APPENDIX G – METHOD USED TO MODEL WATER RECLAMATION FACILITY DISCHARGE IN THE EAST GALLATIN RIVER

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

G1.0 INTRODUCTION TO THE MODELING

A simple steady-state one-dimensional analytical model of the East Gallatin River was developed to evaluate the influence of the Bozeman Water Reclamation Facility (WRF) on nutrient concentrations within the East Gallatin River. The objective of this exercise was to assist in the determination of wasteload and nonpoint source allocations and to provide an estimate of the relative contributions of nitrogen and phosphorus loads at various compliance points in the watershed. Given the available data for the system, we did not have sufficient information about river biology, mass transfer functions, or other state-variables to implement a sophisticated mass-balance modeling approach. Rather we took a simple approach using data from synoptic surveys in August 2005 and September 2009. While parsimonious, it still is grounded in the principles of mass balance as described in the following pages.

G2.0 APPROACH

In its simplest form, the East Gallatin River (wastewater discharge plus upstream water) can be conceptualized as an idealized plug flow reactor flowing downstream of the Bozeman WRF (**Figure G-1**). For simplicity we consider only a single reaction (both biotic and abiotic removal), ignore residence time (exit-age) distributions, and also assume that the parcel of mixed wastewater moving downstream is uninfluenced by other loadings in the channel. Conceptually, it is assumed that interaction between the mixed wastewater (immediately after the point of discharge) and the rest of the downstream watershed is minimal (this is justified later). We also assume a fixed percentage of the mixed wastewater includes a natural background concentration of available nutrients which is roughly 26.7% for nitrogen and 2.9% for phosphorus[1]. Finally, it is assumed that instream concentrations (observed) below the WRF are the combined effect of net assimilation of point and nonpoint sources of pollution. Provided these simplifications are employed, a spatial understanding about system fate and transport in the East Gallatin River (on a concentration basis) can be made. Likewise, assimilated load contributions of point and nonpoint sources can be estimated according to modeled wastewater uptake and ambient water quality monitoring data.

While the approach detailed above is instructive, it does hinge on several key assumptions. First, the theoretical decay/treatment of wastewater must be known. In subsequent paragraphs we describe a method for estimation of the site-specific response that includes the use of chloride (Cl^-) as a hydrologic tracer thereby integrating the effects of both dilution and nutrient uptake. In addition, we assume that downstream effects, whether dilution- or load-based, have no influence on the overall treatment efficacy[2] of the reactor. We have no way to verify this assumption, but do show that groundwater and tributary influences on concentration are not significantly important (short of one spatial location). Finally, we assume that the reaction rate (for pollutant removal) is spatially invariant. Shifts in turbidity, heterotrophic influences, or other effects are therefore assumed not to occur.

[1] The natural background load (upstream of the WRF) was calculated to be 20.9% and 26.7% of the mixed wastewater contribution for total nitrogen and nitrate, and 2.9% for total phosphorus, respectively (based on up-downstream water quality data).

[2] It is well known that first-order reactions in plug flow reactors remove mass proportional to the concentration. Therefore at higher concentrations, greater treatment occurs. Consequently if significant changes occur downstream from the initial mixing point (altering concentration beyond what is accounted for by uptake) treatment will be influenced.

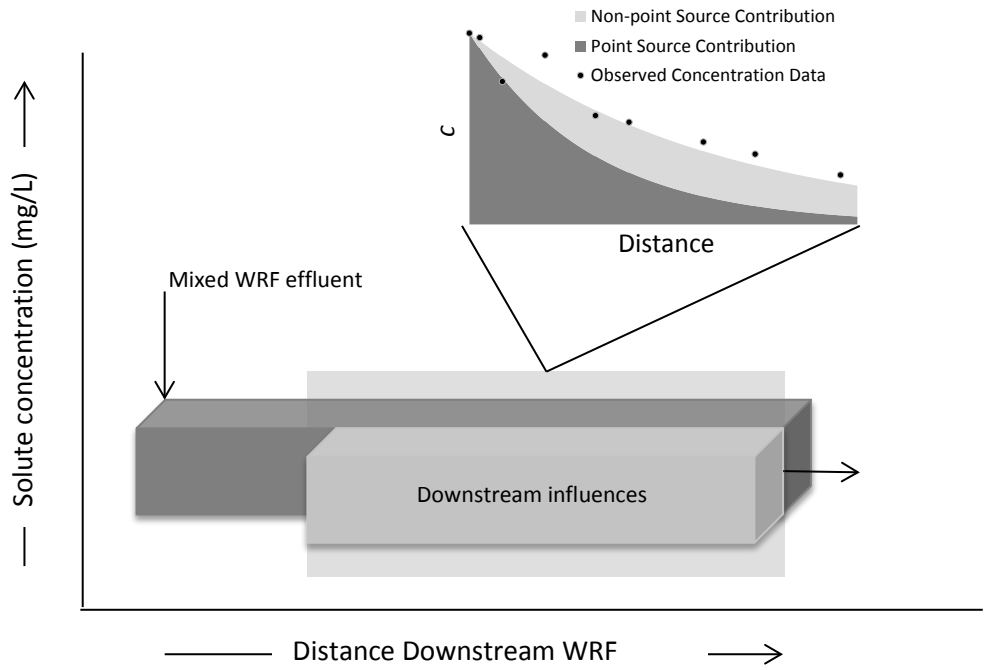

Figure G-1. Conceptual model of plug-flow used to evaluate nutrients in the East Gallatin River.
In this instance the mixed WRF effluent does not interact with downstream influences (short of initial mixing). Thus the relative concentration contribution (*c*) at any downstream distance can be identified as the sum of the assimilated wastewater contribution and the assimilated nonpoint source characteristics in the channel network.

In the case of the East Gallatin River, two things enable the simplifications identified previously to be made. First, the concentrations of incoming tributaries are reasonably high for nutrients (**Table G-1**). For example, concentrations were TN=1.15 mg/L, NO_3^-=0.78 mg/L, and TP=0.033 mg/L (all flow-weighted), which are quite high for the Rocky Mountains. Likewise, NO_3^- was a large part of the total nutrient measurement (i.e., 85% ±8% SD) which is indicative of nonpoint source pollution. Groundwater concentrations for NO_3^- are on the same order of magnitude too (Kendy, 2001) (ranging from <0.05 to 1-2 mgN/L groundwater). Thus inflows to the river are the same order of magnitude as the concentration in the river. Diluting or additive effects will likely not greatly influence the rate or instream treatment.

Table G-1. Concentrations of influent tributaries during September 2009 synoptic survey.

Tributary (STORET ID)	River Station (mi)[a]	Flow (ft^3/s)	TN (mg/L)	NO_3^- (mg/L)	TP (mg/L)	TSS (mg/L)
Churn Creek (ET03)	0.92	3.72	0.47	0.19	0.024	15
Hyalite Creek[b] (HY01)	7.97	27.87	1.91	0.19	0.090	19
Thompson Creek (TH01-M05TMPSC01)	14.08	14.88	1.12	1.07	0.013	---
Ben Hart Creek (BH01)	18.59	25.32	1.11	1.09	0.011	8
Smith Creek (SM01)	21.08	52.91	1.12	1.00	0.031	8
Story Creek (ST01)	22.71	11.3	0.82	0.80	0.011	2
Dry Creek (DY01)	23.23	11.03	0.48	0.27	0.021	28
Cowan Creek (ET01)	24.01	6.94	1.05	0.95	0.018	16
Gibson Creek (GB01)	24.27	9.43	0.82	0.69	0.011	2

[a]WRF at station 0. River stationing taken from Gallatin County GIS department waterways shapefile.
[b]This data does not fit with the rest of the NO_3^- to TN ratios in the watershed.

Second, in examination of the longitudinal nutrient concentration profile of the river (**Figure G-2**), it is apparent that TN and NO_3^- and TP concentrations decline throughout the river network in a typical exponential fashion following the addition of wastewater effluent. This effect is much more pronounced following the facility upgrade in fall of 2007 (e.g., spatial dilution of nutrients has become less pronounced), and thus it seems like application of a simple model will have some merit in evaluating nutrient transport processes in the watershed (although for P it appears is if dilution is still a very important process especially in the upper reaches).

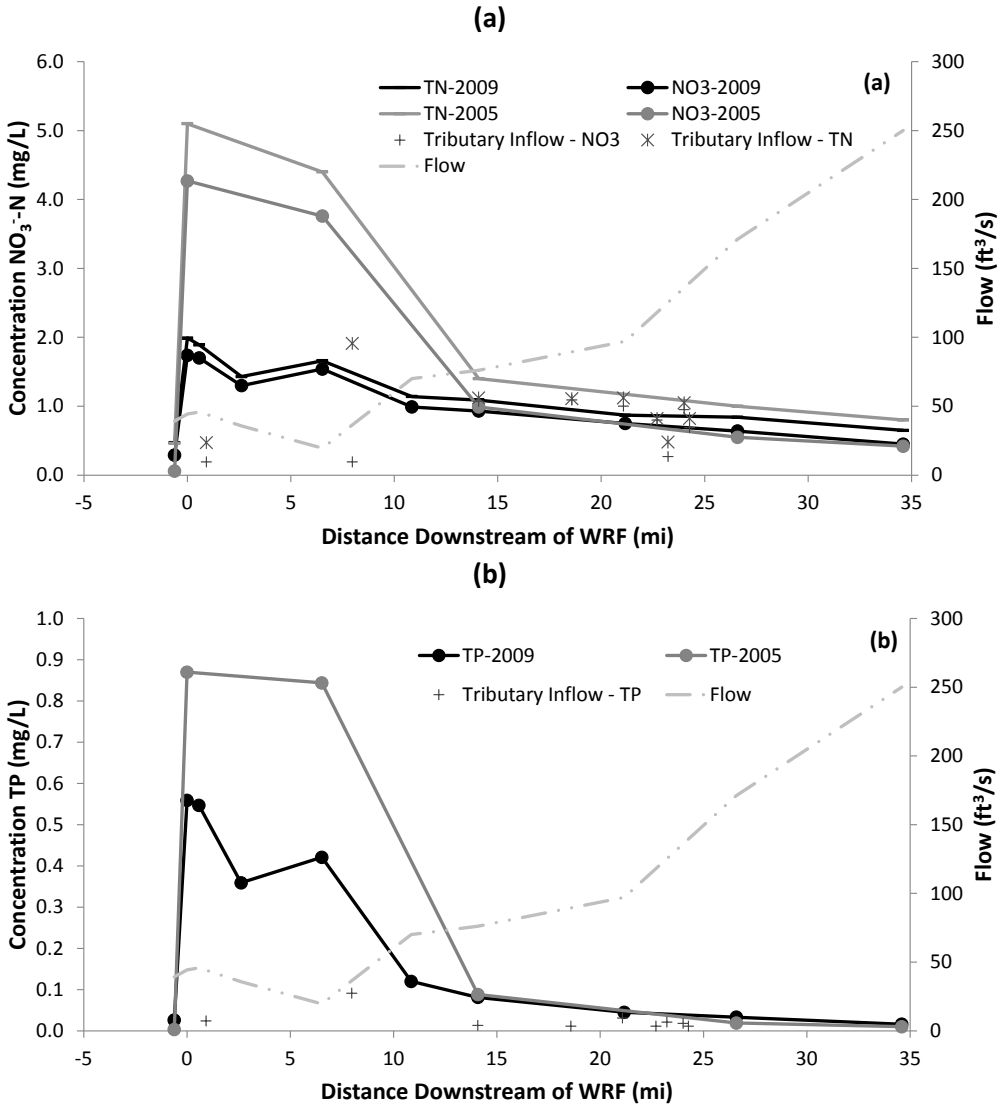

Figure G-2. Plots of nutrient concentration and flow data for the East Gallatin River and tributaries.
(a) Nitrogen species including both TN and NO3- for the August 2005 and September 2009 synoptic surveys. (b) Same but for total phosphorus (TP). It is important to note that the relative concentration of the tributary inflow with respect to mainstem channel concentration determines the relative magnitude of dilution (if any occurs).

Given the previous understanding, two things need be considered with respect to the biotic and abiotic responses in the East Gallatin River prior to make a coherent modeling analysis. These are: (1) dilution or assimilative effects from incoming groundwater or tributary inflows and (2) nutrient uptake. Both are discussed in the following pages.

G3.0 DILUTION AND NUTRIENT UPTAKE ANALYSIS

A synoptic survey of chloride data (Cl^-) from 2005 (STORET query) was analyzed to evaluate the effects of dilution within the river. Cl^- is a conservative natural hydrologic tracer[3] (Covino et al., 2010; Haggard et al., 2001; Marti et al., 2004) and data collected during 2005 are shown in **Figure G-3** (including flow measurements from both 2005 and 2009). Hydrologic conditions were similar both years, with percent deviation less than 5%, and there was significant dilution of Cl^- near Hyalite Creek (mi 7). In addition, dilution occurs in the lower reaches based on flow increases (albeit these are not observed in the Cl^- data as the system has returned to background Cl^- levels).

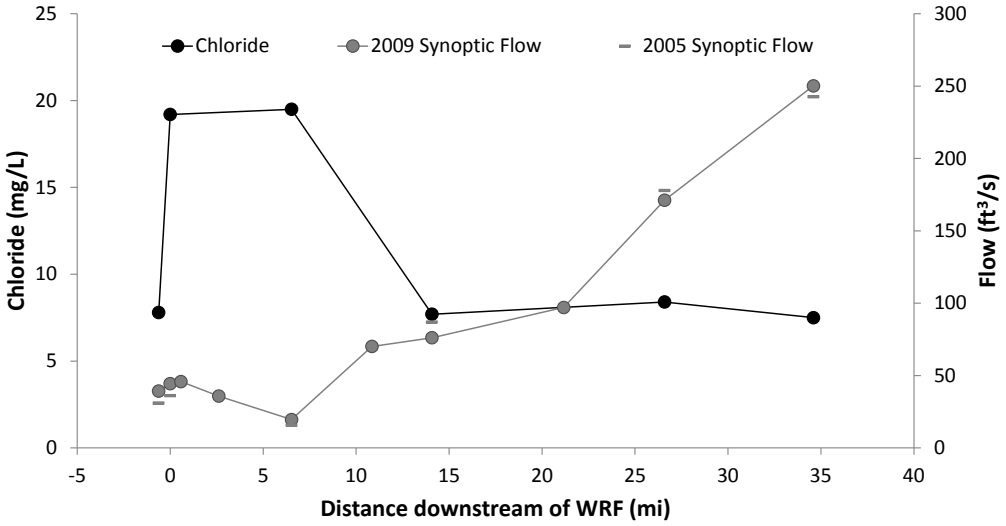

Figure G-3. Longitudinal chloride concentrations and flow measurements in the East Gallatin River. Significant dilution occurs in the vicinity of Hyalite Creek as evidenced by the decline in chloride (Cl-) concentration and in the lower river based on flow increases. According to the flow measurements, it appears as if water transfers (inflows/outflows) are relatively consistent during the late summer period.

While a qualitative understanding of dilution is useful, quantitative methods are necessary to determine the relative effect on the concentration profile. Marti et al., (2004) and Haggard et al., (2006) describe a procedure for longitudinal correction of data in wastewater streams by considering dilution in combination with a simple nutrient decay model. They assume that percent water dilution (*D*) of Cl^- at each sampling site can be calculated as,

$$D = 100 - \left(\frac{Cl_x}{Cl_0} \times 100\right) \quad (1)$$

(1)

where Cl_x=the river chloride concentration (mg/L) at sampling site *x* and Cl_0=concentration of chloride (mg/L) in the mixed wastewater effluent (where it has been mixed with the stream completely). While there is no implication of mass transfer (i.e., the calculation is simply ratio-based and it is inferred that concentration reductions are a result of Cl^- deplete inflows with respect to the surface water

[3]Assuming influent Cl^- concentrations are low relative to the wastewater concentration (which they are).

concentration), the approach does provide a way to estimate instream fate and transport in the absence of more robust data. Computed percentages of dilution (*D),* and associated dilution factors, are shown in **Table G-2**.

Table G-2. East Fork Gallatin River chloride dilution analysis using 2005 data.

Site ID	River Station (mi)[a]	Cl^- (mg/L)	*D* (%)	Cl^- Dilution factor[b]	NO_3^- Dilution factor	TP Dilution factor
M05EGALR05 (Upstream WWTP)	-0.62	7.8	---	---	---	---
M05EGALR06 (Mixed effluent)	0	19.2	0	1.00	1.00	1.00
M05EGALR07 (Spain bridge)	6.52	19.5	-1.6	1.02	1.02	1.02
M05EGALR08 (Dry Creek Rd)	14.08	7.7	59.9	0.40	1.01	0.40
M05EGALR09 (Spaulding bridge)	26.59	8.4	56.3	0.44	1.82	2.63
M05EGALR10 (above confluence w/ Gallatin)	34.59	7.5	60.9	0.39	2.38	5.00

[a] WRF at station 0.
[b] Dilution factor calculated as 1-*D*/100.

Percent dilutions in **Table G-2** range from 0[4] to 60.9% for Cl^-, but concentrations are very near background in the lower river hence the apparent influence of nutrient dilution may be underestimated. In addition, the dilution factor is contingent on the concentration of the river being greater than background. However for both NO_3^- and TP influent, they are above the river concentrations at several locations (referring back to **Figure G-2**). Thus a secondary correction was also made in the dilution factor where nutrient inflows actually add to the instream concentration. We used the relative ratio between influent nutrient concentration (N_i) and instream concentration (N_x) to make this correction (i.e., N_i/N_x) where N_i was conservatively estimated at 1 mg/L for N and 0.05 for P[5]. In these cases the opposite of dilution occurs.

Finally, we simultaneously solved for net uptake (or wastewater decay coefficient, kc) at all locations along the reach according to the dilution factor using the equation in Marti et al., (2004) with adjustment for nutrient accretion,

$$N_x = N_0 \times \frac{Cl_x^-}{Cl_0^-} \times \frac{N_i}{N_x} \times e^{-\frac{k_c}{U}x} \quad (2)$$

where N_x and N_0 are the concentrations of nutrient (mg/L) at distance *x* downstream from the WWTP (m), N_i=influent nutrient accretion concentration (mg/L), *U*=reach average velocity (m/d), and k_c =first-order wastewater nutrient decay rate (/d). Solution was arrived at numerically using the Frontline Generalized Reduction Gradient (GRG) nonlinear solver in Microsoft Excel™.

Calculated k_c's were 2.29 /d for N and 3.56 /d for P[6], which are shown in **Table G-3** along with various comparisons from the literature. First-order uptake rates from the literature range from about 0-30.3 /d

[4] Calculated negative dilution percentage ignored.
[5] These are based on approximate averages of flow-weighted tributary/groundwater inflows. The calculation was made as: if

for NO_3-N and 0.6-30.3 /d for PO_4-P. Thus our calculated values are near the low end of the range. It is important to note that uptake rates are generally lower for wastewater influenced streams than natural systems (Haggard et al., 2001; 2006). This is because nutrient uptake downstream of wastewater facilities is often saturated which diminishes the capacity for nutrient removal.

Table G-3. Estimated wastewater uptake coefficients and lengths for the East Gallatin River

Location		*Reported*[a] V_f (x 10^{-5} m/s)	Calculated k_c (/d)[b]	Uptake length (S_{net}) (mi)	Source
This Study	NO_3-N PO_4-P[c]	--- ---	2.29 3.56	10.1 6.5	---
Wastewater influenced systems					
Wastewater enriched stream in AR	NO_3-N PO_4-P	---[d] 2.3-7.5	--- 0.6-1.9	--- 4.2-8.3	Haggard et al. (2006)
15 wastewater enriched streams in Spain	NO_3-N PO_4-P	--- ---	--- ---	0.1-19.8 0.1-8.9	Marti et al. (2004))
Wastewater enriched stream, AR	NO_3-N PO_4-P	--- ---	--- ---	1.9-7.5 5.6-19.3	Haggard et al. (2001)
South Elkhorn Creek, KY	PO_4-P	---	---	12.1	Birge et al. (1989)[e]
Otter Creek, FL	PO_4-P	---	---	2.1-6.9	Reddy et al. (1996)[e]
River Wey, England	NO_3-N PO_4-P	--- ---	--- ---	0-10.9 4.6-9.4	House and Dennison (1998)[e]
Sand/Caddo Creeks, OK	PO_4-P	---	---	28.4-31.6	Wesolowski (1999)[e]
Un-impacted streams/rivers					
West Fork Gallatin River	NO_3-N	1.0-4.3	2.5-10.8	1.4-2.2	Covino et al. (2010)
Pioneer/Cliff Creek, ID	NO_3-N PO_4-P	2.3-8.2 11.3-12.1	5.8-20.5 28.3-30.3	0.3-1.1 0.2	Davis and Minshall (1999)
11 Streams in Grand Teton National Park	NO_3-N	0-15	0-37.5	---	Hall and Tank (2003)
Published studies on 4th order streams/rivers	NO_3-N PO_4-P	0.3-7.8 1.8-9.7	0.8-19.6 4.6-24.2	0.1-3.0	Ensign and Doyle (2006)

[a] Uptake rate was calculated on the basis of uptake velocity (V_f) which is the preferred metric of benthic nutrient uptake independent of concentration and hydrologic characteristics of the stream (2006).
[b] Assuming depth of 1.13 ft (0.35 m) from 2009 survey of Gallatin River.
[c] TP assumed to be a surrogate for PO_4-P
[d] Significant conversion of ammonia to NO_3 occurring (no net uptake of nitrate)
[e] Cited by Haggard et al., (2006)

Net nutrient uptake lengths were also examined (**Table G-3**). Uptake length (km) is the distance typically traveled in dissolved form before uptake (Stream Solute Workshop, 1990) which is a direct measure of retention efficiency (Haggard et al., 2001; 2006; Marti et al., 2004). It can be computed as,

$$S_{net} = \frac{1}{k_c/U} \div 1000 \quad (3)$$

where S_{net}=net uptake length. In the East Gallatin River, calculated uptake lengths were 10.1 and 6.5 mi, respectively for TN and TP, meaning phosphorus assimilates more quickly than nitrogen. Values are very

similar to those reported for other wastewater enriched streams[7] (Haggard et al., 2001; Gücker et al., 2006; Haggard et al., 2006; Marti et al., 2004).

Finally, in a quasi-validation of our approach, we extended the same methodology to the data from 2009. It was assumed that dilution factors during each period were identical (no Cl^- data were available during 2009), and model fits for both the calibration (2005) and corroboration (2009) are shown in **Figure G-4**. Generally, these show reasonable agreement (r^2>0.73) and therefore some validity exists in our results. However, deviation from the 1:1 line does result with both NO_3^- and TP, thus some caution should be exercised in application of the model.

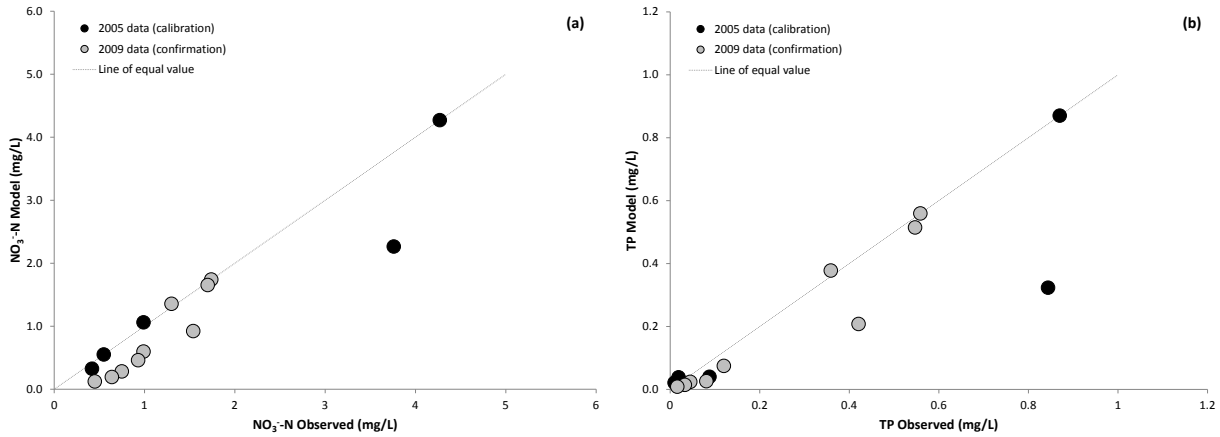

Figure G-4. Comparisons of the Marti et al., (2004) model with that of the synoptic measured data. The relative wastewater uptake rate (k_c) for the East Gallatin River was determined in combination with the effect of dilution. Results are shown for both (a) NO_3^- and (b) TP (note: TP was used as a surrogate for soluble P).

G4.0 JUSTIFICATION FOR MODEL

The exponential decay model described previously (last term in **Eq. 2**) warrants discussion as it provides the basis for pollutant source contributions in the watershed. While we have already defined the relative contributions of point and nonpoint source contributions unknowingly, further insight is gained using a more conventional application. Plug flow[8] (as assumed in **Eq. 2**) occurs when advective flux moves pollutants downstream (i.e., ignoring dispersion) such that a mass balance can be achieved by the following ordinary differential equation at steady-state with first-order uptake (Chapra, 2008),

$$0 = -U\frac{dc}{dx} - k_c c \qquad (4)$$

where U=velocity (m/d), c=pollutant concentration (mg/L or g/m^3), and k_c=first-order uptake rate coefficient or decay constant (/d) defined previously.

[7] Uptake length is significantly longer in a wastewater influenced stream than a natural system and uptake studies on unimpacted waterbodies may not be applicable to point source influenced streams (Marti et al., 2004; Haggard et al., 2006).

[8] The use of a plug flow is valid as Péclet number (Pe) (i.e., ratio of advection to dispersion) is large (>>10) meaning dispersion can be omitted from the analysis. The actual dispersion coefficient of the river was not known and we estimated this value using empirical methods (Fischer et al., 1979).

By separation of variables in **Eq. 4**, and integrating, the common result occurs (Chapra, 2008),

$$c_{(w+b,x)} = c_0 e^{-\frac{k_c}{U}x} \quad (5)$$

where, $c_{(w+b,x)}$=the concentration of the decayed wastewater plus the natural background concentration (this has been substituted for c in **Eq. 4**), c_0=the initial concentration of mixed effluent at the point source (mg/L) and x=distance downstream of this location (m). In this instance, the uptake rate[9] (k_c) reflects the net effect of various nutrient removal mechanisms including biological and abiotic uptake, settling, etc., and does not consider benthic accumulation or release (Stream Solute Workshop, 1990). The concept is valid for both NO_3^- and TP[10].

It is also important to note that the wastewater decay rate (which when separated from the rest of the downstream channel influences) allows determination of the theoretical decay curve of the wastewater. Hence the difference between the computed wastewater decay and the actual observed instream water quality data becomes the assimilated contribution of nonpoint sources in the East Gallatin River. This is illustrated on a concentration basis in **Figure G-5a** and **Figure G-5b** but could be translated to loads provided flows in the river are known. Interestingly, the initial slope of the decay in the water quality data in the wastewater zone[11] very closely fits the estimated curve.

Calculation of the percent contribution of each source at each spatial location (x) is arrived at by,

$$c_{np,x} = c_{obs,x} - r_{nb} c_{(w+b,x)} - r_w c_{(w+b,x)} \quad (6)$$

where $c_{np,x}$=the nonpoint source concentration contribution at station x, $c_{obs,x}$=the observed concentration (smoothed) at station x, r_{nb}= the ratio of background load to wastewater load at the point of wastewater mixing, and r_w= the ratio of wastewater load to background load (note: r_{nb}=1- r_w). It is assumed that the ratio between background concentration and wastewater is the same throughout the reach (i.e., there is no preference for a wastewater NO_3^- molecule as opposed to a background molecule). We have illustrated this analysis for 2009 data in **Figure G-5c and Figure G-5d**.

What is most interesting is that the relative difference between the estimated nonpoint source contributions for N and P is very different. For example, the river appears to be much more influenced by wastewater TP than NO_3-N (**Figure G-5c** and **Figure G-5d**). This is counterintuitive, as uptake preference exists for soluble P. Such a result suggests two things. First, the apparent decline in NO_3^- contribution from the WWTP is not a function of enhanced nutrient uptake at all, but rather increased nonpoint source contributions in the lower watershed[12]. Second, an emphasis on treatment of P at the wastewater facility may be of greatest water quality benefit until nonpoint N sources are adequately

[9] Uptake (k_c) is presented on volumetric basis although it can also be used interchangeably as a mass transfer coefficient (length/time) provided flow depth (h) is known.
[10] It should be noted that TP was used as a surrogate for available phosphorus given the large percentage of wastewater contribution (~13%), and high soluble nutrient concentrations from the facility.
[11] We define this as the first 10,000 meters below the plant prior to any major tributary/groundwater exchanges.
[12] The magnitude of NO_3^- sources in the watershed seems to be large during the low-flow summer period based on the concentration and magnitude of tributaries and groundwater inflow. This does not suggest that at a later time, algae do not senesce or slough, or the wastewater fraction is reconstituted at some other time in the watershed.

controlled in the lower watershed (or as trading strategies are formulated accordingly)[13]. Finally, regardless of the downstream impacts, the point source input to the East Gallatin River without doubt diminishes the ability of the stream to withstand other anthropogenic input (see Haggard et al., (2001) to confirm this this auspice). Watershed-wide collaboration to reduce nutrients from both point and nonpoint sources is therefore recommended.

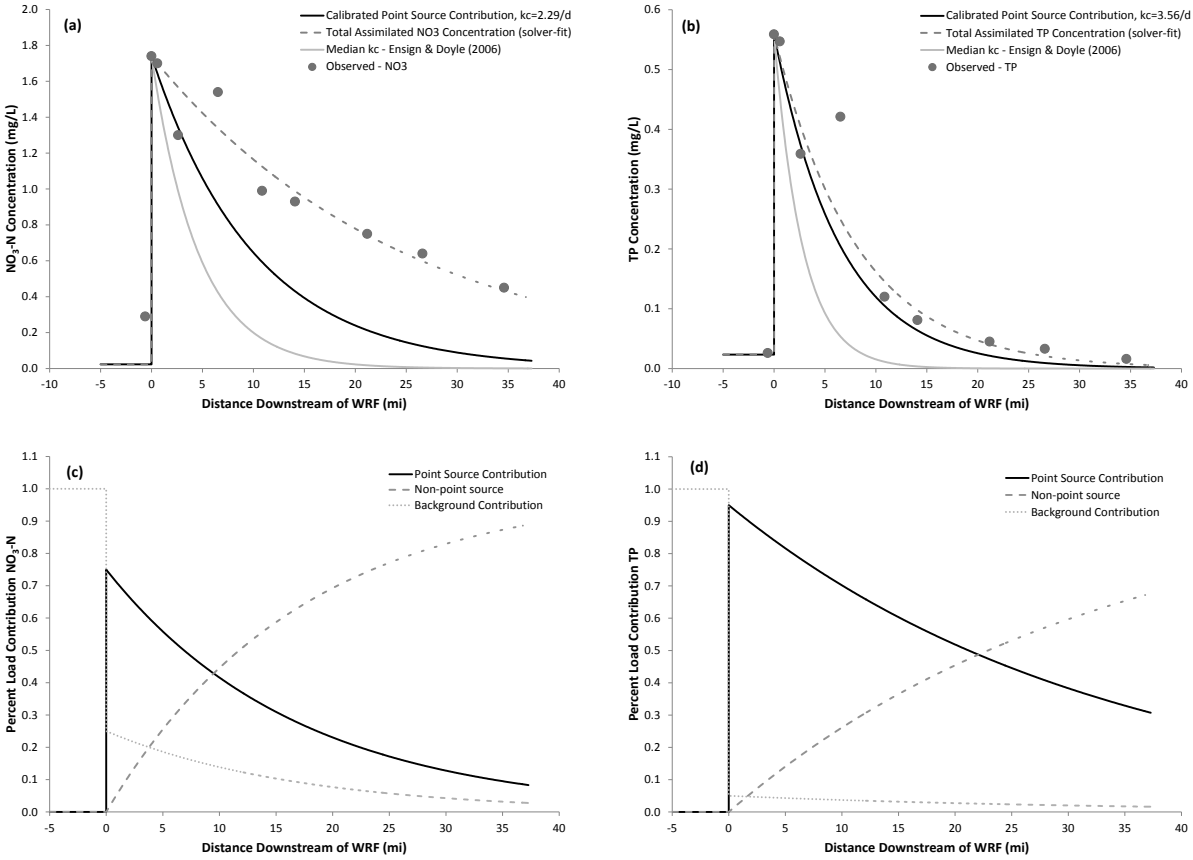

Figure G-5. Illustration of use of a simple plug-flow decay model for East Gallatin River.
(a) Application of the model to NO_3^- concentration data collected during 2009 to identify the relative contributions of point and nonpoint sources in the watershed (b) Same but for TP (surrogate of SRP) for the same year. (c) Estimated source contributions of NO_3^- in the watershed including background, point source, and nonpoint source categories. (d) Same as previous but for TP.

At this point we should pause, and reiterate that the validity of our argument hinges on good knowledge of the decay coefficient of the mixed wastewater (k_c) and other assumptions detailed in previous pages. In addition, we have made one other assumption about mass transport that should be addressed. The whole stream channel velocity (U) was estimated to be a single value throughout the analysis. We know this not to be true, but contend there is little deviation during the summer baseflow period. Velocity observations made by DEQ during 2009 were 1.4 ft/s (±0.4 SD, n=13). High summer flows (3x greater

[13] It is important to note that Hyalite Creek downstream of the WRF is a significant P source to the river and also a significant flow contribution. Therefore it is strongly recommended that more detailed modeling be completed to identify whether P reductions at the WRF will be of any benefit in the lower watershed (short of upstream of Hyalite Creek).

than those observed in 2009) did not have vastly different velocities either (1.9 ft/s, Cleasby and Dodge, (1999). Thus, such an approximation seems reasonably valid.

Finally, we should note the obvious need for better and more inclusive spatial water quality data, and additional water quality modeling. This will undoubtedly reduce uncertainty and better constrain our understanding of the system. As a consequence we recommend more detailed collections of hydrologic and hydraulic information (for mass transport), monitoring of *in situ* water quality parameters (including diurnal DO, pH, etc.), as well as instream water quality state-variables such as nutrients, algal collections, etc. Lastly, a more sophisticated modeling approach would greatly enhance this analysis.

G5.0 MODEL APPLICATION TO LOW-FLOW AND CURRENT EFFLUENT CONDITIONS

The model described previously was developed using flow and concentration data specific to the historical conditions of the East Gallatin River. Significant upgrades to the city of Bozeman WRF have occurred since, however. Therefore evaluation of conditions appropriate to the TMDL is necessary. These low-flow and effluent conditions are described in the following paragraphs.

Flow upstream of the WRF in 2009 (i.e., USGS 06048700 East Gallatin River below Bridger Creek) was 39.2 ft^3/s, which is very close to the long-term monthly average for August and September (i.e., 45 and 42 ft^3/s respectively) (**Figure G-6**). DEQ determined the 14Q5 for this site to be 20.3 ft^3/s over the summer critical period (July 1 – September 30) using DFLOW. However, the period of record is short[14], which limits the validity of our conclusion. Likewise, the city of Bozeman WRF discharge was relocated from downstream of USGS 06048700 to upstream of the gage in December 2009 further complicating low-flow statistical analysis.

The only long-term record of historical conditions is the Gallatin River at Logan, MT (USGS 06052500), which is significantly downstream of the project site and integrates both the East and West Gallatin rivers. However, by studying the long-term record for this site we find that the last decade shows significant annual departure below mean annual streamflow which suggests DEQ's calculated 14Q5 (20.3 ft^3/s) is not representative of a longer-term conditions. Thus our initial estimate is likely an underestimation.

As such, a review of McCarthy (2006) is more informative. While no low-flow frequency statistics have been tabulated for the existing gage on the East Gallatin River (e.g., USGS 06048700[15]), combined statistics for two inactive gages, USGS 06048000 East Gallatin River at Bozeman (which is 0.5 mi upstream from Bridger Creek) and also 06048500 Bridger Creek near Bozeman, are useful. The sum of these waterbodies (and consequently their low-flow statistics) reflects the expected value of critical flow conditions in the river. The 14Q5 for each of those waterbodies is shown in **Table G-4**, which yields a

[14]Only 10 years of data are available for the East Gallatin River gage site (2002-2012).
[15] The current low-flow frequency update for the state omits this site as well (personal communication Pete McCarthy; 1-18-2013).

14Q5 of 33.3 ft^3/s[16] (very similar to 2009), which was the mixing flow used for the final load allocation in the watershed.

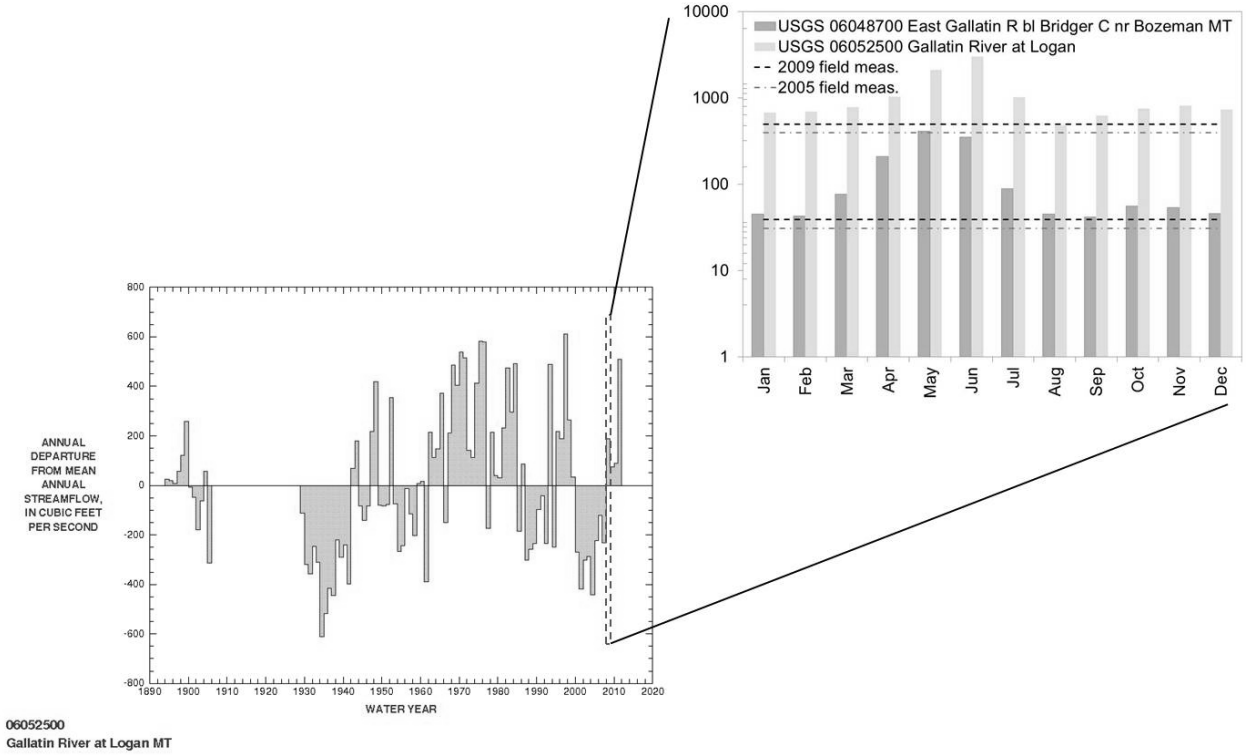

Figure G-6. Streamflow summary for the Gallatin and East Gallatin rivers over their period of record.
A reasonable linear correlation (r^2=0.90) exists between the rivers, thus it was inferred that flow conditions at each gage are similar.

Table G-4. Magnitude and probability of seasonal low flow from July-October (McCarthy, 2006).

Location	Gage ID	14Q5 Flow(ft^3/s)	Seasons of Record
East Gallatin River at Bozeman, MT	06048000	28	22
Bridger Creek near Bozeman, MT	06048500	5.3	24
East Gallatin R bl Bridger C nr Bozeman MT	06048700	33.3^{EST}	---

[EST] Estimated as the sum of the combined flows from 06048000 and 06048500

Ambient water quality information for the TMDL analysis was determined using unpaired instream data collected in the East Gallatin River downstream of the Bridger Creek confluence, and upstream of the WRF discharge location over the last 5 years (STORET query). The mean values of the available data were used to represent ambient water quality in the East Gallatin River. For TN, the mean was 0.406 mg/L (*n*=5). For TP, the mean was 0.022 mg/L (*n*=5). Hence there was very little difference between the means and medians for each site.

Post-upgrade discharge Monitoring Reports (DMRs) for the Bozeman WRF were available only for one year, but historical data span from April 1997 to November 2012. In order to determine the applicability

[16] We feel this to be a better estimation of the design flow due to our concerns with the short period of record used in the DFLOW analysis. Subsequently, conditions used to develop the model in 2009 (39.2 ft^3/s) are quite similar to the 14Q5 and reflect probable critical low-flow conditions for the river.

of using post 2011 upgrade DMR data for the model, long-term trends were examined. The 30-day mean discharge from the facility has remained fairly consistent with peak discharges generally occurring in May and June which correspond to the lowest observed discharge nutrient concentrations (**Figure G-7**). The 30-day mean discharge has been particularly consistent on a seasonal basis for the last 6 years. Over this period, the average July-1-September 30 discharge equals 8.34 ft^3/s.

While discharge has remained consistent, the results of facility upgrades in 2007 and 2011 have been met with declines in the 30-day means for TN, NO_3+ NO_2, and TP (**Figures G-8, G-9 and G-10**). Nutrient concentrations have decreased with each subsequent upgrade. However, there is only a single summer season of DMR data available since the October 2011 upgrade. It is also recognized that the facility is currently operating better than expected therefore summer nutrient concentrations may rise in the future as more systems and components of the facility come on line[17].

The dataset post-2011 upgrade was therefore determined to be too small and not representative of long-term operating conditions at the facility. Alternatively, the design performance specifications for the most recent upgrade will be used to simulate discharge concentrations from the WRF to the East Gallatin River. The facility has a design performance effluent of 7.5 mg/L TN and 1.0 mg/L TP, and we used those values in our analysis (**Table G-5**).

Table G-5. Parameters used to determine initial model conditions post-2011 WRF upgrade

Source	Flow (ft^3/s)	TN (mg/L)	TP (mg/L)
City of Bozeman WRF	8.34	7.5	1.0
East Gallatin River	33.3	0.406	0.022
c_o	---	1.83	0.218

To calculate the initial concentration (c_0) for the existing condition analysis, the mixing equation below was used,

$$c_0 = \frac{c_{egal} \cdot Q_{egal} + c_{wrf} \cdot Q_{wrf}}{Q_{egal} + Q_{wrf}} \quad (7)$$

where c_0 = mixed concentration in the East Gallatin River below the WRF discharge; c_{egal}= July 1 – September 30 mean nutrient concentration in the East Gallatin River above the WRF discharge; Q_{egal}= 14Q5 of the East Gallatin River upstream of the WRF discharge; c_{wrf} = facility design performance nutrient treatment concentration of WRF effluent post-2011 upgrade; Q_{wrf}= July 1 – September 30 mean discharge from 2007-2012. From **Table G-5**, initial concentrations immediately downstream of the WRF discharge were calculated to be 1.83 mg/L TN and 0.218 mg/L TP.

[17] Based on communication with facility managers. In particular, the new sludge dewatering system which will return a significant side stream loading of both phosphorus and ammonia which could negatively impact biological nutrient reduction performance.

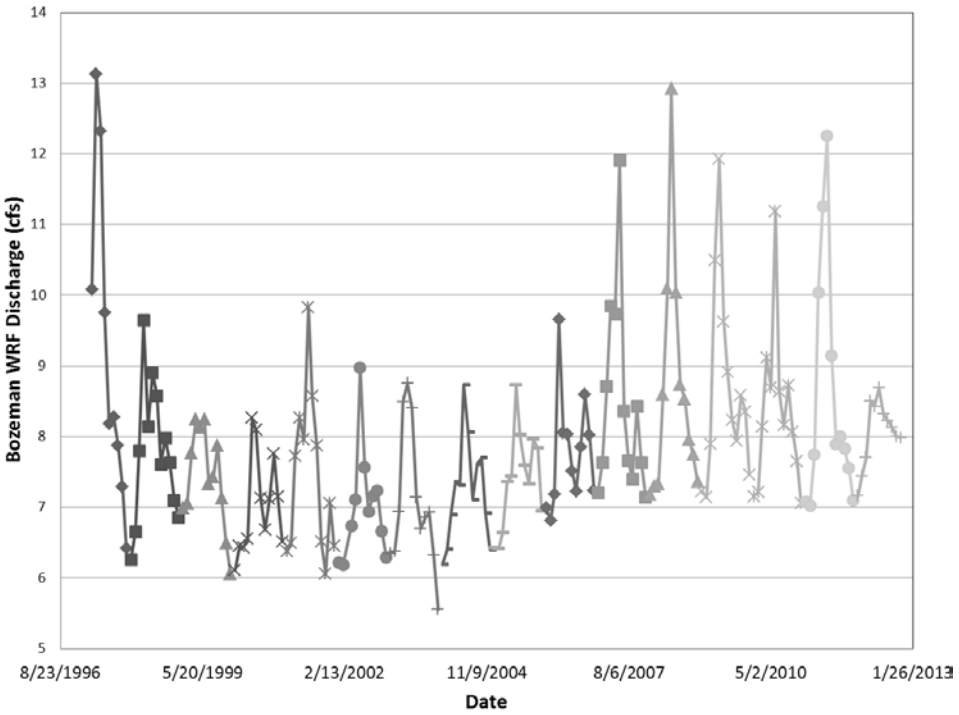

Figure G-7. 30-day average discharge from the city of Bozeman WRF to the East Gallatin River.

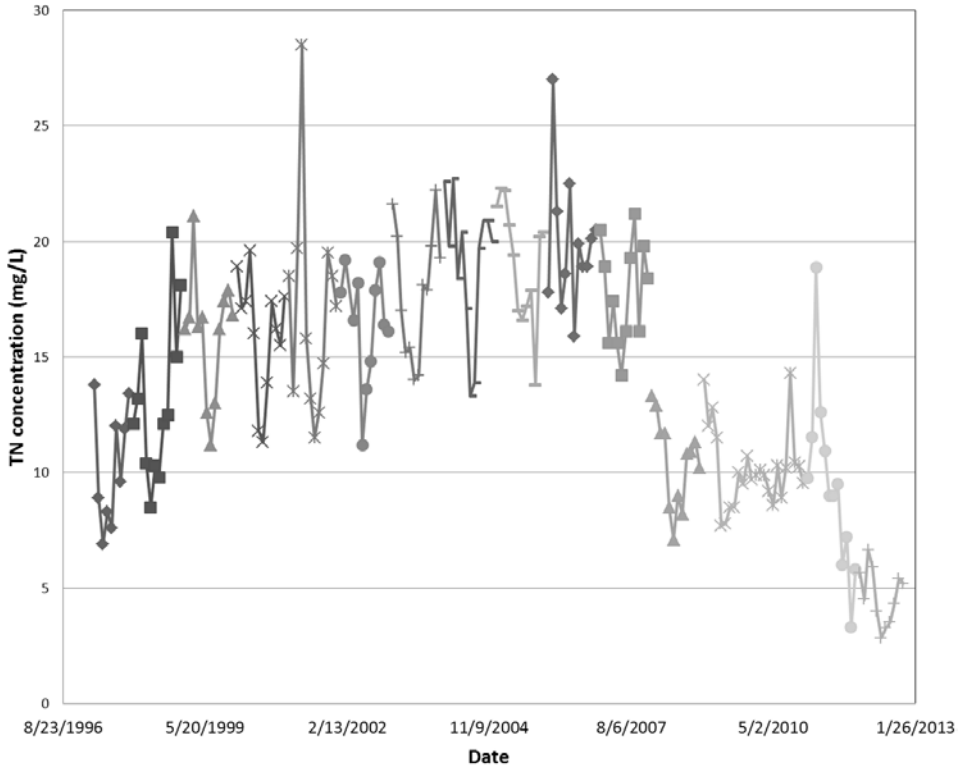

Figure G-8. 30-day average total nitrogen concentration in city of Bozeman WRF effluent.

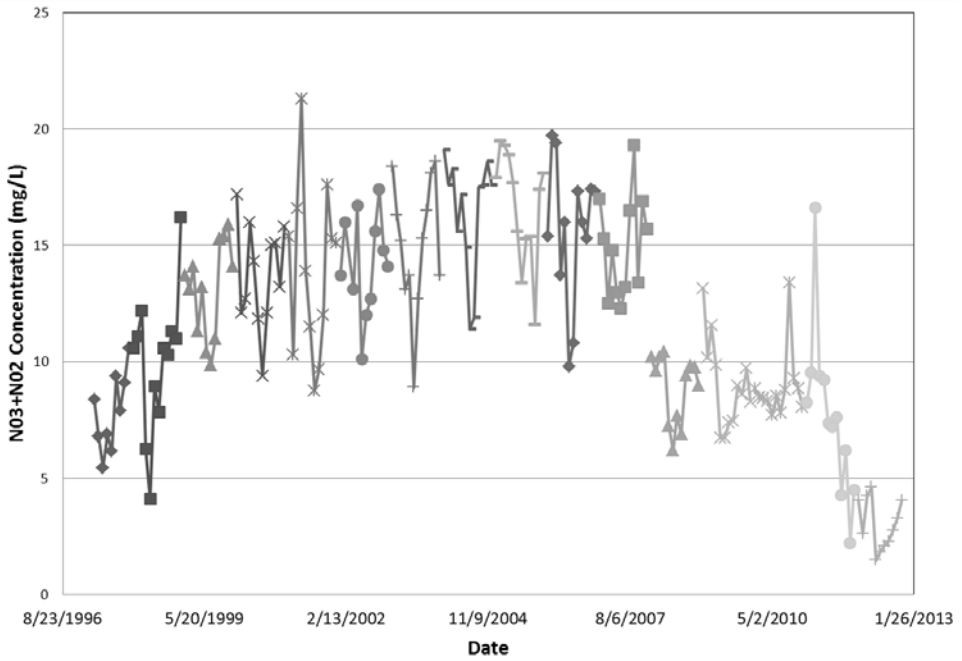

Figure G-9. 30-day average NO_2+NO_3 concentration in city of Bozeman WRF effluent.

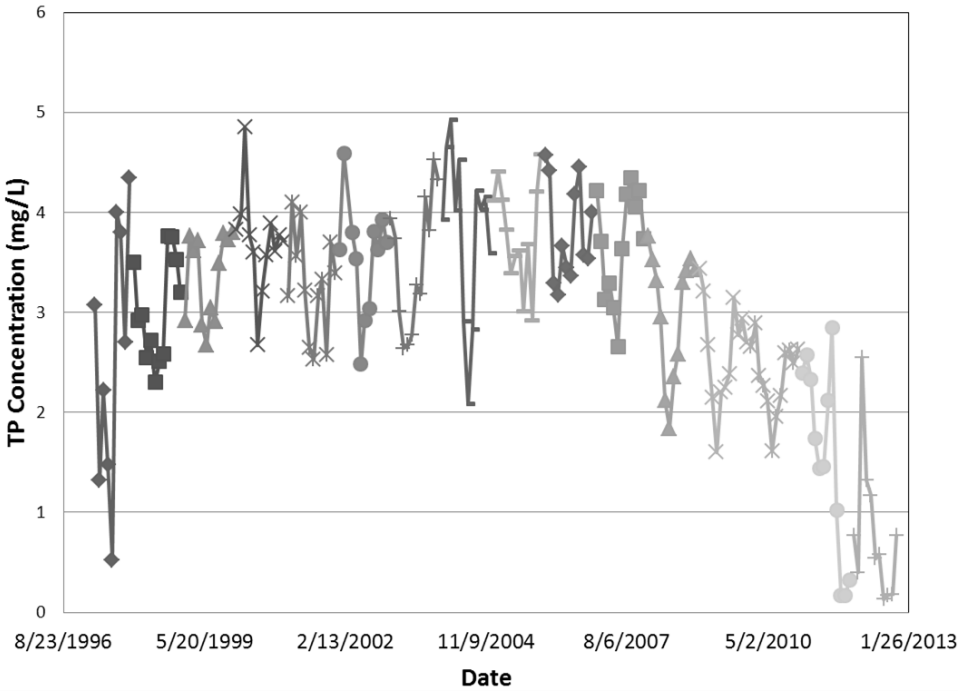

Figure G-10. 30-day average total phosphorus concentration in city of Bozeman WRF effluent.

The model was then used to evaluate TN and TP[18] concentrations and source contributions using the parameters identified in **Table G-5**. These scenarios represent the design performance discharge

[18] While the model is implicitly based on the removal of bioavailable fractions of NO_3^- and SRP, we applied it for TN and TP which is appropriate for wastewater streams where a large percentage of the total nutrient measurement is in a bioavailable form.

concentrations, the July 1 – September 30 WRF mean discharge since 2007, and the 14Q5 for the East Gallatin River downstream of the Bridger Creek confluence (33.3 ft^3/s). Model runs are intended to represent low flow conditions in the East Gallatin River downstream of the WRF discharge and results of the low flow scenario are found in **Figure G-11**.

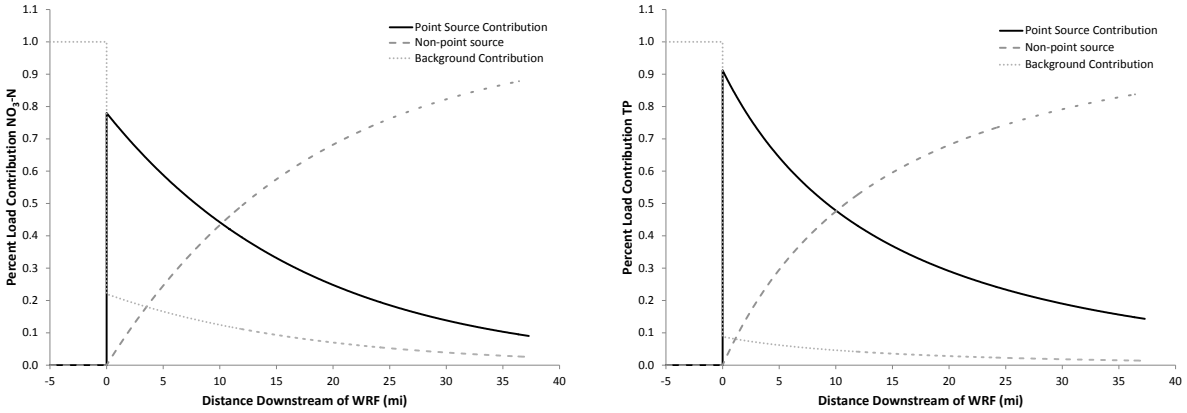

Figure G-11. Low flow analysis of WRF contribution along the East Gallatin River

Immediately below the WRF discharge, the WRF represents 78% of the TN concentration (**Figure G-11**) which decreases to 10% of the observed concentration at the mouth of the East Gallatin River. As stated previously, the apparent decline in nitrogen contribution from the WRF is more a function of increased nonpoint source contributions in the lower watershed rather than enhanced nutrient uptake. Based on the 2009 synoptic sampling data (i.e., a survey that included most of the tributary streams in the lower watershed and associated flow contributions) these sources are believed to be significantly contributing to the N load during the summer period.

Regarding TP, 91% of the instream concentration fraction is from the WRF immediately downstream of the discharge location, which decreases to 15% at the mouth of the East Gallatin River (**Figure G-11**). Hyalite Creek flows into the East Gallatin River approximately 6 miles downstream from the WRF discharge and contributes a large natural TP concentration to the East Gallatin River. Unlike TN, 2009 tributary data for TP in the lower watershed did not exceed water quality targets in all cases. This indicates that the uptake and adsorption are main drivers for decreasing instream TP concentrations in the lower watershed.

A tabulation of contributing percentages for TN and TP at different compliance points of the watershed is shown in **Table G-6** and **Table G-7** respectively.

Table G-6. Relative point and nonpoint source contributions for TN at different compliance points downstream of the WRF discharge

East Gallatin River Segment Description	River Station (mi)[a]	Point Source (%)	Nonpoint Source (%)
Bridger Creek to Hyalite Creek confluence	0.5	75.5	24.5
Hyalite Creek to Smith Creek confluence	10.8	42.1	57.9
Smith Creek confluence to mouth	26.6	16.9	83.1

[a]River station 0 (zero) is the WRF discharge location on the East Gallatin River

Table G-7. Relative point and nonpoint source contributions for TP at different compliance points downstream of the WRF discharge

East Gallatin River Segment Description	River Station (mi)[a]	Point Source (%)	Nonpoint Source (%)
Bridger Creek to Hyalite Creek confluence	0.5	87.3	12.7
Hyalite Creek to Smith Creek confluence	10.8	45.7	54.3
Smith Creek confluence to mouth	26.6	21.9	78.1

[a]River station 0 (zero) is the WRF discharge location on the East Gallatin River

G6.0 LIMITATIONS AND UNCERTAINTY

The analysis completed in the previous pages provides a likely snapshot of the relative contributions of point and nonpoint sources in the watershed. The evaluation is valid only for low-flow conditions when biological activity, and hence nutrient uptake, is similar. We make no reservations about its use for conditions outside those mentioned. Additionally, the methodology was quite simple (perhaps too much so), and relied on scant data, and many assumptions. As such, there is likely a great deal of uncertainty associated with our conclusions.

Most notably, the instream wastewater decay rate is critically important. All results hinge on its relative correctness. We used a peer-reviewed approach to estimate its value, however, in the lower reaches river chloride was near background levels which made interpretation difficult (especially where nutrient inflows were higher than the background concentration). As such a scaling factor was devised to adjust for the increases in concentration, but this basis is not well-found. Likewise, a number of other assumptions regarding critical low-flow conditions and model suitability were made for the TMDL. While the results seemed reliable according to the slope of the modeled wastewater decay profile (and associated literature comparisons for wastewater dominated streams), undoubtedly there is uncertainty in our analysis. We made no attempts to quantitate this uncertainty. As a consequence, further data collection in conjunction with more sophisticated modeling is recommended to improve the results. It is strongly suggested this be done before pollutant trading or other management schemes are considered or implemented in the watershed.

G7.0 LITERATURE CITED

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