Duncan Dam Project Water Use Plan DDMWORKS-3

Reference: DDMWORKS-3

DDMWORKS-3: Duncan Lake Reservoir Phosphorus Retention: Updated Analysis of Dam Operational Impacts (2021)

Study Period: 2021

Ecoscape Environmental Consultants Ltd.

November 2022

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DDMWORKS-3: Duncan Lake Reservoir Phosphorus Retention: Updated Analysis of Dam Operational Impacts (2021)

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EXECUTIVE SUMMARY

Ecoscape Environmental Consultants Ltd. in coordination with Larratt Aquatic Consulting Ltd. was contracted by BC Hydro Power Authority (BC Hydro) to provide environmental consulting services related to the Kootenay Lake Nutrient Restoration Program, specifically, phosphorus (P) retention within Duncan Lake Reservoir (DLR). Dissolved forms of P (Total Dissolved Phosphorus; TDP) control the overall productivity of waterbodies in the Kootenay system. The intensive initial assessment and modelling conducted by Perrin and Korman in 1994-95 indicated significant TDP retention within DLR. The nutrient dynamics of DLR may have shifted over the decades through climatic or Duncan Dam (DDM) operational changes. This document summarizes the results of 2021 P sampling and the re-assessment of P retention in DLR. It concludes with a re-evaluation of P retention due to DDM operations and assesses the appropriateness of the current DDMWORKS-3 funding.

Our P re-assessment approach included sampling of TDP and Total Phosphorus (TP) at three inflowing (nutrient import) sites, including the upper Duncan River within the large reservoir drawdown zone, and the dam outflow (nutrient export) site. These sites were sampled during each limnological season, on six dates between April and October 2021. Despite unprecedented heat and high flows in the spring, the 2021 TP concentrations were all within the range of values documented in 1994-95. However, the 2021 TDP concentrations were significantly different and below the expected range of the 1994-95 data. It is not known for certain what is driving the lower concentrations of TDP. The 1994-95 data exhibited spikes in TDP concentrations, especially during the spring, while the 2021 did not show any TDP spikes, perhaps because the bi-weekly sampling in 1994-95 could capture more TDP spikes than the much less frequent 2021 sampling. Additionally, TDP loading in the drawdown zone was much higher in 1994-95 than in 2021. Some uncertainty in these results may have been due to the 66% of 2021 TDP samples that were below the ultra-low 1.0 µg/L detection limit. Alternately, genuine change in the climatic regime and possibly in DLR limnology may have contributed to the observed decline in TDP inputs. A detection limit was not reported by Korman and Perrin (1997), making it difficult to seamlessly compare the two datasets.

The re-assessment of P retention was undertaken by recreating the 1997 methods to develop an updated nutrient budget and independent baseline values. A variety of hydrologic variables and temporal lags were explored to model inflow and outflow P concentrations at all sampling sites. These updated models were compared with existing models to determine the most accurate estimate against the 1994-95 baseline values. This exercise identified several computational errors in the previous evaluation. Annual operational impacts of DDM were best modeled by reproducing the Consultative Committee (CC) process using the DDM_Nutrient excel sheet without the identified computational errors. It predicted 81.6% TDP retained in DLR compared to the phosphorus budget baseline.

The CC corrected model was used to estimate retention for the different operating regimes originally assessed in the Water Use Plan (Alt A, SD73 & Nutrient Alternative), to determine TDP retention from DDM operations (calculated as the difference between Nutrient Alternative and SD73 – the status quo). DDM operations, as per the CC corrected model, retained 1.4 Metric Tons (MT) of TDP. This was 0.2 MT more than the original model. An increase of 0.2 MT represents a 16.6%, or ⅙ increase in TDP retained. This calculation is based on the 1994-95 data only and does not incorporate, nor reflect the reduction in TDP observed in 2021. Given this, the original payment for 1.2 MT of retained TDP due to DDM operations may in fact be an overcompensation. However, we cannot say with certainty whether the DDM program was over or undercompensated, because of the infrequent sampling in 2021. If TDP concentrations in DLR are in fact lower than when originally assessed in 1994-95, then several assumptions will need to be agreed upon (such as the rate of change in TDP concentrations over the 26-year period) to effectively evaluate the P retention due to DDM operations and to assess the appropriateness of DDMWORKS-3 funding.

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This project was managed by Teri Neighbour, Natural Resource Specialist with BC Hydro and technically reviewed by Dr. Guy Martel, Ecosystems Scientist with BC Hydro.

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LIST OF ACRONYMS AND DEFINITIONS

Alt A	Alternative A operating regime used for 1968-1999
BC	British Columbia, Canada
BC Hydro	BC Hydro Power Authority
CC	Consultative Committee
CRT	Columbia River Treaty
DDM	Duncan Dam
DLR	Duncan Lake Reservoir
Ecoscape	Ecoscape Environmental Consultants Ltd.
Euphotic zone	The layer of water that receives enough sunlight for photosynthesis to occur, varying greatly with season and latitude.
GCLAS	Graphical Constituent Loading Analysis System
Inorganic phosphorus	Also referred to as orthophosphate or soluble reactive phosphorus (SRP)
KLNRP	Kootenay Lake Nutrient Restoration Program
km	kilometres
m	metres
m asl	metres above sea level
monomictic	Having only one seasonal period of free circulation each year
MSPE	Mean squared prediction error
MT	Metric Ton
N	Nitrogen
NO_3	Nitrate
NH_4	Ammonium
Nutrient Alternative	Theoretical nutrient optimal operating regime created by maximizing reservoir elevation within the CRT constraints
Oligotrophic	An aquatic environment that has low nutrient levels and therefore low primary production
Operating Regimes	Alternative A, SD73 and Nutrient optimal operating considered for DDM
P	Phosphorus – a macronutrient required for the growth of aquatic organisms
PPT	precipitation load
PP	Particulate phosphorus
R	Residual nutrient retained
Roving site	Sample site that follows the reservoir water level, moving ~25 km to stay within the dewatering drawdown zone which encompasses the northern half of DLR

SRP	soluble reactive phosphorus
TDP	Total dissolved phosphorus – includes all organic and inorganic phosphorus compounds
Thermocline	A steep temperature gradient in a body of water, marked by a warm layer above and a cooler water layer below.
TN	Total nitrogen
TOR	Terms of reference
TP	Total phosphorus
SD73	SD73 operating regime used since 2006.
Stratification	When water masses with different properties such as salinity, oxygenation density and temperature form layers that act as barriers to water mixing.
SW_{in}	Sum off all surface water loads
SW_{out}	Surface water load leaving the system
USGS	US Geological Survey
WUP	Water Use Plan
WRTDS	Weighted Regressions on Time, Discharge, and Season
ΔS	Change of nutrient mass in lake storage

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1.0 INTRODUCTION

Ecoscape Environmental Consultants Ltd. (Ecoscape) in coordination with Larratt Aquatic Consulting Ltd. was contracted by BC Hydro Power Authority (BC Hydro) to provide environmental consulting services related to the Kootenay Lake Nutrient Restoration Program (KLNRP). The KLNRP is undertaken in both the north and south arms of Kootenay Lake to offset impacts of the Duncan and Libby Dams. These dams, constructed in 1967 and 1973, respectively, have impacted native fish populations. Decreasing lake primary productivity is attributed to changes to the hydrograph, alterations to nutrient inputs to Kootenay Lake, blocking access for fish spawning and flooding of rearing/spawning habitats (BC Hydro, 2019).

Decreased productivity in Kootenay Lake led to significant declines in Kokanee (*Oncorhynchus nerka*), and subsequent declines in Gerrard Rainbow Trout (*Oncorhynchus mykiss*) and Bull Trout (*Salvelinus confluentus*), as Kokanee are their primary food source. To offset the loss in productivity, liquid fertilizer has been added annually to Kootenay Lake since 1992. The response of phytoplankton, Daphnia and Kokanee populations has been positive. Prior to fertilization (1985-1991), the average in-lake Kokanee biomass was 3.4 kg/ha, compared to post fertilization (1992-2016), where the average Kokanee biomass increased to 7.2 kg/ha (Bassett et al., 2018).

The annual KLNRP budget for both the north and south arms of Kootenay Lake is approximately 1.8 million, of which BC Hydro contributes ~ $180,000 annually through DDMWORKS-3. BC Hydro's contribution is equal to 1/5.7th or 17.5% of the previous year's fertilization costs. This ratio is based off a $100,000 contribution (in 2004 dollars), which at the time was 1/5.7th of the total $570,000 cost of the fertilization program (BC Hydro and Power Authority, 2008). To accommodate for inflation, this ratio has been upheld since 2004.

The objective of DDMWORKS-3 is to provide annual funding to KLNRP to enhance the aquatic food supply in the north arm of Kootenay Lake equivalent to the operational component of nutrient supply lost to the Lower Duncan River and Kootenay Lake through retention in the Duncan Lake Reservoir (DLR) (BC Hydro, 2019). The operational component of phosphorus retention is defined as the difference between the SD73 operating regime and a nutrient optimized alternative.

The purpose of this contract is to re-evaluate the effectiveness of DDMWORKS-3 contributions by re-assessing phosphorus retention in DLR 26 years after the initial assessment. Phosphorus retention in DLR was last assessed in 1994-1995, as part of a study that determined DLR's phosphorus budget and provided an overview of the reservoir's limnology (Perrin & Korman, 1997). Although DLR's limnological characteristics should be stable, changes to Duncan Dam (DDM) operations or significant climatic/weather shifts could have altered DLR's hydrology, limnology and consequently its nutrient balances.

This reassessment and modelling approach integrated methodologies from a literature review of recent phosphorus retention studies (Akers et al., 2020), and included input by a Technical Review Committee. The approach incorporated additional phosphorus collection from DLR in 2021, to supplement the original phosphorus data from 1994-95.

2.0 BACKGROUND AND CONTEXT

2.1 Duncan Lake Reservoir Characteristics and Operations

The DLR is 44 km long and it has an average width of 1.8 km at full pool. It extends northward from the Duncan Dam along the Duncan River channel and includes the original Duncan Lake which was approximately 17 km long and 1.6 km wide (Perrin & Korman, 1997). The Duncan Reservoir has a mean and maximum depth of 52 m and 117 m, respectively (Perrin and Korman 1997). The reservoir surface elevation at full pool in late summer is 576.68 m asl. This elevation drops in fall/winter by 13 - 30 m during an annual drawdown to 546.9 m asl in early spring which is close to the surface elevation of the original lake. The reservoir surface area at full pool is 7,350 ha but it declines to 2,190 ha at full drawdown, producing an approximately 5,160 ha dewatered zone that occurs mostly in the northern half of the reservoir. The drawdown zone is comprised of glacial till that is prone to erosion and channel braiding (Perrin & Korman, 1997; Porto et al., 2016).

The very large drawdown zone of DLR was identified as an important driver of phosphorus loading (Perrin & Korman, 1997). A number of studies have focused on the importance of drawdown zones in reservoirs (Furey et al., 2004; Klotz & Linn, 2001; Shantz et al., 2004). The DLR drawdown zone encompasses the northern half of the reservoir as well as the narrow littoral band that is normally a key productivity zone. The dewatering, freezing, and increased erosion of exposed drawdown substrates drive changes in the littoral zone including:

- accelerated sediment transport to deeper water;
- reduced nutrient and organic matter in littoral area;
- substrate coarsening;
- increased sediment resuspension, nutrient release, and turbidity during substrate re-wetting under reservoir refill; and
- reduced benthic habitat quality (Carmignani & Roy, 2017).

Freshet was also identified as a key period of phosphorus influx to DLR (Perrin & Korman, 1997). Freshet and storm delivery of turbid inflows are important to the DLR nutrient budget and are widely recognized as key sources of nitrogen (N), phosphorus (P) and silica. The main catchments that drain into the reservoir include the upper Duncan River, Howser Creek and Glacier Creek. The Duncan River basin represents 55% of the total catchment area for the reservoir, while Howser and Glacier catchments occupy 17% and 11%, respectively. The remaining 17% is comprised of smaller catchments with first to third order streams, some of which are ephemeral or have no defined stream channels (Perrin & Korman, 1997).

The DLR is used to provide storage and downstream flood control as per the Columbia River Treaty (CRT). There are no power generating facilities at the Duncan Dam (DDM). DDM operations are guided by the following constraints (BC Hydro and Power Authority, 2008) (Figure 2-1):

- Maximum reservoir elevation at full pool (between 576.38 and 576.68 m) during the period between August 1st and August 10th;
- Maintain full pool, or within 0.3 m of this level, until Labour Day;
- Elevation target (<569.8 m) on December 31; and
- Low pool elevation targets (<551.0 m high snow years; <564.4 m low snow years), with a minimum elevation drawdown of 546.87 m.
- Minimum monthly discharge is 3.0 m^3/s, under the CRT.

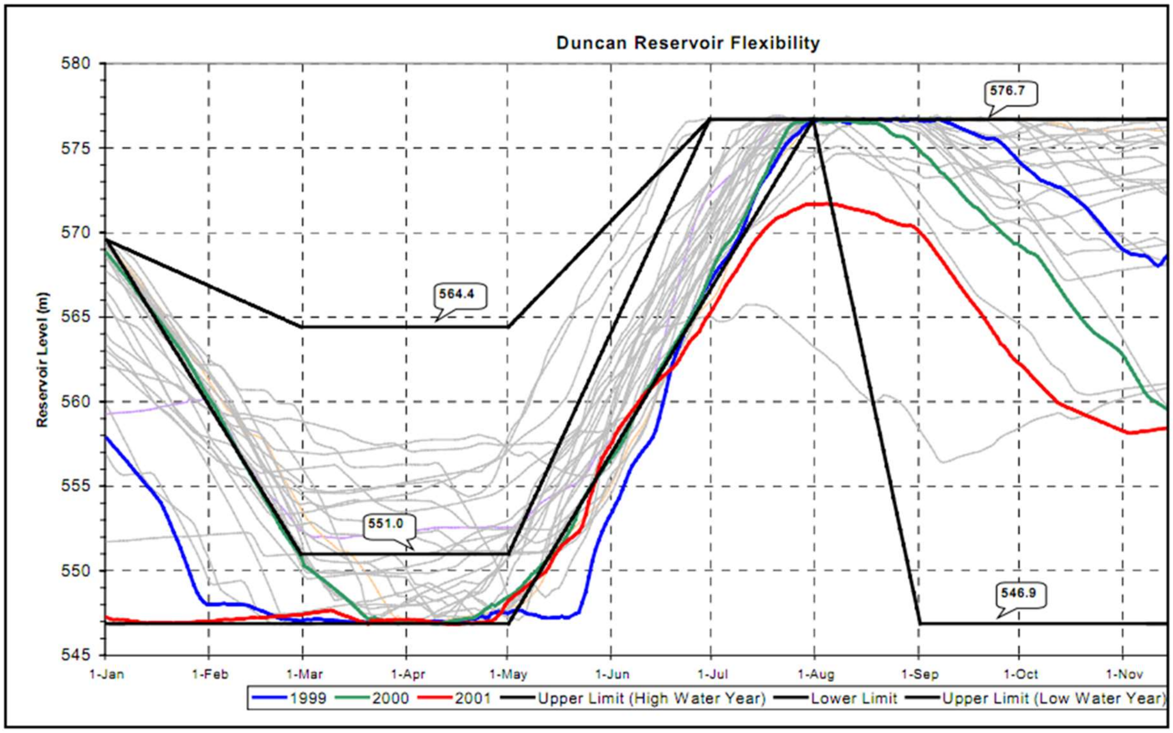

Figure 2-1. Elevation constraints of the Duncan Lake Reservoir (Leake & Perrin, 2004).

As part of the Consultative Committee (CC) process for the DDM Water Use Plan (BC Hydro and Power Authority, 2005), different operating regimes that fall within these constraints were explored to estimate the impact of the DDM operations. The operational impacts are discussed in more detail in later sections of this document.

2.2 Previous Phosphorus Retention Assessment

2.2.1 Duncan Lake Reservoir Limnology

Perrin & Korman (1997) found that DLR was monomictic, ultra-oligotrophic and P-limited, with significant phosphorus retention. The reservoir water column was isothermal and near 4°C in winter, while a weak thermocline developed between 10 to 15 m in summer. The water column remained fully oxygen-saturated year-round. Heavy rainfall events and the spring freshet produced turbidity with peak concentrations up to 50 NTU in the depth interval of 6-15 m due to stream inflow plumes (Perrin & Korman, 1997).

Perrin & Korman (1997) sampled P inputs, including tributaries and precipitation, and P outputs at the DDM and downstream tributaries. Their study design involved sites on the upper Duncan River upstream and downstream of the drawdown zone to capture effects from fluvial resuspension and from release of pore water from the fluvial drawdown zone. Samples were analyzed for NO_3, NH_4, total N, and soluble reactive P (SRP), total dissolved P (TDP), particulate P (PP) and Total P (TP). The nutrient sample data was supplemented with limnological and biotic information.

Perrin & Korman (1997) found that, like most hydro reservoirs world-wide, DLR represented a huge phosphorus sink (Maavara et al., 2015). Particulate P (PP) dominated all fractions of TP varying from <2 µg/L at low flows to >70 µg/L during the spring freshet. TDP concentrations ranged from <2 µg/L in summer months to 4.4 µg/L at high flows in the spring. SRP concentration was typically near 1 µg/L but it dropped to 0.5 µg/L in summer in all streams. Concentrations of all forms of N and P increased in the upper Duncan River in passage through the drawdown zone, a process attributed to particulate resuspension and release of substrate pore water. The drawdown zone contributed 78.5% of PP, 15.9% of TDP, and 74.4% of TP loads entering the reservoir from the upper Duncan River (Perrin & Korman, 1997).

The authors concluded that of the annual TP load (111 MT), 90.3% (100.6 MT) was retained in the reservoir. This retention resulted from 93.5% retention of PP (96.3 MT), 52% retention of TDP (4.4 MT) and 48% retention of SRP (1.2 MT). PP retention was attributed to precipitation of particulates whereas the retention of soluble P was explained by biological uptake and sorption, followed by precipitation. The greatest P retention occurred in the spring when the reservoir was filling.

A total of 46.6 MT of TP was exported from the Duncan watershed to Kootenay Lake in 1994-95. Of this total load, only 7.4 MT was soluble and potentially biologically available. PP export amounted to 39.2 MT. The Lardeau River contributed 77% of this load and the Duncan River upstream of the Lardeau contributed the remaining 23%. Most of the PP came from the Lardeau River whereas most of the soluble P came from the Duncan system. Settlement of particulates in the reservoir explained this difference.

2.2.2 Calculation of Phosphorus Retention

Perrin & Korman (1997) generated an estimate of P retention within the DLR following their one-year sampling period. Their sampling methods used to calculate the nutrient budget were very thorough, and align with methods utilized over the past 25 years (Akers et al., 2020).

Nutrient budgets consist of measuring the difference between the quantity of a nutrient introduced to a system and the quantity leaving the system. For outflow and inflow sources (rivers, streams & precipitation), water volume over time is multiplied by each site's respective nutrient concentration to produce a quantity or weight (Equation 1).

Equation 1:

$$P_{Rsvr} = (P_{InConc.} \cdot V_{In}) - (P_{OutConc.} \cdot V_{Out}),$$

where:

P_{Rsvr} = phosphorous (mass) retained in the reservoir

$P_{InConc.}$ = inflow phosphorus concentration

V_{In}= inflow water volume

$P_{OutConc.}$ = outflow phosphorus concentration

V_{Out} = outflow water volume

Inflows to the DLR consist of 55% Upper Duncan, 17% Howser Creek, 11% Glacier Creek, and 17% smaller streams, as calculated by catchment area (Perrin & Korman, 1997). Phosphorus retention was determined using DLR daily reservoir volume as estimated using the BC Hydro live storage model and the inflow measured on the Upper Duncan River (Perrin & Korman, 1997). The creek volumes were calculated using the above ratios taken from the remaining volume, calculated from live storage volume, minus the Upper Duncan inflow. In addition, Perrin & Korman, (1997) only measured nutrient concentrations at Glacier and Howser creeks, and approximated the concentration of the additional smaller creeks (totalling 17% of inflow) to be the mean of the two measured creeks. The TDP concentrations for Howser and Glacier creeks during freshet differed by a factor of 5, suggesting that approximating the concentrations in the other creeks introduced a degree of error in the value of inflow nutrient concentrations (Akers et al., 2020).

Of the annual total inflow values of phosphorus, all creeks (Glacier, Howser & others) contributed 36%, 25% and 14.3% of SRP, TDP and TP respectively compared to the 45% contribution anticipated based on water volume/catchment size. More specifically, the unmeasured creeks contributed 14%, 9.75% and 5.6% of SRP, TDP and TP respectively. Estimating nutrient concentrations within unmeasured streams is a common practice in mass balance calculations (Moran et al., 2012; Smeltzer & Quinn, 1996).

The outflow concentrations of the DLR were calculated using nutrient samples and flow data from the spillway of the DDM (Station 08NH126). With the outflow and inflow volume data, Korman & Perrin (1997) used the average volume between sampling periods (ranging from 2-4 weeks) multiplied by the sampled concentrations to generate their retention estimate for the DLR.

2.2.3 Duncan Lake Reservoir Nutrient Modelling

Many empirical models for TP retention within the DLR have been explored (Akers et al., 2020) each considering a variety of hydraulic, morphological, and temporal predictors (Binsted & Ashley, 2006; Gray & Kirkland, 1979; Larsen & Mercier, 1976; Kirchner & Dillon, 1975; Perrin & Korman, 1997). The most thorough model to date was developed as a component of the Consultative Committee (CC) process related to the Duncan Dam Water Use Plan (DDM WUP) (BC Hydro and Power Authority, 2005). The CC process identified that the reservoir operations could impact the DDM P retention values, therefore the committee opted to determine some updated values for P retention within the reservoir. The CC process developed the following equation:

Equation 2:

$$[TDP]_{outQ} = 11.84 \cdot 10^8 \cdot {}^{[TDP]_{inQ}}\!/_{V_{Resvr}}$$

Where,

$[TDP]_{outQ}$ Concentration of TDP in DDM Discharge (µg/L)

$[TDP]_{inQ}$ Concentration of TDP in Duncan River inflow (µg/L)

V_{Resvr} is the groundwater inflow load

The intent of Equation 2 was to explain “the relationship between outflow concentration of TDP with seasonal averages of the DLR volume and inflow concentrations,” (BC Hydro and Power Authority, 2005). The analysis is based on the empirical relationship expressed above derived from one year of data collected in 1994 -95 (BC Hydro and Power Authority, 2005). Equation 2 assumes that seasonal influx concentrations observed for 1994-95 are representative of other years and the volume of water per season is the limiting factor in determining an estimate of TDP retained (BC Hydro and Power Authority, 2005).

Overall, the model is relatively simple; seasonal TDP inflow estimates are held constant, and the volume (assumed to be the average) for a given season is altered to provide an estimate of the TDP that left via the dam discharge. Taking the difference of the TDP inflow and the estimated TDP outflow gives an estimate for the TDP retained. The CC process used Equation 2 to estimate TDP for various operating regimes (Appendix H; BC Hydro and Power Authority, 2005), specifically alternative A (power optimized), SD73 (new WUP alternative that benefits other areas of interest in the DLR and downstream), and Nutrient (nutrient optimal flow that meets CRT conditions) (Figure 2-2). The different TDP estimates for these three alternative regimes were used to generate the contribution amounts to compensate for the DDM’s nutrient retention because operations would prioritize more power optimized alternatives, rather than the less retentive alternative. Throughout the CC process, caveats were stated regarding the preliminary nature of these calculations and recommendations were made to develop more robust predictive models (Appendix H; BC Hydro and Power Authority, 2005).

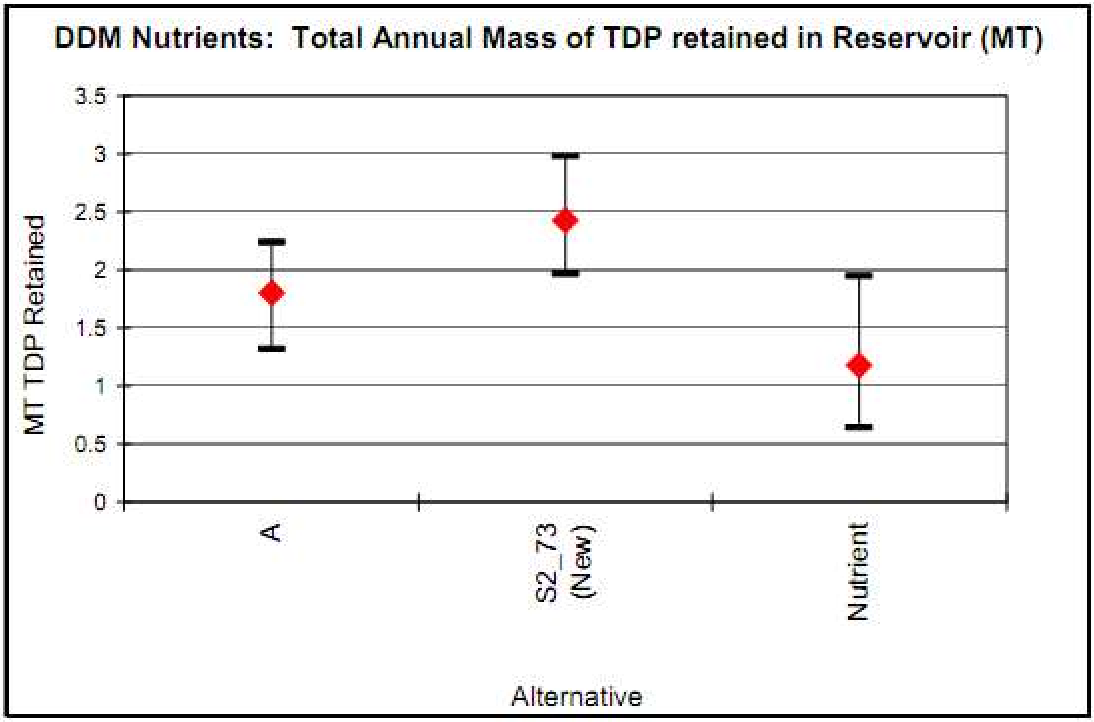

Figure 2-2. Estimated total annual mass of TDP retained (Metric Tonnes) in Duncan Lake Reservoir for three alternative operating regimes (BC Hydro and Power Authority, 2005).

To summarize, during the CC process, the Fish Technical Subcommittee concluded that DDM operations could result in approximately double the nutrients, specifically TDP, being retained when compared to employing a nutrient optimal operating alternative (BC Hydro and Power Authority, 2005). The preferred operation alternative SD73 (the new status quo following the CC process) was estimated to retain 2.42 +/- 0.45 MT of TDP, compared to the nutrient optimal alternative which was estimated to retain 1.21 +/- 0.75 MT of TDP (Appendix H; BC Hydro and Power Authority, 2005). Given the sensitivity of retention of DDM operations, the subcommittee recommended partial funding up to $100,000 towards the KLFP (BC Hydro and Power Authority, 2005). At the time of this recommendation, $100,000 was set as a fixed value, and represented approximately 1/5.7th or 17.5% of the cost of the program; to adjust this value for inflation, the actual payment amount was set as 1/5.7th of the previous year's total cost of the program (BC Hydro and Power Authority, 2008).

3.0 METHODS

Perrin & Korman (1997) undertook a thorough assessment of the DLR limnology, including its nutrient contributions to Kootenay Lake. They also identified contributions from other sources such as downstream tributaries. Regular sampling over a designated period determines the accuracy of nutrient estimates. Perrin & Korman (1997) included sampling every two weeks during all seasons except winter, when they sampled monthly. Lower sampling frequency in winter was deemed acceptable by Perrin & Korman (1997), because relatively stable winter minimum inflows do not include large fluctuations in P loading.

The scope of the 2021 water sampling was much more limited than the 1994-95 sampling program (Table 3-1). The primary intent of the 2021 sampling was to determine if TDP concentrations in 2021 were within the range of the 1994-95 data. Following a presentation of the proposed approach to the Technical Steering Committee, the Committee recommended expanding the sampling parameters, beyond just TDP, to also include Total Phosphorus (TP).

While the 2021 sampling program limited our ability to quantify the many variables that comprise a modern phosphorus budget (Akers et al., 2020), we were able to collect and determine TP and TDP concentrations for the most important P input, surface water, which accounted for >99% of DLR's P inputs in the 1994-95 study.

Table 3-1. Sampling events during 1994, 1995 and 2021.

Month	Jan				Feb				Mar				Apr				May				Jun				Jul				Aug				Sep				Oct				Nov				Dec			
Week	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
1994																																		x		x		x		x	x		x			x		
1995			x				x			x		x		x		x		x		x	x		x		x		x	x		x		x		x														
2021															x					x			x				x					x							x									

3.1 Phosphorus Sampling in 2021

The seasons of the limnological year for DLR were defined as fall (Sep – Nov), winter (Dec – Apr), spring (May – Jun) and summer (Jul – Aug) (Perrin & Korman 1997). Six sampling events were undertaken between April and October 2021 on the following dates: Apr 19-20, May 26-27, Jun 14-15, Jul 19, Aug 24, and Oct 15. The goal of the 2021 program was to sample at least once during each season, with the remaining two sampling trips targeting key limnological events including moderate to peak production and reservoir drawdown. In addition, where possible, we were mindful to align sampling with storm events that were likely to result in nutrient spikes.

The sampling import and export sites matched those of the 1994-95 study and are summarized in Table 3-2 and Figure 3-1. The three import tributaries included Upper Duncan River, Glacier Creek and Howser Creek. The export site was located at the Duncan Dam (DDM). Consistent with Perrin & Korman (1997), water samples were collected at the upper end of the channel below the low level outlet gates on the northwest side of Duncan Dam.

As previously highlighted, a major input of P is related to the dramatic water elevation changes within DLR, specifically the dewatering, freezing and erosion experienced within the fluvial drawdown zone. The impact of the drawdown zone was accounted for by sampling P at the roving site within the upper Duncan River channel at the reservoir's edge, consistent with the 1994-95 methodology. Sampling this site integrated TP and TDP contributions of the drawdown zone within the inflow measurements. The drawdown zone was sampled on April 20, May 27 and Jun 14, 2021, either by boat or truck access (Figure 3-1). BC Hydro provided a boat and operator to access the roving site, but as the reservoir edge expanded north, access by boat proved difficult due to shallow conditions, interference with woody debris and stumps and difficulty identifying the edge of the upper Duncan River channel. Alternatively, areal imagery was used to determine locations where the upper Duncan River channel meandered close to the eastern shore of the reservoir and could be accessed by foot.

Once the reservoir reached full pool, the remaining three samples were taken from the upper Duncan River site (Figure 3-1). Other import sample sites included the largest tributaries, Glacier and Howser creeks. Each of the creeks were sampled immediately upstream of bridge crossings on the Duncan Lake Forest Service Road that extends along the eastern and northern perimeter of the reservoir (Figure 3-1). Safety procedures were diligently followed and safety equipment (i.e., radio, In-Reach, pfds) was utilized during each sampling event to ensure the wellbeing of field personnel.

Table 3-2. Import and export sampling stations in 2021. All 6 dates = Apr, May. June. July, August & October.

Site Type	Station Name	Description	Latitude / Longitude	Data Obtained	Dates Sampled
Import	Station 08NH119 (upper Duncan River)	Sampled when DLR was at or close to full pool.	50° 38' 19.51'' N 117° 02' 59.69'' W	TP, TDP and In-situ data	Jul1 9 Aug 24 Oct 15
Import	Upper Duncan River Roving site	Roving site near the wetted margin, but within the inflow river channel –sampled when DLR was less than full-pool.	Site location changed depending on water levels. See Figure 3-1.	TP, TDP and In-situ data	Apr 20 May 27 June 14
Import	Glacier Creek	Sampled approximately 30 m upstream of the Glacier bridge crossing via a small footpath to the right bank of the creek.	50° 17' 05.18"N 116° 55'10.36"W	TP, TDP and In-situ data	All 6 dates
Import	Howser Creek	Sampled approximately 50 m upstream of the Howser bridge crossing via a small footpath to the left bank of the creek.	50° 27' 49.39"N 116° 54' 58.28"W	TP, TDP and In-situ data	All 6 dates
Export	Station 08NH126	Duncan Dam Spillway	50° 15' 05'' N 116° 56' 51'' W	TP, TDP and In-situ data	All 6 dates

Note: The calculated daily combined inflow from Glacier and Howser creeks and other small tributaries were multiplied by the average TDP concentration measured in Howser Creek and Glacier Creek to determine total daily import of TDP from small tributaries. An assumption in this approach was that TDP concentrations measured in Howser and Glacier creeks are representative of those in the other unmeasured smaller tributaries.

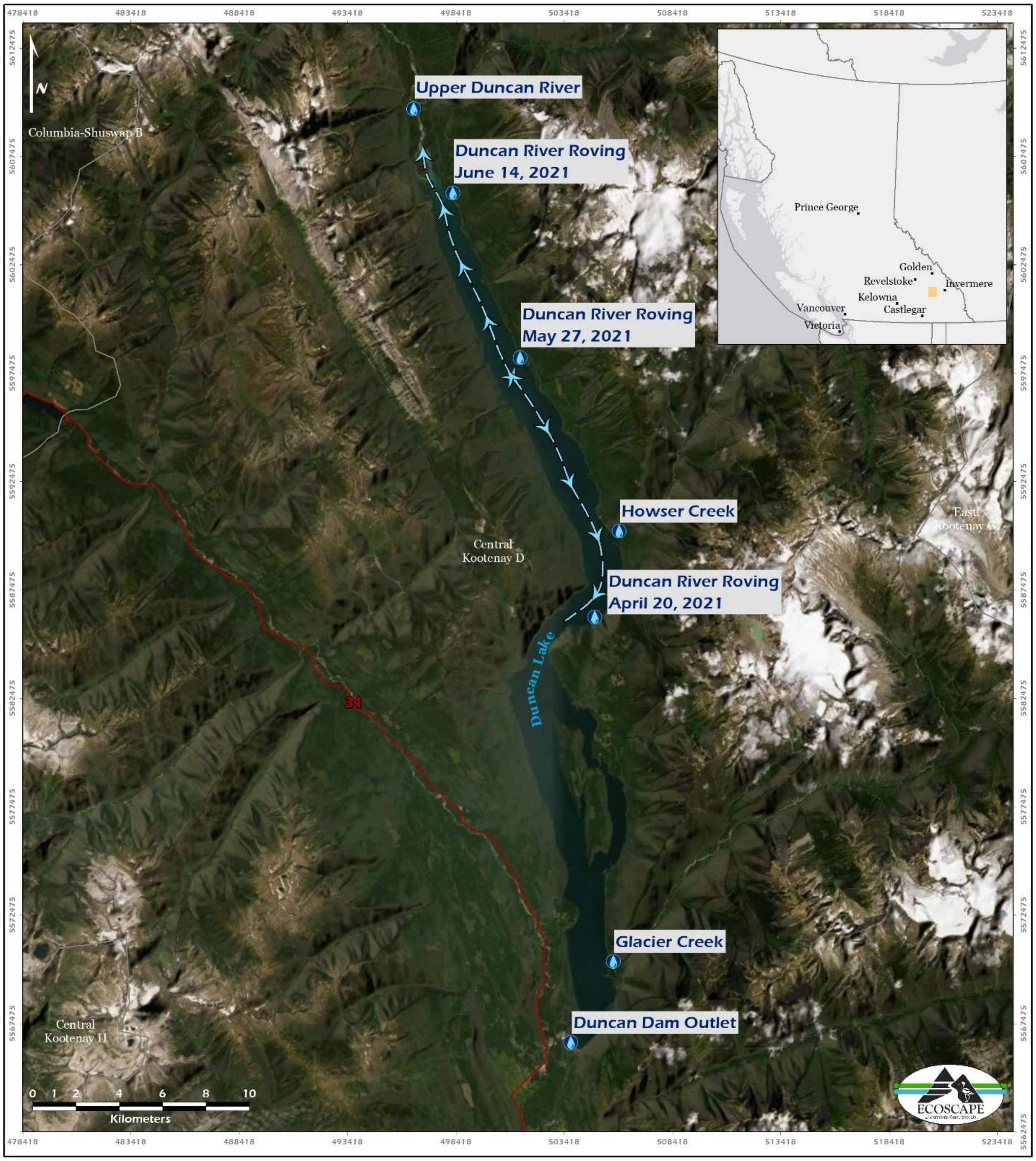

Figure 3-1. Import and Export Sampling Locations (2021). The arrows indicate the northern most wetted edge of the reservoir when the elevation fluctuates throughout the year.

During each sampling event, one water sample was collected in either a triple rinsed gallon container (Glacier and Howser creeks) or with a clean Van Dorn sampler (upper Duncan River and Duncan Dam Outlet). Water from the collection vessel was distributed into prelabeled amber glass containers and stored on ice prior to shipment to ALS Laboratories for analysis of TP and TDP. Water for TDP was field filtered using a syringe and 0.45-micron filter. In addition to the three import and one export samples, one duplicate, one field blank and one travel blank were analyzed for TP and TDP, for a total of 7 samples per trip. A duplicate sample was randomly assigned to one of the four sites and was obtained from the same collection container as the site sample. Duplicate samples were used solely to provide quality control on nutrient analysis and values where not incorporated within subsequent analysis. Nitrile gloves were worn throughout the sample processing.

Given the ease and affordability of *in-situ* data collection, the following parameters were also collected at each import and export site using a YSI multimeter. *In-situ* data included:

a. Site name
b. Date
c. Time
d. Water temperature (°C)
e. pH
f. Oxidation Reduction Potential (ORP)
g. Dissolved Oxygen (mg/l and %)
h. Conductivity (µS/cm and µS/cm A)
i. Total Dissolved Solids (ppm)
j. Salinity
k. Turbidity
l. Latitude and Longitude

Water Survey of Canada does not operate flow gauges on Glacier, Howser or smaller creeks. The daily water input of these tributaries was determined as the difference between the change in reservoir storage volume and the difference between inputs from Duncan River inflow, and discharge at the dam (Perrin & Korman, 1997). The residual daily volume was then allocated to the tributaries proportionally to their percentage of catchment size, 17%, 11%, and 17% to the Howser, Glacier and other small tributaries respectively.

Similar to Perrin & Korman (1997), our approach was to collect P samples on Glacier and Howser creeks, and then multiply the calculated daily combined inflow from Glacier, Howser and other smaller tributaries by the average TDP concentration measured in Glacier and Howser, to estimate the total daily import of TDP from other smaller tributaries. This approach assumes that P concentrations measured in Glacier and Howser were representative of those in the unmeasured smaller tributaries. We are aware that this approach introduces a level of error (Akers et al., 2020), however, in 1994-95, the smaller unmeasured tributaries contributed <10% of all the TDP to

DLR, therefore, the enhanced precision of sampling additional creeks was not deemed worth the added sampling effort and cost of analyses.

3.2 Re-Evaluation of Phosphorus Budget

The re-assessment of phosphorus retention was done in four parts:

1. First, we recreated the analysis conducted by Perrin & Korman (1997), to confirm that their methodologies were understood and reproducible.
2. Second, we explored alternative methods presented in the literature review to develop nutrient budgets when flow sample frequency and nutrient concentration sampling frequency occur at different time steps (i.e., daily flow values & bi-weekly concentration samples) (Akers et al., 2020).
3. Thirdly, we reevaluated Perrin & Korman's (1997) methodology to incorporate drawdown P contributions using a linear interpolation.
4. Lastly, we compared our 2021 sample values with those of the 1994-95 program to explore how P-concentrations may have changed over time.

3.2.1 Part 1: Approach and Assumptions of Phosphorus Retention using 1994-95 Data

Using the raw values provided within *Appendix C: Chemical concentrations at stream sites in the Duncan catchment, 1994-95* (Perrin & Korman, 1997), we recreated their retention calculations as closely as possible using their described methods. Our analysis was based on the following assumptions:

- Perrin & Korman (1997) held nutrient concentrations between samples constant (i.e., 5 μg/L TP concentration would be multiplied by the total volume of water at a specific site between samples).

The initial fall/winter sampling (September to January, 1994-95) methods only sampled the upper Duncan River and did not sample within the Duncan River drawdown zone. To compensate for the missing drawdown zone input, Perrin & Korman (1997) used a linear interpolation between the September concentrations and the January concentrations within the drawdown zone (Figure 3-2). Specifically, Perrin & Korman were addressing the January 1995 TP concentration discrepancies, where the Duncan River samples in the drawdown zone were ~30 μg/L, compared to TP samples taken upriver that were only 8 μg/L on the same day.

When daily inflow volume discrepancies arose (reservoir volume change was incongruous with Dam outflow and upper Duncan inflow resulting in *negative* creek inflow volumes), we attributed this to wind and waves producing inaccurate reservoir elevations used to derive the reservoir volume. Subsequently creek inflow volumes were set at zero for the day, and adjustments were made to storage volume and dam outflow following Perrin & Korman's (1997) methods:

- At any flow <10 m^3s^{-1} where a water balance error occurred, the outflow at the dam was adjusted to remove the error (balance flows with change in storage volume). The flow of <10 m^3s^{-1} was considered low at the dam, given that the lowest was 3 m^3s^{-1} and the highest was 316 m^3s^{-1} in 1994-95.

- At any flow >10 m^3s^{-1} where a water balance error occurred, the storage volume was adjusted to remove the error.

By reanalyzing the data following the 1997 methods, we were able to develop our own baseline values, which differed from Perrin & Korman (1997) by only 1-3%. The driving factors contributing to the minimal difference are likely small methodological inconsistencies dealing with flow volume discrepancies and potentially using different river flow and reservoir volume values provided through the Water Survey of Canada and BC Hydro. By developing our own baseline, we ensure that any differences in future analyses are the result of the updated methods, rather than inconsistent methodologies between our approach and that of Perrin & Korman (1997).

3.2.2 Part 2: Updating the 1994-95 Phosphorus Budget – Daily Estimation

While the sampling frequency used by Perrin & Korman (1997) aligned with modern approaches, their analytical methods for calculating overall P retention are now outdated. Rather than holding a nutrient concentration consistent across multiple days, daily estimates of concentration are now widely used. These daily concentration estimates are produced using continuous water flow data and instantaneous nutrient concentration data. Various methods and programs exist to produce these estimates including local interpolation, such as the Graphical Constituent Loading Analysis System (GCLAS) (Koltun et al., 2006), load estimation, such as used within the LOADEST program (Runkel et al., 2004), or weighted regression, such as Weighted Regressions on Time, Discharge, and Season (WRTDS) (Hirsch et al., 2010). The aim of these various methods is to increase the resolution of concentration data as it relates to hydrological events (i.e., large rainfall or peak freshet flows), and reduce the errors produced by longer time steps.

We explored each of the three following methods for generating daily estimates for the 1994-95 data:

- Local Regression – Moving averages incorporating a weighted mean
- ARIMA – Auto Regression Integrated Moving Average
- Loess – Local Polynomial Regression

Note that these methods were explored to update the 1994-95 phosphorus budget and are not related to the retention models discussed in Section 3.3.

3.2.3 Part 3: Updating the 1994-95 Phosphorus Budget – Drawdown Zone Interpolation

The second update to the 1994-95 phosphorus budget was to expand on the drawdown correction undertaken by Perrin & Korman (1997). Specifically, the linear interpolation between the September concentrations in the upper Duncan River and the January concentrations in the Duncan River as it flowed through the drawdown zone failed to reflect any of the changes in P concentrations that occurred at the Upper Duncan River site. For example, on Sept. 13, 1994, the Upper Duncan River TP concentration was 4.9 µg/L (the initial date used for the linear interpolation), but on Sept. 26, 1994, the TP concentration was 20.4 µg/L (Figure 3-2). The linear interpolation does not reflect this spike to 4 times the starting value, thus underestimating the concentration within the drawdown zone. To correct for the shortcomings of the linear interpolation, we defined a function that determined TP & TDP as a product of the Upper Duncan River flow and the reservoir elevation for this period from September 1994 to January 1995.

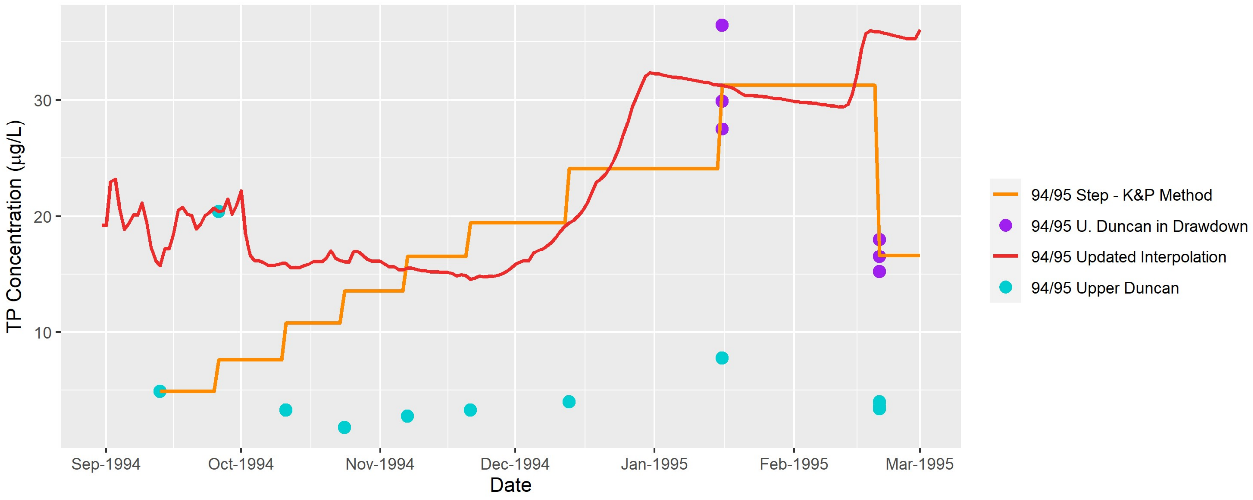

Figure 3-2. Total Phosphorus measured in the upper Duncan River, Sept-Mar 1994-95. TP concentrations are represented by light blue dots showing 1994-95 samples taken within the Upper Duncan River outside of the drawdown zone and purple dots showing 1994-95 samples taken within the Upper Duncan River in the drawdown zone. The orange line represents the interpolation used to estimate TP within the Upper Duncan River in the drawdown zone by Perrin and Korman (1997), whereas the red line uses the same 1994-5 data set but uses a weighted equation (Equation 3) that defined TP for the Upper Duncan River in the drawdown zone as a product of reservoir elevation and river flow.

3.2.4 Part 4: Comparing Phosphorus Values in 1994-95 & 2021

Ultra-low phosphorus data (TP and TDP) collected in 2021 were compared with data from 1994-95, using box and line plots. To tease apart variation at the Duncan River roving and full pool site, graphs are presented with a date of transition from roving to full pool (Figure 4-3 & Figure 4-4). Reservoir elevation and inflows during each sample year were compared. Similarly, *in Situ* data, including turbidity and pH, were graphed to help inform TP and TDP results and our understanding of the 2021 results. Finally, 2021 P detection limits were included on graphs to aid with interpretation. Perrin and Korman (1997) did not report a detection limit and therefore we had some difficulty in comparing the two datasets. Finally, a duplicate analysis was also undertaken given that many of the TDP samples were near or below the detection limit and some duplicate concentrations varied from sample concentrations.

3.3 Modeling Retention and Estimation of Operational Impacts

We began our exploration of modeling P retention and estimation of operational impacts by re-producing the methods used during the 2004 Consultative Committee (CC) process. Specifically, this involved deriving their equation used to estimate seasonal retention and secondly to use this equation to estimate annual retention for a variety of dam operation alternatives. Following this reproduction, we explored modelling inflow P concentrations at the Upper Duncan River, Glacier and Howser Creek using readily available hydrologic data (flow, elevation, volume, surface area, etc.). Lastly, P concentration flowing out of the reservoir was modelled using similar hydraulic data to reflect the mixing and settling characteristics of the reservoir.

3.3.1 Reproduction of CC Process: TDP Model & Associated Estimates

To our knowledge, no formal documentation exists that clearly defines the methods and assumptions used when developing the following equation for estimating retention of TDP:

Equation 2:

$$[TDP]_{outQ} = 11.84 \cdot 10^{8} \cdot {}^{[TDP]_{inQ}}\!/_{V_{Resvr}}$$

The brief explanations provided in Section F and Appendix H of the CC report (BC Hydro and Power Authority, 2005), and the various sheets of calculations within the *DDM_Nutrient* excel sheet provided by BC Hydro, were used as a template to reproduce the entire process using R (R Core Team, 2021), a statistical programming language that is ideal for reproducible complex data manipulation and analysis.

We used Equation 2 to estimate TDP retention within various operational regimes, as was done during the CC process. The specific assumptions in our estimations of the operational regimes used in the CC process are based on descriptions within the CC documentation and correspondence with BC Hydro (pers. comm., Alf Leake, 2020):

- Alternative A – The method used for 1968-1999 dam operations.
- Alternative SD73 – This was the reservoir flow constraints and elevation benchmarks chosen to shape operations following the CC report; therefore, all flow values after the CC report (2006-present) need not be altered (status quo).
- Nutrient Alternative – Theoretically, maintaining the maximum allowed reservoir elevation will minimizing nutrient retention (Figure 2-1).

The constraints that dictate the reservoir elevation, based on the CRT, include:

- Maximum reservoir elevation at full pool (between 576.38 and 576.68 m) during the period between August 1 and August 10;
- Maintain full pool, or within 0.3 m of this level, until Labour Day;
- Elevation target (<569.8 m) on December 31; and
- Low pool elevation targets (<551.0 m high snow years; <564.4 m low snow years), with a minimum elevation drawdown of 546.87 m.
- Minimum monthly discharge is 3.0 m^3/s.

Reproducing the various retention values provided an opportunity to evaluate potential methodological errors and to once again generate an independent baseline to assess our updated model.

3.3.2 Modelling Inflow Phosphorus Concentration

Our updated TDP concentration modelling approach differs from the 2004 CC process in four main ways:

1. Rather than aggregate multiple concentration values into seasonal averages (such as Equation 2), we maintained each sample as its own data point to be used when building our predictive model.
2. Each of the unique inflow concentration values are predicted based on hydraulic variables, rather than simply using a season average as a determinant of inflow TDP concentration.
3. Each of the three main inflow sources were treated as unique inputs.
4. Our modelling methods incorporated considerations of time, including date and varying lag times (4, 7, 14, 30, 60 & 90 days) between flow events prior to TDP sampling days.

Predictor variables for inflow P concentrations were pulled from the literature review (Akers et al., 2020), specifically rates of flow at Glacier Creek, Howser Creek, the Upper Duncan River and reservoir elevation. Reservoir elevation was chosen due to the uptake/discharge of nutrients as water travels through the drawdown zone. Each of these predictors were calculated daily, in contrast to the bi-weekly or monthly P sampling. To explore the impact of flow and elevation change preceding a nutrient sample date, a series of flow and elevation metrics were calculated over lag windows of 4, 7, 14, & 30-days (Laini et al., 2018). The various metrics explored are summarized in Table 3-3. Predictor selection was conducted using correlation matrices of flows and elevation metrics with nutrient concentrations.

Table 3-3. Predictor metrics for flow and elevation considered for inflow models.

Predictor	Description	Lag Window	Source
Flow Mean / Elevation Mean	Mean of the daily values for the period	Yes	Laini et al., 2018
Flow Median / Elevation Median	Median of the daily values for the period	Yes	Laini et al., 2018
Minimum Flow / Elevation	Min of the daily values for the period	Yes	Laini et al., 2018
Maximum Flow / Elevation	Max of the daily values for the period	Yes	Laini et al., 2018
Range of Flow / Elevation	Difference between maximum and minimum daily values	Yes	Laini et al., 2018
CV of Flow / Elevation	Coefficient of variation in daily values	Yes	Laini et al., 2018
Hy5 of Flow / Elevation	Variability in flows divided by median values. Variability is calculated as the 90th-10th percentile range	Yes	Laini et al., 2018
Pattern of Flow / Elevation	Difference between maximum and minimum daily values multiplied by net fall or rise.	Yes	Laini et al., 2018
Rise Rate Flow / Elevation	Average positive differences between daily values	Yes	Richter et al., 1996
Fall Rate Flow / Elevation	Average negative differences between daily values	Yes	Richter et al., 1996

Following variable selection, various modelling methods were compared using a 5-fold cross validation. Parametric regression models considered included a stepwise multilinear regression, ridge regression, local polynomial regression, partial least squares (PLS) and non-parametric models included a random forest model. The optimal model, with the lowest overall and relative mean squared prediction error (MSPE) from the cross validation was the random forest model for both TDP and TP. Both random forest models were tuned, with an optimal number of trees being one with a terminal node size of eight for both response variables.

3.3.3 Modelling Outflow Phosphorus Concentration

Similar methods were explored to predict nutrient outflow concentration from the Duncan Dam. While flow and elevation were the main determinants of inflow concentrations, outflow concentrations were influenced by more diverse hydraulic processes, such as retention time, stratification, and nutrient sedimentation, as outlined within the literature review accompanying this project (Akers et al. 2020). Specific predictors explored are summarized in Table 3-4. Each predictor was explored over an array of lag windows: 4, 7, 14, 30, 60 & 90 days. Like inflow modelling, the metrics described in Table 3-34 were calculated for each of the predictor variables outlined below where logically appropriate. Predictor selection was conducted using correlation matrices of flow, elevation, and other metrics with nutrient concentrations.

Optimal model selection was conducted using the same 5-fold cross validation methods described for inflow models above. The optimal models for TDP and TP outflow were a partial least squares regression & a random forest model, respectively.

Table 3-4. Predictor variables considered for outflow models.

Predictor	Description	Lag Window
Area Water Loading	The ratio of water volume inflow to reservoir surface area	Yes
Hydraulic Washout	The ratio of water volume outflow to reservoir volume	Yes
Retention Time	The ratio of reservoir volume to water volume inflow	Yes
Elevation	Elevation of the reservoir – Fill in for depth	Yes
Surface Area	Surface area of the reservoir; influences size of pelagic zone	Yes
Volume	Volume of the reservoir	Yes
Water Volume Inflow	Water Volume entering the reservoir	Yes
Total P Conc Inflow	Average TDP or TP concentration at inflow sites	Yes
Total P Weight Inflow	Total weight of TDP or TP at inflow sites (conc * volume)	Yes
Glacier P Conc Inflow	Average TDP or TP concentration at Glacier Creek ~5km from the dam	Yes
Glacier P Weight Inflow	Total weight of TDP or TP at Glacier Creek ~5km from the dam (conc * volume)	Yes

In summary, the amount of phosphorus retained in the Duncan Lake Reservoir is the difference between inflow P and outflow P. Estimating this difference from intermittent samples requires the models introduced in this section and discussed further below.

3.3.4 Estimating Phosphorus Retention for Dam Operation Alternatives

Following the identification of suitable models that incorporates smaller time steps, total TDP & TP released and retained within the DLR were calculated for the 1994-95 sampling period. This revisiting of the original data provides a reference between the various models and phosphorus budgets. The best model was then used to analyze the different operational influences on TDP retention. We compared nutrient retention during status quo operation (SD73) with an operation that maximized TDP transfer to Kootenay Lake – the nutrient optimal operation (following similar methods to those of Leake & Perrin (2004), Appendix H of BC Hydro and Power Authority (2005) and as per the TOR). This SD73 operation is confined by CRT requirements and other hard constraints of the DDM. The updated estimates for these two operation regimes were compared to evaluate the performance measure outlined within the WUP, and either verify or refute the findings of the preliminary analysis conducted as part of the CC process (BC Hydro and Power Authority, 2005). Lastly, these new estimates were used to assess the current DDMWORKS-3 funding contribution.

4.0 RESULTS AND DISCUSSION

4.1 2021 Phosphorus Concentrations, 1994-95 Comparison with 2021 Results

The 2021 sampling covered the major flow periods of the DLR (April to October), with the 2021 hydrologic cycle having above average peak flows through June due to the unprecedented heat experienced throughout the province (Figure 4-1).

Despite the unusually warm temperatures, 2021 total phosphorus (TP) samples were within a similar range to those found within the 1994-1995 study (Figure 4-2), with the most dissimilarity occurring at the dam outflow location. As was observed within the 1994-95 sampling period, Upper Duncan 2021 samples from the drawdown zone had significantly higher TP concentrations than samples taken upriver; an average of 44 µg/L compared to 9 µg/L (Figure 4-2 and Figure 4-3). The DDM drawdown zone is still acting as a significant nutrient source to the reservoir and this aligns with research elsewhere (Furey et al., 2004; Kaufmann et al., 2014; Shantz et al., 2004; Carmignani and Roy, 2017).

TDP values observed within the 2021 sample period were significantly different ($t(23) = 6.5, p = 1.2 \times 10^{-6}$) than those observed in 1994-95 (Figure 4-2 & Figure A-2), with 66% of samples occurring below the ultra-low detection limit of 1.0 µg/L. The independence assumption of our samples is violated within this t-test, which would bias our result towards being similar. Given the significance of the test despite this bias, it can be concluded that the 2021 values for TDP fall outside of the expected range based on the 1994-95 data. Once again, both sample periods showed the most dissimilarity occurring at the dam outflow location. However, TDP loading in the Upper Duncan River drawdown zone appeared to be far lower in 2021 than it was in 1994-95 (Figure 4-2 & Figure 4-4).

Context for the DLR nutrient regime is provided by TDP data collected in the adjacent Beaver Creek, Woolsey Creek, and Illecillewaet River watersheds (Province of BC, 2021). These watersheds had TP in similar ranges to the Duncan River (peak of ~200 µg/L) but have never recorded a TDP concentration greater than 2 µg/L in the 9 years that TDP has been recorded (TP data 1987-2021; TDP data 2012-2021). While these neighbouring creeks and rivers do not have matching climate and geographic conditions to the Duncan River, the proximity of their headwaters (with 1 km of the Beaver Creek) suggests they should behave similarly. This regional context aligns with the 2021 TDP data more than the 1994-95 TDP data. It is possible that the 1994-95 concentrations represent an atypical year or are the product of a methodology error.

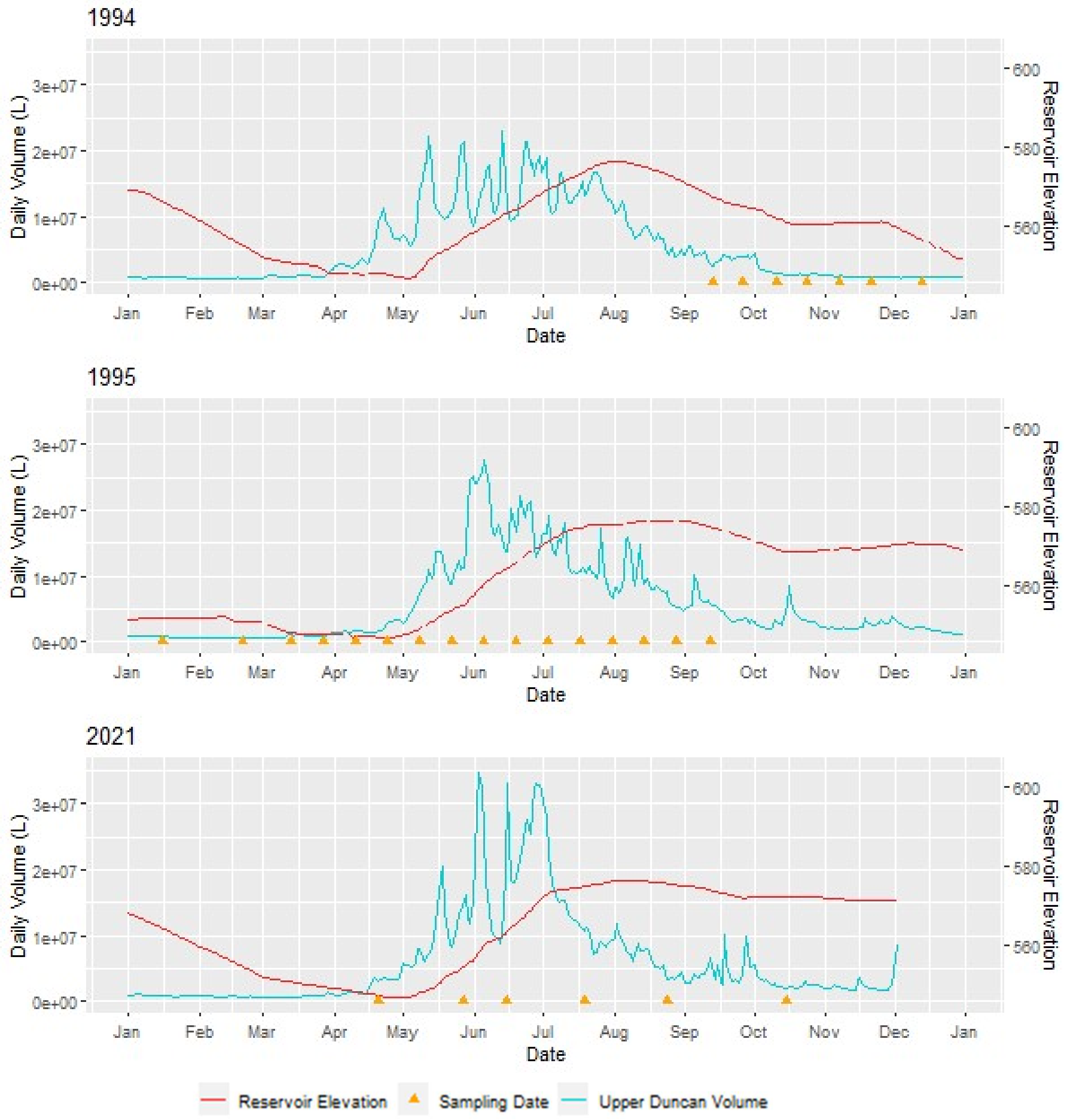

Figure 4-1. Reservoir elevation and inflow water volume from the upper Duncan River in sample years 1994, 1995 & 2021. Sample dates are indicated by orange triangles.

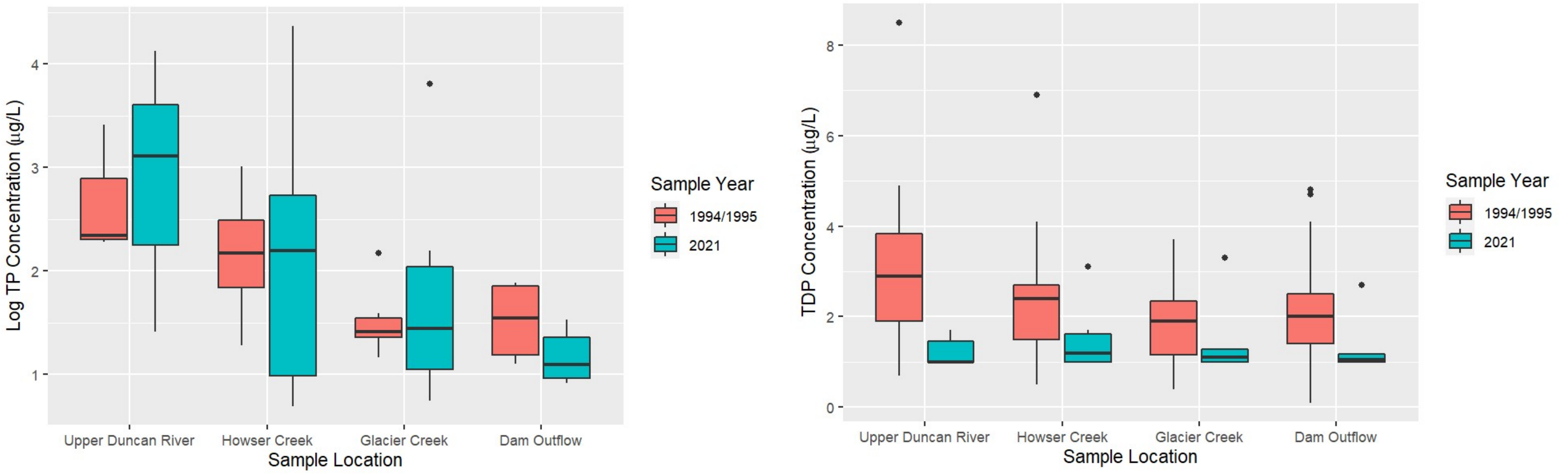

Figure 4-2. (Left) Log of total phosphorus concentration (µg/L) at the sample locations. (Right) Total dissolved phosphorus concentrations (µg/L) at the sample locations. Each box represents six (6) samples, where the closest sampling date from the 1994-1995 period was paired with each sample from 2021 (i.e., samples from the third week of April in 1995 & 2021 are included, whereas the first week of April samples from 1995 are not included in the boxplot). Any 2021 TDP data below the 1 µg/L detection limit is displayed as the detection limit

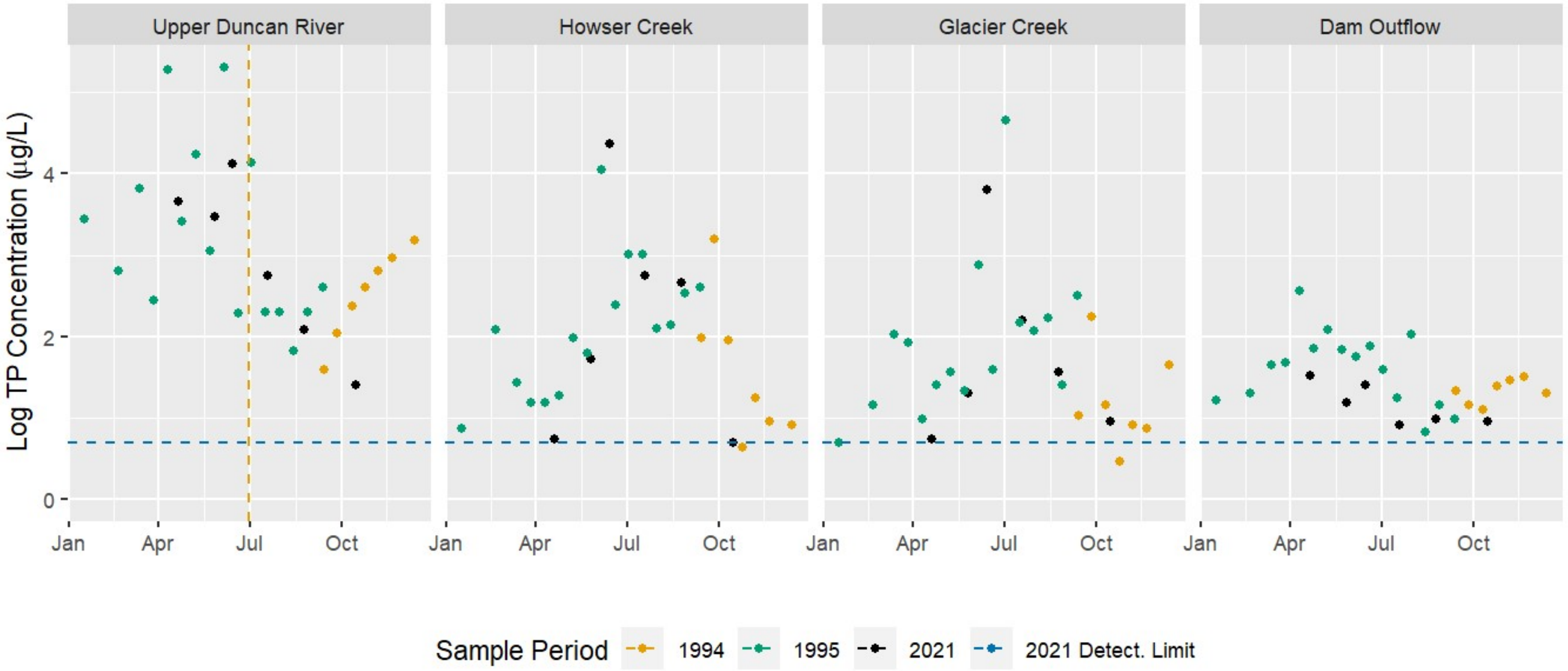

Figure 4-3. Log of total phosphorus concentration (µg/L) at sample locations. Twenty-one (21) samples at each site were taken in the 1994-95 sampling period, with bi-monthly sampling from March-November and monthly sampling from December, January & February. Six (6) samples occurred at each site in 2021 in April, May, June, July, August & October. The horizontal blue dashed line identifies the 2021 detection limit for TP concentrations, and the vertical dashed orange line denotes the date where sampling transitioned from the Upper Duncan River in the drawdown zone to upstream.

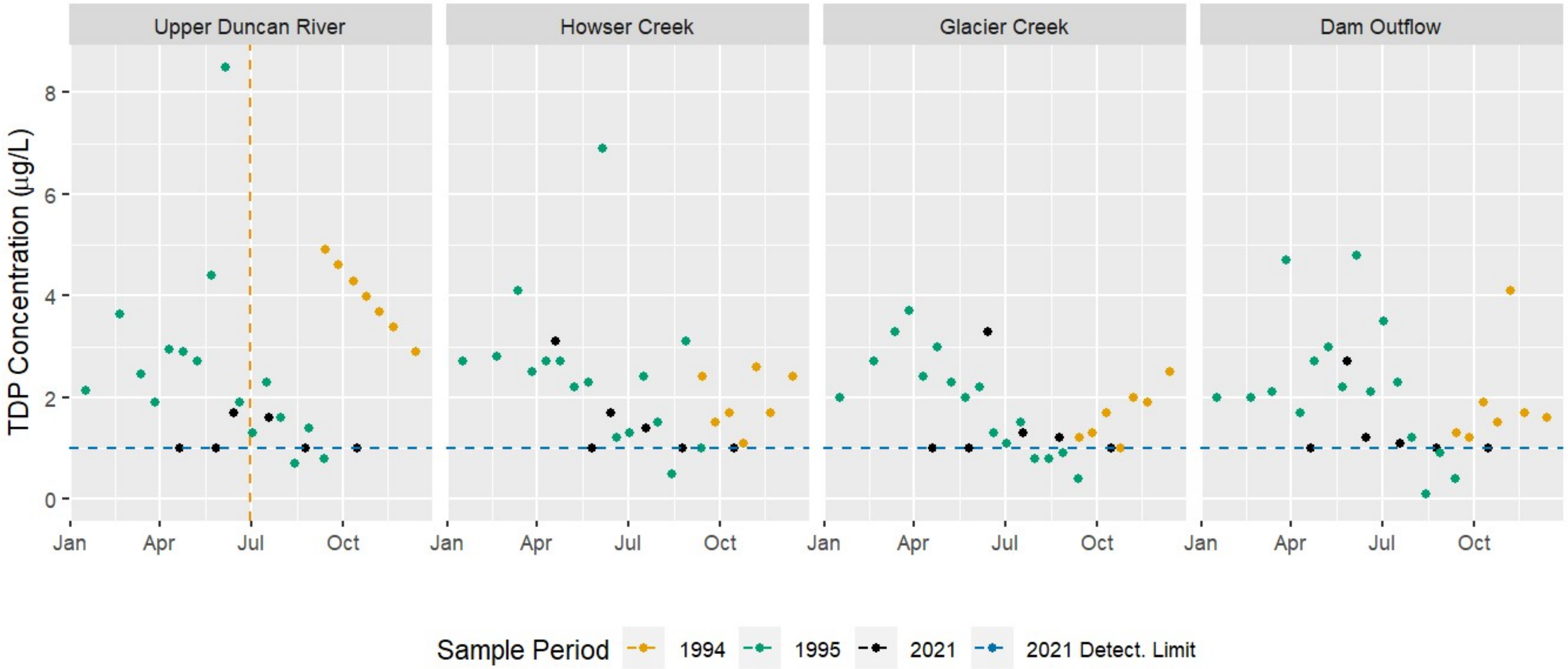

Figure 4-4. Total dissolved phosphorus concentration (µg/L) at sample locations. Twenty-one (21) samples at each site were collected in the 1994-95, with bi-monthly sampling from March-November and monthly sampling from December-February. Six (6) samples occurred at each site in 2021 in April-August & October. Any 2021 TDP data below the 1 µg/L detection limit is displayed as the detection limit. The horizontal blue dashed line identifies the 2021 detection limit for TDP, and the vertical dashed orange line denotes the date where sampling transitioned from the drawdown to the Upper Duncan River location.

The percentage of TDP:TP in inflowing creek samples was ~10-30% in 1994-95 and dropped to 4-20% 2021, reflecting the apparently larger decline in TDP imports compared to TP, particularly from the Upper Duncan River. Interestingly, the TP percentage was stable in the discharge near ~4-5% during both sampling periods. In oligotrophic environments such as DLR, TP is often 10 to 50 times higher than TDP because TP measures phosphorus bound to sediment suspended in the water.

Sample variability, even at the 2-week intervals, included nutrient spikes through all sampling periods (Figure 4-4). These nutrient spikes demonstrate that TDP concentrations are changing more rapidly than our sampling frequencies can discern. This variability may explain the overall low TDP values for the 2021 sampling period since only 6 monthly samples were taken in 2021 compared to the 21 bi-weekly samples in 1994-95. The chances of capturing nutrient peaks decline with infrequent sampling. Temporal variability in TDP is widely observed in regional watersheds (Province of BC, 2021).

On a larger temporal scale, we are still limited in our ability to comment on TDP variability because of reduced sampling. Fortunately, mid-September was sampled both in 1994 and 1995, and provides a context for the annual variability in TDP. For the upper Duncan River, TDP concentration was 4.9 µg/L on Sept. 13th, 1994, and 0.8 µg/L on Sept. 12th, 1995, representing a difference of over 600% despite the same sample locations and methods. This level of variability at the same location, only a year apart, suggests that although most 2021 samples are lower than those observed in the 1994-95 sampling for similar dates, they may not be indicative of a larger climatic and/or nutrient shift.

Korman and Perrin (1997) reported nine instances where TDP concentrations were below the lowest commercially available detection limit. However, they did not report a detection limit for their TP or TDP sampling, which has raised concerns regarding the validity of the nutrient processing methods they employed. Unfortuantely they provide little detail beyond stating that samples were digested and analyzed using Menzel and Corwin's (1965) potassium persulfate method.

Today's lowest commercially available detection limit is 1.0 µg/L using the ultra-trace by colorimetry method APHA 4500-P E (mod) at ALS Laboratories which involves persulphate digestion. The 2021 travel and field blanks were all below detection limit indicating in-field and lab accuracy.

Duplicate samples for TP were most similar, the closest pair being 4.1 µg/L and 3.9 µg/L (a 0.2 µg/L difference), and the worst pair being 4.1 µg/L and 2.2 µg/L (a 1.9 µg/L difference; Table 4-1). One pair of TP duplicates was below the detection limit of 2 µg/L while the paired sample was 2.1 µg/L. The TP duplicate analyses indicate an acceptable level of accuracy.

The TDP duplicate analysis are difficult to interpret due to the low TDP concentrations. Duplicate samples for TDP were affected by the low TDP sample concentrations. Only one pair of samples was above the detection limit (1.3 µg/L and 1.9 µg/L), three pairs were below detection limit, and the remaining two pairs had one below detection and one above (1.2 µg/L and 1.0 µg/L) (Table 4-1).

Table 4-1. Summary of 2021 duplicate samples.

Date	Sample Location	TP (µg/L)	TP Duplicate (µg/L)	TDP (µg/L)	TDP Duplicate (µg/L)
2021-10-15	Upper Duncan River	4.1	2.2	0.5*	0.5*
2021-08-24	Howser Creek	14.3	11.3	1.0	0.5*
2021-07-19	Glacier Creek	9.0	5.2	1.3	1.9
2021-05-26	Glacier Creek	3.7	3.0	0.5*	0.5*
2021-04-19	Glacier Creek	2.1	1.0 *	0.5*	0.5*
2021-06-15	Duncan Dam outlet	4.1	3.9	0.5*	1.2

* Sample below detection limit (with value reported as half of limit)

If we assume that the data from both sample campaigns are sufficiently robust to support the conclusion that TDP, particularly TDP in the Upper Duncan River site, has declined significantly between 1994-95 and 2021, this 26-year TDP decline could be accounted for by:

Regional Hydrology

- Duncan River at DLR is expected to continue to experience increasingly higher winter flows, earlier snowmelt, higher peak flows, earlier peak flow, and lower summer/fall flows (Carver, 2022). These important hydrographic changes may alter sediment transport (affects TP) and groundwater inflows (affects TDP) to the river.[1]
- The 2021 hydrologic cycle had above average peak flows through June due to the unprecedented heat experienced throughout the province which could alter the timing and amount of P delivered to the DLR (Figure 4-1).
- Increased frequency of extreme weather events over the past 20 years (Carver, 2022) can cause short pulses of sediment-bound TP transport. The rate of occurrence of extreme weather events is predicted to accelerate.
- Changes in upstream flows and nutrient delivery with more extreme hydrographs is likely to affect all DLR tributaries.

DLR Management

- Recent dam operations have achieved more consistent reservoir elevation movement throughout the year, unlike the inconsistent elevations observed in spring months throughout the 1990s (Figure 4-1).
- The DLR drawdown zone historically experienced more periods of watering-dewatering, freeze-thaw, and channel braiding than it does currently. This

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[1] Increased flows transport more sediment (TP), while decreased flows allow more influx of groundwater which carries more dissolved nitrogen (NO3, NO2 ammonia, etc.).

decrease in drawdown variability may be contributing to the decreased TDP observed in the spring upper Duncan River sampling (Figure A-1).

- The drawdown zone had experienced ~26 annual drawdown cycles from 1969 to 1995 and should have released most of the initial nutrient surge from the original wetland/floodplain/forest soil areas prior to the 1994-95 sampling. However, nutrient release, particularly P, may have decreased further by the 2021 sampling following 26 more drawdown cycles due to anoxic/oxic nutrient depletion in drawdown soils. Alternately, decreased vegetation in the upper 10 m of the drawdown zone documented between 2009 and 2018 (Rood et al. 2019), can alter nutrient cycling.

Nutrient Travel within the DLR

- Passage of nutrients through DLR is subject to climatic drivers affecting primary productivity, stability of stratification, creek plume travel depths, etc.
- Sediment and particulate P settling out of the water column may change as the inflow regime is altered by climate and land use within the watershed.

The sum of these changes will affect nutrient delivery to and retention within the DLR. Their cumulative effects are challenging to predict.

In summary, the 2021 sampling results demonstrate a overall decrease in TDP measured at most sites, particularly TDP loading in the Upper Duncan River drawdown zone appears to be far lower in 2021 than it was in 1994-95. We have limited ability to pinpoint the mechanisms that have resulted in these decreased TDP levels in 2021. This is particularly challenging due to TP levels in 2021 closely mirroring seasonal values and variation of the 1994-95 baseline.

4.1.1 2021 In-Situ Measurements

We also collected in-situ field measurements (Table 4-2; Table A-1). These data indicate that the DLR system is well oxygenated, alkaline, has low dissolved solids (TDS, salinity, conductivity) and has significant suspended solids (turbidity). The inevitable heat gain as water progresses through the reservoir system is evident. The data for Howser Creek demonstrates that this inflow has greater density than the receiving reservoir water and that its inflow plume will plunge. Water from other creeks may also plunge, depending on the depth of matching density in the reservoir water column and stratification. Retention time of inflows within the reservoir may therefore be less than the theoretical retention time.

Turbidity at the dam outflow was far lower than inflowing creek turbidity in all years due to particulate settling within the reservoir. However, the outflow averaged 1.81 ± 1.28 NTU in 2021which indicates significant fine sediment/particulate export from the deep DLR water. DLR outflow turbidity was even higher between Apr-Sept 1995, averaging 11.3 ± 6.71 NTU. Turbidity apparently reached 15-20 NTU in freshet 1995, while turbidity was stable at ~2 NTU through the 2021 freshet but increased to 4.2 NTU in mid-summer (Figure 4-5). These turbidity differences suggest change in how sediment is imported to and exported from DLR.

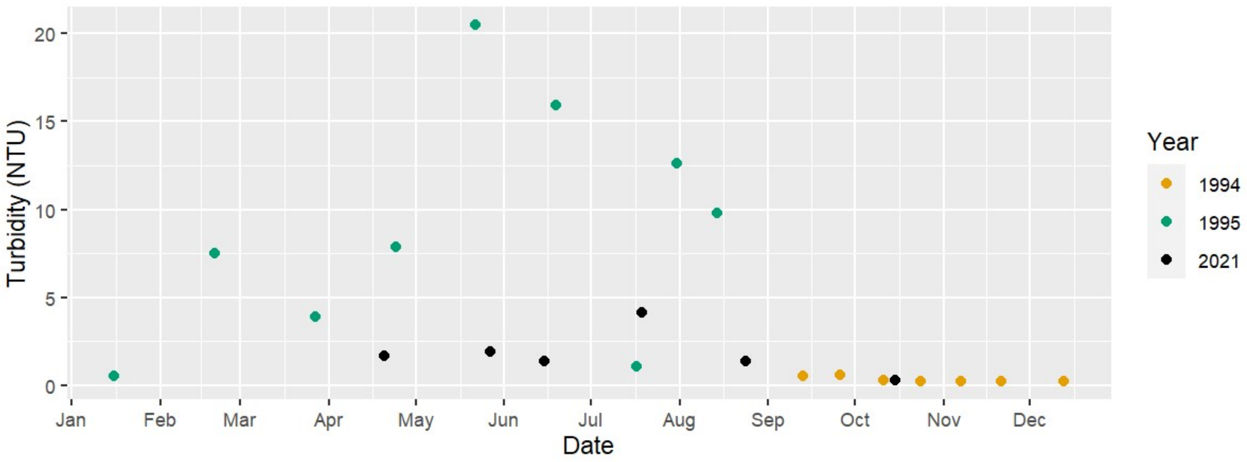


Figure 4-5. Turbidity (NTU) measured at the Dam outflow across sampling years (1994 & 1995).

Table 4-2. Range (*mean +/- sd*) of *in-situ* 2021 field measurements at sample locations.

Parameter	Upper Duncan	Glacier Creek	Howser Creek	Dam Outflow
Temperature (°C)	9.62 ± 3.27	10.4 ± 3.17	10.07 ± 2.59	11.02 ± 1.22
pH	7.91 ± 0.18	7.76 ± 0.41	7.91 ± 0.39	7.69 ± 0.17
Dissolved Oxygen (%)	98.35 ± 3.8	98.83 ± 9.77	104.58 ± 5.1	92.28 ± 10.98
Dissolved Oxygen (mg/L)	11.25 ± 0.97	11.11 ± 1.41	11.8 ± 0.71	10.19 ± 1.34
Conductivity (µS/cm)	71.06 ± 12.57	57.06 ± 10.05	93.06 ± 26.12	77.72 ± 6.1
Total Dissolved Solids (mg/L)	67.85 ± 16.9	52.68 ± 11.58	86.86 ± 27.34	69.24 ± 6.58
Salinity (psu)	0.05 ± 0.01	0.04 ± 0.01	0.07 ± 0.02	0.05 ± 0.01
Turbidity (NTU)	11.03 ± 7.18	3.43 ± 4.39	12.15 ± 14.1	1.81 ± 1.28
Oxidation Reduction Potential (mV)	84.82 ± 41.44	81.17 ± 28.58	91.35 ± 13.97	89.28 ± 20.38

pH can be depressed for decades after reservoir flooding due to the release of decomposition products. The difference in pH from Apr-Oct 1994-95 after 27 years, and Apr-Oct 2021 after a further 26 years was 8.01 ± 1.07 to 7.91 ± 0.18 at the inflow Upper Duncan Site and 8.23 ± 0.58 to 7.69 ± 0.17 at the DLR outflow site. While the inflow pH was essentially unchanged, the dam outflow pH was lower in 2021 and may indicate genuine change in the DLR.

4.2 Re-evaluation of 1994-95 Phosphorus Budget

4.2.1 Re-creation of Phosphorus Retention using 1994-95 Data

Through recreating the 1997 methods, we were able to develop our own baseline values, which differed from the original results (Perrin & Korman, 1997) by only 1-3% among sampling locations. This small difference likely arose from methodological differences dealing with flow volume discrepancies and potentially from using different river flow & reservoir volume values provided through the water survey of Canada and BC Hydro. Developing our own baseline ensures any differences in future analyses are the result of the updated methods, rather than the differences highlighted above.

4.2.2 Updating the 1994-95 Phosphorus Budget – Daily Interpolation Between Samples

Perrin & Korman (1997) held nutrient concentrations consistent across multiple days between samples. Our exploration of generating more accurate daily estimates for concentration included the exploration of the following three interpolation methods, given their pre-exiting integration within R (R Core Team, 2021):

- Local Regression – Moving averages incorporating a weighted mean
- ARIMA – Auto Regression Integrated Moving Average
- Loess – Local Polynomial Regression

Unfortunately, given the spread of the 1994-95 data (with one sample every 2 weeks over 12.5 months over multiple sites), we had an insufficient sample size to accurately develop an interpolation. Specifically, because the samples have a large amount of variation with some high *outliers*, these resulted in each of the interpolation methods not only under-inflating these spikes, but also predicting periods of negative nutrient concentration, which is impossible. In the end, no regression interpolation method was successful in producing realistic daily concentration estimates and we opted to use a linear interpolation between samples to estimate daily concentrations. We believe this method more accurately reflects the nutrient concentration patterns within our inflow sites compared to holding estimates constant as was done in the 1997 report because nutrient concentration is found to fluctuate more dramatically in other studies.

Note that the interpolation methods were explored to update the 1994-95 phosphorus budget and are not related to the retention models discussed in section 3.3. These daily interpolation techniques were explored to solely improve our baseline estimate of TDP & TP retained within the 1994-95 period.

4.2.3 Updating the 1994-95 Phosphorus Budget – Drawdown Zone Interpolation

The second change we made to Perrin & Korman’s (1997) methods was to use a better estimate for nutrient concentrations for the upper Duncan River as it flowed through the drawdown zone between September and January. The function we used to define the daily concentration as a product of daily flow and inverse reservoir elevation is represented in the equation below:

Equation 3: $$P_{D.River\ in\ Drawdown} = flow \cdot 0.237459 \cdot {}^{202.265}/_{elevation - 545}$$

The results of this equation for estimating both TDP and TP reflect how both nutrient values within the drawdown zone are different than the upstream Duncan River concentration values as flow and elevation changes (Figure 3-2**:** Korman & Perrin, 1997). The differences observed for TP within the delta interpolation, closely mirror the median difference between upper Duncan and the delta for the spring of 65 ug/L.

We followed the same methodology to calculate annual retention used within the 1997 report. We incorporated the linear interpolation between sample dates, the updated delta interpolation values for the 1994-95 data set and generated daily nutrient weights accordingly. A seasonal breakdown of inflow, outflow, and retention of metric tonnes of TDP and TP are summarized in Table 4-3. Overall annual TP and TDP retention increased by 1.24% and 0.37% respectively between the two nutrient budgets. This change is largely due to implementing a linear interpolation that reduces the overinflated inflow nutrients (e.g., Upper Duncan in Spring) caused by periods with nutrient spikes that were held constant for multiple weeks.

Table 4-3. Nutrient retention (MT) comparison between 1994-95 & 2021 update nutrient budget.

	Total Phosphorus (TP)				**Total Dissolved Phosphorus (TDP)**			
1994-95	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer
Upper Duncan	2.759	7.763	77.09	13.52	0.957	0.3772	4.122	0.9837
Small Streams	1.161	0.5645	7.806	6.742	0.2641	0.3825	0.9806	0.4997
Inflow	3.92	8.327	84.9	20.26	1.221	0.7596	5.103	1.483
Outflow	3.694	4.319	0.1059	2.551	1.518	1.767	0.05007	0.5919
Total Retained	0.226	4.009	84.79	17.71	-0.2973	-1.007	5.053	0.8915
Percent Retained	**5.8%**	**48.1%**	**99.9%**	**87.4%**	**-24.3%**	**-133%**	**99.0%**	**60.1%**
2021 Update	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer
Upper Duncan	1.559	7.687	71.32	16.36	0.8711	0.4007	4.203	1.006
Small Streams	1.124	0.5319	5.884	8.381	0.266	0.3779	1.022	0.4899
Inflow	2.682	8.219	77.21	24.74	1.137	0.7786	5.224	1.495
Outflow	3.751	4.235	0.1086	2.585	1.455	1.773	0.04921	0.7894
Total Retained	-1.068	3.984	77.1	22.16	-0.3183	-0.9941	5.175	0.7061
Percent Retained	**-39.8%**	**48.4%**	**99.9%**	**89.6%**	**-28.0%**	**-128%**	**99.1%**	**47.2%**

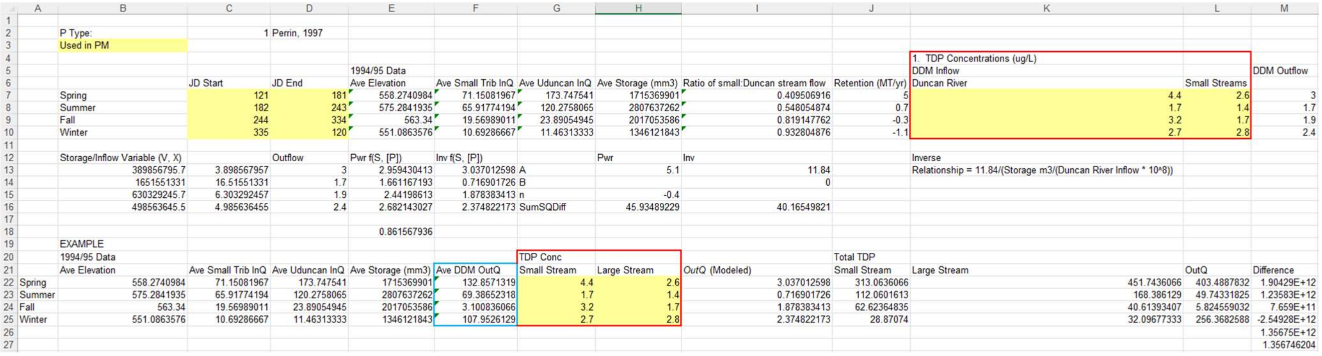
4.3 Modelling Retention and Estimating Operational Impact

To determine a long-term estimate of TDP retention without the collection of annual TDP data, the development of an accurate model with hydraulic predictors is important. We reproduced the Consultative Committee (CC) process model and explored independent inflow and outflow models.

4.3.1 Reproduction of Consultative Committee Process TDP Model & Associated Estimates

As previously described, we reproduced the Consultative Committee (CC) process model from the *DDM_Nutrient* excel sheet provided by BC Hydro. Within the excel sheet we discovered an error within the calculations, where the seasonal TDP concentrations for small stream and large stream (Upper Duncan River) were switched in the workflow (Figure 4-6). In addition, the outflow volumes from DDM where inconsistent with the actual values observed. Specifically, the excel sheet showed the average daily dam outflow rates as 133, 69, 3 & 107 L/s for Spring, Summer, Fall & Winter respectively, rather than the actual 3, 107, 133 & 69 L/s. The combination of these two mistakes resulted in the estimate of TDP retained being 1.36 MT rather than the actual 3.73 MT retained calculated by the same equation with appropriate corrections.

Considering these errors, we continued with a re-creation of retention estimates for the different operation regimes (Alt A, SD73 & Nutrient Alternative), but maintained two versions of our re-creation, one maintaining the errors and the other correcting for the errors (Table 4-4). Our recreated median values while maintaining the CC report errors were within 0.2 MT of TDP either released or retained, which we deemed acceptable as a comparison considering other error sources that could have resulted in the discrepancy. These potential sources of error included the range of dates included in the annual estimates and the methods used to deal with volume discrepancies resulting in negative small stream flow estimations. The implications of the CC process modelling errors are discussed following the presentation of 2021 models for retention estimates below.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1													
2		P Type:	1	Perrin, 1997									
3		Used in PM											
4											1. TDP Concentrations (ug/L)		
5					1994/95 Data						DDM Inflow		DDM Outflow
6			JD Start	JD End	Ave Elevation	Ave Small Trib InQ	Ave Uduncan InQ	Ave Storage (mm3)	Ratio of small:Duncan stream flow	Retention (MT/yr)	Duncan River	Small Streams	
7		Spring	121	181	558.2740984	71.15081967	173.747541	1715369901	0.409506916	5	4.4	2.6	3
8		Summer	182	243	575.2841935	65.91774194	120.2758065	2807637262	0.548054874	0.7	1.7	1.4	1.7
9		Fall	244	334	563.34	19.56989011	23.89054945	2017053586	0.819147762	-0.3	3.2	1.7	1.9
10		Winter	335	120	551.0863576	10.69286667	11.46313333	1346121843	0.932804876	-1.1	2.7	2.8	2.4
11													
12		Storage/Inflow Variable (V, X)		Outflow	Pwr f(S, [P])	Inv f(S, [P])		Pwr	Inv		Inverse		
13		389856795.7	3.898567957	3	2.959430413	3.037012598	A	5.1	11.84		Relationship = 11.84/(Storage m3/(Duncan River Inflow * 10^8))		
14		1651551331	16.51551331	1.7	1.661167193	0.716901726	B		0				
15		630329245.7	6.303292457	1.9	2.44198613	1.878383413	n	-0.4					
16		498563645.5	4.985636455	2.4	2.682143027	2.374822173	SumSQDiff	45.93489229	40.16549821				
17													
18					0.861567936								
19		EXAMPLE											
20		1994/95 Data					TDP Conc			Total TDP			
21		Ave Elevation	Ave Small Trib InQ	Ave Uduncan InQ	Ave Storage (mm3)	Ave DDM OutQ	Small Stream	Large Stream	*OutQ* (Modeled)	Small Stream	Large Stream	OutQ	Difference
22	Spring	558.2740984	71.15081967	173.747541	1715369901	132.8571319	4.4	2.6	3.037012598	313.0636066	451.7436066	403.4887832	1.90429E+12
23	Summer	575.2841935	65.91774194	120.2758065	2807637262	69.38652318	1.7	1.4	0.716901726	112.0601613	168.386129	49.74331825	1.23583E+12
24	Fall	563.34	19.56989011	23.89054945	2017053586	3.100836066	3.2	1.7	1.878383413	62.62364835	40.61393407	5.824559032	7.659E+11
25	Winter	551.0863576	10.69286667	11.46313333	1346121843	107.9526129	2.7	2.8	2.374822173	28.87074	32.09677333	256.3682588	-2.54928E+12
26													1.35675E+12
27													1.356746204

Figure 4-6. Screenshot of the DDM_Nutrients excel sheet with the switched concentration cells bordered in red, and the mixed dam outflows outlined in blue.

Table 4-4. Nutrient retention and release (MT) for different dam operation regimes 1968-1999.

Annual Mass of TDP Retained (MT)	**10th Percentile**	**Median**	**90th Percentile**
Alt A			
CC Report	1.32	1.80	2.24
CC Recreated with Excel Errors	1.03	2.04	3.41
CC Recreated with Corrections	3.03	3.86	5.00
SD73			
CC Report*	~2.0	~2.4	~3.0
CC Recreated with Corrections**	2.96	3.52	3.98
Nutrient Optimal			
CC Report*	~0.6	~1.2	~1.95
CC Recreated with Corrections	1.12	2.12	3.14
Annual Mass of TDP Released (MT)	**10th Percentile**	**Median**	**90th Percentile**
Alt A			
CC Report	5.21	5.62	6.00
CC Recreate with Excel Errors	4.41	5.81	7.36
CC Recreate with Corrections	4.29	4.88	5.52
SD73			
CC Report*	~4.5	~4.9	~5.3
CC Recreated with Corrections**	4.55	5.28	6.04
Nutrient Optimal			
CC Report*	~5.4	~5.9	~7.2
CC Recreate with Corrections	5.21	6.56	7.60

* SD73 & Nutrient Optimal Values Estimated from Box & Whiskers Plot from Appendix Non Operating Alternatives (BC Hydro and Power Authority, 2005).

** SD73 estimations are from 2006-2019 only.

4.3.2 Modelling Inflow Phosphorus Concentration

The inflow model differed from the CC process model by attempting to eliminate aggregated data, predicting unique inflow concentration values, treating inflow sources as unique inputs, and considering time and varying lag windows prior to TDP sampling days.

Predictor selection was conducted using correlation matrices of flow and elevation metrics with TDP and TP across varying lag windows and isolating the most likely candidates based on strong linear relationships. Inflow nutrient concentrations for both TDP & TP were predicted by flow and elevation on the sample day as well as multiple variations in flow and elevation the week preceding sampling (Table 4-5). The random forest models had a root mean square error (RMSE) of 1.3 and 30.52 for TDP and TP respectively. The larger RMSE for TP is the result of the more diverse range of values of TP (1 to 202 ug/L). The most important predictors within the models included day of elevation, flow hy5 (7-day window), and elevation pattern over a 7-day window for TDP and flow hy5 (7-day window), flow pattern (magnitude of rise or fall) for a 7-day window, sample location and date for TP.

Table 4-5. Explanatory variables of inflow TP & TDP concentration models.

Response Variable	Explanatory Variable	Window of Days	Variable Importance
TP	Flow – Hy5	7 Days	140.98
TP	Flow – Absolute rise fall rate	7 Days	102.99
TP	Location – Upper Duncan, Glacier & Howser	NA	96.95
TP	Date – as Julian day	NA	96.26
TP	Flow	Day of	85.58
TP	Elevation	Day of	56.79
TP	Flow – Fall rate	7 Days	56.62
TP	Elevation – Pattern, Delta max min	7 days	42.45
TDP	Elevation	Day of	0.581
TDP	Flow – Hy5	7 Days	0.311
TDP	Elevation – Pattern, Delta max min	7 days	0.286
TDP	Date – as Julian day	NA	0.249
TDP	Flow – Absolute rise fall rate	7 Days	0.193
TDP	Flow	Day of	0.175
TDP	Flow – Rise Rate	7 Days	0.047
TDP	Location – Upper Duncan, Glacier & Howser	NA	0.015

Overall, the random forest models captured the range of both TP and TDP concentrations except for outliers observed at the Upper Duncan River for both TDP and TP, and the Howser Creek outlier for TDP (Figure 4-7, Figure 4-8, Figure A-3). The random forest model was chosen for prediction of TDP and TP because of its ability to incorporate non-parametric variables, and as such, it was the best model for predicting outlier events. The model's inability to successfully capture the outliers in the Upper Duncan and Howser rivers indicates that there are likely additional factors that influence those peak phosphorus concentrations that were not included in our methods. These factors may involve precipitation patterns in the upper watershed, and flow-driven factors including freshet lag or groundwater to streamflow interactions.

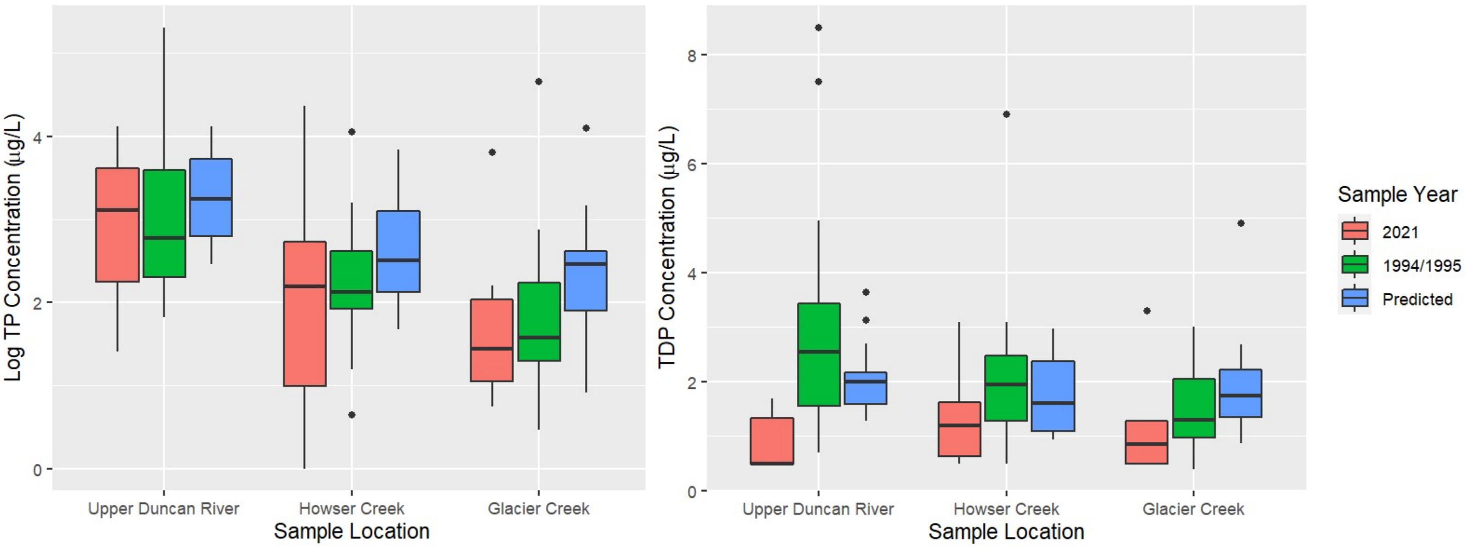


Figure 4-7. Random forest model predicted versus observed TDP & TP concentration (µg/L) at inflow sampling locations for April-October in respective sampling years.

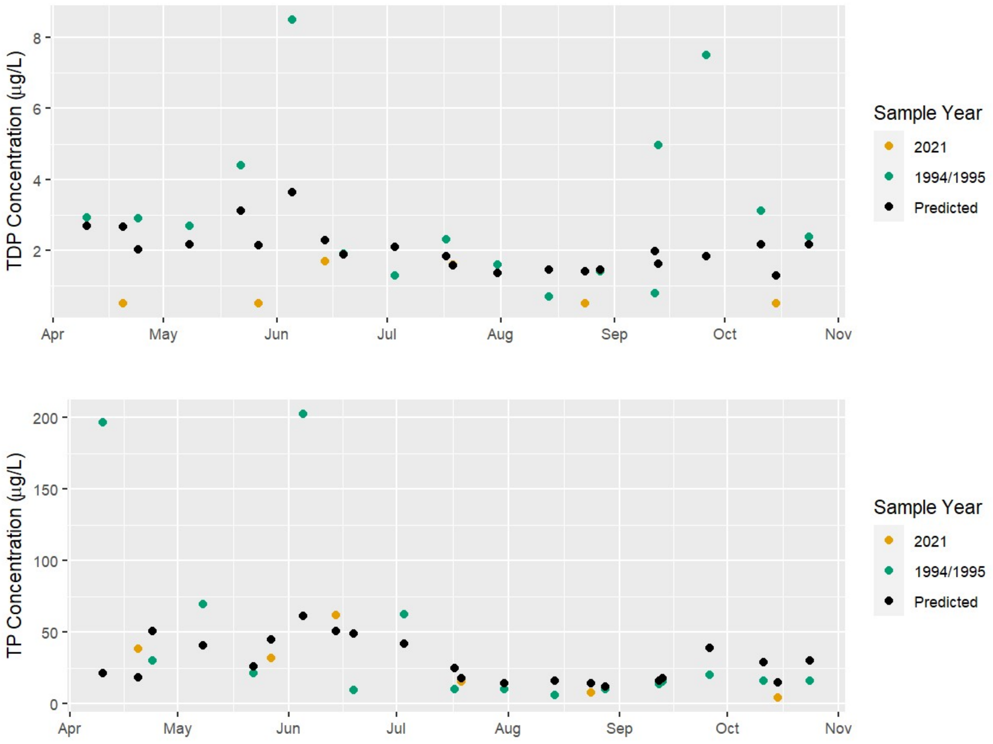


Figure 4-8. Random forest model predicted versus observed TDP & TP concentration (µg/L) for the Upper Duncan River, inclusive of sampling within the drawdown zone for April-October in respective sampling years. Note: Predicted values presented within this figure are those corresponding to the sampling date.

4.3.3 Modelling Outflow Phosphorus Concentration

Outflow nutrient concentrations for both TDP & TP were more dependent on larger lag times, between 7 and 90 days, than inflow predictors (Table 4-6). This is to be expected due to the movement of water & nutrients through the reservoir, which is highly dependent on the DLR retention time.

We conducted variable selection by comparing the hydraulic metrics (Table 3-4) with TDP and TP across varying lag windows and isolating the most likely candidates based on the highest correlation. Except for nutrient inflow from Glacier Creek, most predictors were reservoir characteristics that represented change 30 or 90 days prior to sampling. The partial least squares regression for outflow TDP concentration was optimal with two components, had an RMSE of 0.91 and explained 41.82% of the variance (Figure 4-9 & Figure A-4). The random forest model for TP had an RMSE of 0.34, with the most important predictors being mean-elevation-90-days-prior-to-sampling, 30-day-period-retention-time, and day-of-the-year.

Table 4-6. Explanatory variables of outflow TP & TDP concentration models.

Response Variable	Explanatory Variable	Window of Days	Variable Importance
TP	Mean Elevation	90 Days	0.0237
TP	Retention Time	30 Days	0.0204
TP	Date – as Julian day	NA	0.0144
TP	Hydraulic Washout	30 Days	0.0104
TP	Volume – Hy5	7 Days	0.0098
TP	Water Volume Inflow	90 Days	0.0018
TP	Glacier TP weight – Hy5	7 Days	-0.0026
TDP	Date – as Julian day	NA	---
TDP	Mean Elevation	90 Days	---
TDP	Inflow TDP Concentration – Minimum Value	60 Days	---
TDP	Glacier TDP Concentration – Mean Value	7 Days	---
TDP	Water Volume Inflow	90 Days	---
TDP	Inflow TDP Weight – Median Value	7 Days	---
TDP	Hydraulic Washout	90 Days	---

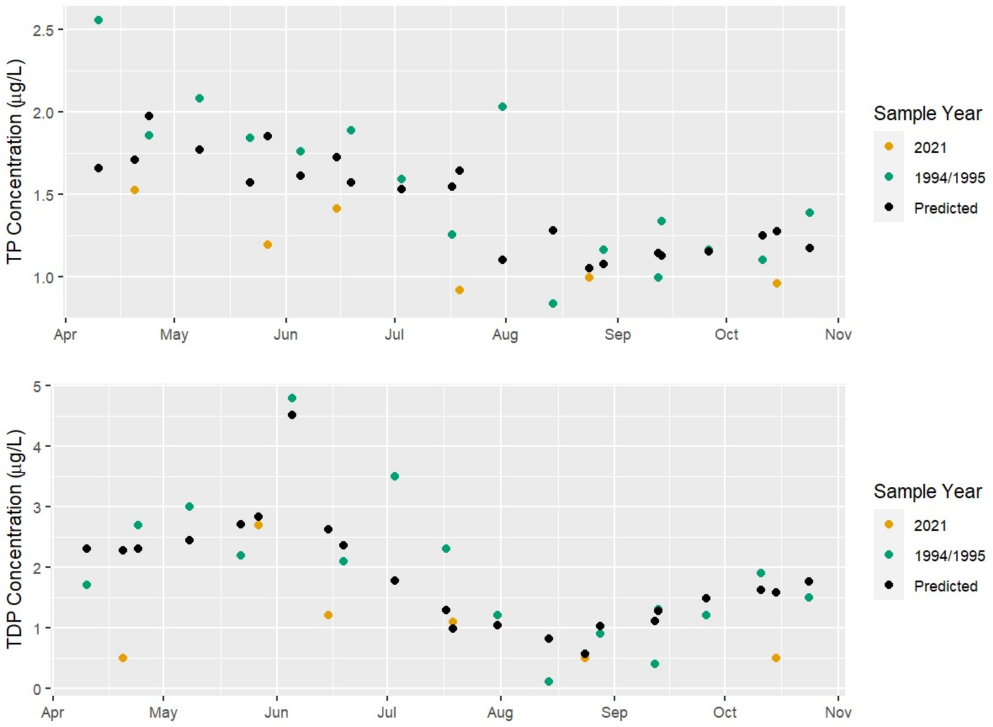


Figure 4-9. Predicted versus observed TDP & TP concentration (µg/L) at the outflow sampling location for April-October in respective sampling years. Note: Predicted values presented within this figure are those corresponding to the sampling date.

4.3.4 Comparison of Phosphorus Retention Models

This report marks the third attempt to estimate phosphorus retention in the DLR through modelling using the 1994-95 sampling data (Table 4-7). Our update to the 1994-95 phosphorus budget is the most accurate baseline to compare with our 2021 predictive models. This is because our updated phosphorus budget was inclusive of the outliers that were not accurately estimated for the 1994-95 season in any other models. Specifically, we used a linear interpolation between sample dates and updated the fall drawdown zone interpolation.

We used our updated phosphorus budget as the baseline to compare the predictions from the various models for the 1994-95 season (Table 4-7). While this approach has limitations (such as the inter-sample variability discussion in Section 4.1), no other estimate of annual retention is available since the 2021 sampling did not cover the entire year and presented values incongruous with the 1994-95 data. Lastly, it is important to remember that the nutrient budgets used actual observed values to estimate retention, whereas the predictive models are estimating retention values based off seasonal averages (the CC equation) or hydrologic predictors.

The 2004 CC report model (Equation 2) estimated TDP retention at 1.35 MT (due to computational errors), which underestimated the retention compared to our updated phosphorus budget baseline of 4.57 MT, therefore accounting for only 29.5% of TDP retained. The corrected CC model better estimated TDP retention (3.73 MT of 5.75 MT) and accounted for 81.6% of TDP retained. Lastly, the 2021 random forest and partial least squares models for estimating TDP inflow and outflow have incorporated more complex predictors, but the increased computation requirements and the underestimation of outlier events make it less useful for predicting the impact of DDM operations, accounting for only 59.7% of TDP retained (2.73 MT of 5.75 MT) (Table 4-7).

Due to the increase computational complexity and decreased accuracy of the 2021 models, we decided to use the corrected CC report model to comment on the funding contribution of BC Hydro towards the Kootenay Lake Fertilization Program.

Table 4-7. TDP inflow, outflow and retention (MT) comparison of different models using 1994-95 data.

TDP Models	Inflow	Outflow	Retention	% Accuracy to Baseline
K&P's Nutrient Budget	8.4	4.1	4.3	94%
Ecoscape update to K&P's Budget	8.64	4.07	4.57	–
CC Report DDM_Nutrients excel	7.14	5.78	1.36	29.5%
Ecoscape CC corrected DDM model	8.25	4.52	3.73	81.6%
Ecoscape 2021 Models	6.68	3.95	2.73	59.7%
TP Models	**Inflow**	**Outflow**	**Retention**	**% Accuracy to Baseline**
K&P's Nutrient Budget	111.4	10.8	100.6	98.4%
Ecoscape Update to K&P's Budget	112.9	10.7	102.2	–
Ecoscape 2021 Models	93.0	9.78	83.3	81.5%

5.0 COMPENSATION

The purpose of this study was to re-evaluate the nutrient retention caused by DDM operations and assess the appropriateness of the current DDMWORKS-3 funding. Currently, BC Hydro contributes ~$180,000 annually through DDMWORKS-3, which is equal to 17.5% of the previous year's fertilization costs. This proportion is based on a $100,000 contribution (in 2004 dollars), which at the time was 17.5% of the $570,000 total cost of the fertilization program (BC Hydro and Power Authority, 2008). To accommodate for inflation, this proportion has been upheld since 2004.

We updated Korman and Perrin's 1994-95 phosphorus budget to provide a robust baseline of TDP retention and compare the various retention models. As per Section 4.3.4, the correction of the 2004 CC report model (equation 2) proved to be the most accurate model, predicting 81.6% of TDP retained when compared to the phosphorus budget baseline. Following the same methodology of the CC report, we used this model to estimate retention for the different operating regimes (Alt A, SD73 & Nutrient Alternative) (Table 4-4). By generating these estimates under the different regimes, we can capture the sensitivity of TDP retention due to DDM operations by comparing the difference between the Nutrient alternative and SD73.

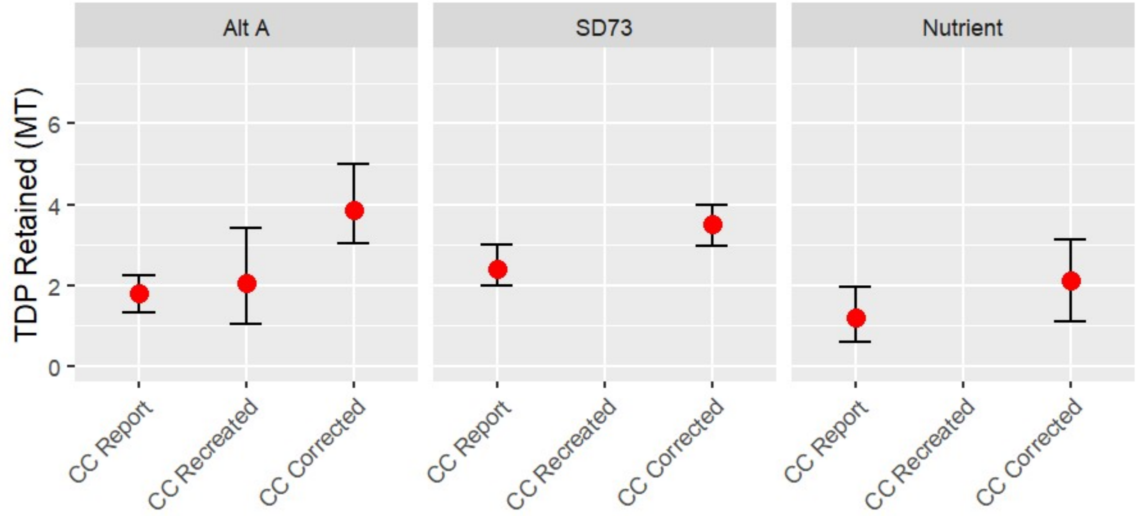


Figure 5-1. Annual TDP retained as modelled using the CC report equation under different operating alternatives. CC report refers to the values reported within the CC report, CC recreated maintained the errors and the CC corrected refers to the model without errors. Alt A includes flow information from 1968 to 2000, SD73 includes 2006-2020 and the Nutrient optimal includes 1968-2021. Error bars are 95% confidence intervals.

Using the corrected CC report model, the status quo operation alternative, SD73, was estimated to retain 3.52 +/- 0.45 MT of TDP (Figure 5-1). This is ~ 1.1 MT more TDP retained than was initially estimated for this operational alternative during the CC process (~2.4 MT) (BC Hydro and Power Authority, 2005). As well, the TDP retention estimate for the nutrient optimal alternative differed by ~0.9 MT using the corrected model compared to the original (2.12 vs ~1.2 MT). While the estimated TDP retention increased for each alternative using the new model, the difference between these two alternatives (SD73 – Nutrient) for each model was only 0.2 MT:

CC Report Model: SD73 – Nutrient = 2.4 – 1.2 = ~1.2 MT

CC Corrected Model: SD73 – Nutrient = 3.52 – 2.12 = ~1.4 MT

The increase of 0.2 MT represents a 16.6%, or ⅙ increase in TDP retained, which in turn indicates an under-compensation of DDMWORKS-3. This underpayment assumes that the initial DDMWORKS-3 contribution amount of $100,000 was set as a monetary value of a specific amount of TDP retained (Figure 5-2). If we assume that the initial contribution amount valued 1.2 MT of TDP retained at $100,000, then the 0.2 MT not accounted for would be worth $16,666 in 2004, and approximately $31,778 in 2021 based on inflation (Figure 5-2).

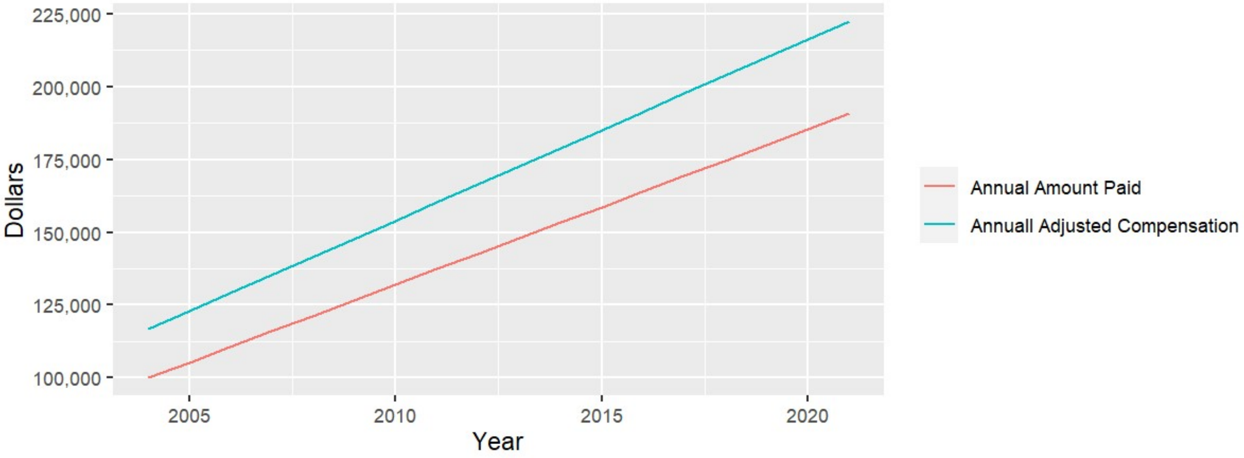


Figure 5-2. Annual Compensation of DDMWORKS-3 scenarios adjusted for the 0.2 MT miscalculation within the 2004 CC Process. The cumulative underpayment accounts for the estimated underpayment from 2004-2021. Refer to paragraph below for uncertainties in the estimate.

This underpayment estimate is easily quantifiable but is based on the corrected CC report model using the 1994-95 data. That estimate does not incorporate, nor reflect, the observed reduction of inflow and outflow TDP documented in 2021. Conversely, if the DLR experienced a true TDP decline over the last 26 years, this would indicate that paying for the original 1.2 MT of retained TDP may in fact be an overcompensation. We are unable to confidently comment on the potential changes in the DLR nutrient regime over the last 26 years because of various limitations in both the 1994-95 and 2021 sampling programs.

First, the sampling frequency of both the 1994-95 study and the 2021 study cannot discern the rapid changes in TDP concentration observed at the Upper Duncan River inflow site (Section 4.1, Figure 4-4). Only six samples were collected in 2021, at ~30-45 days apart. There is a high potential that the 2021 sampling *missed* the entire range of TDP concentrations relative to the 1994-95 sampling. The literature infers that a frequency of bi-weekly (Dantoin & Robertson, 2018) or even monthly (Sheibley et al., 2014; Torres et al., 2007; Moran et al., 2013) is standard for generating phosphorus budgets but within highly fluctuating systems such as reservoirs, some researchers have sampled as frequently as twice daily (Shantz, 2004). Given the rapid change of TDP concentrations observed in 1994-95, particularly in the drawdown zone of the Upper Duncan River, more frequent sampling would be beneficial.

Second, Korman & Perrin (1997) observed TDP contributions from the drawdown zone of 15.9% (determined by subtracting the Upper Duncan River samples 2 km upstream of the DLR confluence from samples taken within the drawdown zone in the Upper Duncan River). While the 2021 sampling plan was limited to samples solely within the drawdown zone, the observed values were consistently lower than those from 1994-95. This may be the result of the low 2021 sampling frequency, or it could be indicative of the drawdown zone releasing less TDP over time. In addition, creeks and rivers in the area (Beaver Creek, Woolsey Creek, and the Illecillewaet River; Province of BC, 2021) have recorded similar TDP levels to those observed within the 2021 DLR inflow samples. This emulation of nearby watersheds suggests a possible regional TDP nutrient shift.

A few studies investigated the drivers of annual variability of P within the same watershed. Sheibley et al. (2014) and the BC Provincial Water Quality Monitoring (2022) have recorded P concentrations across multiple years, but did not analyze the causes of annual variability. This lack of research undermines our ability to determine if 2021 represents an overall decline in the DDM nutrient regime, or if the low TDP concentrations are the result of annual variability within the system. This is further compounded by the impact of the DLR elevation, which during 1995 was held lower than 550m asl for ~165 days, compared to ~65 days in 2021. This variation in the dewatered time for the drawdown zone may be impacting its contribution of TDP.

Finally, the 2021 sampling dates did not align with peak flow events (Figure 4-1). This is partially due to the 2021 peak flow events having a greater intensity and shorter duration than in 1995. Missing these peak flow events, which coincided with peak TDP concentration in 1995 (Figure 4-4), further complicated our ability to comment on long-term trends.

At present, we can estimate under-compensation, but there is no way of determining whether there was over-compensation given the limited data and uncertainties surrounding the TDP concentrations observed in 2021. If we assume that a decrease in the DDM TDP nutrient regime has occurred, compensation is further complicated by the lack of effective method to determine when the decrease in TDP began, and its trajectory. To address this issue, further agreement would be required among stakeholders for the next course of action.

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7.0 APPENDICES

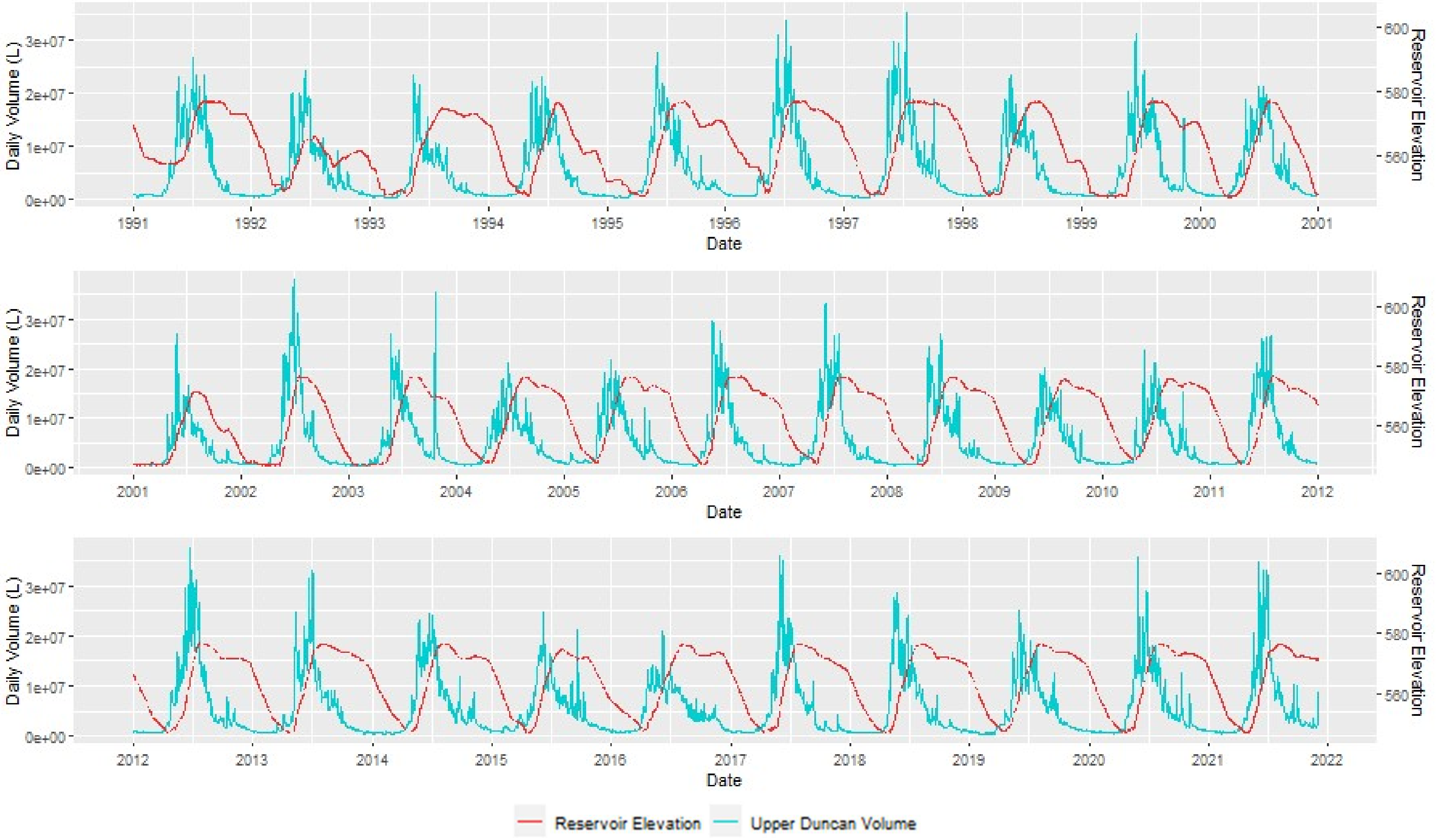

Figure A-1. Reservoir volume and inflow from the upper Duncan River between 1990 and 2021. Note the stabilization in reservoir elevation patterns following the cumulative committee process in the early 2000s regardless of variations in Upper Duncan volume.

Table A-1. In situ results of 2021 field measurements at sample locations by date.

Sampling Location	Date	Latitude	Longitude	Temp (°C)	pH	Dissolved Oxygen (%)	Dissolved Oxygen (mg/L)	Conductivity (µS/cm)	Total Dissolved Solids (mg/L)	Salinity (psu)	Turbidity (NTU)	Oxidation Reduction Potential (mV)
Upper Duncan River	2021-04-20	50.2540	116.5555	5.7	8.21	98.6	12.37	89.10	91.786	0.070	16.9	124.3
Upper Duncan River	2021-05-27	50.3208	116.5850	9.9	7.77	99.9	11.30	75.10	68.591	0.050	10.3	104.7
Upper Duncan River	2021-06-14	50.3614	117.0127	12.9	7.81	101.4	10.70	55.20	46.658	0.030	16.6	86.4
Upper Duncan River	2021-07-19	50.3818	117.0302	13.1	8.06	91.9	9.66	--	--	0.058	17.2	5.4
Upper Duncan River	2021-08-24	50.3818	117.0302	10.3	7.88	102.1	11.44	64.80	58.550	0.040	5.0	85.3
Upper Duncan River	2021-10-15	50.3818	117.0302	5.8	7.75	96.2	12.03	71.08	73.650	0.050	0.2	102.8
Howser Creek	2021-04-19	50.2749	116.5460	9.1	8.68	107.4	12.37	130.00	121.243	0.090	0.3	97.2
Howser Creek	2021-05-26	50.2749	116.5460	11.1	7.88	109.3	12.01	77.20	68.239	0.050	2.3	67.6
Howser Creek	2021-06-14	50.2749	116.5460	12.2	7.63	110.0	11.81	60.70	52.310	0.040	22.5	84.6
Howser Creek	2021-07-19	50.2749	116.5460	12.7	7.76	98.7	10.47	--	--	0.079	34.7	93.6
Howser Creek	2021-08-24	50.2749	116.5460	9.7	7.78	103.4	11.75	97.50	89.570	0.070	12.8	96.4
Howser Creek	2021-10-15	50.2749	116.5460	5.6	7.71	98.7	12.39	99.90	102.962	0.070	0.3	108.7
Glacier Creek	2021-04-19	50.1706	116.5512	8.7	8.60	102.8	11.97	69.10	65.202	0.050	-0.2	103.6
Glacier Creek	2021-05-26	50.1706	116.5512	10.3	7.58	104.2	11.69	45.00	40.699	0.030	0.8	71.3
Glacier Creek	2021-06-14	50.1706	116.5512	14.7	7.56	106.5	10.81	59.50	48.132	0.030	6.6	76.8
Glacier Creek	2021-07-19	50.1706	116.5512	13.1	7.61	79.8	8.40	--	--	0.034	10.8	30.6
Glacier Creek	2021-08-24	50.1706	116.5512	9.8	7.54	102.0	11.57	48.60	44.496	0.030	2.5	100.1
Glacier Creek	2021-10-15	50.1706	116.5512	5.8	7.67	97.7	12.24	63.10	64.852	0.050	0.1	104.6
Dam Outflow	2021-04-20	50.1515	116.5707	8.7	7.92	103.9	12.09	80.08	76.207	0.060	1.7	115.2
Dam Outflow	2021-05-27	50.1515	116.5707	11.6	7.55	99.4	10.81	71.10	62.147	0.040	1.9	94.2
Dam Outflow	2021-06-15	50.1515	116.5707	12.3	7.61	98.4	10.53	80.00	68.733	0.050	1.4	79.7
Dam Outflow	2021-07-19	50.1515	116.5708	11.2	7.90	73.3	8.05	--	--	0.075	4.2	61.5
Dam Outflow	2021-08-24	50.1515	116.5708	11.2	7.57	90.5	9.94	71.90	63.481	0.050	1.4	76.8
Dam Outflow	2021-10-15	50.1515	116.5708	11.1	7.58	88.2	9.70	85.50	75.620	0.050	0.3	108.3

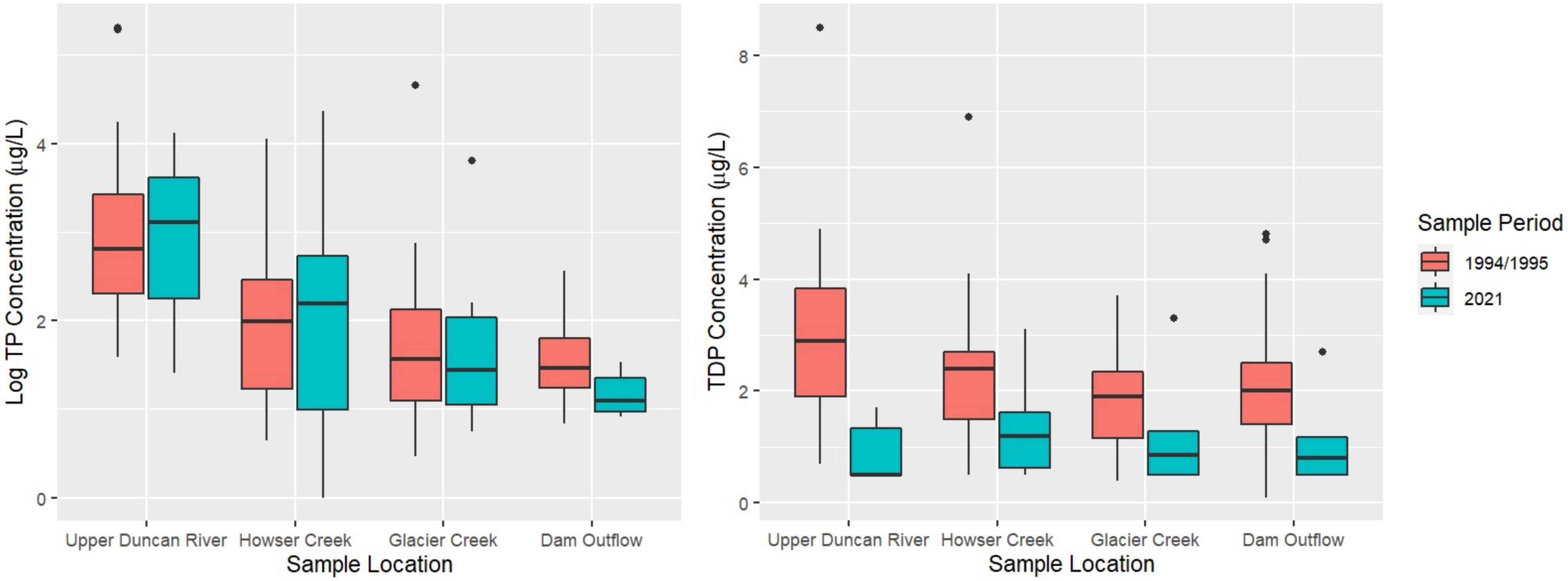

Figure A-2. (Left) Log of total phosphorus concentration (µg/L) at the sample locations. (Right) Total dissolved phosphorus concentrations (µg/L) at the sample locations. Twenty-one (21) samples at each site were taken in the 1994/1995 sampling period, with bi-monthly sampling from March-November and monthly sampling in December, January & February. Six (6) samples occurred at each site in 2021 in April, May, June, July, August & October. Any 2021 TDP data below the 1 µg/L detection limit is displayed as ½ the detection limit.

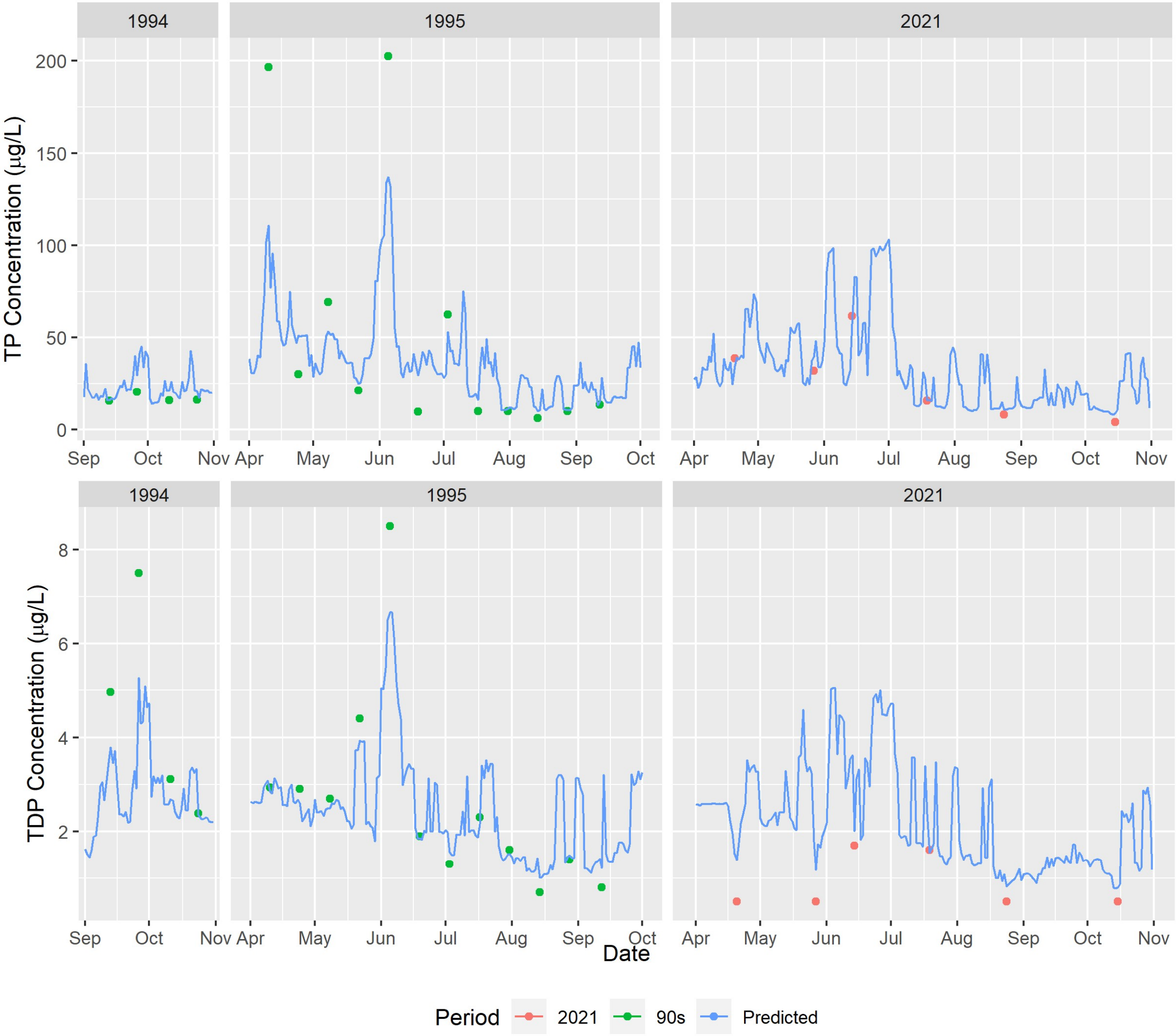

Figure A-3. Random forest model predicted versus observed TDP & TP concentration (µg/L) for the Upper Duncan River, inclusive of sampling within the drawdown zone for April-October in respective sampling years. The predicted values presented within this figure are daily estimates based on flow and reservoir characteristics unique to each day within the sampling periods.

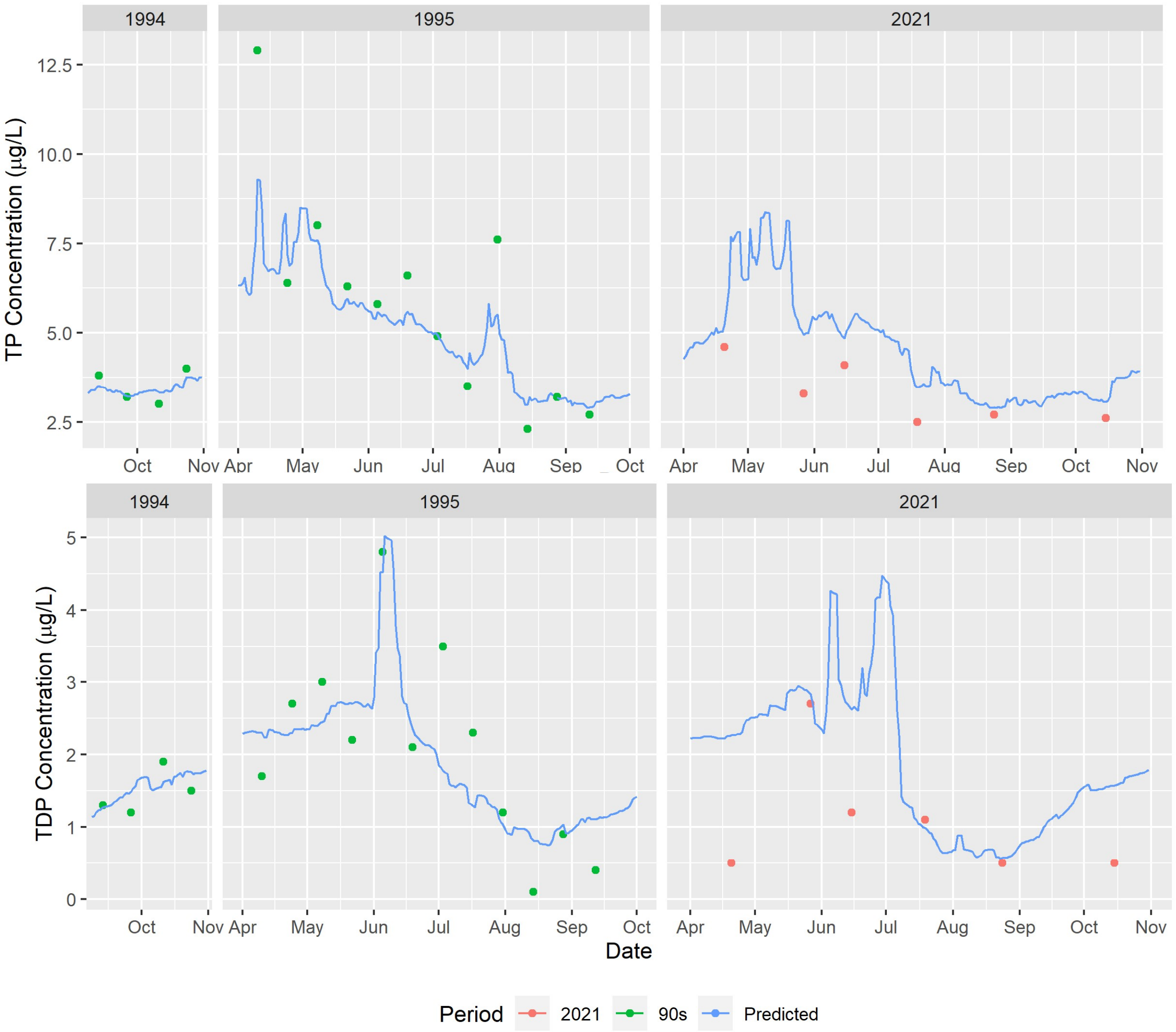

Figure A-4. Predicted versus observed TDP & TP concentration (µg/L) for the Duncan Dam (DDM) outflow. TP concentrations were predicted using a random forest model, whereas the TDP concentrations were predicted using a partial least squares regression. The predicted values presented within this figure are daily estimates based on flow and reservoir characteristics unique to each day within the sampling periods.