Scientific Basis for N-Sink

Excerpted from:


1. Landscape N sinks

N-Sink identifies three types of landscape N sinks: riparian wetlands, lentic water bodies (ponds, lakes, or reservoirs), and lotic water bodies (stream reaches). All landscape N sinks are characterized as having Low, Medium, or High potential for N removal, based on estimates calculated for each sink. Because each type of sink has a different range of N removal potential, we have currently chosen to create break points for Low/Medium/High that differ for the three types (Table 1). For example, 30% removal would be considered High for stream reaches, but Low for riparian wetlands. This approach recognizes the inherent characteristics of the different types of sink that affect critical N removal factors, such as retention time. The breakpoints can be changed in future versions.

Table 1. N-Sink High/Medium/Low N removal designations for landscape N sinks

<table>
<thead>
<tr>
<th>N Sink Type</th>
<th>% N removal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Riparian Wetlands</td>
<td>&gt; 60%</td>
</tr>
<tr>
<td>Pond/Lakes/Reservoirs</td>
<td>&gt; 50%</td>
</tr>
<tr>
<td>Stream Reaches</td>
<td>&gt; 30%</td>
</tr>
</tbody>
</table>

*Note: Sections 3.1.1, 3.1.2, and 3.1.3 are adapted from Kellogg et al. (2010).*

1.1 Riparian Wetlands

Riparian wetlands have been identified by many researchers as a significant potential sink for nitrogen. Mayer et al. (2007) performed a meta-analysis on data available in the scientific literature, based on a wide range of field studies, to identify trends between
riparian N removal efficiency and riparian buffer width, surface vs. subsurface flow, and vegetation.

Using widely available GIS data, vegetation type and surface vs. subsurface processes cannot be readily identified. However, riparian land use and soils can be readily identified. It has been well documented that riparian zones are most effective as N sinks when undeveloped and vegetated, and relatively ineffective if hydrologically altered to bypass the riparian ecosystem through residential, agricultural or other types of development (e.g., Carpenter et al., 1998). Research also suggests that riparian wetlands, characterized by hydric soils, act as effective N sinks while riparian areas with non-hydric soils are less reliable N sinks (e.g., Lowrance et al., 1997; Gold et al., 2001; Groffman et al., 2009). Hydric soils provide conditions that favor microbial denitrification: high water table, low dissolved oxygen, and high soil organic matter to provide carbon as an electron donor.

N-Sink therefore uses a series of if/then statements to estimate riparian N removal efficiency. If land use is developed, then we assume no removal. If land use is undeveloped and soils are non-hydric, then we assume no removal. If riparian land use is undeveloped and soils are hydric (i.e., wetland soils), then N removal efficiency is based on the width of the undeveloped (vegetated) hydric soils (Table 2). Regression equations provided by Mayer et al. (2007) guide estimates of N removal effectiveness in vegetated riparian areas as a function of buffer width. The selected width classes recognize commonly used regulatory limits. These estimates are comparable to estimates derived from field assessments that are used to direct management efforts in the Neuse River watershed (Osmond et al., 2008).

Table 2. N-Sink estimates of N removal based on width of riparian wetland

<table>
<thead>
<tr>
<th>Riparian Land Use</th>
<th>Hydric Soil Status</th>
<th>Width (m)</th>
<th>% N removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developed</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vegetated</td>
<td>Non-hydric</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Hydric</td>
<td>&lt; 5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 to 15</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 to 30</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 30</td>
<td>80</td>
</tr>
</tbody>
</table>

a Width classes are based on current regulatory practices and are relevant to local decision-makers.
1.2 Lentic Waterbodies: Ponds, Lakes and Reservoirs

Ponds, lakes and reservoirs are potentially large sinks for N because of their long retention times (Seitzinger et al., 2002, 2006; Harrison et al., 2009), and hypoxic and anoxic benthic zones that provide conditions favoring denitrification. A linear regression analysis of lake and reservoir data from Seitzinger et al. (2002), representing a variety of lentic waterbodies, yields the following relationship between N removal and the ratio of reservoir depth, D [m], and residence time, T [years]:

\[ \text{N removal (\%)} = 79.24 - 33.26 \times \log_{10}(D/T) \]  
(1)

Average lake/reservoir depth can be expressed as volume, \( V [\text{km}^3] \), divided by surface area of the lake/reservoir, \( A_r [\text{km}^2] \). Residence time, \( T [\text{y}] \), can be expressed as volume, \( V [\text{km}^3] \), divided by annual discharge, \( Q_{yr} [\text{km}^3 \text{y}^{-1}] \). Thus,

\[ \frac{D}{T} [\text{m y}^{-1}] = \frac{(V/A_r)}{(V/Q_{yr})} \times 1000 = \frac{Q_{yr}}{A_r} \times 1000 \]  
(2)

We can use available spatial data to estimate discharge at any point in the drainage network as

\[ Q_{yr} = A_d \times Q_{norm} \times 0.031536 \]  
(3)

where \( A_d [\text{km}^2] \) is the drainage area to the point of interest (i.e., the N sink), and \( Q_{norm} [\text{m}^3 \text{s}^{-1} \text{km}^2] \) is the regional estimate of discharge normalized by drainage area, and converted to \([\text{km}^3 \text{y}^{-1} \text{km}^{-2}]\). These regionally explicit normalized flow data are widely available and can be found in USGS reports and USGS online databases (e.g., Armstrong et al., 2004; USGS, 2009). Thus we obtain the ratio

\[ \frac{D}{T} [\text{m y}^{-1}] = \frac{Q_{yr}}{A_r} \times 1000 = Q_{norm} \times \left( \frac{A_d}{A_r} \right) \times 31.536 \]  
(4)

This Alpha version of N-Sink uses a default normalized discharge of 0.022 \( \text{m}^3 \text{s}^{-1} \text{km}^2 \) (2.0 \( \text{ft}^3 \text{s}^{-1} \text{mi}^2 \)). Based on 25 years of data (1976-2000) the mean annual normalized discharge for the South Coastal region of southern New England is \( Q_{norm} = 0.022 \text{ m}^3 \text{s}^{-1} \text{km}^{-2} \), about 80% of the winter/spring normalized discharge, indicating that high flows dominate annual discharge (Armstrong et al., 2004). The selection of normalized discharge warrants careful consideration.
For lakes/reservoirs, absolute change in estimated % N removal with changes in normalized discharge, Q_{norm}, with respect to the mean. The range of changes in Q_{norm} reflects the observed range in monthly normalized discharge for southern New England.

Figure 1

Fig. 1 illustrates the absolute change in estimated % N removal with changes in normalized discharge, Q_{norm}, for the range of monthly flows observed in the South Coastal region of southern New England (0.004 to 0.028 m$^3$s$^{-1}$km$^2$, for the months of September and April, respectively). Because estimated % N removal is directly related to D/T and D/T is proportional to Q_{norm}, the absolute change in % N removal is independent of drainage area. However, the importance of drainage area is expressed by the % N removal at any given Q_{norm}. For example, for Q_{norm} = 0.022 m$^3$s$^{-1}$km$^2$, % N removal is estimated to be 75% at A_d/A_r = 2, 41% at A_d/A_r = 20, and 18% at A_d/A_r = 100 (Figs. 2 & 3).

Fig. 2

For lakes/reservoirs, % change in estimated N removal (as %) with changes in Q_{norm} with respect to the mean, for a range of the ratio A_d/A_r, drainage area to reservoir area. The range of changes in Q_{norm} reflects the observed range in monthly normalized discharge for southern New England.
Due to occasional water releases, reservoirs can be viewed as hydrologically distinct from lakes and ponds. Outflow from reservoirs can be regulated by dam(s), thereby shifting residence time from that expected for a natural lake based on drainage area. Because of the uncertainty associated with dam manipulation schedules, N-Sink treats reservoirs the same as lakes when characterizing N removal potential.

1.3. Lotic Waterbodies: Stream Reaches

The role of streams in watershed nitrogen dynamics has been the focus of intensive research, with early studies formulating the nutrient spiraling model (e.g., Newbold et al., 1981), which has since been used to assess in-stream denitrification (e.g., Royer et al., 2004). The wide range of observed nitrogen loss rates within streams has spurred research using both field experiment techniques and statistical approaches based on spatial data. The Lotic Intersite Nitrogen Experiment (LINX) has used N addition and isotopic analysis to explore the extent to which stream characteristics – hydrodynamic, chemical, and metabolic – might explain the wide variation among streams in nitrogen uptake, removal and cycling.

Alexander et al. (2000) developed a hybrid statistical/mechanistic mass-balance model to estimate N flux in the Mississippi basin (SPARROW – SPAtially-Referenced Regression
On Watershed attributes, correlating observations of stream N flux with spatially referenced N sources and physical characteristics of the landscape and water bodies. Regression results showed that N loss rates were inversely related to stream depth and that much of the N removal in streams was occurring in lower order reaches. They concluded that the proximity of N sources to higher order streams and rivers is an important factor in N delivery to the Mississippi basin outlet. Recognizing the variability of stream function among different regions of the U.S., SPARROW has since been developed for other parts of the country, including New England (Moore et al., 2004). An important result of the New England modeling effort was the lack of statistically significant annual modeled N reduction for streams with flows greater than 2.83 m$^3$ s$^{-1}$, highlighting the importance of lower-order streams in mitigating watershed N export.

Alexander et al. (2007) further refined this New England SPARROW model to investigate and quantify the influence of headwater streams of the northeastern U.S. on N delivery to downstream waters. The extent of N removal and cycling in streams, including the permanent removal of N via denitrification, is limited by the extent of interaction with the stream channel and hyporheic zone, both of which decrease with increasing stream order and drainage area. Alexander et al. (2007) incorporated what was currently known about N transport to arrive at an expression for the fraction of N transported along a stream reach as a function of stream characteristics. We used this expression as follows:

$$N \text{ (\%)} \text{ removed \ along \ stream \ reach} = (1 \ - \ \exp (-\theta_{s1}D_{B52}^{\theta_{s2}})) \times 100$$

(5)

where $\theta_{s1} = 0.0513$ m d$^{-1}$, $\theta_{s2} = -1.319$, $D =$ water depth [m], and $T =$ time of travel [d].

Water depth, $D$, is expressed as a function of mean annual stream flow, $Q$ [m$^3$ s$^{-1}$] (Alexander et al., 2000):

$$D = 0.2612Q^{0.3966}$$

(6)

This expression originates from Leopold and Maddock (1953) with flow data from 112 streams in the South and MidWestern U.S. Kellogg et al. (2010) used similar methods to examine the appropriateness of this expression to estimate stream reach depths in southern New England and found close agreement (within 10%) when $Q$ is less than 10 m$^3$ s$^{-1}$. N-SINK therefore uses Eq. 6 to estimate stream depth because it is based on a larger sample of streams that encompasses a wide range of geographic settings and is in line with widely-used relationships.

Mean travel time, $T$ [d], along a given stream reach can be expressed as reach length [m]/ mean velocity [m d$^{-1}$]. Reach length can be extracted from the spatial data using
simple GIS tools. The mean velocity of a dissolved constituent along a stream reach can then be estimated using available spatial data applied to the following relationship (Jobson, 1996; Equation 14):

$$V \ [\text{m s}^{-1}] = 0.020 + [0.051 \times (D'_a)^{0.821} \times (Q'_a)^{-0.469} \times Q/D_a]$$

(7)

where \(D_a\) = drainage area \([\text{m}^2]\) to the downstream point of the stream reach under consideration, \(D'_a\) = dimensionless drainage area = \((D_a^{1.25} \times \sqrt{g})/Q_a\), \(Q_a\) = mean annual discharge from the stream reach \([\text{m}^3 \text{ s}^{-1}]\), \(Q'_a\) = dimensionless relative discharge = \(Q/Q_a\), and \(g\) = acceleration of gravity = 9.8 m \(s^{-2}\).

For stream reaches, the normalized discharge, \(Q_{\text{norm}}\), and the drainage area, \(A_d\), affect the extent to which stream water can interact with sediments and other stream features. A higher discharge rate \((Q_{\text{norm}} \times A_d)\) translates into a shorter retention time. Water depth, \(D\), retention time (i.e., time of travel), \(T\), and N removal within each stream reach can be estimated using spatial data combined with regionally explicit USGS stream flow data applied to each reach.

**Stream Reaches**

<table>
<thead>
<tr>
<th>Absolute change in N removal (as %) with change in (Q_{\text{norm}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A_d) = drainage area ((\text{km}^2))</td>
</tr>
</tbody>
</table>

![Fig. 4](image)

For stream reaches, absolute change in % N removal from a 1 km stream reach over a range of normalized discharge, \(Q_{\text{norm}}\), and drainage area, \(A_d\).
As for lakes/reservoirs, this Alpha version of N-Sink uses a default value for normalized discharge of 0.022 m$^3$ s$^{-1}$ km$^2$ (2.0 ft$^3$ s$^{-1}$ mi$^2$). Sensitivity of % N removal estimates from a 1 km stream reach to changes in Q$_{\text{norm}}$ is illustrated in Figures 4 and 5.

2. Landscape N Sources

N-Sink currently recognizes two types of N sources: unsewered developed land and agriculture as row crops. Future versions can be modified to recognize a more extensive array of sources and corresponding loads.

2.1 Developed Land

N-Sink lumps all developed land (e.g., residential development, institutional, commercial) and assumes that it leaches N at a rate similar to unsewered medium density residential development. Future versions of N-Sink will distinguish between different types of developed land, such as different densities of residential...
development, and different types of agricultural land. Future versions will also allow the user to change the N loading rate from selected areas.

N-Sink assumes that unsewered developed land contributes 41.7 lb N/acre/yr, from the combined contributions of septic systems and lawns, based on the following assumptions:

For one household (or dwelling unit, d.u.), N input to the septic system is 8.8 lb N/cap/yr (U.S. EPA, 2002). If we assume an average of 3 people/household, this comes to 26.4 lb N/d.u./yr. Medium density residential is typically characterized by ½ acre zoning, or 2 d.u./acre. Thus, septic system input is 52.8 lb N/ac/yr. We assume that 21% of that N leaches from the septic system (Gold et al., 1990), which comes to 41.7 lb/ac/yr. Gold et al. (1990) also found that fertilized lawns contributed only a fraction of the total N load.

2.2. Agricultural Land

N-Sink currently assumes that agricultural land is cultivated as row crops, with N loading similar to silage corn. This is a crop that is common to southern New England and can contribute N loads comparable to unsewered residential development. N-Sink assumes crops are fertilized with manure and that no cover crop is planted. By assuming no cover crop, we are presenting a “worst case” scenario. Cover crops can serve to sequester excess nutrients present in the soil, and reduce the leaching of nutrients from the field. N-Sink uses the average of two years of data presented in Gold et al. (1990), arriving at a load of 53.7 lb N/ac/yr from agricultural row crops.

N sources are characterized as Low, Medium, or High in N loading, based on the area and loading rate. The Low N loading is characterized as < 5,000 lb N/yr, Medium is 5,000 to 25,000 lb N/yr, and High is > 25,000 lb N/yr. Note that the Table of Contents mis-labels the units as lb/acre/yr. This will be addressed in future versions. In particular, we may find that distinguishing developed lands according to intensity (lb/acre/year) rather than total load (lb/yr) would be more useful to decision makers.