Physical Circulation Study of Proposed Steelhead Trout Net pen Site 3 in Rufus Woods Lake, Columbia River

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1. Introduction

This report documents the results of recent physical studies in Rufus Woods Lake (RWL), a run-of-the-river-reservoir of the Columbia River in north central Washington State. The reservoir has been used over 20 years for the net pen culture of salmonid fishes, most recently and prominently in the culture of sterile, triploid, rainbow trout (steelhead). Pacific Aquaculture Inc. is one of two growers in the lake and by far the larger of the two companies. It operates two existing sites (Site 1 and Site 2, see Figure 1) and has proposed installation of a third pen site in the reservoir.

This report is to transmit the results of physical limnological studies in late 2010 and 2011 targeted at understanding the suitability of the proposed site for fish culture and resulting ecological effects. A formal review of all the literature associated with this reservoir and net pen effects is beyond the scope of this report, the reader is referred to other documentation provided for Tribal and Federal agencies as part of the permit application process. Although the name of the water body is Rufus Woods Lake, at least the upper two thirds of it is riverine like in nature, with strong currents and a deep vee profile unlike any of the other Columbia River reservoirs in Washington State.

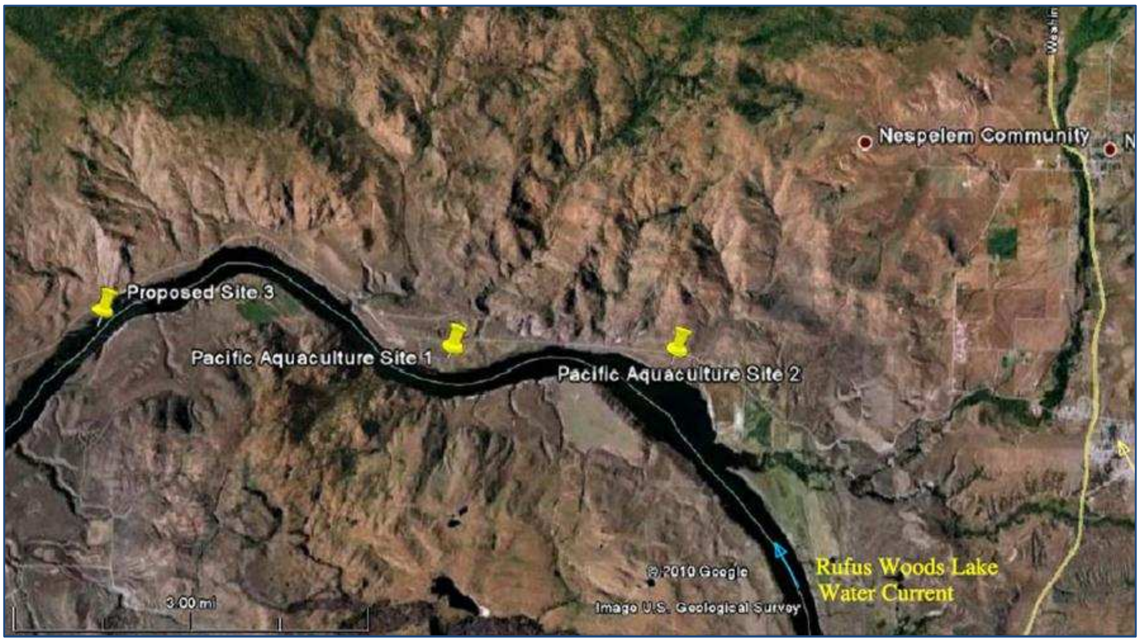


Figure 1 Vicinity map showing existing Sites 1 and 2 and proposed Site 3 on Rufus Woods Lake near the town of Nespelem on the Colville Confederated Tribes reservation.

2. Methods

A Teledyne RDI 300 kHz acoustic Doppler current profiler (ADCP) was installed into a Subs A2 current meter housing and was anchored at the sites described below for data collection. This current meter, like all ADCP units, is a type of sonar that measures currents by reflecting sound energy off small particles in the water and does so throughout a series of layers or bins in the water column. The special subs A2 current meter housing was required to keep the profiler vertically oriented in the water during strong currents; otherwise, accuracy of the collected data would be impaired (see Fig. 2 with current meter as the black and red unit in the middle). The unit measures both current velocity and direction and in this case was configured to do so every 15 min. during its operation at 2 m depth intervals throughout the water column (except for a 3 m surface bin).

Figure 2. ADCP meter in Subs A2 float.

In addition to current meter studies, water parcel tracking was conducted through the use of windowshade drogues that are rectangular, nylon fabric constructed drift objects shaped like window shades, weighted on the bottom edge and attached to surface floats by thin but strong twine. The drogues pivot on a swivel and quickly assume the ambient flow rate of water when launched. They are placed at a known GPS-measured location and time; they may be tracked downstream with a GPS to produce position and speed estimates. In the present study, all releases were made at a single point: the upstream end of the proposed net pen Site 3 cage array. Typically drogues were released as a pair, one shallow and one deep at the same time. The goal of this portion of the study was to understand if currents are suitable for distributing wastes over a broad area where they can be aerobically (with oxygen) assimilated by the food web. Areas with circular flows (eddies or gyres) are to be avoided as are persistent flows in only one pathway or towards the shore and shallow areas. In this study the main goal was to document water motion during contrasting low and high flow rates that are predictable to some extent given Grand Coulee Dam operation patterns, low in early morning and weekends, high during daylight hours on weekdays when peak load demand occurs.

3. Grand Coulee Dam Discharge and Measured River Flow Velocities

Table 1 summarizes the dates and locations of the current meter deployment. An additional current meter deployment upstream of existing net pen Site 1 was conducted for six days to be able to compare current velocity at a proven, high quality site to the new, proposed site. We used hourly Grand Coulee Dam discharge data correlated to change up current velocity at both sites. We evaluated hourly correlations with and without hourly lag periods of up to 18 hours and were able to determine that there is no lag period between increases of discharge and rates of water flow at the proposed site about 20 miles downstream of the dam. The best correlation coefficient ("r") was with no lag time and a value of 0.983 of a possible 1.0 as indicated by the red bar in Figure 3. Data from the zero time lag period is displayed in Figure 4 showing the excellent correlation. We fitted a linear equation but other types of fits may be more appropriate for extrapolating beyond the high end data (i.e., power or exponential equations).

Table 1. Summary of Rufus Woods Lake current meter deployment facts in Jan.-Feb. 2011.

Location	Coordinates N and W	Bottom Depth*
Proposed Site 3 (upstream end of proposed pens) River Mile 576.4	48.14379° - 119.15583°	~ 30 m (104')
Existing Site 1 (170 m upstream of upriver end of existing pens) Pens at River Mile 579.0	48.137730° -119.092775°	~ 34 m (111')

*Depth approximate ≠ ADCP depth that was ~2 m above the bottom in the Subs A2 float

Location	Installation Time	Recovery Time	Measurements
Proposed Site 3 (upstream end)	1-7-2011 1600hr	2-9-2011 1015hr	3,146 15-min intervals
Existing Site 1 (upstream end)	2-9-11 1100hr.	2-15-2011 1345hr	588 15-min intervals

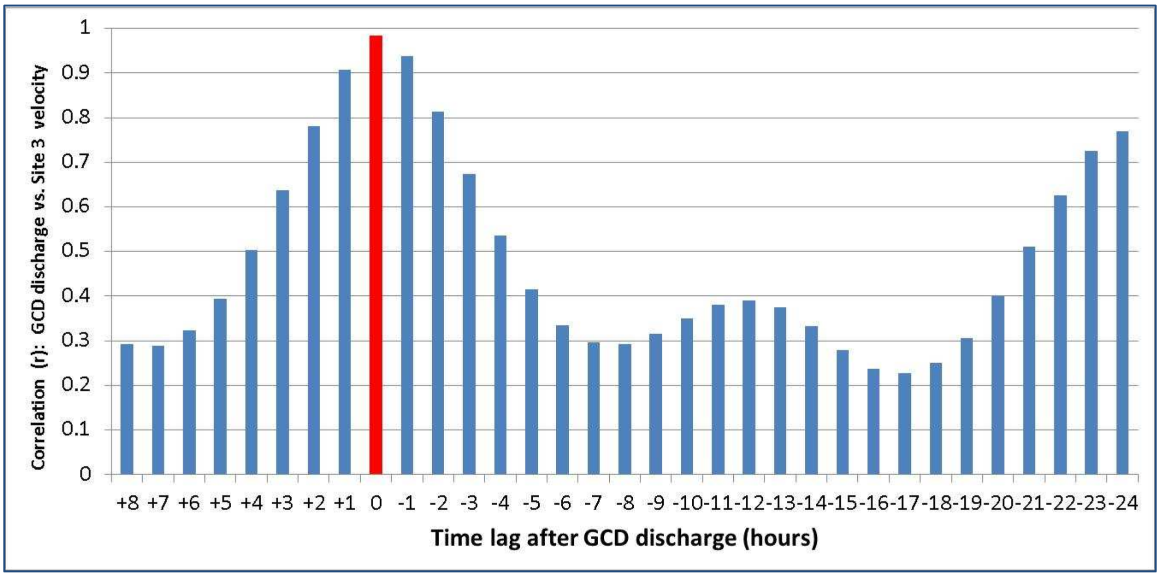


Figure 3. Time lag before and after Grand Coulee Dam (GCD) discharge and current meter measurements in the top 12 meters at proposed Site 3 in Rufus Woods Lake and correlation coefficient (r).

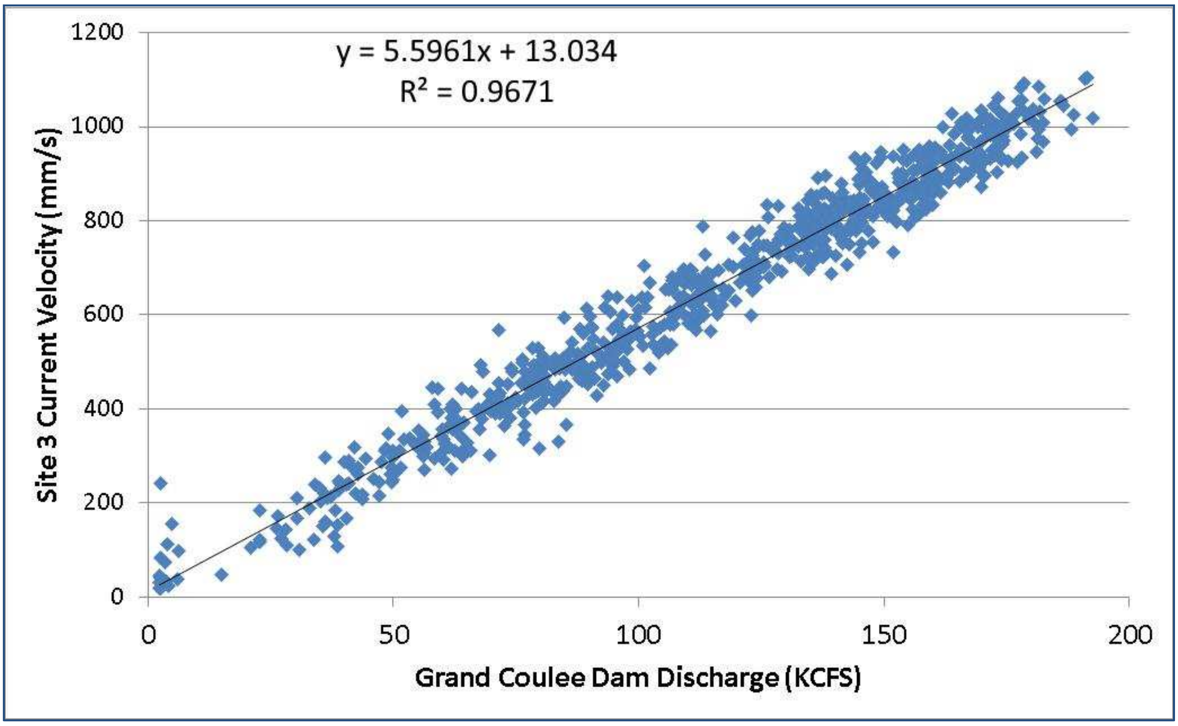
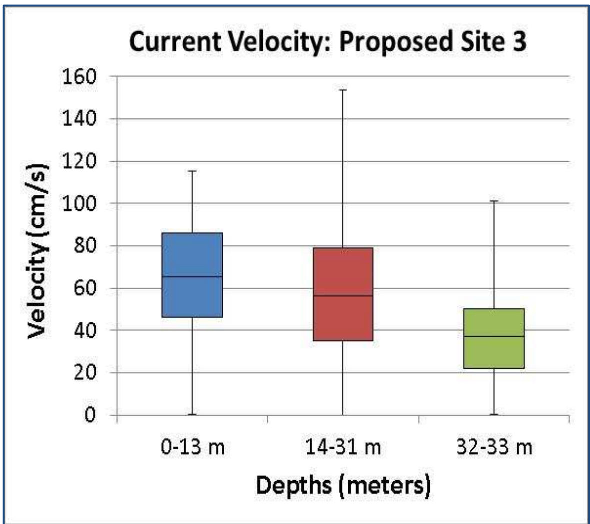


Figure 4. Site 3 water current velocities in top 12 m of the water column versus simultaneous hourly mean discharge at Grand Coulee Dam in the pertinent time periods discussed above. Coefficient of determination (R^2) and linear equation shown.

Data was downloaded from the recovered current meter and processed in Teledyne RDI software and through the use of Excel spreadsheet analysis. The entire database was inspected for outliers and improbable patterns or artifacts by conducting statistical summary queries in Excel. Frequency diagrams and box/whisker plots were constructed using quality assured data.

4. Current Meter Results: Overview

Current meter results are summarized in Figure 5 in a format known as a "box and whisker" plot. Extreme ranges of flow are shown by the thin black vertical line and the colored boxes represent 50% of the velocity observations with the average velocity as the horizontal line across the center of the colored box. The data is displayed as groups of ADCP bins from near surface (to 13 m), mid depth (14 to 27 or 31 m) and a single deepest layer (28 to 29 or 33 m, depending on site location). The surface layer was selected as it approximates the depth of the cages to be used, and the deepest layer was nearest the bottom and the intervening depths were the balance. As will be seen below, there are other credible ways to break out the data, based on current velocity discontinuities (i.e., observed major changes in the mid layer depths at both sites).



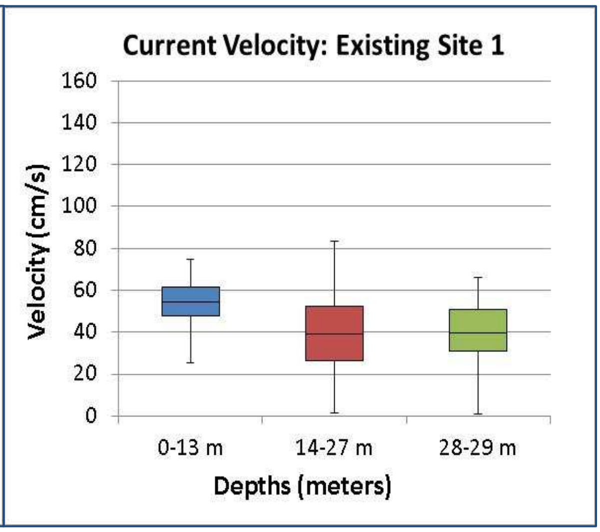


Figure 5. Box and Whisker Plot showing extreme ranges of current velocity (thin vertical lines), 50% of observations (25% each in the colored boxes) and the average flow (as the thin black horizontal line in the colored boxes). Proposed Site 3 plot from raw data, existing Site 1 plot reflects adjustments to make the time period comparable to Site 3 as explained in the narrative.

Mean velocities for existing net pens in Puget Sound Washington do not exceed about 30 cm/s average velocity, but maximum velocities are not known. Our estimate is that the most extreme is greater than Site 1 in this monitoring period but less than that observed at Site 3 except during the most extreme spring tides

Mid water current velocity was also stronger at Site 3, but the deepest layer had similar velocities at both sites as shown in Figure 5. Table 2 summarizes results for each measurement bin from surface to near bottom at Site 3. Table 3 does the same for Site 1. The data for Site 1 includes both raw data, from a period of time of higher flows than the Site 3 recording, as well as the same data that was normalized by applying a fractional coefficient drawn from the ratio of Grand Coulee Dam discharge during both periods of time.

Table 2. Summary of velocity measurements from different depth bins at Site 3.

Site 3	Bin Depth (Max. meters)	3	5	7	9	11	13	15	17	19	21
Per depth bin	Mean cm/s	63.6	65.2	65.7	66.0	66.2	66.4	66.7	66.9	67.2	65.0
	SD	24.9	25.3	25.4	25.5	25.6	25.6	25.7	25.7	25.8	23.7
	Min cm/s	0.5	0.6	0.2	0.6	0.7	0.9	0.5	0.1	0.9	0.7
	Max cm/s	113.1	115.1	113.7	113.6	113.6	113.2	115.9	115.3	116.2	115.4
	Count	3146	3146	3146	3146	3146	3146	3146	3146	3146	3146
	Bin Depth (Max. meters)	**23**	**25**	**27**	**29**	**31**	**33**				
	Mean cm/s	27.9	58.1	63.0	51.9	41.4	37.2				
	SD	15.6	29.5	24.5	19.7	18.7	20.5				
	Min cm/s	0.4	0.9	1.5	0.2	0.8	0.2				
	Max cm/s	104.6	153.8	129.9	101.0	93.8	101.0				
	Count	3111	3146	3145	3146	3146	3146				
	Depth Range meters	**0-13**	**14-31**	**32-33**				**0-13**	**14-31**	**32-33**	
Bin averages	Mean cm/s	65.5	56.5	37.2			Min	0.2	0.1	0.2	
	SD	25.4	26.9	20.5			Quartile1	46.3	35.3	22.3	
	Min cm/s	0.2	0.1	0.2			Mean	65.5	56.5	37.2	
	Max cm/s	115.1	153.8	101.0			Quartile3	86.2	78.8	50.5	
	Count	18876	28278	3146			Max	115.1	153.8	101.0	

The current meter velocity data were transformed into frequency bar chart plots, by grouped depths, as shown in Figure 6. The plots have the same X and Y axes for more valid comparison and the readers should note, the Site 1 comparison plots show data that had been normalized (i.e., reduced in velocity) as explained above to be comparable to the time period during which the Site 3 data was collected.

These results show some striking differences between the sites that are not obvious in the average velocity statistics. For the surface layer (0 to 13 meters deep) shown in Figure 6, proposed Site 3 indicates a broad distribution covering nearly the entire range of velocities from 15 to 105 cm/s. In contrast, velocities at existing Site 1 were centered almost entirely between 40 and 70 cm/s, with no observations below approximately 25 cm/s (see Table 3 minimum values for these depths).

Table 3. Summary of current velocity measurements from different depths at Site 1.

Site 1	Bin Depth (Max. meters)	3	5	7	9	11	13	15	17	19	21
Per depth bin	Mean cm/s	69.4	72.1	73.5	74.1	73.9	60.4	35.2	69.4	68.3	53.2
	SD	10.7	11.1	11.2	11.3	11.2	12.2	17.0	14.3	12.4	15.8
	Min cm/s	37.6	38.2	36.2	39.8	37.4	32.6	5.7	11.5	30.3	9.4
	Max cm/s	91.2	93.7	96.3	95.9	97.1	89.5	108.0	101.3	91.1	85.3
	Count	588	588	588	588	588	588	588	588	588	588
	Bin Depth (Max. meters)	23	25	27	29						
	Mean cm/s	38.0	39.6	51.2	51.5						
	SD	16.1	17.6	20.6	19.4						
	Min cm/s	1.7	2.6	2.6	1.5						
	Max cm/s	75.3	75.1	86.1	86.0						
	Count	588	588	588	588						
Bin averages (not normalized for Site 3 data collection period)	Depth Range meters	0-13	14-27	29-29				0-13	14-27	29-29	
	Mean cm/s	70.6	50.7	51.5			Min	32.6	1.7	1.5	
	SD	12.3	21.0	19.4			Quartile1	62.0	34.5	40.5	
	Min cm/s	32.6	1.7	1.5			Mean	70.6	50.7	51.5	
	Max cm/s	97.1	108.0	86.0			Quartile3	79.7	67.9	66.2	
	Count	3528	4116	588			Max	97.1	108.0	86.0	
Bin averages (Normalized)	Depth Range meters	0-13	14-27	29-29				0-13	14-27	29-29	
	Mean cm/s	54.4	39.1	39.7			Min	25.1	1.3	1.2	
	SD	9.5	16.2	14.9			Quartile1	47.8	26.6	31.2	
	Min cm/s	25.1	1.3	1.2			Mean	54.4	39.1	39.7	
	Max cm/s	74.8	83.2	66.3			Quartile3	61.4	52.3	51.0	
	Count	3528	4116	588			Max	74.8	83.2	66.3	

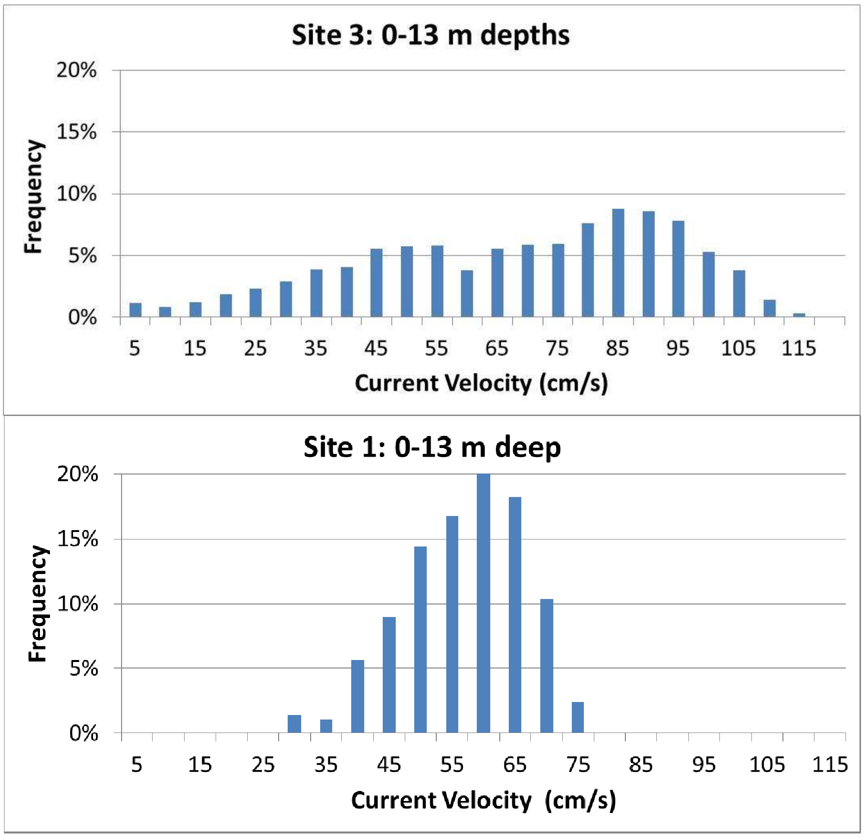
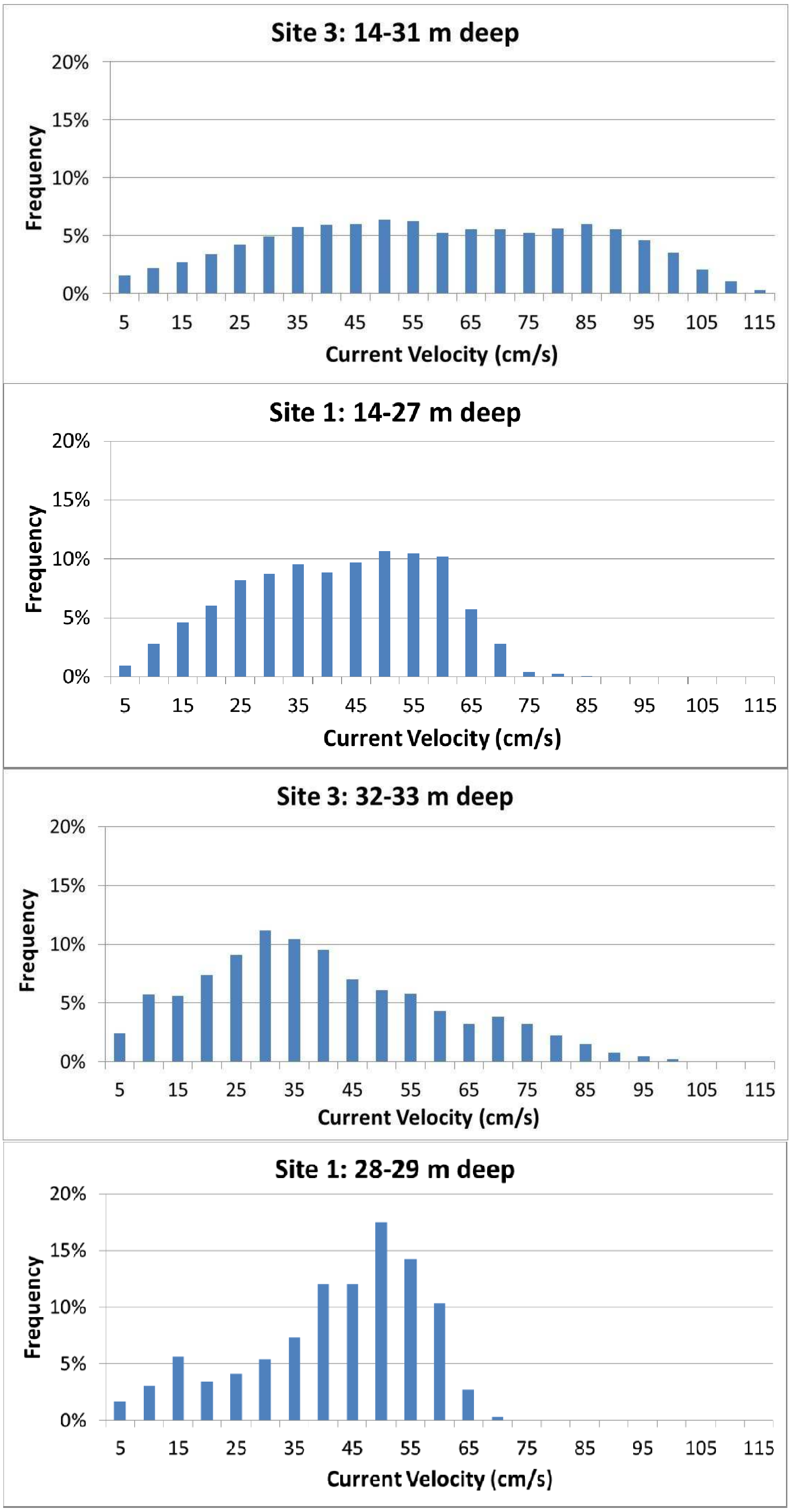


Figure 6. Current velocity frequency plots at proposed Site 3 and existing Site 1.

Figure 6 continued.



For the subsurface depths (14 to 31 or 28 meters deep, depending on the site), an equally profound difference is to be observed in figure 6. Site 3 data indicated a very regular but bimodal distribution spanning the entire range of current velocities similar to what occurred for surface velocities. However, the distribution of subsurface flows for Site 1 was narrowly concentrated at velocities less than 70 cm/s.

At the deepest layer (32 to 33 m deep) at Site 3, a unimodal (single, bell shaped) distribution with median values of around 30 cm/s and higher values less frequently occurring and skewed to the right were observed (Fig. 5). However at Site 1 the very deepest layers at a median value of around 50 cm/s and the general distribution was skewed to the left.

The above current velocity data may be interpreted in several ways. From a fish cultural point of view, both sites are very capable of sustaining commercial quantities of fish. The principal controlling factor of commercial fish culture besides water temperature is oxygen supply, which increases with increasing water velocity as long as the flows are within the normal swimming speed range of the fish (about 1.5 to 2 fish body lengths per second).

With regard to oxygen flux supplied by currents, Site 1 benefits from a relative lack of low flow periods, i.e., notice the complete lack of velocity bars less than 30 cm/s in the Site 1 current speed frequency diagram for surface depths in Figure 7. We believe this difference to be real and not an artifact of the measurement methods described above. To reiterate, Grand Coulee Dam discharge and resultant flow velocities in the river were higher during the Site 1 data collection period. That required us to apply a fractional coefficient to those data to be comparable to the dam discharge and velocity data observed during a separate time period at Site 3. Had the data been collected concurrently at both sites, a different frequency distribution with additional velocity bars within the low flow range may have been evident for Site 1, but not to the extent that would produce an equivalent result to Site 3.

Viewing the data only from the environmental effects point of view, Site 3 may be considered superior. Not only were the mean surface flows stronger, which will result in better dispersion of organic wastes for eventual food web assimilation, but subsurface and the deepest layer current velocities far exceeded that of Site 1. Modeling simulation and field studies of fish net pens in a number of locations worldwide have shown that resuspension, transport and aeration of the organic wastes on the bottom is essential for optimum net pen siting. Resuspension of waste feces occurs at near bottom (2 m above bottom) velocities of approximately 3.5 cm/s. Resuspension of waste feed pellets occurs at approximately 9.5 cm/s and these rates vary slightly with size of fish being reared (Cromey et al., 2002). From this perspective, the stronger the current flow the less likely wastes will become “consolidated” on the bottom, a process that occurs after some period of quiescent flows less than the resuspension speed.

To further examine and understand the current meter results, we provide some figures below from the software program WinADCP that provides color visuals. Figure 7 illustrates velocity profiles throughout the water column for the entire deployment at site three. The color bar scale at the top shows current velocities from slow (blue colored) to fast (yellow and blue), with blue-green and green at intermediate rates. The image shows relatively high current velocities in the upper 22 m depths with some notable exceptions prior to and after day 10. There was a sharp discontinuity below 22 m and particularly in a narrow band at that point, where current velocities were generally less.

Immediately below, velocity by each depth bin is shown as a line plot and illustrates variability among the bins. These data were shown previously in this report and more usefully as the frequency bar charts. The third image is another line plot showing direction of flow over time for each of the bins. Most of the data falls neatly within a narrow range, indicating the downstream direction at the site, but considerable variation occurred in some of the bins throughout the deployment as indicated by the purple and blue-green lines. The fourth image of Figure 7 shows only four of these bins to allow a more precise examination. Surface bins 1 and 6 (0 to 3 m and 11 to 13 m) had little variance compared to subsurface bins 12 and 15 (23 to 25m and 27 to 29 m). It is also easy to see that the direction variation is tightly coupled to reduced velocities, compare the blue bars in the top image to this fourth image in Figure 7. These data illustrate that variance of flow direction is inversely correlated with flow velocity. When the river slows down, direction of flow is more variable, but only within the deeper layers.

Site 1 velocity profile is shown in the top of Figure 8. Blue patches indicating low flow are also shown below about 20 m and in a narrow band at about 15 m. The largest patches occur after three days (72 hours) and co-occur with a reduction of flows in the upper layers. Similar to what occurred at site 3, correction of flow variation increased when velocity was slow, as shown in the lower image of Figure 8.

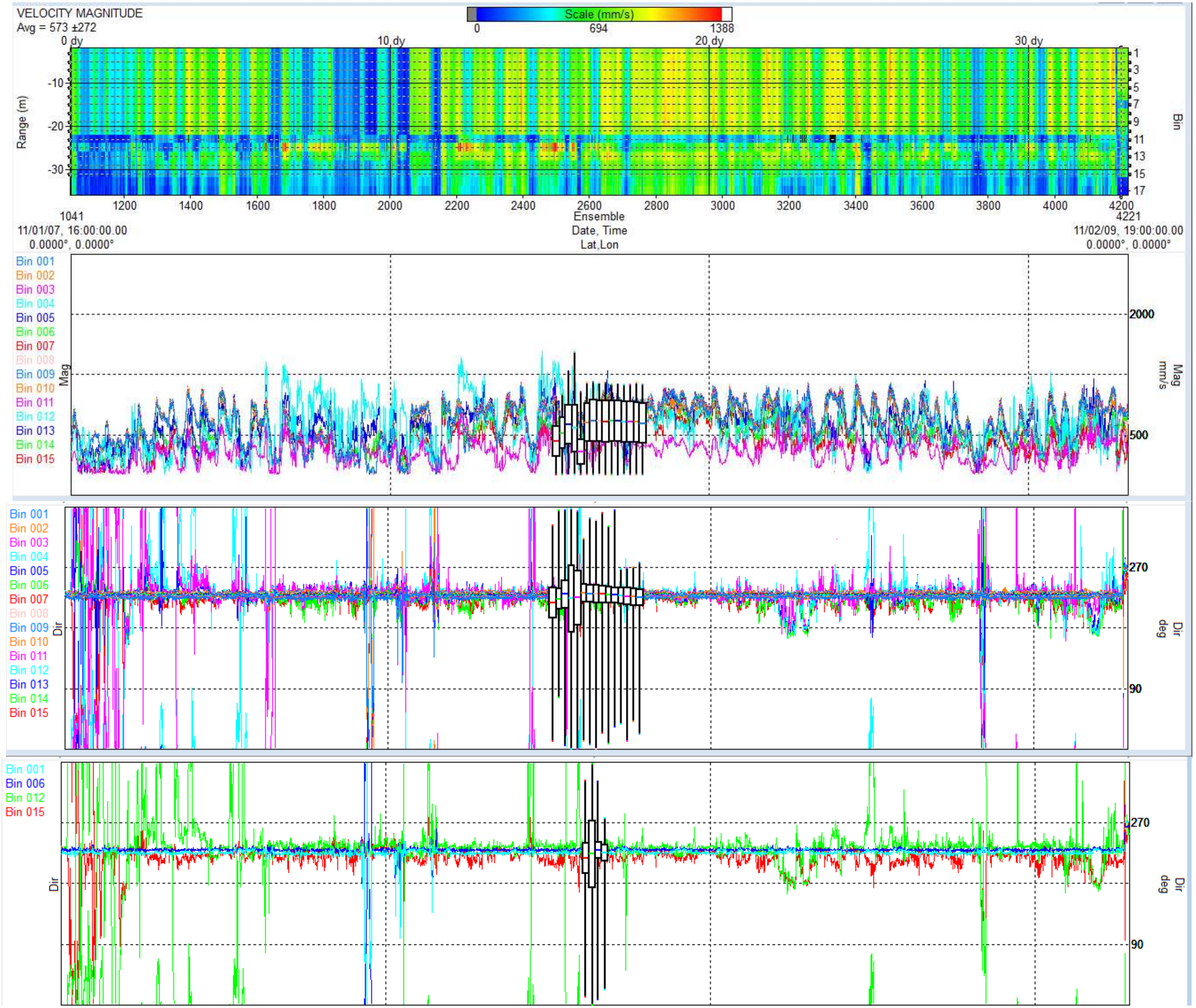


Figure 7.
Site 3
Velocity Profile in mm/sec

Velocity by each bin

Direction by 2 m bins

Direction bins 1 & 6, mid depth (bin 12) & deep (bin 15)

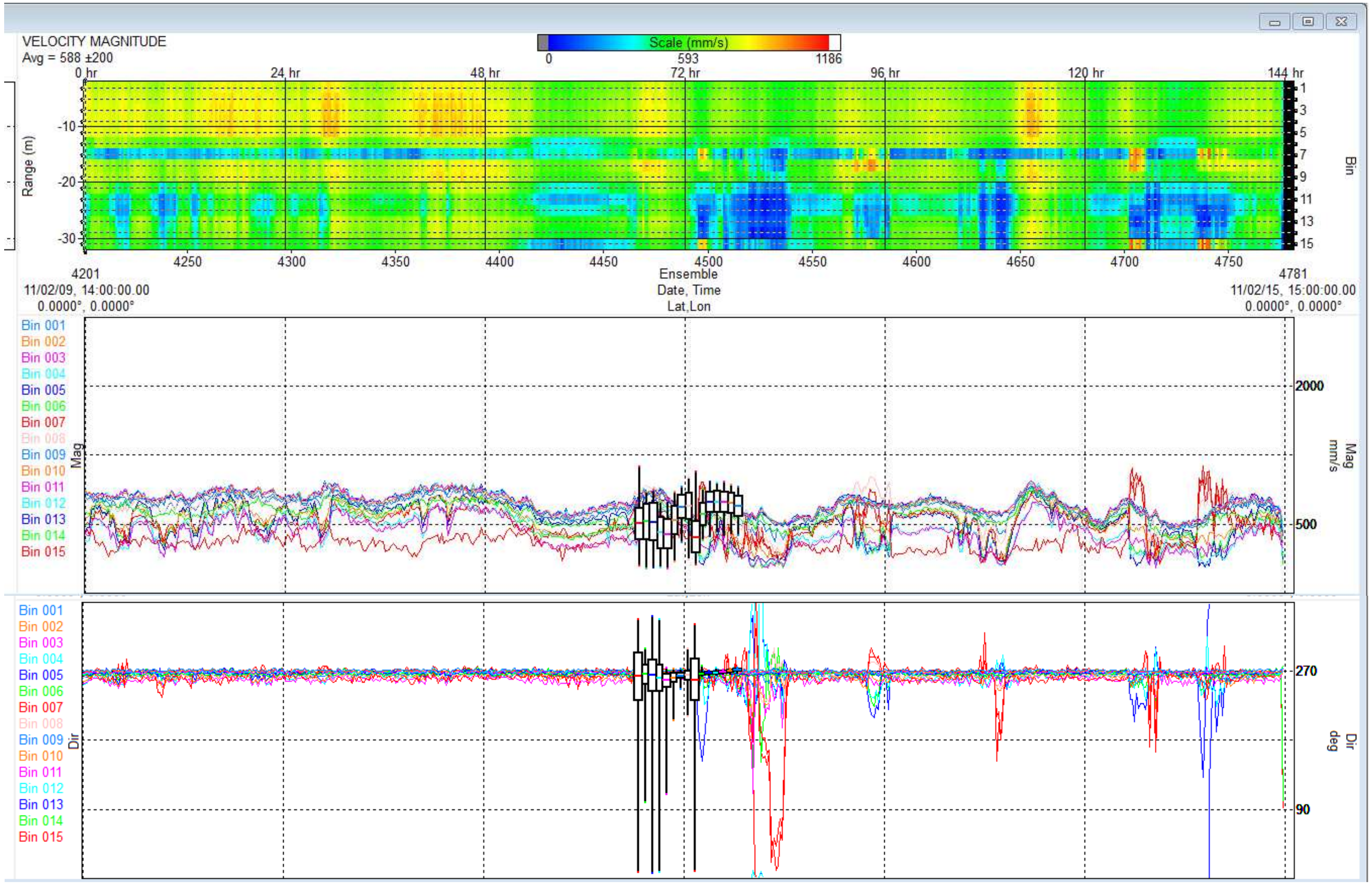


Figure 8. Site 1 Velocity profile in mm/sec

Velocity by each bin

Direction by each bin

5. Current Meter Results: Direction of Flow

Figures 9 and 10 present mean directional flow profiles for three depth intervals on a polar chart for Sites 3 and 1, respectively. Direction of flow was discussed above and for Site 3, Figure 9 shows the variation that was seen in current meter data and drogue paths, which is minor at the point of the current meter but cumulatively results in a significant change in the pathway that deep water flows versus the shallow water. In this case it was in the preferred direction, offshore toward the middle of the reservoir. For Site 1, a minor amount of variation was noted for mid water depths, as shown in Figure 10.

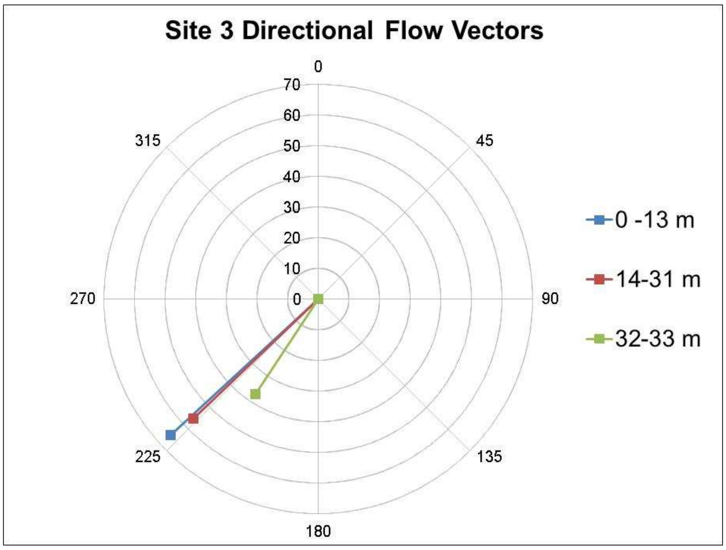


Figure 9. Directional flow polar plot for Site 3.

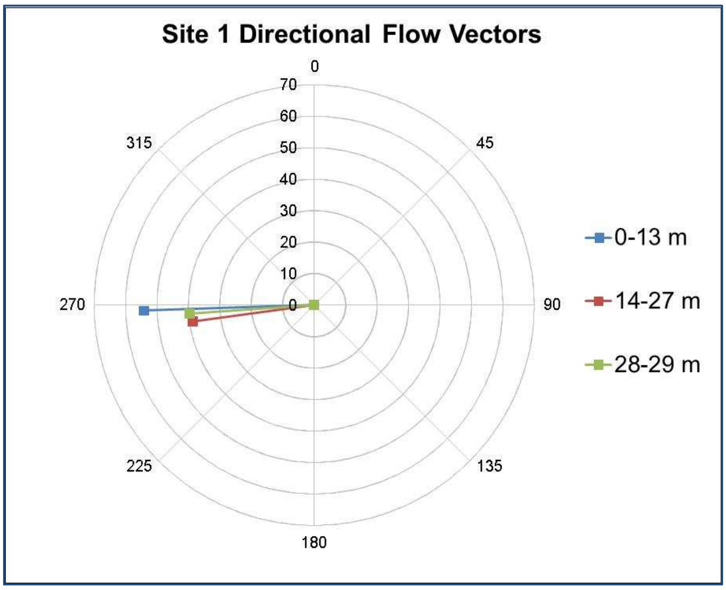


Figure 10. Directional flow polar plot for Site 1.

6. Drift Object Studies

In this section we present drogue (aquatic drift object) results from three different days of surveying. The goal of this work was to release drogues at surface and subsurface depths during low flow and higher flow events. Low flows periods are easier to measure in the fall when this work was done, but by carefully scheduling timing, moderately high flow events were measured too. Table 4 presents a summary of the transport rates of drogues in this study. After the preliminary study of 7 Oct 2010, a low flow day of 7 November 2010 and a higher flow day of 8 November 2010 were the subject of this portion of the study.

Tables 5 through 17 present the tabular data used to produce the aerial view plots of Figures 11 to 23. In general, recorded drogue speed was similar for shallow vs. deep drogues but tended to be faster near the farm site than further downstream, particularly after a mile downstream from the release point where the river channel begins to widen and bend slowly from a southwesterly to a westerly direction. A wider channel and equal depth may result in slower water currents. The channel is about 330 m wide at the farm site versus a mile downstream where it is 490 m wide.

Table 4. Depth and average velocity results for drogue tracking releases.

Date	7 Oct 2010: Preliminary Study Day								7 Nov 2010: Low Flow Day								8 Nov 2010: Higher Flow Day									
Set #	1		2		3		4		1		2		3		4		1		2		3		4		5	
Depth (m)	6	12	6	12	6	12	6	12	2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10	2	10
Mean rate (cm/s)	68.2	64.6	52.2	56.3	45.4	44.7	30.4	39.2	24.0	25.6	26.9	24.8	29.5	29.8	33.3	30.5	64.1	66.0	69.0	68.1	70.0	64.7	61.5	64.0	55.1	52.9
Mean rate (knots)	1.3	1.3	1.0	1.1	0.9	0.9	0.6	0.8	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.6	1.3	1.3	1.4	1.3	1.4	1.3	1.2	1.3	1.1	1.0

Another generality can be seen in many of these drogue path plots: i.e., the tendency for the deeper of the two simultaneously-released drogues to travel further offshore than the shallower unit. This occurred more often in stronger flows than in weak flows and indicates that dispersion from the fish farm site will be aided by this pattern, as opposed to having flows toward the shallow nearshore. During low flow events, however, both drogues tended to remain closer to the right bank (looking downstream) and some of them grounded along the shore after about a mile where a rocky bottom becomes shallower. Most sedimentation that will occur from this site will be visible within a few hundred feet or less from the net pens. It is extremely unlikely that particulate organic wastes (fish feces or waste feed) from the net pen will travel intact to a distance of a mile downstream to accumulate in the slightly shallower area of the right bank near the bend in the river. Additional data beyond what is shown here was collected that included long-term drogue paths for many miles downstream, but those data and figures are not reported here as in almost all cases, strokes gravitated to the center line of the river for straight sections or to the thalweg (i.e., the deep channel on the outside radius of a band of the river).

Table 5. Data for 7 Oct 2010 Drogue Set 1. The column S, O, R? indicates start, observation or recovery of drogue.

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
7	6	S	288	296	8:47	8:51	0:04	194.2	80.9	1.6	
28	12	S	288	296	8:47	8:51	0:04	194.2	80.9	1.6	
7	6	O	296	297	8:51	8:55	0:04	169.5	70.6	1.4	
28	12	O	296	297	8:51	8:55	0:04	169.5	70.6	1.4	
7	6	O	297	299	8:55	9:02	0:07	251.5	59.9	1.2	
28	12	O	297	298	8:55	9:02	0:07	268.1	63.8	1.3	
7	6	O	299	300	9:02	9:09	0:07	304.9	72.6	1.4	
28	12	O	298	301	9:02	9:10	0:08	293.0	61.0	1.2	
7	6	O	300	303	9:09	9:35	0:26	1008.6	64.7	1.3	
28	12	O	301	302	9:10	9:34	0:24	851.3	59.1	1.2	
7	6	O	303	310	9:35	10:15	0:40	1453.0	60.5	1.2	
28	12	O	302	309	9:34	10:14	0:40	1251.0	52.1	1.0	
								mean 6 m =	**68.2**	**1.3**	
								mean 12 m =	**64.6**	**1.3**	

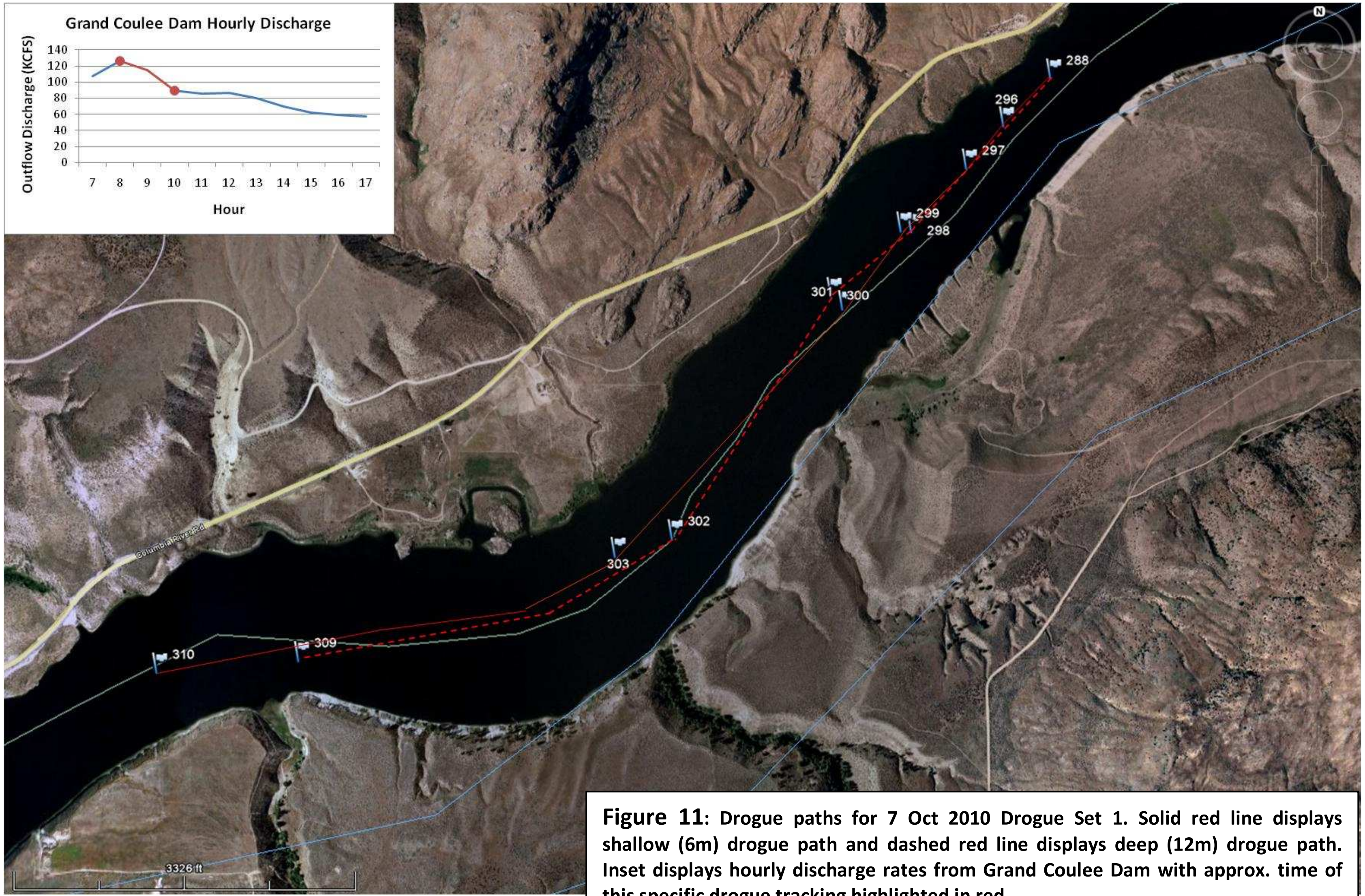


Figure 11: Drogue paths for 7 Oct 2010 Drogue Set 1. Solid red line displays shallow (6m) drogue path and dashed red line displays deep (12m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.

Table 6: Data for 7 Oct 2010 Drogue Set 2

Drogue No.	Depth of Drogue (m)	S, O, R ?	GPS Waypoint Start	GPS Waypoint Observ.	Time Start	Time Observ.	Time Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
4	6	S	288	304	9:46	9:51	0:05	154.7	51.6	1.0	
34	12	S	288	304	9:46	9:51	0:05	154.7	51.6	1.0	
4	6	O	304	305	9:51	9:57	0:06	261.1	72.5	1.4	
34	12	O	304	306	9:51	9:57	0:06	252.4	70.1	1.4	
4	6	O	305	308	9:57	10:05	0:08	258.3	53.8	1.1	
34	12	O	306	307	9:57	10:05	0:08	262.6	54.7	1.1	
4	6	O	308	312	10:05	10:20	0:15	398.0	44.2	0.9	
34	12	O	307	311	10:05	10:19	0:14	410.4	48.9	1.0	
4	6	O	312	340	10:20	10:57	0:37	864.1	38.9	0.8	
34	12	O	311	341	10:19	10:58	0:39	695.0	NA	NA	aground
								mean 6 m =	**52.2**	**1.0**	
								mean 12 m =	**56.3**	**1.1**	

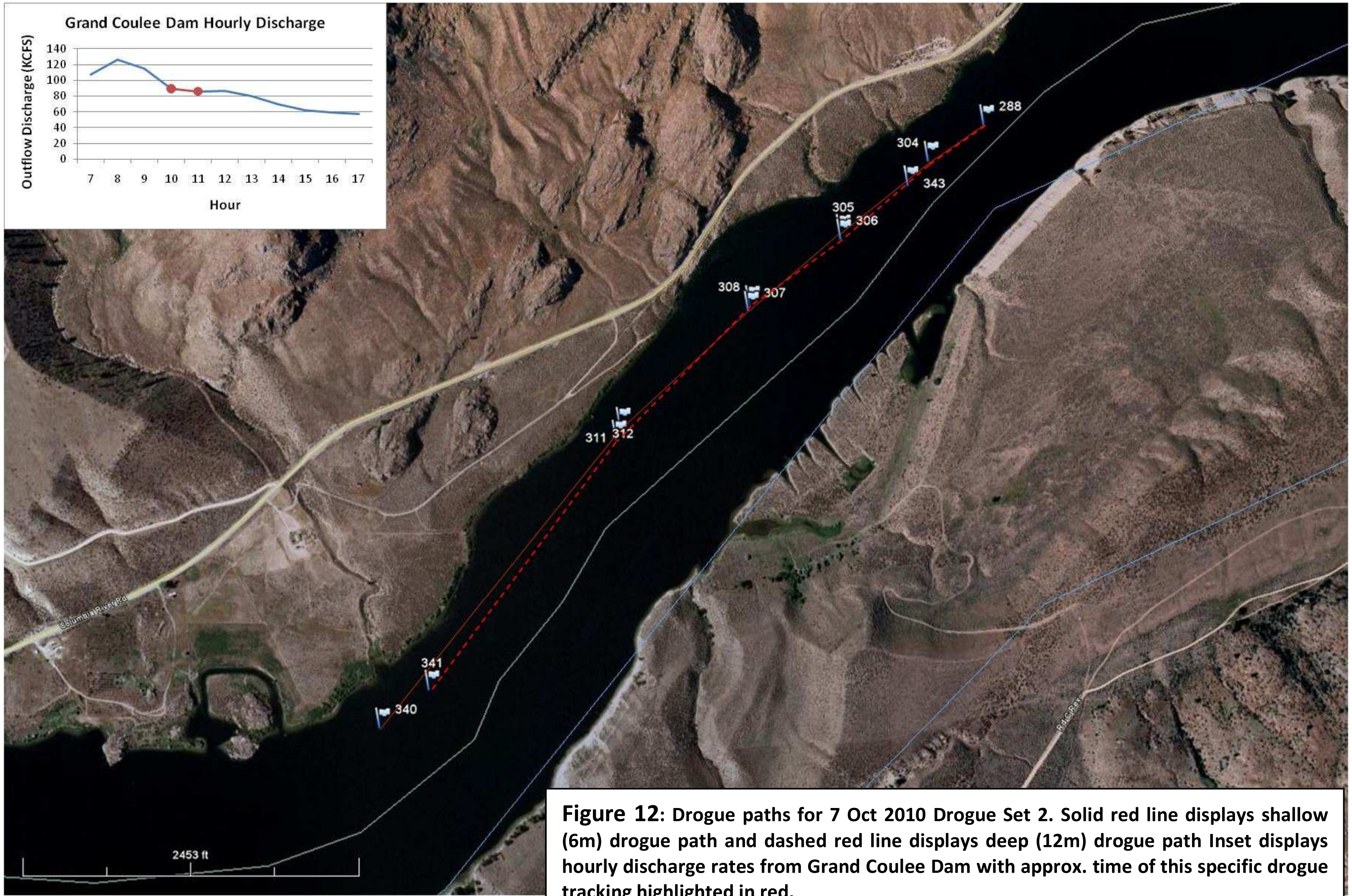


Figure 12: **Drogue paths for 7 Oct 2010 Drogue Set 2. Solid red line displays shallow (6m) drogue path and dashed red line displays deep (12m) drogue path Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 7: Data for 7 Oct 2010 Drogue Set 3

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
10	6	S	288	342	11:05	11:13	0:08	232.2	48.4	0.9	
34	12	S	288	343	11:05	11:14	0:09	217.8	40.3	0.8	
10	6	O	342	344	11:13	11:26	0:13	316.8	40.6	0.8	
34	12	O	343	345	11:14	11:26	0:12	308.9	42.9	0.8	
10	6	O	344	353	11:26	12:03	0:37	1046.0	47.1	0.9	
34	12	O	345	352	11:26	12:02	0:36	1099.7	50.9	1.0	
								mean 6 m =	**45.4**	**0.9**	
								mean 12 m =	**44.7**	**0.9**	

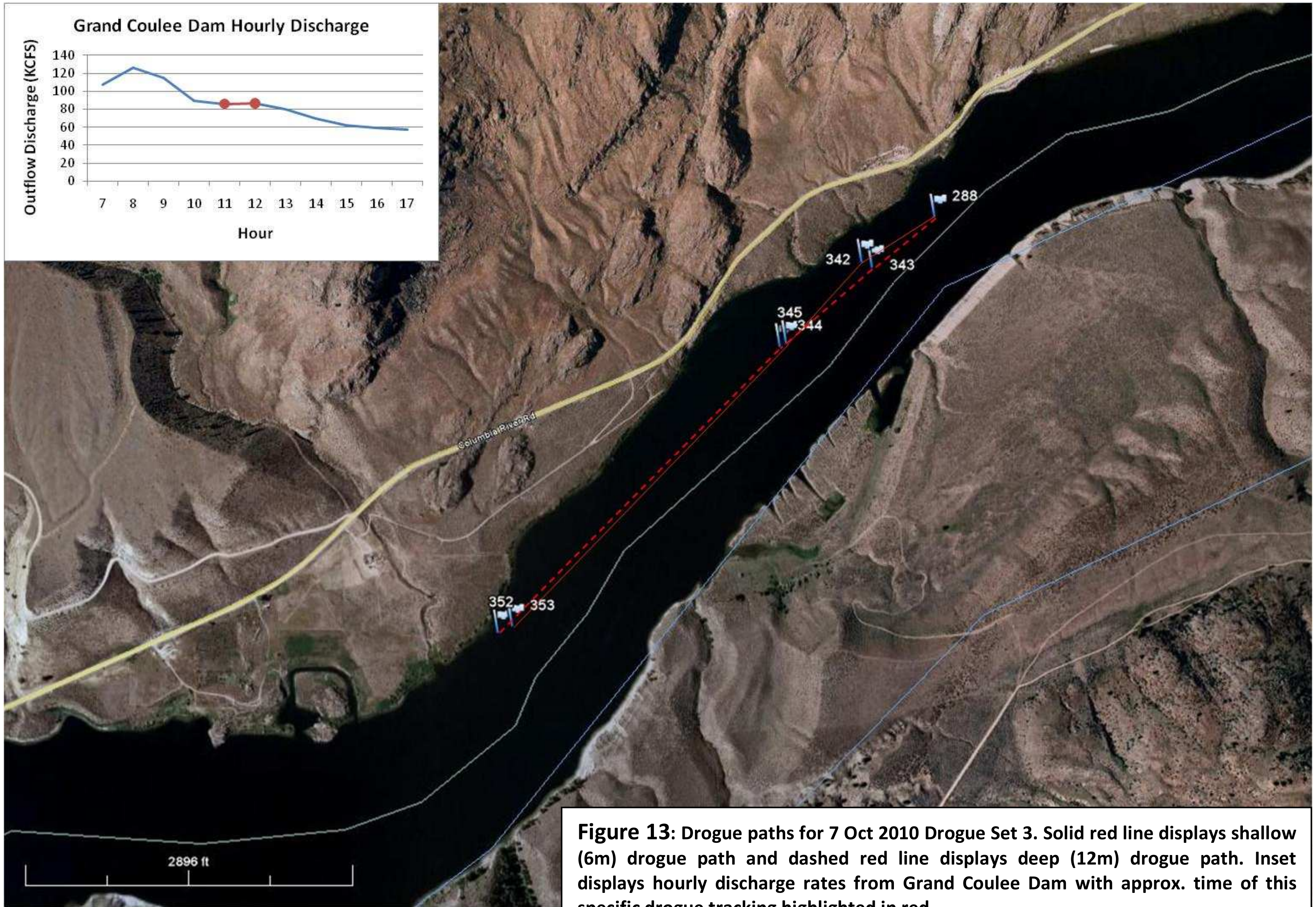


Figure 13: Drogue paths for 7 Oct 2010 Drogue Set 3. Solid red line displays shallow (6m) drogue path and dashed red line displays deep (12m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.

Table 8: Data for 7 Oct 2010 Drogue Set 4

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
7	6	O	288	1005	15:10	15:16	0:06	134.2	37.3	0.7	
28	12	O	288	1005	15:10	15:16	0:06	134.2	37.3	0.7	
7	6	O	1005	1006	15:16	15:22	0:06	139.0	38.6	0.8	
28	12	O	1005	1007	15:16	15:22	0:06	139.0	38.6	0.8	
7	6	O	1006	1008	15:22	15:33	0:11	184.9	28.0	0.5	
28	12	O	1007	1009	15:22	15:33	0:11	210.2	31.9	0.6	
7	6	O	1008	1010	15:33	15:43	0:10	135.3	22.6	0.4	
28	12	O	1009	1011	15:33	15:43	0:10	294.3	49.1	1.0	
7	6	O	1010	1012	15:43	15:57	0:14	215.4	25.6	0.5	
28	12	O	1011	1013	15:43	15:58	0:15	145.6	NA	NA	aground
								mean 6 m =	**30.4**	**0.6**	
								mean 12 m =	**39.2**	**0.8**	

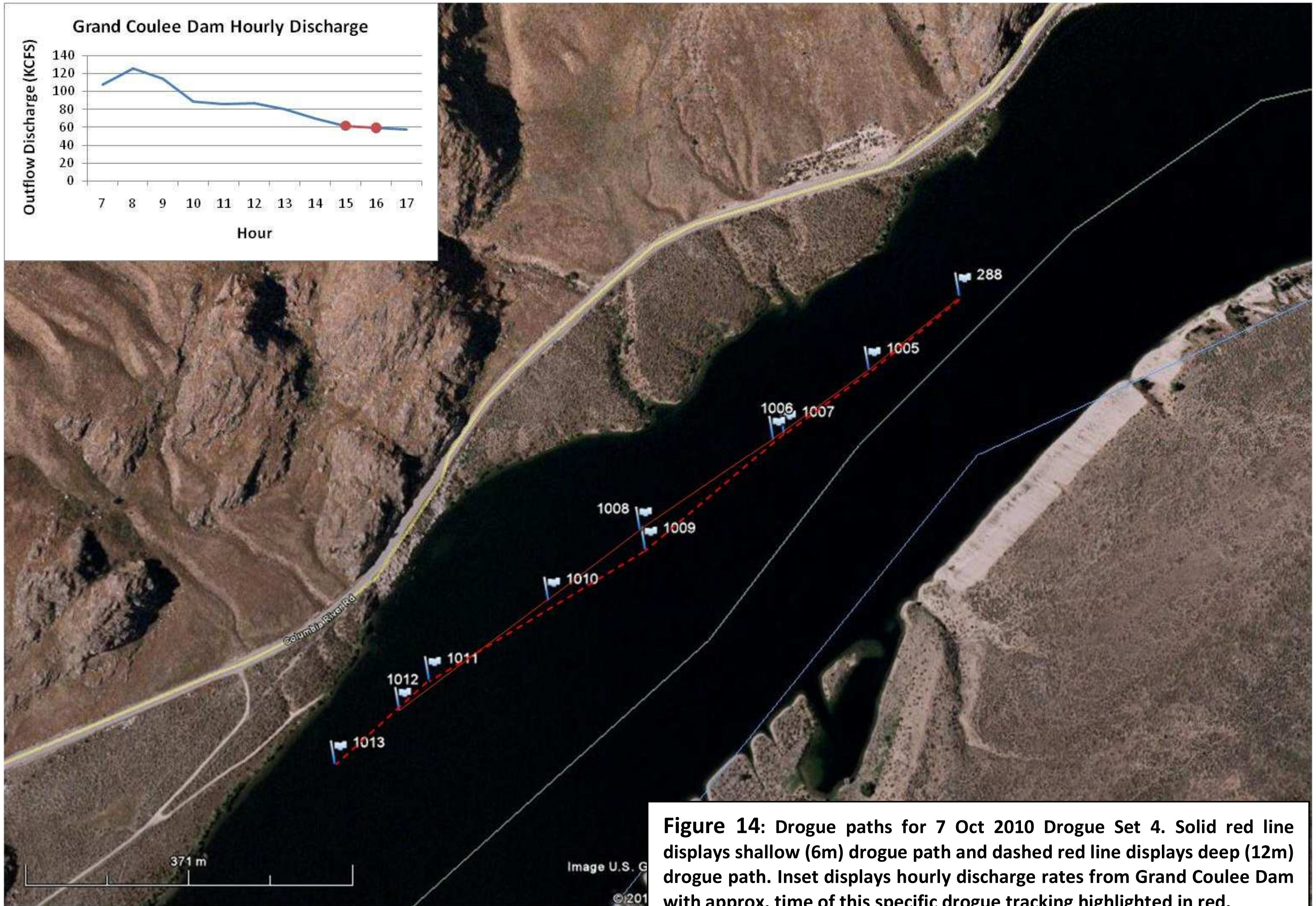


Figure 14: **Drogue paths for 7 Oct 2010 Drogue Set 4. Solid red line displays shallow (6m) drogue path and dashed red line displays deep (12m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 9: Data for 7 Nov 2010 Drogue Set 1

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
7	2	S	3	83	12:52	13:08	0:16	208.3	21.7	0.4	
34	10	S	3	84	12:52	13:08	0:16	229.7	23.9	0.5	
7	2	O	83	87	13:08	13:25	0:17	206.6	20.2	0.4	
34	10	O	84	88	13:08	13:26	0:18	200.9	18.6	0.4	
7	2	O	87	91	13:25	13:43	0:18	216.3	20.0	0.4	
34	10	O	88	92	13:26	13:44	0:18	219.6	20.3	0.4	
7	2	O	91	103	13:43	14:39	0:56	816.6	24.3	0.5	
34	10	O	92	101	13:44	14:37	0:53	861.5	27.1	0.5	
34	10	O	101	112	14:37	15:06	0:29	529.9	30.5	0.6	
7	2	O	103	110	14:39	15:04	0:25	469.1	31.3	0.6	
7	2	R	110	117	15:04	15:32	0:28	449.3	26.7	0.5	
34	10	R	112	115	15:06	15:29	0:23	456.1	33.1	0.6	
								Mean 2 m =	**24.0**	**0.5**	
								Mean 10 m =	**25.6**	**0.5**	

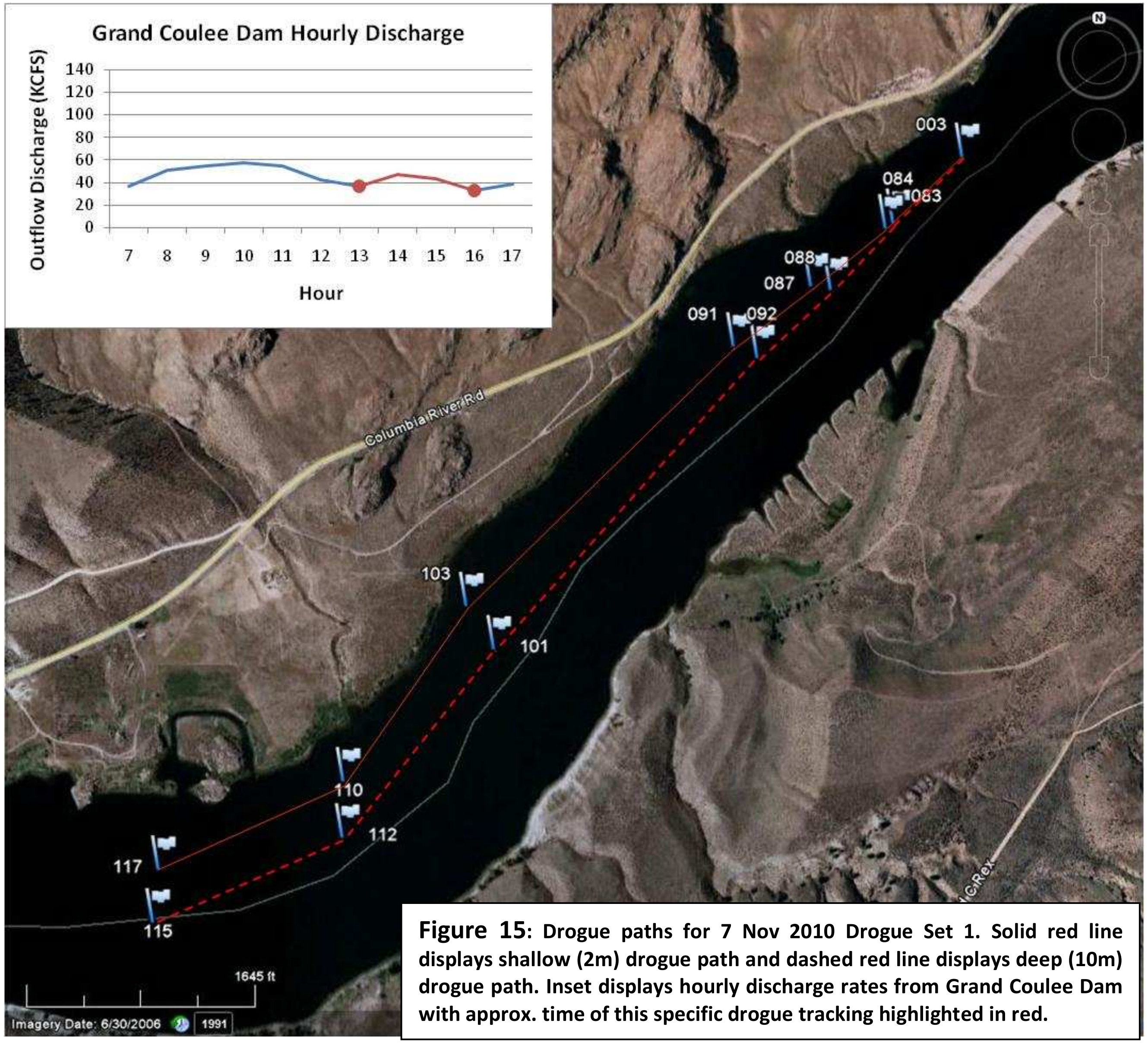


Figure 15: **Drogue paths for 7 Nov 2010 Drogue Set 1. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 10: Data for 7 Nov 2010 Drogue Set 2

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
4	2	S	82	85	12:53	13:09	0:16	222.7	23.2	0.5	
30	10	S	82	86	12:53	13:10	0:17	219.4	21.5	0.4	
4	2	O	85	89	13:09	13:27	0:18	224.8	20.8	0.4	
30	10	O	86	90	13:10	13:28	0:18	206.5	19.1	0.4	
4	2	O	89	93	13:27	13:44	0:17	246.3	24.2	0.5	
30	10	O	90	94	13:28	13:46	0:18	236.7	21.9	0.4	
4	2	O	93	100	13:45	14:36	0:51	857.9	28.0	0.5	
30	10	O	94	102	13:46	14:37	0:51	785.8	25.7	0.5	
4	2	O	100	113	14:36	15:07	0:31	608.9	32.7	0.6	
30	10	O	102	111	14:37	15:05	0:28	505.9	30.1	0.6	
30	10	R	111	116	15:05	15:31	0:26	475.0	30.4	0.6	
4	2	R	113	114	15:07	15:28	0:21	407.1	32.3	0.6	
							Mean 2 m =		**26.9**	**0.5**	
							Mean 10 m =		**24.8**	**0.5**	

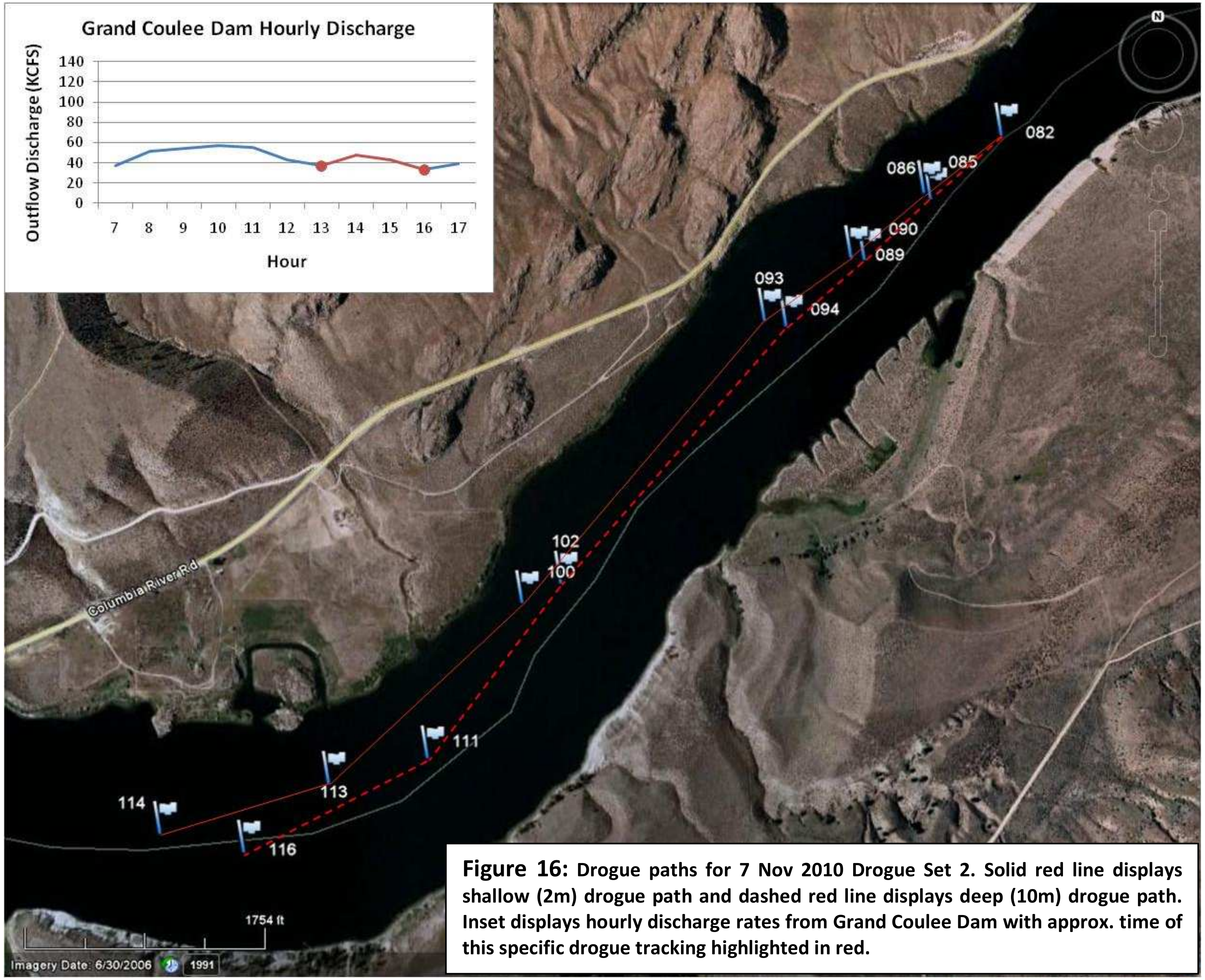


Figure 16: **Drogue paths for 7 Nov 2010 Drogue Set 2. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 11: Data for 7 Nov 2010 Drogue Set 3

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
8	2	S	3	104	13:52	14:41	0:49	885.9	30.1	0.6	
18	10	S	3	105	13:52	14:42	0:50	867.4	28.9	0.6	
8	2	O	104	108	14:41	15:01	0:20	359.7	30.0	0.6	
18	10	O	105	109	14:42	15:02	0:20	392.2	32.7	0.6	
8	2	R	108	118	15:01	15:34	0:33	562.5	28.4	0.6	
18	10	R	109	119	15:02	15:35	0:33	552.4	27.9	0.5	
								Mean 2 m =	**29.5**	**0.6**	
								Mean 10 m =	**29.8**	**0.6**	

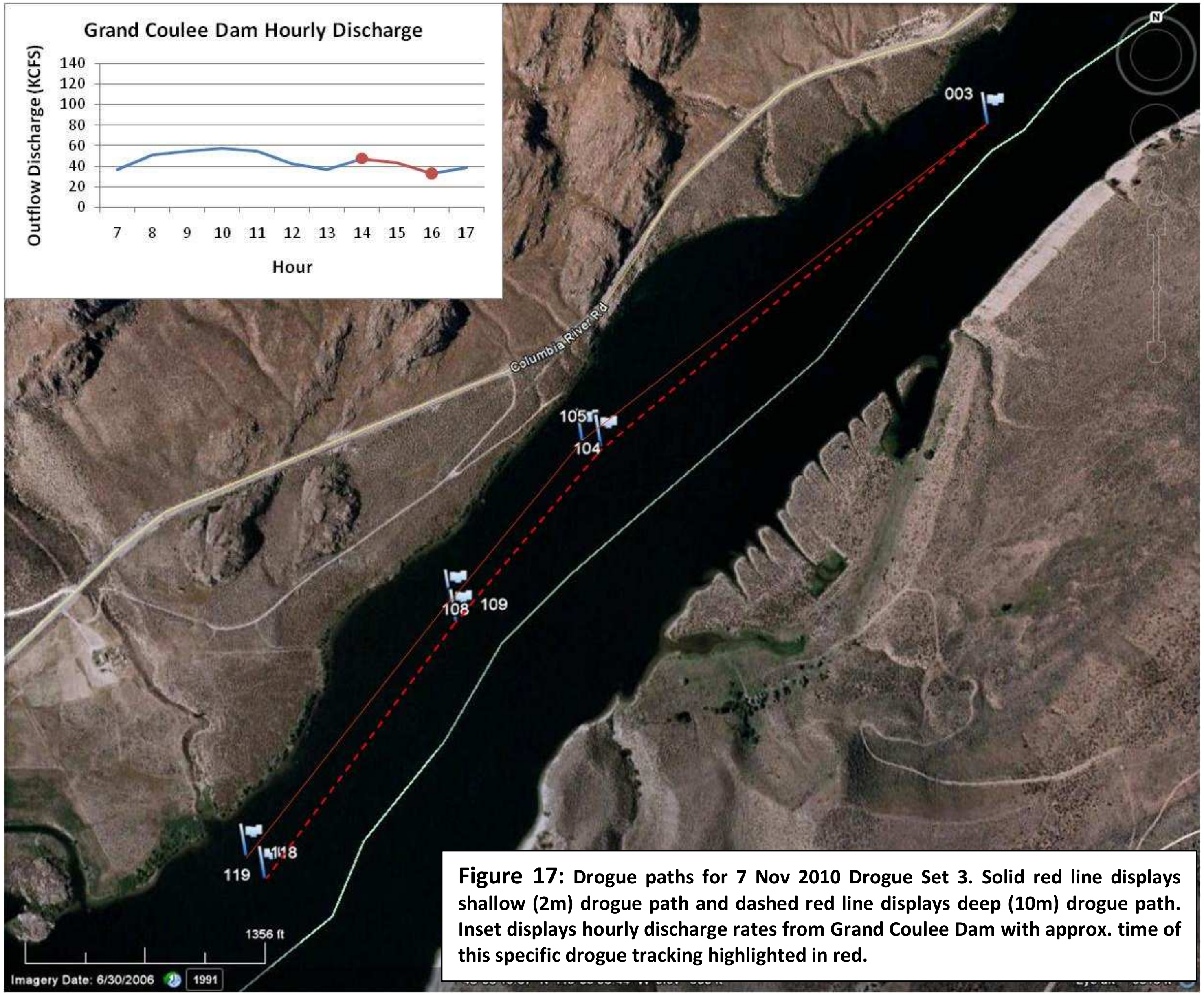


Figure 17: **Drogue paths for 7 Nov 2010 Drogue Set 3. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 12: Data for 7 Nov 2010 Drogue Set 4

			GPS Waypoint		Time						
Drogue No.	**Depth of Drogue (m)**	**S, O, R ?**	**Start**	**Observ.**	**Start**	**Observ.**	**Elapsed min**	**Distance m**	**Rate cm/s**	**Rate Knots**	**Comments**
5	2	S	3	106	14:44	14:57	0:13	256.4	32.9	0.6	
28	10	S	3	107	14:44	14:57	0:13	231.9	29.7	0.6	
5	2	R	106	120	14:57	15:37	0:40	807.9	33.7	0.7	
28	10	R	107	121	14:57	15:38	0:41	768.5	31.2	0.6	
								Mean 2 m =	**33.3**	**0.7**	
								Mean 10 m =	**30.5**	**0.6**	

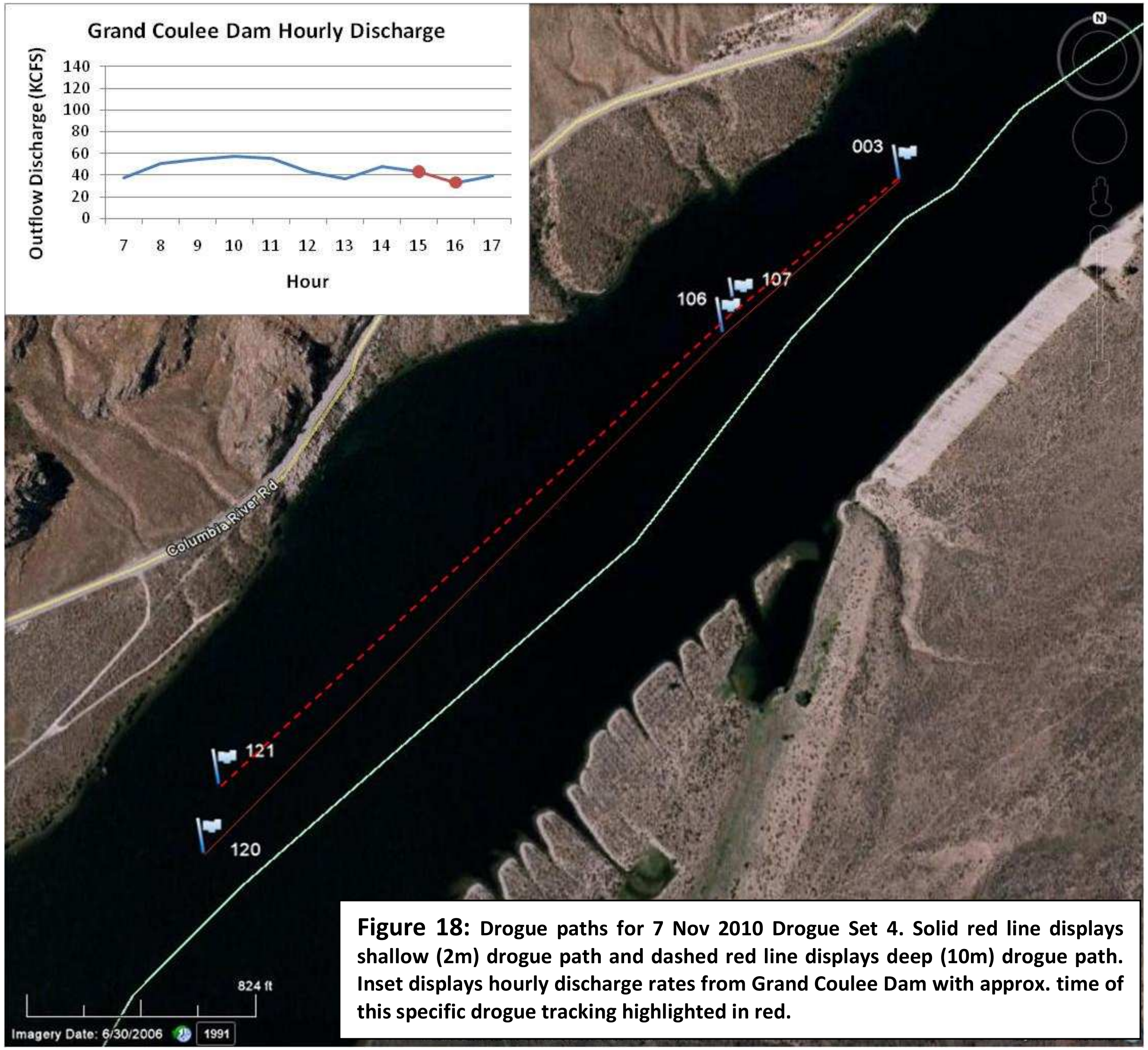


Figure 18: **Drogue paths for 7 Nov 2010 Drogue Set 4. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 13: Data for 8 Nov 2010 Drogue Set 1

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
5	2	S	3	122	7:53	8:01	0:08	380.0	79.2	1.6	
18	10	S	3	123	7:53	8:02	0:09	382.4	70.8	1.4	
5	2	O	122	124	8:01	8:07	0:06	241.5	67.1	1.3	
18	10	O	123	125	8:02	8:08	0:06	258.5	71.8	1.4	
5	2	O	124	126	8:07	8:16	0:09	312.7	57.9	1.1	
18	10	O	125	127	8:08	8:16	0:08	364.3	75.9	1.5	
5	2	O	126	128	8:16	8:24	0:08	315.1	65.7	1.3	
18	10	O	127	129	8:16	8:26	0:10	381.5	63.6	1.2	
5	2	O	128	132	8:24	8:38	0:14	534.0	63.6	1.2	
18	10	O	129	133	8:26	8:39	0:13	504.2	64.6	1.3	
5	2	O	132	134	8:38	8:45	0:07	261.7	62.3	1.2	
18	10	O	133	135	8:39	8:45	0:06	176.5	49.0	1.0	
5	2	O	134	137	8:45	8:52	0:07	230.8	55.0	1.1	
18	10	R	135	138	8:45	8:53	0:08	85.7	NA	NA	aground
5	2	R	137	139	8:52	8:56	0:04	149.2	62.2	1.2	
								Mean 2 m =	**64.1**	**1.3**	
								Mean 10 m =	**66.0**	**1.3**	

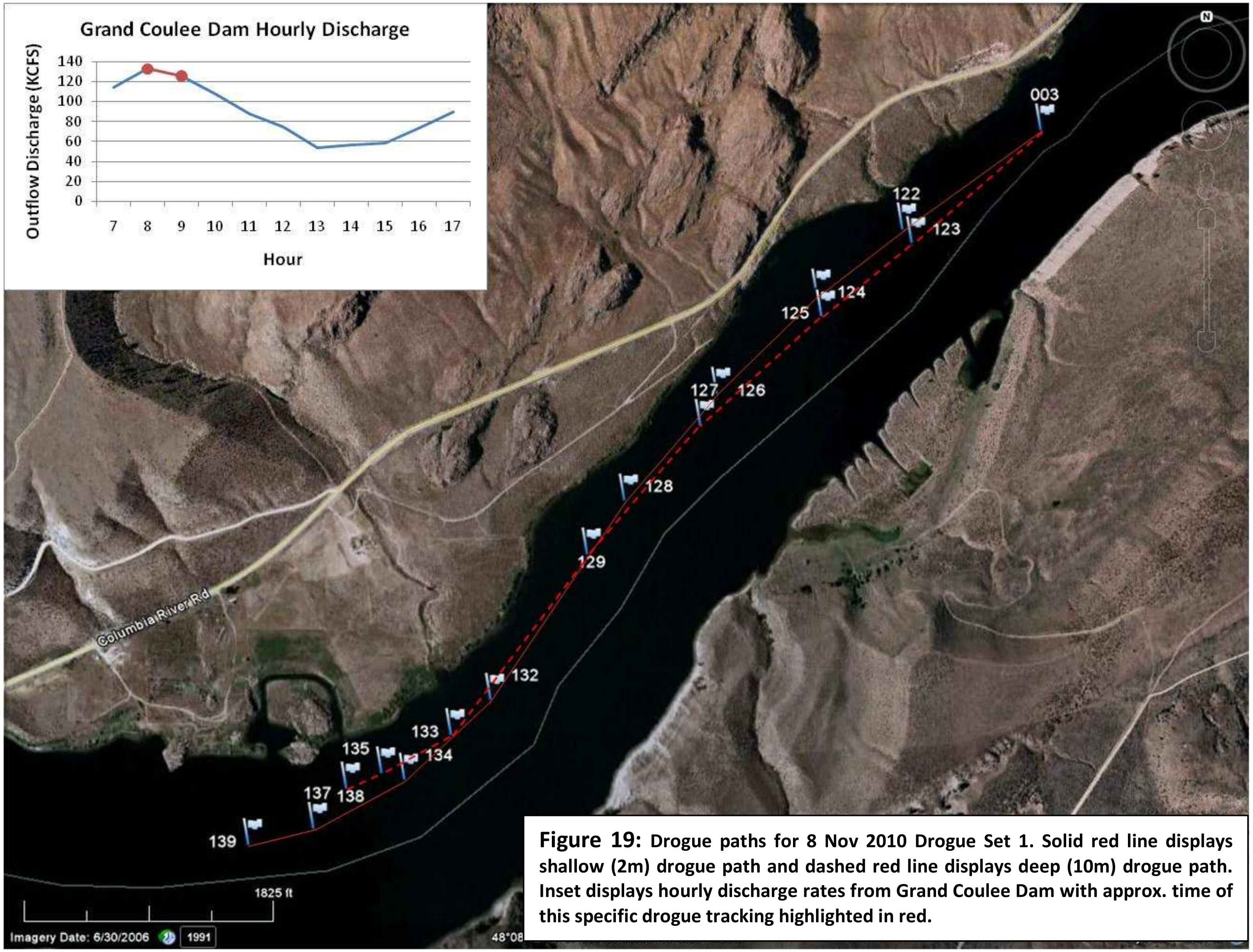


Figure 19: Drogue paths for 8 Nov 2010 Drogue Set 1. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.

Table 14: Data for 8 Nov 2010 Drogue Set 2

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
8	2	S	3	130	8:29	8:35	0:06	241.6	67.1	1.3	
30	10	S	3	131	8:29	8:35	0:06	264.6	73.5	1.4	
8	2	O	130	136	8:35	8:49	0:14	657.2	78.2	1.5	
30	10	O	131	136	8:35	8:49	0:14	635.6	75.7	1.5	
8	2	O	136	140	8:49	9:00	0:11	473.2	71.7	1.4	
30	10	O	136	141	8:49	9:00	0:11	477.3	72.3	1.4	
8	2	O	140	144	9:00	9:15	0:15	592.7	65.9	1.3	
30	10	O	141	145	9:00	9:16	0:16	571.6	59.5	1.2	
8	2	R	144	146	9:15	9:22	0:07	260.8	62.1	1.2	
30	10	R	145	147	9:16	9:23	0:07	249.7	59.5	1.2	
								Mean 2 m =	**69.0**	**1.4**	
								Mean 10 m =	**68.1**	**1.3**	

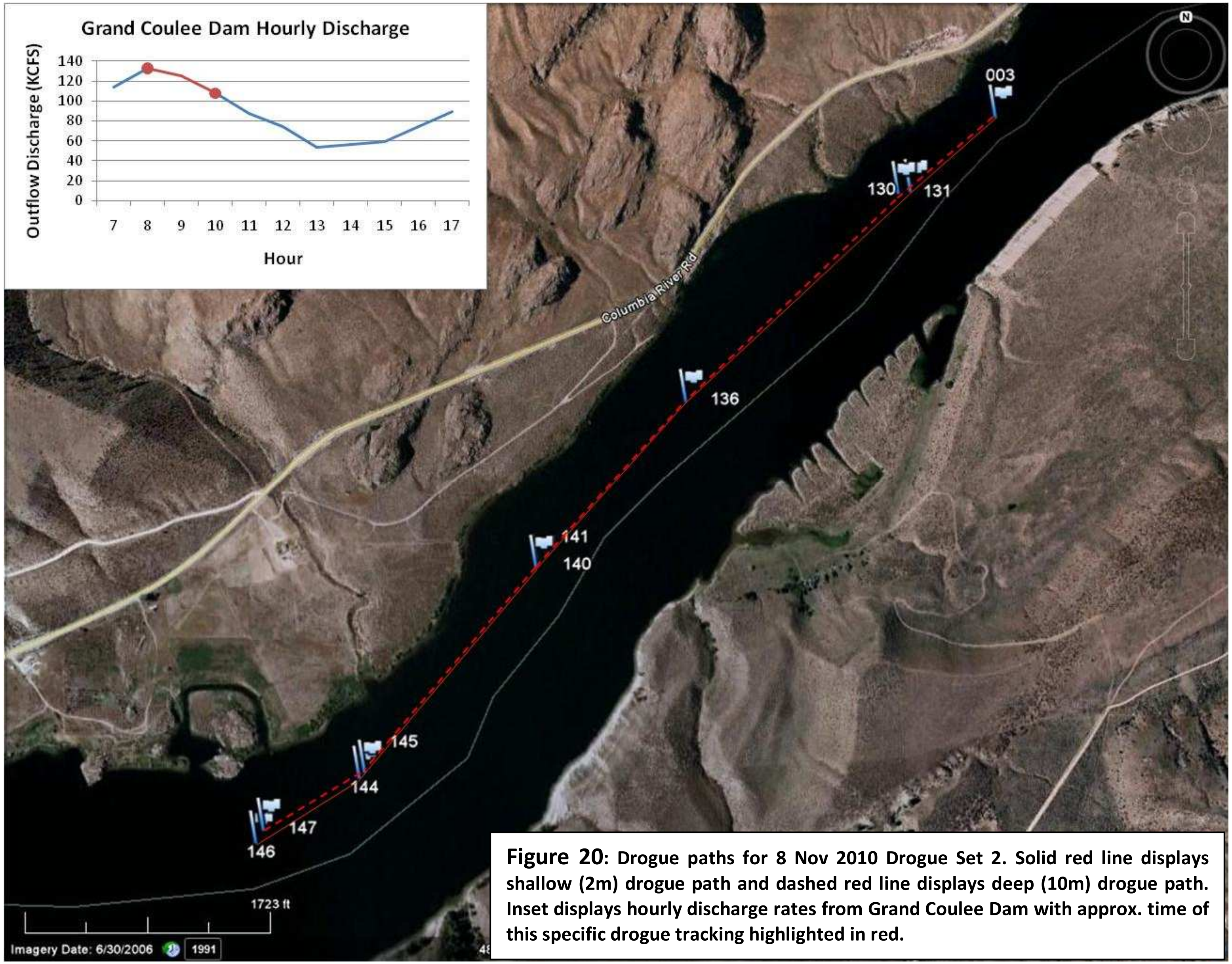


Figure 20: **Drogue paths for 8 Nov 2010 Drogue Set 2. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 15: Data for 8 Nov 2010 Drogue Set 3

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
5	2	S	3	142	9:04	9:10	0:06	307.2	85.3	1.7	
18	10	S	3	143	9:04	9:11	0:07	309.4	73.7	1.4	
5	2	O	142	148	9:10	9:28	0:18	760.8	70.4	1.4	
18	10	O	143	149	9:11	9:29	0:18	709.3	65.7	1.3	
5	2	O	148	152	9:28	9:43	0:15	589.8	65.5	1.3	
18	10	O	149	153	9:29	9:44	0:15	608.8	67.6	1.3	
5	2	O	152	156	9:43	9:51	0:08	336.2	70.0	1.4	
18	10	O	153	157	9:44	9:52	0:08	318.0	66.2	1.3	
5	2	R	156	158	9:51	10:02	0:11	385.6	58.4	1.1	
18	10	R	157	159	9:52	10:04	0:12	360.6	50.1	1.0	
								Mean 2 m =	**70.0**	**1.4**	
								Mean 10 m =	**64.7**	**1.3**	

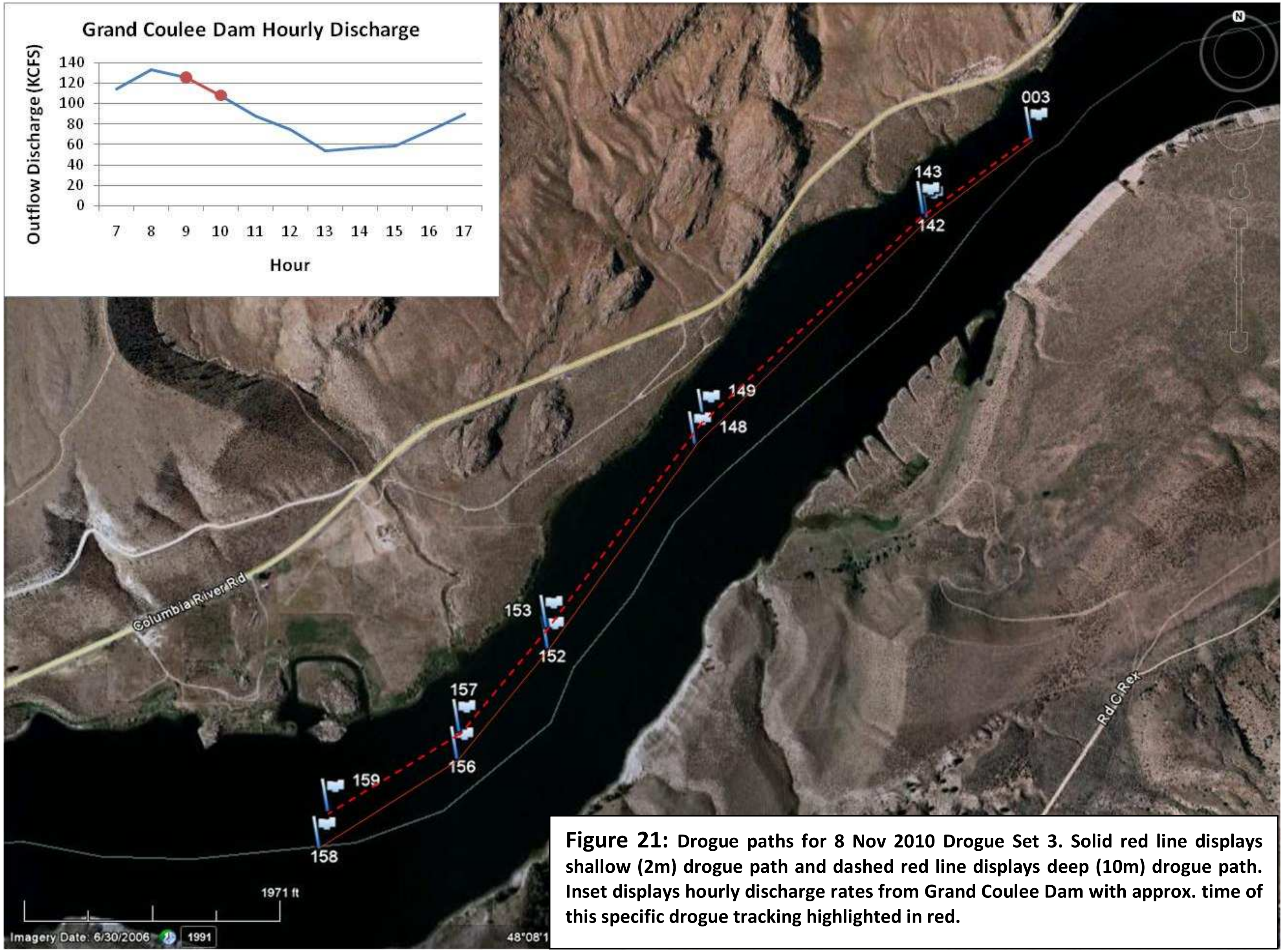


Figure 21: **Drogue paths for 8 Nov 2010 Drogue Set 3. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

Table 16: Data for 8 Nov 2010 Drogue Set 4. S = start, O = observation, R = Recovery

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
8	2	S	3	150	9:32	9:39	0:07	262.1	62.4	1.2	
30	10	S	3	151	9:32	9:39	0:07	296.7	70.6	1.4	
8	2	O	150	154	9:39	9:47	0:08	320.8	66.8	1.3	
30	10	O	151	155	9:39	9:48	0:09	356.0	65.9	1.3	
8	2	O	154	160	9:47	10:07	0:20	777.6	64.8	1.3	
30	10	O	155	161	9:48	10:08	0:20	753.3	62.8	1.2	
8	2	O	160	164	10:07	10:24	0:17	664.1	65.1	1.3	
30	10	O	161	165	10:08	10:25	0:17	578.2	56.7	1.1	
8	2	O	164	168	10:24	10:34	0:10	328.6	54.8	1.1	
30	10	R	165	169	10:25	10:36	0:11	243.0	NA	NA	aground
8	2	R	168	170	10:34	10:44	0:10	328.7	54.8	1.1	
								Mean 2 m =	**61.5**	**1.2**	
								Mean 10 m =	**64.0**	**1.3**	

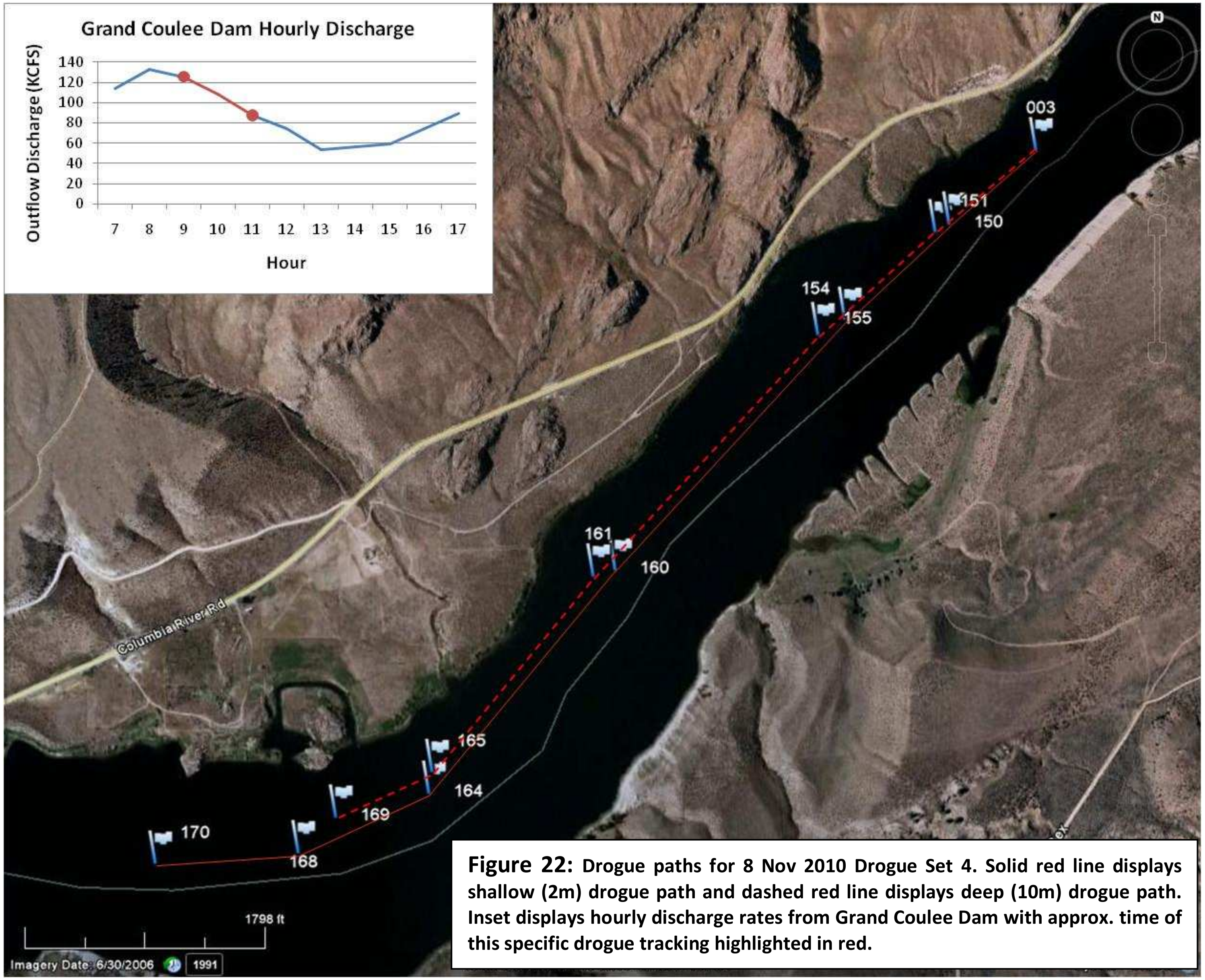


Figure 22: Drogue paths for 8 Nov 2010 Drogue Set 4. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.

Table 17: Data for 8 Nov 2010 Drogue Set 5

			GPS Waypoint		Time						
Drogue No.	Depth of Drogue (m)	S, O, R ?	Start	Observ.	Start	Observ.	Elapsed min	Distance m	Rate cm/s	Rate Knots	Comments
5	2	S	3	162	10:14	10:20	0:06	259.5	72.1	1.4	
18	10	S	3	163	10:14	10:20	0:06	268.7	74.6	1.5	
5	2	O	162	166	10:20	10:30	0:10	345.5	57.6	1.1	
18	10	O	163	167	10:20	10:30	0:10	365.0	60.8	1.2	
5	2	O	166	171	10:30	10:49	0:19	689.9	60.5	1.2	
18	10	O	167	172	10:30	10:49	0:19	636.0	55.8	1.1	
5	2	O	171	175	10:49	11:07	0:18	604.7	56.0	1.1	
18	10	O	172	176	10:49	11:09	0:20	489.5	40.8	0.8	
5	2	O	175	177	11:07	11:28	0:21	506.3	40.2	0.8	
18	10	O	176	178	11:09	11:29	0:20	391.1	32.6	0.6	
5	2	R	177	181	11:28	11:36	0:08	212.4	44.2	0.9	
18	10	R	178	182	11:29	11:39	0:10	65.2	NA	NA	aground
								Mean 2 m =	**55.1**	**1.1**	
								Mean 10 m =	**52.9**	**1.0**	

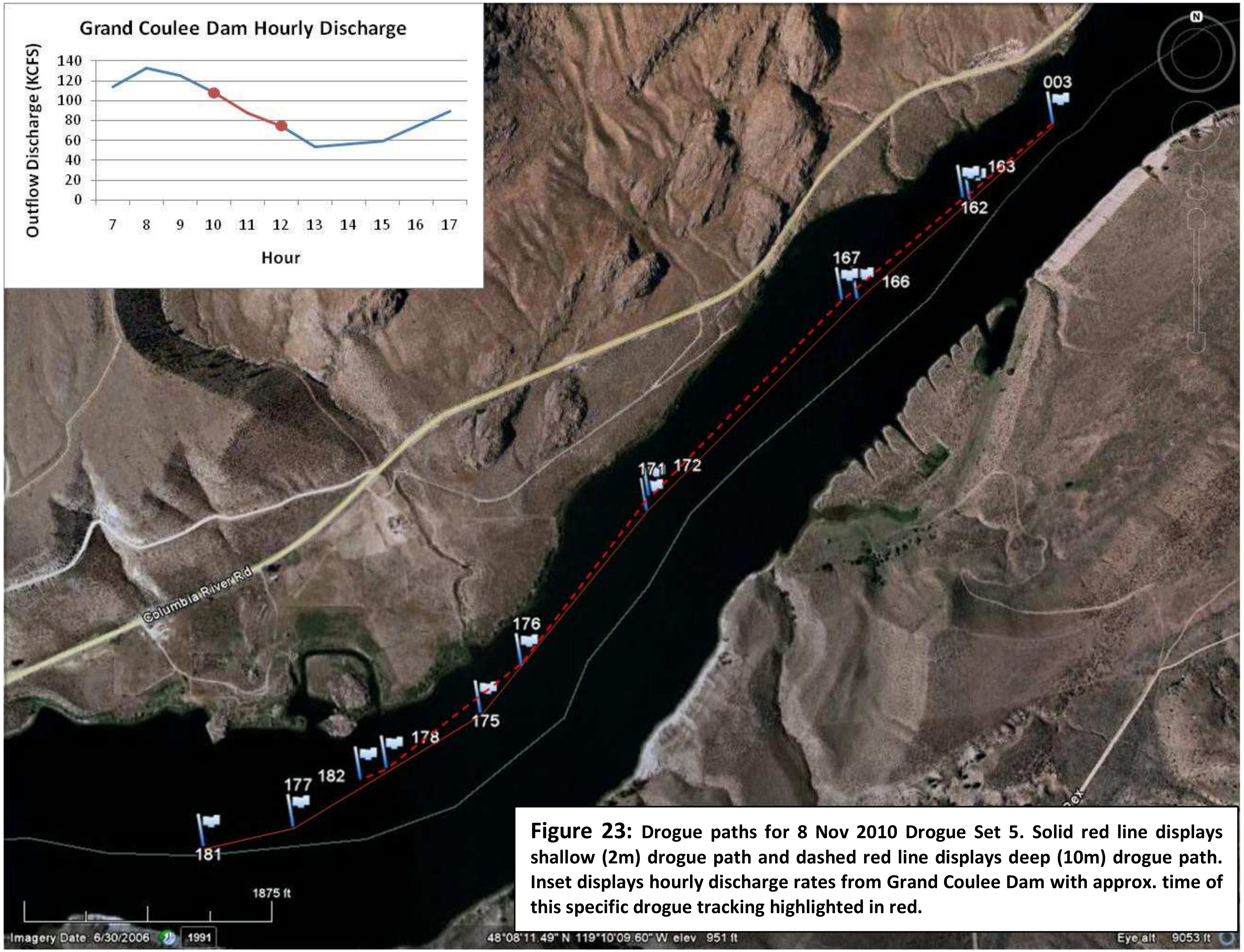


Figure 23: **Drogue paths for 8 Nov 2010 Drogue Set 5. Solid red line displays shallow (2m) drogue path and dashed red line displays deep (10m) drogue path. Inset displays hourly discharge rates from Grand Coulee Dam with approx. time of this specific drogue tracking highlighted in red.**

7. Conclusions

Proposed net pen Site 3 in Rufus Woods Lake is located in a relatively narrow, fast flowing reach of Rufus Woods Lake, Columbia River that more adequately is described as a river, than a lake. The site was selected in part because of the narrowness of the river and the strong flows that were observed there in a preliminary study. A current meter study indicated that Site 3 hydrodynamics compared favorably with existing Site 1 conditions, with substantially higher rates of flow in surface and subsurface layers. The deepest measured layers had approximately similar or slightly less velocity than existing site 1.

Frequency analysis of the current meter data showed very different distributions of energy within differing depth ranges. For surface flows, Site 3 had a broad spectrum of flow rates, but Site 1 data were more tightly grouped in the moderate flow rate category. For subsurface depths, a similar circumstance occurred, but Site 3 had a distribution of faster flows far exceeding that of Site 1. The differences diminished in the deepest measured layer, with similar overall but slightly stronger flows on average at Site 1.

Drift object studies were conducted over a range of river discharge conditions in fall 2010. These studies showed the same high rates of water current velocity at the net pen sites, and sometimes slowed slightly by a distance of one mile downstream. The drogues rarely grounded, but when they did it was over one mile downstream near the bend in the river where it is much wider than at the farm site. Drogues set at deep levels tended to move more quickly toward the main channel of the river than shallow drogues.

Compared to modern net pen sites in Puget Sound and elsewhere, velocities at the proposed site 3 are extremely strong, more than 100% faster than the most current swept sites known. Moreover, periods of no flow are either very infrequent or nonexistent. In marine waters slack tidal periods occur for extended periods of time, exceeding an hour in some cases. At these times dissolved oxygen supply to the pens is greatly reduced and during warm water periods may result in oxygen stress to the fish. Stress may lead to disease or directly to mortality, and accordingly, the strong and persistent flows in Rufus Woods Lake help explain why fish culture has been so successful in net pens in this location. Unlike marine net pens however, there is relatively little variation in flow direction in the Lake, which results in a relatively narrow initial pathway of particulate and dissolved waste dispersion. Any seasonal deposition upon the bottom is to some degree mitigated by the extra strong flows that will aerate, resuspend, and transport waste downstream to be utilized in reservoir. Due to the long distance to Chief Joseph dam pool, the probability of particulate waste being transported to the pool and buried are minimal. This was demonstrated in stable isotope tracing studies (Rensel 2010) that will be pursued in year 2011.

Overall, proposed Site 3 is a highly energetic location for a net pen that should be able to accommodate a biomass of fish similar to that grown at existing Site 1.

8. Literature Cited

Cromey, C.J., Nickell, T.D., Black , K.D. 2002. DEPOMOD – modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214:211-239.

Rensel, J.E. 2010. Tracing of fish farm effects on sediment and food web of Rufus Wood Lake, Columbia River, 2009 Results. Prepared by Rensel Associates Aquatic Sciences, Arlington WA for Pacific Aquaculture Inc. and the Colville Confederated Tribes, Nespelem, Washington. 38 pp.