environment SOUTHLAND REGIONAL COUNCIL
Te Taiao Tonga

Memorandum

For Your Information

To: The Independent Hearing Panel for the proposed Southland Water and Land Plan

From: Roger Hodson

Date: Wednesday, 12 July 2017

File Reference: pSWLP

Subject: ***Response to Hearing Panel Question's 12 June***

Message:

At the hearing for the proposed Southland Water and Land Plan on 12 June 2017, two Memoranda were tabled, being:
(1) Memorandum from Roger Hodson in respect of Setbacks dated 25 May 2017; and
(2) Memorandum from Roger Hodson in respect of Site Exceedance dated 9 June 2017. .

The Independent Hearing Panel has asked further questions in respect of those memoranda. The questions and my responses are set out below.

(1) Memorandum – Setbacks.

Question: Figure 1.0 on page 10 shows a large amount of data scatter, accordingly:

1. *What is the correlation coefficient for the first formula in the figure (slopes from 0 to 10 degrees)?*

Response:

The figure (referred to as figure 1.0 in previous memorandum) in question is reproduced from Figure 4 on page 81 of Zhang et al. (2010). The units of the 'x' axis are in % slope not degrees. Zhang et al. (2010) use the model illustrated to define the break point where the relationship between buffer slope and sediment removal efficiency changes from positive to negative. The inflection point is estimated to be 10% slope, with a 95% confidence interval of 8.14 to 11.725 % slope.

Zhang et al. (2010) go on to select a final model for predicting sediment removal efficacy (Table 3 on page 82 of Zhang et al. (2010)). For sediment removal the R^2 value increased from 0.373 to 0.654 when vegetation (mixed grass and trees or grass/trees only) buffer slope and buffer width (soil drainage type was not statistically significant) were added to the final model. The authors provide a segmented linear model, and I have used equations for mixed grass and trees vegetative cover, equation "a" for slopes less than 10% and equation "c" for slopes greater than 10% (from table 3 on page 82 of Zhang et al. (2010)). Note that in table 1.0 of the memorandum dated 25 May 2017 I have converted slopes from % to degrees.

Question:

2. *What are the corresponding margins of error (i.e. plus or minus x%) in the figures presented in Table 1.0 on that same page.*

<u>Response:</u>

In the original publication, Zhang et al. (2010) do not provide a margin of error around each of vegetation/slope/buffer width predicted contaminant removal efficiencies, and similarly I am unable to provide a margin of error for the individual estimates. However, Zhang et al. (2010) do provide a 95% confidence interval for the initial theoretical model for sediment removal by buffer width only, see figure 3(a) on page 80 of Zhang et al. (2010), reproduced in part below as figure 1.0 (note this is not the final model which included vegetation type, slope and buffer width).

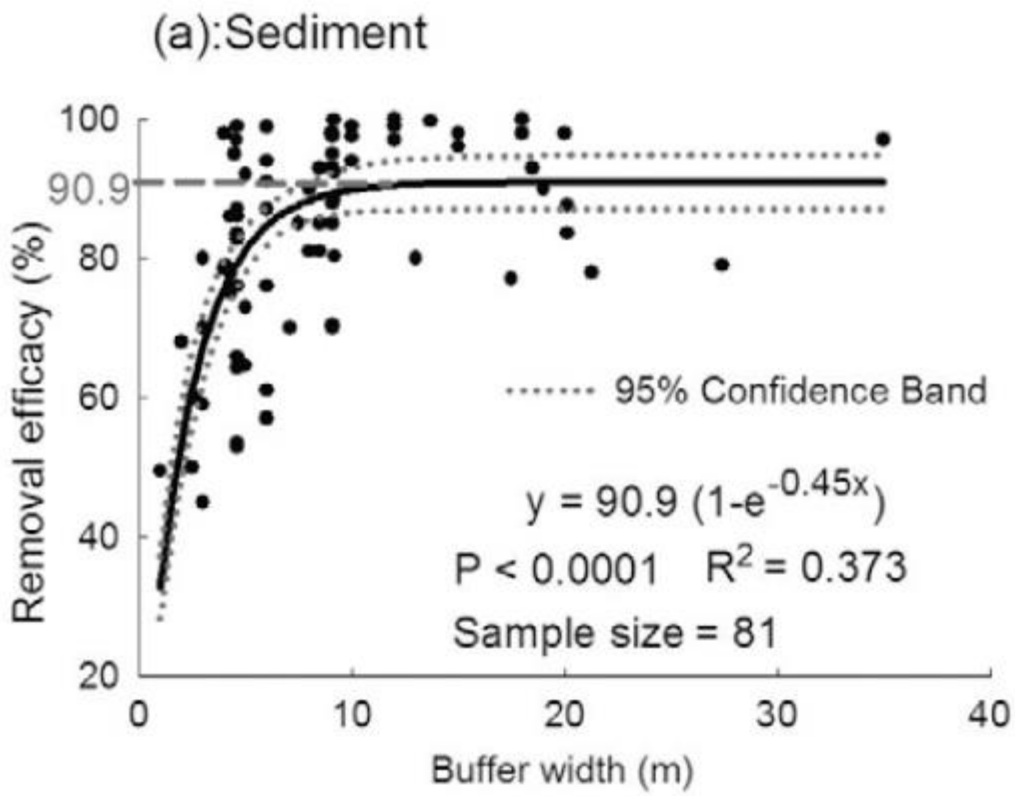

Figure 1. Sediment removal efficacy vs buffer width. From figure 3(a) on p. 80 of Zhang et al. (2010).

(2) Memorandum – Site Exceedance
Question:
For each of Tables 1.0 to 6.0 could Mr Hodson please provide the monitoring period?
For example, Figures 1.0 and 3.0 indicate that the monitoring period for Tables 1.0 and 3.0 is 2012 to 2106, does that mean five calendar years?

<u>Response:</u>

I can confirm that the monitoring periods for each of the figures reproduced in the memorandum dated 9 June 2017 are the same as those that were produced in the opening presentation on 22 May 2017. I have tabulated the respective monitoring periods for each figure below (Table 1.0)

Figure number (9 June 2017 Memorandum)	**Monitoring period**
1.0 Secondary Contact Recreation	January 2012 – December 2016 (5 years)
2.0 Primary Contact Recreation	December 2011 – March 2016 (5 summer monitoring periods)
3.0 Lakes – Total Nitrogen	January 2012 – December 2016 (5 years)
4.0 Lakes Phytoplankton	January 2012 – December 2016 (5 years)
5.0 Slime algae – Periphyton in Rivers	Summer 2001/2002 – Summer 2010/2012, n ≥ 6 *
6.0 Macroinvertebrate Community Index	Summer 2009/10 – Summer 2013-14 (5 years), n ≥ 3

*Assessment provided from predicted level of benthic periphyton (chlorophyll-a) and frequency, i.e. level exceeded 8% (1 month) of the time for the default class and 17% (2 months) for the productive class, using the site mean and the exponential distribution. As described in opening presentation on 22 May 2017, and in Snelder et al. (2013).

References

Snelder, T., Biggs, B., Kilroy, C., Booker, D. 2013. National Objective Framework for periphyton. Prepared for Ministry for the Environment. NIWA Client Report No:CHC2013-122
http://www.mfe.govt.nz/sites/default/files/national-objective-framework-periphyton.pdf

Zhang, X., Liu, X., Zhang, M., Dahlgren, R., A. 2010, A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in reducing Nonpoint Source Pollution. Journal of Environmental Quality

Published January, 2010

A Review of Vegetated Buffers and a Meta-analysis of Their Mitigation Efficacy in Reducing Nonpoint Source Pollution

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Vegetated buffers are a well-studied and widely used agricultural management practice for reducing nonpoint-source pollution. A wealth of literature provides experimental data on their mitigation efficacy. This paper aggregated many of these results and performed a meta-analysis to quantify the relationships between pollutant removal efficacy and buffer width, buffer slope, soil type, and vegetation type. Theoretical models for removal efficacy (Y) vs. buffer width (w) were derived and tested against data from the surveyed literature using statistical analyses. A model of the form $Y = K \times (1 - e^{-b \times w})$, $(0 < K \leq 100)$ successfully captured the relationship between buffer width and pollutant removal, where K reflects the maximum removal efficacy of the buffer and *b* reflects its probability to remove any single particle of pollutant in a unit distance. Buffer width alone explains 37, 60, 44, and 35% of the total variance in removal efficacy for sediment, pesticides, N, and P, respectively. Buffer slope was linearly associated with sediment removal efficacy either positively (when slope ≤ 10%) or negatively (when slope > 10%). Buffers composed of trees have higher N and P removal efficacy than buffers composed of grasses or mixtures of grasses and trees. Soil drainage type did not show a significant effect on pollutant removal efficacy. Based on our analysis, a 30-m buffer under favorable slope conditions (≈ 10%) removes more than 85% of all the studied pollutants. These models predicting optimal buffer width/slope can be instrumental in the design, implementation, and modeling of vegetated buffers for treating agricultural runoff.

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Agricultural nonpoint-source pollution has been listed as one of the leading sources of pollution in rivers and water bodies throughout the world (World Resources Institute, 1992). This pollution, which includes sediment, nutrients, and pesticides, can be transported off-site to surface waters via runoff events generated either by irrigation or natural precipitation. Agricultural management practices, such as vegetated buffers, constructed wetlands, and conservation tillage, have been used to reduce the runoff of these pollutants.

Vegetated buffers are widely used in agricultural production for reducing agricultural nonpoint-source pollution and have been well-studied in the scientific literature. They are designed to use vegetation to remove sediment, nutrients, and pesticides from surface water runoff through filtration, deposition, adsorption, and infiltration (Dillaha et al., 1989). A variety of terms are used in the literature to describe vegetated buffers, including "vegetative filter strips", "grass filters," "vegetative buffer strips," "filter strips," or "buffer strips." This paper uses the term "vegetated buffers" to refer to all the buffers represented by these terms.

Many studies suggest that vegetated buffers are effective in removing pollutants from runoff (e.g., Dillaha et al., 1989; Vought et al., 1994; Syversen, 2002, 2005; Uusi-Kämppä et al., 2000). For example, Patty et al. (1997) found that buffers with widths of 6, 12, and 18 m could reduce 87 to 100% of suspended sediment, 47 to 100% of nitrate, 22 to 89% of soluble P and 44 to 100% of the herbicide atrazine from agricultural runoff. The pollutant mitigation efficacy of vegetated buffers depends on three factors: (i) the physical properties of the buffer, such as width, slope, soil type, and vegetation cover; (ii) the properties of the pollutant in question, such as the sediment particle size, the form of N or P, or the biophysical properties of pesticides (e.g., water solubility and half-life); and (iii) the placement of the buffer, such as its proximity to pollutant sources (Norris, 1993). The relative importance of these factors varies in the literature depending on the specific experimental settings of the studies. It is essential to quantify the impacts of these factors for effective design and implementation of vegetated buffers.

Most studies investigating the pollutant removal efficacy of vegetated buffers focused on field or plot experiments which were set up under very specific conditions. Due to the specificity of site conditions and experimental settings of these studies, the identi-

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Table 1. Summary of collected data.

Variables	Sediment	Nitrogen	Phosphorus	Pesticides
Number of study sites	27	10	10	4
Number of buffers	56	22	19	8
Data on buffer width	81	61	52	49
Data on buffer slope	79	12	8	0
Data on vegetation	81	61	52	49
Data on soil drainage type	81	61	52	12

fied relationships between buffer efficacy and associated factors were often inconsistent. To obtain a systematic understanding of vegetated buffer mitigation efficacy, results from studies conducted under different experimental settings and site conditions should be compared with this in mind and synthesized to obtain general insights.

Due to the multi-pollutant nature of agricultural runoff, studies must also compare the buffer removal efficacy for multiple pollutants. Existing review papers addressing the efficacy of vegetated buffers are either focused on a single type of pollutant such as sediment (Liu et al., 2008), N (Mayer et al., 2007), P (Dorioz et al., 2006), or pesticides (Reichenberger et al., 2007, Otto et al., 2008); or they cover multiple types of pollutants in a descriptive nature (Muscutt et al., 1993). Although these review papers synthesized information on the efficacy of vegetated buffers, they did not provide a statistical analysis for the results of the studies reviewed, nor did they determine a theoretical framework for the relationship between the pollutant removal efficacy of buffers and their key design factors. Therefore, the objectives of this paper were (i) to aggregate data from studies on the mitigation efficacies of vegetated buffers for removing sediment, N, P, and pesticides; and (ii) to quantify the relationships between pollutant removal efficacy and buffer design factors through theoretical models and statistical analysis of the aggregated data.

Materials and Methods

Literature Review

A total of 73 studies published in peer reviewed journals provided quantitative results on pollutant removal by vegetated buffers, of which 63 were original studies and 10 were literature reviews. These papers were carefully examined to record detailed information on author, year, location, buffer width, slope, area

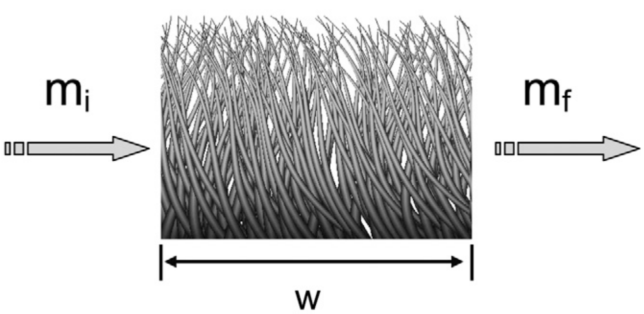

Fig. 1. Model variables in an illustrated vegetated buffer. m_i is the mass inflow of pollutant and m_f is the mass outflow of the pollutant after exiting a buffer of width *w*.

to source ratio, pollutant type, soil type, vegetation type, inflow pollutant mass and concentration, outflow pollutant mass and concentration, and percent of pollutants trapped by buffers.

Surveyed data were compiled to perform meta-analyses for buffer design factors: width, slope, vegetation type, and soil drainage type (see Supplemental Table S1 in the supplemental information). A total of 81 data points were collected on buffer width, slope, vegetation type, and soil drainage type for sediment removal (Table 1). Few data were available on slope for removal of N, P, and pesticides, however, more than 49 data points were identified for the other three variables. Different forms of N and P were reported in surveyed studies and were pooled for statistical analysis to ensure power. The forms of N were total N (44%), nitrate (46%), and ammonium (10%). The forms of P were soluble P (48%) and total P (52%).

Theoretical Framework: Buffer Width

Both "width" and "length" have been used in the literature to describe the dimension of buffers, depending on their shape. Here we define "buffer width" as the dimension parallel to runoff flow. Studies on buffer efficacy frequently reported that wider buffers removed more pollutants, but they often did not quantify the relationship between buffer width and pollutant removal efficacy. Qualitatively, one would expect that the pollutant reduction would increase as width increases, at some point reaching a limit where further increasing the buffer width will not substantially increase the efficacy. This expectation was based on two reasons. First, while infiltration is taking place, pollution mass is lost to infiltration with each successive unit of buffer width. Second, the most easily trapped forms (e.g., large sediments) of pollutants will be easily trapped in the upper buffer while the smaller particles (or soluble forms) will be more difficult to trap. Therefore, a point will be reached where effectively all of the pollutant has been removed and additional buffer width will make little difference.

The quantity we have chosen to model with respect to pollutants is the total mass of the pollutant removed by the buffer. We chose mass over concentration because mass balance is often used to study environmental transport of pollutants. If data on actual pollutant mass measurement did not exist, mass was calculated by multiplying concentration and flow. The removal efficacy can be defined in the following equation:

$$Y = \left(\frac{m_i - m_f}{m_i}\right) \times 100\% = \left(1 - \frac{m_f}{m_i}\right) \times 100\% \qquad [1]$$

where Y is the percent efficacy, m_i is the mass of the pollutant inflow into the buffer, and m_f is the mass of the pollutant outflow from that same buffer (Fig. 1).

Assuming the runoff water is a well mixed column and contains pollutants both in dissolved and adsorbed phases. We make the following assumption:

The probability that any given amount of pollutant will be removed by the buffer is constant for a given distance traveled through the buffer.

If the probability of removal is constant, then the decrease in pollutant mass with distance is proportional to the mass itself:

$$\frac{dm}{dx} = -b \times m \quad [2]$$

where m is the mass of the pollutant, x is the distance into the buffer, and b is the probability of removal per unit length for a given pollutant (here defined as constant with respect to x). The solution to this differential equation is of the form:

$$m = A \times e^{-bx} \quad [3]$$

Using the following boundary conditions (from the definition of efficacy in Eq. [1]):

$$\text{at } x = 0,\ m = m_i;\ \text{at } x = w,\ m = m_f \quad [4]$$

where w is the total width of the buffer (Fig. 1), we find that $A = m_i$ and that

$$\frac{m_f}{m_i} = e^{-b \times w} \quad [5]$$

Substituting Eq. [5] into Eq. [1] yields the following relationship between efficacy (Y) and buffer width (w):

$$Y = (1 - e^{-b \times w}) \times 100\% \quad [6]$$

This equation should hold for each of the pollutants in question (with a different value of b for each pollutant) as long as Eq. [2] holds and the probability of removal per unit length (b) is constant within the buffer.

In practice, a constant (K) must be introduced to fit the data:

$$Y = K \times (1 - e^{-b \times w}),\ 0 < K \leq 100 \quad [7]$$

This constant reflects the practical limit on the ability of a vegetated buffer to remove a pollutant from runoff. This quantity is developed further in the discussion section.

The assumption used to derive Eq. [2] is reasonable based on two reasons. First, removal of dissolved pollutants by infiltration, which is the major mechanism, is proportional to the mass of water that infiltrates. For example, when saturated hydraulic conductivity is attained, infiltration becomes constant. In this case change in pollutant mass per unit width is also constant. Second, the main mechanism for removal of adsorbed pollutant is sedimentation and sorption. Both processes are dependent on initial pollutant mass.

However, this is a gross oversimplification. The assumption does not hold on the following conditions where: (i) water totally infiltrates within a buffer and no outflow occurs at the end of the buffer; (ii) additional pollutant mass is released from the buffer itself; and (iii) the probability that the particle will be removed depends on the runoff velocity, particularly for the case of sediment, in which velocity decreases due to friction as the runoff travels through the buffer. Nevertheless, this assumption captures the basic behavior of pollutants in the buffer and can be applied to all the pollutants studied in this meta-analysis.

Theoretical Framework: Effect of Buffer Slope on Sediment Removal

As buffer slope increases, runoff velocity increases, reducing the residence time of runoff in the buffer and reducing removal efficacy. There is evidence, however, that a slight slope facilitates runoff and encourages laminar flow across the buffer, increasing removal efficacy (Wenger, 1999). Modeling the effects of slope on laminar flow and residence time are beyond the scope of this paper; however, the data can be fit with a segmented linear model (broken-stick model) to reflect the change in regime, such as increased laminar flow and decreased residence time. This is done by choosing a critical slope, S_c, at which the latter effect dominates and the efficacy begins to decrease. The two regimes are then independently fit to the data as follows;

$$Y = \alpha + \beta_1 \times x - \beta_2 \times (x - S_c) \times I \quad [8]$$

Where x is the slope of the buffer in percent, Y is the pollutant removal efficacy, and α, β_1 and β_2 are fitting parameters. The breakdummy $I = 1$ if x is greater than the break value S_c, or 0 otherwise. The model can be rewritten to the following form:

$$Y = \begin{cases} \alpha + \beta_1 \times x & \text{when slope} \leq S_c \\ \alpha + (\beta_1 - \beta_2) \times S_c + \beta_2 \times x & \text{when slope} > S_c \end{cases} \quad [9]$$

This model constrains the two lines to join. The values of the break point S_c, α, β_1, and β_2 can be estimated using a nonlinear algorithm (Piegorsch and Bailer, 2005).

Theoretical Framework: Vegetation and Soil Type Classification

Different vegetation types may remove different pollutants with varying efficacies. The studies reviewed in this paper gave species names in many cases, but this study group vegetation using a functional classification scheme. Many grasses will function similarly in a vegetated buffer, and many trees will function similarly in a buffer. In the analysis, vegetation type was classed as either grasses, trees, or a mixture of grasses and trees.

In the literature, soil type was described in a variety of ways, including 'sandy' or 'clay' and in a few cases information was given regarding percentage of sand, silt, and clay. To simplify this variable, the soil type was categorized by how well the soil drains. This classification captures the functional effect of soil type on efficacy, because how well the soil drains will affect infiltration of runoff water. In the analysis, soil drainage types were classified as well drained, moderately drained, and poorly drained.

Since the variables of vegetation type and soil drainage type are categorical, dummy variables were used in the analysis to indicate vegetation and soil drainage type: trees (Veg1 = 1), mixture of grasses and trees (Veg2 = 1), and grasses (Veg1 = Veg2 = 0); and well drained (Sol1 = 1), moderately drained (Sol2 = 1), and poorly drained (Sol1 = Sol 2 = 0).

Statistical Analysis

This section describes the statistical analyses which test the fit of the aggregated data to Eq. [7] and [8]. The aggregated efficacy data extracted from the reviewed studies were analyzed using a set of statistical procedures. Boxplots were created to examine the distribution of efficacy values. The relationship between pollutant removal efficacy and buffer width was fitted to the theoretical model as shown in Eq. [7] using nonlinear

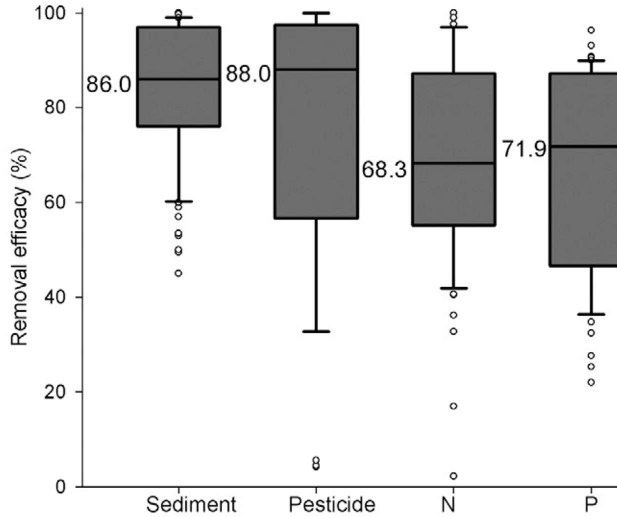

Fig. 2. Boxplot of pollutant removal efficacy values. The lower and upper boundary of the box indicates the 25th and 75th percentile, respectively. A line within the box marks the median. Bars above and below the box indicate the 90th and 10th percentiles. The hollow circles represent observations that are not within the range of the 10th to 90th percentile. The numbers displayed next to the boxes are the median value of removal efficacy. Sample sizes are 81, 49, 61, and 52 for sediment, pesticide, N (includes various forms of nitrogen), and P (includes various forms of P), respectively.

regression analysis. The relationship between buffer slope and sediment removal efficacy was fitted to the segmented linear regression model as shown in Eq. [8]. A preliminary statistical model with all the variables including buffer width, slope, vegetation type, soil drainage type, and site was built and tested for the significance of each independent variable. Statistical tests were performed to test the interactions among these variables. Results indicated that none of these interaction terms were significant; therefore the models were built without them.

A final model was built based on the independent variables that were found to be statistically significant. To examine the differences between and within study sites, a mixed effect model was first built with a random error associated with site. However, the parameter of site and its associated random error were found to be not significant with P values > 0.8 for all pollutant models. Therefore, site was removed from the models. Statistical diagnostics (including the normal probability plot of residuals, a plot of the residuals vs. the fitted values, and a histogram of the residuals) were used to determine whether the residuals met the statistical analysis assumptions (in particular the normality and constant variance assumptions). Models were selected based on their goodness-of-fit measures such as the R^2 value and adjusted R^2 value. All the statistical analyses were performed using SAS 9.1 (SAS Institute Inc., 2004) and SigmaPlot 10 (Kuo and Fox, 1993).

Results and Discussion

Pollutant Removal Efficacy

Figure 2 shows the distribution of removal efficacy values of vegetated buffers grouped by pollutants across a range of widths (0.5–35 m) and slopes (2–16%). The median removal efficacy is highest for pesticides (88%), followed by sediment (86%), P (71.9%), and N (68.3%). Sediment removal efficacy has the lowest standard deviation (14.4) of the four pollutants with a range of 45 to 100% (Daniels and Gilliam, 1996; Patty et al., 1997). In contrast, N removal efficacy has the widest range (2.2–99.9%) and standard deviation (21.1). Phosphorus removal efficacy has a smaller range (22–96.3%) than N, but the same standard deviation (21.1). Pesticide removal efficacy varies the most (standard deviation = 28.5) with a wide range in efficacy (4.2–99.9%) (Murphy and Shaw, 1997; Patty et al., 1997; Watanabe and Grismer, 2001) (Fig. 2).

Effects of Buffer Width

Regression equations and parameter estimates from the fit of the data to the theoretical model (Eq. [7]) are summarized in Table 2. Estimates of K, which represents the maximum removal efficacy of the buffer, ranged from 89.5 to 93.2. Estimates of parameter b, which reflects the probability of removal per unit distance of a given particle of pollutant, ranged from 0.157 to 0.446. All the models were statistically significant (P < 0.001) with R^2 values of 0.373, 0.597, 0.437, and 0.352 for sediment, pesticide, N, and P, respectively (Table 2).

Figure 3 shows the relationship between buffer width and pollutant removal efficacy for sediment (Fig. 3a), pesticides (Fig. 3b), N (Fig. 3c), and P (Fig. 3d). In all cases, as is expected for an exponential function such as Eq. [7], the removal efficacy increases quickly with increase in buffer width and the rate of increase becomes smaller as the buffer gets wider until the efficacy approaches a maximum value (the removal capacity). Of the buffers studied for sediment removal, 97% were < 20 m in width and more than 60% were <10 m. Buffer widths from pesticide removal studies range from 0.5 to 18 m. Removal capacity for pesticides was the highest of the four pollutants with pesticide removal efficacy reaching as high as 93.2% (Fig. 3b). More than 96% of the buffers studied for N and P removal were < 20 m wide. Nitrogen and P removal efficacy showed a similar pattern, though N removal efficacy reaches

Table 2. Nonlinear regression models and parameter estimates using buffer width as the independent variable.

	$Y = K \times (1 - e^{-bx})$				Estimate of K			Estimate of b		
Pollutant	N	R^2	SE†	P	K	SE‡	P	b	SE§	P
Sediment	81	0.373	11.44	<0.001	90.9	1.96	<0.001	0.446	0.047	<0.001
Pesticide	52	0.597	18.30	<0.001	93.2	5.86	<0.001	0.215	0.045	<0.001
Nitrogen	61	0.437	15.94	<0.001	92.0	6.40	<0.001	0.160	0.028	< 0.001
Phosphorus	52	0.352	17.18	<0.001	89.5	7.47	<0.001	0.157	0.033	< 0.001

† Residual standard deviation of regression model.

‡ Standard error of the estimate of K.

§ Standard error of the estimate of b.

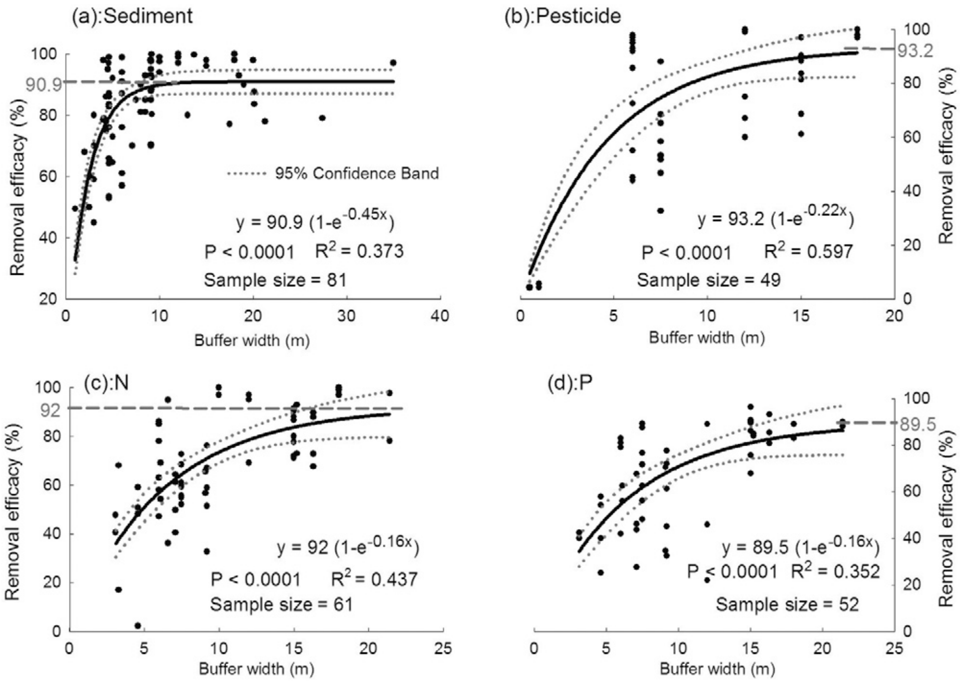

Fig. 3. Pollutant removal efficacy vs. buffer width for each pollutant. Black dots are data and lines are model predictions. Dotted red lines indicate 95% confidence band. The limiting value of *K* is shown in pink with a dotted line. Details of the model are given in each figure for (a) sediment, (b) pesticides, (c) N, and (d) P.

a slightly higher removal capacity (92%) than P (89.5%) (Fig. 3c, 3d).

Interpretation of *K* and *b*

The meta-analysis results demonstrate that the relationship between pollutant removal efficacy and buffer width can be described by a model of the form $Y = K \times (1 - e^{-b \times w})$, $(0 < K \leq 100)$. Although the maximum removal capacity K can be 100 according to the model, the estimate of K is always smaller. There are several reasons for this finding. First, the variance of data for statistical estimates of K is essentially the mean of the removal capacities of many different buffers built under various experimental designs. For a given pollutant, some designs may have a low probability for pollutant removal and therefore have a low efficacy for a given width, pulling down the overall removal average. Second, if our simplified model has overlooked mechanisms that have a significant impact on efficacy as a function of distance, the inadequacy of the model itself may result in a low value of K for a given pollutant. For instance, additional nutrients may be released from vegetation or soil during transport through the buffer (Chaubey et al., 1995; Lowrance and Sheridan, 2005), and this may cause nutrient mass in outflows to be higher than our theoretical model can predict because it assumes no new pollutant is added within the buffer. Finally, chemical partitioning between the water and sediment column maintains pollutant residues in water as long as the amount of runoff water is not zero.

Although K is an estimate of the practical limit on the efficacy of a buffer, some of our data points reach 100% efficacy. These data might be from situations where no runoff water flows out of the buffer, in which our model does not hold. Another possible reason is that there is an analytical detection threshold for each pollutant below which no pollutant will be detected despite the continued presence of the pollutant in runoff. This threshold indicates that the pollutant may be present at low concentrations despite the fact that the analytical analysis does not detect it.

Although our analysis is based on the assumption that the probability of pollutant removal by the buffer is constant with respect to distance traveled through the buffer, more sophisticated models can be built by more realistically modeling the probability of removal as a function of x. Many studies have shown that removal efficacy may be high in the first few meters of a buffer but decreases as pollutants travel through the buffer. For example, accumulation of sediment changes the microtopography of a buffer and turns the runoff flow from laminar to concentrated flow (Gharabaghi et al., 2006). In this case, b could be described as a function of microtopography and flow rate. In addition, the estimates of b increase in the order of P, N, pesticide, and sediment indicating that b may be associated with solubility of the pollutant. Further research is needed to investigate the underlying source/sink processes for each pollutant to model the efficacy when the probability of pollutant removal in a buffer is not constant throughout the buffer. This can be realized when more data become available in the future.

Effects of Buffer Slope

In the literature reviewed, buffer slope varied from 2% (Daniels and Gilliam, 1996, Van Dijk et al., 1996) to as high as 16% (Dillaha et al., 1989). The break point (S_c) where the relationship between buffer slope and sediment removal efficacy changes from positive to negative is estimated to be 10% with a 95% of confidence interval of 8.14 to 11.72%. Figure 4 shows the fit of the data to the proposed model (Eq. [8]) which is as follows:

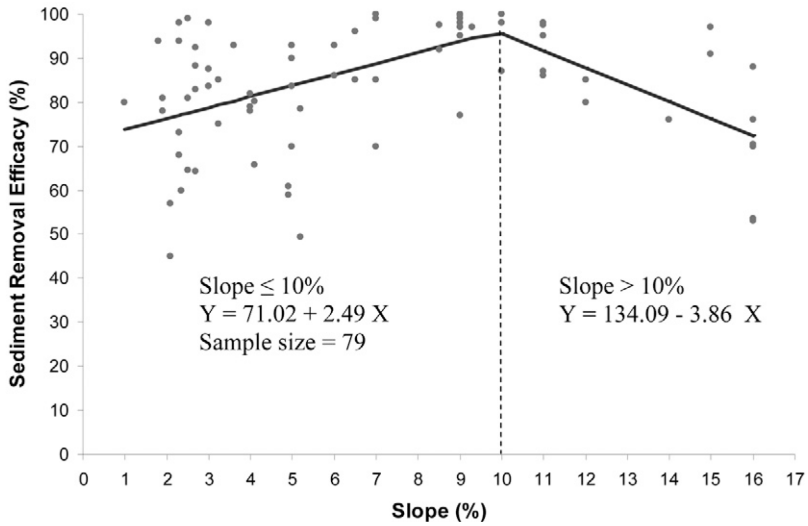

Fig. 4. Correlation between sediment removal efficacy and buffer slope.

$$Y = \begin{cases} 71.02 + 2.49 \times x & \text{when slope} \le 10\% \\ 134.09 - 3.86 \times x & \text{when slope} > 10\% \end{cases} \qquad [10]$$

As shown in Eq. [10], the parameters α, β_1, and β_2 are estimated to be 71.02 (SE = 3.65), 2.49 (0.67), and –3.86 (1.14), respectively. All the estimates are statistically significant with P values < 0.001. Sediment removal efficacy increases as slopes increase from 0 to 10%. Buffers steeper than 10% become less effective with increasing slope (Fig. 4). The fit to our aggregated data suggests that with 95% confidence, a slope between 8.14 and 11.72% is optimum for removing sediments by vegetated buffers.

Effects of Vegetation Type and Soil Drainage Type

The impacts of vegetation type on pollutant removal efficacy were statistically significant for all pollutants except pesticides. Buffers composed of only grasses or trees remove more sediment than that with mixed grasses and trees (Table 3). For N and P removal, vegetation composed of trees has a higher removal efficacy than vegetation composed of grasses or mixed grasses and trees (Table 3). The impact of soil drainage type on pollutant removal efficacy was not statistically significant (Table 3) and therefore, soil drainage type was not included in the final model. Models which include all selected factors are shown in Table 3, with R^2 values of 0.654, 0.492, 0.475, and 0.597 for sediment, N, P, and pesticides, respectively. The P values of these models show that the models were all highly significant (Table 3).

Sediment Removal Efficacy

Vegetated buffers are generally effective in removing sediment from runoff. Buffer width, slope, and vegetation type are important factors for designing an effective buffer. Buffer efficacy is more sensitive to a change in width at smaller widths, as expected for an exponential relationship. Table 4 shows that, increasing the buffer width from 5 to 10 m would increase sediment removal efficacy by 10 to 15%. With a 10% slope, a 20-m buffer composed of only grasses or trees would remove almost all the sediment from runoff (Table 4). The results illustrated that increasing width to more than 20 m does not appreciably increase removal efficacy. This is due to the fact that large soil aggregates (> 40 μm in diameter), sand and silt particles are deposited by sedimentation within the first few meters of the buffer (Gharabaghi et al., 2006), while small aggregates and fine clay particles are removed by infiltration in a wider buffer. When the infiltration rate is lower than flow rate, fine particles are unlikely to be removed from the water column.

A vegetated buffer with a slope of about 10% (8.1–11.7%) is optimum for sediment removal. Increasing buffer slope from 5 to 10% would increase sediment removal efficacy by about 10%, while increasing slope from 10 to 16% would reduce the sediment removal efficacy by about 20% (Table 4). A slight slope (≤ 10%) may facilitate runoff and laminar flow over the buffer. In contrast, increased steepness (> 10%) could increase the flow velocity of the runoff water, reducing residence time of runoff water and therefore reducing sediment trapping efficacy.

Buffers composed of only grass species or trees remove more sediment as compared with buffers composed of a mixture of grasses and trees. The data for mixed grasses and trees were mainly from two studies, Schmitt et al. (1999) and Väänänen et al. (2006). Schmitt et al. (1999) planted young trees and shrubs in the lower half of vegetated buffers and found no impact on filter performance, while the buffers in the Väänänen et al. (2006) study had very low efficacies due to high runoff volume and velocity. These significantly lower efficacies might be caused by other factors such as placement of trees and runoff velocity.

R^2 values for sediment removal increased from 0.373 to 0.654 when vegetation and slope were added as additional independent variables, indicating the significant impact of slope and vegetation in addition to buffer width in accounting for variation in the data. The full model with buffer width, vegetation type, and slope explained 66% of the total variance in buffer efficacy. Since the nonlinear model contains linear components (slope, vegetation type, and soil type), it is inevitable to have predictions of Y over 100. In this case, the value of 100 was assigned to the removal efficacy.

The unexplained variation in sediment removal efficacy could be due to other factors, such as the type of runoff flow. For example, shallow, uniform flow is essential in maintaining a high pollutant

Table 3. Effects of selected variables and model statistics.

	Sediment	Nitrogen	Phosphorus	Pesticide
Buffer width	Exponential	Exponential	Exponential	Exponential
Vegetation	Grasses/trees > mixed grass and trees†	Trees > grasses/mixed grasses and trees	Trees > grasses/mixed grasses and trees	Not significant
Soil drainage type	Not significant	Not significant	Not significant	Not available
Slope	Positive when slope ≤ 10% Negative when slope > 10%	Not available	Not available	Not available
Full model	(a) Slope ≤ 10%; mixed grasses and trees $Y = 6.9 + 2.0 \times X_{slope} + 61.0 \times (1 - e^{-0.35 \times x_{width}})$ (b) Slope ≤ 10%; grasses/trees only: $Y = 21.7 + 2.0 \times X_{slope} + 61.0 \times (1 - e^{-0.35 \times x_{width}})$ (c) Slope > 10%; mixed grasses and trees $Y = 64.9 - 3.8 \times X_{slope} + 61.0 \times (1 - e^{-0.35 \times x_{width}})$ (d) Slope > 10%; grasses/trees only $Y = 79.7 - 3.8 \times X_{slope} + 61.3 \times (1 - e^{-0.35 \times x_{width}})$	(a) Mixed grasses and trees/grasses only $Y = 10.2 + 91.4 \times (1 - e^{-0.11 \times x_{width}})$ (b) Trees only $Y = 23.9 + 91.4 \times (1 - e^{-0.11 \times x_{width}})$	(a) Mixed grasses and trees/ grasses only $Y = 30.5 + 147 \times (1 - e^{-0.03 \times x_{width}})$ (b) Trees only $Y = 59.8 + 147 \times (1 - e^{-0.03 \times x_{width}})$	$Y = 93.2 \times (1 - e^{-0.22 \times x_{width}})$
Statistics	$R^2 = 0.654$ $N = 81$ $P < 0.001$	$R^2 = 0.492$ $N = 61$ $P < 0.001$	$R^2 = 0.475$ $N = 52$ $P < 0.001$	$R^2 = 0.597$ $N = 49$ $P < 0.001$

† This means that buffers with grasses only or trees only vegetation had higher pollutant removal efficacy compared to buffers with mixed grasses and trees vegetation.

removal efficacy in vegetated buffers. Helmers et al. (2005) found through modeling buffer sediment trapping that as the convergence of overland flow increases, sediment-trapping efficacy is reduced. Dosskey et al. (2002) revealed that the "effective buffer area", which is the area of the buffer that field runoff would encounter, accounted for 6 to 81% of the total buffer area. The modeled sediment trapping efficacy ranged from 15 to 43% for the effective area compared to 41 to 99% for the total area (Dosskey et al., 2002). These results reflected the extent of concentrated flow and its subsequent impact on sediment-trapping efficacy (Dosskey et al., 2002). Therefore, the maintenance of sheet flow, which is typically difficult, is very important in maintaining sediment removal efficacy. Because our model does not include this factor, the higher degree of variance which is not accounted for is expected. The actual sediment removal efficacy may be lower than predicted under concentrated flow conditions and we did find a lower sediment removal efficacy at the watershed scale compared to the field scale.

Nitrogen and Phosphorus Removal Efficacy

Vegetated buffers are effective for removing N and P, with removal efficacy of 92% and 89.5%, respectively. The models suggest that buffer width and vegetation together explain about 50% of the variation in N removal efficacy and 48% of the variation in P removal efficacy (Table 3). Increasing the buffer width from 5 to 10 m would increase the removal efficacy by about 20% and 18% for N and P, respectively (Table 4). A 20-m buffer removes about 91 to 100% and 97 to 100% of N and P, respectively (Table 4).

Buffers composed of trees generally remove more N from runoff. The significant difference indicates that subsurface removal of N may be an important mechanism since trees could better remove N with their deeper rooting system. The potential importance of subsurface hydrology and biogeochemistry for N removal has been suggested in a previous study (Mayer et al., 2007). Denitrification rates are often greatest when the groundwater table is near the surface and when microbially-labile carbon and nitrate N are in good supply (Bradley et al., 1992; DeSimone and Howes, 1996; Groffman et al., 2002). The presence of oxygen is often the controlling factor for nitrate removal since denitrification is an anaerobic process and oxygen inhibits the reaction.

However, the impacts of vegetation on P removal are more complicated. Our study found that trees generally remove more P than grasses. Phosphorus removal also differs between different grass species. A study by Abu-Zreig et al. (2004) in a field near Elora, ON, Canada suggested that native grass species were more effective in removing P than ryegrass and red fescue, and McFarland and Hauck (2004) found that coastal

Table 4. Predicted pollutant removal efficacy.

		Predicted removal efficacy, %			
	Buffer width =	5 m	10 m	20 m	30 m
Sediment	(a) Slope = 5%; mixed grass and trees	67	76	78	78
	(b) Slope = 5%; grass/trees only	82	91	93	93
	(c) Slope = 10%; mixed grass and trees	77	86	88	88
	(d) Slope = 10%; grass/trees only	92	100†	100	100
	(e) Slope = 15%; mixed grass and trees	58	67	68	68
	(f) Slope = 15%; grass/trees only	73	81	83	83
Nitrogen	(a) Mixed grass and trees/grass only	49	71	91	98
	(b) Trees only	63	85	100	100
Phosphorus	(a) Mixed grass and trees/grass only	51	69	97	100
	(b) Trees only	80	98	100	100
Pesticide		62	83	92	93

† If predicted values exceed 100, the value of 100 was assigned instead.

Bermuda grass was more effective in trapping P than sorghum [*Sorghum bicolor* (L.) Moench] or wheat (*Triticum aestivum* L.).

Even though some studies indicated that soil properties can affect P removal efficacy, we did not find a significant effect associated with soil drainage type. Cooper et al. (1995) revealed that in riparian zones the degradation of soil structure following compaction by grazing resulted in a decrease in buffer efficacy. Studies found higher retention efficacy for total P and dissolved P by sandy soil than silty clay (Magette et al., 1989; Schwer and Clausen, 1989). However, soil drainage type as an independent variable was not significant in any of our models.

Although we were not able to obtain enough data on slope for N and P removal, we suspect that slope would have had significant impacts on buffer efficacy given the significant contribution of slope to the sediment removal model. Further research on the effects of slope is needed to obtain a more thorough understanding of N and P removal by vegetated buffers.

Pesticide Removal Efficacy

Vegetated buffers showed high removal efficacy for pesticides. Based on our model, a buffer of 30 m could remove 93% of the pesticides from runoff. Buffers wider than 30 m do not appreciably improve the removal efficacy. This prediction is mainly based on a model built with studies performed on herbicides, with soil and water partition coefficients (K_{oc}) ranging from 100 to 1000. Pesticides with K_{oc} > 1000 (strongly hydrophobic), such as pyrethroids and many organophosphates, can adsorb strongly to organic carbon in sediment. Since sediments are easily removed by buffers, these pesticides are more easily removed by vegetated buffers. This indicates that vegetated buffers could be even more effective in removing these hydrophobic pesticides than the model predicts because the model is based on pesticides with contrasting K_{oc}.

Buffer width alone explained over half of the variation in pesticide removal efficacy, while vegetation type did not show a significant impact on pesticide removal efficacy. Although we were not able to obtain enough data on slope and soil type for pesticide removal, we suspect that adding slope and soil type to the model would help explain additional variation. The unexplained variation could also be due to physiochemical properties of pesticides such as K_{oc}. For water soluble pesticides, infiltration was expected to be the main retention process, while sorption to sediments was expected to be the main retention process for hydrophobic pesticides. However, due to the extremely skewed distribution of K_{oc} values for the pesticides used in the studies, we were unable to perform statistical analyses on the effect of K_{oc}. Nevertheless, the R^2 value of 0.597 confirmed that buffer width was a very important factor governing the efficacy of pesticide removal by vegetated buffers.

Model Uncertainties

Although our models captured a reasonable amount of variance in buffer removal efficacy, the model predictions contain uncertainty due to three primary reasons. First, our model is an oversimplification of a complex set of processes. In addition to the factors studied, the area of the field which is the source of the runoff, irrigation amount (simulated or natural rainfall) and duration of the studies (days vs. months vs. years) may also play important roles. Seasonality of vegetation within buffers may also cause the efficacy to vary during different times of year. While buffers are typically effective when newly installed, their efficacies may decrease as they age (Wenger, 1999).

Second, the environmental settings and management scenarios of the studies vary considerably. Buffers installed under different climate conditions may perform differently and require different management. Increased infiltration by buffers may allow pollutants to reach groundwater in areas with highly permeable soil and shallow groundwater tables. Finally, the models for N, P, and pesticide removal would be greatly improved had there been enough information on buffer slope available in the literature. The optimum buffer width and slope to achieve reduction for multiple pollutants may differ from the predictions presented in this paper. However, the model revealed the quantitative relationships between mitigation efficacies of vegetated buffers and their width, vegetation type, and slope. This information could serve as baseline data for setting guidelines for buffer implementation and installation. In addition, estimated parameters could facilitate further investigations on buffer efficacy beyond field scale. Researchers have initiated modeling efforts to evaluate different scenarios to implement best management practices at the watershed scale. Their modeling results have been limited by lack of knowledge of the relationships between buffer efficacy and key buffer design factors (Arabi et al., 2007). The results of this paper could be a valuable addition to the current knowledge base and thus assist in future modeling efforts to study the mitigation efficacy of vegetated buffers.

Conclusions

This study quantified the relationship between pollutant removal efficacy and key buffer design factors, concluding that efficacy is largely influenced by the buffer width, slope, and vegetation type. Statistical models found that buffer width was a significant factor in the removal of all the pollutants, explaining 37, 60, 44, and 35% of the total variance in removal efficacy for sediment, pesticides, N and P, respectively. Buffer slope was shown to be significantly associated with sediment removal efficacy, with slopes in the range of 8.14 to 11.72% being optimal. Regarding vegetation type, buffers composed of trees have higher N and P removal efficacy than other vegetation types. The models established in this analysis are highly useful not only in the prediction of the removal efficacy of various pollutants, but also in the creation of the optimal buffer design to achieve a desired reduction of multiple pollutants simultaneously. These models can therefore provide valuable information for simulating vegetated buffer efficacy at the watershed scale, which is increasingly becoming a useful scientific tool for making effective policy and regulation decisions to reduce nonpoint-source pollution.

Supplemental Information Available

Aggregated data from the literature review on buffer width, vegetation type, soil drainage type and slope, as well as the sources of the data are available as supplemental information (Supplemental Table S1) at http://jeqscijournals.org.

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References

Abu-Zreig, M., R.P. Rudra, M.N. Lalonde, H.R. Whiteley, and N.K. Kaushik. 2004. Experimental investigation of runoff reduction and sediment removal by vegetated filter strips. Hydrol. Processes 18:2029–2037.

Arabi, M., R.S. Govindaraju, and M.M. Hantush. 2007. A probabilistic approach for analysis of uncertainty in the evaluation of watershed management practices. J. Hydrol. 333:459–471.

Bradley, P.M., M. Fernandez, and F.H. Chapelle. 1992. Carbon limitation of denitrification rates in an anaerobic groundwater system. Environ. Sci. Technol. 26:2377–2381.

Chaubey, I., D.R. Edwards, T.C. Daniel, P.A. Moore, and D.J. Nichols. 1995. Effectiveness of vegetative filter strips in controlling losses of surface-applied poultry litter constituents. Trans. ASAE 38:1687–1692.

Cooper, A.B., C.M. Smith, and M.J. Smith. 1995. Effects of riparian set-aside on soil characteristics in an agricultural landscape: Implications for nutrient transport and retention. Agric. Ecosyst. Environ. 55:61–67.

Daniels, R.B., and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60:246–251.

DeSimone, L.A., and B.L. Howes. 1996. Denitrification and nitrogen transport in a coastal aquifer receiving wastewater discharge. Environ. Sci. Technol. 30:1152–1162.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint source pollution-control. Trans. ASAE 32:513–519.

Dorioz, J.M., D. Wang, J. Poulenard, and D. Trevisan. 2006. The effect of grass buffer strips on phosphorus dynamics–A critical review and synthesis as a basis for application in agricultural landscapes in France. Agric. Ecosyst. Environ. 117:4–21.

Dosskey, M.G., M.J. Helmers, D.E. Eisenhauer, T.G. Franti, and K.D. Hoagland. 2002. Assessment of concentrated flow through riparian buffers. J. Soil Water Conserv. 57:336–343.

Gharabaghi, B., R.P. Rudra, and P.K. Goel. 2006. Effectiveness of vegetative filter strips in removal of sediments from overland flow. Water Qual. Res. J. Can. 41:275–282.

Groffman, P.M., N.J. Boulware, W.C. Zipperer, R.V. Pouyat, L.E. Band, and M.F. Colosimo. 2002. Soil nitrogen cycle processes in urban riparian zones. Environ. Sci. Technol. 36:4547–4552.

Helmers, M.J., D.E. Eisenhauer, M.G. Dosskey, T.G. Franti, J.M. Brothers, and M.C. McCullough. 2005. Flow pathways and sediment trapping in a field-scale vegetative filter. Trans. 48:955–968.

Kuo, J., and E. Fox. 1993. Sigmaplot user's manual. Jandel Scientific, San Rafael, CA.

Liu, X., X. Zhang, and M. Zhang. 2008. Major factors influencing the efficacy of vegetated buffers on sediment trapping: A review and analysis. J. Environ. Qual. 37:1667–1674.

Lowrance, R., and J.M. Sheridan. 2005. Surface runoff water quality in a managed three zone riparian buffer. J. Environ. Qual. 34:1851–1859.

Magette, W.L., R.B. Brinsfield, R.E. Palmer, and J.D. Wood. 1989. Nutrient and sediment removal by vegetated filter strips. Trans. ASAE 32:663–667.

Mayer, P.M., S.K. Reynolds, Jr., M.D. McCutchen, and T.J. Canfield. 2007. Meta-analysis of nitrogen removal in riparian buffers. J. Environ. Qual. 36:1172–1180.

McFarland, A.M.S., and L.M. Hauck. 2004. Controlling phosphorus in runoff from long term dairy waste application fields. J. Am. Water Resour. Assoc. 40:1293–1304.

Murphy, G.P., and D.R. Shaw. 1997. Effects of vegetative filter strip width on reducing fluometuron and norflurazon losses in surface runoff. Tech. Bull. 214. Mississippi Agric. and Forestry Exp. Stn., Mississippi State Univ., Starkville.

Muscutt, A.D., G.L. Harris, S.W. Bailey, and D.B. Davies. 1993. Buffer zones to improve water quality: A review of their potential use in UK agriculture. Agric. Ecosyst. Environ. 45:59–77.

Norris, V. 1993. The use of buffer zones to protect water quality: A review. Water Resour. Manage. 7:257–272.

Otto, S., M. Vianello, A. Infantino, G. Zanin, and A. Di Guardo. 2008. Effect of a full-grown vegetative filter strip on herbicide runoff: Maintaining of filter capacity over time. Chemosphere 71:74–82.

Patty, L., B. Réal, and J.J. Gril. 1997. The use of grassed buffer strips to remove pesticides, nitrate and soluble phosphorus compounds from runoff water. Pestic. Sci. 49:243–251.

Piegorsch, W.W., and A.J. Bailer. 2005. Analyzing environmental data. John Wiley & Sons, New York.

Reichenberger, S., M. Bach, A. Skitschak, and H.-G. Frede. 2007. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness: A review. Sci. Total Environ. 384:1–35.

SAS Institute Inc. 2004. SAS 9.1.3 Help and documentation, 2002–2004. SAS Inst. Inc., Cary, NC.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. J. Environ. Qual. 28:1479–1489.

Schwer, C.B., and J.C. Clausen. 1989. Vegetative filter treatment of dairy milkhouse waste-water. J. Environ. Qual. 18:446–451.

Syversen, N. 2002. Effect of a cold-climate buffer zone on minimising diffuse pollution from agriculture. Water Sci. Technol. 45:69–76.

Syversen, N. 2005. Effect and design of buffer zones in the Nordic climate: The influence of width, amount of surface runoff, seasonal variation and vegetation type on retention efficiency for nutrient and particle runoff. Ecol. Eng. 24:483–490.

Uusi-Kämppä, J., B. Braskerud, H. Jansson, N. Syversen, and R. Uusitalo. 2000. Buffer zones and constructed wetlands as filters for agricultural phosphorus. J. Environ. Qual. 29:151–158.

Väänänen, R., M. Nieminen, and M. Vuollekoski. 2006. Retention of phosphorus in soil and vegetation of a buffer zone area during snowmelt peak flow in Southern Finland. Water Air Soil Pollut. 177:103–118.

Van Dijk, P.M., F. Kwaad, and M. Klapwijk. 1996. Retention of water and sediment by grass strips. Hydrol. Processes 10:1069–1080.

Vought, L.B.M., J. Dahl, C.L. Pedersen, and J.O. Lacoursiere. 1994. Nutrient retention in riparian ecotones. Ambio 23:342–348.

Watanabe, H., and M.E. Grismer. 2001. Diazinon transport through inter-row vegetative filter strips: Micro-ecosystem modeling. J. Hydrol. 247:183–199.

Wenger, S. 1999. A review of the scientific literature on riparian buffer width, extent and vegetation. Univ. of Georgia, Athens.

World Resources Institute. 1992. The 1992 Information please environmental almanac. Houghton Mifflin Co., Boston, MA.