MANAGEMENT RECOMMENDATIONS FOR RESERVOIR RELEASES FROM UPPER SNOW LAKE: LEAVENWORTH NATIONAL FISH HATCHERY

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Executive Summary

A review of existing hydrologic information collected in the Snow Creek Watershed, streamflow records from Icicle Creek above Snow Creek, and characteristics of Upper Snow Lake's watershed suggest the following about management options for Upper Snow Lake:

1) When full, Upper Snow Lake contains enough water to supplement instream flows in Icicle Creek downstream of the Leavenworth National Fish Hatchery diversion structure.

2) Approximate total annual yield of the Upper Snow Lake Watershed ranges from 4,400 ac-ft to 13,000 ac-ft, with an average of 8,600 ac-ft between 1994 and 2005.

3) Approximate October-July yield of the Upper Snow Lake Watershed ranges from 3,800 ac-ft to 11,800 ac-ft, with an average of 7,800 ac-ft between 1994 and 2005.

4) The estimated probability that Upper Snow Lake will fill after releasing 80 cfs in August and September is about 30% for any given year.

5) The estimated probability that Upper Snow Lake will fill after releasing 60 cfs in August and September is about 60% for any given year.

NOTE: Continuing hydrologic monitoring in the Snow Creek Watershed may produce additional information that could alter some of the results and conclusions in this report.

Introduction

This report reviews existing hydrologic information collected by the U.S. Fish and Wildlife Service Water Resources Branch (WRB) in the Snow Creek Watershed near Leavenworth, WA. Additionally, it presents estimates of inflows to Upper Snow Lake from its contributing watershed and the probable risks associated with releasing different volumes of stored water from the lake. These data are used to assess the feasibility of releasing water from Upper Snow Lake to supplement streamflow in Icicle Creek downstream of the hatchery's diversion. .

Hydrologic Monitoring in Snow Lakes Basin

The WRB established 4 hydrologic monitoring sites in the Snow Creek Watershed in 1992 (Figure 1). These sites help quantify water use under water rights for Snow and Nada Lakes. Water level data is collected on Snow Creek where it enters Upper Snow Lake (1), at the Snow Lake Drain (2), at the outlet to Nada Lake (3), and at Snow Creek's confluence with Icicle Creek (4).

During the last 10 years monitoring stations have typically only been operated for 2 to 3 months of the year, when water is released from Upper Snow Lake. However, beginning in 2004, WRB staff have tried to operate the loggers for longer periods of time to collect additional information on natural hydrologic conditions in the basin and the hydrologic effects of releasing water from Snow Lake.

Upper Snow Lake Site Description

At present Upper Snow Lake is the only actively managed lake in the Snow Creek Watershed and our analysis will focus primarily on watershed contributions to it. The lake sits near the center of the Snow Creek Watershed at an elevation of 5420 ft (Figure 1). The contributing area of the lake's watershed is 2,515 acres, or 35% of the Snow Creek Watershed. Of this 72%, or 1825 acres, is included in the watershed of Snow Creek above Upper Snow Lake. Elevations in the lake's watershed range between 5,420 ft to over 8,600 ft at top of the highest peaks. Nearly 30% of the watershed is above 6,400 ft. This portion is populated by numerous alpine lakes, several permanent snow fields, and two small glaciers.

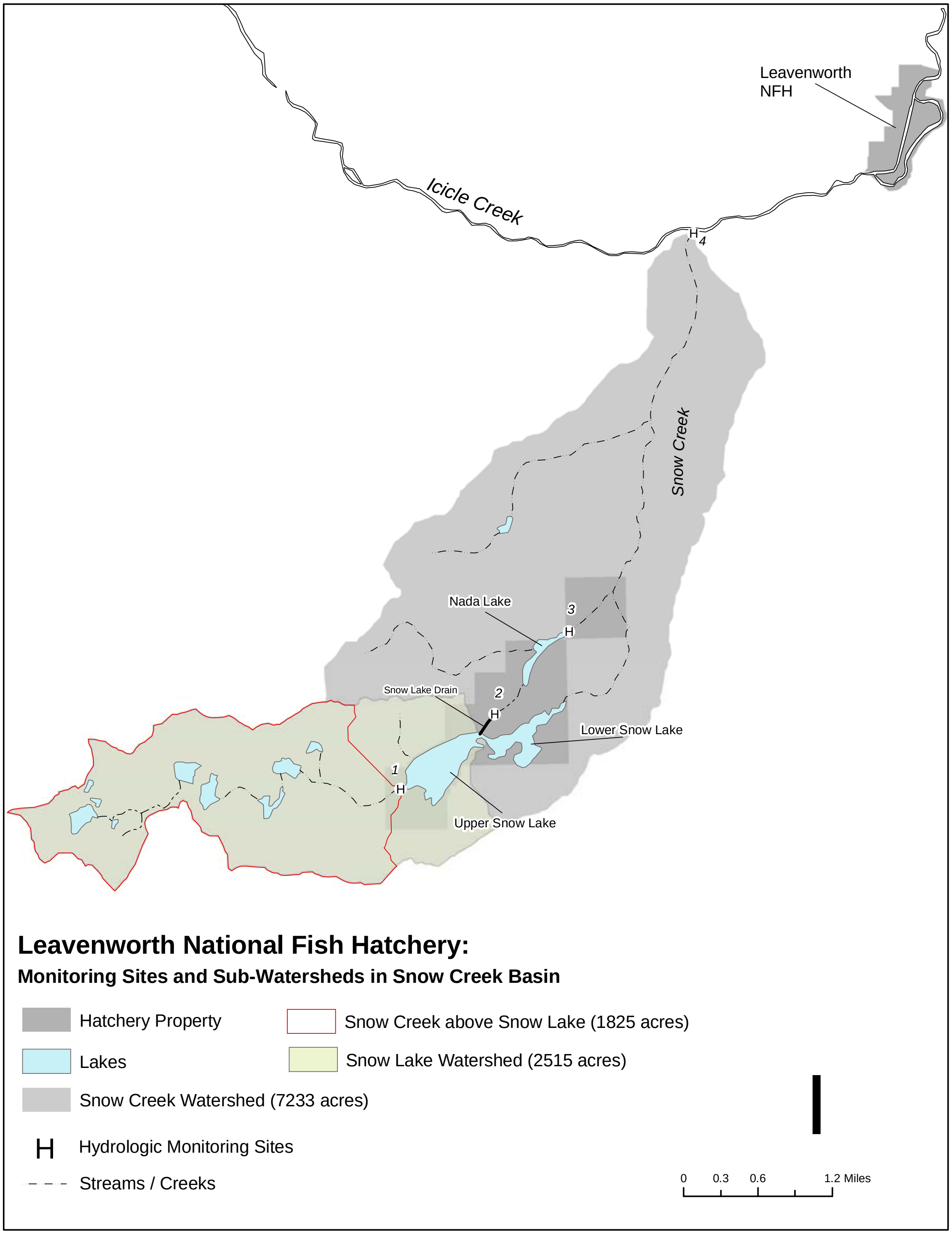

Figure 1: Location of hydrologic monitoring stations and sub-watersheds in the Snow Lakes Basin. Monitoring site numbers correspond to specific sites: 1) Snow Creek at Snow Lake, 2) Snow Lake Drain, 3) Nada Lake Outlet, and 4) Snow Creek at Icicle Creek

Upper Snow Lake Water Budget

Water storage in Snow Lake was expanded in the early 1940's when a small 10-foot dam was built at the northeast end of the lake. Water enters Upper Snow Lake directly through precipitation, overland flow from surrounding hillslopes, and runoff from small tributaries and Snow Creek. Groundwater contributions and losses to the lake are considered relatively small since the lake is situated on top of bedrock with presumably little groundwater storage. Outflows from the lake are evaporation, spill over the lake's dam, and releases from the lake through the outlet drain. Water also passes between Upper Snow Lake and Lower Snow Lake through a small 9 ft^2 hole at the base of the upper lake's dam. The hole acts as an additional inflow or outflow depending on the water level in the upper lake. Flow through the hole is small relative to the volume of water stored in the Upper Snow Lake. In 2005, approximately 200 ac-ft, less than 2% of the upper lake's volume, passed through the hole.

Water Available in Upper Snow Lake

Storage in Upper Snow Lake was estimated by the U.S. Bureau of Reclamation (BOR) in 1939 around the time they built the dam and drain. The lake is approximately 150 ft deep and at full capacity stores approximately 12,450 ac-ft (Figure 2).

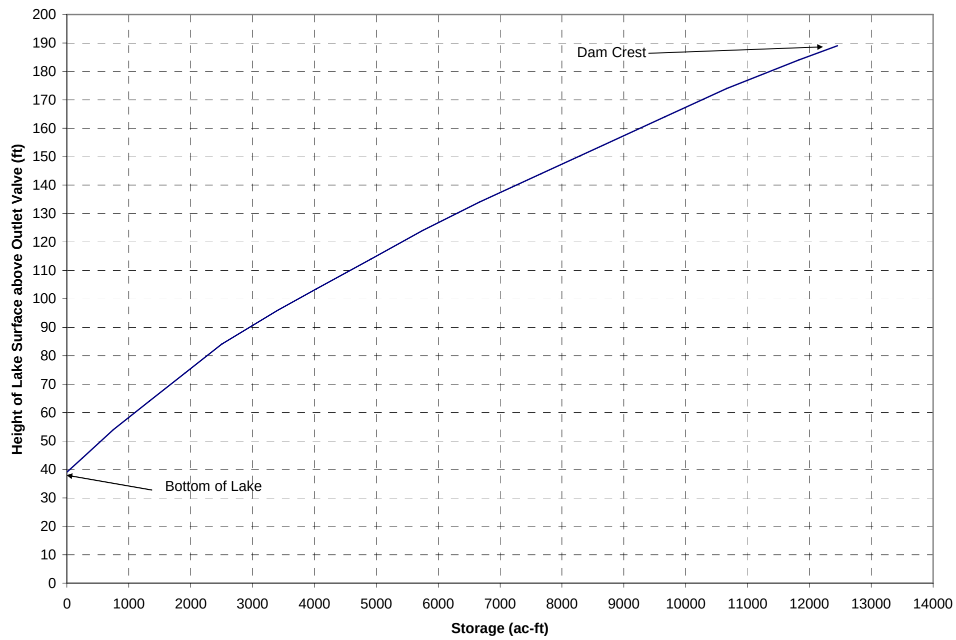

Figure 2: Approximate storage volume in Upper Snow Lake at various water surface heights above the lake's outlet valve. The crest of the lake's dam is approximately 189 ft above the outlet valve. The bottom of the lake is approximately 39 ft above the outlet valve. From Bjork (1993).

Measurements of the lake's water surface height are made at a pressure gage on the outlet works below the lake. Recent measurements of changes in lake levels following known changes in storage have confirmed the accuracy of the BOR's design storage curve.

Water is released from the lake by opening a 20-inch butterfly valve mounted on a 36-inch pipeline in the tunnel below the lake. Between 1998 and 2005, the valve has been opened an average of 77 days; typically between mid-July and mid-October. The total volume released from the lake has ranged from 1,100 to 6,300 ac-ft with an average release of 3,700 ac-ft (Table 1). After the outlet valve is turned off in October, inflows to Upper Snow Lake gradually fill the lake until the valve is opened the following summer. 2001 is the only year the lake did not fill completely. That year, below average snowpack did not produce sufficient runoff in the watershed to offset releases from the summer of 2000.

Table 1: Observations of Upper Snow Lake water surface elevations between 1998 and 2005, corresponding volume of stored water (ac-ft), changes in volume and water surface elevation between observations. With the exception of March 2005, observations are made when outlet valve is opened and closed for the year.

Valve	Date	Height of Lake Surface abv. Outlet (ft)	Storage (ac-ft)	Change Since Last Obs. (ac-ft)	Change in Elevation Since Last Obs. (ft)
open	7/17/1998	189	12,450		
close	10/10/1998	129	6,190	-6,260	-60
open	9/2/1999	189	12,450	6,260	60
close	10/15/1999	143	7,560	-4,890	-46
No Reading in Spring 2000					
close	10/11/2000	104	4,070		
open	6/20/2001	148	7,960	3,890	44
close	10/3/2001	136	6,860	-1,100	-12
open	8/2/2002	189	12,450	5,590	53
close	10/9/2002	178	10,990	-1,460	-12
open	7/16/2003	189	12,450	1,460	12
No Reading in Fall 2003					
open	7/4/2004	189	12,450		
close	9/28/2004	164	9,660	-2,790	-25
close	3/10/2005	188	12,360	2,700	24
open	7/21/2005	189	12,450	90	1
close	10/3/2005	137	6,960	-5,490	-52

Data from our monitoring network indicates all of the water released from the lake reaches the mouth of Snow Creek at Icicle Creek (see Figure 1). We do not have data indicating if there are significant losses in Icicle Creek streamflow between the mouth of Snow Creek and the hatchery's diversion. However, the river's location in Icicle Creek Canyon suggests streamflow losses to the subsurface are probably not significant. Therefore, for this analysis, we will assume all water released from Upper Snow Lake finds its way to the hatchery's diversion on Icicle Creek.

To operate the hatchery, an average of 40 cfs is removed from Icicle Creek between June and October. When full, Upper Snow Lake stores enough water to meet the hatchery's needs and provide supplemental water for instream flows below the hatchery's diversion. Additionally, the hatchery's water rights to Upper Snow and Nada Lake exceed the upper lake's total volume. Although draining the lake completely is both technically and legally feasible whether or not it fills the following year is less clear.

Estimated Inflows to Upper Snow Lake

Estimating inflows to Upper Snow Lake from its watershed is complicated by the dearth of hydrologic data for the watershed. The Service's hydrologic monitoring in the basin has captured data on Snow Creek inflows to the Upper Lake for some months of some years but monitoring is typically limited to months when the outlet valve is open. Without direct measurements of inflows, change in storage information from Table 2 can be used to estimate inflows or outflows from the lake.

Change in storage after the valve is closed reflects differences between inflows and outflows at the upper lake. For example, in 2001 observations indicate the lake's surface rose from 104 to 148 ft above the valve between October 2000 and June 2001. Because the valve was closed and outflows were limited to some evaporation, these data suggest approximately 3,890 ac-ft flowed into the lake from its watershed. In other years infrequent observations of Upper Snow Lake's water level prevent estimating inflows because the date when the lake reaches its maximum water level is unknown. Typically the lake fills long before the first WRB visit in June or July. By then, the lake is full but an unknown volume of water spills over the lake's dam. Under these conditions estimating storage from differences in lake levels will under predict total inflows because spill over the dam is ignored. From Table 1 data, estimating inflows using change in storage is only possible in water years 2001 and 2005 (Table 2).

Table 2: Change in storage in Upper Snow Lake for two time periods when there were no outflows through the outlet valve or over the dam crest.

Time Period	Water Year	Change in Storage (ac-ft)
oct-jun	2001	3,890
oct-mar	2005	2,700

Although limited, these data in Table 2 are important because they are direct measurements of watershed inflows, or watershed yield, to Upper Snow Lake. To assess the risks associated with releasing water from Upper Snow Lake the hatchery must have estimates of watershed yield for longer time periods and multiple years.

Montgomery Water Group (Montgomery) estimated the yield of the watersheds for Upper Snow Lake, Lower Snow Lake, and Nada Lake in their 2004 report (Montgomery 2004a). Montgomery used precipitation records from a nearby SNOTEL site to estimate annual runoff by assuming all precipitation, minus losses, falling on the watershed translates into runoff at the watershed mouth. Montgomery (2004a) estimates the combined yield of all three watersheds ranges from 6,930 ac-ft to 17,900 ac-ft with a median of 10,700 ac-ft.

In this report estimates of watershed yield differ from Montgomery's for 2 reasons: first, instead of relying on depth of precipitation information we use Icicle Creek streamflow records to predict the depth of runoff per acre (Equation 1); second, we only considered the Upper Snow Lake watershed because it is the only actively managed lake in the basin.

$$\text{Runoff Depth (ft)} = \text{Monthly Total Runoff (ac-ft)} / \text{Watershed Area (acres)} \qquad (1)$$

Table 3, presents runoff depth per acre for the last 12 years of Icicle Creek records. Annual watershed yield for Upper Snow Lake (Table 3, Column 5) is estimated using Equation 1 and the Icicle Creek runoff depth estimates.

Table 3: Estimates of total annual runoff by water year for the Upper Snow Lake Watershed. Column 2) Annual runoff depth per acre from Icicle Creek streamflow records. Column 3) Precipitation depth per acre minus estimated losses to evaporation (18 in.). Column 4) Montgomery's estimates of precipitation depth per acre minus losses to evaporation (18 in.). Column 5) Estimated annual runoff from Upper Snow Lake Watershed (ac-ft). Column 6) Estimated October-July runoff from Upper Snow Lake Watershed (ac-ft). Column 7) Percent of total annual runoff represented by October-July runoff.

1 **Water Year**	2 **Runoff Depth / Acre (in)**	3 **Precip Estimates - Losses (in)**	4 **Montgomery's Estimates – Losses (in)**	5 **Total Annual Runoff(ac-ft)**	6 **Total Oct-Jul Runoff (ac-ft)**	7 **% Total Oct-Jul**
1994	27	33	20	5,600	5,300	95
1995	42	56	38	8,900	8,200	92
1996	62	68	51	13,000	11,800	91
1997	56	61	52	11,600	10,700	92
1998	39	34	25	8,200	7,100	87
1999	52	50	45	10,900	9,700	89
2000	41	37	35	8,600	7,900	92
2001	21	13	10	4,400	3,800	86
2002	47	43	37	9,900	9,200	93
2003	31	26	20	6,400	6,000	94
2004	40	36	34	8,300	7,200	87
2005	30		20	6,900	6,400	93
Average	**42**	**42**	**32**	**8,600**	**7,800**	**91**
Max	**62**	**68**	**52**	**13,000**	**11,800**	**95**
Min	**21**	**13**	**10**	**4,400**	**3,800**	**86**
Median	**41**	**37**	**34**	**8,500**	**7,600**	**92**

Calculations of runoff depth per acre are about 30% greater than Montgomery's (2004a) net precipitation depths. In theory they should match each other more closely. Of the two, runoff depth is probably more accurate because it is based on streamflow measurements which integrate runoff from precipitation and snowmelt after natural losses from the watershed. For comparison we reviewed estimates of monthly precipitation totals for the Upper Snow Lake Watershed (OSU 2005). These data were used to calculate the values in Table 3, Column 3 and match our runoff depth estimates more closely than Montgomery's. These data suggest precipitation in the basin is higher than Montgomery's estimates and indicate runoff depth may provide reasonable approximations of Upper Snow Lake's watershed yield. To test these methods, monthly runoff depth was used to predict inflows to Upper Snow Lake for change in storage data from Table 2 (Table 4).

Table 4: Comparison of measured depth of runoff with estimated depth of runoff for the Upper Snow Lake watershed.

Time Period	Water Year	Change in Storage (ac-ft)	Measured Depth of Runoff /Acre (in)	Estimate Depth of Runoff / Ac. (in)	Predict change in storage	% difference
oct-jun	2001	3,890	19	18	3,710	-4.6
oct-mar	2005	2,700	13	16	3,380	25.2

Our estimates of runoff from the Upper Lake's watershed match well with the known 2001 change in storage but over predict 2005 inflows. One explanation is the measured change in storage data does not account for flow into Lower Snow Lake through the hole at the base of the upper lake's dam. This outflow adds roughly 200 ac-ft to the October-March inflows for a total of 2,900 ac-ft, or a 17% difference between predicted and actual change in storage. Additionally, because runoff depths are derived from Icicle Creek data they may tend to over predict runoff for portions of the watershed where streamflow is not the dominant inflow process. In spite of the discrepancies between predicted and actual inflows, the differences between the values are small enough to suggest our technique provides reasonable approximations of inflows to Upper Snow Lake. Ongoing data collection in Snow Creek Watershed by WRB will allow for additional refinement of our yield estimates.

Estimated Exceedence Probability of Inflows

For lake management, October to July inflows are more important than annual values because the hatchery needs to know how much water enters the lake after the valve closes in the fall and before it is opened the following summer. More importantly, the hatchery must know the risk of not filling the lake after releasing a known volume of water.

Figure 3 illustrates the percent chance that predicted inflows between October and July will meet or exceed a certain volume. Assuming conditions in the past are similar to those in the future, there is approximately a 58% chance that October to July inflows to Upper Snow Lake will meet or exceed 7,000 ac-ft in any given year. For the 12 years of estimated runoff data the maximum inflow between October and July was 11,800 ac-ft and the minimum was 3,800 ac-ft (Table 3). Watershed yield may still exceed or be less than these values. However, from the available data the probability that October-July runoff into Upper Snow Lake will be equivalent to the total lake volume (12,450 ac-ft) is less than 8%.

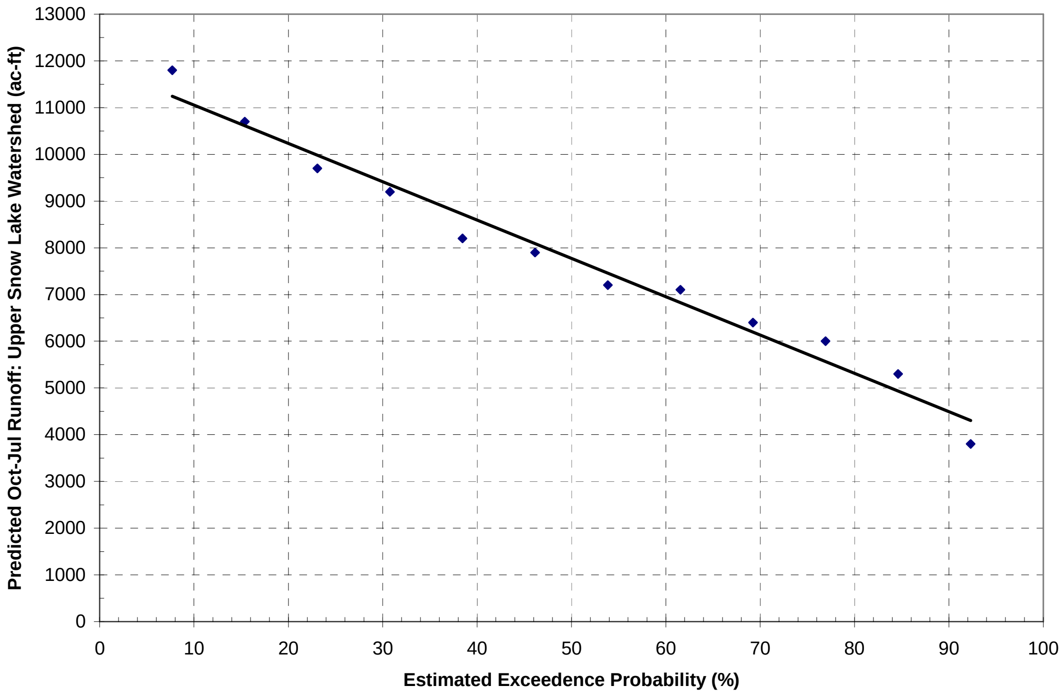

Figure 3: Estimated exceedence probability of October-July inflows to Upper Snow Lake. Based on estimated runoff between water years 1994 and 2005.

Management Scenarios

Table 5A and 5B are matrices of different water release scenarios from Upper Snow Lake. These tables can be used to estimate the total volume of water that will be released from Upper Snow Lake (Table 5A) and the estimated probability that the watershed will contribute an equivalent volume to the lake between October and July (Table 5B).

From these data presented in Table 5, hatchery staff can weigh the probable risk that inflows will meet or exceed the volume of water released from Upper Snow Lake. For example, releasing an average of 60 cfs from Upper Snow Lake for 70 days equates to a volume of 8,320 ac-ft (from Table 5A). This amount would offset the hatchery's diversion from Icicle Creek and provide an additional 20 cfs for instream habitat below the diversion. From Table 5B, there is a 43% chance inflows to the lake during the following winter and spring will match the amount released. Alternatively, there is a 57% chance inflows will not match releases and the lake will not fill by the time the hatchery needs the water the following year.

Table 5: A) Volume of water (ac-ft) removed from Upper Snow Lake for different flow scenarios. B) estimated probability that inflows to Upper Snow Lake will meet or exceed the released volumes from 5A. The row corresponding to average hatchery diversions from Icicle Creek is shaded (40 cfs). Total lake volume is about 12,450 ac-ft.

A

Average Release from Upper Lake (cfs)	Days Upper Snow Lake Valve is Open								
	40	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
20	1580	1980	2380	2770	3170	3560	3960	4360	4750
30	2380	2970	3560	4160	4750	5350	5940	6530	7130
40	3170	3960	4750	5540	6340	7130	7920	8710	9500
50	3960	4950	5940	6930	7920	8910	9900	10890	11880
60	4750	5940	7130	8320	9500	10690	11880		
70	5540	6930	8320	9700	11090	12470			
80	6340	7920	9500	11090	12670				
90	7130	8910	10690	12470					
100	7920	9900	11880			Exceeds Total Volume of Lake			
110	8710	10890							
120	9500	11880							

B

Average Release from Upper Lake (cfs)	Days Upper Snow Lake Valve is Open								
	40	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
20	> 92	> 92	> 92	> 92	> 92	> 92	> 92	91	86
30	> 92	> 92	> 92	93	86	79	72	65	58
40	> 92	> 92	86	76	67	58	48	39	29
50	> 92	83	72	60	48	36	25	13	< 8
60	86	72	58	43	29	15	< 8		
70	76	60	43	27	10	< 8			
80	67	48	29	10	< 8				
90	58	36	15	< 8					
100	48	25	< 8			ExceedsTotal Volume of Lake			
110	39	13							
120	29	< 8							

Worst Case Scenarios

A worst case scenario is multiple years where the lake does not fill completely by the time the hatchery needs to open the valve. In these cases the volume of water in the lake is insufficient to match the hatchery's need to divert 40 cfs from Icicle Creek. One example is if runoff in the basin is equivalent to the estimated 95% exceedence volume (about 4,000 ac-ft) for two consecutive years (Table 6).

Table 6: Possible worst case scenario with 2 consecutive years of low inflows (4,000 ac-ft) between October and July. All values in acre-ft.

	Starting Volume	Volume Released	Ending Volume	Equivalent flow
Year 1	12,450	9,500	2,950	60 cfs @ 80 days
Year 2	6,950	6,950	0	44 cfs @ 80 days
Year 3	4,000	4,000	0	25 cfs @ 80 days

Although these data suggest the hatchery will be able to meet the hatchery's minimum requirements in 2 of the 3 years, the hatchery will only be able to supplement flows downstream of its diversion in the first year. By year 3 the hatchery will have difficulty meeting its own water use needs and may have to adjust management practices to account for the inability to release sufficient water from Upper Snow Lake. However, the estimated probability of two consecutive years of 4,000 ac-ft inflows is very small, less than 1%.

Management Recommendations

Our analyses suggest there is enough water flowing into Upper Snow Lake to support releasing additional water to supplement instream habitat downstream of the hatchery's diversion. In wet years, releases from Upper Snow Lake may not be necessary. During these years, flow in Icicle Creek will probably be sufficient to meet hatchery water needs and maintain "good" to "fair" instream habitat quality downstream of the hatchery's diversion (Montgomery 2004b, Table 2-5).

Montgomery's (2004b) analysis suggests that in average runoff years, Icicle Creek habitat downstream of the hatchery will be compromised in August and September due to low flows. In these years releases from Upper Snow Lake can be managed to meet hatchery needs and provide some supplemental water in September. To avoid "severe degradation" habitat quality, one scenario might be releasing an average of 40 cfs in August and increase releases to average 60-70 cfs during September. This would equate to releasing about 6,200 ac-ft; the estimated probability of the lake re-filling the following year would be about 68%.

Streamflow records from Icicle Creek in 2005 indicate that conditions in July, August, and September were comparable to Montgomery's "very low flow" scenario (Table 2-8, 2004b). In these years releases from Upper Snow Lake will need to be at least 40 cfs in August and September to match the hatchery's diversion. If the lake is full, there is sufficient water to release an additional 40 cfs for supplementing instream flows downstream of the hatchery. To maintain "minimum" habitat quality, the hatchery could release as much as 80 cfs for 60 days, or a total of 9,500 ac-ft, without draining the lake. However, releases of this magnitude increase the chance the lake will not fill the following year. The estimated probability of inflows matching or exceeding 9,500 ac-ft is about 30% for any given year.

In summary, I would recommend the hatchery manage the lake so it is full going into a very dry year. Years with similar runoff characteristics to 2001 and 2005 are times when releases from Upper Snow Lake will be most important for meeting hatchery needs and supplementing instream flows downstream of the hatchery's diversion. In years where runoff in Icicle is closer to the average, I would recommend trying to keep releases between the 60% and 70% exceedence probabilities, or between 7,000 and 6,000 ac-ft.

Final Recommendations

1) Manage Upper Snow Lake with the goal of having the lake full during years where runoff in Icicle Creek is anticipated to be similar to 2001 and 2005.

2) Continue hydrologic monitoring in Snow Creek basin. Focus monitoring effort on characterizing the hydrology of the watershed. In particular, collect information that will help quantify yield of the Upper Snow Lake Watershed.

3) Setup telemetry systems on all three monitoring sites in the Snow Creek Watershed so conditions at Upper Snow Lake can be monitored more consistently from Leavenworth.

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