An Analytical Framework for Evaluating the Impacts of a Riparian Corridor on a Receiving Stream

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Abel Porras P.E. and Aditi Busgeeth

City of Austin
Watershed Protection Department
Environmental Resource Management Division

Abstract
This report represents an initial effort to quantify the hydrologic and nitrogen removal effects of a forested riparian corridor in Austin, Texas, on its receiving stream. Values from peer-reviewed literature were input into models simulating flow and nitrogen transport through the surface and subsurface. The flow model examined the contribution of subsurface processes in both upland and riparian areas on a monthly time scale and results accurately mimicked monthly discharge at a downstream gage. The model was able to allocate flow between the upland and riparian areas, showing that the riparian areas were important sources of baseflow during the summer months. The results from the nitrogen model were less conclusive due to the sparsity of the data and the commensurate conversion of that data into model results. Nevertheless, the model pointed toward riparian areas being more effective than upland areas at removing nitrogen on both a per area basis and as a percentage of incoming nitrogen. Furthermore, the nitrogen model provides information for future study, identifying where deficiencies lie in current knowledge about nitrogen in Austin-area watersheds and providing a framework to evaluate riparian area impacts.

Introduction

Riparian areas, defined as the transitional zone between the aquatic and the upland communities (Naiman and Decamps 1997), contain a unique, diverse, and complex community of organisms and soil properties where biogeochemical processes tend to occur at high rates (McClain et al. 2003). Healthy riparian areas promote deep infiltration through preferential flow paths in the soil matrix caused by deeply rooted vegetation. The vegetation also increases overland roughness slowing down surface runoff and allowing more time for the water to infiltrate. This results in a recharging of ground water volumes and reduction of storm discharge to receiving streams. In turn, downstream flood events and streambed scouring become attenuated (Hawes and Smith 2005).

In addition, dense vegetation communities and associated soil microbiota in healthy riparian areas support removal and processing of pollutants through a variety of mechanisms including deceleration of surface flows that promote deposition, infiltration, sorption onto soil, and plant and microbial uptake (Dosskey 2001). Nitrogen load reduction has been shown to be higher for riparian buffer restoration practices (1,086 ±4,973 Kg N/Km-yr) than those for hyporheic restoration (226 ±692 Kg N/Km-yr) or floodplain reconnection (86±402 Kg N/Km-yr) (Lammers and Bledsoe 2017) thus highlighting the relative importance of improving riparian function relative to other restoration interventions for nitrogen removal. In urban riparian areas hydrological factors control denitrification potential (Groffman et al. 2002; Gift et al. 2010; Lammers and Bledsoe 2017) and higher nitrogen inputs increasing actual denitrification rates (Li et al. 2014).

This report presents theoretical flow and nitrogen models for an urbanized Austin creek that will serve to inform decision makers on the relative impact of riparian buffers on the receiving streams for both hydrologic and chemical improvements. For simplicity, the terms riparian buffer, vegetated filter strip, riparian zone, and buffer strips were deemed synonymous for this report.

Methodology

A mass balance equation was used to develop two models to quantify the impacts of the riparian corridor on the receiving stream. The first model evaluates the hydrological contribution of the riparian area to baseflow by examining the water balance on a monthly scale. The second model looks at the riparian corridor effect on the nitrogen transport to the creek on a quarterly basis. The difference in time scales for the two models was needed given the scarcity of nitrogen data to calibrate the nitrogen model. This also resulted in a de-coupling of the models. Ideally, results from the flow model could be used to determine the flow of nitrogen. However, to calibrate each model, that link had to be severed.

Study site

The study area, WLR3, is the upstream headwater section of the Waller Creek watershed and encompasses 1.09 square miles (Figure 1) and has been fully urbanized since the late 1990's. The downstream section is bound by Koenig Lane where a USGS flow gage has collected flow data since 1987. Quarterly water quality samples have been collected every other year just downstream from the USGS gage at 51st Street as part of the City's routine surface water monitoring program, the Environmental Integrity Index (City of Austin 2002). A more detailed description of the area has been reported elsewhere (Glick et al. 2016).

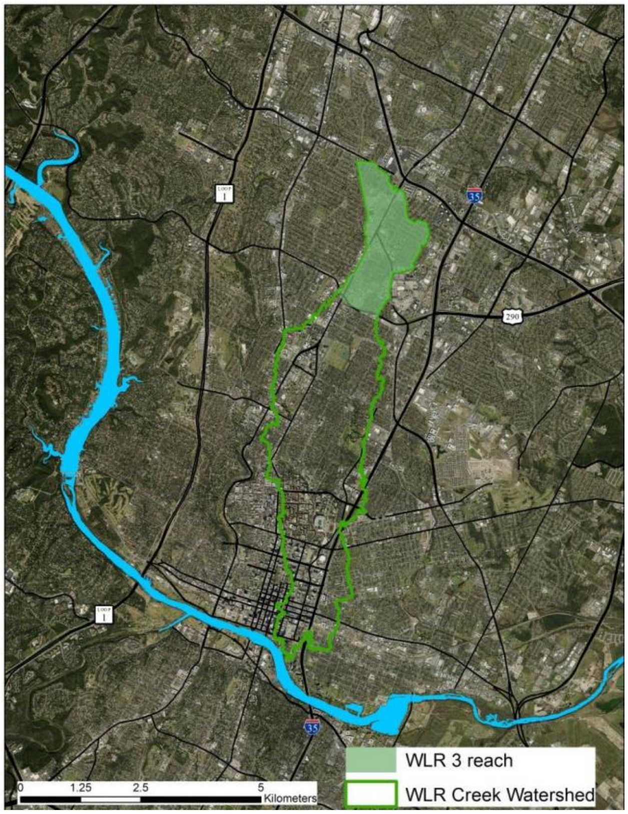

Figure 1 Waller Creek watershed (green outline) and WLR3 study area (green shade) in Austin, TX

Hydrologic model equations

To develop the monthly hydrologic model, the following equation was used:

$$P - E \pm S = D \quad (1)$$

In this simple mass balance equation, P is the monthly precipitation, E is the monthly average evapotranspiration, S is the monthly supplying/receiving flow through subsurface, and D is the monthly discharge of the stream. Under this model, P, E, and D are all given through various data sources given in the Hydrologic Model Parametrization section below. The flow from the subsurface cannot be immediately measured but can be inferred by re-arranging Equation 1:

$$P - E - D = S \quad (2)$$

Since WLR3 is at the headwater and there are no other tributaries entering the stream, the monthly discharge, D, should contain all of the precipitation falling on the study area. Thus, a negative value for S indicates that the monthly precipitation was not a sufficient source for the monthly stream discharge. Any measured discharge, then, must originate from the subsurface. Similarly, a positive value for S points to an abundance of precipitation that is not immediately discharged, and thus, must be stored in the subsurface.

Furthermore, it can be postulated that the flow from the subsurface is comprised of two sources: flow from upland areas into the subsurface, Q_U, and flow from riparian areas into the subsurface, Q_R.

$$P - E - D = Q_U + Q_R \quad (3)$$

These two sources are distinguished from each other by the following three factors: the impervious cover, the hydraulic conductivity of the underlying soil, and the distance of each source to the creek. These three factors can be incorporated into Equation 3 via Darcy's Law:

$$Q = K_{sat} \cdot \frac{\Delta h}{L} \quad (4)$$

In Darcy's Law, K_{Sat} is the saturated hydraulic conductivity, Δh is the change in head over the length L of the flow path. The hydraulic conductivity and the distance of each source to the creek share a one to one correspondence between two of the factors listed above and Darcy's Law. To develop a relation between Δh and impervious cover, a sub-model of Δh can be developed using data that is available, since the change in head cannot be accurately measured, short of monthly averages of well readings for that watershed. Instead, impervious cover can be introduced to tie in the third distinguishing factor into the larger model via this Δh sub-model:

$$\Delta h \propto \frac{P-E}{CN} \quad (5)$$

The impervious cover of a watershed can be described by a Soil Conservation Service curve number, *CN*, which relates the condition of the soil along with the average impervious cover into a number between 0 and 100. The more impervious the soil and its surroundings, the higher the curve number. Thus, higher curve numbers reduce the amount of hydraulic head in the subsurface by restricting the supply of water through its imperviousness. Mathematically, we would say that the change in head is proportionally related to the supply of water, *P-E*, and inversely proportional to the curve number, *CN*. Hence, Equation 5 above.

Note that the above description for Equation 5 describes the change in head as proportional to the measured values. To make Equation 5 into an equality, an error term must be introduced. It should also be noted that the saturated hydraulic conductivity is also an estimate of subsurface conditions and is also subject to error. The error in change in head and the saturated hydraulic conductivity can be combined into one overall error factor to describe flow through the subsurface:

$$Q = \varepsilon \cdot K_{sat} \cdot \frac{P-E}{CN \cdot L} \quad (6)$$

Substituting Equation 6 into Equation 3:

$$P - E - D = \alpha \cdot \left(K_{sat} \cdot \frac{P-E}{CN \cdot L}\right)_U + \beta \cdot \left(K_{sat} \cdot \frac{P-E}{CN \cdot L}\right)_R \quad (7)$$

The subscripts "U" and "R" represent the hydraulic conductivity, curve number, and length for upland and riparian areas, respectively. This formulation allows for an allocation of subsurface flow between subsurface upland flow and subsurface riparian flow based on physical properties (i.e. Darcy's Law).

That allocation can be inferred from the error correction factors, α and β. The variables *P*, *E*, and *D* can be obtained for any watershed with a flow gage and a nearby weather station. The variables K_{Sat}, *CN*, and *L* are estimated based on the overall land features of the watershed. The terms α and β can then be chosen so that the actual values of subsurface discharge flow (i.e. *P* - *E* - *D*) are similar to the modeled values of Q_R and Q_U. That is, given the monthly values of subsurface discharge flow (the left-hand side of Equation 7), there exists a unique value of α and β that will simulate those monthly values of subsurface discharge flow (allocated between riparian and upland subsurface flow) via a physical model (the right hand side of Equation 7). It is then assumed that these unique values of α and β can predict future values of subsurface discharge flow and can be used to explain the differences between subsurface upland flow and subsurface riparian flow.

To determine that unique value of α and β, a combination of two methods were used. First the squared errors between the measured values, P – E – D, and the modeled values, $Q_U + Q_R$, were calculated and summed.

$$Error = \sum(y_i - \hat{y}_i)^2 \quad (8)$$

In this equation, y_i are the measured values and $\hat{y}_i$ are the modeled values. Equation 8 can be re-written as:

$$Error = \left\{y_i - \left[\alpha \cdot \left(K_{sat} \cdot \frac{P-E}{CN \cdot L}\right)_U + \beta \cdot \left(K_{sat} \cdot \frac{P-E}{CN \cdot L}\right)_R\right]\right\}^2 \quad (9)$$

All the variables in this equation are given with the exception of α and β. The goal is to find α and β such that the sum of squared errors are minimized. To do this, the derivative of Equation 8 is taken with respect to α and β and then set to zero. This produces two equations (the derivatives) and two unknowns (α and β). The final step would be solving these two equations for the two unknowns. The values that establish α and β indicates the amount of uncertainty in the variables, K_{Sat} , CN, and L. It also is an indication of the importance of subsurface upland flow relative to subsurface riparian flow.

It is important to highlight that this model assumes that upland runoff discharges directly to the stream thus bypassing the riparian area (Figure 2). This was done to approximate the surface flow routing from the upland through the riparian to the creek. The assumption was that as precipitation falls on and saturates the riparian surface, upland flow bypasses the riparian surface and thus, flows directly to the stream. The model thus, treats surface flow as a parallel or separate model, which is similar to the approach taken by Fovet, et al. (2015) that focused on sub-surface flow dynamics. Subsurface flow is connected between the upland, riparian, and stream zones with flow moving to and from storage in the subsurface.

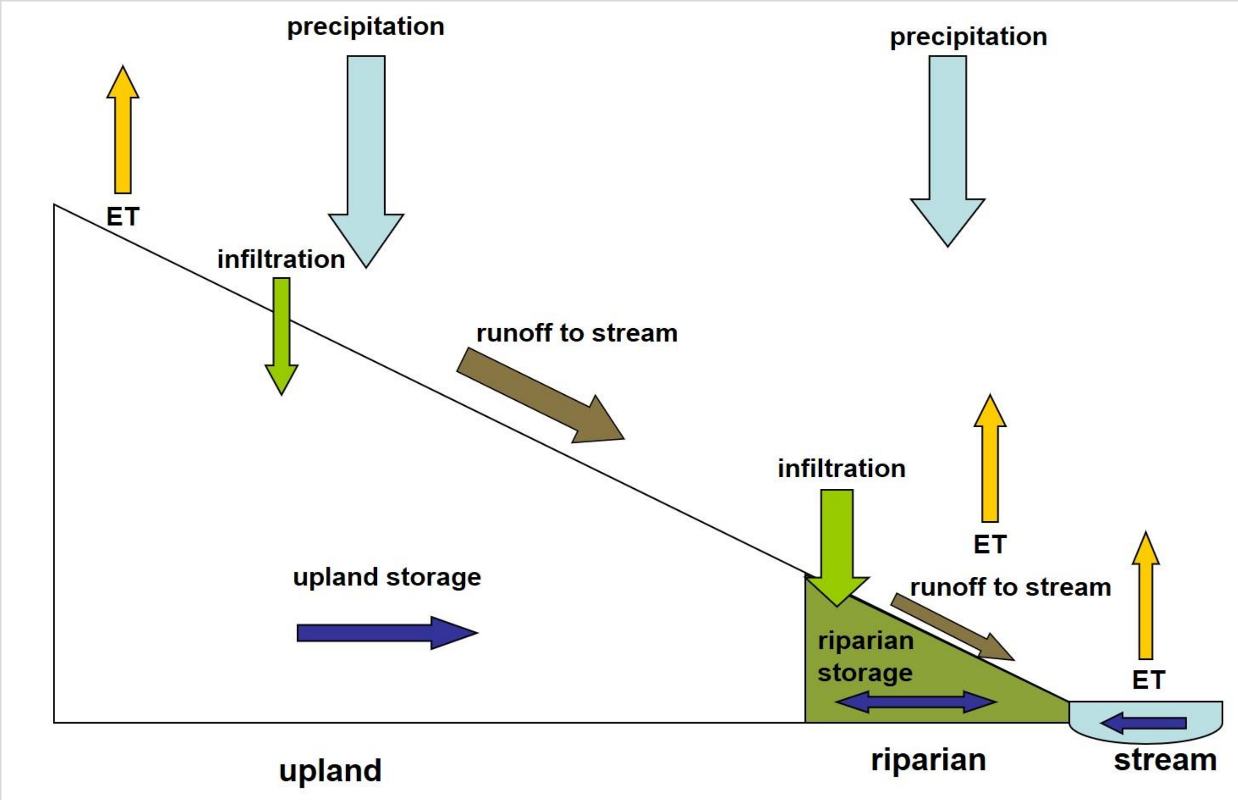

Figure 2: Depiction of hydrological model. Notice that runoff from both upland and riparian surface runoff discharges to the stream and that subsurface storage in the riparian area can flow to upland storage as well as the stream.

<u>Hydrologic model parameterization</u>
The flow model was applied to the watershed of Waller Creek upstream of Koenig Lane (Figure 1). Additional estimates needed for the flow model included curve numbers of 89 and 73 for the upland and riparian areas, respectively, and a saturated hydraulic conductivity was approximated at 0.03 ft/hr and 0.05 ft/hr for the upland and riparian areas, respectively. The curve numbers were obtained from the Drainage Criteria Manual (DCM) (City of Austin). This study area consists mostly of clay soils, which are considered to be in Hydrologic Group D. From Table 2-7 in the DCM, soils in Hydrologic Group D and in a fully developed urban area with grass cover of 50% (as assumed for the upland areas) are assigned a curve number of 89. For riparian areas, which were considered to be brush in good conditions, a curve number of 73 was deemed appropriate. The hydraulic conductivity tests conducted by ERM staff in the area also showed similar values to those estimated above.

The parameters α and β were then calibrated in the flow model using 60 monthly data points (from 2008, 2009, 2010, 2015, and 2016) for precipitation, evapotranspiration, and discharge at Waller Creek and Koenig Road. Monthly values of precipitation and evapotranspiration were obtained from National Oceanic and Atmospheric Administration (NOAA) weather station USW0013958 at Camp Mabry, Austin, Texas (in inches); the discharge data was obtained from USGS flow gage station 08156910 in ft^3/s. The discharge was then converted to inches by determining the total amount of discharge for each month and then dividing by the drainage area. The monthly subsurface storage was determined from these values by using Equation 2.

Nitrogen model equations

A second model of the effect of the riparian zone was developed in conjunction with the flow model. This model consisted of simulating nitrogen through the uplands, into the riparian zone, and into the receiving stream. As such, the model was partitioned into three connecting sub-models: the upland sub-model, the riparian sub-model, and the receiving stream sub-model. Outputs from the upland sub-model were input into the riparian sub-model for both surface runoff as well as subsurface storage. This model, therefore, differs from the hydrological model in that surface runoff from the upland area is routed to the riparian area. However, this model does not allow riparian nitrogen storage to move to upland subsurface storage. Outputs from the riparian sub-model were input into the creek sub-model (Figure 3).

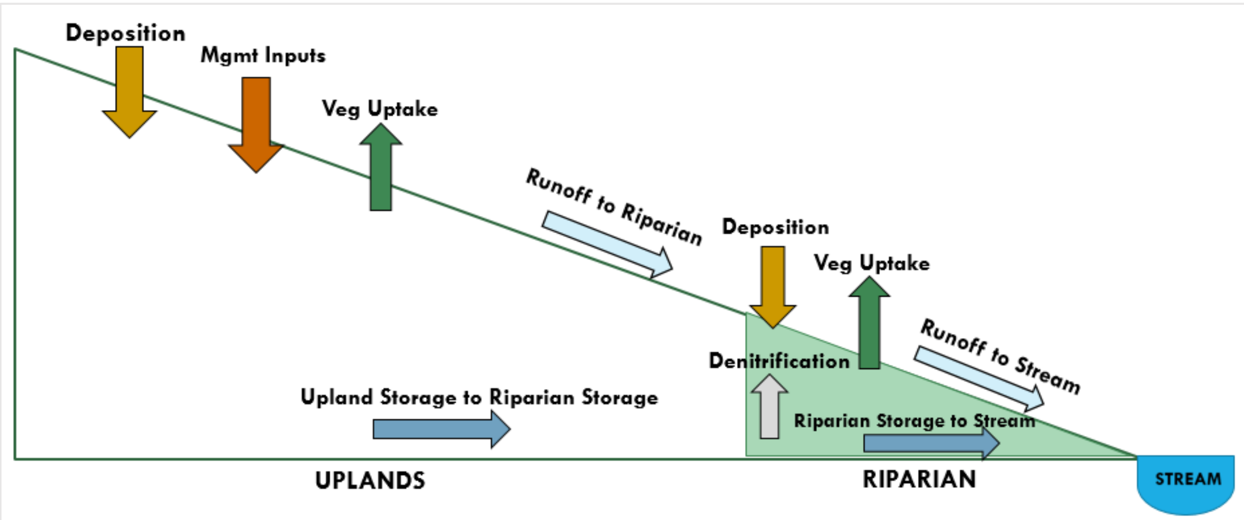

Figure 3: Schematic of Nutrient Transport in the Watershed.

In Figure 3, the inputs or sources, "Deposition" and "Mgmt Inputs", represent atmospheric deposition and the land application of nitrogen (typically due to fertilizer and pet waste), respectively. The sinks, "Veg Uptake" and "Denitrification", depicts the loss (or unavailability) of nitrogen in the system due to vegetative uptake and the denitrification in the soil due to other biologic factors, respectively. The remaining nitrogen is then transported downgradient through surface runoff ("Runoff to Riparian" or "Runoff to Stream") and subsurface flow of nitrogen ("Upland Storage to Riparian Storage" or "Riparian Storage to Stream"). While the surface transport of nitrogen is conserved, only a fraction of the subsurface nitrogen is transported downgradient to incorporate nitrogen's absorption (or retention) in the soil.

Mathematically, then, the nitrogen model for the upland sub-model can be expressed as:

$$Input_{Upland} - Sink_{Upland} = Output_{Upland} \quad (10)$$

In this equation $Input_{Upland}$ is the sum of atmospheric deposition and management inputs. The term $Sink_{Upland}$ is the sum of vegetative uptake and soil retention, where soil retention is some fraction, φ, of the nitrogen input remaining after vegetative uptake. Finally, $Output_{Upland}$ is the sum of the inputs and sinks and is partitioned into two components, "Runoff to riparian" and "Upland storage to riparian" (Table 1). Concentrations for "Runoff to riparian" are taken from Glick et al (2009).

The mass in the "Runoff to riparian" is calculated based on the volume of water in "Runoff to riparian" and the remaining mass from $Output_{Upland}$ is allocated to "Upland storage to riparian".

Table 1: A summary of Nitrogen sources and sinks in the Upland Areas of the watershed

$Input_{Upland}$	(+) Atmospheric Deposition (+) Management Inputs
$Sink_{Upland}$	(-) Vegetative Uptake (-) Soil Retention (φ)
$Output_{Upland}$	Surface Runoff to Riparian Upland Storage to Riparian

The nitrogen model for the riparian sub-model can be expressed similarly as:

$$Input_{Riparian} - Sink_{Riparian} = Output_{Riparian}$$

In this equation $Input_{Riparian}$ is now the sum of atmospheric deposition and surface runoff from the upland sub-model. There are no management inputs, since it was assumed that fertilizer is rarely applied in greenbelts adjacent to creeks. The term $Sink_{Riparian}$ is the sum of vegetative uptake, denitrification, and soil retention, where soil retention is some fraction, ψ, of the nitrogen input remaining after vegetative uptake and denitrification. Finally, $Output_{Riparian}$ is the nitrogen remaining in the system and is partitioned into two components, "Runoff to stream" and "Riparian storage to stream" (Table 2). Similar to above, "Runoff to stream" is taken from Glick (2009) and the remaining mass is assumed to be in "Riparian storage to stream".

Table 2: A summary of Nitrogen sources and sinks in the Riparian Areas of the watershed

$Input_{Riparian}$	(+) Atmospheric Deposition (+) Surface Runoff from Uplands
$Sink_{Riparian}$	(-) Vegetative Uptake (-) Denitrification (-) Soil Retention** (ψ)
$Output_{Riparian}$	Surface Runoff to Stream Riparian Storage to Stream

Unlike the flow model, however, there was insufficient data to calibrate the model. Quarterly Total Kjeldahl Nitrogen data was collected from Waller Creek at 51st Street during the

Environmental Integrity Index (EII) monitoring program. The sampling results, which are taken as concentrations (in mg/L), were converted to total mass (kg) by multiplying the concentration by the total flow (ft^3) in the stream over the quarter. Since this method of computing actual mass of nitrogen in the system is overly simplistic, comparing this converted data to the model results should also be viewed with caution. Therefore, assessment of the model would be acceptable if results are within an order of magnitude of the sampled data.

<u>Nutrient model parameterization</u>

Inputs to the model consisted of the nitrogen sources and sinks (Table 3). The inputs were computed on a quarterly basis in order to calibrate with quarterly data collected via the City of Austin's routine monitoring program, the EII.

Table 3: Values for the sources and sinks of nitrogen in Upland Areas

$Input_{Upland}$	(+) Atmospheric Deposition (+) Management Inputs Fertilizer Pet waste	National Atmospheric Deposition Program's Total Deposition Maps Base rate for irrigation =1.6 kg/yr Plus fertilization in spring, summer, fall = 80 kg/ac of pervious cover for Parks, 160 kg/ac of pervious cover for all other land uses (Turner 2012). 754 kg quarterly (Hobbie et al. 2017)
$Sink_{Upland}$	(-) Vegetative Uptake (-) Soil Retention	15 kg/ha in spring and summer and 5 kg/ha in fall and winter (Peterjohn and Correll 1984) 8% of nitrogen in soil is retained – estimate based on best professional judgement
$Output_{Upland}$	Surface Runoff to Riparian Upland Storage to Riparian	1.9 mg/L per rain event (Glick et al. 2009) =Inputs – Sinks – Surface Runoff
$Input_{Riparian}$	(+) Atmospheric Deposition (+) Surface Runoff from Upland	National Atmospheric Deposition Program's Total Deposition Output from Upland Runoff
$Sink_{Riparian}$	(-) Vegetative Uptake (-) Denitrification	23 kg/ha in spring and summer and 15 kg/ha in fall and winter (Peterjohn and Correll 1984) 34 µg N/ (kg soil · d) (Kaushal, Groffman, Mayer, Striz, and Gold

	(-) Soil Retention	2008) Estimated 50% in winter, 75% in fall 50% of nitrogen in soil is retained (Mayer et al. 2007)
$Output_{Riparian}$	Surface Runoff to Stream Riparian Storage to Stream	0.78 mg/L (Glick et al. 2009) =Inputs – Sinks – Surface Runoff

Data for the atmospheric deposition of nitrogen for 2008-2010 and 2015 was sourced from Total Deposition Maps (National Atmospheric Deposition Program). Total deposition includes wet and dry deposition, which was calculated by the NADP (Schwede et al. 2014). Data was not available for 2016, so averages from 2008-2010 and 2015 were used.

The Management Inputs term was computed to account for non-depositional sources of nitrogen in the uplands: irrigation, fertilizer application, wastewater leaks, and pet waste. A nitrogen balance method for estimating fertilizer and irrigation inputs of nitrogen was devised for the Barton Springs segment of the Edwards Aquifer (Turner 2012) and was utilized for this analysis. To incorporate pet waste, N input from an urban watershed with similar residential density as the study area was estimated from a similar study (Hobbie et al. 2017)

It was assumed that soil upland denitrification rates were negligible. Riparian denitrification rates calculated for unrestored reaches in the Chesapeake Bay (Kaushal, Groffman, Mayer, Striz, and Arthur 2008) were used in our model. It is important to note that denitrification rates are not constant and are controlled by % water filled pore space in soils (Machefert and Dise 2004) and thus this model uses an oversimplification of denitrification in the system. The denitrification rates were converted from µg of N per kg of soil per day to kg per quarter by assuming a soil density of 2,590 kg soil per cubic foot over the volume of the Waller 3 creek watershed (i.e. the surface area of Waller 3 watershed multiplied by a depth of 6 inches). Surface runoff for nitrogen in the upland and riparian were taken from Glick et al. (2009). Their method used statistical techniques to estimate nitrogen concentration values over various land uses.

Results

Hydrologic model

It appears the flow model provides fair estimates of monthly stream flow from storage (Figure 4). Furthermore, the parameters α and β provide an indication of the allocation between flow from storage in riparian and further upland areas. Thus, the sub-surface areas for upland and riparian zones can be considered their own proper systems[1] with each either receiving flow (in which case flow is positive) or discharging flow (in which case flow is negative) (Figure 5).

[1] Refer to Equations 3 and 6 to see this.

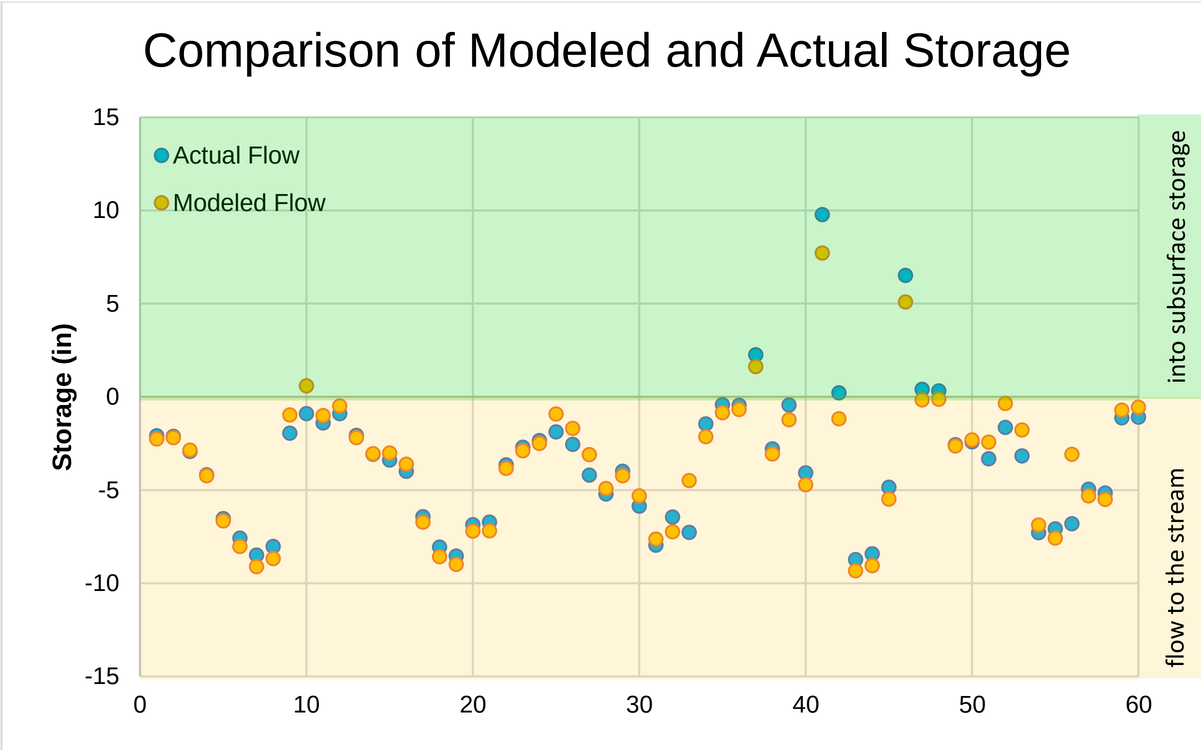

Figure 4: Results from Flow Model compared to Actual Flow Measured: Positive values indicate that the subsurface is receiving flow (i.e. flow is entering the system) and negative values indicate that the subsurface is discharging flow to the creek (i.e. flow is exiting the system).

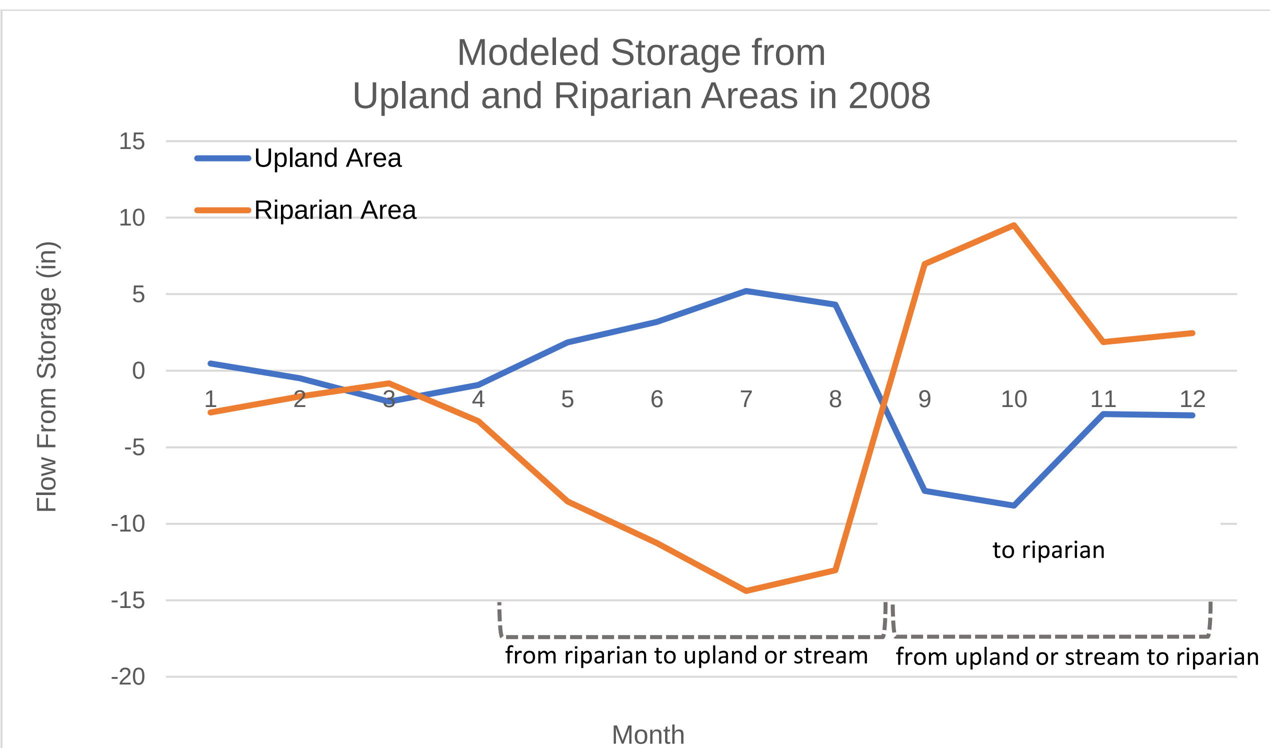

Figure 5: Flow Allocated between Riparian and Upland Areas per the Hydrologic Model in 2008

From about April to August of 2008, the riparian areas provided sub-surface flow to the upland areas and the stream. During September through December of 2008, the inverse occurred with the upland area providing sub-surface flow to the riparian area. Even though the riparian area in Waller Creek is small, it still supplies substantial flow to the creek.

Nitrogen Model

When the nitrogen parameter values (Table 3) are input into the mass balance model, the results underestimate the quarterly baseflow nitrogen measured at the EII monitoring site (Waller @ 51st). (Figure 6). One likely reason was due to the heterogeneity of the watershed, which consists of various land uses, soil types, management inputs, and vegetation uptake rates. The model uses a single assumption for each of these inputs for the upland area and another for the riparian area, so this heterogeneity is not incorporated into the model. In addition, denitrification rates are likely much lower in this headwater urban stream than what is reported in the literature for the Chesapeake Bay; this section of Waller Creek does not have perennial flow and saturated soil conditions so denitrification may occur only sporadically (Duncan et al. 2013). Furthermore, the computation of nitrogen through EII data was simplistic and does not account for storm flow water quality, which contains more nitrogen than base flow, while accounting for contributions to the total flow over the quarter. Therefore, this model should not be taken as a direct indicator of what has occurred in the watershed. Rather, the model can still function as a learning tool in three regards.

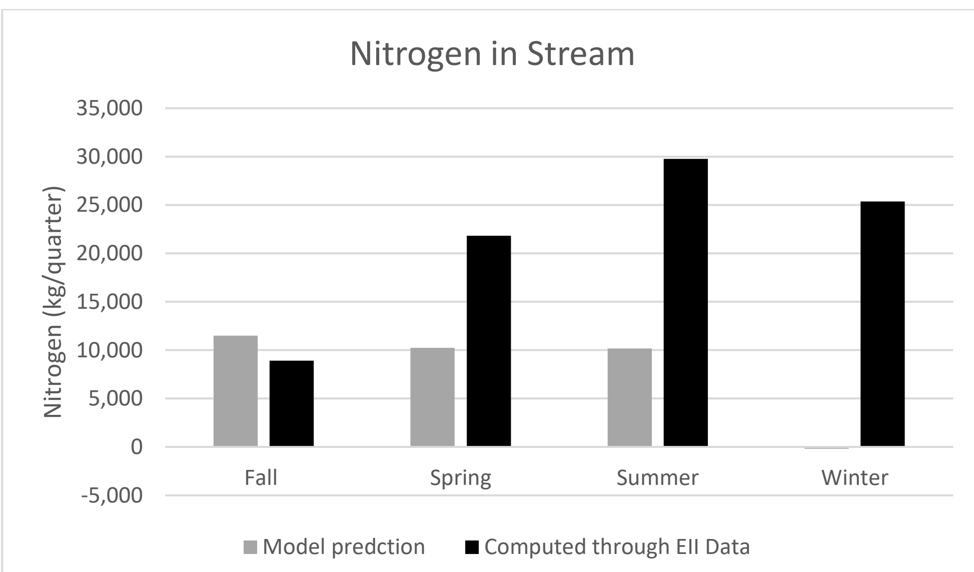

Figure 6: Comparison of Nitrogen in stream predicted by model with Nitrogen in stream obtained through data collection under EII.

First, this model can inform users where deficiencies lie in knowledge about nitrogen in this system. For instance, the model predictions above rely on parameter estimates mostly from the literature. These estimates are not site specific and can be highly variable and dependent on extraneous factors (e.g., social behavior, climate, geomorphological characteristics of the stream, degree of flow permanence). Furthermore, the model suggests that land management inputs are a significant source of nitrogen when compared to other sources or sinks. This underscores the importance of having a better characterization of local land management inputs. Similarly, the largest nitrogen sinks in the model were from denitrification and retention, both occurring in the soil. Estimates of denitrification are highly variable in time and space and dependent on numerous hydrological and biogeochemical factors including stream level fluctuation, sediment hydraulic conductivity and heterogeneity, ambient and stream temperature, availability and ratio of nutrients and carbon (Shuai et al. 2017). This also points to the need for more local data on nitrogen sinks in the environment.

Based on the model results, users can also infer from this model that subsurface processes, such as denitrification and soil retention (which are volume-dependent) are the main drivers of nitrogen consumption, rather than surface processes, such as vegetative uptake or storm water run-off. Per this model, then, the differences in consumption on a per volume basis of upland areas offsets the higher consumption rates of riparian areas. That is, higher consumption rates found in riparian areas cannot match the volumetric based retention found in upland areas. However, since this is an uncalibrated model, it is unclear to what extent this inference holds, and as such, this observation merits further investigation.

A second use of this model is to assist decision makers in setting *a priori* goals to measure the "success" of riparian function. For example, looking at the total amount of nitrogen removed shows that riparian areas will likely outperform upland areas except in winter months. (Figure 7).

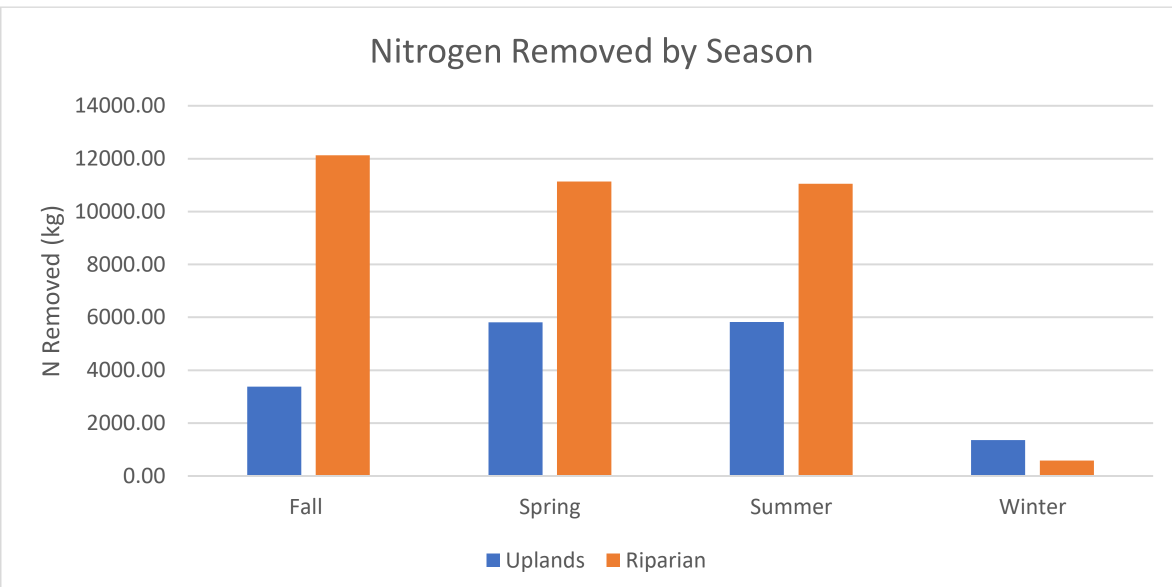

Figure 7: Nitrogen removed from Upland and Riparian Regions by season

An alternative way to evaluate the value of riparian areas to a receiving stream is to look at nitrogen removal on a per area basis, which shows riparian areas far exceeding nitrogen removal rates compared to developed upland areas (Figure 8). Knowing these two different types of success metrics and how they can potentially respond can also inform how future riparian restoration is documented or prioritized.

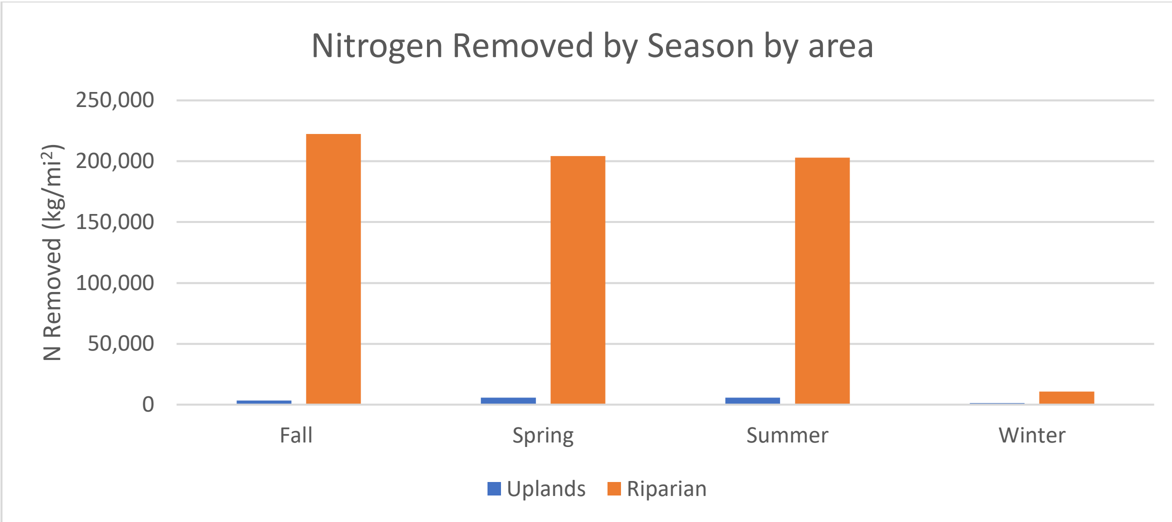

Figure 8: Nitrogen removed per area from Upland and Riparian Regions by season

Thirdly, this model can be used to examine different scenarios and/or to provide comparative evidence. That is, by changing a parameter in the model that cannot be easily changed in the actual environment, one can deduce its impact or importance and decide whether management or restoration efforts are worth moving in that direction. For example, the width of the riparian area was adjusted to determine the relative potential impacts on water quality for the receiving stream. Results from the scenarios indicate that by increasing the riparian areas to 20% of the watershed (from 5%), the reduction of nitrogen loads from both the upland and riparian areas increased from 24,000 kg to about 24,400 kg in the summer, or only about 2% (Figure 9).

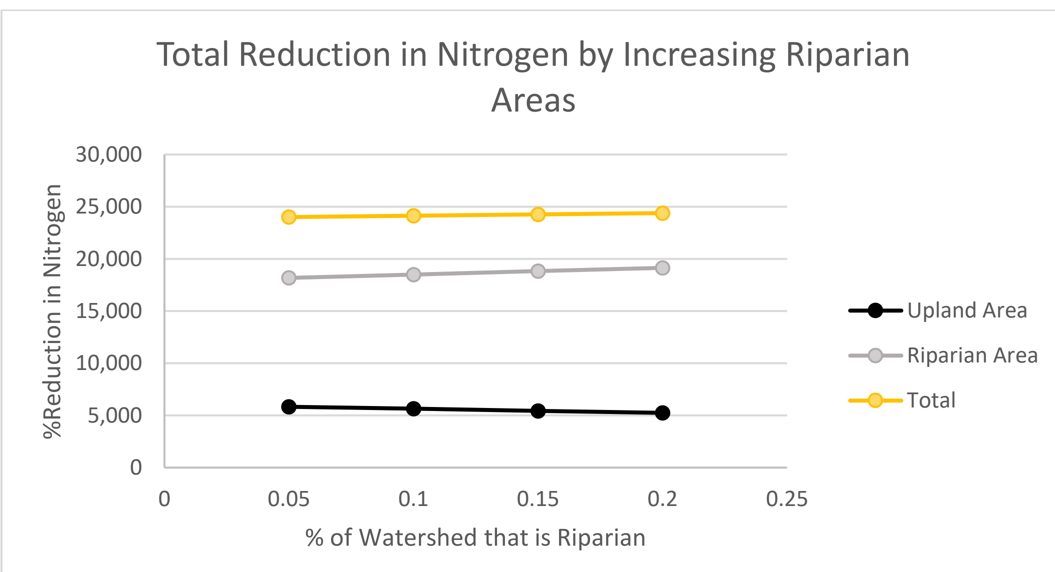

Figure 9: Nitrogen percent removal from Upland and Riparian Regions by adjusting the width of the riparian zone

Conclusion

This report documents a preliminary model to measure the effectiveness of riparian areas in mitigating hydrologic and chemical impacts on a receiving stream. This model was fitted with parameter values attributed from peer-reviewed publications described herein. It was first shown that a simple hydrologic model can be constructed to mimic monthly flow dynamics at Waller Creek. From this simulation, the hydrologic model was able to partition subsurface flow from upland and riparian areas and assess their contribution to the stream. The results of the hydrologic model showed that a large percentage of the flow into and out of the stream comes from the riparian areas, and thus, can have a positive impact on the flow to the receiving stream.

A nitrogen model was also constructed to examine the impacts of a riparian area on stormwater runoff. This model was a simple accounting of various sources and sinks of nitrogen in the watershed and was not accurately calibrated. Per this model, the largest source was land management inputs. The largest sinks of nitrogen were the denitrification and retention that occurs in the soil (i.e. subsurface). Outputs from this model indicate that riparian areas tend to remove or retain large amounts of nitrogen.

While this model met its original objectives as a tool to measure the effectiveness of riparian areas, more advanced, spatially explicit models have been recently utilized to accomplish this same purpose. Moreover, the more advanced models are useful for comparing among different structural controls and can include existing storm drain runoff, as well as smaller time steps. Nevertheless, decision makers can still use this model to test the model assumptions from this report with future studies that can inform future sensitivity or uncertainty analyses. Thus, this parsimonious model is useful in that it sets the foundation for considering what aspects of nitrogen removal in a system are applicable for future study and, more importantly, in establishing *how* to assess the performance of riparian areas in the future. Alternatively, this information herein can inform the direction of other models to incorporate riparian zones into their structure.

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