Bow River Maximum Allowable Load

Linkage of the Total Phosphorus Sources
and the Dissolved Oxygen Target

Bow River Maximum Allowable Load (BRMAL), Linkage of the Total Phosphorus Sources and the Dissolved Oxygen Target | Alberta Environment and Protected Areas

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**Positions of BRMAL Technical Team members may have changed by the time the report was published.*

Contents

Abbreviations

7Q10	Lowest 7-day average flow that occurs (on average) once every 10 years
EPA	Alberta Environment and Protected Areas
BAP	Biologically available phosphorus
BMPs	Best Management Practices
BRBC	Bow River Basin Council
BRID	Bow River Irrigation District
BRMAL	Bow River Maximum Allowable Load
BRPMP	Bow River Phosphorus Management Plan
BRWQM	Bow River Water Quality Model
CBOD5	Five days carbonaceous (nitrification inhibited) biochemical oxygen demand
CBODu	Ultimate carbonaceous biochemical oxygen demand
DO	Dissolved Oxygen
DRP	Dissolved reactive phosphorus
EEMS	EFDC Explorer Modeling System
EPEA	Environment Protection and Enhancement Act
FOC	Frequency of compliance
HEC-RAS	Hydrologic Engineering Center's River Analysis System
LDC	Load Duration Curve
LID	Low Impact Development
LOADEST	LOAD ESTimator
LOWESS	Locally Weighted Scatterplot Smoothing
MAL	Maximum Allowable Load
PO4	Orthophosphate
RWA	Receiving water assessments
SSRSWQF	South Saskatchewan Region Surface Water Quality Framework
SWAT	Soil & Water Assessment Tool
SWMM	Storm Water Management Model
TDP	Total dissolved phosphorus
TIP	Total inorganic phosphorus

TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TOP	Total organic phosphorus
TP	Total Phosphorus
USEPA	United States Environmental Protection Agency
WASP	Water Quality Analysis Simulation Program
WID	Western Irrigation District
WQBELs	Water Quality Based Effluent limits
WQOs	Water quality objectives
WQS	Water quality standard
WRMM	Water Resources Management Model
WWTP	Wastewater treatment plant

1. Introduction

The Bow River provides multiple freshwater ecosystem services. The headwaters of the Bow River are highly regulated with dams and weirs. As the river flows eastward, it receives loadings from one of Canada's largest and fastest-growing population centers. The middle and lower reaches supply water to three Irrigation Districts with a gross annual diversion that represents roughly 50% of the total water diverted by all the Irrigation districts in Alberta (Government of Alberta 2021). The Bow River is a popular inland recreational fishery. A recent study determined a population decline of adult trout from 2003 to 2013 in the presence of multiple stressors (Cahill et al. 2018). Understanding the river's assimilative capacity can help balance the anthropogenic pressures with the protection of the aquatic ecosystem.

A Maximum Allowable Load (MAL) study seeks to identify the amount of a pollutant that can be present in a waterbody while maintaining water quality standards (WQS). This water-quality-based approach for the protection of the aquatic ecosystem considers the waterbody's assimilative capacity.

The constituent of interest in the Bow River Maximum Allowable Load (BRMAL) study is phosphorus. There are different impacts of increased phosphorus in a waterbody linked to the excessive growth of aquatic plants and algae. This study will focus on the potential low dissolved oxygen (DO) concentrations, causing stress in the aquatic ecosystem and leading to a greater likelihood of fish mortality. Other constituents affect DO in a waterbody, such as Biological Oxygen Demand (BOD) and nitrogen. Previous studies have identified phosphorus as the key surrogate measure in the Bow River (Golder Associates 2007). As part of this project, we will identify which nutrient is limiting the algae and macrophyte growth in the study area.

Proponents that require an Alberta Environment Protection and Enhancement Act (EPEA) Approval need to submit environmental assessments to support the goals of environmental protection and sustainable development. These assessments very often look into the effects on the river due to a single activity. The BRMAL investigates the cumulative effects of changes in DO from multiple total phosphorus (TP) sources.

The TP load in the Bow River has long been seen as an important substance to manage. The TP load from municipal discharges showed a significant decrease in the 1980s and then a lesser decrease from 2002 to 2009. In 2008, an Interim Effluent Limits Policy established loading limits for some EPEA Approvals (i.e. Calgary 340 kg/day, Heritage Pointe 1.2 kg/day, and Strathmore 5.2 kg/day). This Policy came about from water quality concerns brought up when Siksika Nation appealed the Strathmore Wastewater Treatment Plant Approval in 2006.

More recently, the Bow River Phosphorus Management Plan (BRPMP) recommended strategies to address sources of phosphorus in the middle reach of the Bow River between the Bearspaw and Bassano dams (Government of Alberta 2014). One of the strategies and actions was establishing phosphorus loading targets for development in the planning area (Figure 1). The BRMAL results will inform this strategy.

The BRMAL study includes two parts: 1) Source Identification and Assessment; 2) Linkage of Water Quality Targets and Sources. The BRMAL results provide science-based information for future load allocations. A separate report documents the Bow River TP Source Identification and Assessment (Martin, 2020). The following sections in this report summarize the results of the linkage of DO guidelines and TP sources. The linkage refers to the relationship between source loadings and the waterbody's response to those loads over time.

The results of this work will support watershed and municipal planning and inform provincial approvals staff who implement the EPEA. The study findings depend on the data, tools and methodology used at the time of this analysis. The BRMAL study may be updated in the future as more information is available.

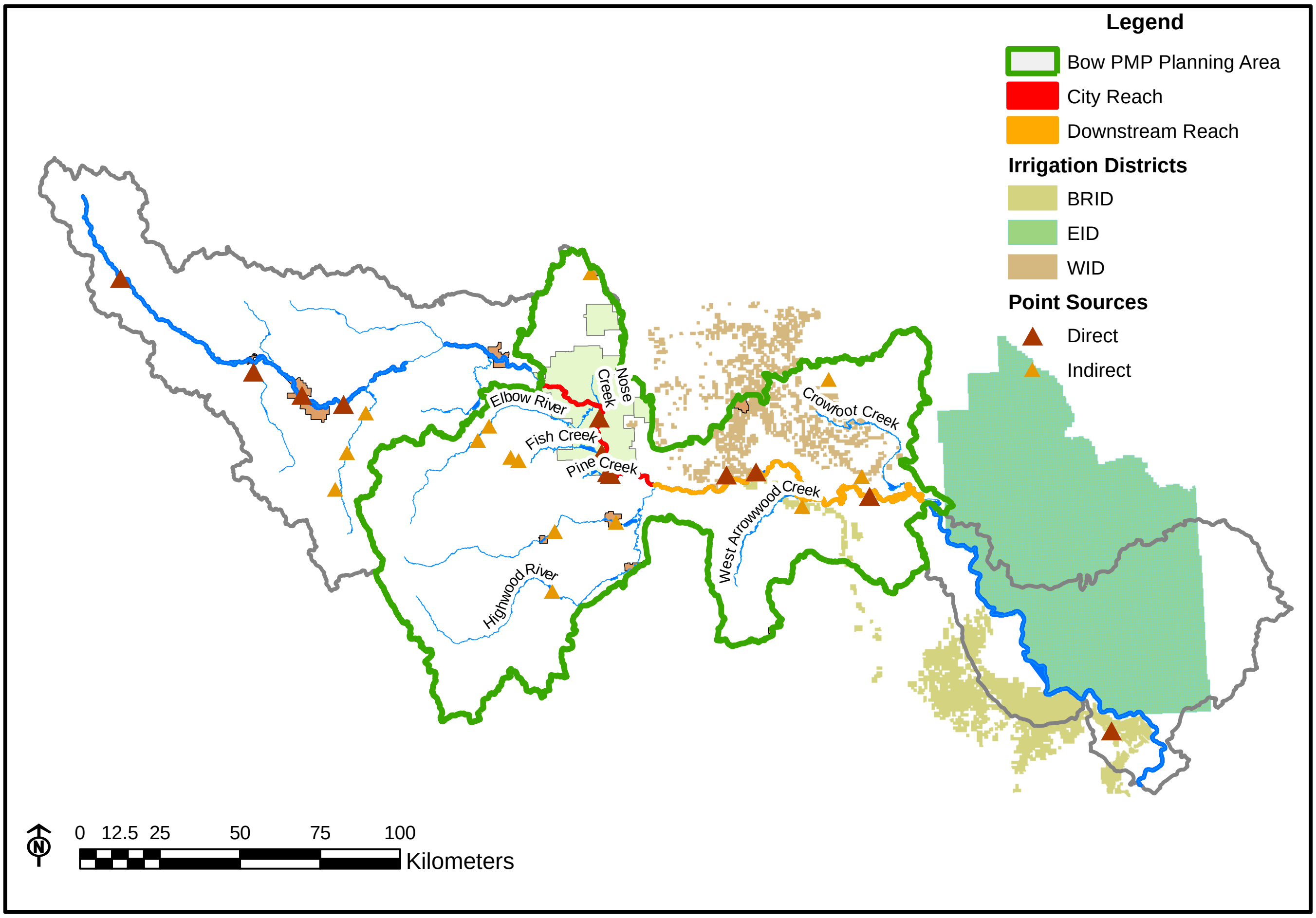


Figure 1. BRPMP Planning Area and BRMAL model domain, which is divided into City Reach and Downstream Reach. The map also shows the location of the Irrigation Districts and point sources.

2. Methodology

The linkage of the substance loads, and the water quality can use a range of techniques, from qualitative assumptions backed by sound scientific justification to sophisticated modelling systems (Figure 2). This linkage is supported by monitoring data that associate waterbody responses to flow and loading conditions (USEPA, 1999).

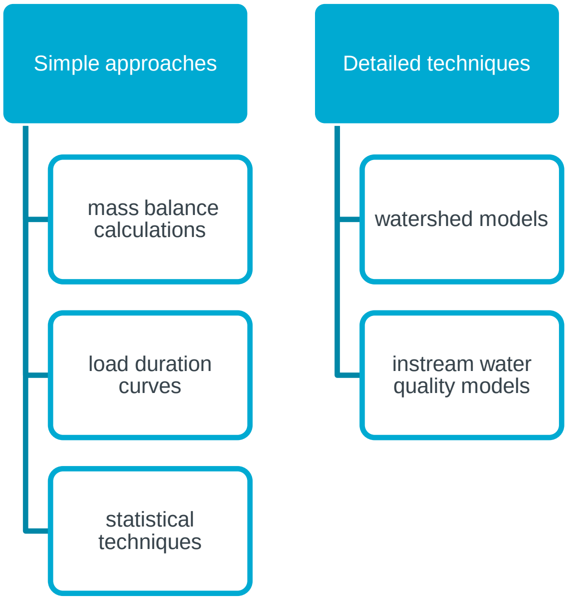


Figure 2. Simple and detailed techniques for linkage of substance loads and water quality.

The appropriate approach depends on available datasets, resources, spatial and temporal considerations, sources of loadings, acceptable uncertainty, and the complexity of the planning area and waterbody. Technical considerations will be the most critical factor in selecting a specific approach or methodology.

The DO concentration depends on multiple factors including, water temperature, turbulence, biomass and the effect of nutrients on their growth rates. Additionally, this constituent is very dynamic, and a sub-daily temporal resolution is desirable to analyze the diurnal cycle. The DO concentrations will change in the studied reach along the river and transversally in many sections. Thus, spatial resolution is also desirable. A MAL project that involves highly dynamic environments and substances that undergo complex interactions will require complex, dynamic models. Simple approaches such as the Load Duration Curve (LDC) can provide context for analyzing monitoring and modelling data, but detailed techniques that account for more than dilution are more appropriate.

2.1 The Bow River Water Quality Model

This study used the Bow River Water Quality Model (BRWQM) to link the TP loading with the DO concentration. The City of Calgary (The City) developed the BRWQM in the early 2000s to support their Total Loading Management Targets (Golder Associates 2007). EPA extended the model domain to Bassano Dam and recalibrated the models in 2009. This model has been widely used by The City and EPA to support provincial approval applications and regional planning. Figure 3 shows a short history of the model.

The model setup divides the study area into two more homogeneous units or sub-reaches, Bearspaw Dam to upstream Highwood River and Highwood River to Bassano Dam. The methodology presented will be consistent for both sub-reaches so that an additive approach can eventually be applied to the complete river reach.

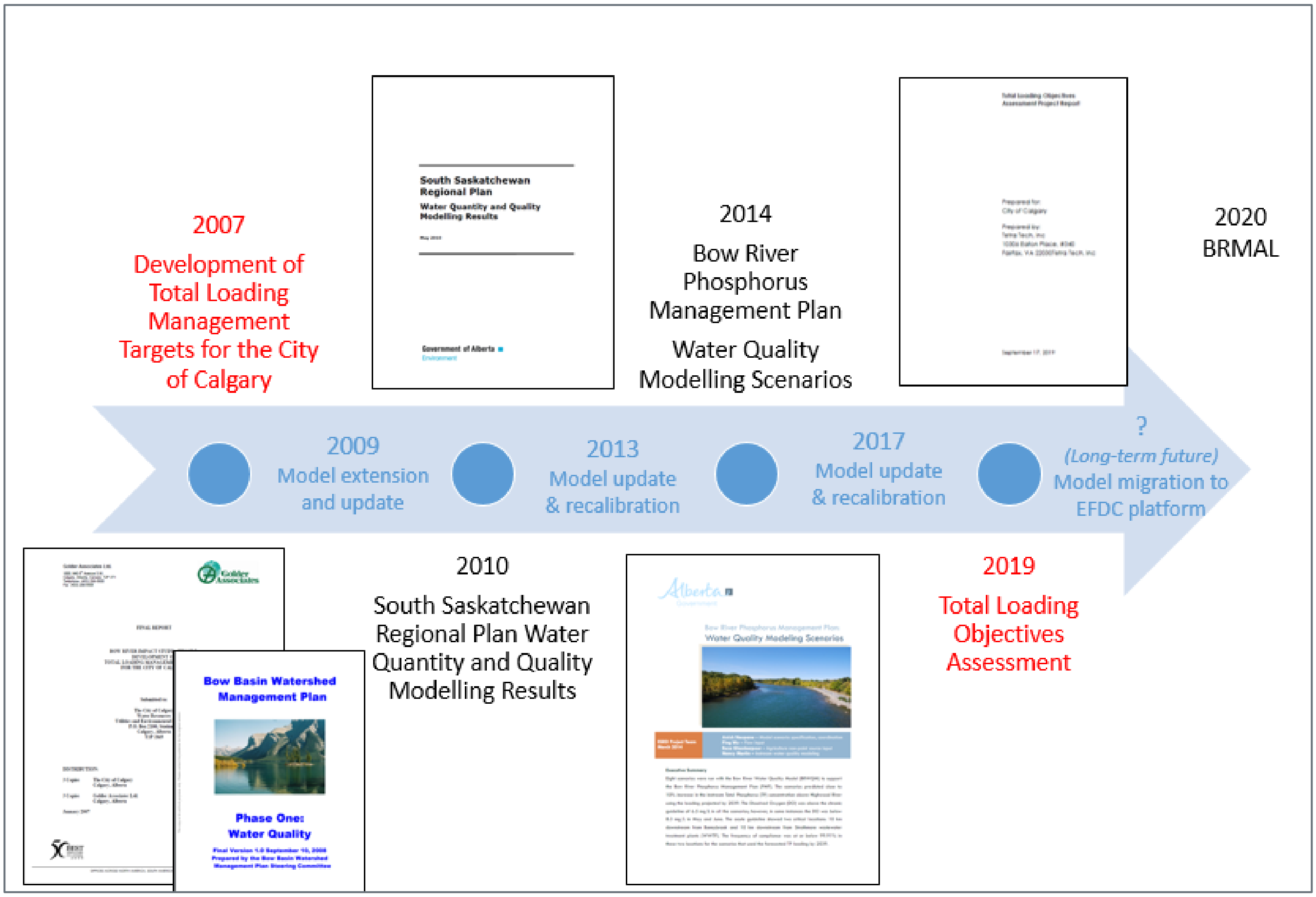


Figure 3. Diagram showing the BRWQM development, model updates and selected applications. Red text shows work done by the City of Calgary, and black text work done by the province.

The BRWQM routes the river flow using HEC-RAS, and WASP simulates the biochemical reactions (Figure 4). The model uses WASP version 5.2 modified to construct an aquatic plant sub-routine. This model version is referred to as WASP-MG (Golder, 2004). Each BRWQM reach has a linked non-point source model. The City Reach has an SWMM model for the urban runoff, and the Downstream Reach has a SWAT model for the agricultural runoff coming from the Crowfoot Creek sub-basin. The SWMM and WASP models are part of the USEPA, Total Maximum Daily Load (TMDL) Modeling Toolbox, and they are frequently used for this type of analysis. EPA's Water Resources Management Model (WRMM) was used to estimate water diversion flows and irrigation return flows (See Section 2.4). Before this study, the City of Calgary and EPA updated and recalibrated the City Reach and Downstream Reach, respectively. Appendix 1 shows selected calibration graphs and statistics.

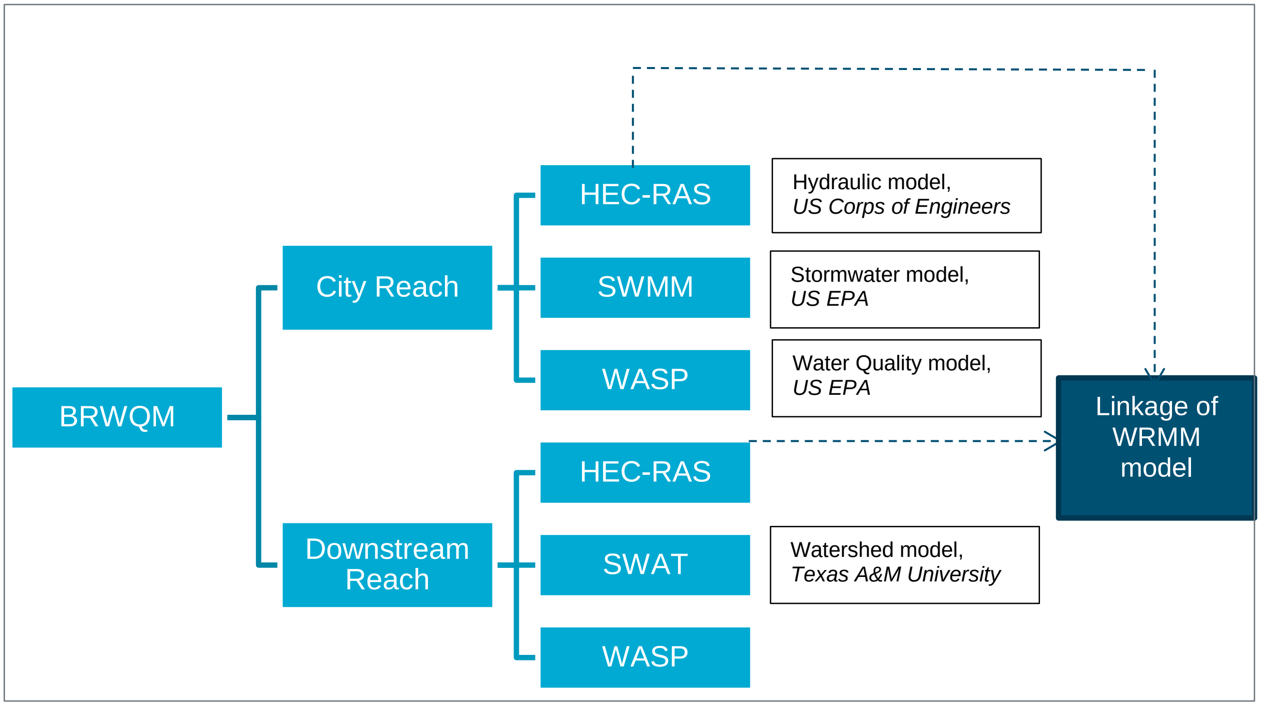
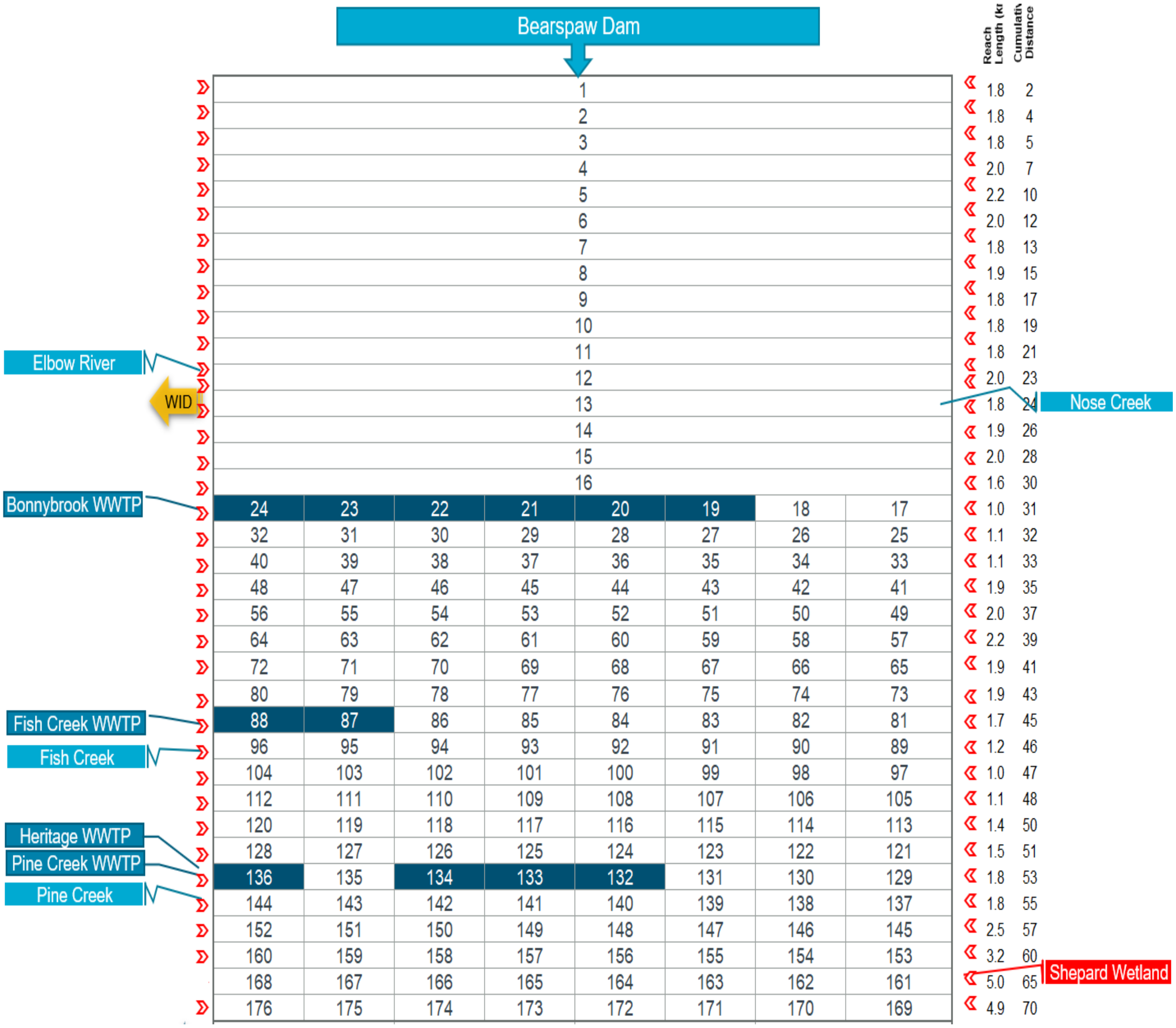


Figure 4. Schematic showing the BRWQM reaches and sub-models.

2.2 Model configuration

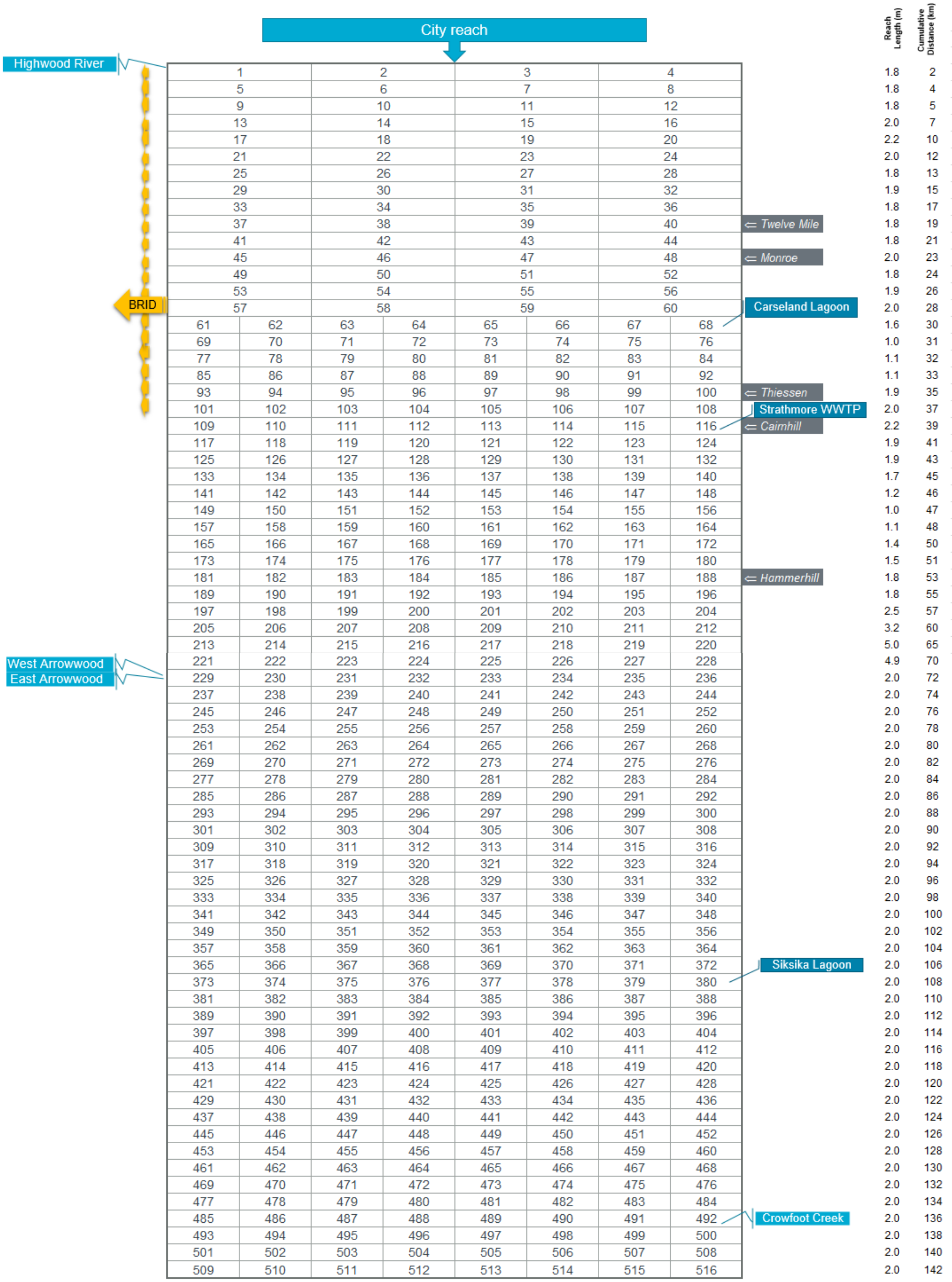
The model setup consists of dividing the study reach into smaller segments. The model estimates each segment's flows, water temperature, and substance concentration. The City's reach starts below Bearspaw Dam and ends above Highwood River. The model has 176 segments in this 70 km river reach. Model segments above Bonnybrook WWTP comprised only one cross-sectional segment spanning the width of the river. Downstream of this point source, each cross-section has eight segments. The segment lengths vary from 1 to 5 km; the width for the cross-section is close to 100 m. The model setup also identifies the segments that receive loadings or are subject to water diversions. The schematic in Figure 5 shows where the different boundary conditions (tributaries, WWTPs, stormwater, water diversions) enter the model domain. The model distributes the TP loadings from Bonnybrook, Fish Creek and Pine Creek WWTPs in different segments to represent the diffusers, which do not span the full width of the river. The stormwater is discharged 50% over each riverbank, except for the input coming from Shepard Slough, which is discharged over the left bank.



								Reach Length (k	Cumulativ Distance
1								1.8	2
2								1.8	4
3								1.8	5
4								2.0	7
5								2.2	10
6								2.0	12
7								1.8	13
8								1.9	15
9								1.8	17
10								1.8	19
11								1.8	21
12								2.0	23
13								1.8	24
14								1.9	26
15								2.0	28
16								1.6	30
24	23	22	21	20	19	18	17	1.0	31
32	31	30	29	28	27	26	25	1.1	32
40	39	38	37	36	35	34	33	1.1	33
48	47	46	45	44	43	42	41	1.9	35
56	55	54	53	52	51	50	49	2.0	37
64	63	62	61	60	59	58	57	2.2	39
72	71	70	69	68	67	66	65	1.9	41
80	79	78	77	76	75	74	73	1.9	43
88	87	86	85	84	83	82	81	1.7	45
96	95	94	93	92	91	90	89	1.2	46
104	103	102	101	100	99	98	97	1.0	47
112	111	110	109	108	107	106	105	1.1	48
120	119	118	117	116	115	114	113	1.4	50
128	127	126	125	124	123	122	121	1.5	51
136	135	134	133	132	131	130	129	1.8	53
144	143	142	141	140	139	138	137	1.8	55
152	151	150	149	148	147	146	145	2.5	57
160	159	158	157	156	155	154	153	3.2	60
168	167	166	165	164	163	162	161	5.0	65
176	175	174	173	172	171	170	169	4.9	70

Figure 5. City Reach model schematics including model segmentation and boundary conditions. Locations of WWTP outfalls are in shaded cells (i.e., Heritage Pointe WWTP 136, Pine Creek WWTP 132-134).

The Downstream Reach starts at the confluence with the Highwood River down to Bassano Dam. The reach has 144 km divided into 516 segments. The first 28 km have four cross-sectional segments and the rest have eight cross-sectional segments (Figure 6). Each segment is 2 km long and the width of the cross-section is from 67 to 112 m. Figure 4 shows the loading sources and boundary conditions. Table 1 shows the summary of relevant characteristics for each modelling reach.



								Reach Length (m)	Cumulative Distance (km)
1		2		3		4		1.8	2
5		6		7		8		1.8	4
9		10		11		12		1.8	5
13		14		15		16		2.0	7
17		18		19		20		2.2	10
21		22		23		24		2.0	12
25		26		27		28		1.8	13
29		30		31		32		1.9	15
33		34		35		36		1.8	17
37		38		39		40		1.8	19
41		42		43		44		1.8	21
45		46		47		48		2.0	23
49		50		51		52		1.8	24
53		54		55		56		1.9	26
57		58		59		60		2.0	28
61	62	63	64	65	66	67	68	1.6	30
69	70	71	72	73	74	75	76	1.0	31
77	78	79	80	81	82	83	84	1.1	32
85	86	87	88	89	90	91	92	1.1	33
93	94	95	96	97	98	99	100	1.9	35
101	102	103	104	105	106	107	108	2.0	37
109	110	111	112	113	114	115	116	2.2	39
117	118	119	120	121	122	123	124	1.9	41
125	126	127	128	129	130	131	132	1.9	43
133	134	135	136	137	138	139	140	1.7	45
141	142	143	144	145	146	147	148	1.2	46
149	150	151	152	153	154	155	156	1.0	47
157	158	159	160	161	162	163	164	1.1	48
165	166	167	168	169	170	171	172	1.4	50
173	174	175	176	177	178	179	180	1.5	51
181	182	183	184	185	186	187	188	1.8	53
189	190	191	192	193	194	195	196	1.8	55
197	198	199	200	201	202	203	204	2.5	57
205	206	207	208	209	210	211	212	3.2	60
213	214	215	216	217	218	219	220	5.0	65
221	222	223	224	225	226	227	228	4.9	70
229	230	231	232	233	234	235	236	2.0	72
237	238	239	240	241	242	243	244	2.0	74
245	246	247	248	249	250	251	252	2.0	76
253	254	255	256	257	258	259	260	2.0	78
261	262	263	264	265	266	267	268	2.0	80
269	270	271	272	273	274	275	276	2.0	82
277	278	279	280	281	282	283	284	2.0	84
285	286	287	288	289	290	291	292	2.0	86
293	294	295	296	297	298	299	300	2.0	88
301	302	303	304	305	306	307	308	2.0	90
309	310	311	312	313	314	315	316	2.0	92
317	318	319	320	321	322	323	324	2.0	94
325	326	327	328	329	330	331	332	2.0	96
333	334	335	336	337	338	339	340	2.0	98
341	342	343	344	345	346	347	348	2.0	100
349	350	351	352	353	354	355	356	2.0	102
357	358	359	360	361	362	363	364	2.0	104
365	366	367	368	369	370	371	372	2.0	106
373	374	375	376	377	378	379	380	2.0	108
381	382	383	384	385	386	387	388	2.0	110
389	390	391	392	393	394	395	396	2.0	112
397	398	399	400	401	402	403	404	2.0	114
405	406	407	408	409	410	411	412	2.0	116
413	414	415	416	417	418	419	420	2.0	118
421	422	423	424	425	426	427	428	2.0	120
429	430	431	432	433	434	435	436	2.0	122
437	438	439	440	441	442	443	444	2.0	124
445	446	447	448	449	450	451	452	2.0	126
453	454	455	456	457	458	459	460	2.0	128
461	462	463	464	465	466	467	468	2.0	130
469	470	471	472	473	474	475	476	2.0	132
477	478	479	480	481	482	483	484	2.0	134
485	486	487	488	489	490	491	492	2.0	136
493	494	495	496	497	498	499	500	2.0	138
501	502	503	504	505	506	507	508	2.0	140
509	510	511	512	513	514	515	516	2.0	142

Figure 6. Downstream Reach model schematics including model segmentation and boundary conditions such as location of WID return flows (gray boxes), lagoons and WWTP outfalls (dark blue boxes).

Table 1. Relevant characteristics for City and Downstream reaches.

Characteristic	City Reach	Downstream Reach
Model domain	Bearspaw Dam to Highwood River	Highwood River to Bassano Dam
Instream models used	HEC-RAS & WASP-MG	HEC-RAS & WASP-MG
Gridding	176 segments ~ 2 km long (1D & 8 lateral segments)	516 segments ~ 2 km long (4 & 8 lateral segments)
Non-point source model	SWMM	SWAT
Bathymetry used	Post-2013 flood	Post-2013 flood
Model calibration period	2007-2014	2005-2015
Main point sources	Bonnybrook WWTP, Fish Creek WWTP, Pine Creek WWTP, Heritage Pointe WWTP	Carseland Lagoon, Strathmore WWTP, Siksika Lagoon
Main non-point sources	Stormwater outfalls & Shepherd slough	WID return flows (12 Mile, Monroe, Thissen, Cairnhill, Hammerhill)
Tributaries	ElBow River, Nose Creek, Fish Creek, Pine Creek	Highwood River, West Arrowwood Creek, East Arrowwood Creek, Crowfoot Creek
Major water diversions	WID diversion	BRID diversion

2.3 Modeling design conditions

A key part of using a water quality model is defining the modelling design conditions. The Water Quality Based Effluent Limits (WQBELs) Procedure Manual provides guidance when determining a Waste Load Allocation in a waterbody (Government of Alberta 1995). MAL and WQBELs procedures are both designed to prevent exceedances of WQS. The main difference in these procedures is that a WQBEL traditionally applies to individual point sources, and MAL analyses will consider the cumulative effects from several point sources and non-point sources. However, some of the principles are transferable.

The main design conditions in the WQBELs are streamflow, background concentration, mixing zone, and effluent variability. The WQBELs manual provides guidance on which conservative values should be used when assuming steady-state conditions. It also provides the frequency of compliance when using dynamic simulations (99.91% or 1-day exceedance in 3 years).

A dynamic model incorporates a wide range of conditions, which represent the current or future water quality in the river. However, we checked how those conditions compare to the critical conditions stated in the WQBELs for steady-state simulations. For example, confirming that the streamflow used for dynamic simulation includes a range of dry and wet years and how these flows compare to the critical 7Q10 flow (the lowest 7-day average flow that occurs on average once every 10 years). The streamflow, background concentration and effluent variability among other dynamic aspects of the modelling are discussed in the next section. Table 2 presents a summary of the modelling design conditions.

Table 2. Modelling design conditions.

Design condition	Description of criteria used in this study
Model reaches	City Reach and Downstream Reach
Model endpoints	Dissolved oxygen
Output time interval	Model output every 1 h
Water Quality Objectives	DO guidelines: 5 mg/L acute and 6.5 mg/L chronic
Duration of exposure	Acute instantaneous, Chronic 7-day average
Frequency of compliance	99.91%
Point of compliance	The minimum DO will be analyzed for all the segments in the river reach. The cross-sections with the lowest DO will be selected to estimate the frequency of compliance.
Load averaging period	Daily load and seasonal average load
Seasonality	Special focus on July to September
Margin of safety	10%

The model results showed the minimum DO for every segment in the river reach. The cross-sections with the lowest DO were selected to estimate the cross-sectional average DO. This approach is less conservative compared with a MAL obtained when the first river segment does not meet the 99.91% frequency of compliance. In this case, a portion of the river can have < 99.91% frequency of compliance, but a few segments (where the loadings are not well mixed) can have natural DO levels and increase the average concentration. The BRMAL Technical Team selected this less conservative approach due to potential model limitations in estimating the transversal diffusion. This can be revisited for future model updates.

Seasonal variation was considered by using a long period of record for water quality and flow. Another approach to consider seasonal variation was seasonal loading capacity. With this approach, allowable loads vary according to the varying assimilative capacity of waterbodies and according to variation in the baseline loads from different sources over a year. The results for the months with higher biomass growth rates (July to September) received special attention.

2.4 Baseline Scenario

2.4.1. Determination of boundary conditions

Before running the model, we defined the Baseline scenario. This scenario represents current conditions (i.e., WWTP infrastructure, diversions, and tributary water quality) superimposed on the streamflow and weather patterns that can happen in the future. The Baseline scenario characterized each TP source loading (see model boundary conditions in Figures 5 and 6). The difference between the total Baseline load and the MAL represents the available load in the river before meeting the WQS.

In many modelling applications, the Baseline scenario is the same as the calibration data set. This approach can be inappropriate if the calibration includes a period with major changes in the loading conditions. The following section presents considerations for defining the baseline for the different boundary conditions.

a) Streamflow

Streamflow affects the magnitude of non-point source loadings and the dilution of point sources. It also determines the level of turbulence and reaeration and affects the water temperature and light penetration. Higher flows can affect the drag coefficient for aquatic plants and attached algae. Low DO events are more common during low flow conditions. Water quality modelling often uses the 7-day average minimum flow with a return period of 10 years (7Q10) to estimate the potential effects of loads in water bodies in steady-state simulations (Government of Alberta 1995).

Appendix 2 shows a comparison of the flows from 1990 to 2015. Based on the flow analysis from that Appendix, the 1994-2001 flow period was used, as it includes 2001 as a potential critical low DO year. A review of the most recent flow data up to 2020 reveals that 2015, 2016, 2017 and 2018 were also low flow years in the Critical DO months (July-September). The flow duration curve for the Critical DO season in the 1990-2020 period shows very low flows for September 2016, 2018 and 2001 (lowest 1st percentile 52.2 -44.1 m^3/s). This means that the selection of the flow period is not overly conservative as other recent years have been comparable to 2001.

For Highwood River, the flow was adjusted to represent the historical conditions if the Highwood Management Plan was implemented in the 90s. The Little Bow and Women's Coulee diversions were estimated with the WRMM. The recorded flows at Highwood River near the mouth were naturalized by adding the diverted flows at Little Bow Canal and Women's Coulee. The naturalized flow was adjusted by removing the water diversions estimated by the WRMM model.

The preliminary run became unstable at some low flows, and those flows were increased as per the table in Appendix 3. The flows causing issues are mainly winter low flows outside the critical DO season.

b) Weather data

DO saturation concentration is inversely proportional to temperature, and higher temperatures usually enhance biomass growth. Therefore, higher temperatures represent critical conditions.

We compared the weekly average air temperature in summer in the last 28 years and checked how they compare to the ones used in the simulation period. Figure 7 shows the maximum weekly average air temperature from 1990 to 2017. The years selected for the model simulation 1994-2001 include a wide range of weekly maximum air temperatures from July through September.

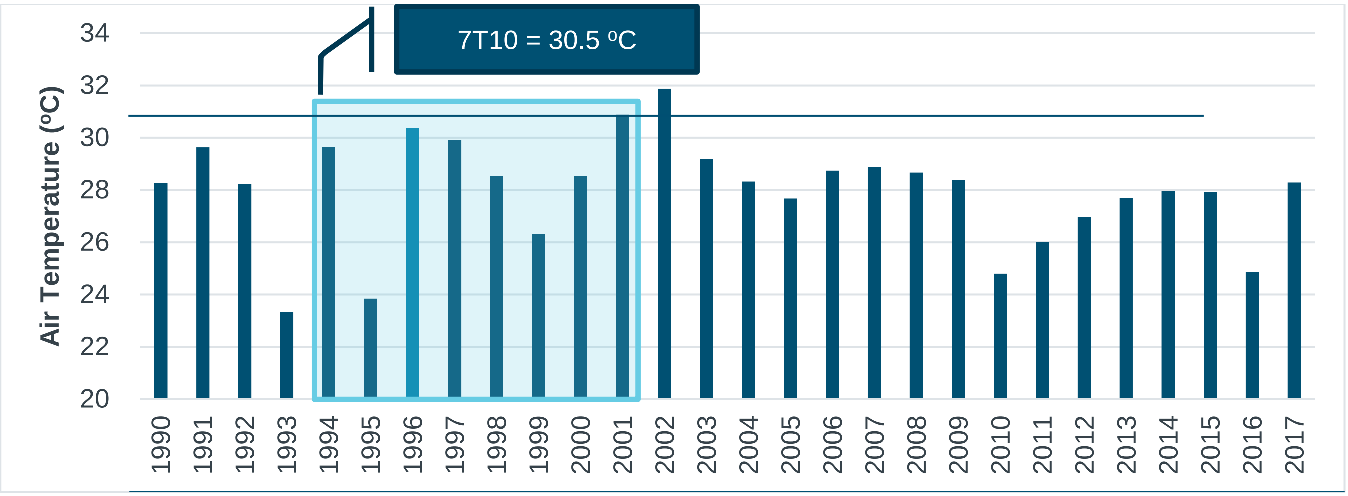


Figure 7. Maximum weekly average air temperature for each year from 1990 to 2017 (Calgary Int. Airport station). Highlighted area shows the years selected for model runs. In this graph, the 7T10 is the highest 7-day average temperature that occurs (on average) once every 10 years.

c) Instream water quality

Since most water quality samples have a monthly sampling frequency, linear interpolation was used to estimate daily input time series. A sensitivity analysis was done using the regression approach from LOADEST for TP. LOADEST is a FORTRAN program for estimating constituent loads in streams and rivers developed by USGS (Runkel et al. 2004). Trend analysis in the mainstem stations helped to understand if concentrations have significantly changed from the simulation period (Natalie Kromrey, EPA, personal communication, October 19, 2017). As no significant trends were observed, (except for a downward trend for ammonia at Carseland and an upward trend for nitrate in winter, representing not a major influence on reducing DO concentrations), the concentrations used to calibrate the model were directly used (BRWQM, time series 1990-2007).

d) Point sources

The baseline load for each point source used recent flow and concentrations for a period that accurately represents typical operating conditions.

Figure 8 shows the change in average daily TP in the Bow River basin for all the point sources since 1990. Although there is a clear decline in total TP load in the early 2000s, trend analysis in recent years found no significant trend (2010-2015; Kendall's tau p-value =0.086). Removing 30 days from the dataset after the 2013 flood draws similar conclusions (p-value = 0.113). The City reported a very consistent TP load in 2015- 2018. For this reason, the 2010-2015 period represents current loading conditions for point sources in the Bow River.

Taube et al. (2016) performed TP trend analyses for Bonnybrook WWTP and Fish Creek WWTP for effluent data from 1981 to 2012. They found a step-down change between 1981 and 1983 (90% TP load reduction) when chemical P removal was introduced at these WWTPs. The TP loading also decreased significantly from 2004 to 2009 based on their trend analysis. A final step-down change in 2006 was attributed to the increased use of alum at the Bonnybrook WWTP.

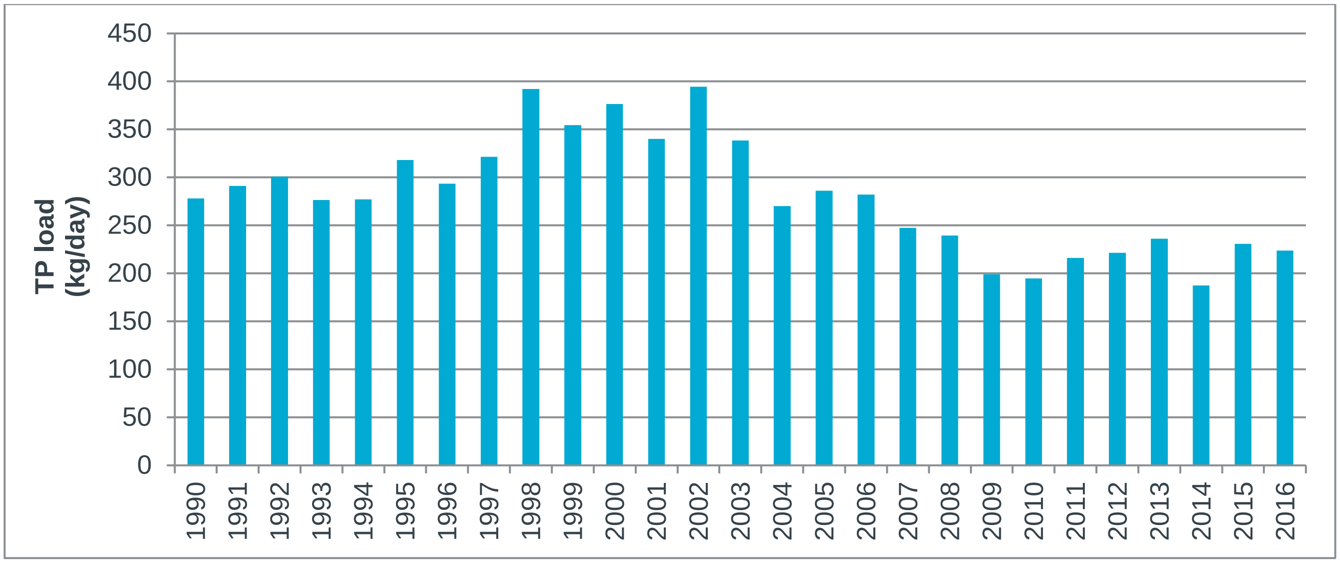


Figure 8. Overall TP load from point sources in the Bow River basin through time.

The point source water quality for the 1994- 2001 simulation period was replaced by randomly applying a year from the 2010-2015 sub-dataset, except for 2013 which was not included due to the plants' upsets during a major flood (Table 3). An alternative method is a synthetic time series estimated using the average load per calendar day from 2010 to 2015 for each point source. However, this approach would smooth some of the high loadings and reduce the effluent variability and was thus not selected.

Table 3. Flow and effluent water quality used to prepare point source input file

Simulation year (instream flow and weather)	Replaced by the load in the year
1994	2014
1995	2011
1996	2014
1997	2015
1998	2010
1999	2011
2000	2012
2001	2012

Some of the effluent water quality parameters were derived. WWTPs measure CBOD5 and it was converted to CBODu, using the equation CBODu=CBOD5/0.31 which is a typical conversion for secondary treatment (Chapra 1997). Most WWTPs measure TP and some measure total dissolved phosphorus, TDP. In the past, TDP was used as a surrogate of total inorganic phosphorus (TIP). Recently, the City of Calgary started measuring dissolved reactive phosphorus (DRP). We performed a sensitivity analysis using TDP and DRP to calculate TIP in the model. For the final simulation, we use City's WWTPs DRP ratios for TIP estimation. Heritage Pointe WWTP does not record TKN and nitrates. Organic nitrogen was estimated from organic P (ON=7.2OP). Dissolved P is also not recorded, so inorganic P was estimated as 0.5TP.

e) Water diversions

Trend analyses for the Western Irrigation District (WID) and Bow River Irrigation District (BRID) total flow diverted per year suggested a statistically significant increase in water diversion by the two irrigation districts in recent years (Table 4). A LOWESS statistical procedure removed the effect of wet and dry years within the Bow River at Calgary station (05BH004).

Table 4. Results of trend analysis on water diversions, 2010-2015

Water Diversion	Parameter	Results
WID	Trend	increasing
	p-value	0.0166
	Statistically significant	Yes
BRID	Trend	increasing
	p-value	0.0167
	Statistically significant	Yes

The WRMM output for WID and BRID water diversions accounts for the water diversion increase in recent years. Water diversion was estimated by the WRMM using current water demand based on irrigation acreage, infrastructure and crop type, as well as maximum diversion volume as per licences and legal cap. These water demand estimates represent additional water they would be required to divert from the Bow River today if the historical weather conditions repeat under current infrastructure, efficiency and crop type rotation. It assumed that this additional water could be diverted using their licence rights, which is a conservative assumption. Linear interpolation was performed on the WRMM weekly output.

f) Rural non-point sources

The WRMM estimated the WID water return flow (RF). The total RF from the WRMM component Block 313 was distributed in the different WID RFs by using the relative contributions estimated for the BRWQM recalibration from 2005 to 2015 (Table 5).

Table 5. Distribution of WID return flow to individual outlets in the model domain.

Return Flow	12 Mile	Cairnhill	Hammerhill	Monroe	Thissen
Contribution %	27%	24%	25%	5%	19%

Alberta Agriculture (unpublished data) has performed trend analyses in the irrigation districts' canals and return flows sampled as part of the Irrigation Districts Water Quality project (Charest, et al., 2012). The data spans 2006, 2007, and 2011-2015. The trend analysis shows no significant change in TP concentration in the WID return flow sampled. Furthermore, WID's primary and secondary canals do not show statistically significant trends for TP. All the sites analyzed for the WID and BRID show no trends for orthophosphate (PO4) except for a secondary canal for WID and BRID. These two secondary canal sites had a declining trend in concentration. Similarly, the available data showed no trend or negative trend for total nitrogen. For this reason, using the historical concentrations in the model provides a conservative approach.

The Baseline scenario used the estimated RF water quality loadings from the most recent BRWQM re-calibration. This time series used return flow WQ monitored by Alberta Agriculture. The concentrations were back-calculated using the BRWQM loading and daily flows. Then, the monthly average concentrations were calculated. The 1994-2001 loadings were estimated using the monthly average concentration and the flow estimated by the WRMM.

g) Urban non-point sources

The City of Calgary provided stormwater flow and loadings estimated with the SUSTAIN-SWMM model. They also included mapping tables to link the data to WASP and HEC-RAS. The SWMM scenario used land use and infrastructure expected in 2018 and weather patterns from the simulation period. The stormwater TP load does not include inputs from construction sites.

2.4.2. TP load contribution in the Baseline scenario

The total TP load in the Baseline scenario was distributed among the source categories as per Figure 9 a). The contributions of the different TP source categories in the Baseline scenario are very similar to the contributions estimated with the Source Assessment report for the 2005-2015 average when removing the loadings from peak flows > 99th percentile (Martin, 2020). In both cases, WWTPs are the major contributor with close to 60% of the total TP load, followed by the background loading coming from upstream Bearspaw Dam (Figure 9).

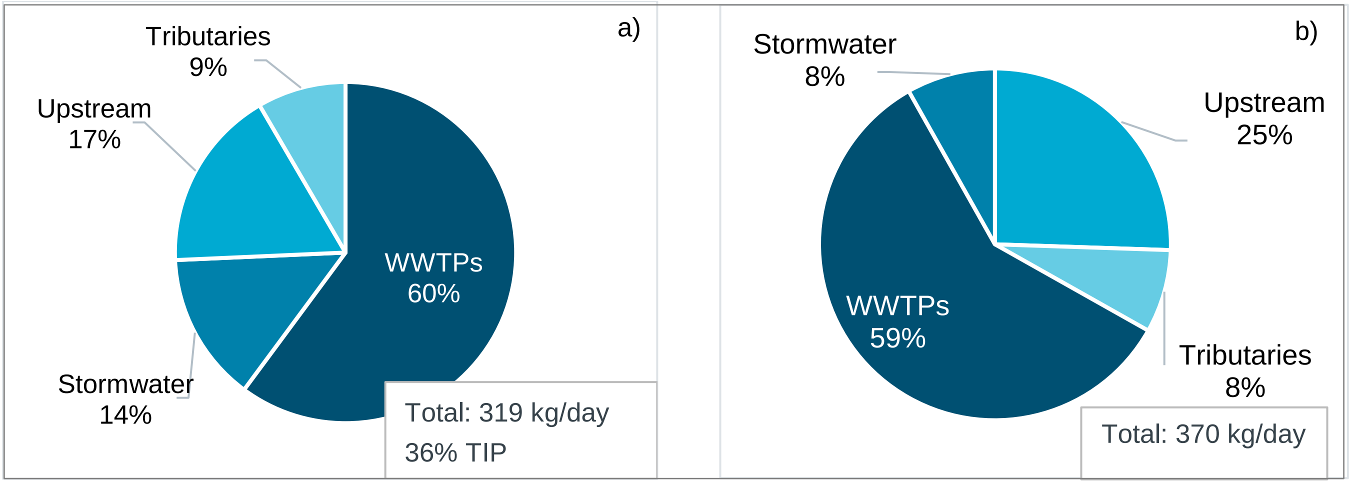


Figure 9. City Reach TP load distribution [kg/day] a) Baseline Scenario (average 1994-2001), b) Source Assessment (average 2005-2015 removing peak flow loadings).

On the other hand, the contributions in the Baseline scenario for the Downstream Reach varied from the ones determined in the Source Assessment report (Figure 10). In the Baseline scenario, the contribution coming from the City of Calgary reach is the largest TP source followed by tributaries. The Source Assessment identified the tributaries and upstream load with a more even TP contribution. The Source Assessment used LOADEST to estimate the tributaries' daily TP load. The regression approach used by LOADEST estimates peak TP loads during the Spring freshet that are very often missed by interpolation. Another reason for the change is that the Source Assessment included data from 2005 to 2015 adjusted by removing the loadings with flows > the 99th percentile (e.g., peak loadings during the 2013 flood). The Baseline scenario used the 1994 to 2001 period using interpolation between monthly grab samples.

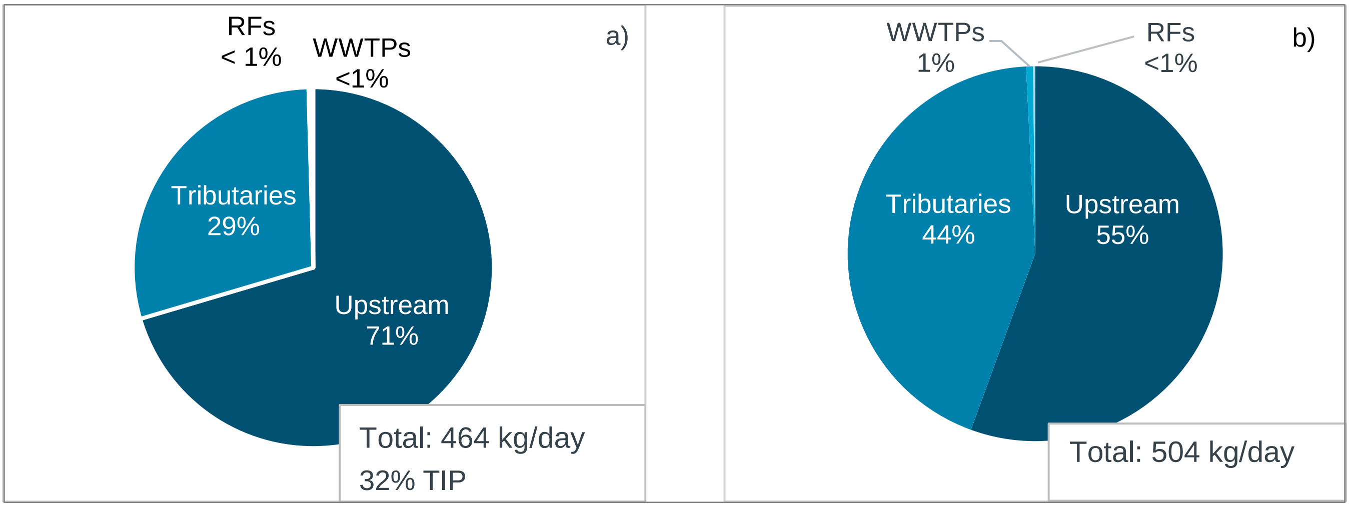


Figure 10. Downstream reach TP distribution [kg/day] a) Baseline Scenario (average 1994-2001), b) Source Assessment (average 2005-2015 removing peak flow loadings).

2.4.3. Confirmation of limiting nutrient

The model estimated the dissolved inorganic phosphorus and nitrogen concentrations at every segment and time step. The model uses these concentrations to calculate the N and P limitation coefficients. The limitation coefficients depend on the bioavailable N and P concentrations and the half-saturation growth rate constants. The half-saturation growth rate constants are determined during the model calibration process and indicate the nutrient concentration at which the growth rate is half the saturated growth rate. The limitation coefficients are a value between 0 and 1, where 0 means high growth limitation and 1 means no growth limitation. The model chooses the nutrient with the minimum value (limiting nutrient) to reduce the saturated growth rate.

2.5 Model iterations

The Baseline scenario predicted the compliance with the DO guidelines under current loading and infrastructure conditions. The spatial distribution of the minimum DO for each segment helped identify critical cross-sections. We increased the loading in a step-wise fashion until reaching the desired frequency of compliance (FOC) of 99.91% for the average DO in the selected cross-sections. Figure 11 provides the overall modelling methodology. The Downstream Reach used the City Reach MAL as the upstream loading. The loading from this source did not change for the model iterations in this reach.

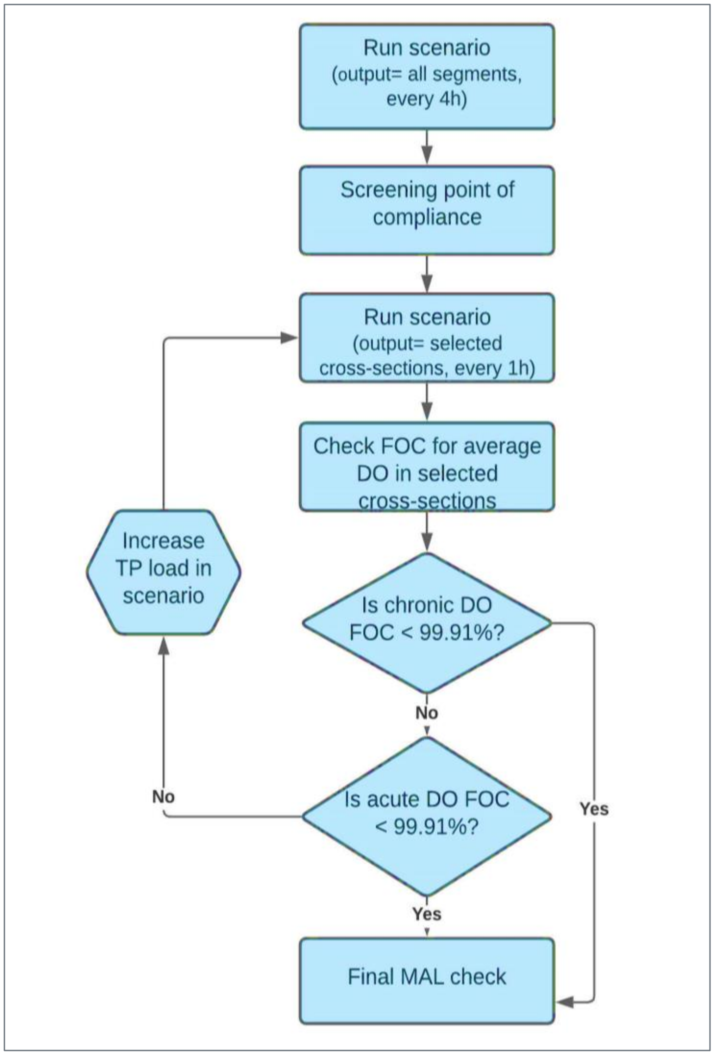


Figure 11. Flow chart showing steps followed during model iterations, FOC = Frequency of Compliance.

There are multiple approaches to increasing the load from the TP sources (Figure 12). Point source-led loading management plans or receiving water assessments (RWA) formulate the scenarios based on future wastewater infrastructure and population, while the other boundary conditions remain the same as in the model calibration. In some cases, these analyses also consider the change in urban non-point source loadings.

The BRMAL study increased all the different sources or boundary conditions including the upstream loading, tributaries, point sources and non-point sources. The Baseline scenario can be increased following different schemes; one of the simplest forms is by increasing all the sources by an equal percentage. The percentage can also be proportional to contributing sources based on their baseline contributions. The BRMAL study ran the scenarios by increasing all the sources in the same percentage, and it explored other alternative approaches such as increasing the load by the ranked contribution of their baseline load.

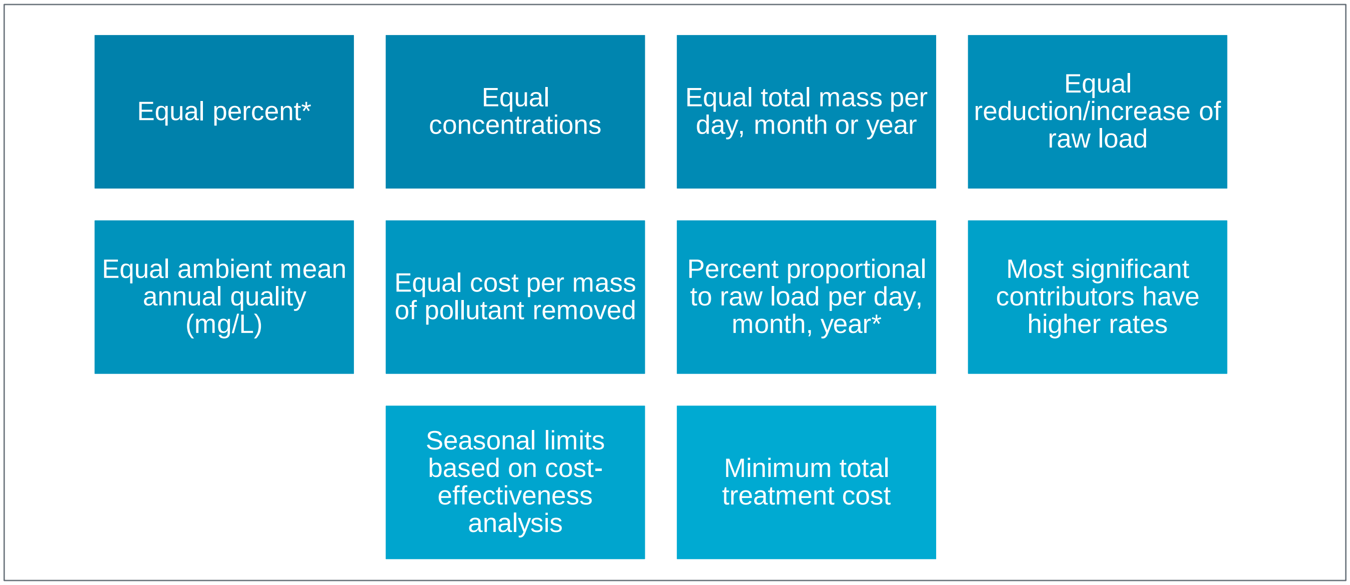


Figure 12. Different approaches to increasing, decreasing or allocating loadings. Adapted from TMDL guidance document (USEPA, 1999). Note: '*' shows the two approaches used for this modelling exercise.

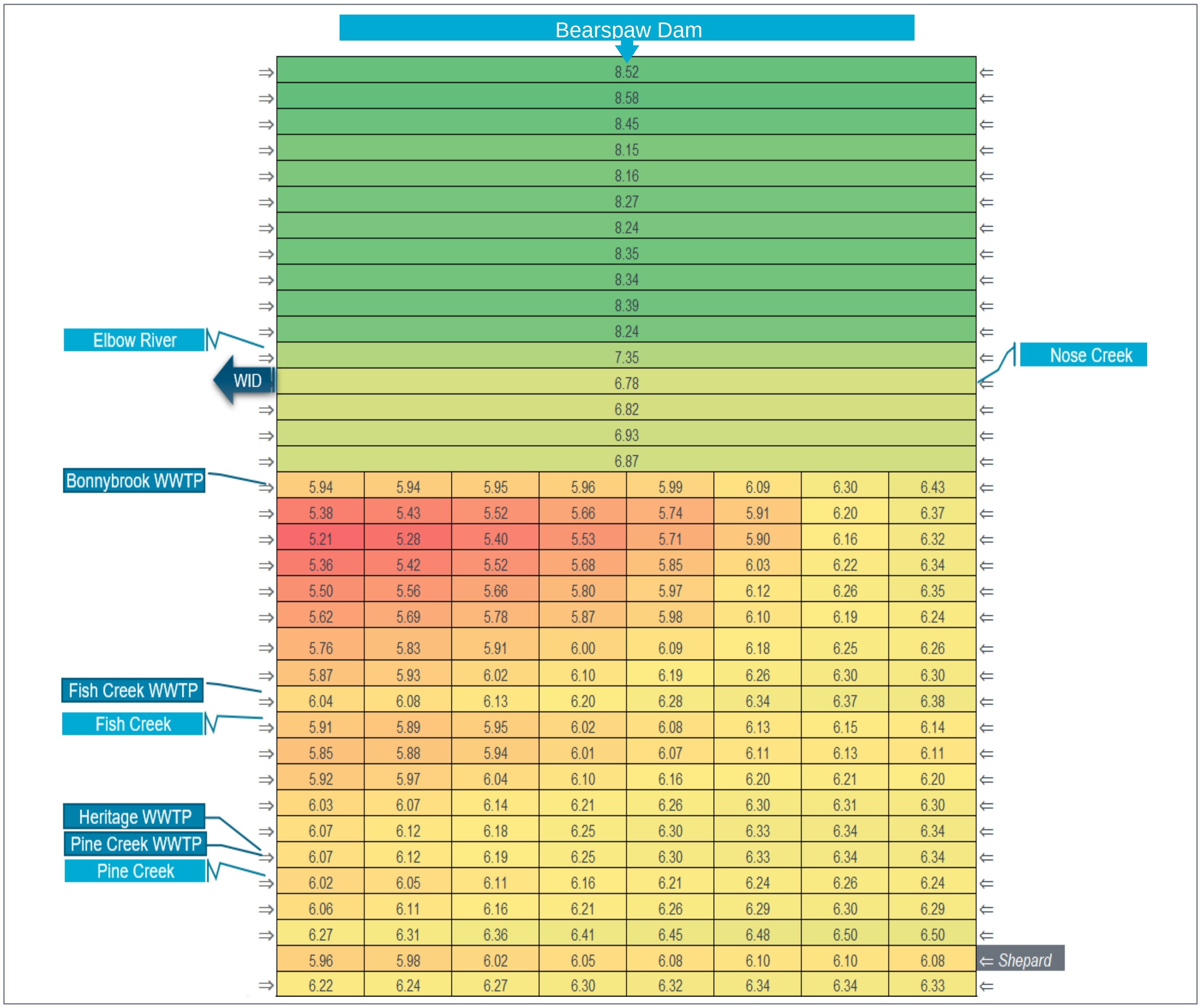
Pre- and post-processing tools based on Excel VBA were developed to support the model application. Multiple options were provided in the pre-processing tool to change the input of the model. The post-processing tool extracts the WASP-MG model results and presents the results in tables, figures, and spatial plots with multiple options. The frequency of compliance was calculated for each segment and visualized using a spatial trend results schematic color-coded to the degree of compliance or DO concentration.

3. Results

3.1 City Reach

Baseline scenario

During the Baseline simulation, DO concentrations never reached values equal to or lower than 5 mg/L, which is the provincial acute guideline (Government of Alberta, 2018) (Figure 13). Thus, both the acute and chronic (6.5 mg/L) frequencies of compliance were 100% for all the segments. The spatial distribution of minimum DO showed a gradient with maximum values at the most upstream segments. The minimum DO decreased downstream of the ElBow River and Nose Creek. The most significant drop in DO was downstream of Bonnybrook WWTP; however, the absolute minimum had a lag time from the outfall location (5.21 mg/L about 3 km downstream of Bonnybrook). The Bonnybrook diffuser extends 75% of the river width, which showed in the DO plume. The minimum DO had a cross-sectional gradient. The most left segments (looking downstream) do not have diffusers, and their DO was higher than the rest of the segments that received effluent. After approximately 3 km, the DO started to recover. The other TP sources showed some local effects in the minimum DO. The simulation showed two smaller DO reduction plumes below Fish Creek and Pine Creek WWTPs. Figure 13 also shows the effect of Shepard Slough on the DO.



8.52							
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8.34							
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7.35							
6.78							
6.82							
6.93							
6.87							
5.94	5.94	5.95	5.96	5.99	6.09	6.30	6.43
5.38	5.43	5.52	5.66	5.74	5.91	6.20	6.37
5.21	5.28	5.40	5.53	5.71	5.90	6.16	6.32
5.36	5.42	5.52	5.68	5.85	6.03	6.22	6.34
5.50	5.56	5.66	5.80	5.97	6.12	6.26	6.35
5.62	5.69	5.78	5.87	5.98	6.10	6.19	6.24
5.76	5.83	5.91	6.00	6.09	6.18	6.25	6.26
5.87	5.93	6.02	6.10	6.19	6.26	6.30	6.30
6.04	6.08	6.13	6.20	6.28	6.34	6.37	6.38
5.91	5.89	5.95	6.02	6.08	6.13	6.15	6.14
5.85	5.88	5.94	6.01	6.07	6.11	6.13	6.11
5.92	5.97	6.04	6.10	6.16	6.20	6.21	6.20
6.03	6.07	6.14	6.21	6.26	6.30	6.31	6.30
6.07	6.12	6.18	6.25	6.30	6.33	6.34	6.34
6.07	6.12	6.19	6.25	6.30	6.33	6.34	6.34
6.02	6.05	6.11	6.16	6.21	6.24	6.26	6.24
6.06	6.11	6.16	6.21	6.26	6.29	6.30	6.29
6.27	6.31	6.36	6.41	6.45	6.48	6.50	6.50
5.96	5.98	6.02	6.05	6.08	6.10	6.10	6.08
6.22	6.24	6.27	6.30	6.32	6.34	6.34	6.33

Figure 13. Spatial distribution of minimum DO (mg/L) in the Baseline scenario, City Reach (green color means higher DO concentrations and red color lower concentrations).

The nutrients spatial distribution and their effect on aquatic plants and algae contributed to the DO longitudinal profile simulated in the Baseline scenario. Figure 14 shows the simulated biomass response to the nutrient loadings along the river. Macrophyte growth was very sensitive to nutrient inputs. The nutrients were not completely mixed along the river cross-section due to the WWTPs outfalls configuration. As a result, the model shows higher macrophyte growth on the right bank. The macrophytes and periphyton growth inversely correlated with each other as they competed for nutrients and light. The periphyton concentration was lower in the reaches with abundant macrophytes.

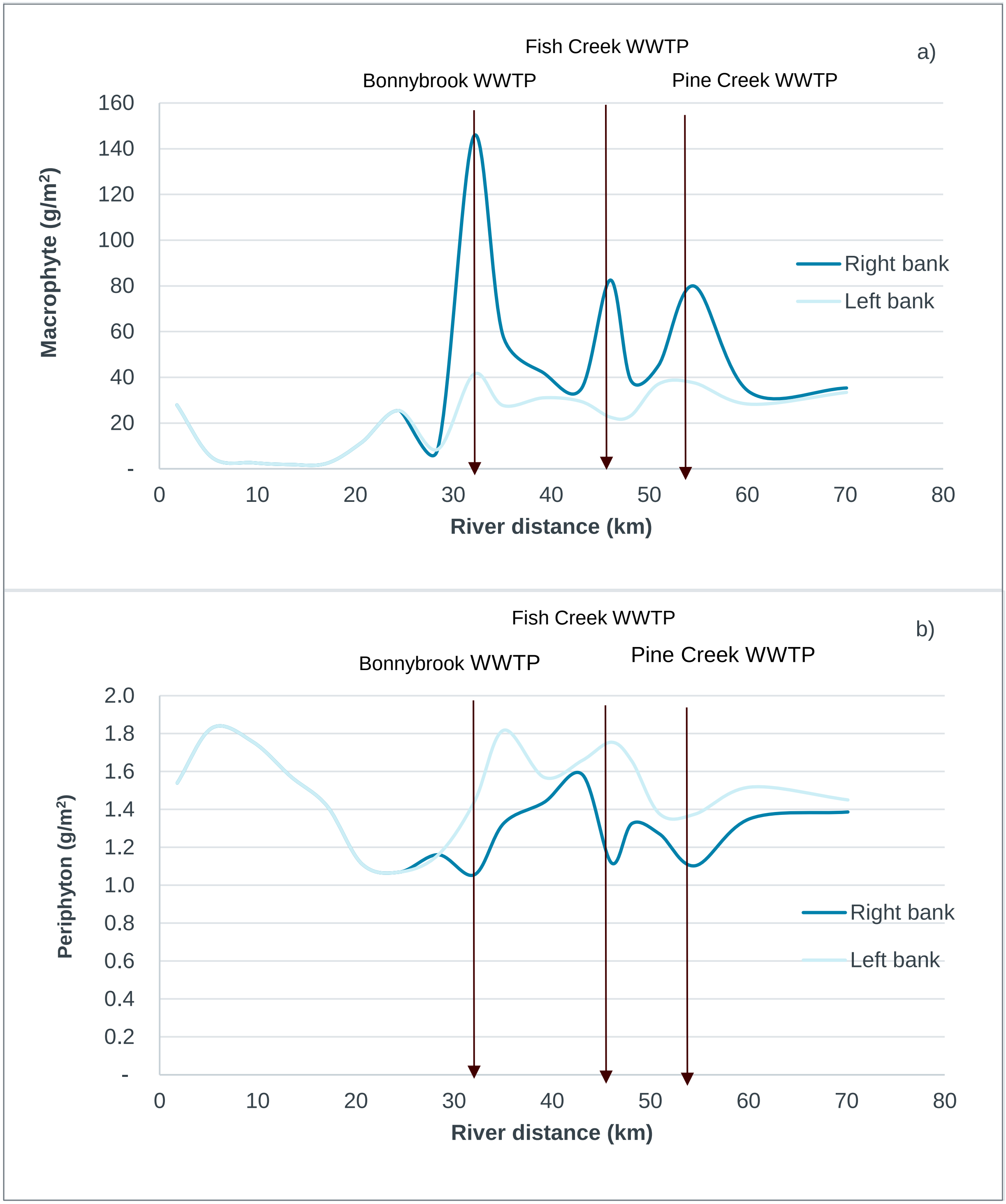


Figure 14. Change of biomass with river distance along the City Reach in the Baseline scenario a) macrophytes, b) periphyton, right and left bank.

Confirmation of P limitation

The model estimated the nutrient limitation coefficients for the Baseline scenario. Figure 15 shows the nitrogen and phosphorus limitation coefficients for each biomass group. The nutrient with the lowest coefficient is the limiting nutrient. All the biomass groups were P limited along this river reach. Figure 15 also shows how the river is more P and N limited upstream of Bonnybrook WWTP.

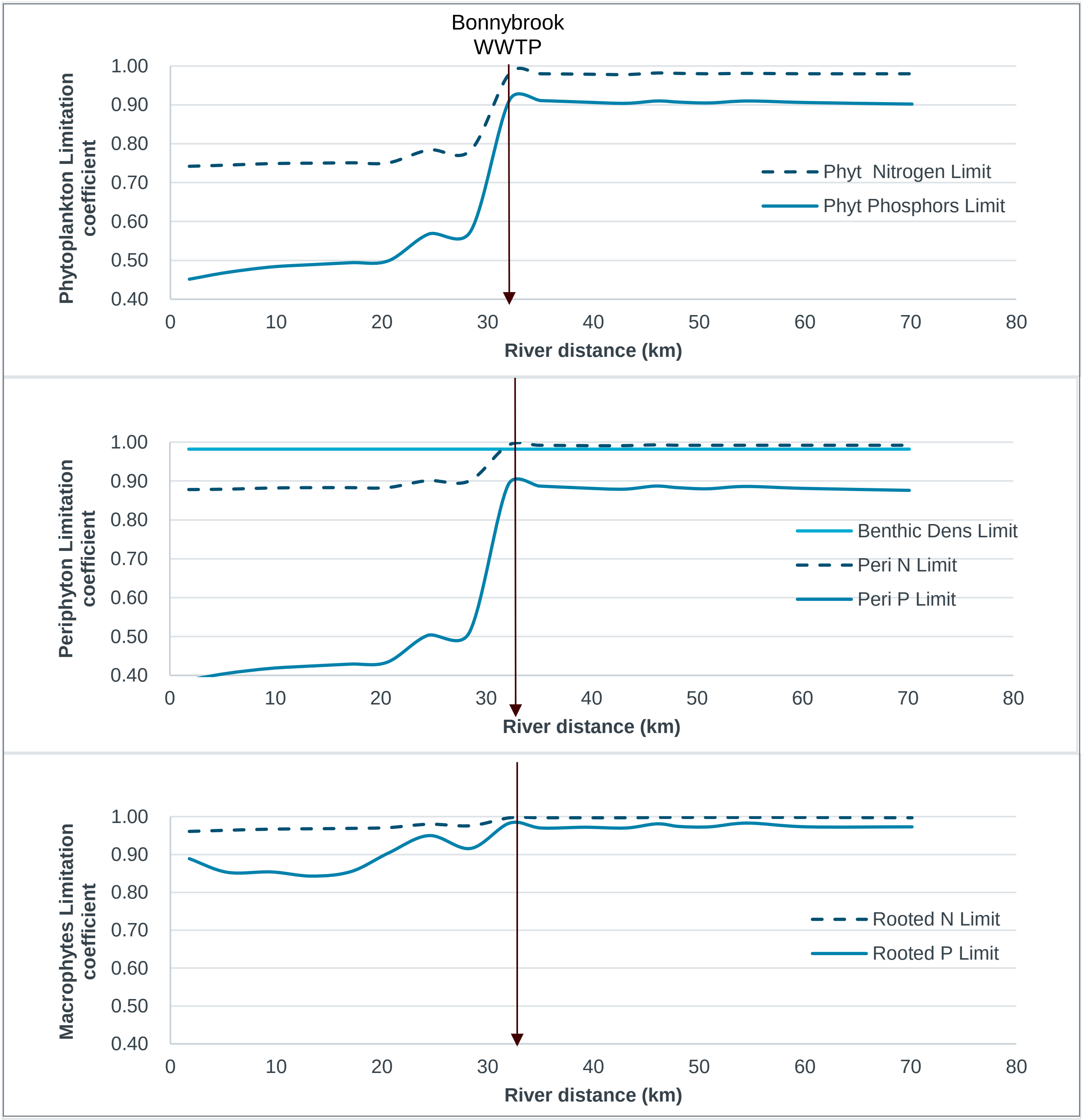


Figure 15. Nutrient limitation coefficients simulated along the City Reach for the different biomass groups during the Baseline scenario, right bank.

Determination of the MAL

The TP loadings in the Baseline scenario were increased for all the boundary conditions (upstream, tributaries, WWTPs and stormwater) by the same percentage. The cross-sections with the lowest average frequency of compliance and minimum DO were downstream of Bonnybrook WWTP (segments 33-40, 41-48, 49-56, 57-64). These four cross-sections and the last two cross-sections from this model reach (161-168 and 169-176) were selected to estimate the cross-sectional average DO and the cross-sectional frequency of compliance. The cross-sectional frequency of compliance for the chronic guideline was always 100% in each scenario.

Table 6 shows how the different scenarios affected the acute frequency of compliance. An increase of 20% of the TP load did not change the 100% frequency of compliance in the river. However, a further 5% increase resulted in a sharp decline in the minimum DO (Figure 16).

Table 6. DO acute frequency of compliance by increasing the City Reach Baseline source TP by an equal percentage.

	TP increase factor by source category				TP source daily average load (kg/day)					DO acute frequency of compliance (%) for selected cross-sections					
Scenario	**Upstream**	**Tributaries**	**WWTPs**	**Stormwater**	**Upstream**	**Tributaries**	**WWTPs**	**Stormwater**	**Total**	**33-40**	**41-48**	**49-56**	**57-64**	**161-168**	**169-176**
Baseline	**1**	**1**	**1**	**1**	**55**	**27**	**192**	**45**	**319**	**100**	**100**	**100**	**100**	**100**	**100**
1.100	1.100	1.100	1.100	1.100	61	30	211	50	**351**	100	100	100	100	100	100
1.200	1.200	1.200	1.200	1.200	66	32	230	54	**383**	100	100	100	100	100	100
1.250	1.250	1.250	1.250	1.250	69	34	240	57	**399**	99.96	99.95	99.97	99.98	100	100
1.270	1.270	1.270	1.270	1.270	70	34	244	57	**405**	99.92	99.92	99.93	99.96	99.99	100
1.275	**1.275**	**1.275**	**1.275**	**1.275**	**70**	**34**	**245**	**58**	**407**	99.91	99.91	99.92	99.95	99.98	100
1.280	1.280	1.280	1.280	1.280	71	34	246	58	**409**	99.91	99.90	99.91	99.95	99.97	100
1.300	1.300	1.300	1.300	1.300	72	35	250	59	**415**	99.89	99.87	99.86	99.91	100	100

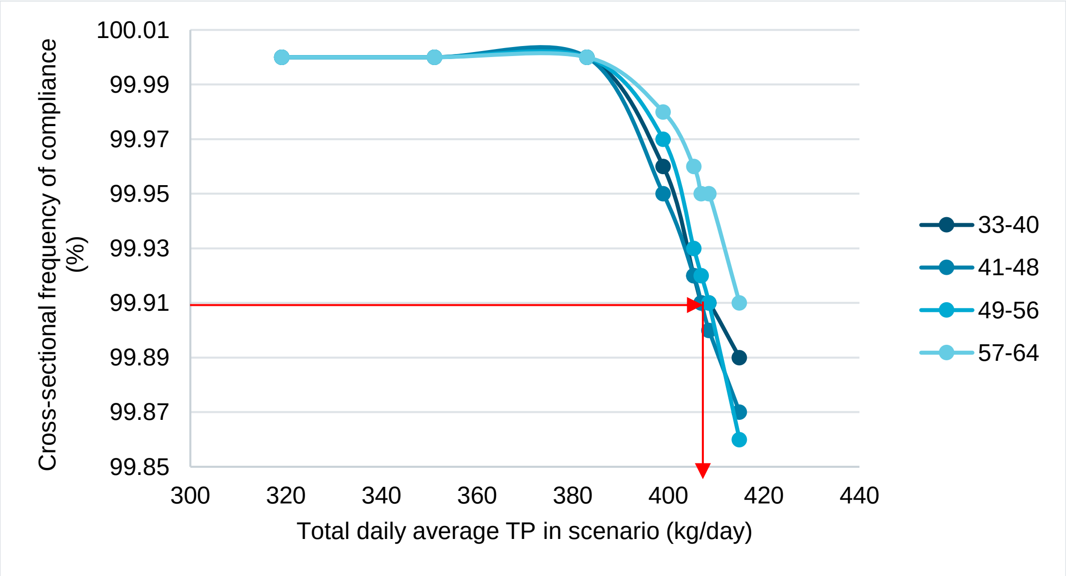
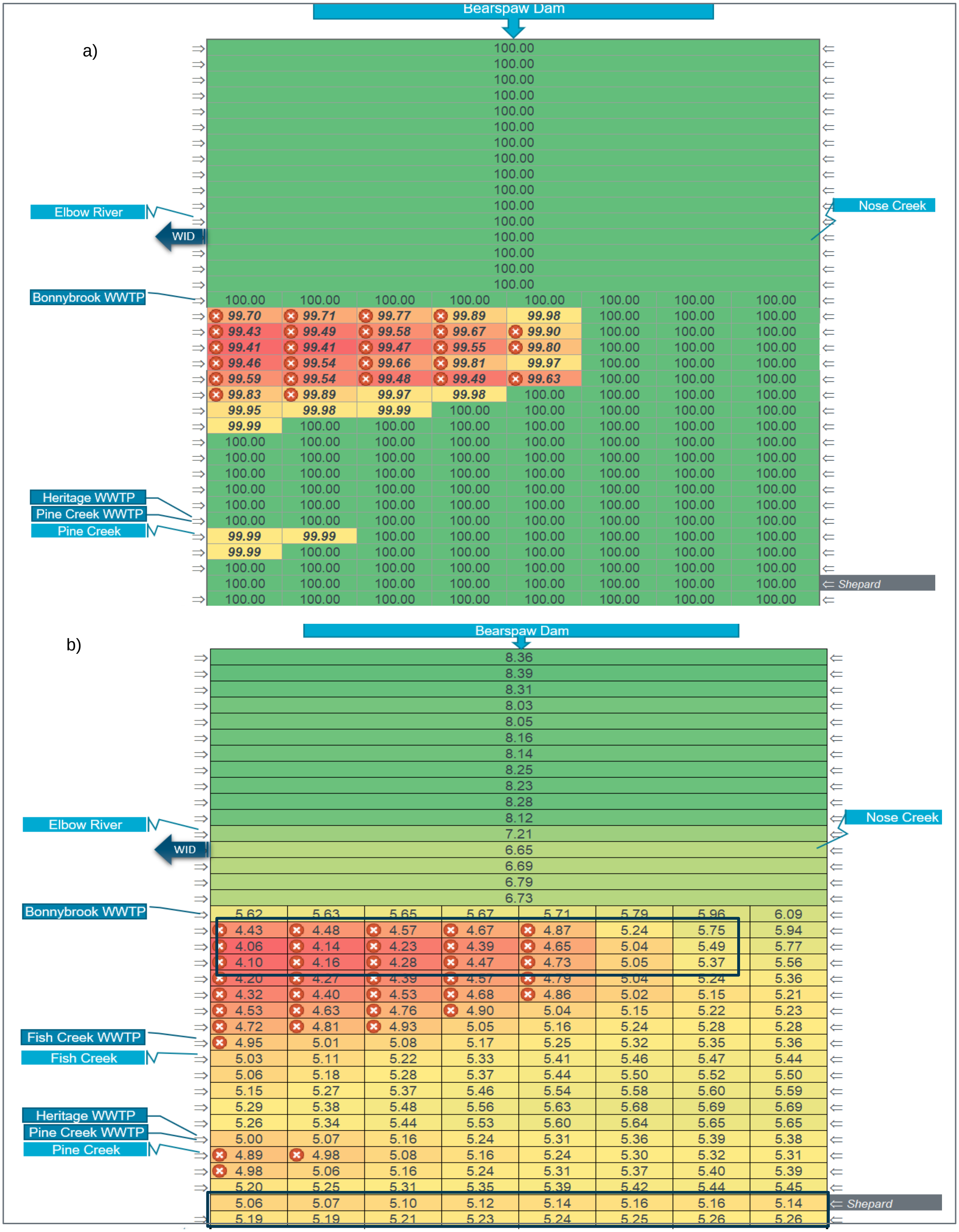


Figure 16. Change of frequency of compliance with incremental TP loading in model scenarios for selected cross-sections downstream of Bonnybrook WWTP.

The river reached the 99.91% frequency of compliance with a 27.5% TP increase and a total load of 407 kg/day. This scenario defines the MAL. This load was reduced by the 10% margin of safety (MOS) to consider the model uncertainty. The difference between the Baseline TP load and the MAL load (after the MOS) was 47 kg/day. The modelling suggests this as the available load in the river reach according to the current configuration. This load represents a 15% net increase. Table 7 summaries the calculation of these numbers with comments.

Table 7. City Reach MAL using an equal percentage increase of TP loadings and cross-sectional average DO.

TP Load (kg/day)		Comments
Baseline	319	
Increase (before MOS)	1.275	
MAL (before MOS)	407	1.275xBaseline
MAL (after MOS)	366	0.90xMAL
Available load	47	MAL (after MOS) – Baseline
Increase (after MOS)	1.15	MAL (after MOS)/ Baseline



a)

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100.00

100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
☒ 99.70	☒ 99.71	☒ 99.77	☒ 99.89	99.98	100.00	100.00	100.00
☒ 99.43	☒ 99.49	☒ 99.58	☒ 99.67	☒ 99.90	100.00	100.00	100.00
☒ 99.41	☒ 99.41	☒ 99.47	☒ 99.55	☒ 99.80	100.00	100.00	100.00
☒ 99.46	☒ 99.54	☒ 99.66	☒ 99.81	99.97	100.00	100.00	100.00
☒ 99.59	☒ 99.54	☒ 99.48	☒ 99.49	☒ 99.63	100.00	100.00	100.00
☒ 99.83	☒ 99.89	99.97	99.98	100.00	100.00	100.00	100.00
99.95	99.98	99.99	100.00	100.00	100.00	100.00	100.00
99.99	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
99.99	99.99	100.00	100.00	100.00	100.00	100.00	100.00
99.99	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

b)

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6.65
6.69
6.79
6.73

5.62	5.63	5.65	5.67	5.71	5.79	5.96	6.09
☒ 4.43	☒ 4.48	☒ 4.57	☒ 4.67	☒ 4.87	5.24	5.75	5.94
☒ 4.06	☒ 4.14	☒ 4.23	☒ 4.39	☒ 4.65	5.04	5.49	5.77
☒ 4.10	☒ 4.16	☒ 4.28	☒ 4.47	☒ 4.73	5.05	5.37	5.56
☒ 4.20	☒ 4.27	☒ 4.39	☒ 4.57	☒ 4.79	5.04	5.24	5.36
☒ 4.32	☒ 4.40	☒ 4.53	☒ 4.68	☒ 4.86	5.02	5.15	5.21
☒ 4.53	☒ 4.63	☒ 4.76	☒ 4.90	5.04	5.15	5.22	5.23
☒ 4.72	☒ 4.81	☒ 4.93	5.05	5.16	5.24	5.28	5.28
☒ 4.95	5.01	5.08	5.17	5.25	5.32	5.35	5.36
5.03	5.11	5.22	5.33	5.41	5.46	5.47	5.44
5.06	5.18	5.28	5.37	5.44	5.50	5.52	5.50
5.15	5.27	5.37	5.46	5.54	5.58	5.60	5.59
5.29	5.38	5.48	5.56	5.63	5.68	5.69	5.69
5.26	5.34	5.44	5.53	5.60	5.64	5.65	5.65
5.00	5.07	5.16	5.24	5.31	5.36	5.39	5.38
☒ 4.89	☒ 4.98	5.08	5.16	5.24	5.30	5.32	5.31
☒ 4.98	5.06	5.16	5.24	5.31	5.37	5.40	5.39
5.20	5.25	5.31	5.35	5.39	5.42	5.44	5.45
5.06	5.07	5.10	5.12	5.14	5.16	5.16	5.14
5.19	5.19	5.21	5.23	5.24	5.25	5.26	5.26

Figure 17. Spatial distribution in MAL scenario, City Reach (TP increase ratio 1.275, total TP load 407 kg/day) a) Acute frequency of compliance, and b) Minimum DO (mg/L) (green color means higher DO concentrations and red color lower concentrations).

Although the cross-sectional frequency of compliance was 99.91%, the frequency of compliance for some individual segments was lower than that as per Figure 17. The model predicts an overall minimum DO of 4.06 mg/L on the right bank 3 km downstream of Bonnybrook WWTP. An increase in macrophyte density of up to 32 g/m^2 drives the decrease in the DO frequency of compliance (Figure 18).

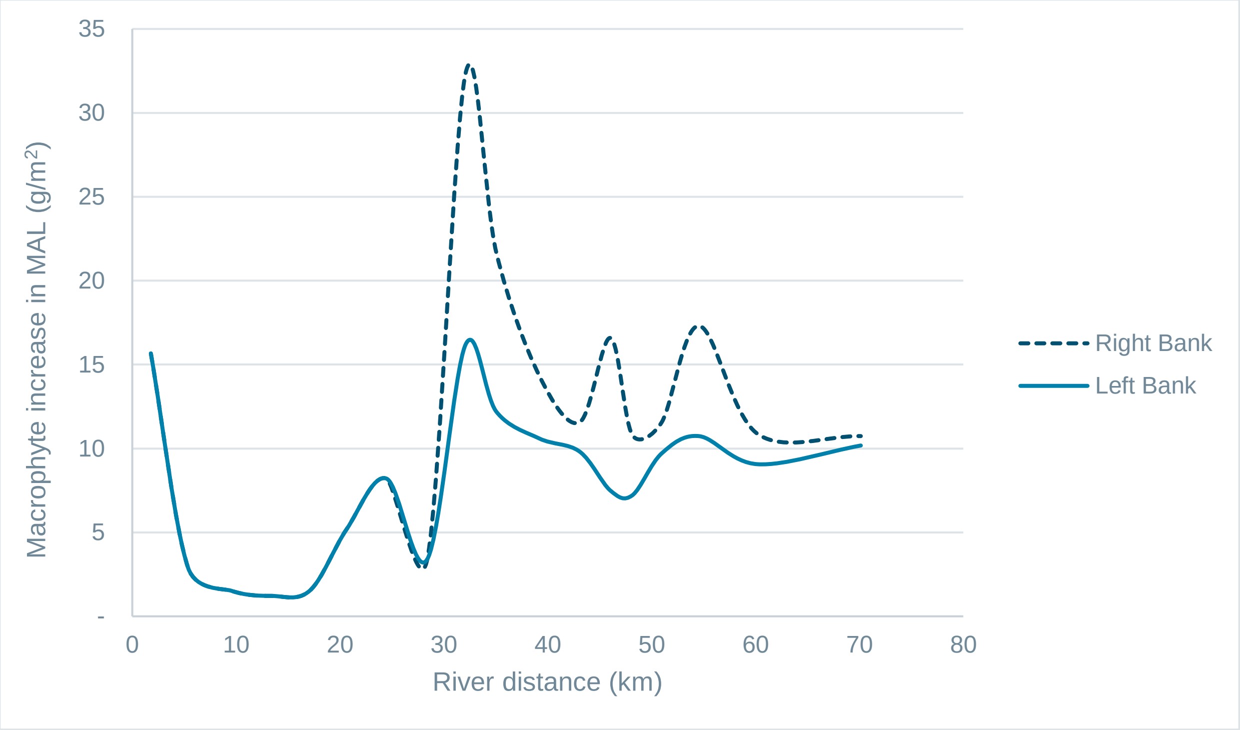


Figure 18. Macrophyte increase in the MAL scenario in comparison with the Baseline scenario for both riverbanks, City Reach.

Besides the nutrient loading, other factors such as river discharge and weather play a role in the DO concentration. The DO reached values below the guideline of 5 mg/L in two years during the simulation period (2000 and 2001). A smaller river discharge characterized those two years, as per Figure 19 (c). The low flow and resulting low drag coefficient could encourage macrophytes to establish in the banks. The model simulated a higher macrophyte density in those two years, as per Figure 19 (b).

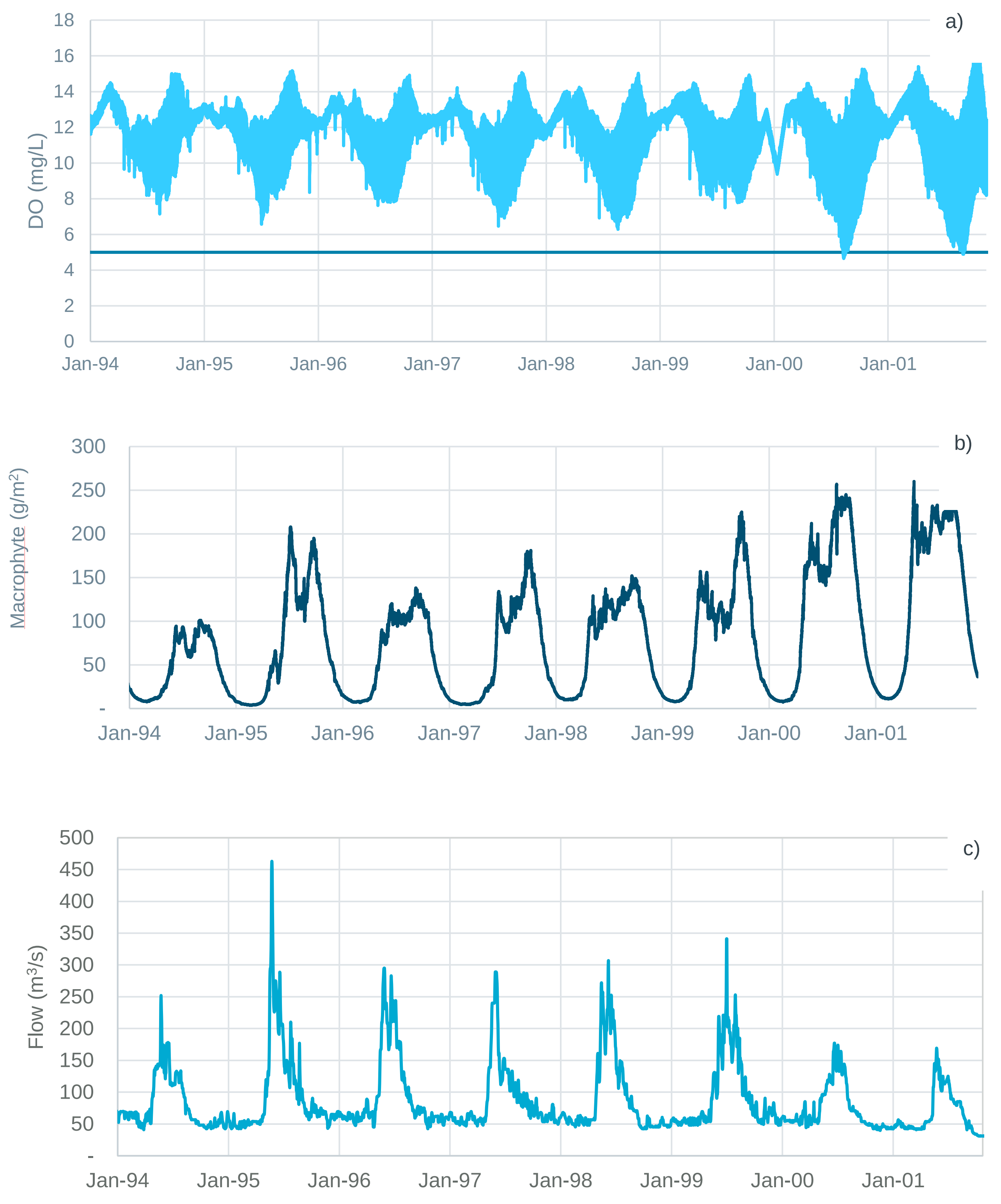


Figure 19. Model results in City Reach MAL scenario segments 41-48 a) Average DO; b) macrophyte density, and c) observed flow at Bow River Below Bearspaw Dam station (05BH008) during the simulation period 1994-2001.

Based on the MAL scenario, the model predicted low DO in late August and early September. In August 2000, the model predicted nine consecutive days with DO below the acute guideline (Figure 20). The DO sag lasted from one hour to up to eight hours per day during the night. This information gives a snapshot of the potential DO sag duration if the loadings increase to the MAL.

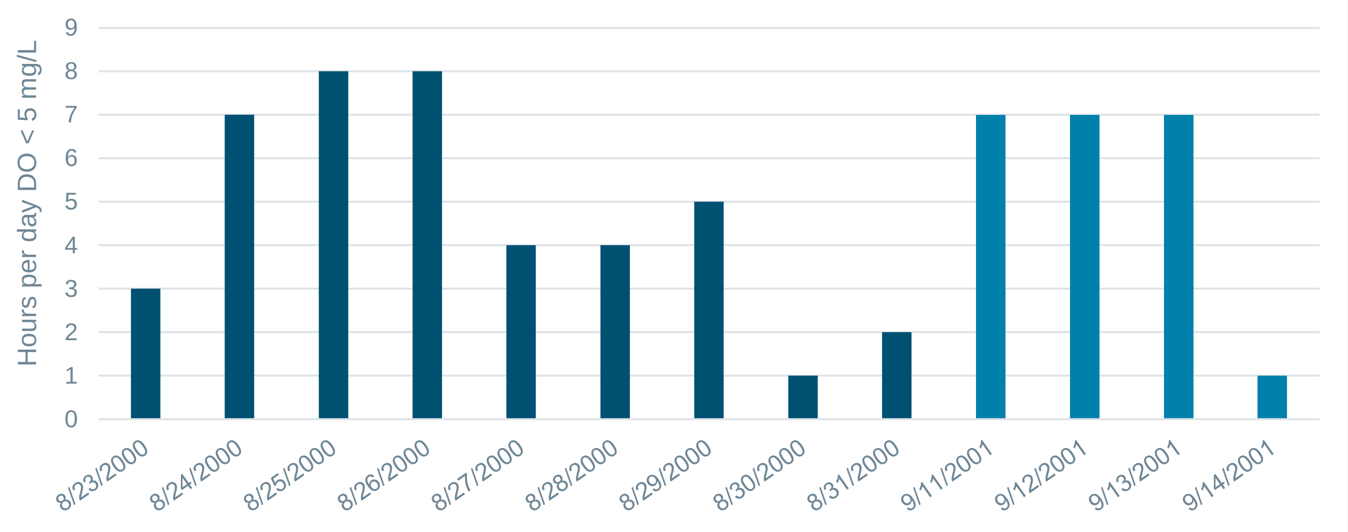


Figure 20. Days and number of hours that the cross-sectional average DO was below 5 mg/L in City Reach segments 41-48, MAL scenario.

3.2 Downstream Reach

Baseline Scenario

Figure 21 shows the macrophytes and periphyton longitudinal profile for the Baseline scenario. The macrophytes showed a maximum density in the boundary with the City Reach, then another increase downstream Carseland. The overall concentration was higher in the right bank. However, the maximum density in the Downstream Reach (just above 6 g/m^2) was much lower than the maximum in the City Reach just above 140 g/m^2.

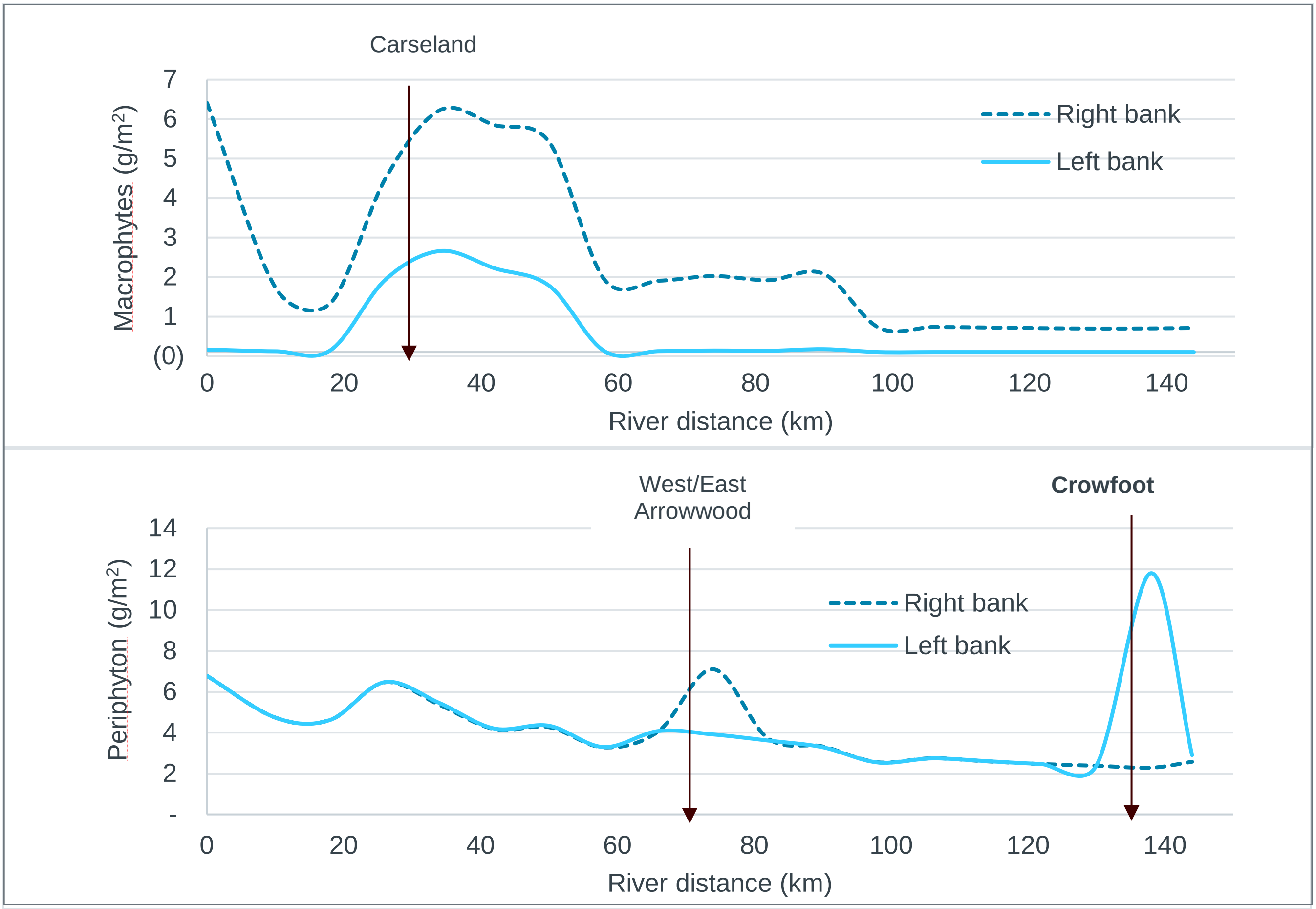
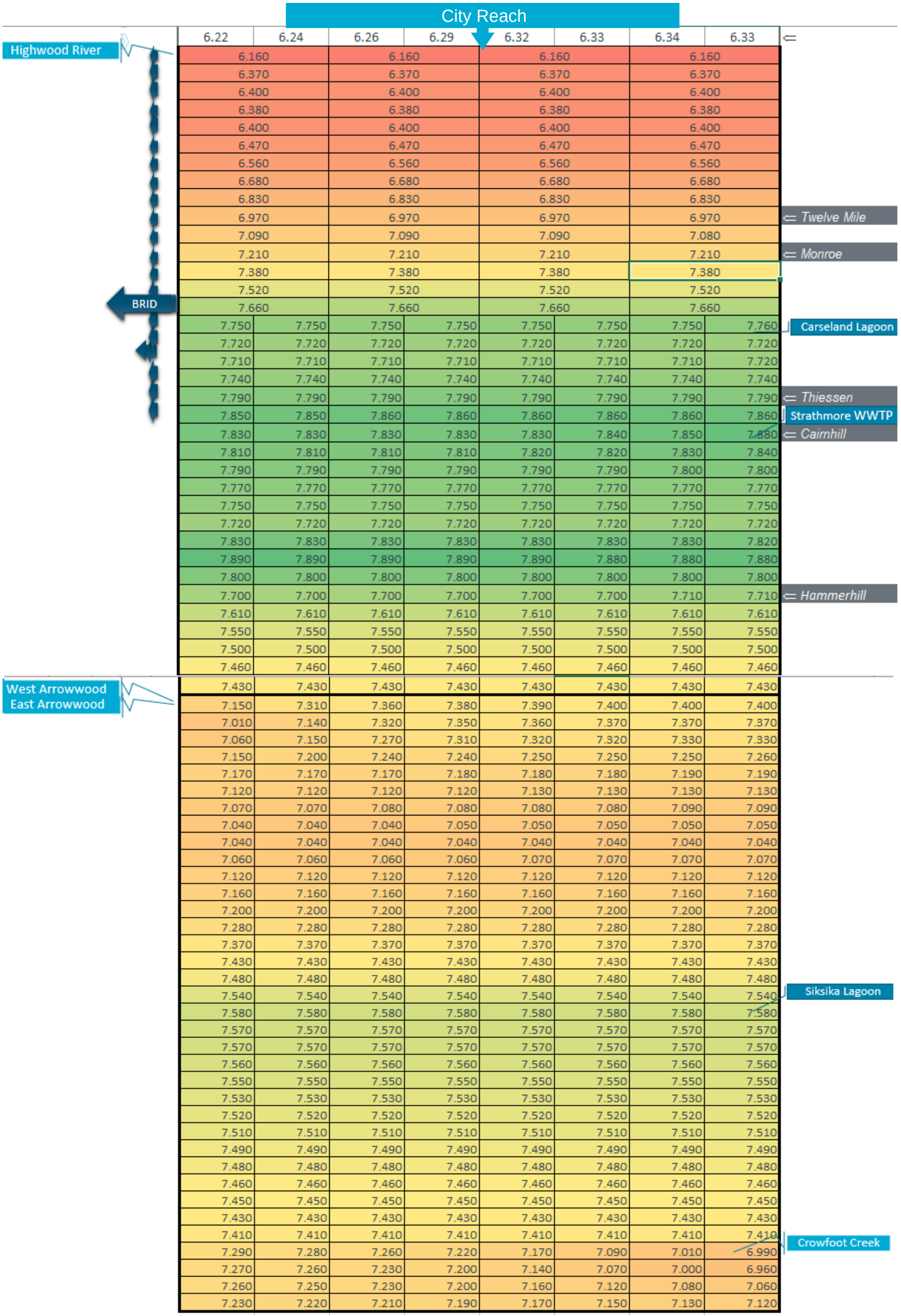


Figure 21. Average periphyton and macrophyte density in the Baseline scenario. Longitudinal profile along the Downstream Reach in both riverbanks.

The effect of the downstream tributaries, West Arrowood, East Arrowood and Crowfoot Creek, was more evident for the periphyton density. There was a peak on the right bank near the West and East Arrowood creeks, and one peak on the left bank near the confluence of the Crowfoot Creek. The model suggests a higher periphyton concentration than macrophyte concentration in this river reach. This finding contrasts with the City Reach which had overall higher macrophyte concentrations. These initial conditions played a role in the model scenarios at different TP loadings.

Similar to the City Reach, the Downstream Reach had a 100% frequency of compliance for the Baseline scenario. The minimum DO was at the most upstream cross-section. The DO increased as it flowed downstream with some local effects of the tributaries (Figure 22).



6.22	6.24	6.26	6.29	6.32	6.33	6.34	6.33
6.160		6.160		6.160		6.160	
6.370		6.370		6.370		6.370	
6.400		6.400		6.400		6.400	
6.380		6.380		6.380		6.380	
6.400		6.400		6.400		6.400	
6.470		6.470		6.470		6.470	
6.560		6.560		6.560		6.560	
6.680		6.680		6.680		6.680	
6.830		6.830		6.830		6.830	
6.970		6.970		6.970		6.970	
7.090		7.090		7.090		7.080	
7.210		7.210		7.210		7.210	
7.380		7.380		7.380		7.380	
7.520		7.520		7.520		7.520	
7.660		7.660		7.660		7.660	
7.750	7.750	7.750	7.750	7.750	7.750	7.750	7.760
7.720	7.720	7.720	7.720	7.720	7.720	7.720	7.720
7.710	7.710	7.710	7.710	7.710	7.710	7.710	7.720
7.740	7.740	7.740	7.740	7.740	7.740	7.740	7.740
7.790	7.790	7.790	7.790	7.790	7.790	7.790	7.790
7.850	7.850	7.860	7.860	7.860	7.860	7.860	7.860
7.830	7.830	7.830	7.830	7.830	7.840	7.850	7.880
7.810	7.810	7.810	7.810	7.820	7.820	7.830	7.840
7.790	7.790	7.790	7.790	7.790	7.790	7.800	7.800
7.770	7.770	7.770	7.770	7.770	7.770	7.770	7.770
7.750	7.750	7.750	7.750	7.750	7.750	7.750	7.750
7.720	7.720	7.720	7.720	7.720	7.720	7.720	7.720
7.830	7.830	7.830	7.830	7.830	7.830	7.830	7.820
7.890	7.890	7.890	7.890	7.890	7.880	7.880	7.880
7.800	7.800	7.800	7.800	7.800	7.800	7.800	7.800
7.700	7.700	7.700	7.700	7.700	7.700	7.710	7.710
7.610	7.610	7.610	7.610	7.610	7.610	7.610	7.610
7.550	7.550	7.550	7.550	7.550	7.550	7.550	7.550
7.500	7.500	7.500	7.500	7.500	7.500	7.500	7.500
7.460	7.460	7.460	7.460	7.460	7.460	7.460	7.460
7.430	7.430	7.430	7.430	7.430	7.430	7.430	7.430
7.150	7.310	7.360	7.380	7.390	7.400	7.400	7.400
7.010	7.140	7.320	7.350	7.360	7.370	7.370	7.370
7.060	7.150	7.270	7.310	7.320	7.320	7.330	7.330
7.150	7.200	7.240	7.240	7.250	7.250	7.250	7.260
7.170	7.170	7.170	7.180	7.180	7.180	7.190	7.190
7.120	7.120	7.120	7.120	7.130	7.130	7.130	7.130
7.070	7.070	7.080	7.080	7.080	7.080	7.090	7.090
7.040	7.040	7.040	7.050	7.050	7.050	7.050	7.050
7.040	7.040	7.040	7.040	7.040	7.040	7.040	7.040
7.060	7.060	7.060	7.060	7.070	7.070	7.070	7.070
7.120	7.120	7.120	7.120	7.120	7.120	7.120	7.120
7.160	7.160	7.160	7.160	7.160	7.160	7.160	7.160
7.200	7.200	7.200	7.200	7.200	7.200	7.200	7.200
7.280	7.280	7.280	7.280	7.280	7.280	7.280	7.280
7.370	7.370	7.370	7.370	7.370	7.370	7.370	7.370
7.430	7.430	7.430	7.430	7.430	7.430	7.430	7.430
7.480	7.480	7.480	7.480	7.480	7.480	7.480	7.480
7.540	7.540	7.540	7.540	7.540	7.540	7.540	7.540
7.580	7.580	7.580	7.580	7.580	7.580	7.580	7.580
7.570	7.570	7.570	7.570	7.570	7.570	7.570	7.570
7.570	7.570	7.570	7.570	7.570	7.570	7.570	7.570
7.560	7.560	7.560	7.560	7.560	7.560	7.560	7.560
7.550	7.550	7.550	7.550	7.550	7.550	7.550	7.550
7.530	7.530	7.530	7.530	7.530	7.530	7.530	7.530
7.520	7.520	7.520	7.520	7.520	7.520	7.520	7.520
7.510	7.510	7.510	7.510	7.510	7.510	7.510	7.510
7.490	7.490	7.490	7.490	7.490	7.490	7.490	7.490
7.480	7.480	7.480	7.480	7.480	7.480	7.480	7.480
7.460	7.460	7.460	7.460	7.460	7.460	7.460	7.460
7.450	7.450	7.450	7.450	7.450	7.450	7.450	7.450
7.430	7.430	7.430	7.430	7.430	7.430	7.430	7.430
7.410	7.410	7.410	7.410	7.410	7.410	7.410	7.410
7.290	7.280	7.260	7.220	7.170	7.090	7.010	6.990
7.270	7.260	7.230	7.200	7.140	7.070	7.000	6.960
7.260	7.250	7.230	7.200	7.160	7.120	7.080	7.060
7.230	7.220	7.210	7.190	7.170	7.150	7.130	7.120

Figure 22. Spatial distribution of minimum DO (mg/L) in Baseline scenario, Downstream Reach (green color means higher DO concentrations and red color lower concentrations).

Confirmation of P limitation

Figure 23 shows the P and N limitation coefficients for the right bank. The left bank shows very similar results. The model estimated an N limitation coefficient close to 0.98. A coefficient equal to 1 means that there is no limitation. Thus, in the downstream reach, the model also predicts P as the limiting nutrient.

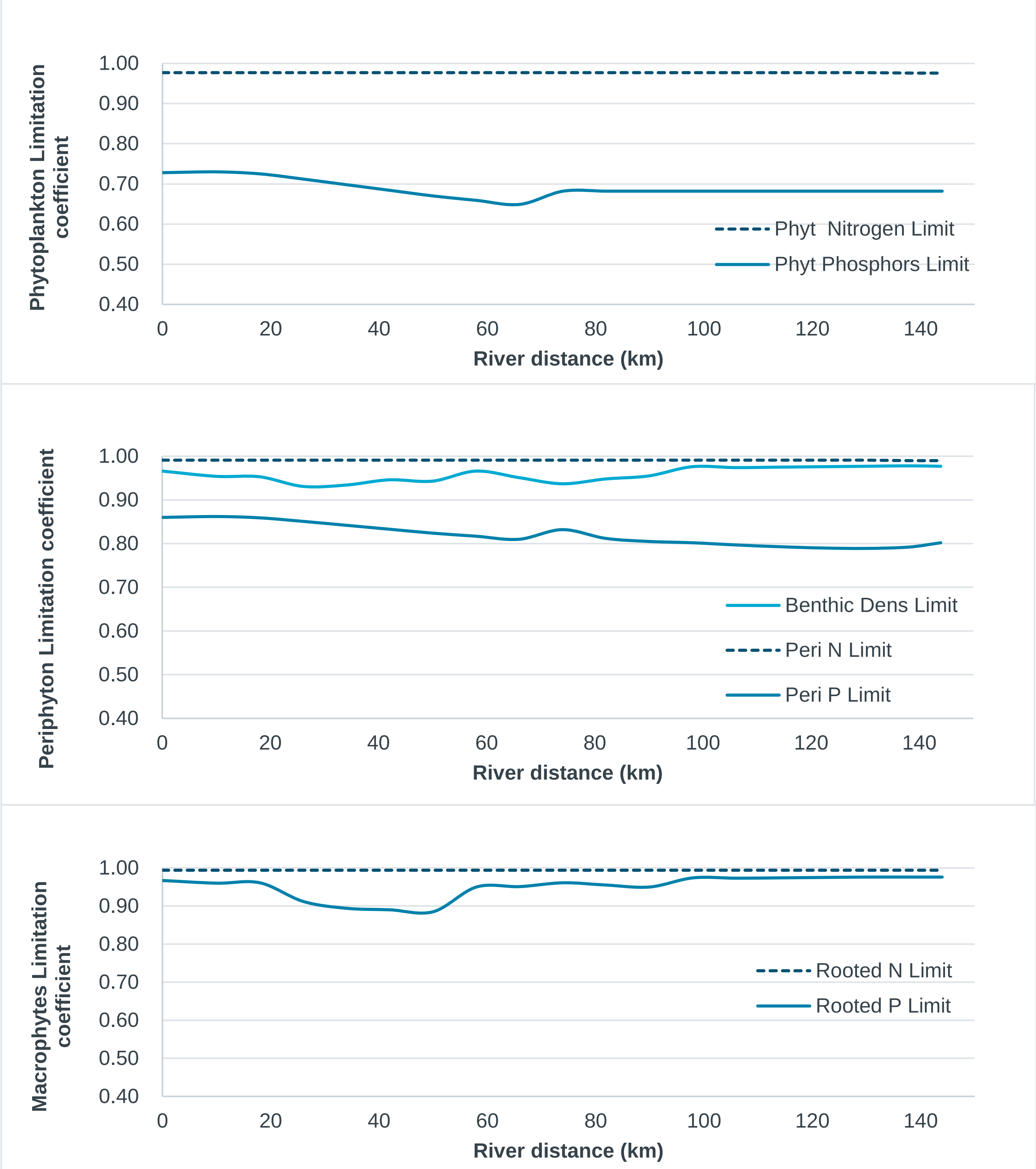


Figure 23. Biomass N and P median limitation coefficients for the simulation period in the right bank segments, Downstream Reach.

Determination of the MAL

The model scenarios increased the TP loading in equal percentages for all the sources. The frequency of compliance was monitored at five cross-sections. Selected cross-sections had a lower DO concentration, downstream of Highwood River (segments 1-4), downstream of East and West Arrowwood creeks (segments 245-252 and 253-260) and downstream of Crowfoot Creek (segments 493-500 and 501-508).

Table 8 shows the results for each cross-section. The upstream TP loading coming from the City of Calgary reach was capped to the MAL previously obtained. From the remaining sources, the tributaries were the dominant TP source.

Table 8. DO acute frequency of compliance increasing the source TP by an equal percentage.

	TP increase factor by source category				TP Source daily average load (kg/day)					DO acute frequency of compliance (%) for selected cross-sections				
Scenario	**Upstream**	**Tributaries**	**WWTPs**	**RFs**	**Upstream**	**Tributaries**	**WWTPs**	**RFs**	**Total**	**1-4**	**245-252**	**253-260**	**493-500**	**501-508**
Baseline	**1**	**1**	**1**	**1**	**322**	**140**	**1**	**1**	**464**	**100**	**100**	**100**	**100**	**100**
4	1.15	4.00	4.00	4.00	372	559	5	3	**939**	100	100	100	100	100
6	1.15	6.00	6.00	6.00	372	838	8	4	**1,222**	100	100	100	99.98	99.97
7	1.15	7.00	7.00	7.00	372	978	9	5	**1,364**	100	100	100	99.92	99.92
7.2	**1.15**	**7.20**	**7.20**	**7.20**	372	1006	9	5	**1,393**	100	100	100	99.91	99.92

The frequency of compliance did not change until reaching a TP loading close to 1000 kg/day. The frequency of compliance dropped drastically with further TP increases (Figure 24).

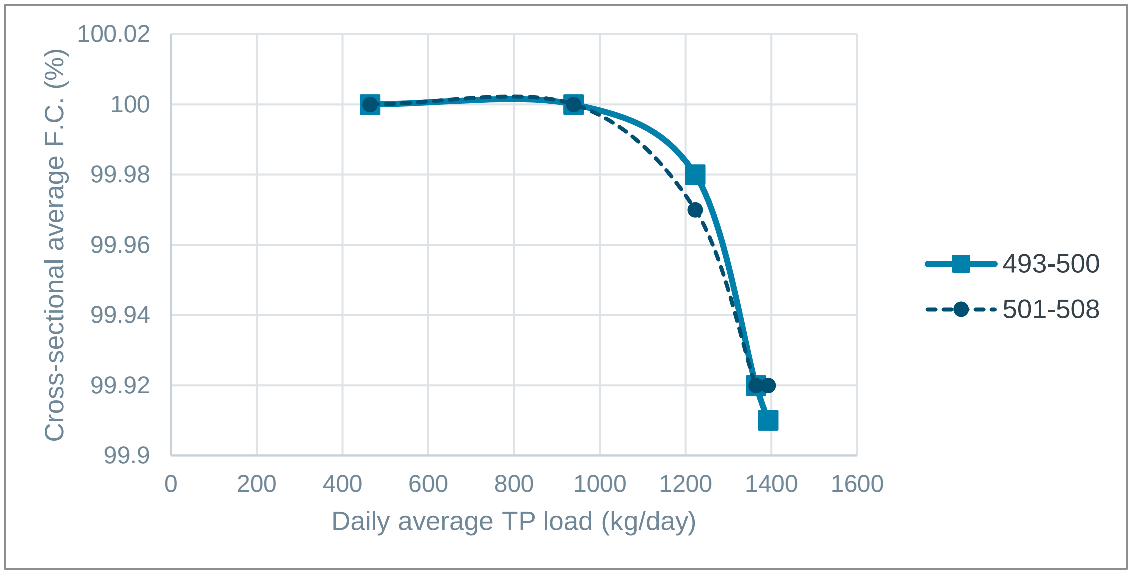


Figure 24. Change in frequency of compliance downstream of Crowfoot Creek for model scenarios.

A TP loading of 1,393 kg/day resulted in the 99.91% frequency of compliance. The MAL after deducting the 10% MOS was 1253 kg/day. The Baseline is considerably below this value.

Table 9. Summary MAL Downstream reach.

TP Load (kg/day) *		Comments
Baseline	464 *(513)*	
Increase (before MOS)	3	*1.15 Upstream, 7.2 Tributaries, WWTPs and RFs*
MAL (before MOS)	1393	
MAL (after MOS)	1253	0.90xMAL
Available load	789 *(740)*	MAL (after MOS) – Baseline
Increase % (after MOS)	2.7 *(2.4)*	MAL (after MOS)/ Baseline

* Values in () show TP load assuming City Reach uses the MAL

The periphyton density downstream of Crowfoot Creek had the most significant change in the biomass after increasing the Baseline TP load to the MAL. The model predicted an increase from 11.80 g/m^2 to 23.38 g/m^2.

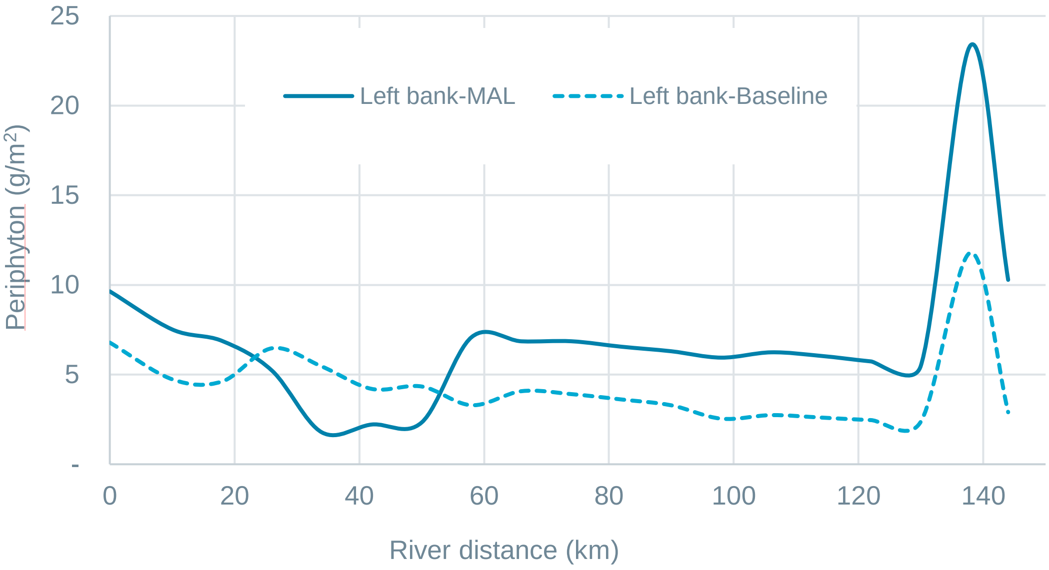
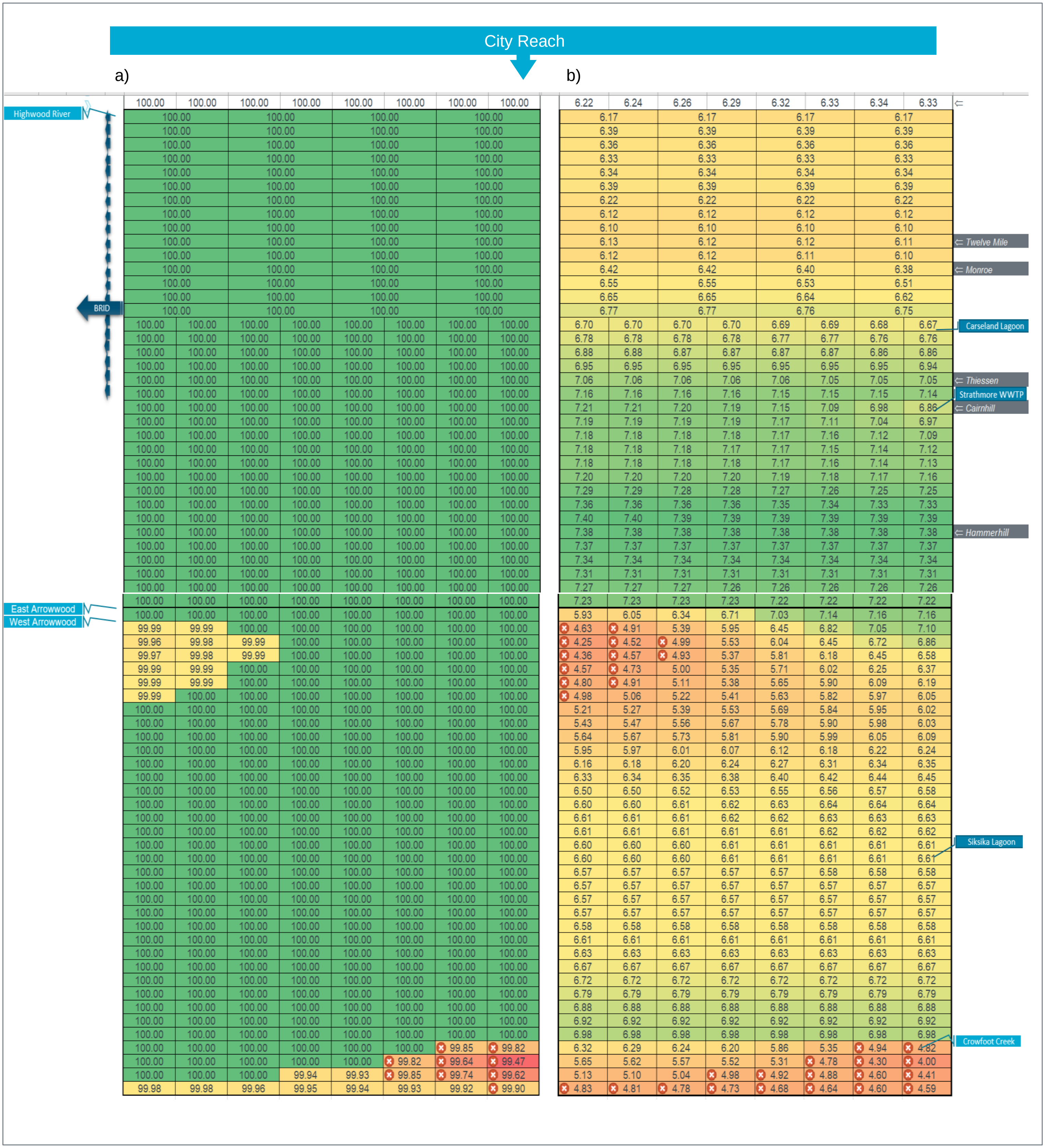


Figure 25. Periphyton change for the left bank for Baseline and MAL scenario.

The MAL was obtained downstream of Crowfoot Creek. The model predicted a minimum DO of 4.00 mg/L on the left bank downstream of Crowfoot Creek at the MAL TP loading (Figure 26).

Similar to the City Reach, the DO in the Downstream reach exhibited values below the guideline in 2000 and 2001. These were the two years with the lowest river discharge from the eight simulated years. The model estimated higher periphyton peaks in these two years (Figure 27).



a)

100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00		100.00		100.00		100.00	
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
99.99	99.99	100.00	100.00	100.00	100.00	100.00	100.00
99.96	99.98	99.99	100.00	100.00	100.00	100.00	100.00
99.97	99.98	99.99	100.00	100.00	100.00	100.00	100.00
99.99	99.99	100.00	100.00	100.00	100.00	100.00	100.00
99.99	99.99	100.00	100.00	100.00	100.00	100.00	100.00
99.99	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	⊗ 99.85	⊗ 99.82
100.00	100.00	100.00	100.00	100.00	⊗ 99.82	⊗ 99.64	⊗ 99.47
100.00	100.00	100.00	99.94	99.93	⊗ 99.85	⊗ 99.74	⊗ 99.62
99.98	99.98	99.96	99.95	99.94	99.93	99.92	⊗ 99.90

b)

6.22	6.24	6.26	6.29	6.32	6.33	6.34	6.33
6.17		6.17		6.17		6.17	
6.39		6.39		6.39		6.39	
6.36		6.36		6.36		6.36	
6.33		6.33		6.33		6.33	
6.34		6.34		6.34		6.34	
6.39		6.39		6.39		6.39	
6.22		6.22		6.22		6.22	
6.12		6.12		6.12		6.12	
6.10		6.10		6.10		6.10	
6.13		6.12		6.12		6.11	
6.12		6.12		6.11		6.10	
6.42		6.42		6.40		6.38	
6.55		6.55		6.53		6.51	
6.65		6.65		6.64		6.62	
6.77		6.77		6.76		6.75	
6.70	6.70	6.70	6.70	6.69	6.69	6.68	6.67
6.78	6.78	6.78	6.78	6.77	6.77	6.76	6.76
6.88	6.88	6.87	6.87	6.87	6.87	6.86	6.86
6.95	6.95	6.95	6.95	6.95	6.95	6.95	6.94
7.06	7.06	7.06	7.06	7.06	7.05	7.05	7.05
7.16	7.16	7.16	7.16	7.15	7.15	7.15	7.14
7.21	7.21	7.20	7.19	7.15	7.09	6.98	6.86
7.19	7.19	7.19	7.19	7.17	7.11	7.04	6.97
7.18	7.18	7.18	7.18	7.17	7.16	7.12	7.09
7.18	7.18	7.18	7.17	7.17	7.15	7.14	7.12
7.18	7.18	7.18	7.18	7.17	7.16	7.14	7.13
7.20	7.20	7.20	7.20	7.19	7.18	7.17	7.16
7.29	7.29	7.28	7.28	7.27	7.26	7.25	7.25
7.36	7.36	7.36	7.36	7.35	7.34	7.33	7.33
7.40	7.40	7.39	7.39	7.39	7.39	7.39	7.39
7.38	7.38	7.38	7.38	7.38	7.38	7.38	7.38
7.37	7.37	7.37	7.37	7.37	7.37	7.37	7.37
7.34	7.34	7.34	7.34	7.34	7.34	7.34	7.34
7.31	7.31	7.31	7.31	7.31	7.31	7.31	7.31
7.27	7.27	7.27	7.26	7.26	7.26	7.26	7.26
7.23	7.23	7.23	7.23	7.22	7.22	7.22	7.22
5.93	6.05	6.34	6.71	7.03	7.14	7.16	7.16
⊗ 4.63	⊗ 4.91	5.39	5.95	6.45	6.82	7.05	7.10
⊗ 4.25	⊗ 4.52	⊗ 4.99	5.53	6.04	6.45	6.72	6.86
⊗ 4.36	⊗ 4.57	⊗ 4.93	5.37	5.81	6.18	6.45	6.58
⊗ 4.57	⊗ 4.73	5.00	5.35	5.71	6.02	6.25	6.37
⊗ 4.80	⊗ 4.91	5.11	5.38	5.65	5.90	6.09	6.19
⊗ 4.98	5.06	5.22	5.41	5.63	5.82	5.97	6.05
5.21	5.27	5.39	5.53	5.69	5.84	5.95	6.02
5.43	5.47	5.56	5.67	5.78	5.90	5.98	6.03
5.64	5.67	5.73	5.81	5.90	5.99	6.05	6.09
5.95	5.97	6.01	6.07	6.12	6.18	6.22	6.24
6.16	6.18	6.20	6.24	6.27	6.31	6.34	6.35
6.33	6.34	6.35	6.38	6.40	6.42	6.44	6.45
6.50	6.50	6.52	6.53	6.55	6.56	6.57	6.58
6.60	6.60	6.61	6.62	6.63	6.64	6.64	6.64
6.61	6.61	6.61	6.62	6.62	6.63	6.63	6.63
6.61	6.61	6.61	6.61	6.61	6.62	6.62	6.62
6.60	6.60	6.60	6.61	6.61	6.61	6.61	6.61
6.60	6.60	6.60	6.61	6.61	6.61	6.61	6.61
6.57	6.57	6.57	6.57	6.57	6.58	6.58	6.58
6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57
6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57
6.57	6.57	6.57	6.57	6.57	6.57	6.57	6.57
6.58	6.58	6.58	6.58	6.58	6.58	6.58	6.58
6.61	6.61	6.61	6.61	6.61	6.61	6.61	6.61
6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63
6.67	6.67	6.67	6.67	6.67	6.67	6.67	6.67
6.72	6.72	6.72	6.72	6.72	6.72	6.72	6.72
6.79	6.79	6.79	6.79	6.79	6.79	6.79	6.79
6.88	6.88	6.88	6.88	6.88	6.88	6.88	6.88
6.92	6.92	6.92	6.92	6.92	6.92	6.92	6.92
6.98	6.98	6.98	6.98	6.98	6.98	6.98	6.98
6.32	6.29	6.24	6.20	5.86	5.35	⊗ 4.94	⊗ 4.82
5.65	5.62	5.57	5.52	5.31	⊗ 4.78	⊗ 4.30	⊗ 4.00
5.13	5.10	5.04	⊗ 4.98	⊗ 4.92	⊗ 4.88	⊗ 4.60	⊗ 4.41
⊗ 4.83	⊗ 4.81	⊗ 4.78	⊗ 4.73	⊗ 4.68	⊗ 4.64	⊗ 4.60	⊗ 4.59

Figure 26. Spatial distribution in MAL scenario, Downstream Reach (total TP load 1393 kg/day) a) acute frequency of compliance, and b) Minimum DO (mg/L) (green color means higher DO concentrations and red color lower concentrations).

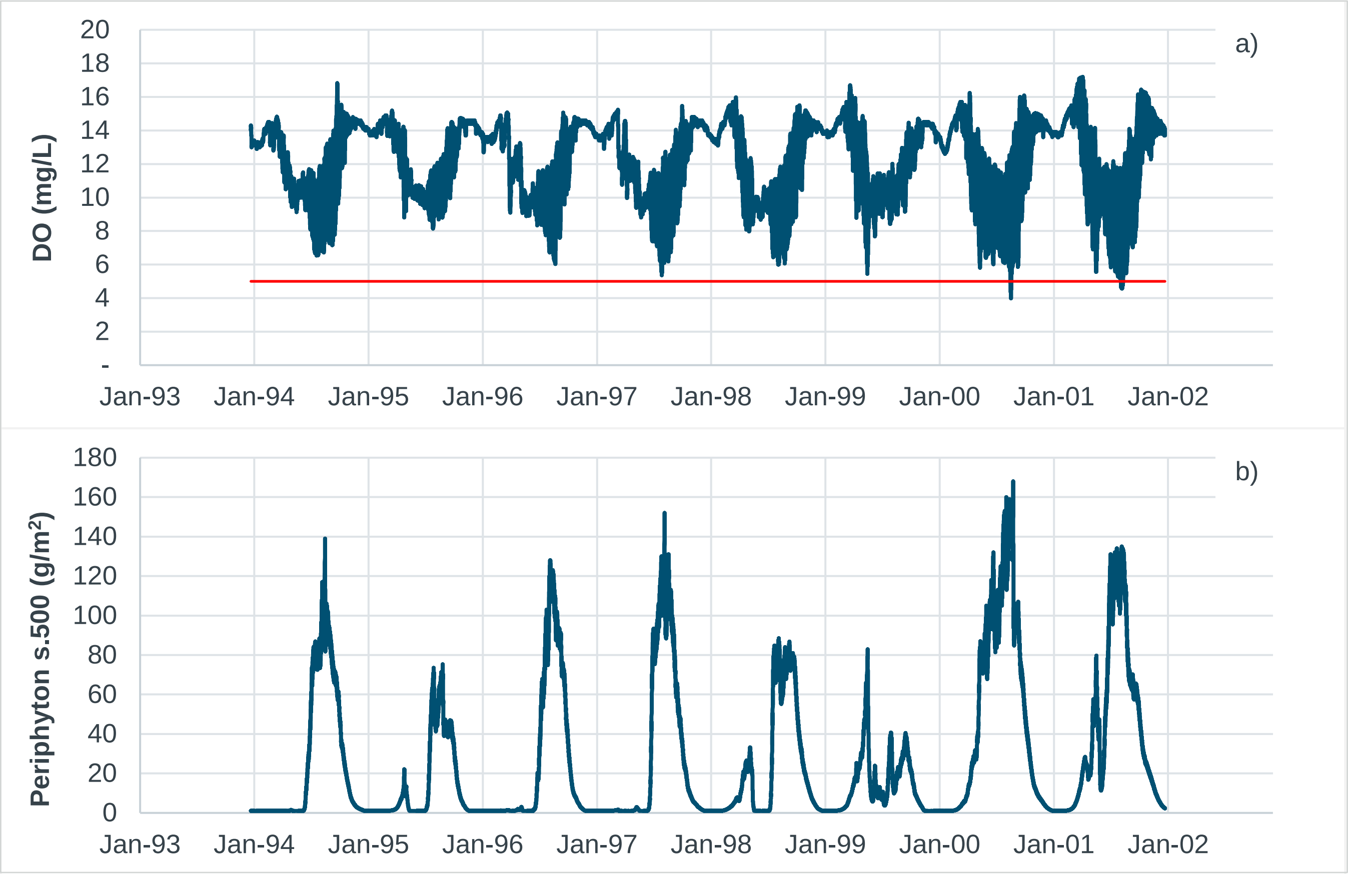


Figure 27. Downstream Reach MAL segment 500 during the simulation period 1994-2001 a) average DO, and b) periphyton density.

Within these two critical years, the DO was below the acute guideline in mid-late August. The DO was below the acute guideline for up to seven consecutive days in 2001. The DO sag lasted from three to eight hours per day (Figure 28).

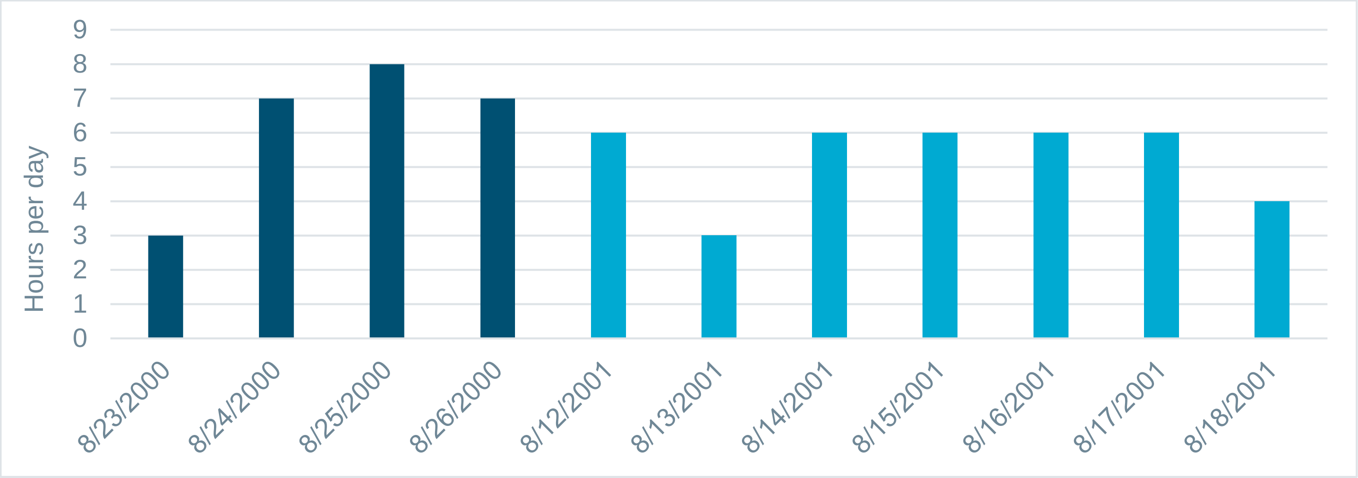


Figure 28. Days and number of hours that the cross-sectional average DO was below 5 mg/L downstream Crowfoot Creek, MAL scenario.

3.3 Sensitivity Analyses

Model output at different time resolutions

The model output resolution should consider the model run time, modelling file size and output variability. The MAL Technical Team requested to analyze the model results using different model output resolutions.

The City Reach was run with outputs every 4-hour, 2.4-hour or 1-hour (i.e., 6, 10 or 24 printed outputs per day). Table 10 shows that as the resolution increased, the frequency of compliance dropped. By analyzing the hourly output and extracting the lowest DO value per day, we get the lowest frequency of compliance.

Table 10. DO acute frequency of compliance using different model output resolution

Cross-sectional average	← Higher frequency of compliance			
	4-hr	**2.4-hr**	**1-hr**	**Min Daily exceed.**
33-40	99.73%	99.68%	99.68%	99.01%
41-48	99.69%	99.66%	99.66%	98.87%
161-168	99.81%	99.81%	99.77%	98.22%
169-176	99.83%	99.82%	99.79%	98.32%

Figure 29 shows the output for the 4-hour, and 1-hour model runs. Although the annual and monthly graphs look the same, plotting a day showed how the additional output in the 1-hour simulation helps characterize the low DO happening at night. For the 4-hour output, 2 out of 6 DO concentrations were below the guideline (33%), while for the 1-hour output, 10 out of 24 (42%).

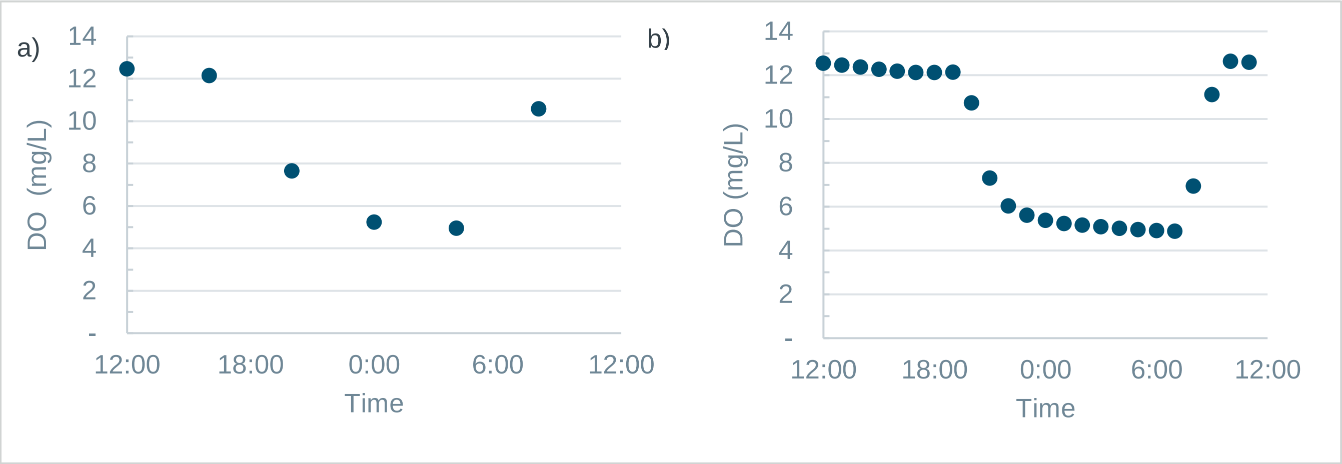
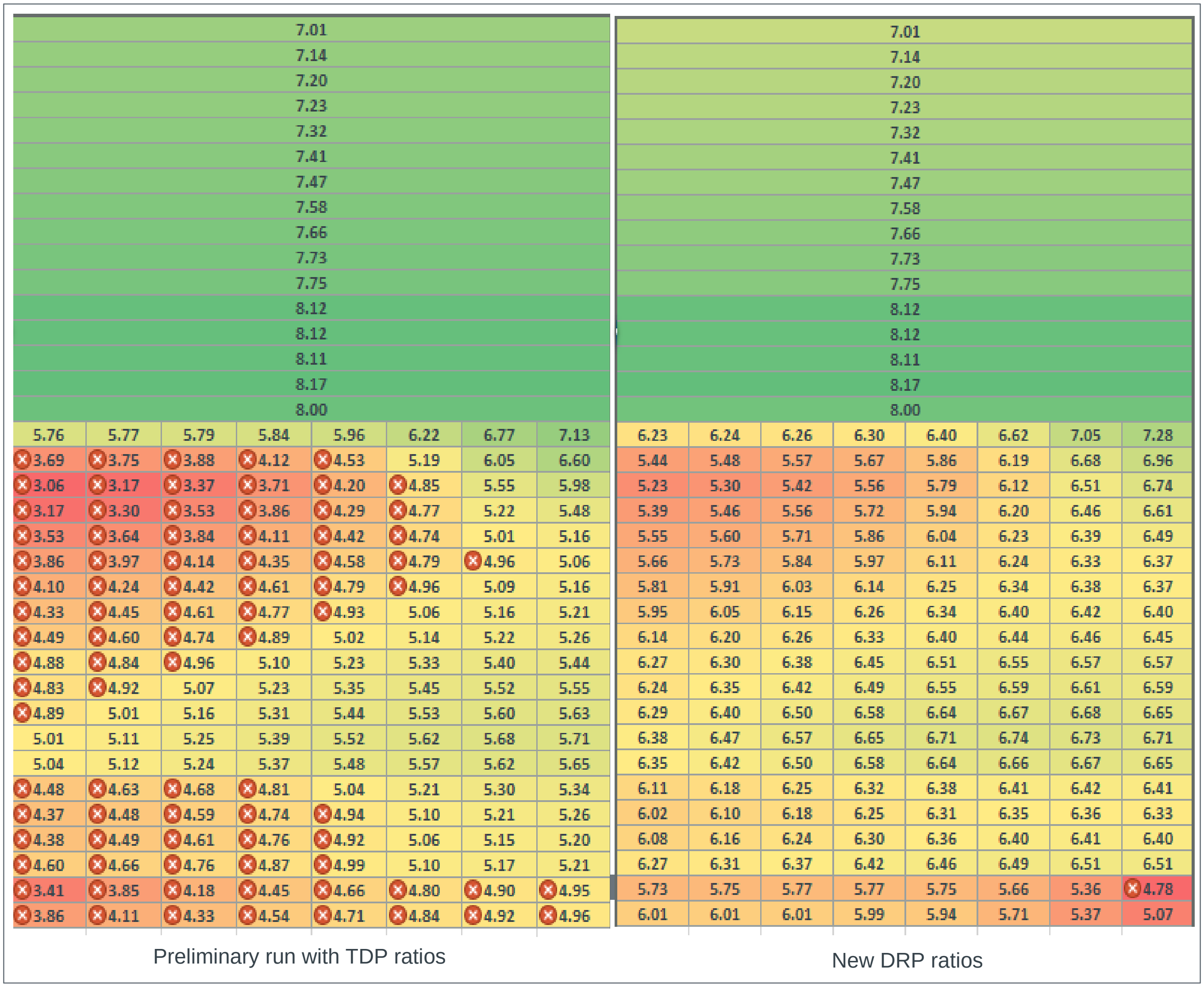


Figure 29. City Reach modelling results at different output resolutions a) 4-hr, b) 1-hr.

As per these results, we decided to run the model with a 4-hour output resolution for screening the cross-sections with the lowest DO concentrations. We checked the model MAL results at the selected cross-sections using the 1-hour output resolution.

TIP determination

The model was sensitive to the method used to define the inorganic and organic TP ratios. In the past, the model used the dissolved fraction (TDP) as a proxy of the inorganic and more readily available TP fraction. The City of Calgary has recently started to measure dissolved reactive phosphorus (DRP). The model was first run using the TDP to calculate the TIP. Later, the model used the DRP to calculate the TIP for the City's WWTPs. The results showed a significant improvement in the minimum DO by using DRP (Figure 30).



7.01							
7.14							
7.20							
7.23							
7.32							
7.41							
7.47							
7.58							
7.66							
7.73							
7.75							
8.12							
8.12							
8.11							
8.17							
8.00							
5.76	5.77	5.79	5.84	5.96	6.22	6.77	7.13
⊗3.69	⊗3.75	⊗3.88	⊗4.12	⊗4.53	5.19	6.05	6.60
⊗3.06	⊗3.17	⊗3.37	⊗3.71	⊗4.20	⊗4.85	5.55	5.98
⊗3.17	⊗3.30	⊗3.53	⊗3.86	⊗4.29	⊗4.77	5.22	5.48
⊗3.53	⊗3.64	⊗3.84	⊗4.11	⊗4.42	⊗4.74	5.01	5.16
⊗3.86	⊗3.97	⊗4.14	⊗4.35	⊗4.58	⊗4.79	⊗4.96	5.06
⊗4.10	⊗4.24	⊗4.42	⊗4.61	⊗4.79	⊗4.96	5.09	5.16
⊗4.33	⊗4.45	⊗4.61	⊗4.77	⊗4.93	5.06	5.16	5.21
⊗4.49	⊗4.60	⊗4.74	⊗4.89	5.02	5.14	5.22	5.26
⊗4.88	⊗4.84	⊗4.96	5.10	5.23	5.33	5.40	5.44
⊗4.83	⊗4.92	5.07	5.23	5.35	5.45	5.52	5.55
⊗4.89	5.01	5.16	5.31	5.44	5.53	5.60	5.63
5.01	5.11	5.25	5.39	5.52	5.62	5.68	5.71
5.04	5.12	5.24	5.37	5.48	5.57	5.62	5.65
⊗4.48	⊗4.63	⊗4.68	⊗4.81	5.04	5.21	5.30	5.34
⊗4.37	⊗4.48	⊗4.59	⊗4.74	⊗4.94	5.10	5.21	5.26
⊗4.38	⊗4.49	⊗4.61	⊗4.76	⊗4.92	5.06	5.15	5.20
⊗4.60	⊗4.66	⊗4.76	⊗4.87	⊗4.99	5.10	5.17	5.21
⊗3.41	⊗3.85	⊗4.18	⊗4.45	⊗4.66	⊗4.80	⊗4.90	⊗4.95
⊗3.86	⊗4.11	⊗4.33	⊗4.54	⊗4.71	⊗4.84	⊗4.92	⊗4.96

Preliminary run with TDP ratios

7.01							
7.14							
7.20							
7.23							
7.32							
7.41							
7.47							
7.58							
7.66							
7.73							
7.75							
8.12							
8.12							
8.11							
8.17							
8.00							
6.23	6.24	6.26	6.30	6.40	6.62	7.05	7.28
5.44	5.48	5.57	5.67	5.86	6.19	6.68	6.96
5.23	5.30	5.42	5.56	5.79	6.12	6.51	6.74
5.39	5.46	5.56	5.72	5.94	6.20	6.46	6.61
5.55	5.60	5.71	5.86	6.04	6.23	6.39	6.49
5.66	5.73	5.84	5.97	6.11	6.24	6.33	6.37
5.81	5.91	6.03	6.14	6.25	6.34	6.38	6.37
5.95	6.05	6.15	6.26	6.34	6.40	6.42	6.40
6.14	6.20	6.26	6.33	6.40	6.44	6.46	6.45
6.27	6.30	6.38	6.45	6.51	6.55	6.57	6.57
6.24	6.35	6.42	6.49	6.55	6.59	6.61	6.59
6.29	6.40	6.50	6.58	6.64	6.67	6.68	6.65
6.38	6.47	6.57	6.65	6.71	6.74	6.73	6.71
6.35	6.42	6.50	6.58	6.64	6.66	6.67	6.65
6.11	6.18	6.25	6.32	6.38	6.41	6.42	6.41
6.02	6.10	6.18	6.25	6.31	6.35	6.36	6.33
6.08	6.16	6.24	6.30	6.36	6.40	6.41	6.40
6.27	6.31	6.37	6.42	6.46	6.49	6.51	6.51
5.73	5.75	5.77	5.77	5.75	5.66	5.36	⊗4.78
6.01	6.01	6.01	5.99	5.94	5.71	5.37	5.07

New DRP ratios

Figure 30. Spatial minimum DO concentrations running the Baseline scenario with different TIP/TP ratios for the City's WWTPs

Table 11 shows the TP ratios used for these scenarios.

Table 11. Use of different ratios to estimate model TIP for the City's WWTPs

WWTP	IP/TP [TDP = TIP]	IP/TP [DRP = TDP]
Bonnybrook	0.37	0.30
Fish Creek WWTP	0.22	0.04
Pine Creek WWTP	0.56	0.11

Bonnybrook WWTP has about 70% of the TDP as DRP, while the other two WWTPs have about 30% of the TDP as DRP (Figure 31). A large proportion of the Fish Creek WWTP and Pine Creek WWTP effluent TP are non-reactive. The higher DRP ratio from Bonnybrook WWTP can be related to the supernatant from the Shepard biosolid lagoons that this plant receives year-round (Khizar Mahmood, City of Calgary, personal communication, August 2019).

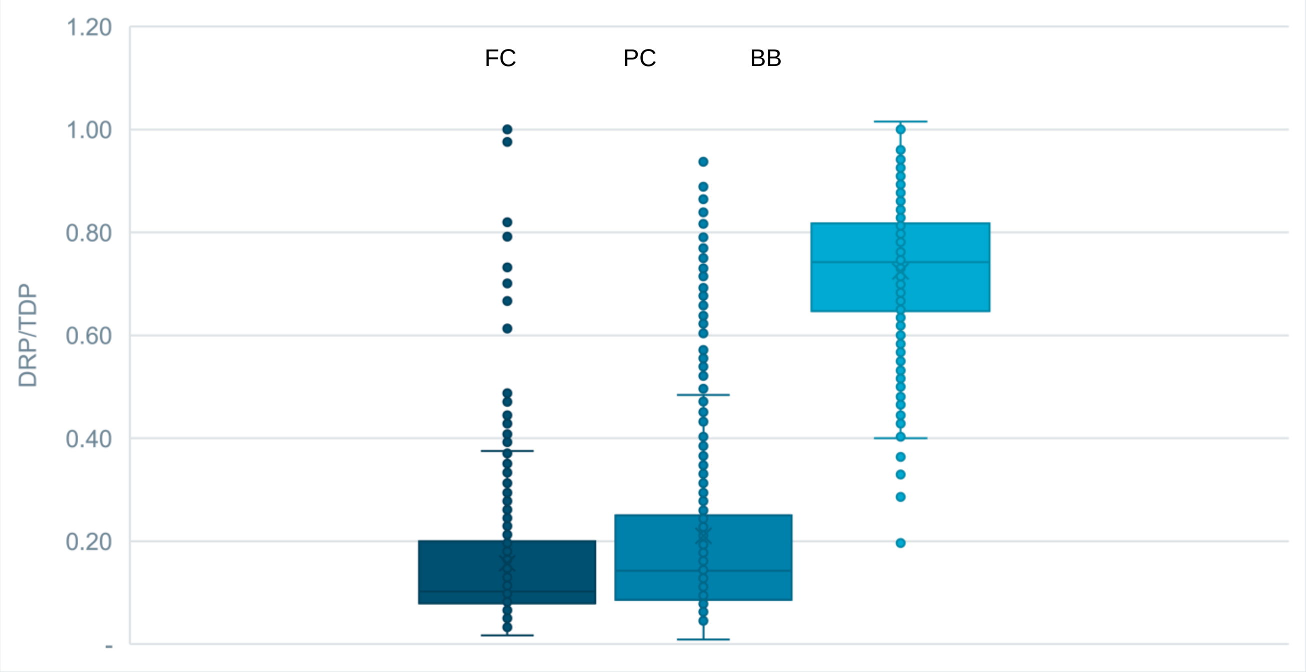


Figure 31. The ratio of dissolved reactive phosphorus to the total dissolved phosphorus. Fish Creek WWTP (FC), Pine Creek WWTP (PC), Bonnybrook WWTP (BB)

Algal bioassays are the most reliable technique for quantifying biologically available phosphorus (BAP) (Li & Brett 2012). Chemical phosphorus characterizations do not always correlate with bioavailability derived from bioassays. Li & Brett (2013) tested the bioavailability of different dissolved phosphorus compounds. Their research showed that several compounds that were operationally classified as reactive P had very low %BAP, whereas other compounds that were classified as non-reactive were nearly entirely bioavailable.

Despite the challenges in determining the truly bioavailable portion of TP, the alum-based P removal process has proved to be very effective at sequestering the P forms that most readily stimulate algal growth (Li & Brett 2012; Melia et al. 2017). As the level of P removal increased, not only was TP reduced to very low levels, but the composition of the P was also changed markedly by sharply declining the %BAP. The MAL Technical Team decided to use the DRP to define the P fraction driving the algae growth from the City's WWTPs.

An analysis of DRP data available for tributaries and mainstem followed to understand the best information available to define the TIP in the input time series from 1994- 2001. EPA has some dissolved orthophosphate (PO4) concentration measurements for the tributaries. The PO4 sampling started in 2013 for Cochrane and ElBow River, and in 2014 for other stations. Figure 32 shows some comparisons between the TDP and PO4 monitored values up to 2018.

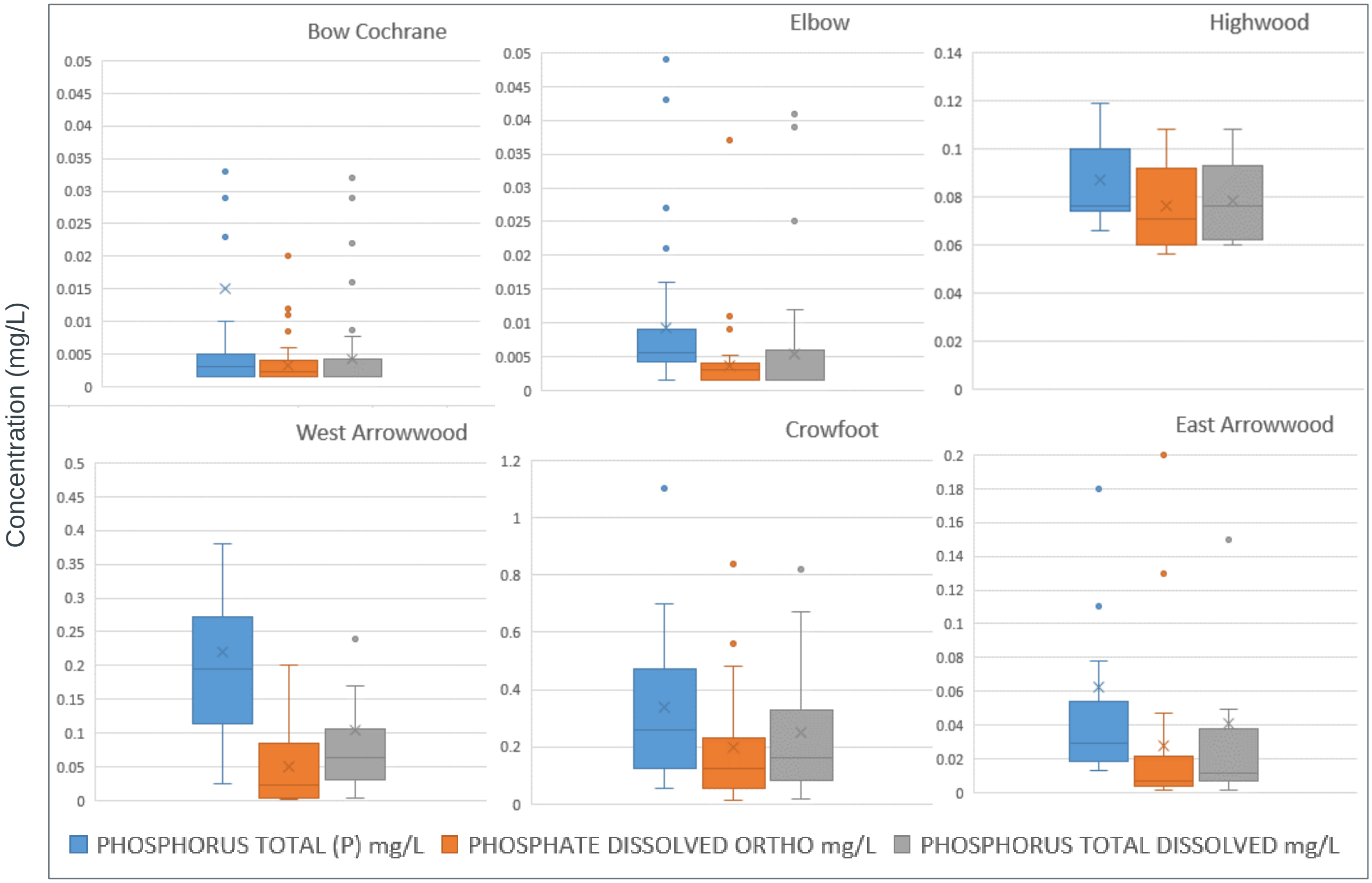


Figure 32. Box plots with TP, TDP and PO4 concentrations measured for the mainstem and tributaries; monitored values up to 2018.

Figure 33 shows a slight difference between the average PO4/TP (0.43) and TDP/TP (0.45) ratios for this recent data. Since PO4 measurements are unavailable in the simulation period 1994-2001, we need to estimate monthly or seasonal PO4/TP ratios with the available data and use them to estimate the TIP in the simulation period. During this analysis, the data set was too small to estimate monthly/seasonal PO4/TP ratios. For this reason, we continued using TDP as a proxy of the inorganic fraction. Using TDP may be less accurate but does provide a more conservative approach. Using PO4 can be reconsidered in the future, as more data becomes available.

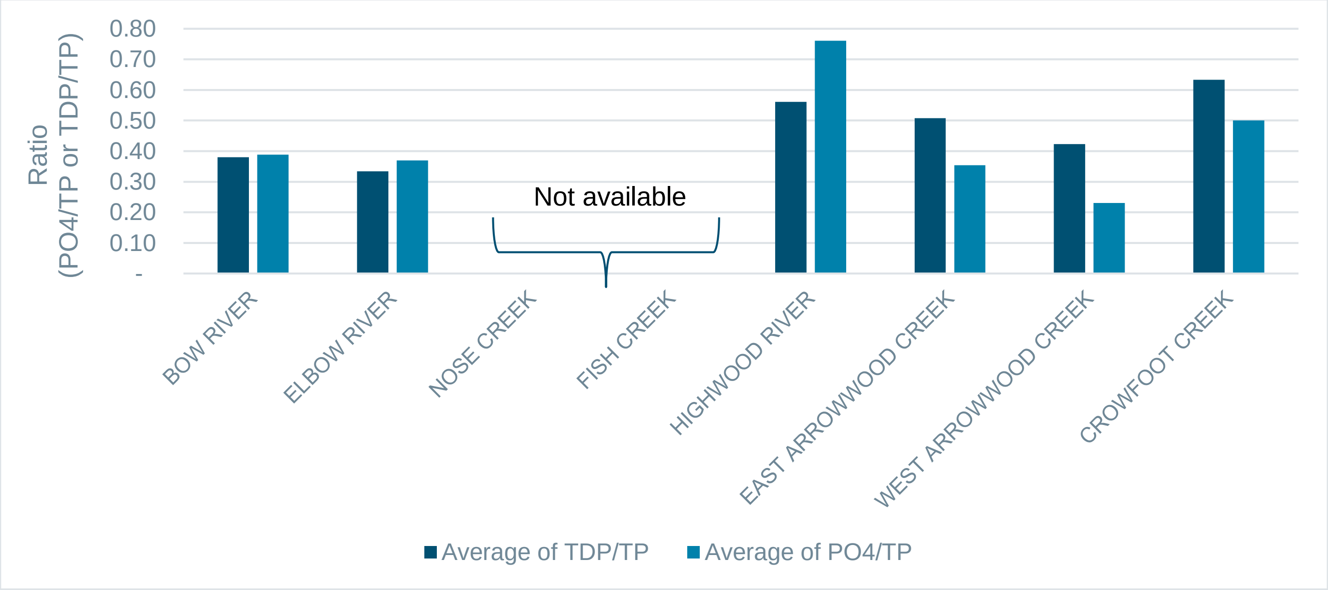


Figure 33. PO4/TP and TDP/TP ratios for tributaries and mainstem (samples taken on the same day)

Alternative rules to increase the TP loading

The scenarios described above increased the TP loading by the same percentage for all the sources. In reality, the TP could increase in the future in many other ways. Two additional approaches were tested using the City Reach. First, the contributors were ranked according to the average daily TP load in the Baseline scenario. Then either 1) the major contributor got a higher TP increase or 2) the major contributor got a lower TP increase. Tables 12 and 13 show the increase factors used for each source category. We did not follow this approach with the Downstream Reach as only three TP sources changed after capping the Upstream TP load to the City MAL.

Table 12. Ranked contribution largest contributor gets a higher TP increase

	TP increase factor				TP Source daily average load (kg/day)					Freq. compliance (%)
Scenario (Overall increase)	**Upstream [2]**	**Tributaries [1]**	**WWTPs [3]**	**Stormwater [2]**	**Upstream**	**Tributaries**	**WWTPs**	**Stormwater**	**Total**	**41-48**
1.13	1.04	1.00	1.20	1.00	57	27	230	45	**360**	100
1.17	1.09	1.00	1.26	1.01	60	27	242	46	**375**	100
1.23	1.14	1.00	1.32	1.06	63	27	253	48	**391**	99.96
1.28	1.20	1.00	1.38	1.10	66	27	265	50	**408**	99.92
1.33	1.25	1.00	1.44	1.15	69	27	276	52	**424**	99.91

Table 13. Ranked contribution largest contributor gets a lower TP increase

	TP increase factor				TP Source daily average load (kg/day)					Freq. compliance (%)
Scenario (Overall increase)	**Upstream [2]**	**Tributaries [3]**	**WWTPs [1]**	**Stormwater [2]**	**Upstream**	**Tributaries**	**WWTPs**	**Stormwater**	**Total**	**41-48**
1.12	1.20	1.50	1.00	1.30	66	40	192	59	**357**	100.00
1.16	1.25	1.56	1.04	1.35	69	42	200	61	**371**	100.00
1.23	1.32	1.65	1.10	1.43	73	44	211	65	**393**	99.96
1.28	1.37	1.71	1.14	1.48	76	46	219	67	**407**	99.92
1.34	1.44	1.80	1.20	1.56	79	48	230	71	**429**	99.78

As per Figure 34, the tested approaches to derive the model scenarios reached the 99.91% frequency of compliance at a similar total TP load. The different increments did not change the overall ranking of the TP sources (WWTPs were still the major contributor in all the different scenarios run).

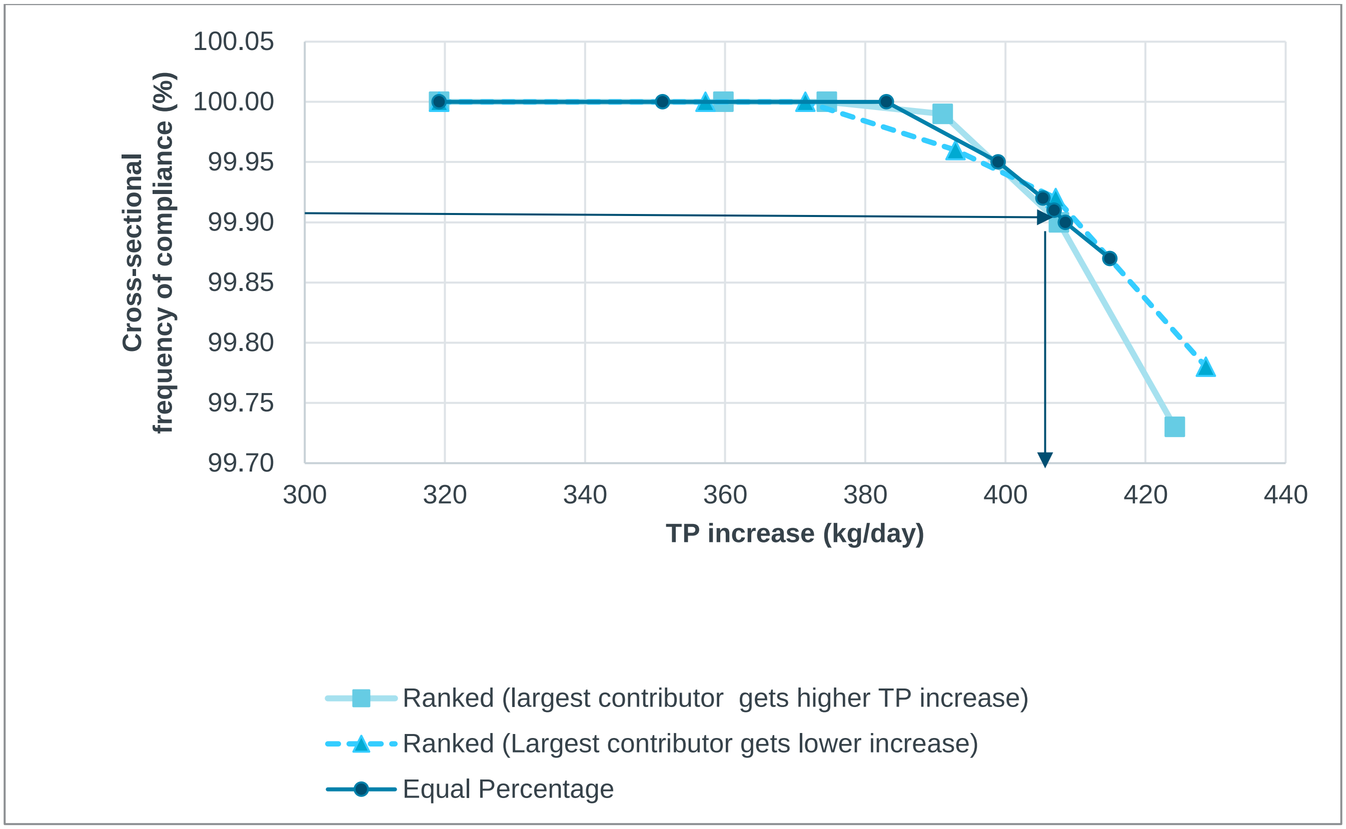


Figure 34. Comparison of different approaches to increase TP load in modelling scenarios.

Use of LOADEST for tributaries and mainstem data gap filling

Upstream and tributary loads (1994-2001) were estimated using the available monitoring concentrations (monthly samples) and methods such as interpolation to fill data gaps. Since these monthly samples are rarely obtained at high river flows (e.g., during a storm event) due to safety reasons, they often miss peak flows and their related loadings.

To better understand the effect of the TP peak loads during the Spring freshet in the minimum DO and frequency of compliance, these boundary loadings were replaced with the loadings estimated by LOADEST during the Source Assessment (Martin, 2020). These loadings use regression of flow and concentration to fill the data gaps.

For the City Reach, the TP loads changed for the headwater, Elbow and Fish Creek. The inorganic fraction was estimated using the same daily ratios used in the Baseline. The Nose Creek and Pine Creek did not have LOADEST estimates available for 1994-2001, so the loadings were not modified (Table 14).

Table 14. Annual average TP loads (kg/day) using interpolation and regression for instream TP loads, Baseline scenario City Reach

	Total TP	WWTPs	Stormwater	Upstream	Tributaries
Interpolation	319.17	191.93	45.20	55.20	26.83
LOADEST	330.96	191.93	45.20	54.10	39.75

LOADEST estimated higher TP loadings during the spring freshet each year. However, during the critical DO season, LOADEST sometimes produced lower estimates than interpolation (Figure 35).

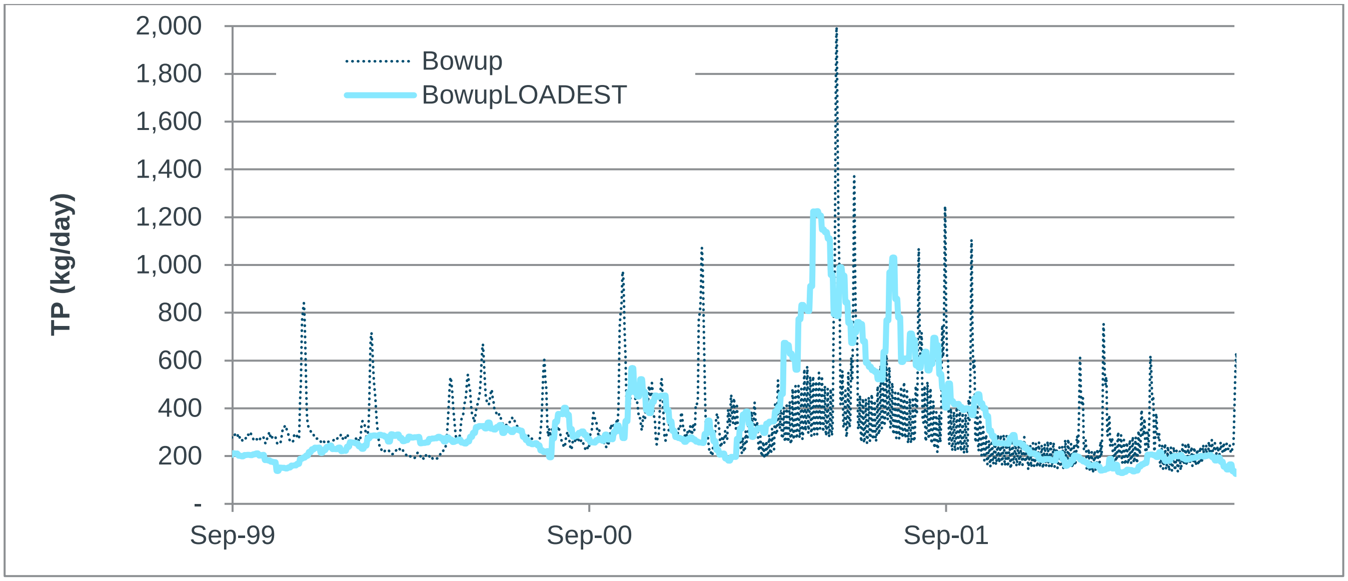


Figure 35. City Reach TP load estimated for Bow upstream boundary (above Bearspaw Dam) using interpolation and LOADEST.

The average June TP load was 27% higher using LOADEST (Figure 36). However, the overall change for the rest of the year was a reduction of 5% with LOADEST. Likewise, the median TP from all the sources was 250 kg/day using interpolation vs 234 kg/day using LOADEST.

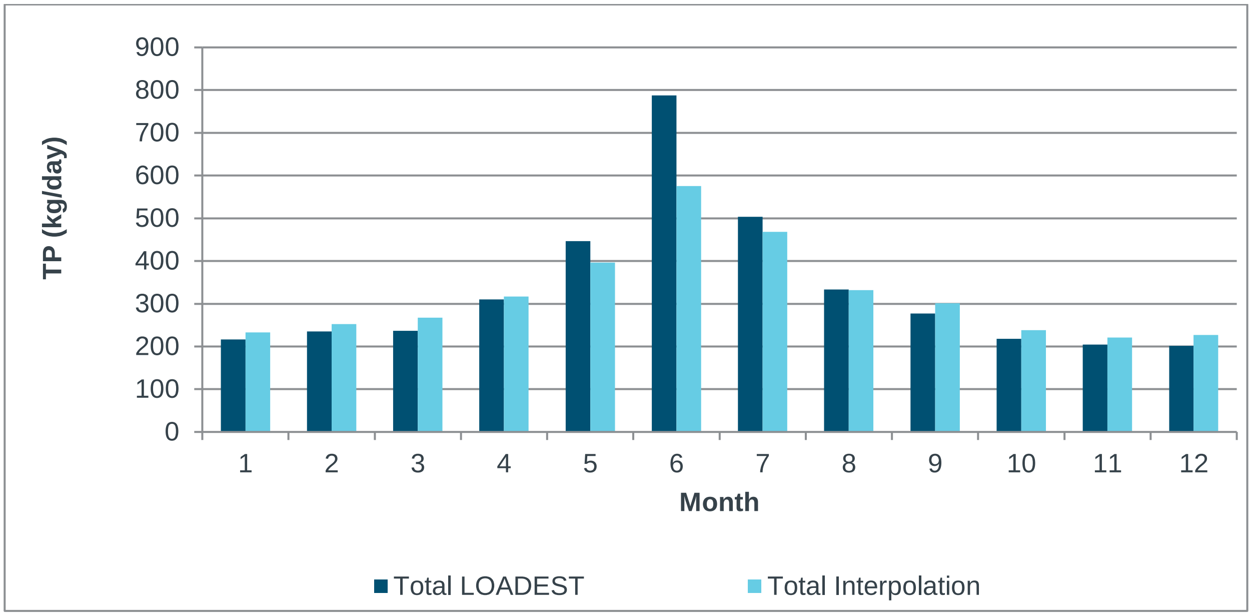
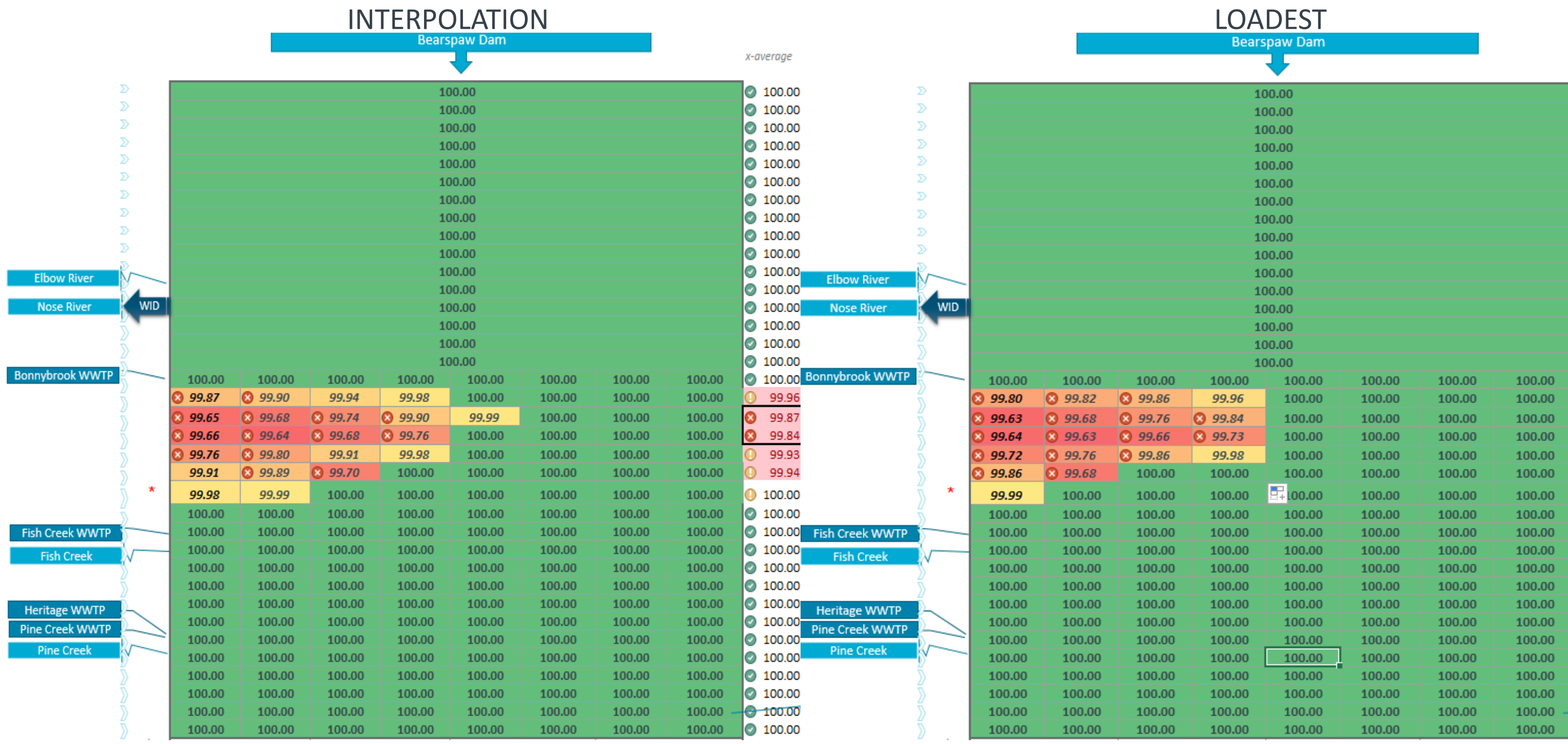


Figure 36. Monthly average TP load for all sources in both methods used to fill instream load data gaps

The model results suggest that the peak TP loadings better defined using LOADEST do not have a large impact on the min DO. The low sensitivity to the peak TP load in the Spring freshet can be due in part to their short duration. According to Suplee et al. (2015), a 14-day duration reflects the most likely time it takes for the growth of lotic benthic algae to reach nuisance biomass levels if nutrients are elevated. The median TP and the loading during the critical DO season seem to be most strongly linked with the minimum DO (Figure 37).



INTERPOLATION

								x-average
100.00								100.00
100.00								100.00
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100.00								100.00
100.00								100.00
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100.00								100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
⊗ 99.87	⊗ 99.90	99.94	99.98	100.00	100.00	100.00	100.00	! 99.96
⊗ 99.65	⊗ 99.68	⊗ 99.74	⊗ 99.90	99.99	100.00	100.00	100.00	⊗ 99.87
⊗ 99.66	⊗ 99.64	⊗ 99.68	⊗ 99.76	100.00	100.00	100.00	100.00	⊗ 99.84
⊗ 99.76	⊗ 99.80	99.91	99.98	100.00	100.00	100.00	100.00	! 99.93
99.91	⊗ 99.89	⊗ 99.70	100.00	100.00	100.00	100.00	100.00	! 99.94
99.98	99.99	100.00	100.00	100.00	100.00	100.00	100.00	! 100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

LOADEST

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100.00							
100.00							
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
⊗ 99.80	⊗ 99.82	⊗ 99.86	99.96	100.00	100.00	100.00	100.00
⊗ 99.63	⊗ 99.68	⊗ 99.76	⊗ 99.84	100.00	100.00	100.00	100.00
⊗ 99.64	⊗ 99.63	⊗ 99.66	⊗ 99.73	100.00	100.00	100.00	100.00
⊗ 99.72	⊗ 99.76	⊗ 99.86	99.98	100.00	100.00	100.00	100.00
⊗ 99.86	⊗ 99.68	100.00	100.00	100.00	100.00	100.00	100.00
99.99	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Figure 37. Results of DO acute frequency of compliance using interpolation or LOADEST to estimate the instream TP load (Equal Percentage TP increase 1.2x scenario)

The reduction in the median TP load resulted in an improvement of the min DO predicted by the model for the Baseline scenario. Using the input files with LOADEST estimations, the MAL was reached when all the sources were increased by 37.5%. This approach produced a MAL of 410 kg/day instead of the 366 kg/day previously obtained. These results suggest an available load of 79 kg (33 kg/day more than using linear interpolation).

For the Baseline scenario in the Downstream Reach, the distribution of TP load changed the two largest sources (Figure 38). The loading coming from the City Reach (Upstream) was the largest TP source based on the annual average loads using interpolation. The tributaries were the largest TP source based on LOADEST estimations.

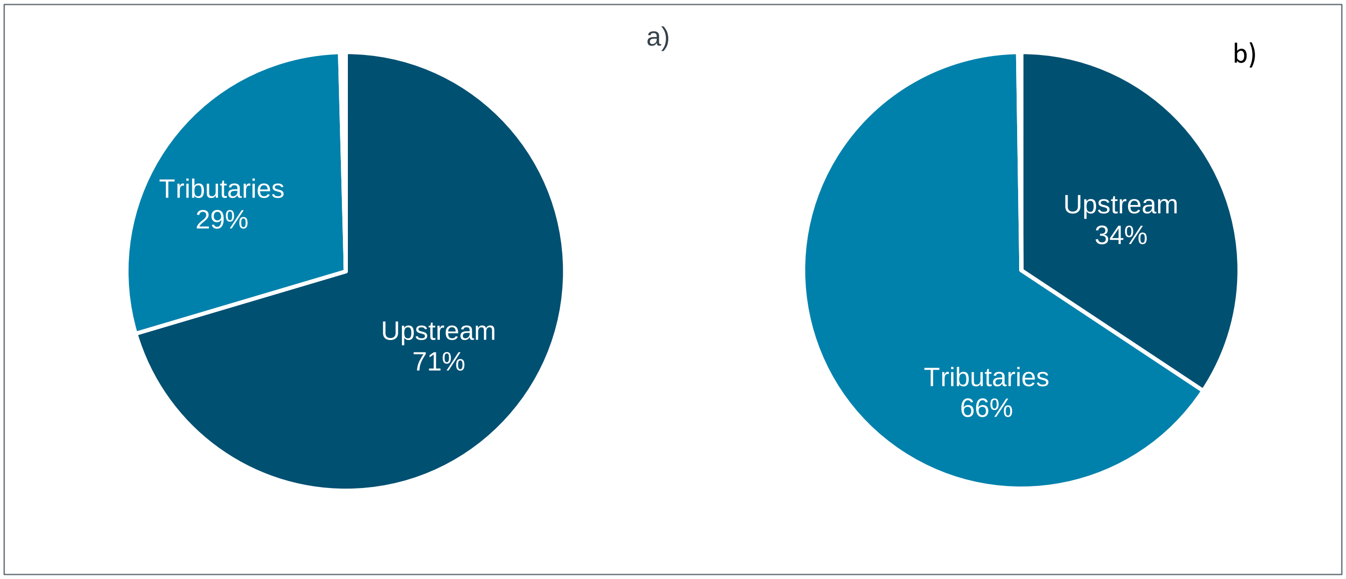


Figure 38. TP annual mean contribution for source categories using a) interpolation and b) LOADEST.

Figure 39 shows how the peak TP was missed using the interpolation of monthly samples. However, the P concentration was higher afterwards in that year. The DO does not change a lot in May and June with the two approaches. Nonetheless, the DO fluctuates less using LOADEST in Summer and Fall.

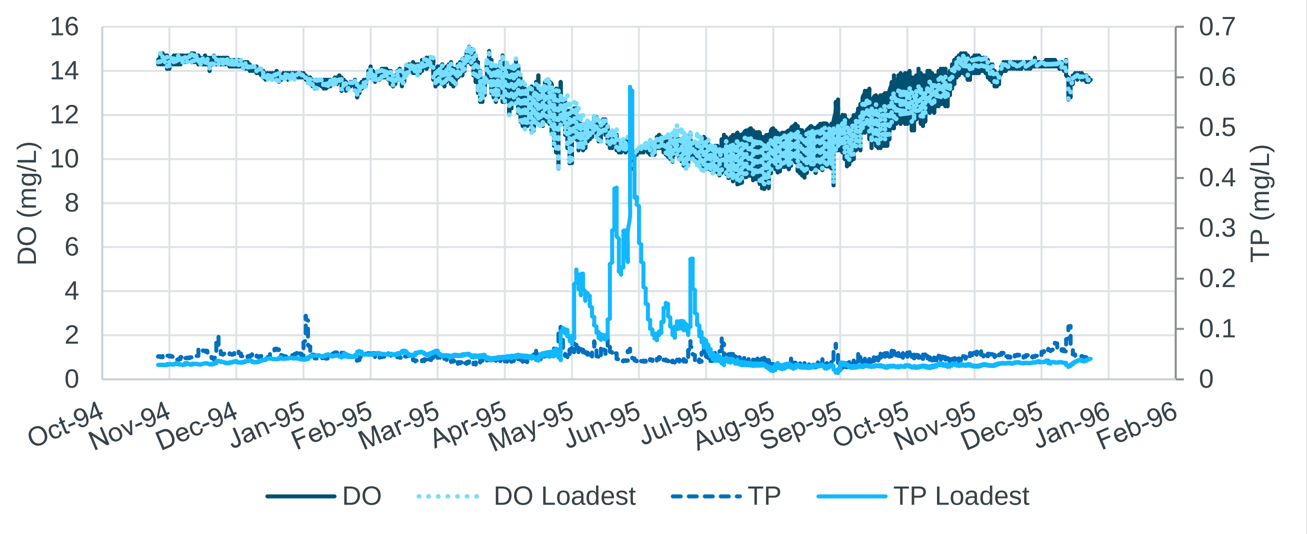
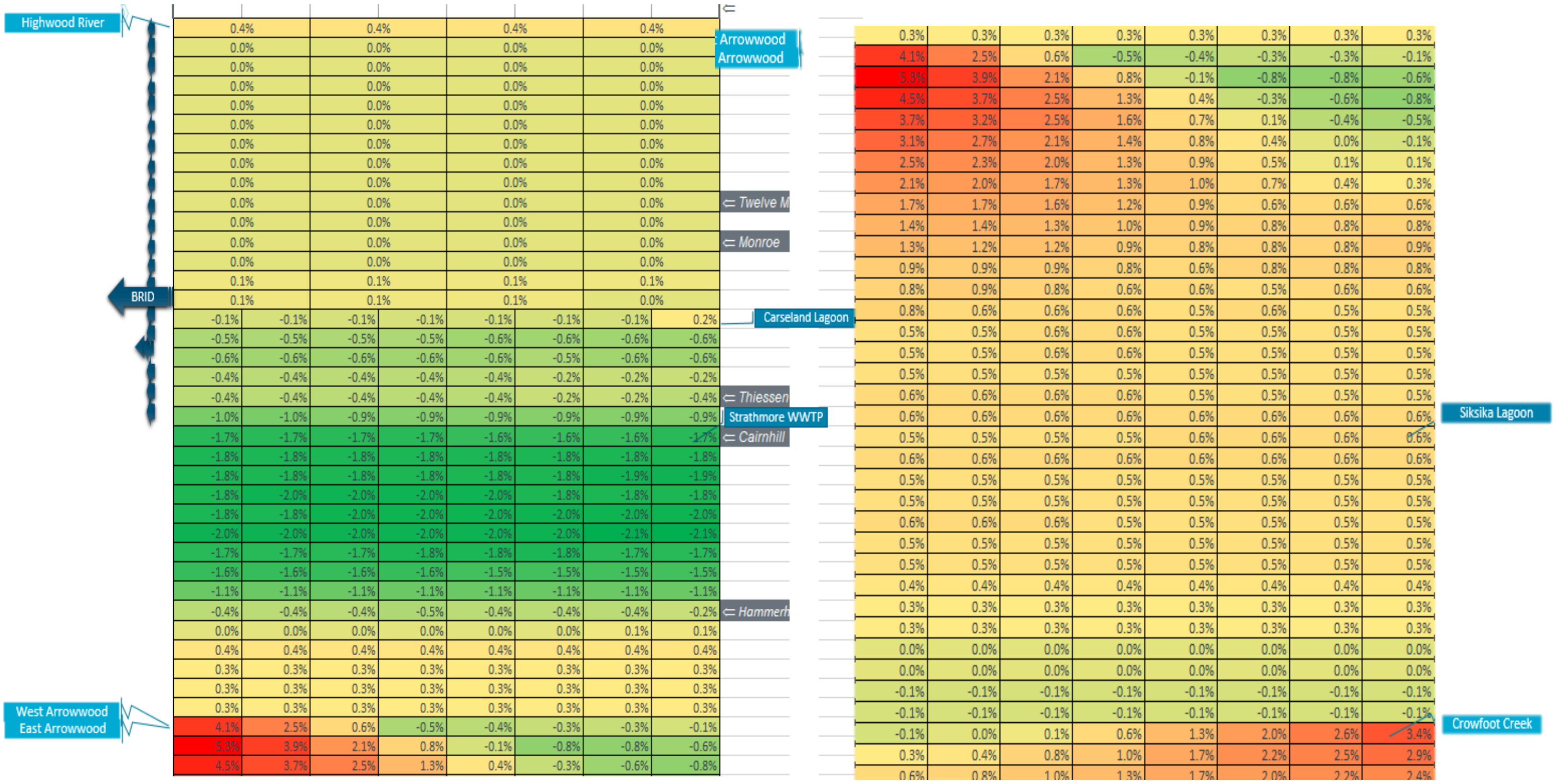


Figure 39. DO simulated using TP load estimated using interpolation or LOADEST, downstream of West and East Arrowwood Creek (segment 229).

The model predicts a change in the minimum DO from -2% to 5% (Figure 40). The DO concentration improves downstream the tributaries where the critical low DO concentrations were observed. Similar to the City Reach, the model predicts a higher



0.4%		0.4%		0.4%		0.4%	
0.0%		0.0%		0.0%		0.0%	
0.0%		0.0%		0.0%		0.0%	
0.0%		0.0%		0.0%		0.0%	
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0.1%		0.1%		0.1%		0.1%	
0.1%		0.1%		0.1%		0.0%	
-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	0.2%
-0.5%	-0.5%	-0.5%	-0.5%	-0.6%	-0.6%	-0.6%	-0.6%
-0.6%	-0.6%	-0.6%	-0.6%	-0.6%	-0.5%	-0.6%	-0.6%
-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	-0.2%	-0.2%	-0.2%
-0.4%	-0.4%	-0.4%	-0.4%	-0.4%	-0.2%	-0.2%	-0.4%
-1.0%	-1.0%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%	-0.9%
-1.7%	-1.7%	-1.7%	-1.7%	-1.6%	-1.6%	-1.6%	-1.7%
-1.8%	-1.8%	-1.8%	-1.8%	-1.8%	-1.8%	-1.8%	-1.8%
-1.8%	-1.8%	-1.8%	-1.8%	-1.8%	-1.8%	-1.9%	-1.9%
-1.8%	-2.0%	-2.0%	-2.0%	-2.0%	-1.8%	-1.8%	-1.8%
-1.8%	-1.8%	-2.0%	-2.0%	-2.0%	-2.0%	-2.0%	-2.0%
-2.0%	-2.0%	-2.0%	-2.0%	-2.0%	-2.0%	-2.1%	-2.1%
-1.7%	-1.7%	-1.7%	-1.8%	-1.8%	-1.8%	-1.7%	-1.7%
-1.6%	-1.6%	-1.6%	-1.6%	-1.5%	-1.5%	-1.5%	-1.5%
-1.1%	-1.1%	-1.1%	-1.1%	-1.1%	-1.1%	-1.1%	-1.1%
-0.4%	-0.4%	-0.4%	-0.5%	-0.4%	-0.4%	-0.4%	-0.2%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
4.1%	2.5%	0.6%	-0.5%	-0.4%	-0.3%	-0.3%	-0.1%
5.3%	3.9%	2.1%	0.8%	-0.1%	-0.8%	-0.8%	-0.6%
4.5%	3.7%	2.5%	1.3%	0.4%	-0.3%	-0.6%	-0.8%

0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
4.1%	2.5%	0.6%	-0.5%	-0.4%	-0.3%	-0.3%	-0.1%
5.3%	3.9%	2.1%	0.8%	-0.1%	-0.8%	-0.8%	-0.6%
4.5%	3.7%	2.5%	1.3%	0.4%	-0.3%	-0.6%	-0.8%
3.7%	3.2%	2.5%	1.6%	0.7%	0.1%	-0.4%	-0.5%
3.1%	2.7%	2.1%	1.4%	0.8%	0.4%	0.0%	-0.1%
2.5%	2.3%	2.0%	1.3%	0.9%	0.5%	0.1%	0.1%
2.1%	2.0%	1.7%	1.3%	1.0%	0.7%	0.4%	0.3%
1.7%	1.7%	1.6%	1.2%	0.9%	0.6%	0.6%	0.6%
1.4%	1.4%	1.3%	1.0%	0.9%	0.8%	0.8%	0.8%
1.3%	1.2%	1.2%	0.9%	0.8%	0.8%	0.8%	0.9%
0.9%	0.9%	0.9%	0.8%	0.6%	0.8%	0.8%	0.8%
0.8%	0.9%	0.8%	0.6%	0.6%	0.5%	0.6%	0.6%
0.8%	0.6%	0.6%	0.6%	0.5%	0.6%	0.5%	0.5%
0.5%	0.5%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%
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0.5%	0.5%	0.5%	0.5%	0.6%	0.6%	0.6%	0.6%
0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%
0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
0.6%	0.6%	0.6%	0.5%	0.5%	0.5%	0.5%	0.5%
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0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%
0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%	0.4%
0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%	0.3%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%
-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%	-0.1%
-0.1%	0.0%	0.1%	0.6%	1.3%	2.0%	2.6%	3.4%
0.3%	0.4%	0.8%	1.0%	1.7%	2.2%	2.5%	2.9%
0.6%	0.8%	1.0%	1.3%	1.7%	2.0%	2.2%	2.4%

Figure 40. Change in minimum DO for Baseline scenario using LOADEST instead of interpolation to estimate daily concentrations for tributaries and mainstem.

maximum TP concentration (increase in max TP for each segment from 30% to 266%), but a lower median TP (decrease from -9% to -5%) using LOADEST.

Table 15 shows the MAL estimated using LOADEST. In this case, the Baseline TP load is much higher than with the interpolation method. As discussed before, LOADEST is better at estimating the TP peaks during the spring freshet. These peaks can happen quickly but bring a large amount of TP load.

Table 15. MAL estimation for Downstream Reach using LOADEST to estimate tributaries and mainstem TP load

TP Load (kg/day)		**Comments**
Baseline	871 *(950)*	
Increase % (before MOS)	5.8	
MAL (before MOS)	5070	
MAL (after MOS)	4563	0.90xMAL
Available load	3692	MAL (after MOS) - Baseline
Increase (after MOS)	5.2	MAL (after MOS)/ Baseline

* Values in () show TP load assuming City Reach uses the MAL

The MAL is within the same order of magnitude using LOADEST or interpolation for the City Reach. However, the MAL estimated using LOADEST for the Downstream Reach is significantly higher than the MAL estimated using interpolation. The different MAL values are because of the Downstream Reach tributaries, especially Highwood River, characterized by flashy peak loadings during the Spring freshet. It is unlikely that these peak loadings will increase at the same rate as the more consistent loadings. The peak loading during the freshet might be closely related to sediment transport from the riverbanks and overland runoff. There is a maximum carrying capacity of the river, so the TP concentration for these already high TP loading events may not increase as much as illustrated in these scenarios. The interpolation method is more conservative. The LOADEST method warrants further consideration.

3.4 Other forms to express the MAL

Loading objectives in the Bow River are currently expressed as an annual average load in kg/day. Many TMDL projects that have assessed water quality issues in lakes use annual average loads as objectives. Unlike rivers, lakes can have a long retention time, so loads will accumulate and gradually change.

Daily loads can also be expressed as a function of factors such as flow and seasons. Temporally variable targets might be desirable when source inputs vary significantly by month or season (USEPA, 2007), which is the case in the Bow River basin.

The MAL requires seasonal considerations. This study has proposed a critical DO season as July through September. This season can be used to manage the TP impact on DO in the river. The final decision on how to express the MAL may need to consider other social/economic implications to manage the TP in the Bow (e.g., planning implications and designing of municipal infrastructure).

Tables 16 and 17 show MAL values expressed as an annual average, critical DO season average and median. An annual average is comprehensive by managing every season and considering the different sources that are prevalent in different seasons. A TP load objective for the whole year can have some indirect benefits to the Bow River water quality, such as controlling TSS loadings. However, we may over-manage the river setting up higher-than-needed standards during periods such as the spring freshet where the current modelling exercise suggests there is not a major influence on the DO.

Table 16. Comparison of different ways to express the MAL for the City reach

TP Load (kg/day)	Annual Average	Crit. DO Average	Annual Median
Baseline	319	368	221
MAL	407	469	282
MAL(MOS)	366	422	254
Available Load	47	54	33
Increment	1.15	1.15	1.15

Table 17. Comparison of different ways to express the MAL for the Downstream Reach

TP Load (kg/day)	Annual Mean	Crit. DO Mean	Annual Median
Baseline	464	477	306
MAL	1,393	1,216	554
MAL(MOS)	1,253	1,095	498
Available Load	789	618	192
Increment	2.70	2.30	1.63

A critical DO season MAL would be more appropriate if this is more stringent than the annual average MAL. Although the critical DO season MAL was more stringent for the Downstream Reach, they were within a similar range. In contrast, there is a significant difference in expressing the MAL as annual mean or annual median. The median or 50th percentile provides lower MALs for both reaches as it neglects the effect of the peak loadings. As per the modelling results, the minimum DO is more sensitive to the median TP. The effect of large TP loadings during the spring freshet did not seem to affect the minimum DO.

By using the annual median MAL, there is a better alignment on how the rivers are managed in the Province as the Surface Water Quality Management Framework sets triggers based on the 50th percentile concentration. Although the median has traditionally been used to manage river systems, this statistic is rarely used for loading sources that are event-driven such as stormwater. It will be hard to allocate a median load for stormwater as the median TP may be close to zero.

If the annual average is selected and used for MAL allocation, allocating a certain amount for more sporadic sources such as stormwater can have a different effect than allocating a loading for other more consistent sources such as WWTPs. A MAL expressed as an annual average can have a different response in the Bow River if we allocate, for example, a) upstream 30%, stormwater 20%, tributaries 20%, WWTPs 30% or b) upstream 30%, stormwater 30%, tributaries 20%, WWTPs 20%. Additionally, if we have a very wet year, the loading for the Downstream Reach can be much higher than the MAL, and we may not see any negative impacts on the DO.

4. Discussion

The model results suggest that current loading conditions are still meeting the DO guidelines even during low flow years. However, the available load capacity in the City Reach is not large (15%). EPA has constantly stated that water quality guidelines and objectives are not 'pollute up to' numbers. This is especially important if these reaches have the goal to improve or maintain current water quality conditions. However, it is recognized that there is pressure for urban development as well as irrigation districts expanding in the downstream reaches. A lot of planning goes to upgrade the WWTPs, add new stormwater ponds and implement other Low Impact Development (LID) practices. This together with the pressure of growth in the Calgary Metropolitan Region could mean that we need to start thinking about Load Allocation mechanisms that are fair for the different stakeholders. The BRMAL gives information to evaluate the potential trade-offs. The modelling work can provide some insight into where the TP load is close to exceeding the assimilative capacity and in which sections we could add/transfer some extra load. This can inform regional WWTP approaches and help distribute point sources strategically within the assimilative capacity. The minimum DO spatial distribution also informs which areas are important to improve DO monitoring for risk assessment. The current locations of DO monitoring are missing these critical areas, so we may lack important information for managing the Bow River.

The Source Assessment study showed the location of the current major TP sources in the entire Bow River mainstem is from below Bearspaw to Carseland (Martin, 2020). The TP load observed upstream from Bearspaw Dam was consistent over the period analyzed, and this properly represented background conditions. The City Reach MAL was reached above Highwood River near the segments closer to the major TP sources during the Critical DO season.

The Downstream Reach has a larger available load capacity. However, the tributaries are a major TP source, and the assimilative capacity of some of the tributaries such as the Highwood River or Crowfoot Creek may be exceeded before noticing effects in the Bow River downstream of these tributaries. This reach does not have a major WWTP facility. The Town of Strathmore WWTP releases a great part of its effluent for irrigation during the open water season. The agricultural Best Management Practices (BMPs) are very important in this reach to keep TP loadings acceptable. However, it is important to mention that the BRMAL could change if new TP point sources operate in this reach. The BRMAL assessment is a planning tool and does not eliminate the need for Receiving Water Assessments for specific discharges to the river. The MAL can be used to set loading objectives for different TP sources as a planning tool and as an 'early warning system' that signals the river is reaching the assimilative capacity. At this point, investigation in the form of confirmatory modelling and reviewing monitoring data is needed.

As per the MAL modelling results, low DO events would be expected during late summer in low flow years. Different management actions can be explored to prevent the risk of low DO, for example, potential flow management during drought years. Increasing the regulated flows and river velocities at specific thresholds can scour macrophytes and epilithic algae (Taube et al. 2016, Chambers et al. 1991, He et al. 2011). Wastewater effluents could also be managed during critical conditions using any effluent storage for a later discharge in the Fall. Lagoons in Alberta discharge their effluent once per year. They could plan their releases to avoid discharging in late Summer.

The modelling work also provided some insights into how the nature of different TP loadings affects differently the minimum DO in the river. For example, a peak loading delivered by the tributaries during the Spring freshet does not affect the minimum DO observed later in the year in the same way that the loading would do if it is distributed constantly during the year. The TP speciation and the level of particulate and less bioavailable fractions will matter in the algae and aquatic plants' growth. This also speaks to the DO being affected by several factors and not only the nutrient levels. The water temperature, river discharge and velocities may inhibit algae and macrophytes' growth. The turbidity also affects the light available and can make it a limiting factor.

More attention may be needed to characterize the TP bioavailable fraction and loading sources' seasonality to better manage the TP in the river. Li & Brett (2012) compared studies quantifying the percentage of P bioavailable in different sources. They found that agricultural and urban runoff and natural stream flows commonly have significantly lower P bioavailability than secondary WWTP effluents. However, the effluents of alum-based tertiary P removal processes have a very low bioavailability compared to these other sources. Therefore, comparing the eutrophication potential without accounting for the degree of bioavailability can under or overestimate the risk for the aquatic environment.

The loading allocation was not assessed as part of this project. This will include a broader conversation that will consider societal issues besides science-based input. Water allocation has a long history in Alberta. Further consideration may be required about how some of the principles in water allocation are transferable to load allocation in the future (e.g., 'first in time first in right' and transfers).

The BRMAL considered the linkages between the source TP loads and the DO response to those loads in the City and Downstream reaches (up to Bassano Dam). However, the effect of those loads does not end there. The TP export to the South Saskatchewan River and transboundary TP export to lentic waterbodies could be explored in the future.

TP and TDP water quality objectives

The Bow River Basin Council (BRBC) published water quality objectives (WQOs) for different Bow River reaches and parameters (BRBC 2008). The BRMAL City Reach was within BRBC's Bow River Central reach, from Downstream Bearspaw Dam to Carseland Weir. The WQOs for TDP and TP in that reach were 0.015 mg/L and 0.028 mg/L, respectively. These WQOs have been widely used in Receiving Water Assessments to support EPEA approvals.

Golder Associates (2007) derived the BRBC WQOs for TP and TDP using the BRWQM. The TDP objective represented the cross-sectional average concentration that maintained DO levels above 5 mg/L using data from April to September. They inferred the TP objective from the TDP objective using observed TP: TDP ratios (55%).

The BRBC report also included a Baseline water quality median for TP and TDP at the Carseland station as 0.016 mg/L and 0.038 mg/L, respectively. These median values were already above the WQOs. The most recent South Saskatchewan Region Surface Water Quality Framework (SSR SWQF) (Government of Alberta 2014) reported TP and TDP triggers for the Carseland station based on historical median concentration for the open water season (April to October). The exceedances for triggers are evaluated through a statistical process (not a direct comparison) but are presented here for context. The triggers were 0.007 mg/L and 0.021 mg/L for TDP and TP, respectively. These concentrations are an improvement from the values reported by the BRBC. However, the TP concentration at the Carseland station is significantly lower than the concentration in the City Reach. The Above Highwood River median TP concentration in the open water season was 0.029 mg/L, while the median concentration Below Carseland Dam in the same period was 0.017 mg/L (2005-2015).

The BRMAL Baseline scenario predicted a TP cross-sectional average concentration of 0.038 mg/L, 3 km downstream of Bonnybrook for the open water season. The BRMAL Baseline TP concentration was already above the BRBC WQO of 0.028 mg/L. However, the minimum DO concentrations predicted were above 5 mg/L more than 100% of the time. The MAL scenario had a TP average concentration of 0.048 mg/L for the open water season. As per the methodology followed in the BRBC report, the model suggests this concentration as the TP water quality objective. This value is based on the river's assimilative capacity for maintaining the DO instream guidelines.

In our modelling, the TP: TDP ratio in the City Reach was close to 0.31. Monitored observed data in this reach has a TP: TDP ratio of 0.36. This ratio is consistent with the SSR SWF value at Carseland (0.33). Based on this ratio, the TDP water quality objective would be 0.017 mg/L. This compares with the BRBC objective of 0.015 mg/L. The TDP: TP ratio used in the BRBC report of 55% is very high, resulting in a lower TP objective. The BRBC's TP objective would be 0.042 mg/L using the most appropriate ratio of 36%.

4.1 Model Limitations

Water quality models are a simplified representation of a very complex system. Even when good data is available, the model will have different limitations and shortcomings. The main BRMAL model limitations are acknowledged below. They are limitations related to the hydrodynamics/transport; and the water quality simulation.

Hydrodynamics and transport

- BRWQM uses a 1D hydraulic model for river velocity. Lateral averaging assumes variations in velocities along river cross-sections are negligible. River velocity near the banks is overestimated.
- This model does not handle mixing zone or near field effects. The concentrations are well mixed within each model cell (approx. 2 km long x 10 m wide)
- Dispersive mixing coefficients are specified with values that range from 0.12 m^2/sec to 0.06 m^2/sec; however, they could change more spatially and temporally.
- Simplification of bathymetry to a single channel (it does not consider river islands, etc.).
- Interpolation between surveyed cross-sections.

Water quality

- One species is enough to model each biotic component (epiphyte, phytoplankton, macrophyte). For example, one growth rate applies to all macrophytes.
- The stoichiometric ratios do not change with time, and one value is representative of each biotic component (e.g., the ratio of N to C is constant for the phytoplankton).
- The fraction of inorganic P is always the same for each point source.
- Mainstem and tributary loading estimated using monthly samples.
- Stormwater input estimated using modelling tools.

4.2 Recommendations for future work

The current modelling results can start guiding the discussions about loading allocation. The MAL can be reassessed after major changes to the loading sources, a major improvement in the monitoring data, or when an updated water quality model is available.

The BRWQM is currently being updated to a new modelling platform using EFDC Explorer Modeling System (EEMS). This will improve some of the current hydrodynamic limitations using HEC-RAS as a 1D hydraulic model. The new platform will provide a better prediction of the effluent plumes and minimum DO zone. This will enable the analysis of the results segment by segment when needed, instead of using a cross-sectional average.

Improved monitoring of the TP bioavailable fraction in the TP sources can help to better characterize the linkage between TP and DO.

The flows were an important component of the DO sag events. Several recent years have been low flow years. If new validation runs are done in the future with an updated model, it will be important to include the most recent low flow years. On top of that, climate change scenarios can be run in the future to better understand how climate change could affect the assimilative capacity of the Bow River.

The input from the stakeholders and the BRMAL Technical Team was crucial for this project. Any future stages of this modelling project will benefit from the involvement of stakeholders and subject matter experts.

5. Conclusions

The BRWQM proved useful in confirming the P limitation in the selected reaches, the changes in primary producers over the model domain, and the changes in DO with increased TP load. The BRMAL recommendations are an annual average load of 366 kg/day for the City Reach and 1253 kg/day for the Downstream Reach.

DO was very sensitive to the bioavailable fraction of TP. TDP and DRP concentrations can be very different for WWTPs using alum flocculation. In contrast, the model was not very sensitive to short peak loadings during the Spring freshet. The modelling work identified the areas where the current TP loadings could cause DO sags in the future. For example, downstream of Bonnybrook WWTP for the City Reach and downstream of Crowfoot Creek for the Downstream Reach. The model also predicted that these low DO events would happen most likely in late summer during low flow years. The current modelling work provides science-based information that can be used for load allocation; to guide Approvals under EPAEA, and for Regional Planning.

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Appendix 1. Model Performance

a) City Reach

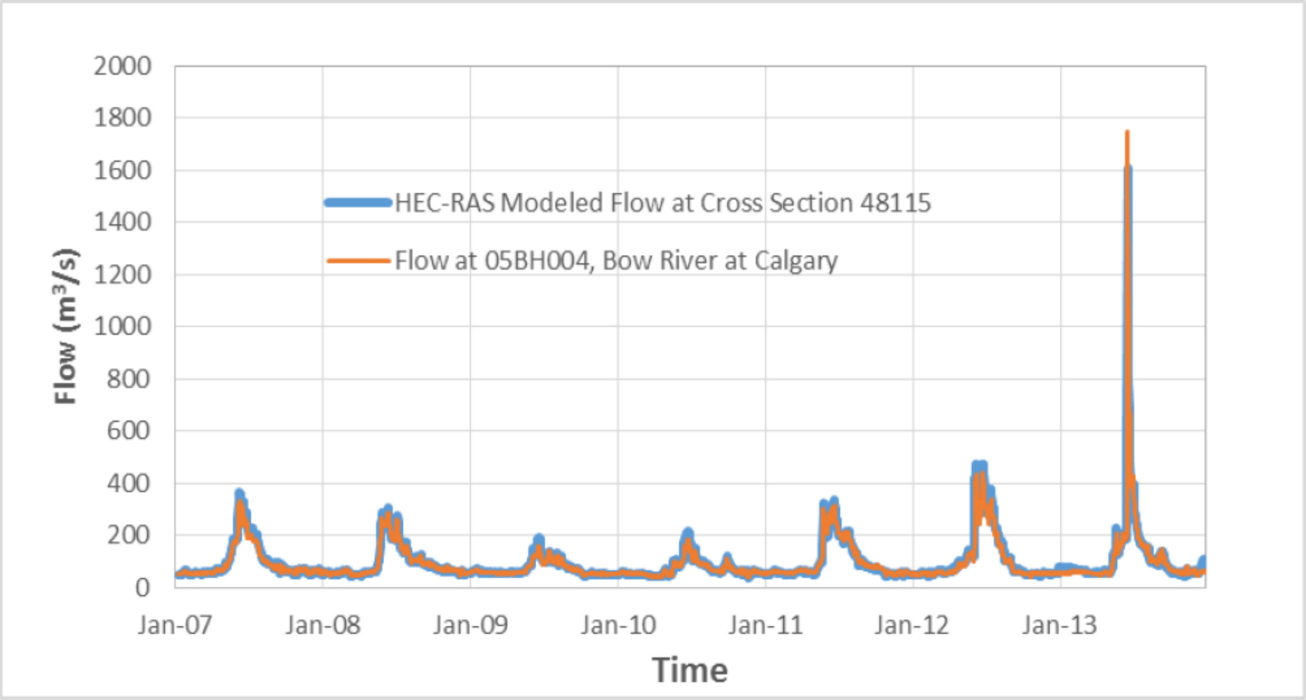
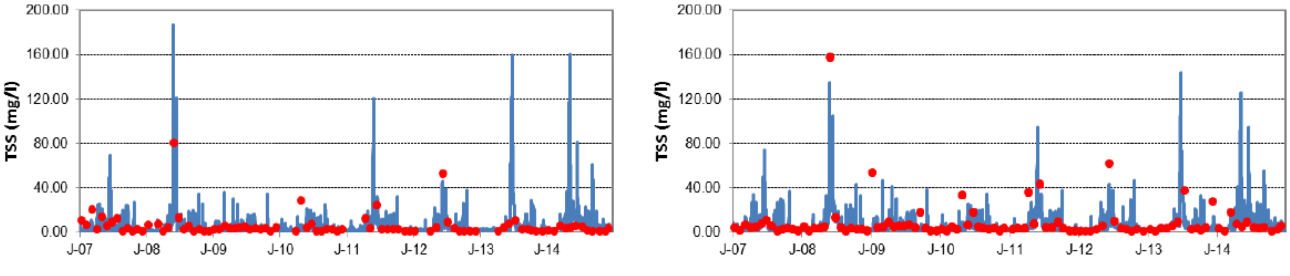
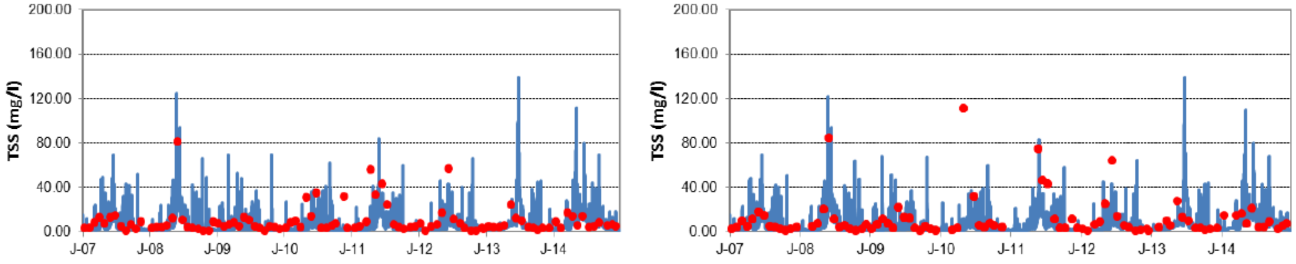


Figure A1 1. Flow calibration City Reach, Bow River at Calgary station



Modelled TSS at WASP-MG Segment 9

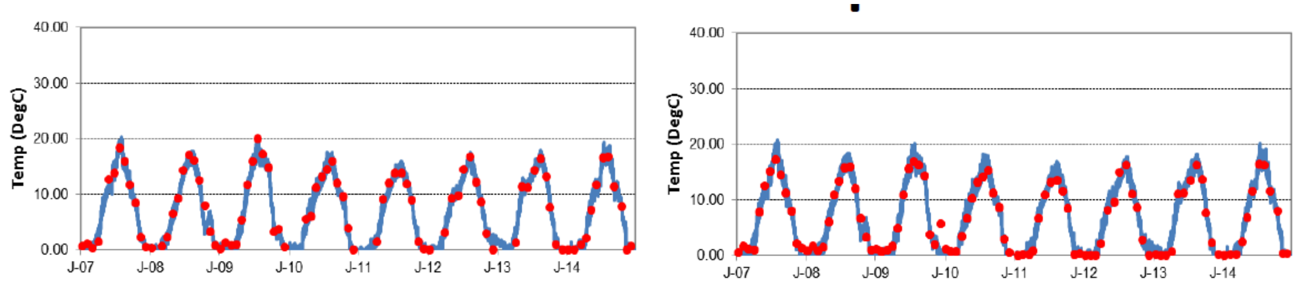
Modelled TSS at WASP-MG Segment 14



Modelled TSS at WASP-MG Segment 141

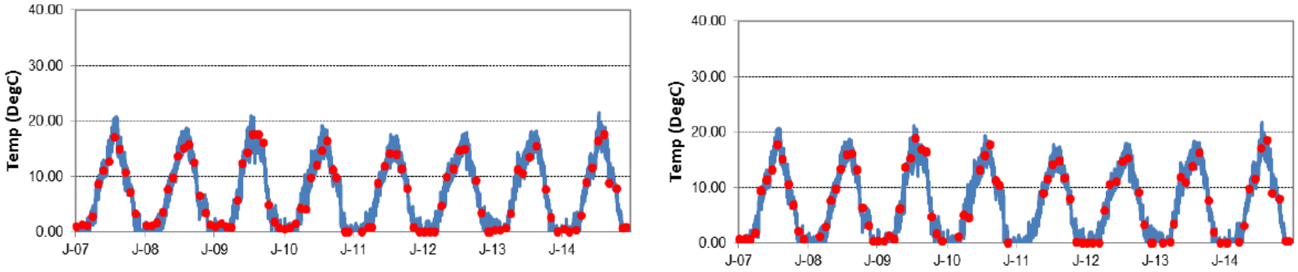
Modelled TSS at WASP-MG Segment 173

Figure A1 2. Calgary Reach TSS calibration at different segments, the blue line is model simulation, and the red dots are observed values.



Modelled Temperature at WASP-MG Segment 9

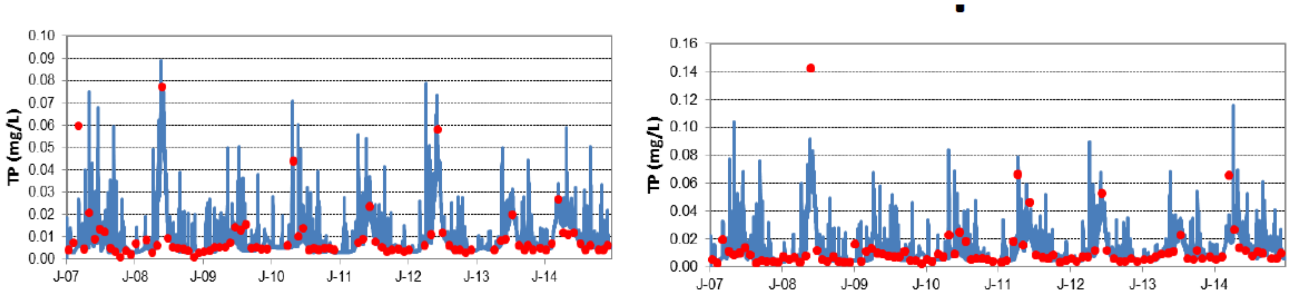
Modelled Temperature at WASP-MG Segment 14



Modelled Temperature at WASP-MG Segment 141

Modelled Temperature at WASP-MG Segment 173

Figure A1 3. Calgary Reach water temperature calibration at different segments, the blue line is model simulation, and the red dots are observed values.



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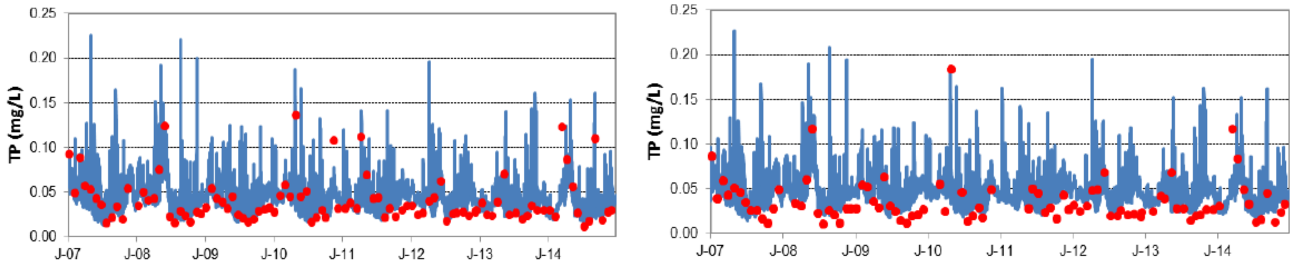
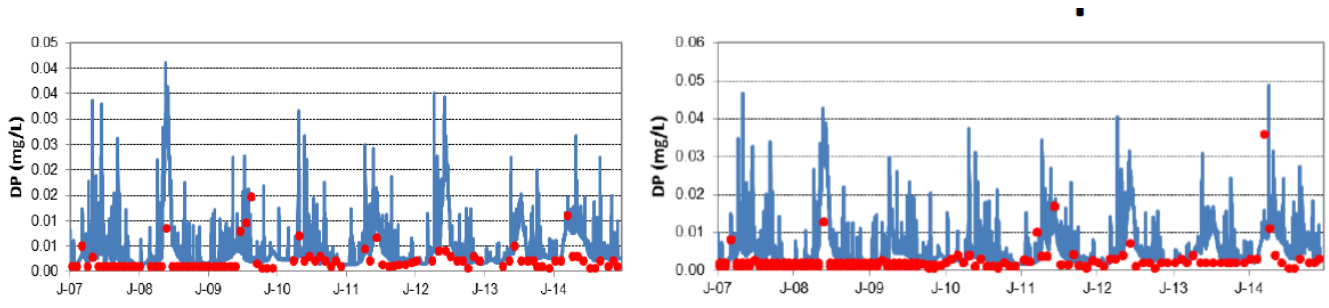
Modelled TP at WASP-MG Segment 14



Modelled TP at WASP-MG Segment 141

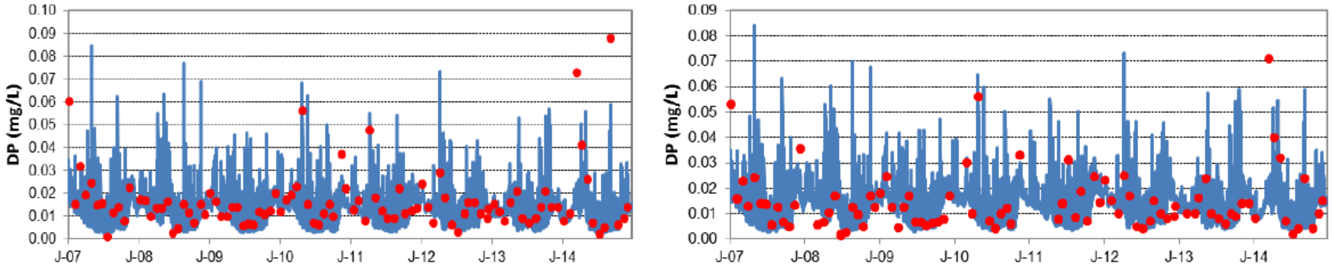
Modelled TP at WASP-MG Segment 173

Figure A1 4. Calgary Reach TP calibration at different segments, the blue line is model simulation, and the red dots are observed values.



Modelled TDP at WASP-MG Segment 9

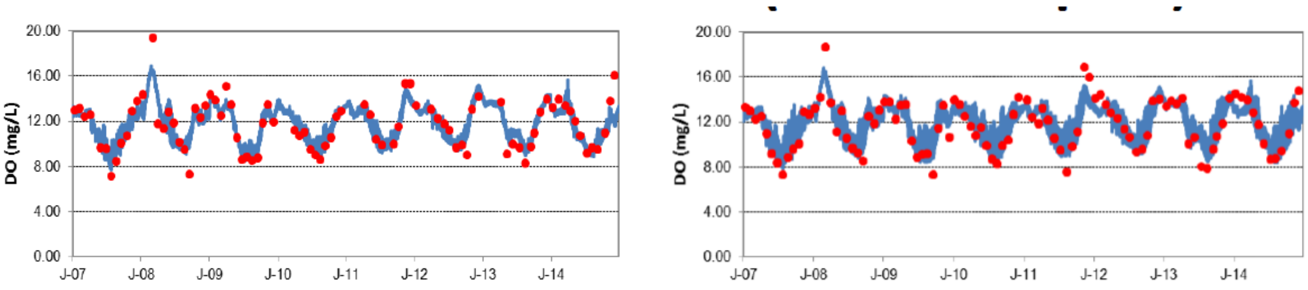
Modelled TDP at WASP-MG Segment 14



Modelled TDP at WASP-MG Segment 141

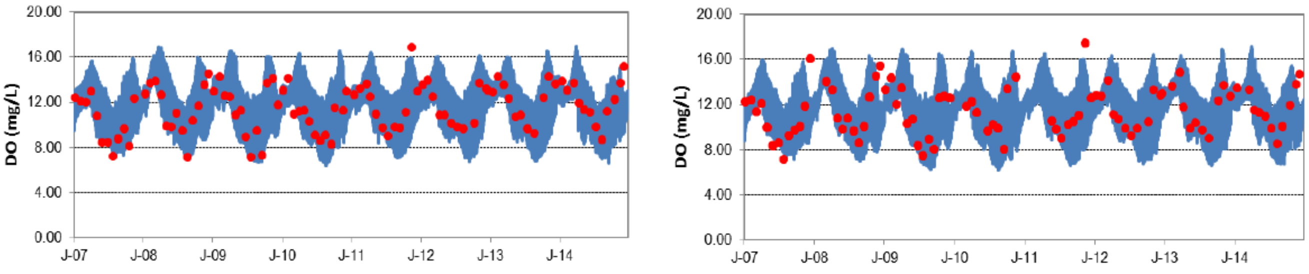
Modelled TDP at WASP-MG Segment 173

Figure A1 5. Calgary Reach DP calibration at different segments, the blue line is model simulation, and the red dots are observed values.



Modelled DO at WASP-MG Segment 9

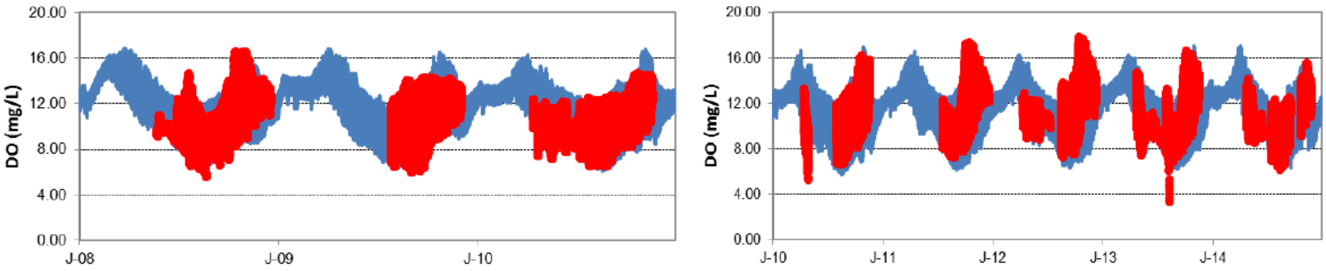
Modelled DO at WASP-MG Segment 14



Modelled DO at WASP-MG Segment 141

Modelled DO at WASP-MG Segment 173

Figure A1 6. Calgary Reach DO calibration at different segments, the blue line is model simulation, and the red dots are observed values.



Modelled DO at WASP-MG Segment 144

Modelled DO at WASP-MG Segment 176

Figure A1 7. Calgary Reach DO calibration at different segments, the blue line is model simulation, and the red dots are observed values.

b) Downstream Reach

The model calibration period was from 2005 to 2013 and validated from 2013 to 2015. The validation used the most recent bathymetry after the 2013 flood.

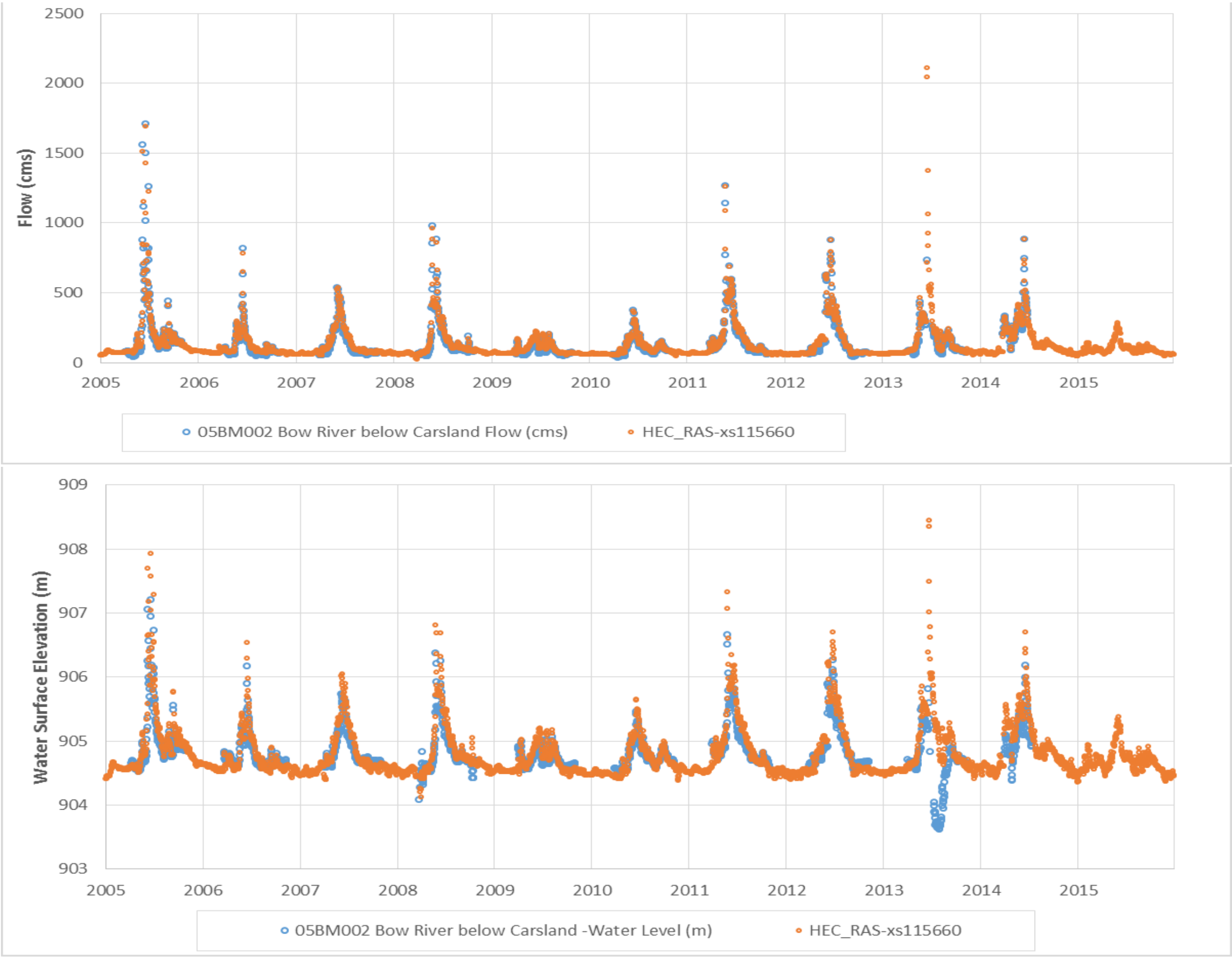


Figure A1 8. Flow and water surface elevation calibration Bow River below Carseland Dam (05BM002) – Post flood bathymetric update.

Table A1 1. HEC-RAS Model Error Statistics June 2013 to December 2015 Pre-flood. Model Error Statistics June 2013 to December 2015 Post-flood (validation).

Type	Mean Data	Mean Model	Absolute Model Error	Relative Model Error
Elevation (m)	920.92 (904.73)	921.18 (905.14)	0.26 (0.41)	0.028% (0.045%)
Flow (m^3/s)	155.26 (210.43)	169.65 (222.87)	14.39 (12.44)	9.270% (5.910%)

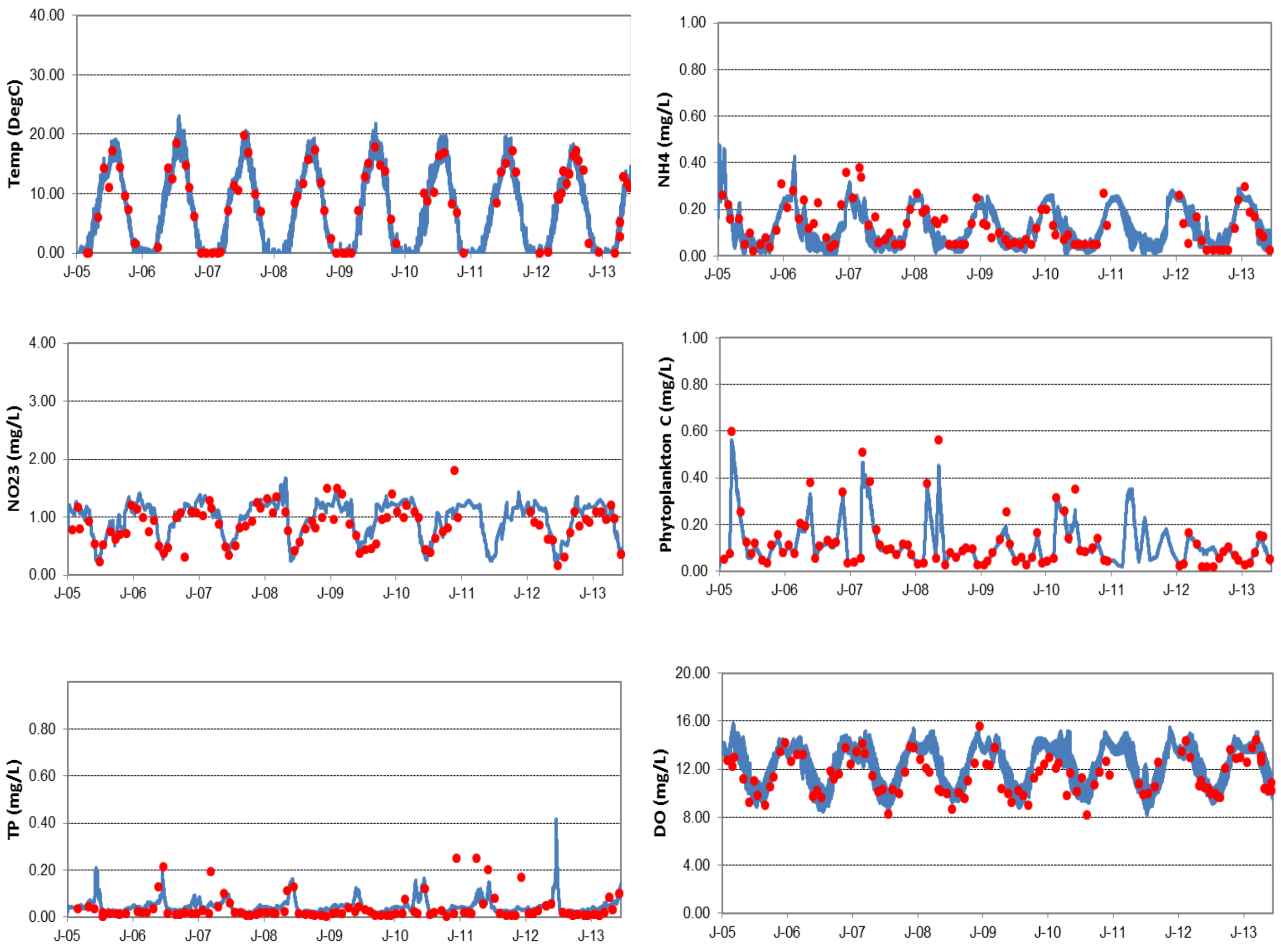


Figure A1 9. Water quality calibration plots- Bow River at Carseland Dam

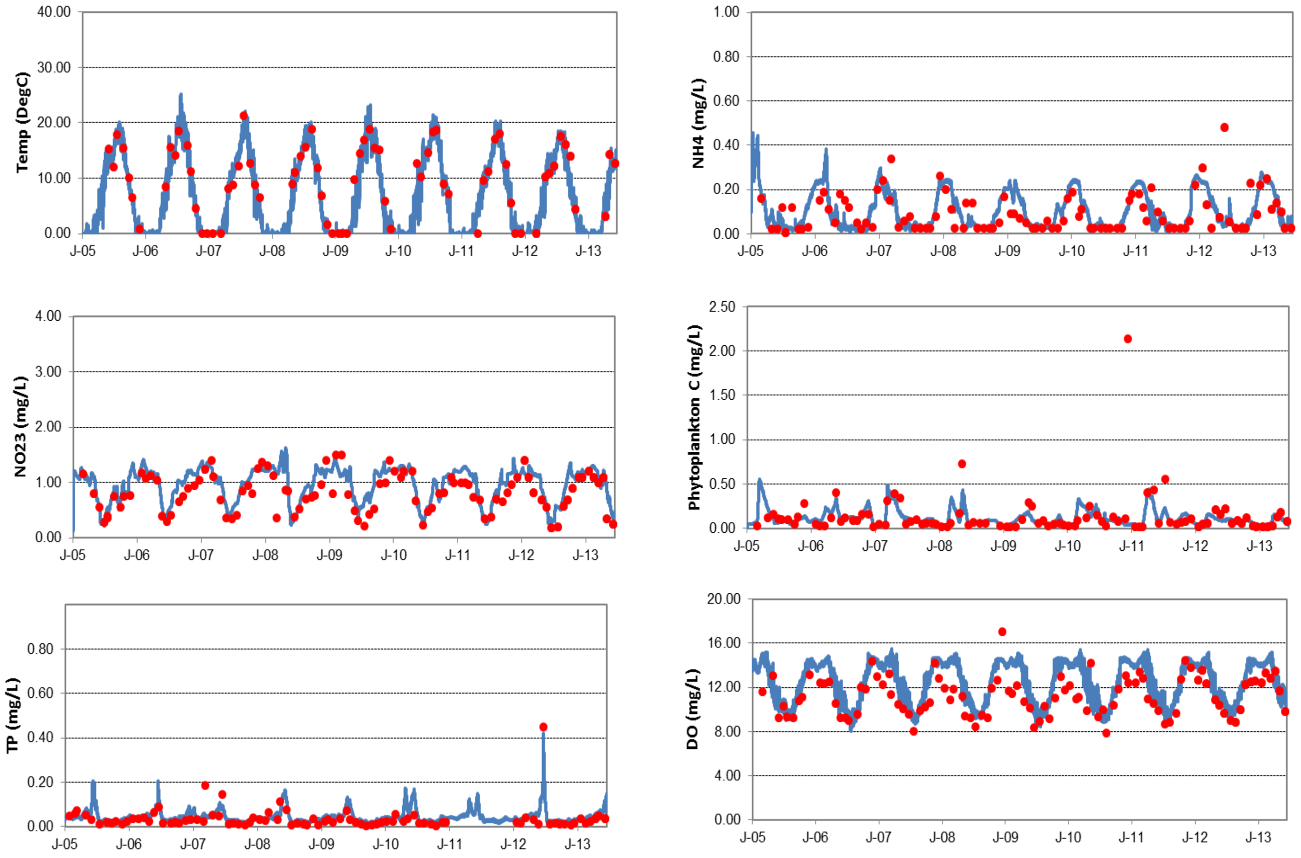


Figure A1 10 Water quality calibration plots Bow River at Cluny

Table A1 2. Error Statistics of WASP-MG Downstream Reach

Water Quality Variables	**Average Data**	**Average Model**	**ME**	**RME**	**RMSE**
Below Carseland					
Ammonia	0.065	0.099	0.033	51.27%	0.003
CBOD	5.841	5.947	0.107	1.83%	2.319
Phytoplankton Biomass	0.073	0.115	0.042	56.82%	0.007
Nitrate/Nitrite	0.807	0.939	0.133	16.44%	0.062
Total Nitrogen	0.946	1.144	0.198	20.89%	0.098
Dissolved Oxygen	10.966	11.502	0.536	**4.89%**	0.828
Total Dissolved Phosphorus	0.00840	0.00916	0.00076	9.07%	0.00009
Total Phosphorus	0.034	0.038	0.004	**12.86%**	0.002
Water Temperature	10.481	9.967	-0.514	**-4.90%**	2.686

At Cluny					
Ammonia	0.058	0.083	0.025	43.51%	0.004
CBOD	6.654	6.186	-0.468	-7.03%	6.390
Phytoplankton Biomass	0.132	0.114	-0.018	-13.74%	0.038
Nitrate/Nitrite	0.741	0.944	0.203	27.43%	0.095
Total Nitrogen	1.032	1.186	0.154	14.95%	0.084
Dissolved Oxygen	10.914	11.986	1.071	**9.82%**	1.542
Total Dissolved Phosphorus	0.00892	0.00869	-0.00023	-2.59%	0.00021
Total Phosphorus	0.045	0.038	-0.007	**-15.38%**	0.005
Water Temperature	8.815	8.489	-0.326	**-3.70%**	4.568

Appendix 2. Flow analyses

a) Baseline scenario to represent the critical low flow

Low flows usually represent a critical condition in terms of DO. Water quality modelling often uses the 7-day average minimum flow with a return period of 10 years (7Q10) to estimate the potential effects of loads in waterbodies. We used this indicator here to compare annual 7-day average minimum flows in the Bow River. The annual 7Q10 (1990-2015) is 38.28 m^3/s at Bow River below Bearspaw Dam. Model calibration for BRWQM used 2007-2014 flow data for the City reach. However, the 7 days average minimum flow for the years 2007-2014 was always higher than 7Q10 and it does not represent critical low flow condition.

The rank of the years for 7-day average minimum flow changes when considering selected seasons i.e. Open water season (Apr-Oct), Ice cover season (Nov-Mar) and Critical DO season (Jul-Sep). Figure A2 1 b shows the 7-day average minimum flow for the Critical DO season. In this case, the critical DO season 7Q10 is 54.08 m^3/s. Again, all the flows within the calibration period 2007-2014 were above the seasonal 7Q10.

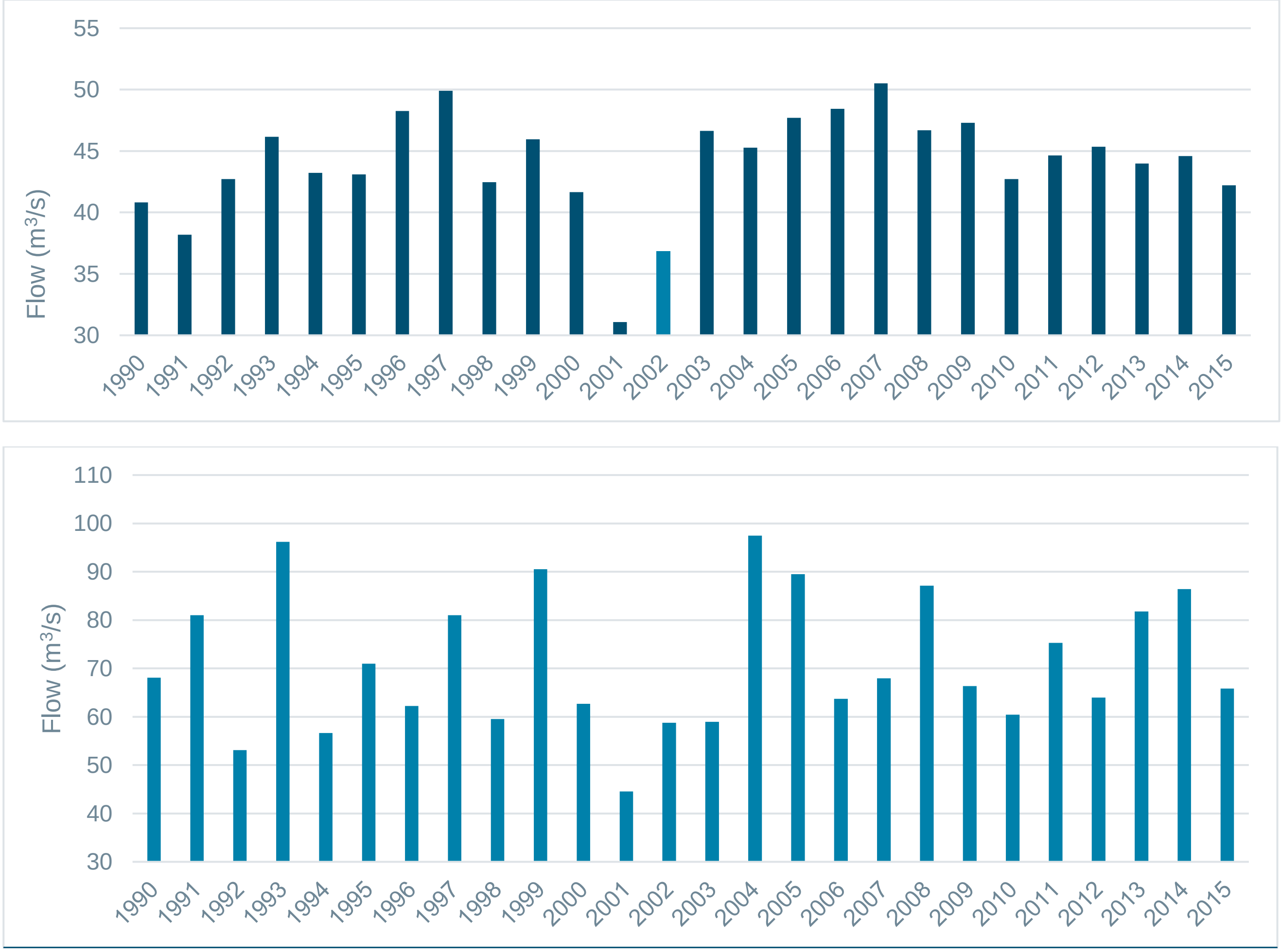


Figure A2 1. a) Min Critical DO season 7Q, b) Min Annual 7Q, Bow River below Bearspaw Dam

The flow duration curve for the Bow River at Calgary (Figure A2 2) shows that the flows in the 1990-2004 period were lower than the flows in the most recent 2005-2015 period.

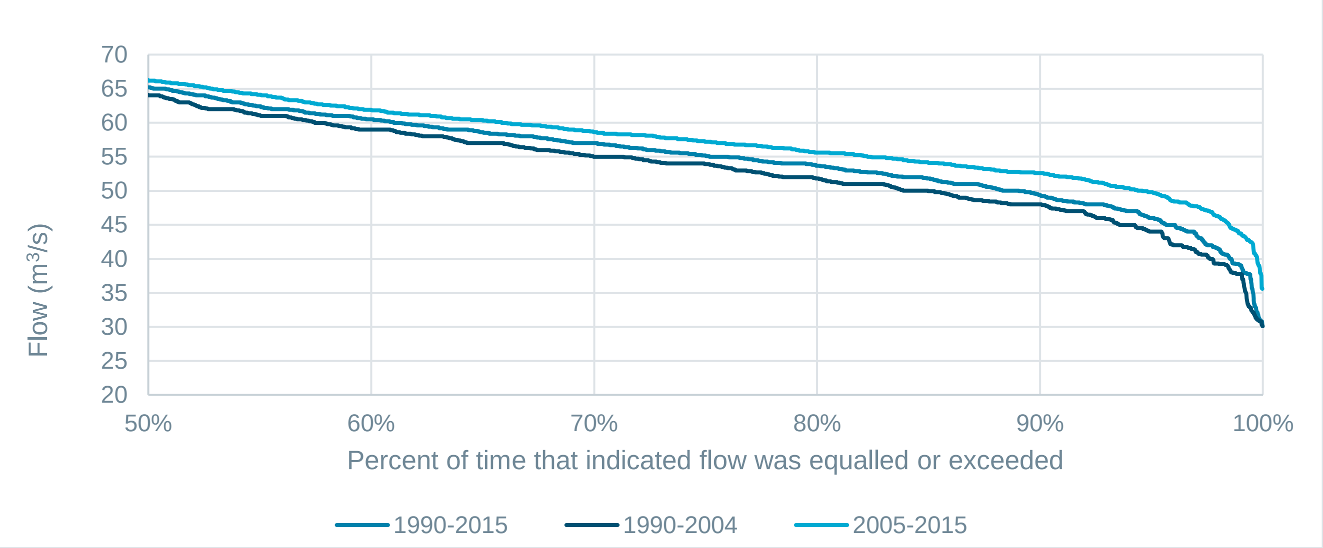


Figure A2 2. Flow duration curve (50th to 100th percentile) for Bow River at Calgary (05BH004) for the data period 1990-2015.

Another way to compare the flows within these two periods is with the accumulated annual water volume. Figure A2 3 shows the range with the lowest and highest year for the period. Again, the 1990-2004 period shows lower annual accumulated volume.

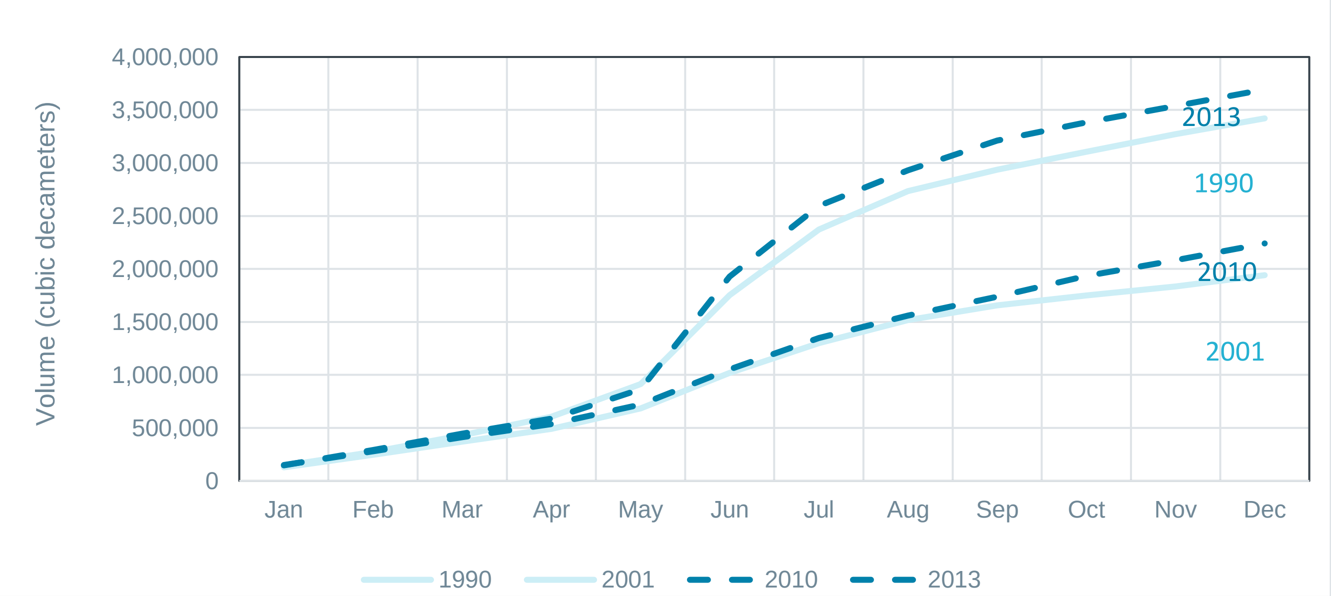


Figure A2 3. Accumulated annual water volume Bow River at Calgary (05BH004).

b) High flows for macrophyte and epilithic algae reduction and scouring

High flows and the drag coefficients associated with them can discourage macrophyte and epilithic algae growth. The annual average 7-day maximum flow during the freshet period was estimated to investigate the historic high flows in the Bow River (Figure A2 4). The freshet period was defined as weeks 21-27 which include all of June and one week before and after June.

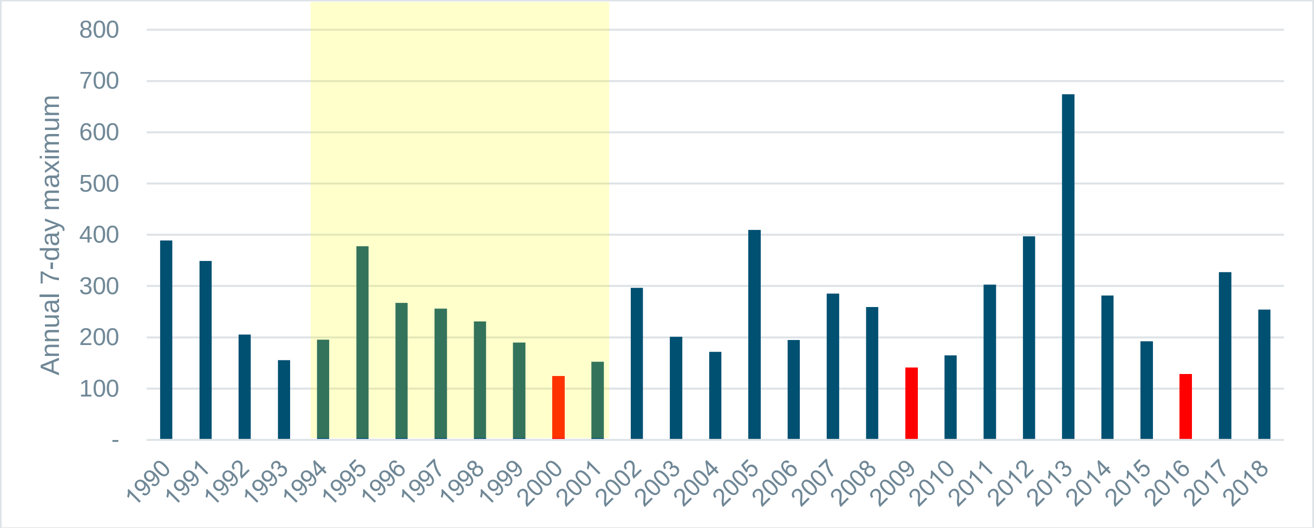


Figure A2 4. Annual 7-day maximum flow during the freshet period. Station: Bow River at Calgary (05BH004) Data Period: 1990-2018.

From the 1990-2018 period, 2000, 2009 and 2016 were three years with the lowest 7-day flow during the freshet (< 150 m^3/s). It is interesting to see that 2000 was the year with the lowest 7-day maximum during the freshet and not 2001.

Table A2 1. Flow thresholds for macrophyte and epilithic algae reduction and scouring

Source	Discharge threshold for	Value (m^3/s)	Type
Taube et al. (2016)	reducing macrophyte	400	Q_{max} annual
Taube et al. (2016)	reducing macrophyte	120	Q_{avg} annual
Taube et al. (2016)	scouring epilithic algae	120	Q_{daily} average
He et al. (2011)	scouring epilithic algae	220	Q_{daily} average

Table A2 1 shows different published thresholds for the reduction of macrophytes and scouring of algae. They depend either on flow or water velocity.

The threshold of 400 m^3/s Q_{max} annual for macrophyte reduction was exceeded only in 1995 during the simulation period (Figure A2 5). The flows during the selected years did not reach the threshold of 120 m^3/s annual average flow (Figure A2 6). Using these criteria 2000 and 2001 were two typical years with no macrophyte reduction due to high flows.

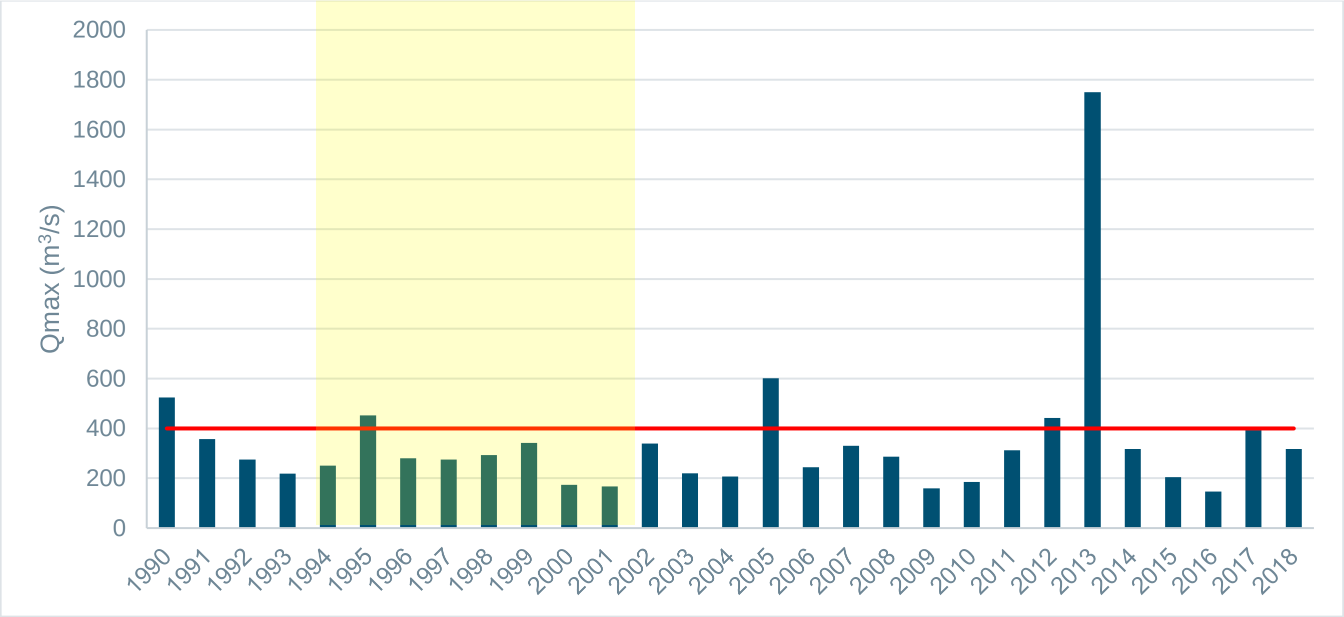


Figure A2 5. Annual Qmax Bow River at Calgary and threshold for macrophyte reduction (400 m^3/s)

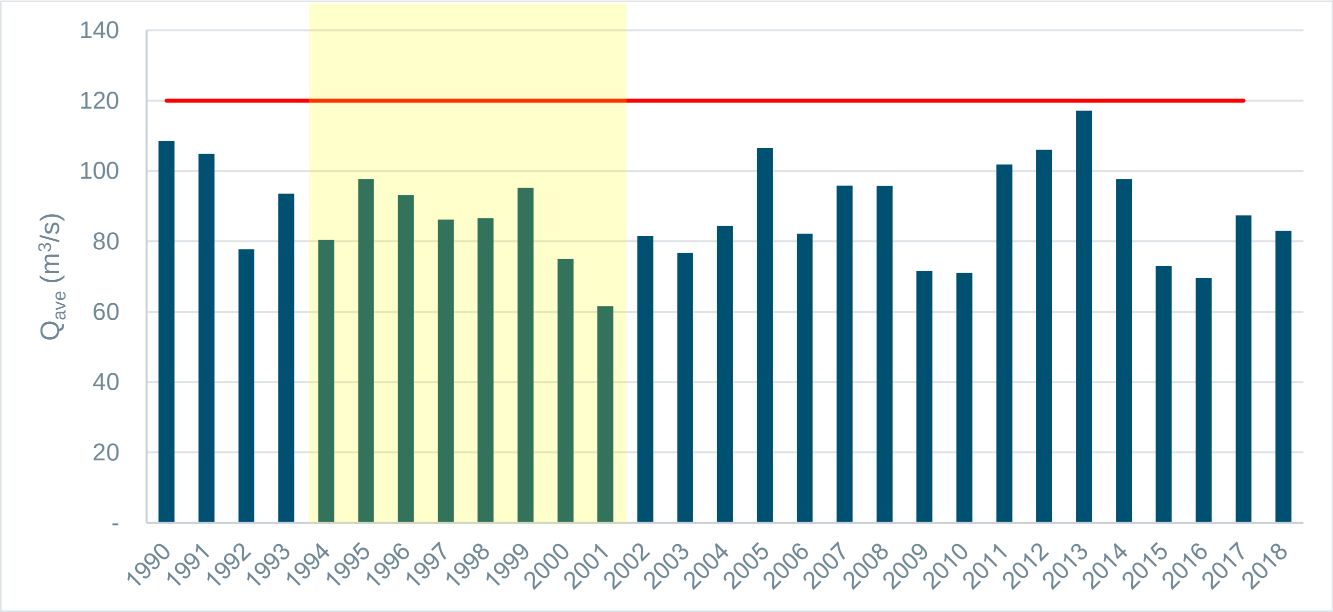


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Figure A2 6. Annual average flow Bow River at Calgary and threshold for macrophyte reduction (120 m^3/s).

While the macrophyte thresholds suggest a few years with reductions, the epilithic algae criteria show several years reaching these values. The flows at Calgary exceeded the 120 m^3/s daily flow threshold almost every year, and almost every year in the simulation period except 2000 and 2001 for the threshold of 220 m^3/s (Figure A2 7).

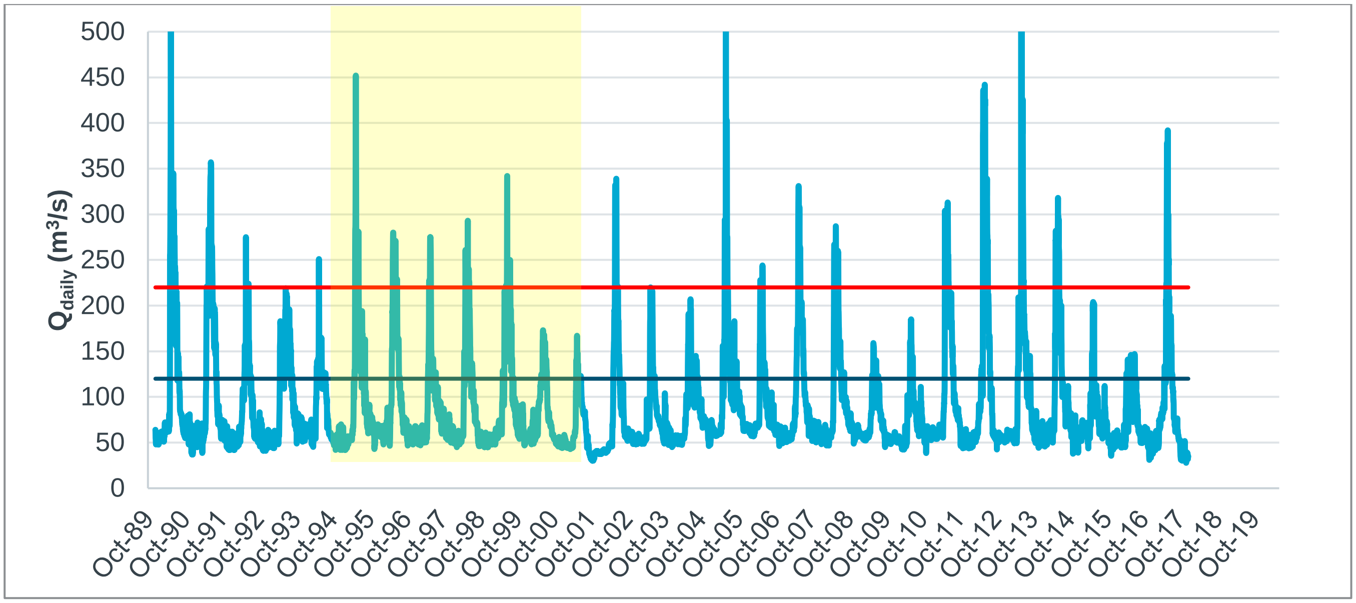

Figure A2 7. Daily average flow Bow River at Calgary gauge station and epiphyte flow thresholds for scouring of 120 m3/s and 220 m3/s.

The graph below (Figure A2 8) shows the number of days for each year that the flows were above the 120 m³/s threshold. During 2001, very few days were above 120 m³/s. Other similar years were 2009, 2010, 2015 and 2016.

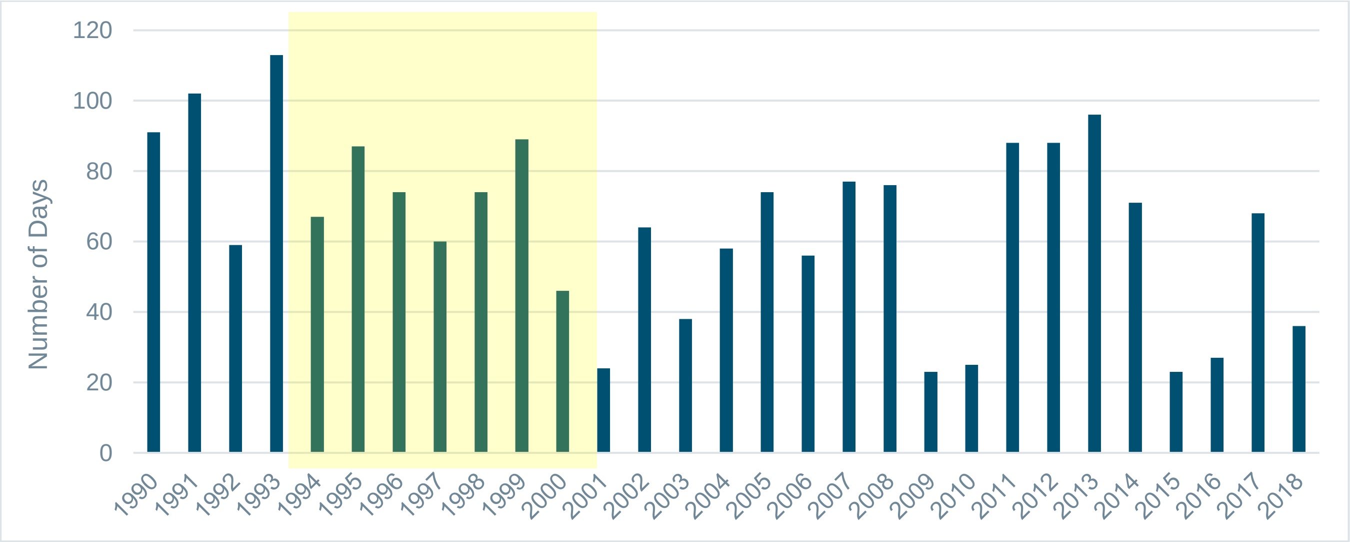

Figure A2 8. Number of days Q > threshold of 120 m3/s; bow at Calgary gauge station.

In addition to these flow thresholds, Chambers et al. (1991) found that macrophytes exhibit limited growth above velocities of 1 m/s. The model has a critical water velocity for epiphyte scouring set to 1.1 m/s. The graph below (Figure A2 9) shows the simulated water velocity for a segment downstream of the Bonnybrook WWTP. Although 2001 was a lower flow year than

2000, the high water velocities in the spring freshet observed in 2001 could have scoured more macrophytes and epiphytes. This could explain why 2000 presented more DO exceedances than 2001.

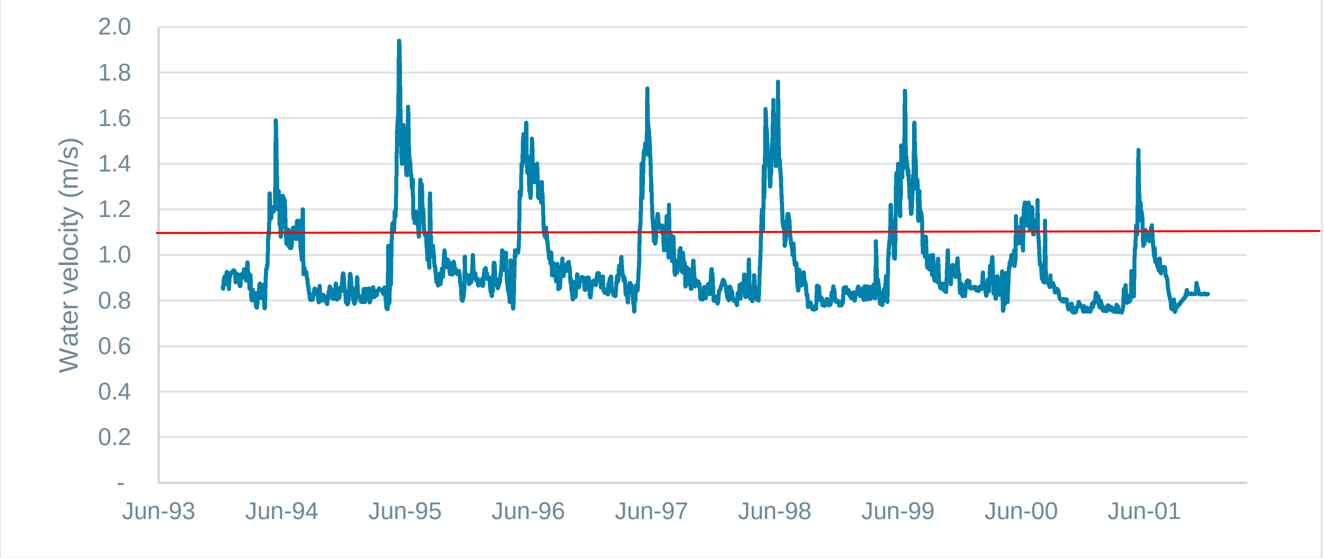

Figure A2 9. Simulated water velocity downstream Bonnybrook (segment 32) and critical water velocity for epiphyte.

The thresholds proposed by Taube et al. (2016) seem to be overly sensitive to the flows or not sensitive. The analysis of the annual 7-day maximum flow during the freshet period and the water velocities seem to be more consistent with the modelling results. Based on that the lower velocities and weekly average flows during the freshet explain in part the high DO exceedances in 2000. Some other years that may have had similar lower scouring effects are 2009 and 2016.

The air temperature is another parameter that could have affected the DO and biomass growth. Figure A2 10 suggests that 2001 had a higher annual 7-day maximum air temperature than 2000.

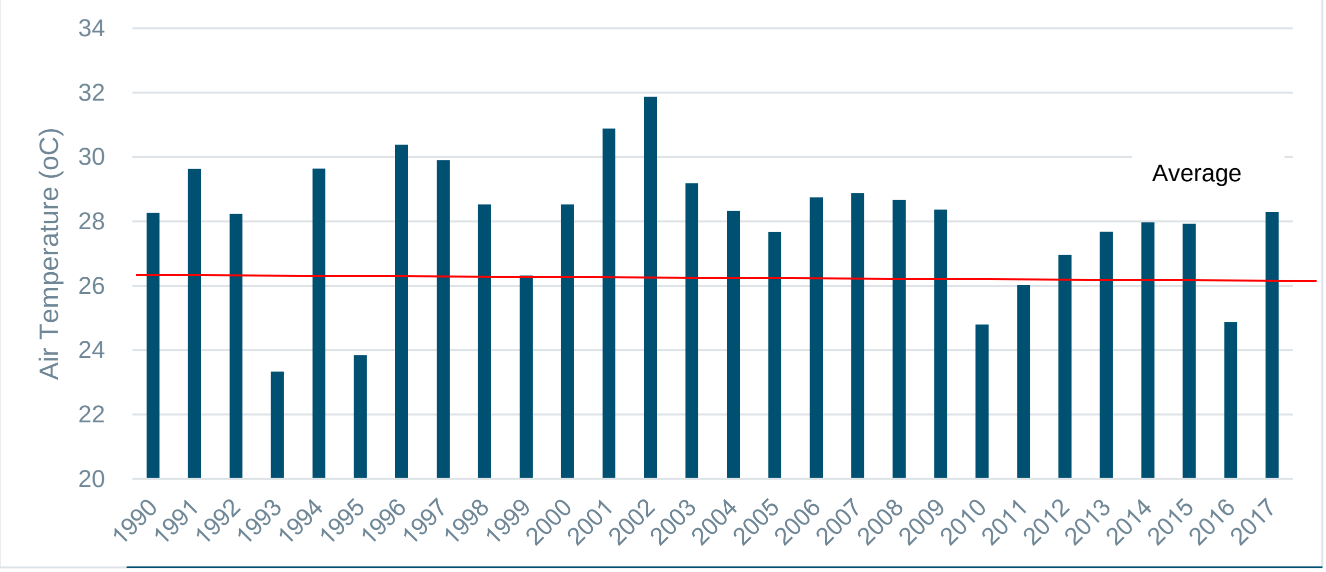

Figure A2 10. Annual/ Critical DO season - Max 7T. Calgary International airport meteorological station.

Appendix 3.

		Final
12/2/2000	39.80	41.0
12/3/2000	41.20	42.0
4/17/2001	41.90	43.0
4/18/2001	41.70	43.0
4/21/2001	43.90	50.0
4/22/2001	42.60	50.0
4/23/2001	45.00	65.0
4/24/2001	45.30	65.0
4/25/2001	45.20	55.0
4/26/2001	42.60	50.0
4/27/2001	48.80	50.0
4/28/2001	51.00	50.0
4/29/2001	50.80	50.0
9/13/2001	45.30	50.0
9/14/2001	40.80	50.0
9/15/2001	43.80	50.0
9/16/2001	43.90	50.0
9/17/2001	43.90	50.0
9/18/2001	46.00	50.0
9/19/2001	48.10	50.0
9/23/2001	43.80	50.0
9/24/2001	43.90	50.0
9/25/2001	45.40	50.0
9/26/2001	45.30	50.0
9/27/2001	46.00	50.0
9/28/2001	47.10	50.0
9/29/2001	45.30	50.0
9/30/2001	43.00	50.0
10/1/2001	43.10	50.0
10/2/2001	38.70	50.0
10/3/2001	37.20	50.0
10/4/2001	36.90	50.0
10/5/2001	35.80	50.0
10/6/2001	35.30	50.0
10/7/2001	35.40	50.0
10/8/2001	35.30	50.0
10/9/2001	35.10	50.0
10/10/2001	34.20	50.0
10/11/2001	33.80	50.0
10/12/2001	34.00	50.0
10/13/2001	33.80	50.0
10/14/2001	34.10	50.0
10/15/2001	33.90	50.0
10/16/2001	34.00	50.0
10/17/2001	32.80	50.0
10/18/2001	32.10	50.0
10/19/2001	32.10	50.0
10/20/2001	32.10	50.0
10/21/2001	31.30	50.0
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11/2/2001	31.10	50.0
11/3/2001	31.00	50.0
11/4/2001	31.10	50.0
11/5/2001	31.10	50.0
11/6/2001	31.00	50.0
11/7/2001	31.30	50.0
11/8/2001	31.30	50.0
11/9/2001	31.10	50.0
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11/28/2001	38.30	50.0
11/29/2001	38.30	50.0
11/30/2001	38.30	50.0
12/1/2001	38.30	50.0
12/2/2001	38.20	50.0
12/3/2001	38.30	50.0
12/4/2001	38.20	50.0
12/5/2001	38.20	50.0
12/6/2001	38.30	50.0
12/7/2001	38.30	50.0
12/8/2001	38.30	50.0
12/9/2001	38.20	50.0
12/10/2001	38.30	50.0
12/11/2001	38.30	50.0
12/12/2001	38.20	50.0
12/13/2001	38.30	50.0
12/14/2001	39.70	50.0
12/15/2001	39.80	50.0
12/16/2001	39.60	50.0
12/17/2001	39.50	50.0
12/18/2001	39.70	50.0
12/19/2001	39.60	50.0
12/20/2001	39.60	50.0
2/21/2001	39.60	50.0
12/22/2001	39.60	50.0
12/23/2001	39.60	50.0
12/24/2001	39.20	50.0
12/25/2001	38.10	50.0
12/26/2001	39.60	50.0
12/27/2001	39.60	50.0
12/28/2001	39.70	50.0
12/29/2001	39.60	50.0
12/30/2001	39.70	50.0
12/31/2001	39.60	50.0