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## **An Analytic Water Quality Model of Onion Creek examining Impacts from a Proposed Wastewater Point Source Discharge**

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### **Abstract**

*A simple analytical stream water quality model developed by Chapra et al. (2014) was applied to the potential wastewater effluent discharge to Onion Creek from the City of Dripping Springs. Three flow regimes (no flow, low flow, and high flow) were input into the model under both winter and summer conditions. The model showed that elevated periphyton biomass would persist for at least 6 miles downstream of the discharge assuming no flow on Onion Creek. This length of biomass could increase given normal to high flows on Onion Creek. The amount of periphyton predicted by the model ranged from 75 mg/m<sup>2</sup> at the downstream length of the biomass to 200 mg/m<sup>2</sup> at the discharge point. Under these conditions, the stream could be classified as eutrophic.*

*A sensitivity analysis showed that the conversion rate of chlorophyll a to phosphorus and the periphyton death rate are important parameters in the model and require further investigation. An uncertainty analysis showed that the length of periphyton biomass in the stream could vary greatly. The sensitivity of the parameters could easily extend that uncertainty in periphyton biomass to include the portion of Onion Creek over the Edwards Aquifer Recharge Zone*

### **Introduction**

The City of Dripping Springs is currently in the process of expanding their Wastewater Treatment Plant (WWTP) to serve future growth in the area. Although the current disposal method is by land application, Dripping Springs is proposing to directly discharge approximately 1.0 million gallons per day (0.995 MGD) of effluent from the WWTP into Walnut Springs, a tributary of Onion Creek. The location for this discharge is estimated to be about 18 to 20 miles upstream from the Edwards Aquifer Recharge Zone (Barton Springs Segment). The City of Austin (COA) has an interest in

the water quality of the aquifer and its primary outlet at Barton Springs due to its US Fish and Wildlife Service Endangered Species Act Section 10(a)(1)(B) Incidental Take Permit for the endangered Barton Springs and Austin blind salamander populations. In addition, Austin has purchased or obtained easements on 9,524 acres of Water Quality Protection Lands in the Onion Creek watershed at a cost of \$66,872,315 to protect the integrity of the creek and the aquifer it recharges.

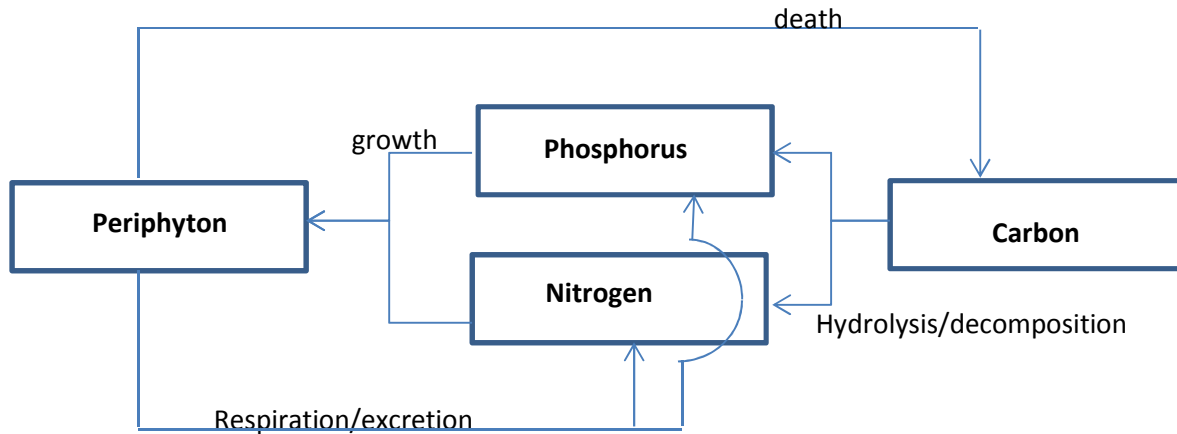
To evaluate the impacts of the WWTP discharge on Onion Creek, City of Austin staff have applied a parsimonious water quality model (Chapra et al., 2014) as well as a more detailed Water Analysis Simulation Program (WASP) model discussed elsewhere (Richter, 2016). This report addresses the parsimonious model as a screening assessment of the creek's response to the WWTP discharge, especially the response of fixed algae (periphyton) to the nutrients in the proposed discharge.

First, the parsimonious analytic model used to quantify nutrient concentrations and periphyton coverage in the flowing stream resulting from a wastewater discharge is described and governing equations provided. Then, site-specific inputs, along with some default values, are used as input in the model to examine the impacts of this direct discharge to Onion Creek. A sensitivity analysis and an uncertainty analysis was also performed, facilitated by the parsimony of the analytic model to determine the influence of default parameters. Further, based on these results, recommendations were made on techniques for establishing limits on the amount and nature of effluent discharge, as well as limiting conditions under which discharge is potentially acceptable. As a caution, this model and its results do not provide the more detailed continuous simulation over time of the stream's response that a dynamic model supplies, but merely provides a quick steady state estimate of the nutrient impacts on the receiving stream from effluent discharge and a method to test potential actions to mitigate the impacts. A more rigorous modeling project including data collection for calibration has also been completed using a widely applied used public domain numerical model, WASP (Richter 2016).

## **Background/Theory**

To develop an initial understanding of the impact of wastewater discharge to a flowing creek, the following conceptual model was developed by Chapra et al. (2014). The available phosphorus and nitrogen discharged from the wastewater treatment plant are consumed by periphyton for its growth. The periphyton will then respire and excrete back some of the phosphorus and nitrogen, while the death of periphyton will contribute to organic matter in the form of carbon. Through hydrolysis and decomposition, the carbon will then revert back to phosphorus and nitrogen, which provides fuel for additional periphyton growth.

**Figure 1: Chapra's Conceptual Model**



This recycling of nutrients can be quantified through the following coupled differential equations.

$$U \frac{dp}{dx} = -\frac{r_{pa}}{H} (C_g - k_r a) + r_{pc} k_h c \quad (1)$$

$$U \frac{dn}{dx} = -\frac{r_{na}}{H} (C_g - k_r a) + r_{nc} k_h c \quad (2)$$

$$U \frac{dc}{dx} = \frac{r_{ca} k_d}{H} a - k_h c \quad (3)$$

$$C_g = k_r a + k_d a \quad (4)$$

For this system of equations, the variables are:

$U$  = stream velocity, m/s

$p$  = phosphorus concentration,  $\mu\text{gP/L}$

$n$  = nitrogen concentration,  $\mu\text{gN/L}$

$c$  = carbon concentration,  $\mu\text{gC/L}$

$a$  = periphyton biomass,  $\text{mgA/m}^2$

$r_{pa}$  = stoichiometric coefficient used to convert periphyton to phosphorus,  $\text{mgP/gC}$

$r_{na}$  = stoichiometric coefficient used to convert periphyton to nitrogen,  $\text{mgN/gC}$

$r_{ca}$  = stoichiometric coefficient that converts periphyton to carbon,  $\text{gC/mgA}$

$r_{pc}$  = stoichiometric coefficient that converts carbon to phosphorus,  $\text{mgP/gC}$

$r_{nc}$  = stoichiometric coefficient that converts carbon to nitrogen,  $\text{mgN/gC}$

$k_r$  = respiration and excretion rate of periphyton, 1/day

$k_h$  = hydrolysis rate of carbon, 1/day

$k_d$  = death rate of periphyton, 1/day

$C_g$  = zero-order periphyton growth rate,  $\text{mg}/(\text{m}^2\text{-day})$

$H$  = depth of the stream, m

$x$  = length along the stream, m

Equations (1) through (3) were developed to account for mass either entering or leaving an infinitesimal system,  $dx$ . Specifically, equations (1) and (2) quantify the amount of phosphorus,  $p$ , and nitrogen,  $n$ , being consumed to fuel the periphyton growth rate (the negative term), and the amount being produced by periphyton respiration/excretion and by carbon hydrolysis (the positive terms). From equation (3) the amount of carbon,  $c$ , is produced by periphyton death (the positive term), but is being depleted by carbon hydrolysis (the negative term). Finally, equation (4)

stipulates that the growth rate of periphyton biomass is equal to the sum of the periphyton death rate and the respiration/excretion rate. Periphyton growth rate,  $C_g$ , has been empirically shown to be also dependent on the availability of light and nutrients. As shown from equations 1 and 2, the amount of nutrients is dependent on the periphyton growth rate. Thus, equations 1 and 2 are coupled with equation 4. This system of partial differential equations has been difficult to solve analytically and has typically been computed numerically.

## Methods

Chapra et al. (2014) provided solutions to this model to quantify the concentrations of phosphorus, nitrogen, periphyton biomass, and carbon (i.e. organic matter from the death of periphyton). Past efforts in constructing a simple analytic model neglected the nutrient recycling that occurs as nutrients move downstream (Thomann and Mueller, 1987). This parsimonious model accounts for nutrient recycling by using an approximate analytic solution to the coupled partial differential equations.

The method of quantifying the nutrient and periphyton concentrations along the stream begins with first determining an initial amount of periphyton at the point source,  $a_0$ , (i.e. the wastewater discharge). Chapra et al. (2014) postulated that because the nutrient concentrations are significantly higher than the half-saturation constant (i.e. the concentration of a nutrient supporting an uptake rate of one half the maximum growth rate), then the periphyton biomass is initially influenced solely by light limitations and respiration and death rates. The initial periphyton biomass is computed through

$$a_0 = \frac{C_{g,T} \phi_{LIGHT} \phi_{NUTRIENTS}}{k_r + k_d} \quad (5)$$

These variables are:

$a_0$  = initial periphyton biomass, mg/m<sup>2</sup>

$C_{g,T}$  = zero-order periphyton growth rate under constant temperature, light, and nutrient concentrations, mg/(m<sup>2</sup>-day)

$\phi_{LIGHT}$  = coefficient of light dependency

$\phi_{NUTRIENTS}$  = coefficient of nutrient dependency

$k_r$  = respiration and excretion rate of periphyton, 1/day

$k_d$  = death rate of periphyton, 1/day

Under the assumption that light, and not nutrients, are initially limiting the periphyton growth, then  $\phi_{NUTRIENTS} = 1$  and the nature of the system of equations is decoupled. From this initial value, equations (1) through (3) can be determined along the stream using the following equations.

$$p(x) = p_0 - (r_{pa} \frac{k_d a_0}{k_h H} - r_{pc} c_0) [1 - e^{-\frac{k_h}{U} x}] \quad (6)$$

$$n(x) = n_0 - (r_{na} \frac{k_d a_0}{k_h H} - r_{nc} c_0) [1 - e^{-\frac{k_h}{U} x}] \quad (7)$$

$$c(x) = c_0 e^{-k_h x / U} + (r_{ca} \frac{k_d a_0}{k_h H}) [1 - e^{-\frac{k_h}{U} x}] \quad (8)$$

From these equations, the concentrations of phosphorus, nitrogen, and organic carbon below a point source can be determined by using the parameters above and the specific location,  $x$ , of interest. These equations hold until either  $p(x)$  or  $n(x)$  equals their respective half-saturation constant. At this point, there are insufficient levels of nutrients to provide for continuing periphyton growth, and the nutrient concentrations remain at these levels. The point,  $x$ , at which either  $p(x)$  or  $n(x)$  equals their respective half-saturation growth is called the *critical distance*.

Prior to *critical distance*, the nutrient concentrations would decrease in a linear manner from the initial discharge concentrations. This *critical distance* also gives an approximation of the length of the periphyton biomass. Prior to this point, periphyton biomass is in nutrient rich waters and its growth and biomass can be calculated. Past this *critical distance*, the periphyton has consumed the available nutrients for growth (even after recycling) and the amount of periphyton becomes nutrient limited and proceeds to decrease in a non-linear manner until a steady state of lower periphyton growth rate is reached. This implies that a minimum amount of periphyton biomass will be present in the stream far below the discharge point as long as the wastewater discharge is flowing. The periphyton may again commence its growth with an additional source of nutrients downstream. Chapra et al. (2014) calculates this amount of periphyton far downstream of the *critical distance* to be:

$$a_{\infty} = \frac{k_h H}{k_d r_{pa}} p_0 \quad (9)$$

or

$$a_{\infty} = \frac{k_h H}{k_d r_{na}} n_0 \quad (10)$$

for either phosphorus or nitrogen limiting concentrations, respectively. Simultaneously, the nutrient concentrations will remain constant past the *critical distance* since the amount of periphyton has become limited, and the further consumption of nutrients is not occurring.

In use for impact assessment, the distance the periphyton biomass is above a threshold value for either ecological degradation or nuisance condition can be found. If this distance is unacceptable, further evaluation of more stringent nutrient control measures under seasonal or receiving water flow restrictions can be made.

## Analysis/Results

To start the analysis, the initial periphyton biomass is calculated. This calculation is mostly determined by the light dependency coefficient, which is determined by the time of year, the turbidity of the stream, and the amount of solar radiation, all of which can vary. Thus, two scenarios are performed for light dependency coefficients; a summer scenario and a winter scenario. An initial periphyton biomass was calculated for each scenario.

### Light Dependency

Latitude of Austin, Texas is 30° N, which provides a daily solar radiation of 400 cal/cm<sup>2</sup> in the winter months and 700 cal/cm<sup>2</sup> in the summer. From Chapra et al. (2014), there is a 1.05

conversion factor to the required units of  $\mu\text{E}/(\text{m}^2\text{-sec})$ . Then, to arrive at the maximum photosynthetically available radiation at solar noon,  $\text{PAR}_m$ , the following equation is used:

$$\text{PAR}_m = \left(\frac{\pi}{T_p}\right) \frac{I_{\text{daily}}}{2} \quad (11)$$

These variables are:

$I_{\text{DAILY}}$  = daily solar radiation,  $\mu\text{E}/(\text{m}^2\text{-sec})$

$T_p$  = length of daylight (i.e.  $t_s$ , time of sunset –  $t_r$ , time of sunrise), day

During the summer months, the sun rises between 6:30 am and 7:00 am and sets between 8:00 pm and 8:30 pm, giving between 13 to 14 hours of sunlight every day. Winter months provide between 10 and 11 hours of sunlight every day. Using these ranges and implementing a Monte Carlo simulation on Equation (11),  $\text{PAR}_m$  yields between 1485 and 1775  $\mu\text{E}/\text{m}^2\text{-s}$  in the winter and between 1950 and 2175  $\mu\text{E}/\text{m}^2\text{-s}$  in the summer.

Calculating the coefficient of light dependency,  $\phi_{\text{light}}$ , requires the following integral:

$$\phi_{\text{light}} = \int_0^1 \frac{\text{PAR}_m \sin[\omega(t-t_r)] e^{-k_e H}}{k_{si} + \text{PAR}_m \sin[\omega(t-t_r)] e^{-k_e H}} dt \quad (12)$$

These variables are:

$\omega = \pi/T_p$ , the angular frequency of length of daylight (1/day)

$t$  = time of day

$k_e H$  = the product of the light extinction coefficient and the depth of stream

$k_{si}$  = half-saturation constant for light intensity,  $\mu\text{E}/(\text{m}^2\text{-s})$

To ensure that the integral converges, the term  $\text{PAR}_m \sin[\omega(t-t_r)]$  equals zero for times before sunrise and after sunset, inclusively<sup>1</sup>. The half-saturation constant for light intensity,  $k_{si}$ , was recommended to be 70  $\mu\text{E}/(\text{m}^2\text{-s})$  in Chapra et al (2014). Also in Chapra et al. (2014), the light extinction coefficient-depth term,  $k_e H$ , was varied from 0.01 to 1.5. A value of 0.01 for  $k_e H$  describes a shallow clear creek and is conservative (i.e. it produces more periphyton). This parameter gets less conservative for larger values. The values used for this report ranged from 0.01 to 0.02. A Monte Carlo simulation was run inputting the ranges depicted above ( $\text{PAR}_m$  and  $k_e H$ ) into Equation 12 to produce a range of coefficients of light dependency. The results are fairly precise (95% of the coefficients fall within 0.01 of each other) and indicate a coefficient of light dependency of 0.52 in the summer and 0.40 in the winter.

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<sup>1</sup> The sine function is used to simulate the gradual increase and decrease of light intensity as the day progresses from sunrise to sunset. However, this function causes the value to be negative before sunrise and after sunset. This implies a loss of light intensity, which is nonsensical. Thus, zero is used when the value of the function is negative.

### Initial Periphyton Biomass

Using the range of coefficients of light dependencies as an input, a range of initial periphyton biomass is calculated through equation (5). The default values from Chapra et al. (2014) are depicted in Table 1 below:

**Table 1: Values for Parameter in Initial Periphyton Biomass**

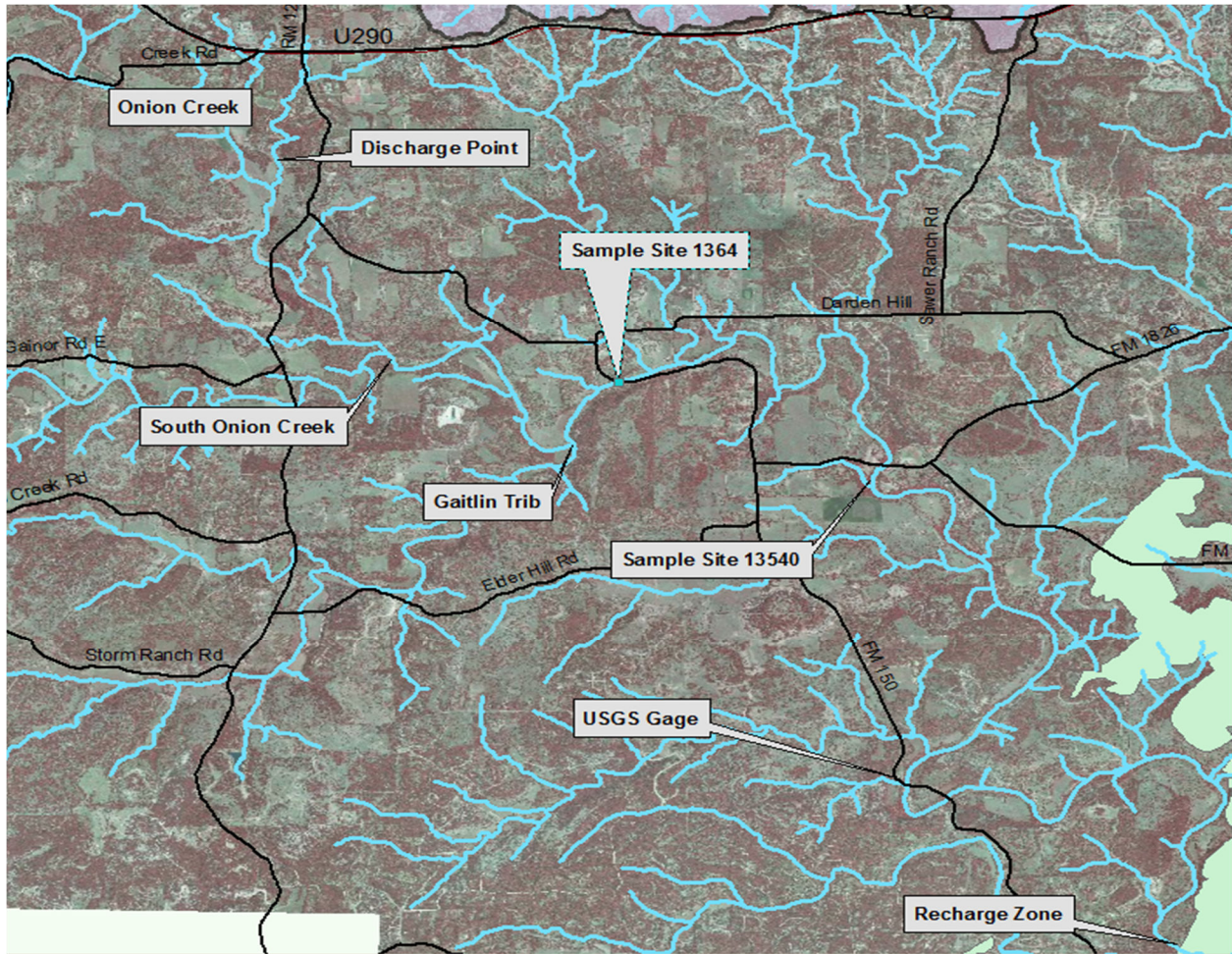
Parameter	Value	Units
$C_{g,T}$	200	mg/(m <sup>2</sup> -day)
$k_r$	0.2	1/day
$k_d$	0.3	1/day

This results in initial values of 207 mg/m<sup>2</sup> of periphyton biomass in the summer and 160 mg/m<sup>2</sup> in the winter.

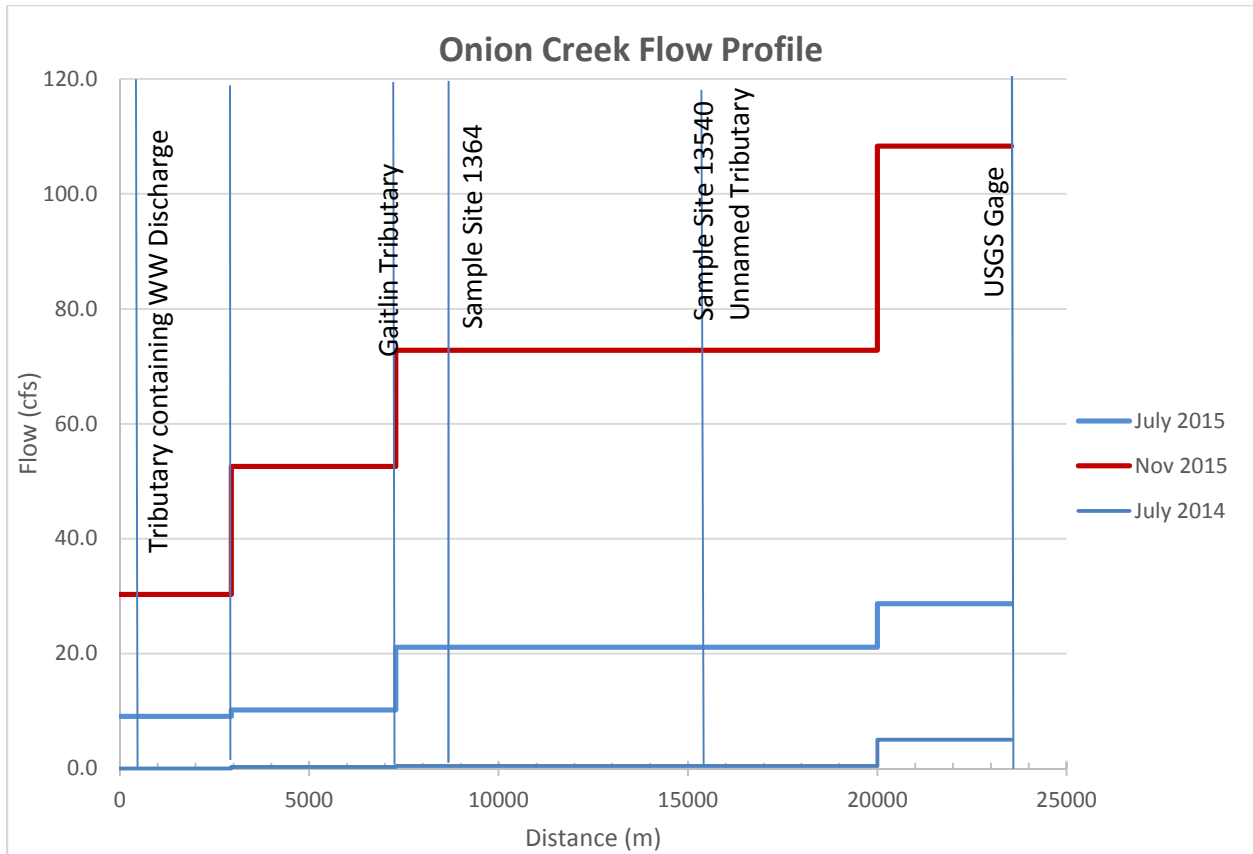
### Physical Topography/Flow Calibration

With an initial periphyton biomass amount, the nutrient concentrations can be calculated at any point downstream of a discharge point using Equations 6 through 8. To make the estimates of nutrient concentrations in accordance with the physical features of the creek, physical information about the creek was collected by the City of Austin and input into the model. The proposed WWTP discharge will be to the Walnut Springs Tributary of Onion Creek northwest of the intersection of Ranch to Market Road 12 and Farm to Market Road 150 (Figure 2).

As flow from the discharge point enters Onion Creek, it heads south and then east to Farm to Ranch Road 12 where it is joined by South Onion Creek and then Gatlin Tributary prior to City of Austin sample site 1364. Further downstream is City of Austin sample site 13540 and then US Geological Survey (USGS) gage #08158700. The stream length from the discharge point to the USGS gage is approximately 15 miles, and a profile of this stream length, including stream flow recorded by the City of Austin, is shown in Figure 3.



**Figure 2: Location of Discharge Point and other Geographic Features**



**Figure 3: Onion Creek Flow Profile**

The flow rates depicted in Figure 3 were recorded by the City of Austin during three sampling events. Flow rates were assumed to be constant between the sampling points for modeling purposes and any increases were attributed to flow from a merging creek or tributary. There is generally an increase in flow in between Sample Site 13540 and the USGS gage possibly due to the influence of two tributaries. At this time, it is unclear how much flow each tributary contributes to Onion Creek. Thus, one increase was approximated at stream length 20,000 meters (12.4 miles).

Flow recorded in July 2014 is practically zero and reflects drought conditions, whereas for August 2015, flow has recovered due to a wetter spring and summer. Flow rates recorded later in the year (November 2015) show measurements from even more rainfall and might approximate high flow conditions. These three flow profiles (July 2014, August 2015, and November 2015) were used to represent low, normal, and high flow conditions, respectively, and the flow characterized in this report as “normal” fits closely with the median flow rate at the USGS gage. In all, six scenarios are presented in the analysis (3 flow conditions each with two light conditions.) For each of these scenarios, the nutrient concentrations and periphyton biomass are calculated along the stream.

To calculate the model parameter stream velocity,  $U$ , in the creek, a rating curve was developed. Using a digital elevation map of the area, several (roughly 40) cross sections were created along the creek from the discharge point to the USGS gage. From these cross-sections, velocity and height were calculated given a flow rate using Manning’s equation. The relationship between

velocity and flow rate and the relationship between height and flow rate at each cross section was calculated and then aggregated into the following power curves.

$$U = 0.74 \cdot Q^{0.25} \quad (13)$$

$$H = 320.15 \cdot Q^{0.00083 \pm 0.0002} - 320.04 \quad (14)$$

For these equations,  $Q$  is the flow rate in cfs,  $U$  is the velocity in ft/sec, and  $H$  is in meters. Note that  $U$  must be converted to m/day in the parsimonious model. These relationships were used to calculate stream height and stream velocity given a flow rate in the parsimonious model.

### Nutrient Concentrations from Model Results

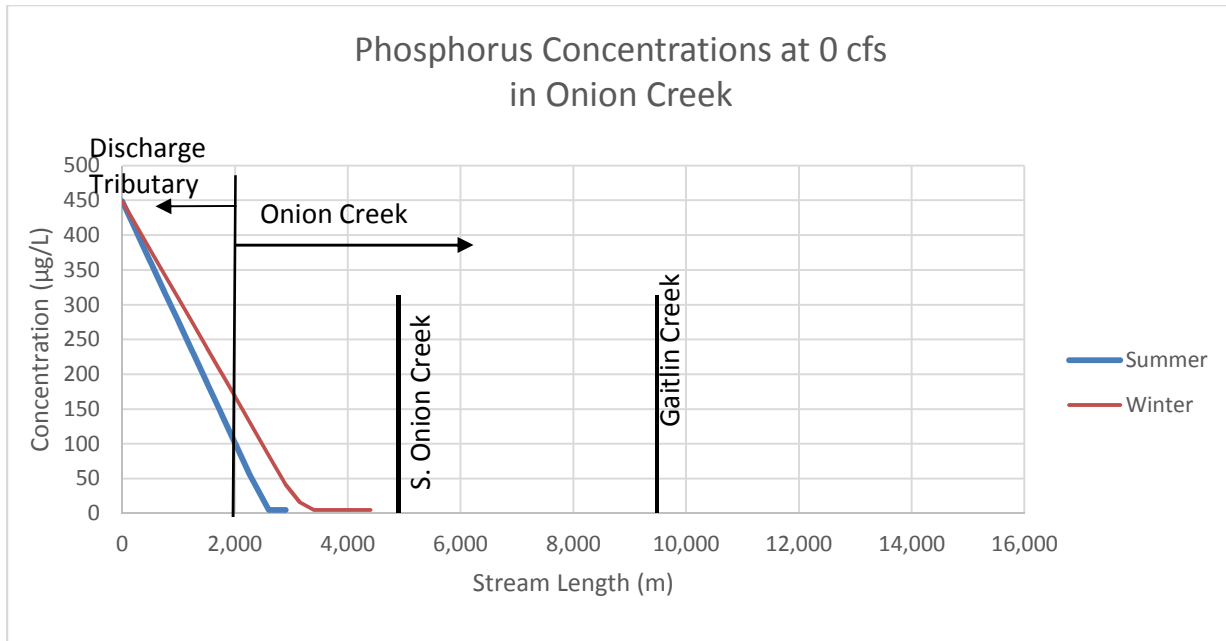
Initial periphyton biomass amounts, stream velocities and stream depths given a flow rate have now been estimated. To complete the model to calculate nutrient concentrations (Equations 6 through 8), values for the remaining parameters (Table 2) were chosen. Default values from Chapra et al. (2014) were used for the half-saturation constants of phosphorus and nitrogen,  $k_{sp}$  and  $k_{sn}$ , respectively, and the hydrolysis and death rates,  $k_h$  and  $k_d$ , respectively.

**Table 2: Values for Parameter in Nutrient Concentrations**

Parameter	Value	Units
$k_{sp}$	5	$\mu\text{g/L}$
$k_{sn}$	20	$\mu\text{g/L}$
$k_h$	0.05	1/day
$k_d$	0.3	1/day
$r_{pa}$	1.2 – 1.7	mgP/mgA
$r_{na}$	7.2	mgN/mgA
$r_{ca}$	0.04	gC/mgA
$r_{pc}$	2.0 – 13.3	mgP/gC
$r_{nc}$	50 – 100	mgN/gC

Default values from Chapra et al. (2014) were only used for two of the five stoichiometric coefficients,  $r_{na}$  and  $r_{ca}$ . The remaining three stoichiometric coefficients were obtained from research performed by Taylor et al. (2014) and Jones et al. (2011), which recognized that these coefficients are concentration dependent. One advantage of a parsimonious model is that it can convert these coefficients into dependent variables over a finite stream segment.

Finally, nutrient loads from preliminary engineering analysis associated with the City of Dripping Springs discharge permit application to the Texas Commission on Environmental Quality (TCEQ) (CMA Engineering 2015) were used in the model. A wastewater discharge of 5,000  $\mu\text{g/L}$  of nitrogen (estimated) and 500  $\mu\text{g/L}$  of phosphorus was used as the initial nutrient concentrations at a flow rate of 1,000,000 gallons per day (1.5 cfs). However, since phosphorus was the limiting nutrient in this analysis, effluent nitrogen does not play a role in the periphyton modeling discussed in the remainder of this report.



**Figure 6: Phosphorus Concentrations downstream of a Wastewater Discharge under Dry Conditions**

Low flow conditions (0 cfs in Onion Creek at the tributary containing the WWTP discharge, see Figure 3) were used to illustrate the mechanics of the model. The WWTP flow (with 500 µg/L of phosphorus at 1,000,000 gal/day or 1.55 cfs) is discharged into the tributary where it joins with Onion Creek at stream length 2000 m and 0 cfs. From there it would mix with background concentrations of phosphorus (assumed to be 5 µg/L of phosphorus for all flow regimes). The resulting phosphorus concentration in Onion Creek would be derived from the equation:

$$p_0 = \frac{(Q_w p_w + Q_r p_r)}{(Q_w + Q_r)} \quad (15)$$

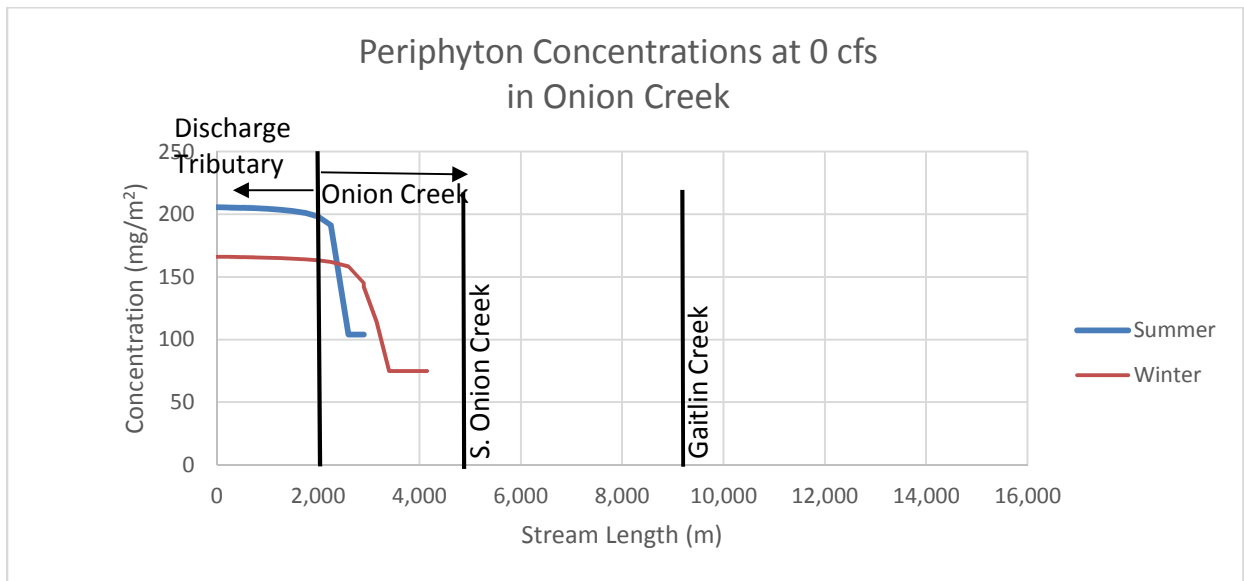
These variables are:

- $p_0$  = resulting phosphorus concentration from mixing, mg/L
- $p_r$  = background phosphorus concentration of Onion Creek, mg/L
- $p_w$  = phosphorus concentration of effluent discharge in tributary, mg/L
- $Q_r$  = flow rate of Onion Creek, ft<sup>3</sup>/s
- $Q_w$  = flow rate of effluent discharge at tributary, ft<sup>3</sup>/s

Under low flow conditions, Onion Creek is assumed to have no flow, so  $Q_r$  is zero and Equation 15 is not needed. For the other flow conditions, Onion Creek would essentially dilute the phosphorus concentrations coming in from the tributary and Equation 15 would be used.

In the no flow scenario above, the phosphorus concentration continues to provide periphyton growth until the stream length of approximately 3500 m (just prior to its confluence with South

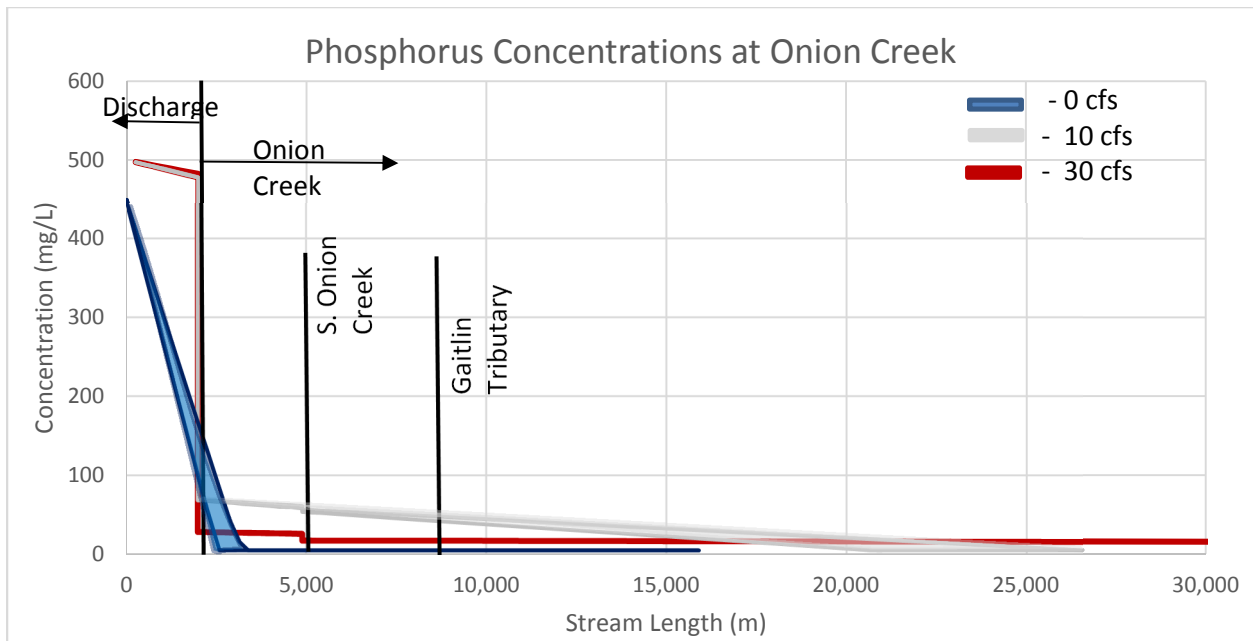
Onion Creek). At this point, the phosphorus concentration has been depleted by periphyton to the half-saturation constant level.



**Figure 7: Periphyton Amounts downstream of a Wastewater Discharge under Normal Flow Conditions**

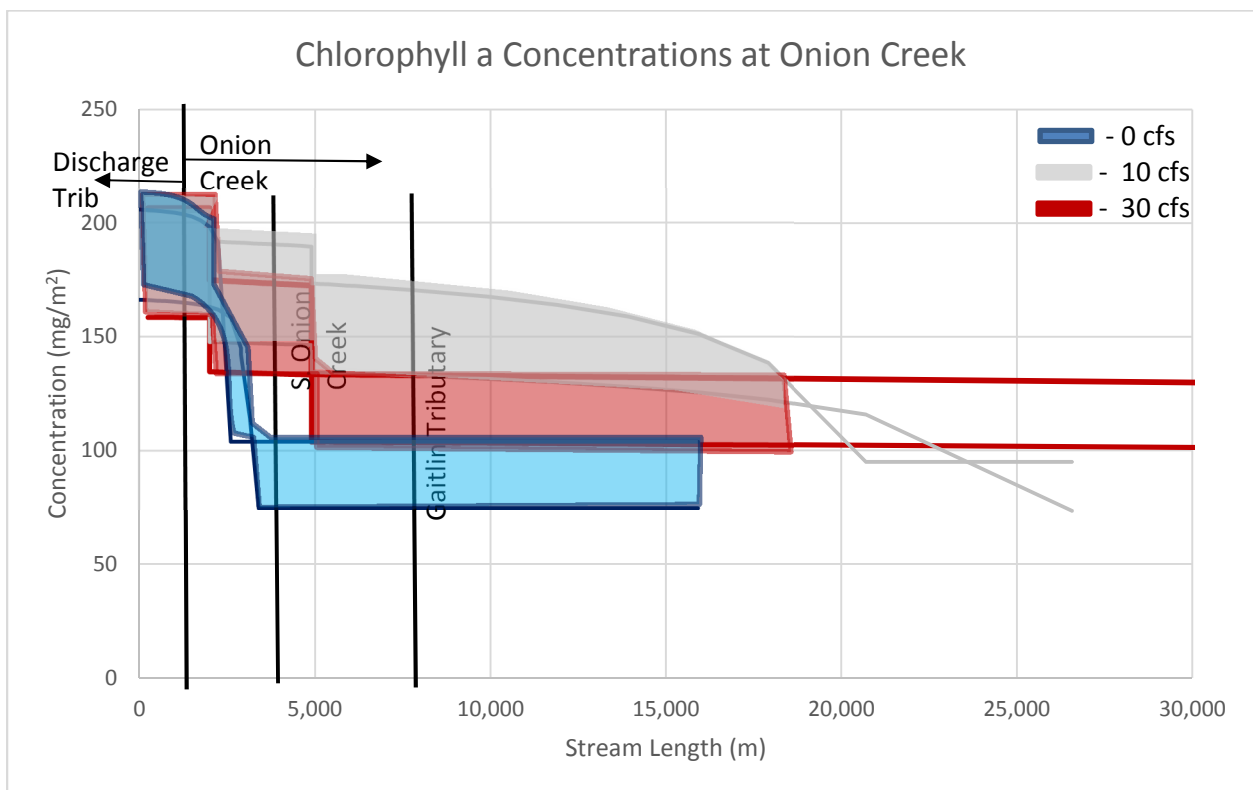
Similarly, periphyton concentrations begin at the summer or winter initial concentration. The amount of periphyton is maintained at this concentration until about the critical distance where phosphorus has been depleted to a concentration that can no longer support further periphyton growth and periphyton concentrations are now maintained at a lower level of 75 mg/m<sup>2</sup> and 114 mg/m<sup>2</sup> in the winter and summer, respectively.

Once the mechanics of the model were demonstrated under low flow conditions, all of the other flow conditions were also evaluated. Figure 8 shows the phosphorus concentrations beginning at the discharge point and then joining with Onion Creek 2,000 meters downstream. The three flow regimes assumed for Onion Creek are shown simultaneously under winter and summer conditions. Thus, the blue, gray, and red bands in the figure comprises flows of 0, 10, and 30 cfs in Onion Creek at the tributary containing the WWTP discharge. The thickness of the band indicates the extents of the phosphorus concentration under summer and winter conditions. Thus, when there is normal flow in Onion Creek, phosphorus concentrations are estimated to be detected between 20,000 and 26,000 meters (12.4 and 16.2 miles) in the summer and winter, respectively, downstream from the discharge point.



**Figure 8: Phosphorus concentrations downstream of a Wastewater Discharge under Low, Normal, and High Flow Regimes and under Summer and Winter Conditions**

A similar graph can be shown for periphyton concentrations.



**Figure 9: Periphyton concentrations downstream of a Wastewater Discharge under Low, Normal, and High Flow Regimes and under Summer and Winter Conditions**

As the flow rate increases, the critical distance also increases (given the parameters listed above). Thus, any dilution of the nutrient plume in the creek by higher flows is offset by higher stream velocities moving the elevated nutrients further downstream. Similarly, higher flows dilute the periphyton concentrations quicker, but amounts of periphyton still remain above 75 mg/m<sup>2</sup>.

As a final note, periphyton amounts are larger in the summer than in the winter due to the longer days which allow for more growth. However, the winter has a longer length of periphyton biomass than in the summer because the nutrients do not get consumed as fast due again to less periphyton growth in the winter.

### Sensitivity Analysis

Thus far, the analysis utilizes the default values given by Chapra et al. (2014) with the nutrient discharge concentrations from the TCEQ permit application, and site specific characteristics for light limitations and flow. A sensitivity analysis is also provided to investigate the response of the *critical distance* due to changes in each of the default values listed in Table 3 using a one at a time approach. However, a slight modification to the model is needed in evaluating changes in  $r_{pa}$ , the stoichiometric ratio that converts periphyton to phosphorus. Equation 16 below denotes the change and was derived (from Chapra's model) to determine the *critical distance* for phosphorus and Table 3 shows the values to be changed. An analytic method to look at sensitivity will be presented first followed by it results in graphical form.

**Table 3: Values for Parameter in Sensitivity Analysis**

Parameter	Default Value	Units
$k_h$	0.05	1/day
$k_d$	0.3	1/day
$a_0$	208	mg/L
$r_{pa}$	1	$\mu\text{g P} / \mu\text{g A}$

$$x_p = \frac{U}{k_h} \ln \left( \frac{a_0 \cdot \frac{[k_r(1-r_p a^2) + k_d]}{H \cdot r_{pa} \cdot k_h} - r_{pc} \cdot c_0}{k_{sp} - p_0 + a_0 \cdot \frac{[k_r(1-r_p a^2) + k_d]}{H \cdot r_{pa} \cdot k_h} - r_{pc} \cdot c_0} \right) \quad (16)$$

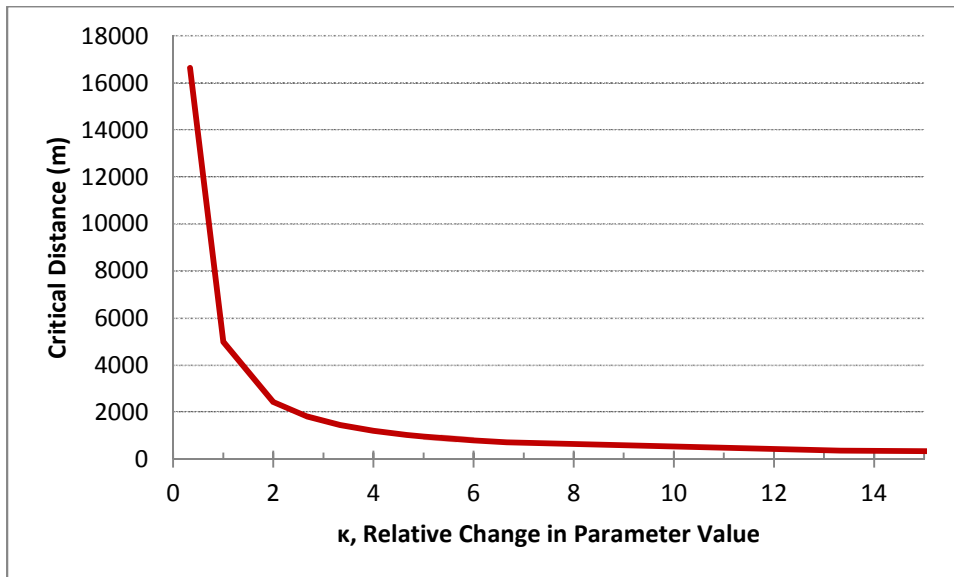
While Equation 16 appears formidable, it can be simplified in a manner that can easily express the sensitivity of the parameters. First, we assume that there is no initial concentration of carbon (i.e.  $c_0 = 0$ ) and that  $k_{sp}$ ,  $k_{sn}$ , and  $p_0$  are constants that will not be subject to the sensitivity analysis. Also, we consider that the sensitivity of both the stream height,  $H$ , and the stream velocity,  $U$ , were accounted for in the analysis above since these parameters are functions of flow. This reduces the equation to the following:

$$x_p = \frac{U}{k_h} \ln \left( \frac{a_0 \cdot \frac{[k_r(1-r_p a^2) + k_d]}{H \cdot r_{pa} \cdot k_h}}{C_p + a_0 \cdot \frac{[k_r(1-r_p a^2) + k_d]}{H \cdot r_{pa} \cdot k_h}} \right) \quad (17)$$

Then, for evaluating parameters  $k_d$ ,  $a_0$ , and  $k_h$ , the parameter  $r_{pa}$  can be set (for now) to the default value of 1, thus reducing the formula further. Finally, when doing sensitivity analyses, one is looking at the impact from a *relative* change in the parameter value rather than an absolute change in the parameter value. Thus, a 30% increase in parameter value equates to 1.3 times the parameter value. Denote this relative change in parameter value  $\kappa$ , and it can be seen that changing the values of the terms  $k_d$ , and  $a_0$  in Equation 17 will have the same effect (keeping in mind that  $r_{pa} = 1$ ). That is:

$$(\kappa \cdot a_0) \cdot \frac{k_d}{k_h \cdot H} = a_0 \cdot \frac{(\kappa \cdot k_d)}{k_h \cdot H} \quad (18)$$

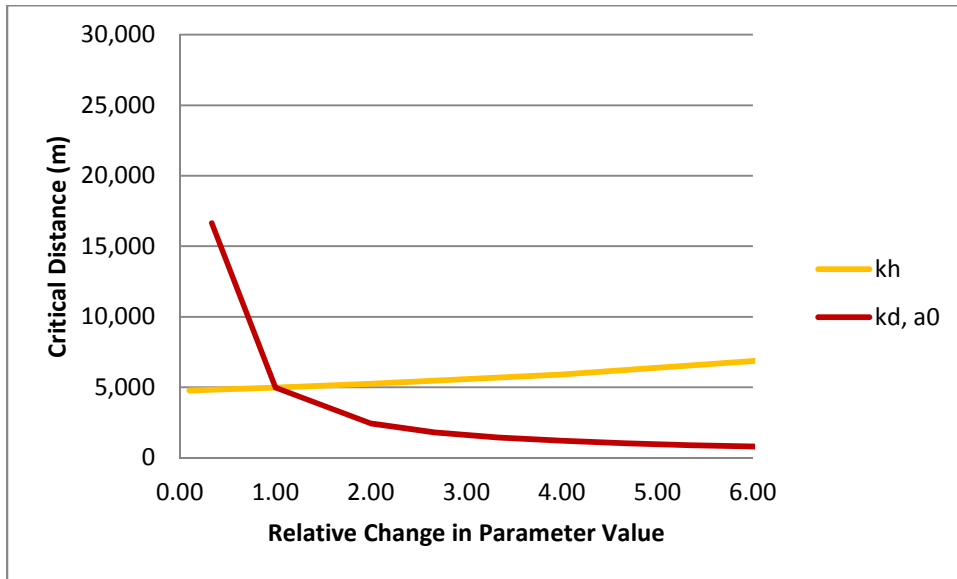
Figure 10, below shows the impact on the *critical distance* due to changing the parameters  $k_d$ , and  $a_0$  in Equation 14.



**Figure 10: Critical Length Response due to a Relative Change in Parameters  $k_d$ , and  $a_0$**

Primarily, this chart shows that the sensitivity of *critical distance* due to these two parameters is non-linear. That is, if either of our estimates of  $k_d$  or  $a_0$  is off by a factor of  $\frac{1}{2}$ , the critical distance doubles. Interpreting this in light of the conceptual model, as the initial periphyton,  $a_0$ , decreases, less phosphorus is consumed resulting in a longer *critical distance* (i.e. a longer plume of phosphorus). Similarly, as the periphyton death rate,  $k_d$ , decreases, all the periphyton growth,  $C_g$ , is directed to periphyton respiration which results in direct nutrient recycling. (Refer to Figure 1 and Equation 4.) Thus, according to this model, there is no loss of nutrients under low  $k_d$  and the critical distance increases in size. In reality, of course,  $k_d$  and  $a_0$  will not go to zero, but the trajectory as it goes towards zero informs the reader on changes in the critical distance. These relative changes in  $k_d$  or  $a_0$  can be considered likely. One can expect estimates of  $a_0$  to be off more than 30% in either direction (a 30% change in  $a_0$  equals about  $\pm 80$  mg/L) just due to seasonal factors. And, it is possible for the periphyton death rate,  $k_d$ , to be off by more than 50% (or a rate about  $0.30 \pm 0.15$  day<sup>-1</sup>). Thus, accurate estimates of the periphyton death rate and  $a_0$  are important in determining impacts to the creek.

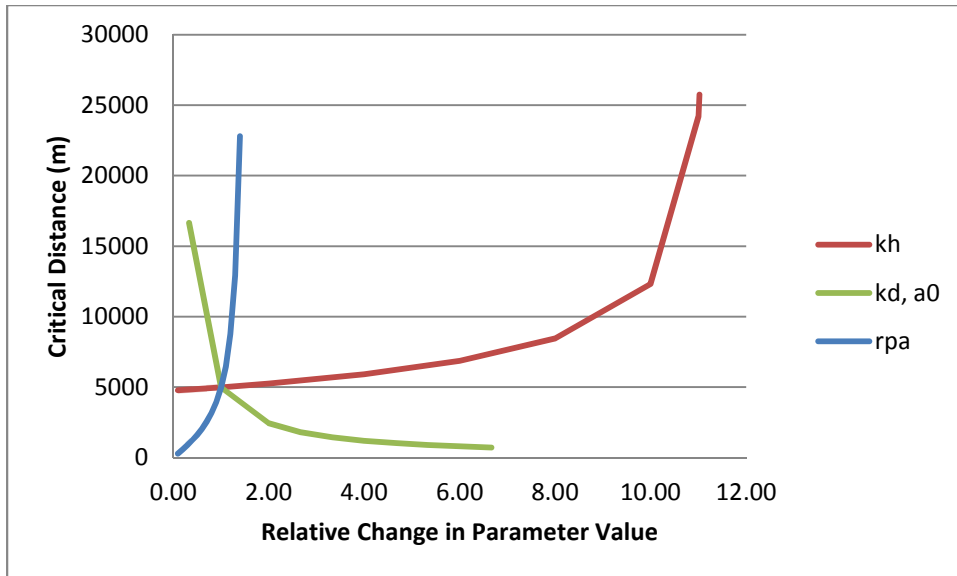
Figure 11 below shows the impact on the critical distance from relative changes in  $k_h$ , the rate of hydrolysis from carbon to the nutrients, as well as including the sensitivity due to parameters  $k_d$  and  $a_0$  from Figure 10 for comparison.



**Figure 11: Critical Length Response due to a Relative Change in Parameters  $k_d$ ,  $a_0$ , &  $k_h$**

This figure shows that the *critical distance* is not very sensitive to changes in the hydrolysis rate,  $k_h$ , compared to  $k_d$  and  $a_0$ . The estimates of  $k_h$  can be off by a factor of 8 and the *critical distance* would only be about twice the *critical distance* from the default values. The sensitivity due to changes in  $k_d$  and  $a_0$ , on the other hand, are more significant.

Finally, sensitivity of the stoichiometry ratio for chlorophyll a to phosphorus,  $r_{pa}$ , are shown in Figure 12.



**Figure 12: Critical Length Response due to a Relative Change in Parameters  $r_{pa}$ ,  $k_h$ ,  $k_d$ , and  $a_0$**

The impact on the critical distance of the stream from the phosphorus to chlorophyll a ratio,  $r_{pa}$ , is highly non-linear and is perhaps the most sensitive. As the ratio,  $r_{pa}$ , approaches 1.5 (or, equivalently, if its current estimate of 1 is off by an increase in 50%), the *critical distance* approaches infinity. None of the other parameters approaches a 70,000 meter (44 miles) *critical distance* within 50% of its default value. Therefore, empirically determining the periphyton phosphorus-to-chlorophyll a ratio in each stream would provide valuable data for model input.

The consideration of the sensitivity of the parameters listed above has helped direct efforts to develop more accurate measurements of the periphyton to phosphorus stoichiometry and to limit potential sources of uncertainty in the model. Current work is underway to evaluate these parameters under site-specific conditions in Austin, Texas.

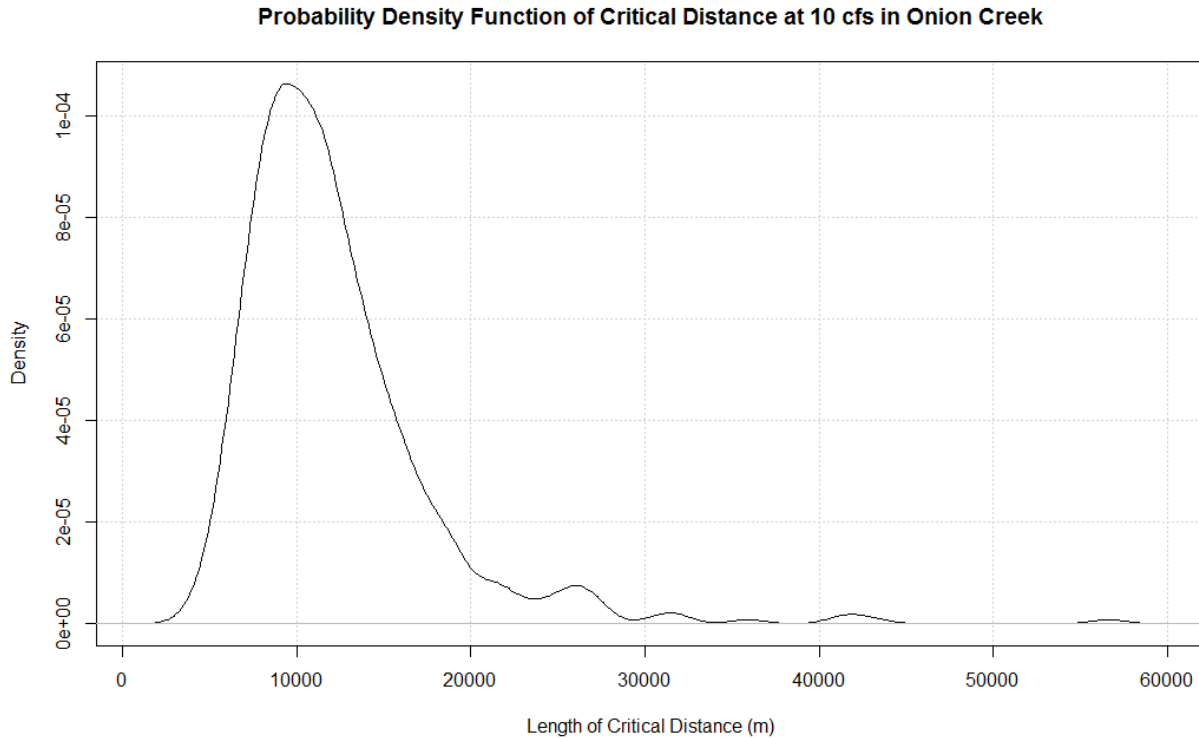
### Uncertainty Analysis

Finally, an uncertainty analysis on the model was completed for determining the expected range of the length at which phosphorus is limiting in the stream given the uncertainty of the inputs. Table 4 below gives the parameters that were varied. Each of these parameters was changed at the same time. The mean values of the parameters are the default values used, and the standard deviations of the parameters are estimated to be about one-fifth the mean value. A normal distribution is assumed for each of the parameters.

**Table 4: Values for Parameter in Uncertainty Analysis**

Parameter	Mean	Standard Dev	Units
$r_{pa}$	1.0	0.1	ugP/ugA
$k_r$	0.2	0.02	1/day
$k_h$	0.05	0.01	1/day
$k_d$	0.3	0.06	1/day
$a_0$	208	17	mg/m <sup>2</sup>

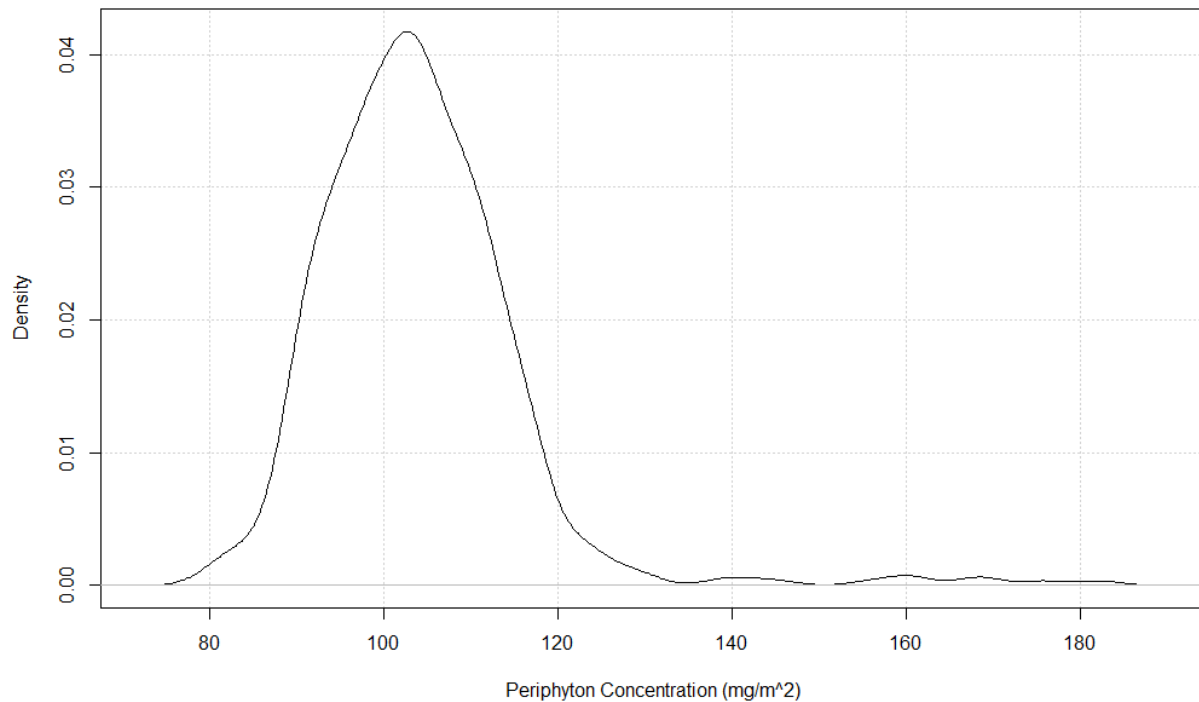
The results from the uncertainty analysis are shown in Figures 13 and 14.



**Figure 13: Results from Uncertainty Analysis of the Length at which Phosphorus is Limiting**

Figure 13 shows the range of *critical distances* in the stream (which is the length at which phosphorus concentrations in the stream equal the half-saturation coefficient). Thus, if the small range of parameter values in Table 4 is fairly accurate, then elevated amounts of phosphorus can be expected to be present between 5,000 and 25,000 meters (3.1 to 15.5 miles) in the summer given a flow rate of 10 cfs in Onion Creek. This is a wide range and further underscores the need for accurate values of the parameters listed in Table 4.

**Probability Density Function of Periphyton Concentration at 10 cfs in Onion Creek**



**Figure 14: Results from Uncertainty Analysis of the Amount of Periphyton**

Similarly, Figure 14 shows the expected range of periphyton at the critical distance in Onion Creek flowing at a rate of 10 cfs in the summer. This range of between 80 and 130 mg/m<sup>2</sup> indicates the high degree of certainty that a eutrophic system<sup>2</sup> will develop given the WWTP discharge loading operating under this parsimonious model.

Concurrent with the Chapra et al. (2014) model, the more sophisticated WASP model was also used for evaluating the discharge (Richter, 2016). This WASP model indicates periphyton concentrations in the range of 50 to 60 mg/m<sup>2</sup> extending 9 to 12 miles. The extent of periphyton along the stream is similar in both models. However, magnitude of periphyton concentrations is significantly lower. From looking at the underlying theory and equation, we ascertained that this difference is due to the extra level of complexity involved with computing the algal biomass using the WASP model. Chapra et al. (2014) proposes that periphyton growth is dependent on light and nutrients, while the WASP model includes factors of water temperature and available space to grow algae in the calculation for biomass accumulation. Also, the benthic algae stoichiometry is used to calculate the nutrients in the water column in the WASP model and not used to directly calculate the periphyton biomass as it is in the parsimonious model. The nutrient limitation for biomass accumulation in WASP is the amount of either nitrogen or phosphorus present in the algal cells compared to some minimum amount of nutrient required for growth designated by the user. Thus it is difficult to directly compare the biomass calculated between both models using the underlying equations. Despite this difference, response of the algae to nutrient addition from wastewater discharge is clearly seen in both models.

<sup>2</sup> A eutrophic system is defined to be one where the periphyton concentration is above 65 mg/m<sup>2</sup> (Dodds, 2006).

## Conclusion

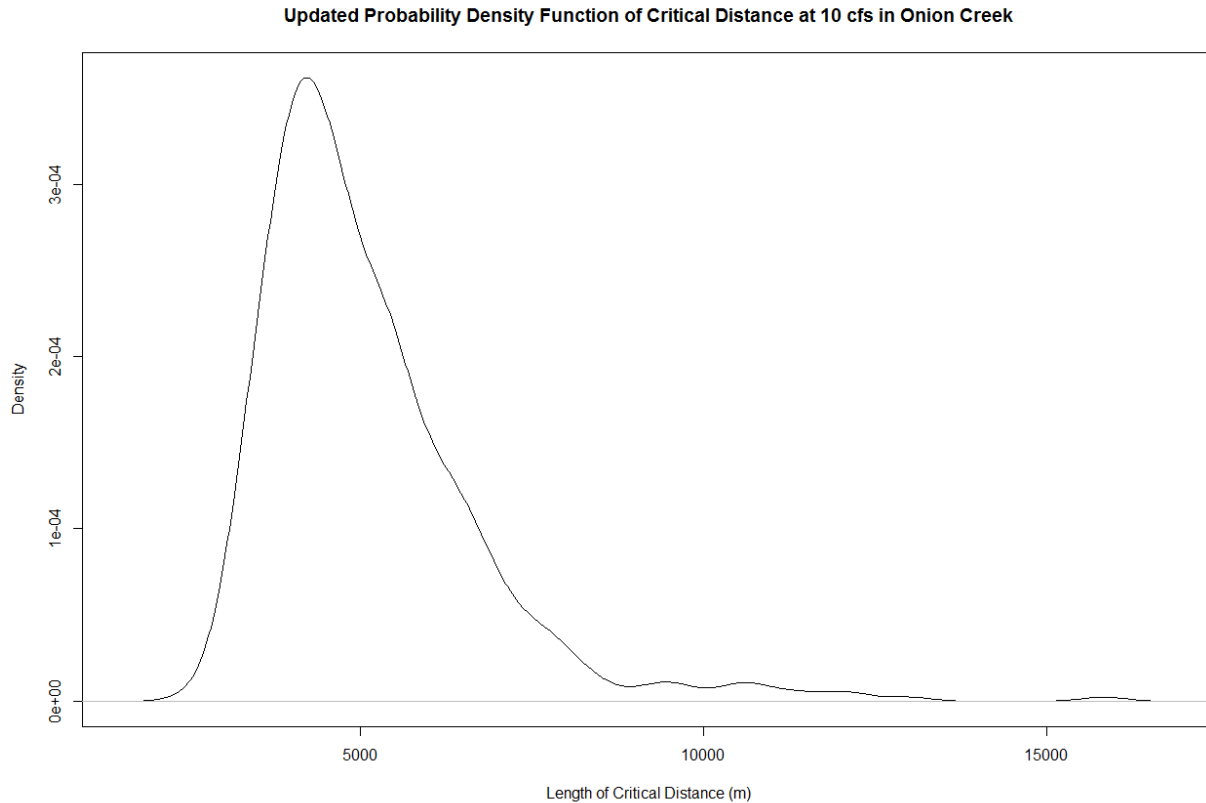
This paper presents results from a parsimonious model developed by Chapra et al. (2014) applied to the evaluation of a potential wastewater discharge from the City of Dripping Springs WWTP to Onion Creek. This model predicts between 6 and 15 miles of elevated periphyton biomass in the creek downstream of the proposed discharge under low and normal flow conditions. Under higher flow conditions, the length of the biomass could extend even further. Lower concentrations of periphyton biomass are estimated in the winter, but this comes at the expense of higher levels of nutrients transported downstream. The amount of periphyton predicted by the model ranged from 75 mg/m<sup>2</sup> at the downstream length of the biomass to 200 mg/m<sup>2</sup> at the discharge point. Under these conditions, the stream would be classified as eutrophic (Dodds, 2006) and the summer levels of periphyton coverage are above that which has been perceived as an aesthetic nuisance (Welch et al. 1988).

A sensitivity analysis shows that the conversion rate of phosphorus to chlorophyll a,  $r_{pa}$ , and periphyton death rate,  $k_d$ , are key parameters in the determination of this predicted length. Therefore, results from this study are highly dependent on the selection of these parameter values. If the phosphorus to chlorophyll a conversion rate is higher than the estimate used in the model or the periphyton death rate is lower than the estimate, then the length of the periphyton biomass could extend into the Recharge Zone of the Barton Springs Segment of the Edwards Aquifer. Therefore, the sensitive nature of these parameters drastically increases the uncertainty of the results. The uncertainty of the predicted elevated periphyton biomass length in the model is estimated to be several miles. A potential next step in improving the accuracy of the model is additional stream sampling of these parameters ( $r_{pa}$ ,  $k_d$ ,  $C_g$ ) along the stream under different flow scenarios to calibrate and validate the model.

A major caveat of any water quality modeling study is that many of the parameters used require calibration and validation. This can be accomplished by routine sampling under known discharge and upstream flow conditions that is repeated occasionally during operation of the WWTP. From this information, samples of the stream taken outside known discharge conditions can be compared to model predictions and can alert staff and management if they are beyond the range of values predicted by the model. In this manner the model can be kept updated for future analyses or as a means to amend the permit. This may prove especially useful given the multiple interim phases, long-range flow projections and potential reuse opportunities that will affect actual discharge conditions. Given the parsimony of this model, any updates to the parameters and modeled scenarios can be performed fairly promptly. During subsequent phases of the plant construction or upon renewal of the permit, TCEQ could then determine through adaptive management if permit limits need to be changed and upgrades to the plant are warranted.

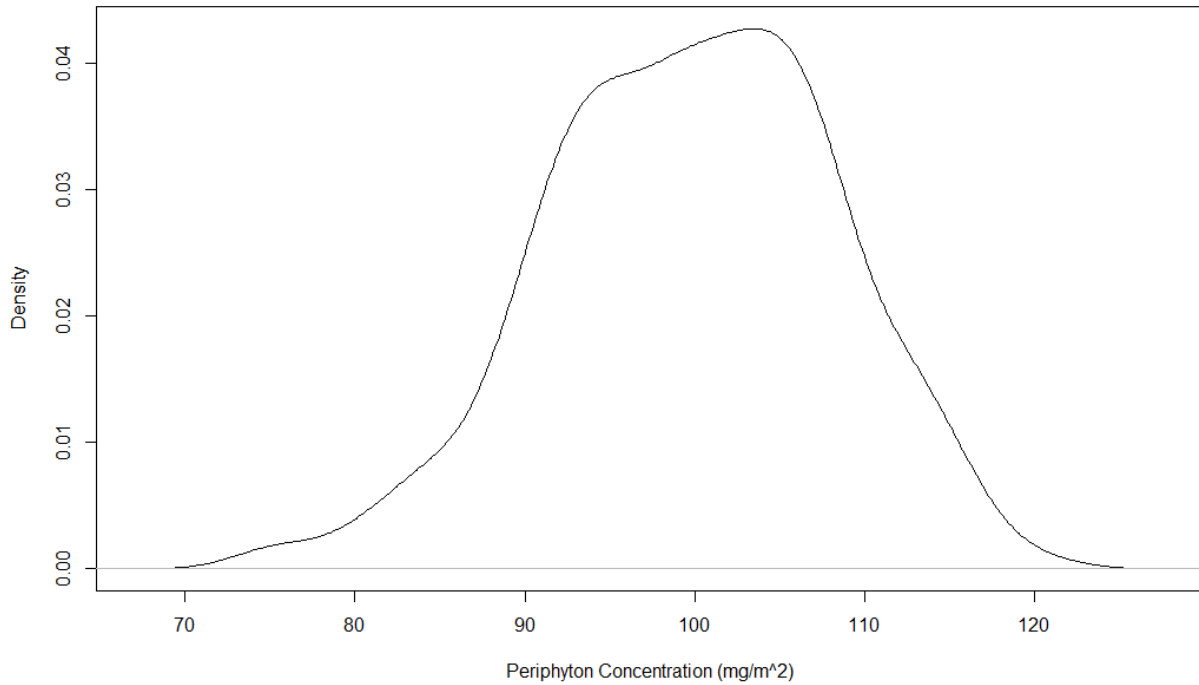
## Updated Model

This proposed phosphorus concentration limit in the draft permit for this facility is less than the 500 µg/L of phosphorus originally used in this report. The updated limit was input into the parsimonious model with an uncertainty analysis conducted. The results showed a critical distance of less than 10,000 meters (6.2 miles) as depicted in Figure 15. The amount of periphyton was estimated to be between 70 and 120 mg/m<sup>2</sup> (Figure 16).



**Figure 15: Results from Updated Uncertainty Analysis on the Critical Distance**

**Updated Probability Density Function of Periphyton Concentration at 10 cfs in Onion Creek**



**Figure 16: Results from Updated Uncertainty Analysis on the Amount of Periphyton**

While the updated results show a smaller longitudinal impact on the stream (6 miles in the updated model compared to an upper estimate of 15 miles in the original model), the amount of periphyton is about the same and significant. This may indicate that even with these lower phosphorus limits on the discharge, excessive algae is still predicted to occur.

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