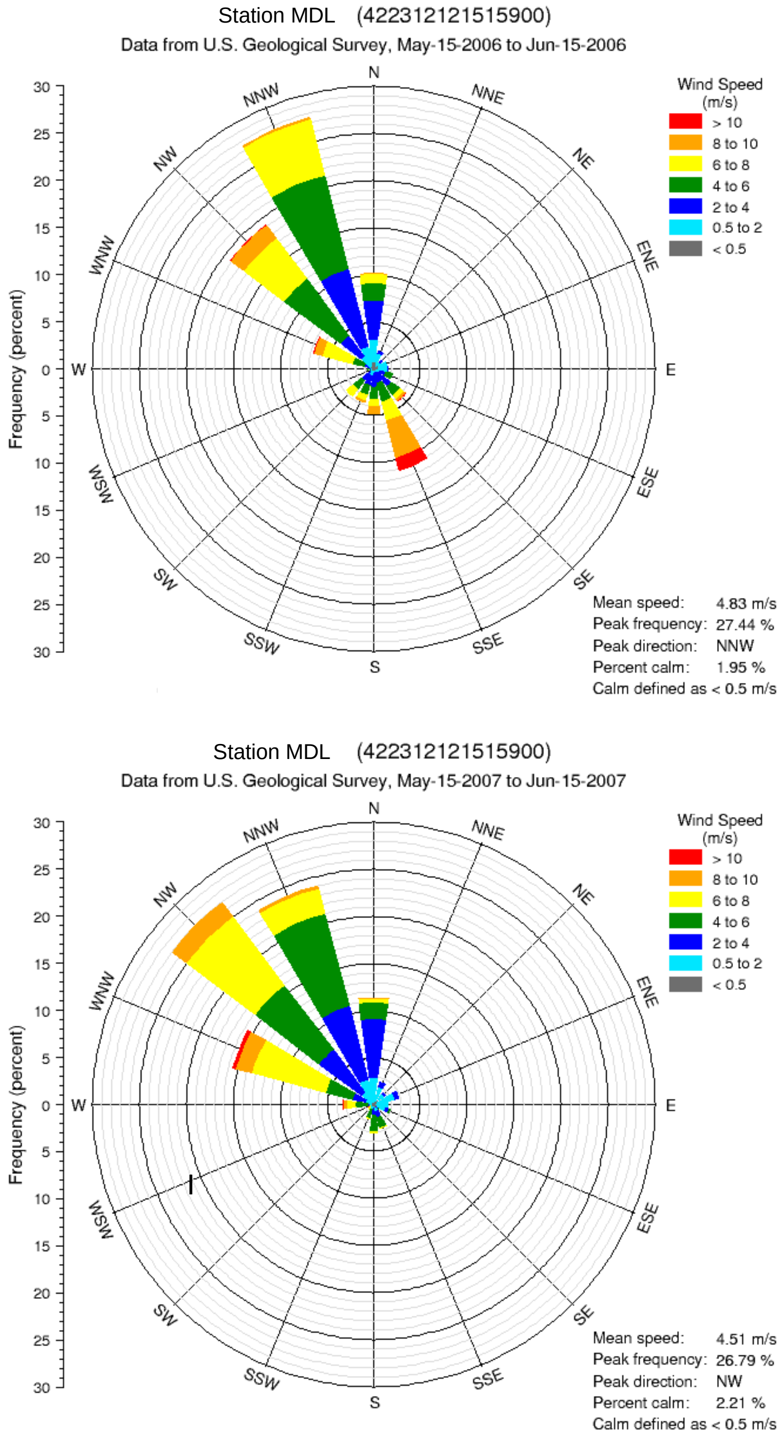

Figure 2. Distribution of wind direction and speed at site MDL, Upper Klamath Lake, Oregon, May 16–June 15, 2006 and 2007.

Basin Hydrology and Pumping Scenarios

The basin hydrology used in the model runs (outflows from the lake and lake elevation) was based on the hydrologic modeling of the Klamath Project operations that was done for the appraisal level study of the LLV project using the Water Resources Integrated Modeling System (WRIMS, Nancy Parker, Bureau of Reclamation, written commun., 2009). The WRIMS study produced, on a twice-monthly basis from March through July, and on a monthly basis otherwise, values for pumping between UKL and LLV, values for the outflows from UKL at A canal and the Link River, and lake elevation. The model was run between 1961 and 2006 under the assumption of No Action and under the assumption that the LLV project had been in place since 1961. From these 46 years of model results, 6 years were chosen to use as input to the UKL hydrodynamic model (table 1) because they represented a range in conditions, as follows:

- In 1991 the increase in the total outflow (the sum of A Canal and the Link River) from the lake during May 16–June 15 with the LLV project in place was the greatest compared to that under the No Action scenario.
- In 1995 the decrease in the outflow from the lake was the greatest compared to that under the No Action scenario (fig. 3).
- The year 1992 was characterized by both the lowest total outflow from the lake and the lowest lake elevation, both with the LLV project in place and under the No Action scenario (figs. 3 and 4).
- The year 1983 was characterized by both the highest total outflow from the lake and the highest lake elevation, both with the LLV project in place and under the No Action scenario (figs. 3 and 4).
- The year 1985 was one of 13 years that were characterized by the maximum amount of pumping from LLV to UKL (15,320 acre-ft or 19×10^6 m^3) during May 16–June 15 and at the same time was characterized by the largest decline in lake elevation with the project in place compared to that under the No Action scenario (fig. 4).
- The year 1989 was characterized by the maximum pumping from UKL to LLV (4,850 acre-feet or 6×10^6 m^3) during May 16–June 15 out of all 46 years of WRIMS simulation.

In general, the period of interest between mid-May and mid-June is not the time when the most transfer of water would be expected, either from LLV to UKL or from UKL to LLV. Pumping to fill LLV is most likely to occur in the early spring prior to the period when the larval drift starts, and pumping from LLV into UKL is most likely to occur in the late summer and fall.

Table 1. Basin hydrology characteristics determined by the Water Resources Integrated Modeling System, Upper Klamath Lake, Oregon, for May 16–June 15 with the Long Lake Valley project and with No Action for 6 years selected for model scenarios. [taf=thousands of acre-feet; ft=feet]

		No Action		With LLV Project			
Year	Williamson River Inflow (taf)	Lake Elevation (ft)	Outflow (Link River plus A Canal) (taf)	Lake Elevation (ft)	Outflow (Link River plus A Canal) (taf)	Pump From LLV to UKL (taf)	Pump From UKL to LLV (taf)
1983	200.91	4,143.17	227.92	4,143.16	227.4	0	0.52
1985	91.62	4,142.89	161.32	4,142.45	173.13	15.32	0
1989	107.12	4,143.04	151.98	4,142.99	151.72	0	4.85
1991	52.87	4,141.26	102.42	4142.50	136.76	10.32	0
1992	15.60	4,138.43	68.28	4,140.62	68.28	0	0
1995	126.52	4,143.14	153.78	4,142.98	139.56	0	0

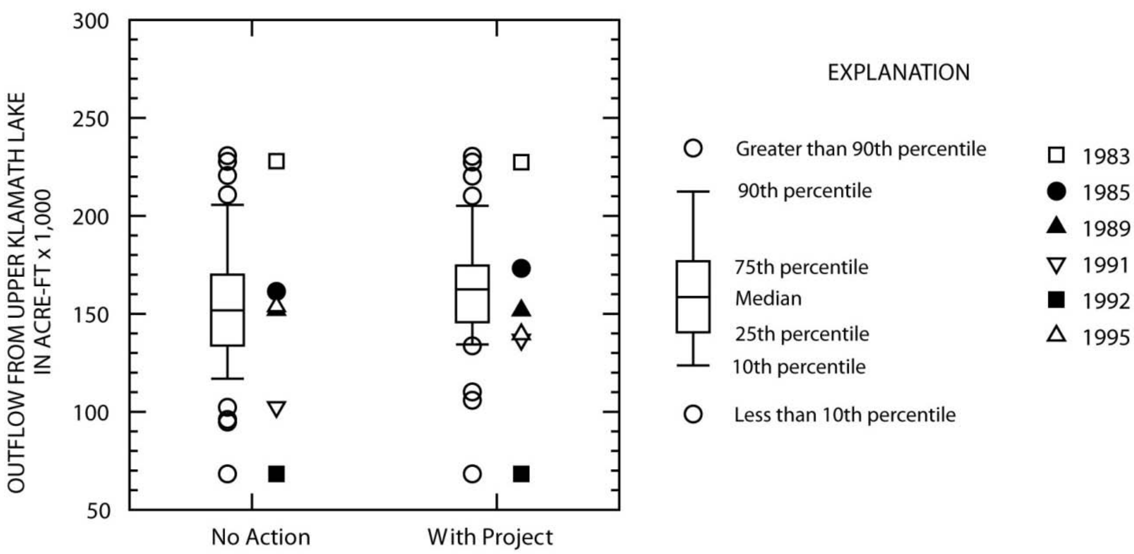

Figure 3. Simulated outflow from Upper Klamath Lake, Oregon, (Link River and A Canal combined), May 16–June 15, 1961–2006 (left) and for the individual years shown (right). Values were determined using the Water Resources Integrated Modeling System with the proposed offstream Long Lake Valley storage (With Project) and without (No Action).

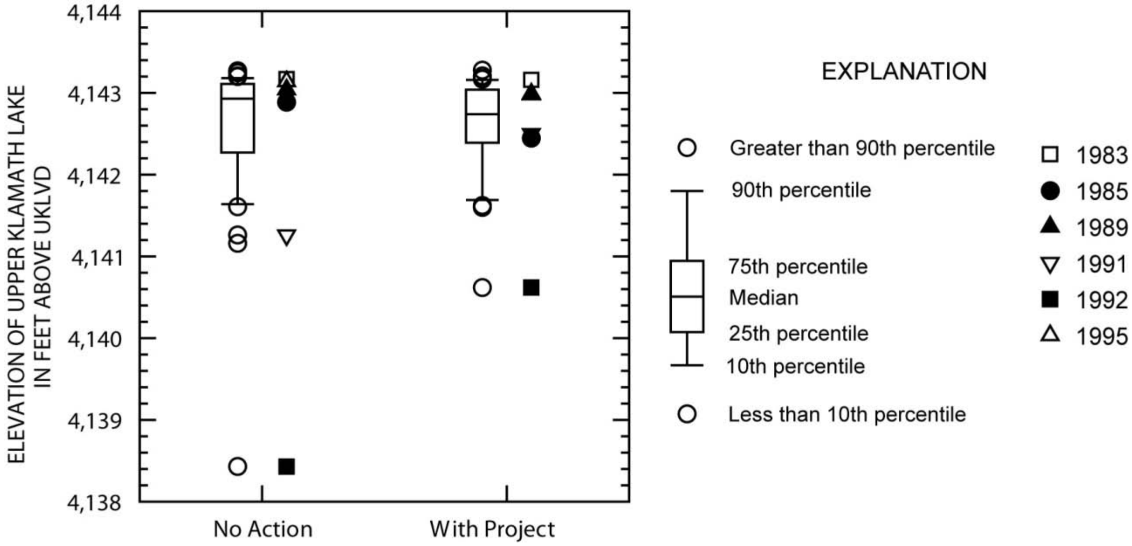

Figure 4. Simulated elevation of Upper Klamath Lake, Oregon, May 16–June 15, 1961–2006 (left) and for the individual years shown (right). Values were determined using the Water Resources Integrated Modeling System with the proposed offstream Long Lake Valley storage (With Project) and without (No Action). UKLVD, Upper Klamath Lake Vertical Datum.

Because of the discrepancy between the monthly or twice-monthly time step used by WRIMS and the 2-minute time step used in the UnTRIM model, output of the WRIMS model was converted to a daily time step, which is the normal resolution for inflows to the model. The lake elevation was linearly interpolated to a daily time step by assigning the WRIMS value to the midpoint of the monthly or 2-week time step. Volume outflows (A Canal and Link River) were first converted to discharge by dividing by the length of the time step and then linearly interpolating to a daily time step by assigning the resulting discharge value to the midpoint of the monthly or 2-week time step. An example of the resulting lake elevation and daily mean outflow discharge is provided in figure 5. Pumping operations were first converted from volume to discharge by dividing by the length of the time step and then spread evenly over each day of the time step. Inflow at the Williamson River would not be managed under project operations, so daily mean data from USGS gaging station 11502500 was used as the inflow at the Williamson River for both the No Action scenarios and the scenarios with the LLV project in place to preserve the true variability at that boundary.

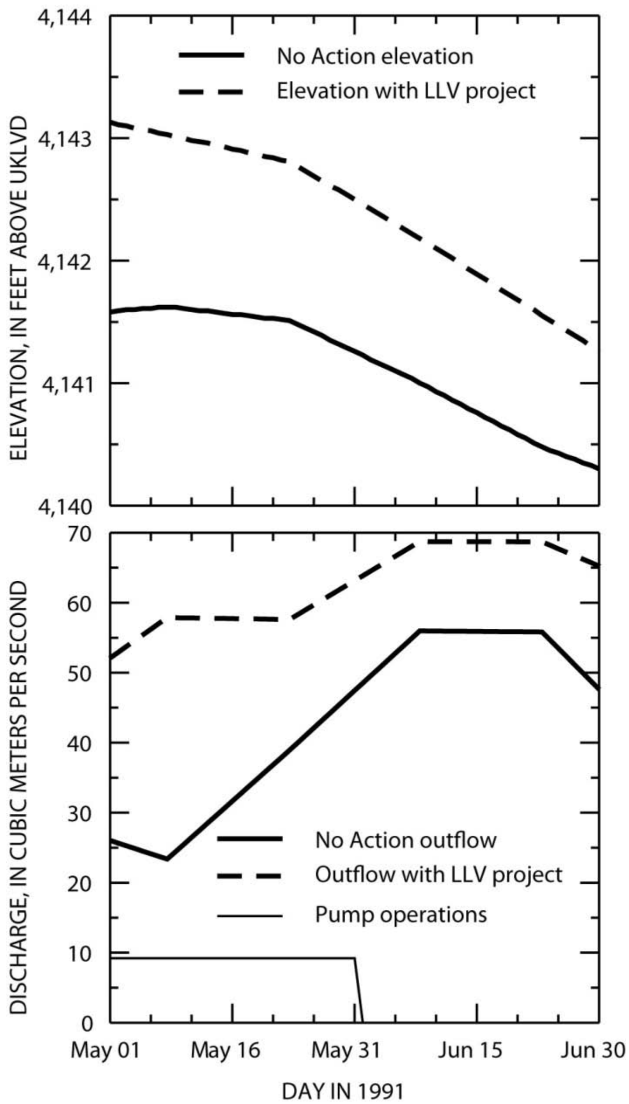

Figure 5. Daily mean values of lake elevation and discharge used in the hydrodynamic model simulations with the Long Lake Valley (LLV) offstream storage (With Project) and without (No Action), May 1–June 30, 1991, Upper Klamath Lake, Oregon. UKLVD, Upper Klamath Lake Vertical Datum.

Larval Sucker Scenarios

Williamson and Sprague River Spawners

A challenge in designing the numerical experiments was to develop boundary conditions for the numerical tracers that would provide a valid representation of larval drift down the Williamson River through time (which is highly variable from year to year) given that measurements of larval drift are available only since 2004 (Ellsworth and others, 2008; Ellsworth and others, 2009). In the absence of definitive rules for how the timing of drift varies with other quantifiable variables such as air temperature or Williamson River discharge, it was decided that the quantitative comparison between the various model runs would be most meaningful if the timing of the input at the Williamson River was kept the same for all of the simulations. Data collected since 2004 show that the drift of sucker larvae into Upper Klamath Lake from the Williamson River usually occurs between late April and mid-June in two distinct peaks, the first of which is dominated by Lost River suckers and the second of which is dominated by shortnose suckers (Ellsworth and others, 2008; Ellsworth and others, 2009). For example, in 2006 the first peak, dominated by Lost River suckers, occurred on May 17, and the second, dominated by shortnose suckers, occurred on June 9 (Ellsworth and others, 2009, table 4).

The second aspect of the boundary conditions that had to be determined was the peak concentration. Again, lacking rules for how the number of larvae in the drift vary from year to year based on other measurable variables, it was decided that to facilitate comparisons between model simulations and between tracers in the same simulation, the most straightforward approach would be to set the concentration of each tracer such that the same amount of each tracer (number of larvae) would always be put into the model system. That number was estimated from 2006 Lost River sucker drift data as follows: The mean larval concentration of 1.7 larvae per cubic meter was assumed to apply for 4 hours every day between 4 and 8 hours after sunset for the 36 days from May 15 through June 20 (values determined from various figures and tables in Ellsworth and others, 2009). During this same period, the average discharge through the Williamson River as measured at USGS gage 11502500 was 42.2 m^3/s. Multiplying the mean larval concentration by the average discharge results in an estimate of 3.7×10^7 Lost River sucker larvae passing by the

Modoc Point Road bridge. This number was rounded up to 10^8, which provided a convenient number to work with as it produced concentrations at the boundary in the range of 0–10. These numbers are not intended to be accurate predictions of the number of larvae entering Upper Klamath Lake, for at least two reasons. First, the larval densities measured by Ellsworth and others (2009) were collected near the surface at the thalweg, where densities were known to be greatest (Tyler and others, 2004), and therefore the concentration applied to the entire discharge should be lower. Second, no account is taken of any loss terms due to predation between the Modoc Point Road bridge and Upper Klamath Lake.

Two numerical tracers were used to simulate populations spawning in the Williamson and Sprague Rivers. An example of how the source concentration of these tracers varied in time between May 8 and June 30 for one basin-hydrology year (1991) is provided in fig. 6. Each tracer was put into the Upper Klamath Lake model in the form of a normal curve in time. The concentration of the first tracer peaked on May 20 and represented the first peak of larvae entering Upper Klamath Lake by way of the Williamson River, dominated by Lost River suckers. The second tracer peaked on June 7 and represented the second peak of larvae entering Upper Klamath Lake from the Williamson River, dominated by shortnose suckers. Thus 80 percent of tracer 1 is put into the system by May 22, and 80 percent of tracer 2 is put into the system by June 9; these dates match approximately the dates for 80 percent of the measured input of Lost River and shortnose larvae, respectively, in 2006 (Ellsworth and others, 2009; fig. 3). The timing of these peaks was the same for every basin-hydrology year. The peak concentration of each tracer, however, was unique in each basin-hydrology year and was calculated so as to always result in a total of each tracer of 10^8 larvae entering Upper Klamath Lake with the Williamson River flow during the course of the simulation (fig. 6).

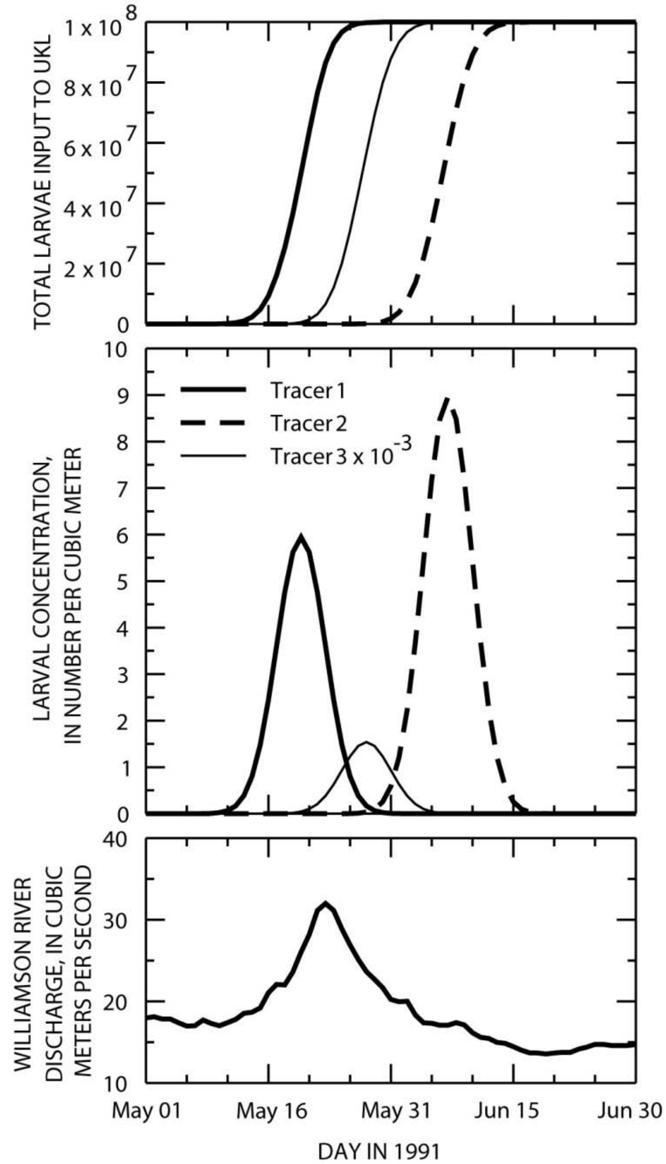

Figure 6. Williamson River discharge, concentration of three tracers used in the hydrodynamic model simulations, and the accumulated amount of each tracer entering the model system from May 1 through June 30, 1991, Upper Klamath Lake basin, Oregon. The concentration of tracer 3 has been divided by 1,000 in order to appear on the same scale as tracers 1 and 2. UKL, Upper Klamath Lake.

Shoreline Springs Spawners

A third tracer was used to represent the swim-up (the process of leaving the sediments and becoming entrained in the currents) of larvae from five shoreline spring locations (fig. 1). Lost River sucker larvae typically are abundant at the shoreline springs between early April and late May, whereas shortnose suckers are scarce at the shoreline springs (Alex Wilkins, Bureau of Reclamation, written commun., 2009). Therefore only one tracer was used to represent swim-up from the shoreline springs. This tracer peaked on May 28 and was input into the model using a very small discharge that would not affect the water mass balance. The concentration of this tracer was the same in every basin-hydrology year and like the other two tracers was calculated so as to result in a total of tracer 3 of 10^8 larvae entering Upper Klamath Lake during the course of the simulation (fig. 6). Few data are available on which to base an estimate of the number of larvae originating at the springs, so the value of 10^8 is arbitrary and was chosen only for consistency with the other two tracers.

Results

The amount of each of the three tracers (representing numbers of larvae) in the entire UKL and Agency Lake system for the scenario represented by each combination of basin hydrology and wind forcing is shown in figure 7 as the percent difference between the scenario with the LLV project in place and with No Action. The differences shown in the figure are calculated for each tracer at 20 days after the peak input (June 9 for tracer 1, June 27 for tracer 2, and June 16 for tracer 3). Negative percent differences indicate that at 20 days after the peak input of tracer, there were fewer larvae in the entire model system in the simulation with the LLV project in place than in the No Action simulation using the same hydrology and meteorology. Positive percent differences indicate that at 20 days after the peak input of tracer there were more larvae in the entire model system in the simulation with the LLV project in place than in the No Action simulation using the same hydrology and meteorology. Negative differences result when the larvae move through the lake and out at either the Link River or A Canal faster with the LLV project in place or are captured in the pumped discharge to LLV. Positive differences result when the larvae move through the lake and out at either the Link River or A Canal slower with the LLV project in place.

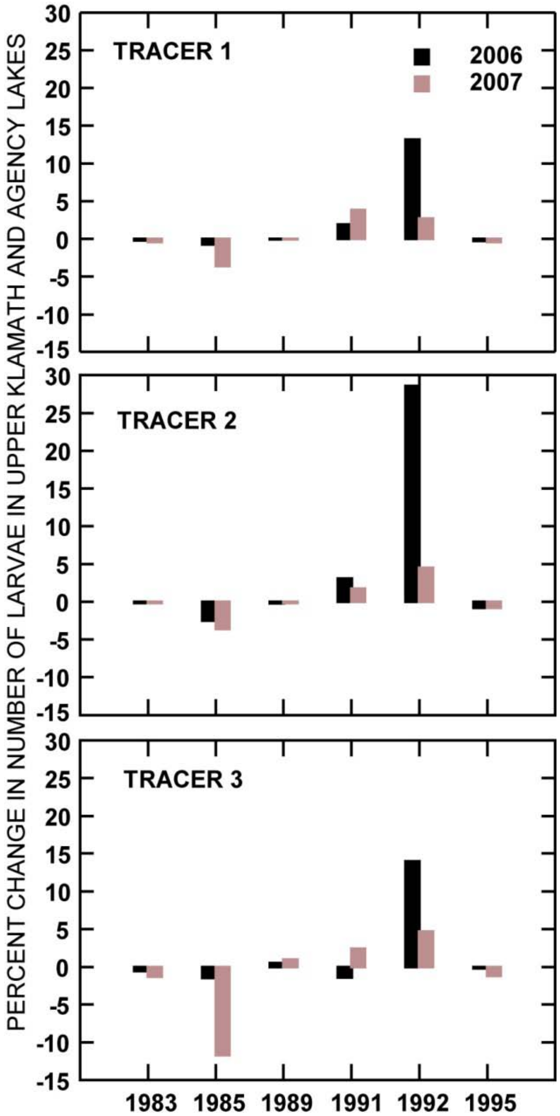

Figure 7. Percent difference in the amount of each tracer in the Upper Klamath Lake, Oregon, model system compared to the No Action scenario 20 days after the peak concentration in the boundary inflow for each tracer. The percent difference is calculated for each combination of basin hydrology and wind forcing.

The data used to produce the graphs in figure 7 are also presented in table form in column 1A of table 2 and are converted to a fraction of the total amount of each tracer input to the modeled system (10^8 larvae) in column 1B. Three years—1983, 1989, and 1995—show small differences, indicating that the operation of the LLV project would not have much effect under those basin hydrology conditions. The three remaining basin hydrology years—1985, 1991, and 1992—show larger differences due to the operation of the LLV project. The 6 years can be summarized in more detail as follows:

- The percent difference is small and negative for 1983 (rows 1, 2, 13, 14, 25 and 26 of table 2), the year characterized by the highest lake elevation and outflow.
- The percent difference is small for 1995 (rows 11, 12, 23, 24, 35 and 36 of table 2), the year characterized by the largest decrease in outflow with the LLV project in place.
- The percent difference is small but positive or negative (between –0.2 percent and 1.0 percent) for 1989 (rows 5, 6, 17, 18, 29 and 30 of table 2), the year characterized by the maximum pumping from UKL to LLV.
- There were large negative differences (as much as –11.7 percent) for 1985 hydrology (rows 3, 4, 15, 16, 27 and 28 of table 2), the year characterized by the maximum pumping from LLV to UKL and the largest decline in lake elevation compared to the No Action scenario.
- Large positive differences (as much as 28.6 percent) were found for 1992 hydrology (rows 9, 10, 21, 22, 33, and 34 of table 2), the year characterized by the lowest lake elevation and lowest outflow.
- The percent differences for 1991 hydrology (rows 7, 8, 19, 20, 31, and 32 of table 2), the year characterized by the largest increase in outflow with the LLV project in place, ranged between –1.4 percent and +3.8 percent, being positive for the two tracers originating in the Williamson River and positive or negative for the tracer originating at the shoreline springs, depending on the wind forcing used.

Further temporal and spatial detail regarding the model results are provided in table 2 in columns 2A/B–5A/B.

Table 2. Change in the number of larvae in four areas of Upper Klamath Lake, Oregon, and in all areas combined, with the Long Lake Valley project in place relative to a No Action scenario for six hydrology scenarios and two wind-forcing scenarios; values were calculated 20 days after the peak input of the tracer into the model system.

["A" columns indicate the percent change in value from No Action, calculated as $100*(N_{wp}-N_{na})/N_{na}$; "B" columns indicate the change as a fraction of the total number of larvae put into the system, calculated as $(N_{wp}-N_{na})/10^{8}$. N_{wp}=number of larvae in the scenario with the Long Lake Valley project in place; N_{na}=number of larvae in the No Action scenario. %, percent. Exponents are expressed as "E" followed by the power of 10; for example, -1.9E-03 is -1.9×10^{-3}]

	Scenario		All areas		North Lake		South Lake		Williamson River Delta		Agency Lake	
Row	Basin Hydro-logy	Wind Forcing	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B
TRACER 1												
1	1983	2006	-0.2%	-1.9E-03	-0.2%	-3.0E-04	-0.3%	-2.7E-04	-0.2%	-2.0E-05	-0.4%	-5.0E-04
2	1983	2007	-0.4%	-2.7E-03	-0.4%	-6.0E-04	-0.7%	-4.8E-04	-0.4%	-5.0E-05	-0.9%	-4.2E-04
3	1985	2006	-0.7%	-6.6E-03	0.2%	3.0E-04	3.7%	4.1E-03	11.3%	6.7E-03	-14.7%	-3.0E-02
4	1985	2007	-3.6%	-3.0E-02	-4.1%	-7.7E-03	-6.2%	-6.7E-03	8.2%	4.1E-03	8.6%	6.2E-03
5	1989	2006	0.0%	0.0E+00	1.0%	1.7E-03	0.8%	8.0E-04	-1.2%	-7.2E-04	-3.4%	-7.0E-03
6	1989	2007	-0.1%	-5.0E-04	0.8%	1.4E-03	-0.7%	-7.0E-04	-1.2%	-6.4E-04	-4.4%	-3.7E-03
7	1991	2006	1.9%	1.8E-02	-7.4%	-1.1E-02	-10.7%	-1.3E-02	20.5%	1.8E-02	56.3%	8.8E-02
8	1991	2007	3.8%	3.2E-02	0.7%	1.3E-03	7.8%	8.0E-03	15.6%	1.0E-02	27.6%	2.1E-02
9	1992	2006	13.2%	1.1E-01	-24.0%	-4.7E-02	30.2%	2.5E-02	234.0%	9.1E-02	735.1%	1.5E-01
10	1992	2007	2.7%	1.8E-02	4.3%	7.2E-03	1.9%	9.6E-04	0.7%	1.4E-05	16.6%	5.1E-07
11	1995	2006	-0.3%	-2.5E-03	1.0%	1.7E-03	1.1%	1.2E-03	-1.6%	-8.2E-04	-5.7%	-1.2E-02
12	1995	2007	-0.4%	-3.6E-03	-0.3%	-5.0E-04	-1.3%	-1.5E-03	2.1%	9.2E-04	-1.6%	-1.3E-03
TRACER 2												
13	1983	2006	-0.2%	-1.4E-03	-0.2%	-4.0E-04	-0.5%	-4.1E-04	0.8%	1.8E-04	0.0%	1.0E-05
14	1983	2007	-0.2%	-1.2E-03	-0.2%	-3.0E-04	-0.4%	-3.5E-04	0.7%	1.3E-04	-0.3%	-1.0E-04
15	1985	2006	-2.5%	-2.2E-02	-0.2%	-3.0E-04	-5.1%	-5.5E-03	-8.6%	-7.5E-03	-11.1%	-8.1E-03
16	1985	2007	-3.6%	-3.1E-02	-2.1%	-3.7E-03	-4.7%	-5.0E-03	-9.3%	-6.2E-03	-10.0%	-7.3E-03
17	1989	2006	-0.2%	-2.0E-03	0.2%	4.0E-04	-0.7%	-8.0E-04	-0.2%	-2.2E-04	-1.6%	-1.3E-03
18	1989	2007	-0.2%	-1.7E-03	0.0%	0.0E+00	-0.7%	-8.0E-04	-0.6%	-4.5E-04	-0.3%	-2.4E-04
19	1991	2006	3.1%	2.6E-02	0.1%	2.0E-04	8.6%	8.2E-03	7.6%	8.7E-03	31.1%	1.8E-02
20	1991	2007	1.7%	1.4E-02	0.9%	1.5E-03	11.7%	1.1E-02	0.4%	3.2E-04	18.0%	1.1E-02
21	1992	2006	28.6%	1.9E-01	16.8%	2.4E-02	70.1%	3.3E-02	12497.6%	1.1E-01	247699.0%	4.4E-02
22	1992	2007	4.5%	3.0E-02	8.9%	1.3E-02	4.9%	2.5E-03	618.8%	1.1E-04	1420.3%	2.9E-07
23	1995	2006	-0.8%	-7.5E-03	1.0%	1.6E-03	-1.1%	-1.3E-03	-1.1%	-7.3E-04	-8.7%	-7.6E-03
24	1995	2007	-0.8%	-7.0E-03	0.2%	3.0E-04	-2.4%	-2.7E-03	-4.0%	-2.3E-03	-3.7%	-2.9E-03
TRACER 3												
25	1983	2006	-0.6%	-2.8E-03	-0.6%	-9.0E-04	-0.6%	-2.6E-04	-1.8%	-1.3E-05	-1.8%	-8.1E-07
26	1983	2007	-1.3%	-3.8E-03	-1.3%	-1.1E-03	-1.4%	-3.4E-04	-2.2%	-6.2E-06	-2.4%	-4.8E-07
27	1985	2006	-1.5%	-1.0E-02	-1.3%	-2.6E-03	-3.1%	-1.7E-03	-20.0%	-8.1E-04	-20.3%	-1.1E-04
28	1985	2007	-11.7%	-6.3E-02	-10.2%	-1.6E-02	-11.5%	-5.4E-03	-31.0%	-9.1E-04	-31.8%	-1.3E-04
29	1989	2006	0.5%	3.5E-03	0.5%	9.0E-04	0.3%	1.4E-04	-1.1%	-5.3E-05	-3.9%	-2.6E-05

Row	Scenario		All areas		North Lake		South Lake		Williamson River Delta		Agency Lake	
	Basin Hydro-logy	Wind Forcing	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B
30	1989	2007	1.0%	5.4E-03	0.8%	1.3E-03	0.8%	3.7E-04	-0.7%	-2.3E-05	-1.3%	-6.7E-06
31	1991	2006	-1.4%	-9.8E-03	-0.9%	-1.8E-03	0.6%	3.5E-04	63.6%	1.9E-03	134.6%	4.0E-04
32	1991	2007	2.4%	1.2E-02	2.8%	4.0E-03	6.7%	2.8E-03	92.4%	1.7E-03	126.0%	2.9E-04
33	1992	2006	14.0%	9.2E-02	26.8%	4.6E-02	7.1%	3.9E-03	11016.2%	3.8E-03	6792.7%	3.8E-04
34	1992	2007	4.7%	2.4E-02	6.8%	8.6E-03	2.5%	1.0E-03	983.5%	4.6E-10	990.2%	2.0E-13
35	1995	2006	-0.2%	-1.4E-03	-0.1%	-2.0E-04	-0.7%	-3.9E-04	-8.1%	-3.5E-04	-9.3%	-5.3E-05
36	1995	2007	-1.2%	-6.8E-03	-1.2%	-2.0E-03	-2.0%	-1.0E-03	-10.1%	-3.3E-04	-10.0%	-4.1E-05

The total number of larvae in the system was calculated as a function of time in four subregions of the Upper Klamath Lake and Agency Lake model system (fig. 8). These results are presented in figures 9–14. In each graph, the information from a single model run is compared against the same conditions of wind forcing and basin hydrology under the No Action scenario. The differences among 1983, 1989, and 1995 are generally too small to be seen (figs. 9, 11, and 14), consistent with the small percent change in number of larvae for those years shown in table 2, column 1A.

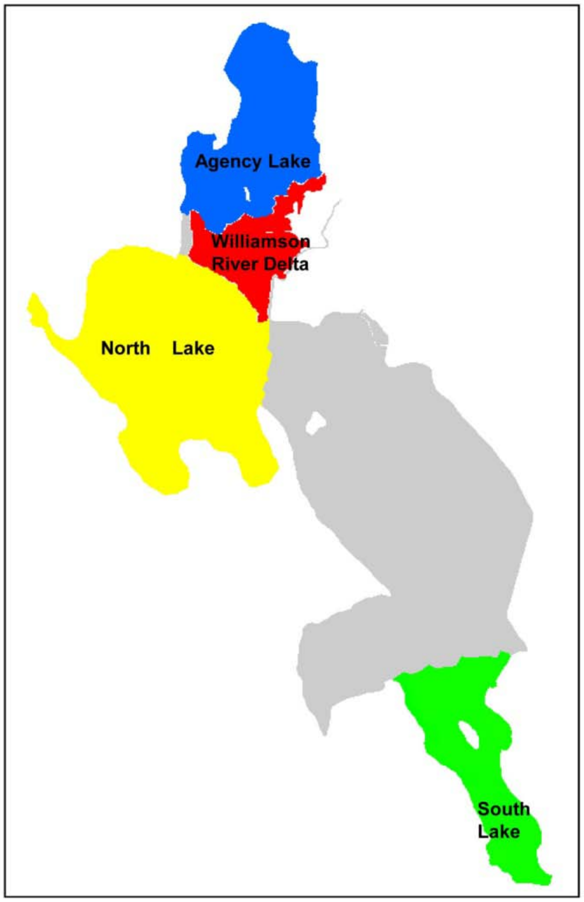

Figure 8. Four areas of Upper Klamath and Agency Lakes, Oregon, defined for the purposes of tracking the amount of each tracer in subareas of the model system.

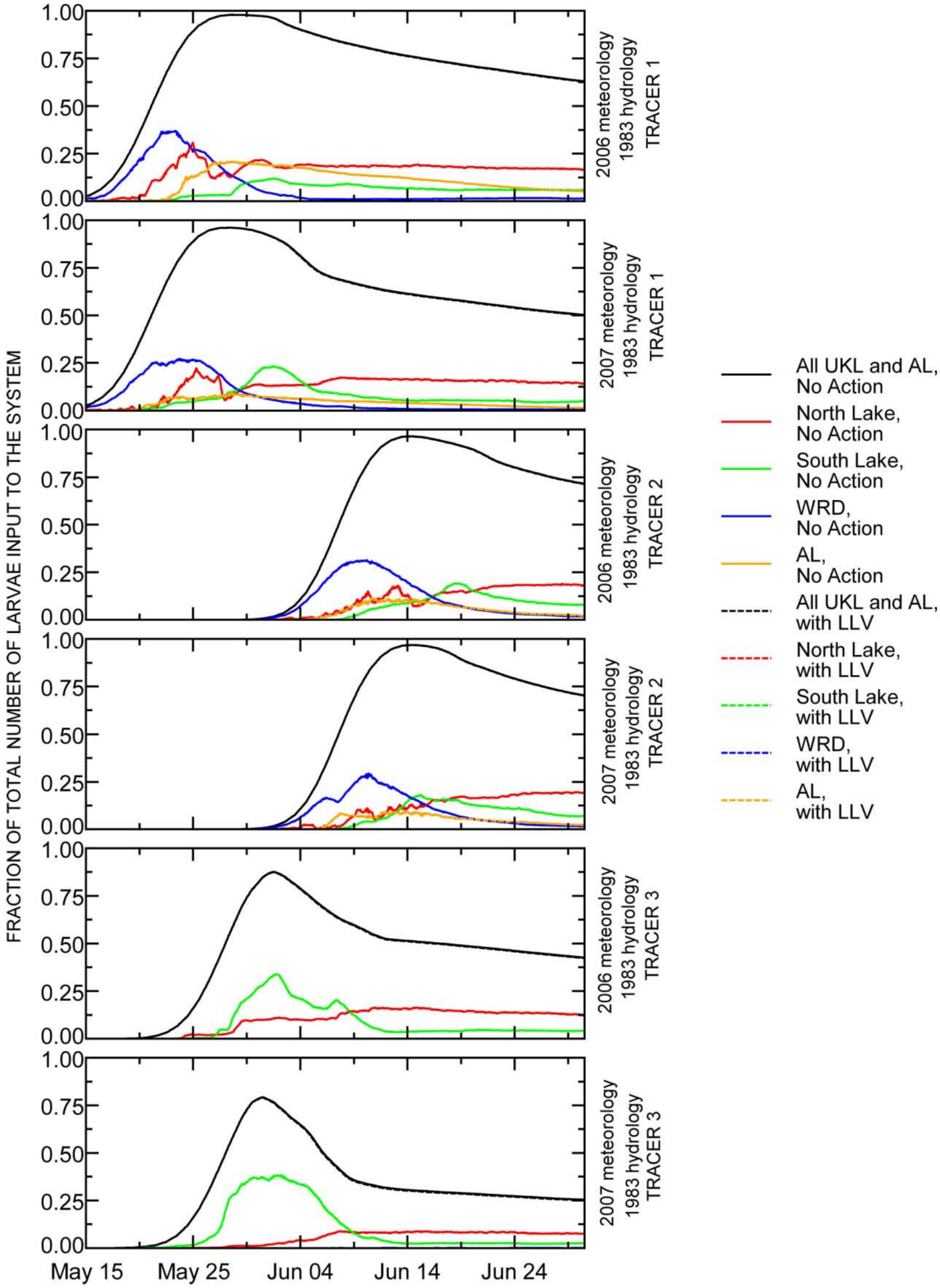

Figure 9. The fraction of larvae in the entire model system and in four subareas of the model system for all model runs that used the 1983 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

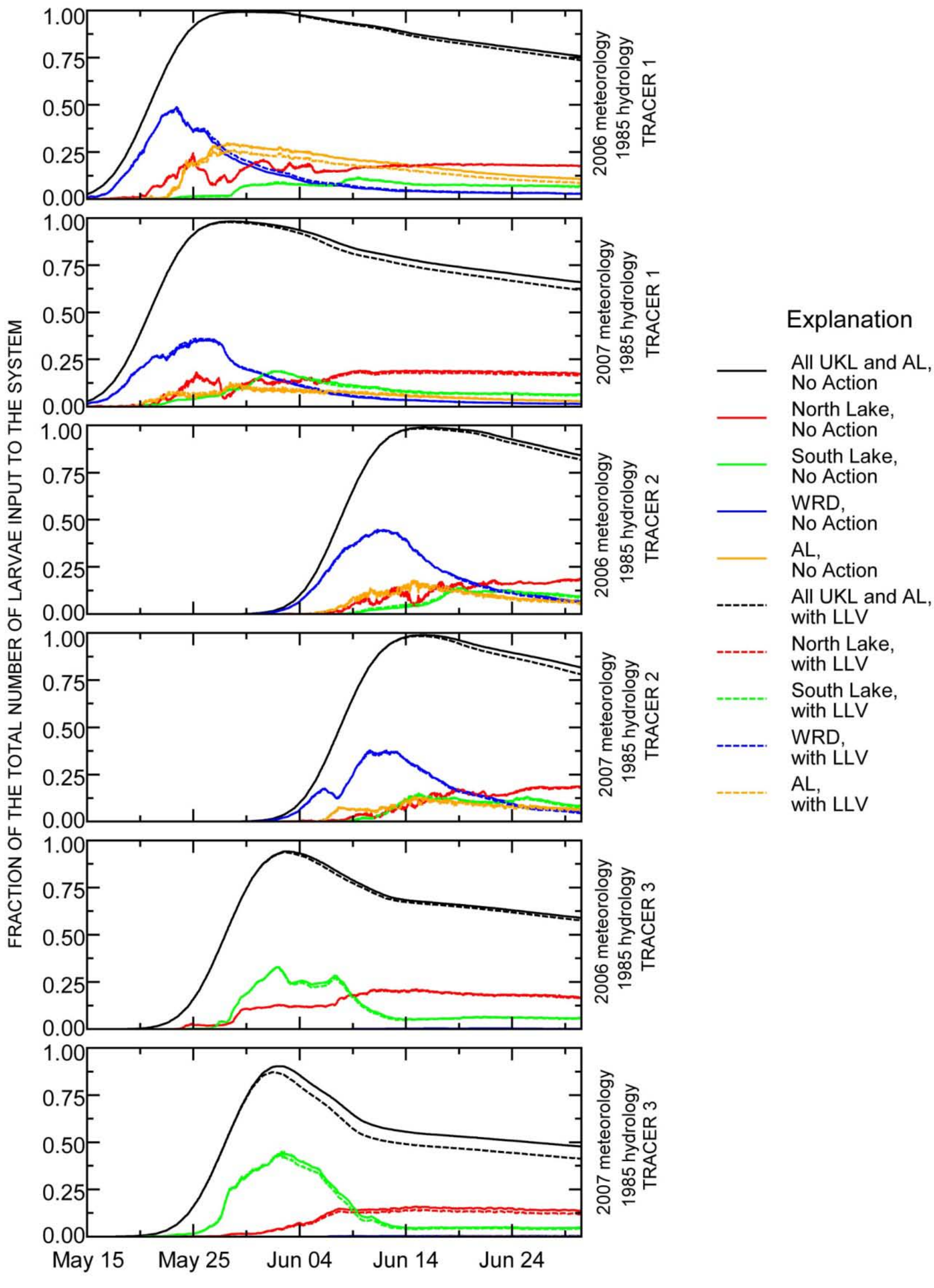

Figure 10. The fraction of larvae in the entire model system and in four subareas of the model system, for all model runs that used the 1985 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario, and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

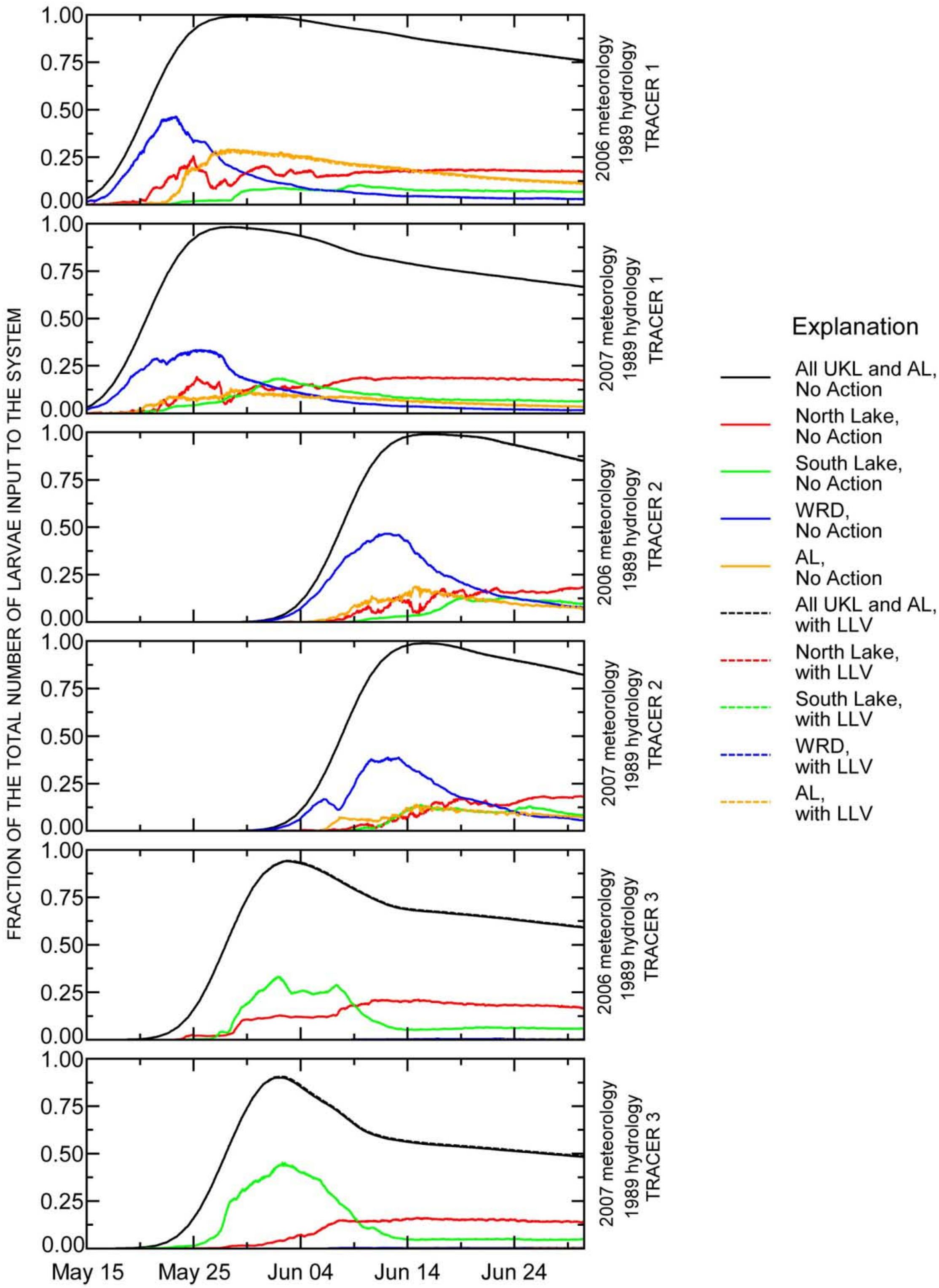

Figure 11. The fraction of larvae in the entire model system and in four subareas of the model system, for all model runs that used the 1989 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario, and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

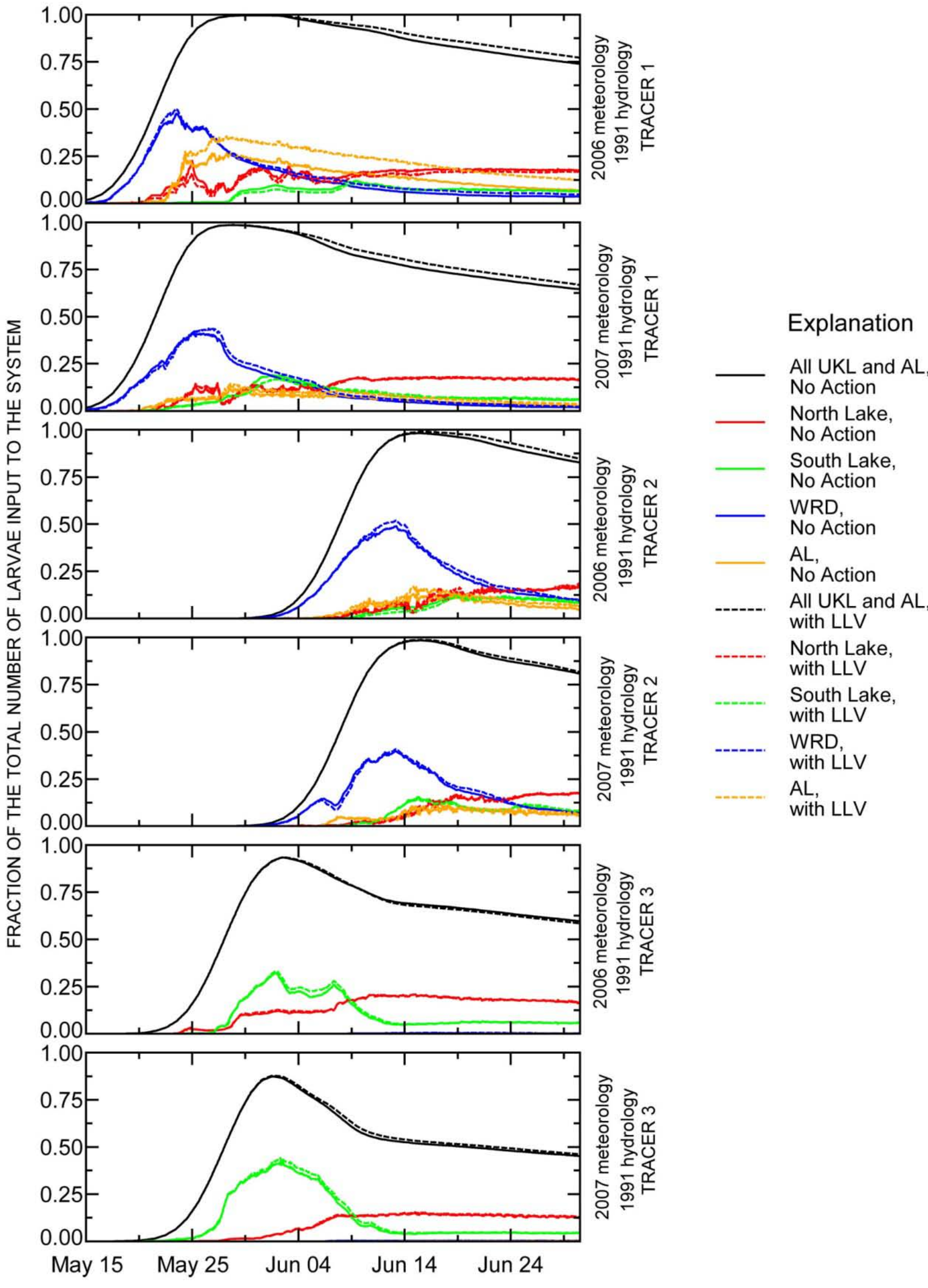

Figure 12. The fraction of larvae in the entire model system and in four subareas of the model system, for all model runs that used the 1991 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario, and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

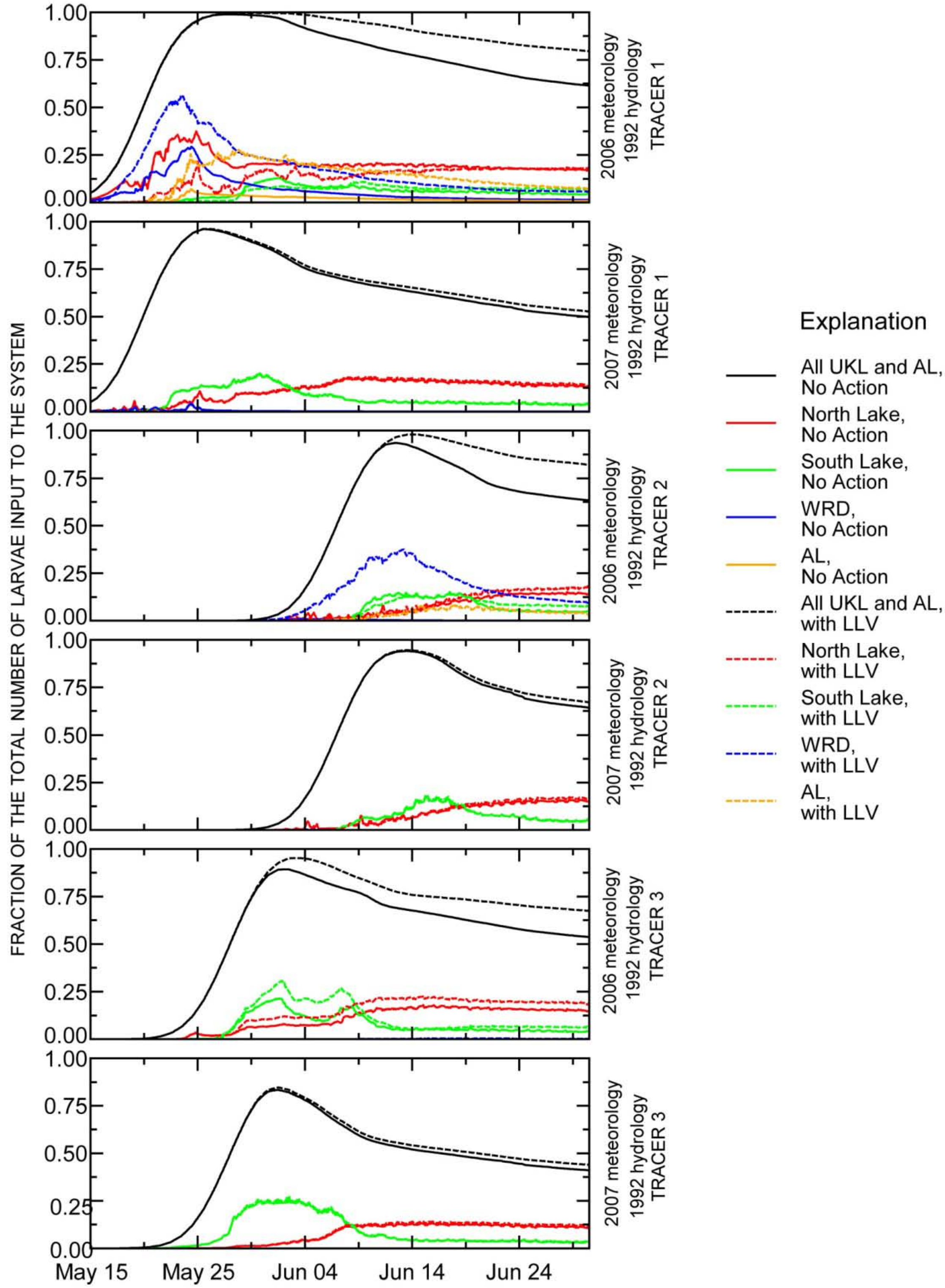

Figure 13. The fraction of larvae in the entire model system and in four subareas of the model system, for all model runs that used the 1992 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario, and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

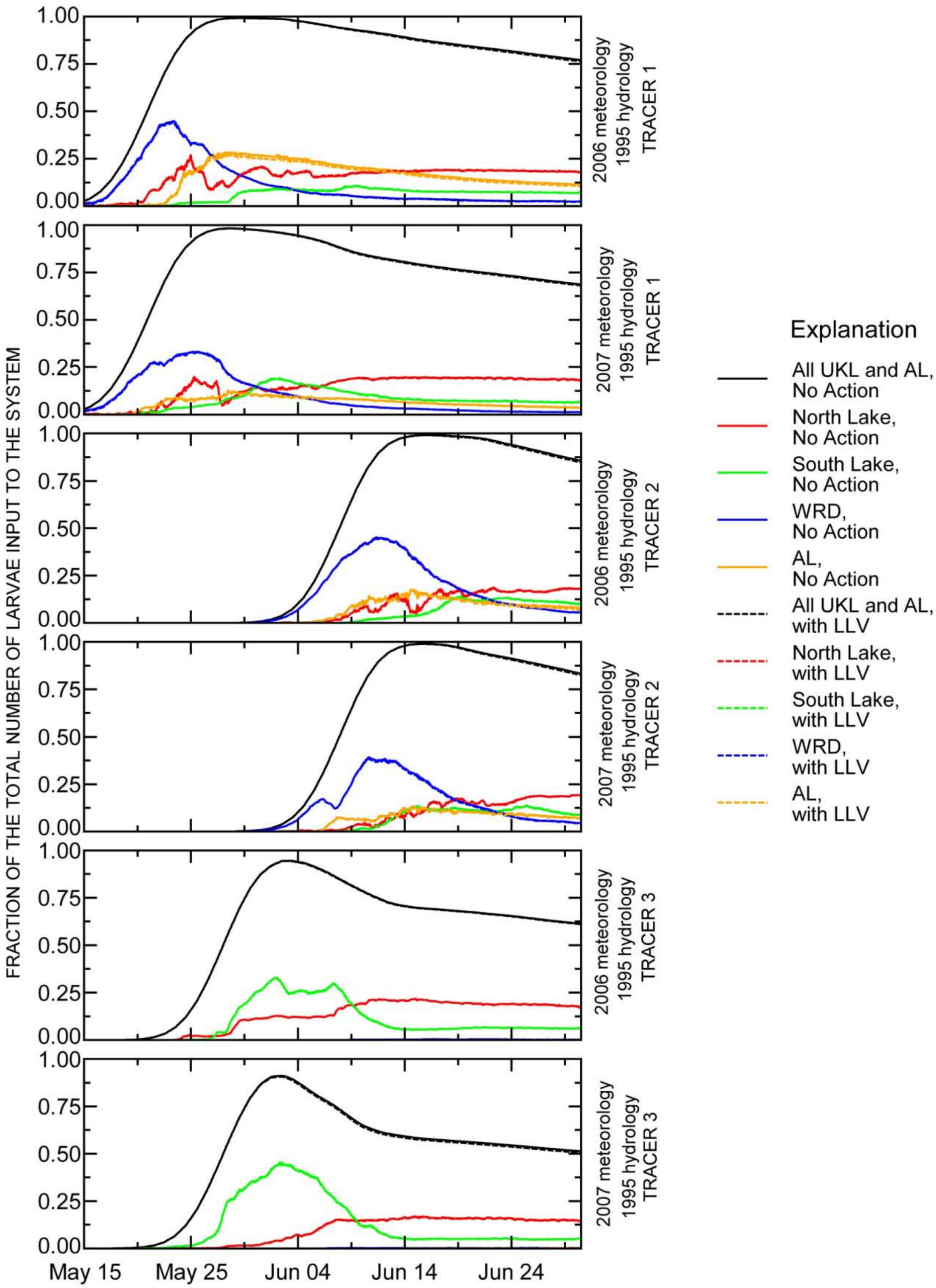

Figure 14. The fraction of larvae in the entire model system and in four subareas of the model system, for all model runs that used the 1995 hydrology for the Upper Klamath Lake basin, Oregon. In each panel, the fraction of larvae as a function of time is shown for both the No Action scenario, and the scenario with the LLV project in place. UKL, Upper Klamath Lake; AL, Agency Lake; WRD, Williamson River delta; LLV, Long Lake Valley.

The largest positive differences in 1991 and 1992 for tracers 1 and 2 originating in the Williamson River are in Agency Lake (table 2, rows 7–10 and 19–22, columns 5A/B), indicating that the operation of the LLV project resulted in more larvae passing through those areas, relative to the scenario without the project. Note that very large percent differences in the “A” column can result from a very small fraction of larvae in the “B” column, which is the case, for example, in the Williamson River delta and Agency Lake in 1992, when 2007 wind forcing was used (table 2, rows 10, 22, and 34, column 5B). The 1992 results show clear differences between 2006 and 2007 wind forcing, because the lake elevation in that year is so low that the connection between the Williamson River channel and the Delta is restricted. The wind reversals of 2006 are more effective at moving water northward from the Williamson River mouth into the Delta and into Agency Lake than the prevailing winds of 2007, which tend to move water from the mouth of the Williamson River southward along the eastern shoreline of the lake. The largest positive differences for tracer 3, which originates at the shoreline springs, are greatest in the northern part of the lake (figs. 12 and 13; table 2, rows 31–34, columns 2A/B) except in the case of 1991 hydrology and 2006 wind forcing, for which the largest positive difference is in the Williamson River delta, but overall the amount of tracer relative to No Action is less (table 2, row 31, columns 1A/B and 4A/B).

The largest negative differences in 1985 for tracers 1 and 2 originating in the Williamson River are greatest in Agency Lake or north lake (fig. 10; table 2, rows 3, 15 and 16, columns 5A/B, row 4, columns 2A/B); negative differences for tracer 3 are greatest in the north (table 2, rows 27 and 28, columns 2A/B). Negative differences for model runs using 1985 hydrology are greater when 2007 wind forcing was used compared to 2006 wind forcing.

Four animations at *http://or.water.usgs.gov/klamath/llv_movies.html* show the concentration of tracer 1 in the model system through time. The first animation, H1985_M2007_T1_noaction, shows the model simulation for 1985 basin hydrology and 2007 wind forcing (prevailing winds) under the No Action scenario, and H1985_M2007_T1_diff shows the difference between the model simulation with the LLV project in place (maximum pumping to UKL and largest lake elevation decline) and the No Action scenario. Similarly, H1985_M2006_T1_noaction shows the model simulation for 1985 basin hydrology and 2006 wind forcing (wind reversal between May 20 and 24 and again between June 2 and 4) under the No Action scenario, and H1985_M2006_T1_diff shows the difference between the model simulation with the LLV project in place and the No Action scenario. In these animations, relative changes in time are more meaningful than the value of larval concentration at any point in time or space because no predation or other loss terms have been included. (Note that very high and low static concentrations in the upper part of the Williamson River delta and in eastern Goose Bay, respectively, are artifacts of the plotting program and are not meaningful.)

Discussion and Conclusions

During spring, when larval suckers drift into Upper Klamath Lake through the Williamson River or swim up from the springs along the eastern shoreline, the direct pumping to and from the proposed Long Lake Valley storage is not likely to be the aspect of the project operations that most affects larval drift and residence time in the lake. Because most of the pumping to fill LLV is likely to occur in early spring before the larval drift starts, and because most of the pumping into UKL from LLV is likely to occur in the late summer and fall, pumping velocities during May and June will usually be small. The availability of the LLV storage will, however, change the way that the elevation of UKL and the outflow at the Link River and A Canal are managed, and those are the aspects of project operations that have the most potential to affect larval transport and residence time during May and June.

The results of the exploratory model runs described in this report indicate that change in lake elevation as a result of project operations could have a large effect on larval transport and residence time in the lake during May and June; this is particularly true if the lake elevation in spring is low enough, as it was during 1992, that the connection between the Williamson River and the recently reconnected Williamson River delta is restricted. In general, even when lake elevation is above the remaining levees that surround the delta, higher lake elevation leads to more of the Williamson River inflow moving into and through the delta and into Agency Lake as well. This was evident in model runs that used 1991 hydrology. The WRIMS simulation of operations showed that a 1.2-ft increase in lake elevation and a 34,300 acre-ft (42.3×10^6 m^3) increase in lake outflow would have resulted with the LLV project in place. The increase in outflow would have been expected to decrease the residence time of larvae in the northern parts of the lake prior to the breaching of the levees at the Williamson River delta, but with the reconnection of the delta, the increase in lake elevation instead resulted in more transport through the delta and Agency Lake, such that concentration in those areas of larvae that entered the lake from spawning sites in the Williamson River increased rather than decreased. Thus, these model runs indicate that the effect of LLV project operations on Williamson River larvae, if the project is built, will be quite different now that the delta has been reconnected than it would have been prior to that reconnection.

To some extent that effect may be overestimated in the model simulations presented here, particularly at elevations close to full pool, because the model grid uses design elevations for the remaining levees surrounding the delta. In the process of implementing the reconnection, the remaining levees were lowered below the elevation designated in the reconnection plans. To make the simulations more accurate, future modeling efforts to predict the effects of LLV project operations should be done after the final surveyed elevations are available and have been incorporated into the model grid.

The model simulations using 1985 hydrology, in which LLV project operations result in an increase in outflow from the lake and a decrease in lake elevation, demonstrate the opposite effect. In that scenario, the concentration of larvae in most areas of the lake decreased relative to the No Action scenario.

The speed and direction of the wind blowing over the lake can have a significant effect on the results. This is because a wind reversal tends to move water entering the lake from the mouth of the Williamson River northward along the shoreline, whereas prevailing winds tend to move the water southward along the shoreline. Thus in the simulation using 1992 hydrology, 2006 meteorology resulted in a greater increase in the larval concentration in the Williamson

River delta and Agency Lake relative to No Action than 2007 meteorology, because water flowing northward from the mouth of the Williamson could enter these areas through breaches in the levees and through Agency Straits. In the simulation using 1985 hydrology, 2006 meteorology resulted in a smaller decrease in the overall larval concentration in the lake relative to No Action than 2007 meteorology, because the wind reversals tend to slow the exit of water at the southern end of the lake.

The limitations of this study are substantial. Although the model simulations can estimate the changes in larval concentration in UKL as a whole and in various subregions as a result of LLV project operations under a range of hydrologic and meteorological conditions, those estimates are not intended to represent the real numbers lost or gained. Rather, the results represent the potential for loss or gain due to LLV project operations that would be superimposed on other losses to the larval population, including predation and other causes of mortality. The average survival of larval suckers between 10 and 15 mm length, for example, has been estimated to be 18 percent (Markle and Dunsmoor, 2007). Compared to the decreases larval concentration due to mortality, therefore, the losses or gains due to LLV project operations resulting from model simulations, which range to as much as 29 percent in the lake overall, are smaller although not insignificant. Prediction is made more complicated by the fact that predation itself is a function of water depth (and, therefore, lake elevation) and vegetation (Markle and Dunsmoor, 2007). Changes in lake elevation due to the operation of the LLV project can, therefore, affect predation rates, both because of the direct effect of elevation on depth, and because, as has been shown by this work, elevation can affect the concentration of larvae in the Williamson River delta, where vegetation may reduce predation losses. Future efforts to use modeling to assess the potential effect of project operations on larval drift and retention would benefit from the inclusion of a predation loss term in the transport equation, with predation rates that can be varied by water depth and location.

A second limitation of this study is the assumption that drift is entirely passive. Although this seems reasonable for small larvae, the drift measurements made in the Williamson River show that the larvae have some ability to limit their drift to nighttime hours; thus, a behavioral component is indicated. This type of behavioral component could be included in future modeling studies if the rules governing the behavior (such as whether the behavior occurs at all or only at certain water depths, or is limited by water velocity) can be developed with some confidence.

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