Journal of Spatial Hydrology
Vol.6, No.2, Fall 2006

Estimating Limiting Nutrient Loadings in an Interacting Surface and Ground Water Basin

Ahmed Said[1]

Abstract

Watershed management requires the determination of both point and non-point sources of pollution within a watershed. The primary non-point source pollutants in a typical watershed are nutrients (mainly nitrogen and phosphorus), sediment, and pesticides. In the Snake River Basin, in Idaho, nutrients from non-point sources (primarily agricultural) are delivered to streams via storm water and irrigation runoff. However, the objectives of this study were to estimate the phosphorus loading from different sources in the Snake River Basin due to storm water events, to calculate the total nitrogen/phosphorus (TN/TP) ratios for land uses, and to compare and a precipitation runoff model and statistical regression with the measurements. The study used the Long-Term Hydrologic Impact Assessment (L-THIA) model to perform the analysis and to estimate the loss and gain in phosphorus loading. The gain was due to ground water discharge and point sources from industrial and commercial trout farms. The loss was attributed to phosphorus absorbance, existence of riparian vegetation, ground water discharge, or dilution from spring inflows. The results showed that phosphorus is the limiting nutrient. The L-THIA model gave more accurate results than the simple statistical regression.

Key Words: L-THIA model, water quality, sediment, Snake River Basin, Idaho

Introduction

Phosphorus (P) and nitrogen (N) are important to all living organisms. However, both of them have been identified as having an impact water quality in certain regions where concentrations have become too high for the ecosystems in which they are found. In normal aquatic ecosystems, the total nitrogen/total phosphorus ratios do not exceed 1 P to every 16 N in biomass and it is typically 7.2. If the TN/TP ratio in the water is less than 7.2, it indicates that nitrogen is limiting (Chapra 1997). The main reason for the difference nitrogen and phosphorus is the relative availability of nitrogen, which is abundant in the atmosphere.

Specific sources of nutrients in the Snake River Basin are non-point sources, point sources (e.g., aquaculture facilities), and ground water recharge. Non-point sources include: (1) agricultural activities (e.g., cattle manure, commercial fertilizer, legume crops), (2) urban runoff, (3) atmosphere deposition, (4) aquaculture facilities, and (5) domestic septic systems.

The largest sources of phosphorus are point sources sewage effluent, subsurface land drainage, and agricultural runoff. In the Eastern Snake River Plain, excessive irrigation is a common practice in the area and creates the potential for nitrate and pesticide leaching and/or runoff. At least 85% of the Eastern Snake River Plain land is in sprinkler irrigation and the other 15% is in flood and furrow irrigation (Lombardo et al., 1999). Nitrogen can also come from nitrogenous waste in human and animal excrement. It can also come directly from the nitrogen in the atmosphere, which is converted into a usable form by nitrogen fixation organisms.

---

[1] *Department of Geosciences, Idaho State University-Boise Center, Boise, ID, USA, Email: asaid@isu.edu,*

The NRCS has estimated the amount of manure produced on an animal unit equivalent basis for various livestock sectors, as well as the nutrient content of that manure (NRCS 1995). The TN/TP ratios range from 2.6 to 3.2 except for dairy animal manure, which reaches 6.4.

Commercial fertilizer consists of primary plant nutrients, such as nitrogen, phosphorus, and potash. Phosphate is not very mobile in soil; it tends to remain attached to solid particles rather than dissolving in water. However, soil erosion can transport a considerable amount of particulate phosphate into streams. The N/P ratio for the whole time ranged from 2.9 to 5.0 and shows an increasing trend. About 11 M tons of nitrogen and 2 M tons of phosphorus are applied annually in commercial fertilizer, which at present has a TN/TP ratio of 5.5 (The Fertilizer Institute 2000).

Like soil erosion, storm water runoff in urban areas can also carry soil particles (minerals, organic matter and attached nutrients) and dissolved nutrients. In addition, irrigation runoff is a significant transporter for nutrients from non-point sources (primarily agricultural). However, this study focuses on the nutrients that are delivered via storm water runoff and therefore, a precipitation runoff model was used. The Long Term Hydrologic Impact Assessment (L-THIA) model is able to deal with a wide range of soils and land use conditions such as those of the Snake River Basin. The model has been successfully implemented in assessing water quality degradation studies (e.g., Bhaduri et al., 2000; Pandey et al., 2000; Grove et al., 2001) based on the change in land uses.

The purposes of this study are to estimate TN/TP ratios in different land uses, to determine the limiting nutrient in the interacting surface and ground water in the Snake River Basin, and to estimate the phosphorus loading from non-point, point sources, and ground water discharge in the Snake River Basin. This information can be used to improve quality of surface and ground waters and to help manage the generation and application of nutrients in the Snake River Basin.

Study Area

The Snake River Basin extends from its headwaters at Jackson Lake in northwestern Wyoming, to the point of its confluence with the Columbia River in Washington. It covers portions of five states: Wyoming, Idaho, Utah, Nevada, and Oregon. The Snake River Plain also is divided into Upper (eastern Snake River Plain) and Middle (western Snake River Plain) segments on the basis of geology and hydrology. This study is limited to that portion of the Snake River Basin, which is located in Idaho. More than twenty major sub-basins contribute to the Snake River and constitute its basin as shown in Figure 1.

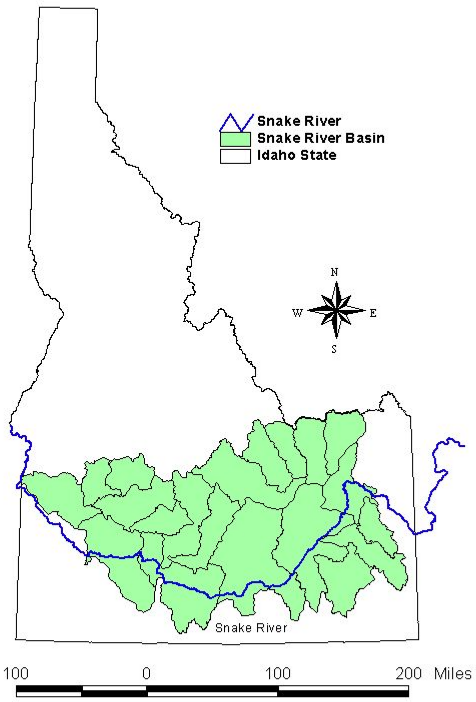

Figure 1: Snake River Basin in Idaho

Material and Methods

Data Collection

Data presented in this study were collected from the U.S. Environmental Protection Agency water quality data base STORET and the USGS data base WATSTORE during all months of the year. Data from thirteen stream gaging stations on the Snake River Basin were used for water years 1980-1989 (Clark 1994). The drainage areas and predominant land use categories around these stations were obtained from the GIS maps (IDWR, 2004). Total nitrogen and phosphorus measured for water years 1993-1995 along with the loss or gain in the loading were used from Clark (1997).

Watershed Modeling

Watershed-scale physically-based hydrologic and NPS water quality models are generally either continuous simulation models for long-term simulation (e.g., AnnAGNPS, HSPF, and SWAT) or single-storm event models (e.g., AGNPS, ANSWERS, DWSM, and KINEROS), or have both capabilities (e.g., CASC2D, MIKE SHE, and PRMS) (Borah and Bera 2003, Wang, et al. 2005). Selecting an appropriate model should take into account the intended use and the accuracy required (McKillop et al. 1999, Wang, et al. 2005). The L-THIA NPS is a single-storm model, but it uses export coefficient approach to predict pollutant loads from each source in the study area. This model is bundled with web-base non-proprietary GIS data layers that can be functioned as an educational tool. In this study, L-THIA was selected to determine the nutrients present in the storm water runoff.

Not all of these models were used for water quality simulation in the Snake River Basin. However, AGNPS, SWAT, and ANSWERS among other models can be used to estimate pollution loads from agricultural lands, but they need numerous data and they are much more sophisticated than L-THIA NPS model (Brusven et al. 1995, Lima et al. 2005).

L-THIA NPS Model

To estimate nutrient loading on the Snake River Basin due to storm water, the Long Term Hydrologic Impact Assessment and Non-Point Source Pollutant (L-THIA NPS) model was used. The model was developed as a spreadsheet application by Harbor (1994) and GIS have been utilized to enhance spatial data management and spatial analyses (Grove 1997). This model was designed to help quantify the impact of land use on the quantity and quality of water and would, therefore be useful for this application. However, nutrients from non-point sources (primarily agricultural) are delivered to Snake River and its tributaries primarily via irrigation runoff and not during storm water events.

The L-THIA NPS model provides long-term average annual runoff estimates for a land use configuration based on actual long-term climate data for an area (Bhaduri et al. 2000). The runoff values are calculated using the curve number (CN) method (SCS 1972). With the annual runoff depth, it is possible to calculate runoff volume. A simple calculation using volume and the event mean concentration (EMC) provides an estimate of the annual loading of chemicals, including nutrients and pesticides (Engel 2001). The model does not take into account the potentially significant effect of soil pH. There are two main input GRID themes that have been used in this study: land use (Figure 2) and soil types (Figure 3).

Precipitation as a text file is a third input and can be obtained from the database linked to the model. The main outputs are runoff depth, runoff volume, and the NPS pollutant concentrations based on the EMC.

Curve Number

Direct average runoff volume Q is predicted for average daily rainfall by using the SCS curve number equation 1 (SCS 1972):

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{1}$$

where Q is the daily runoff, P is the daily rainfall that can be estimated from the long term precipitation or GRID GIS theme, and S is potential infiltration. S varies among watersheds, since soils, land use, and slope may be different and since, with time, soil water content changes. The curve number for the Snake River Basin is shown in Figure 4.

The parameter S in Equation 1 is related to a soil type curve number (CN) by Equation 2 (SCS 1972):

$$S = \frac{1000}{CN} - 10 \tag{2}$$

CN is a function of land use, surface condition, and soil group.

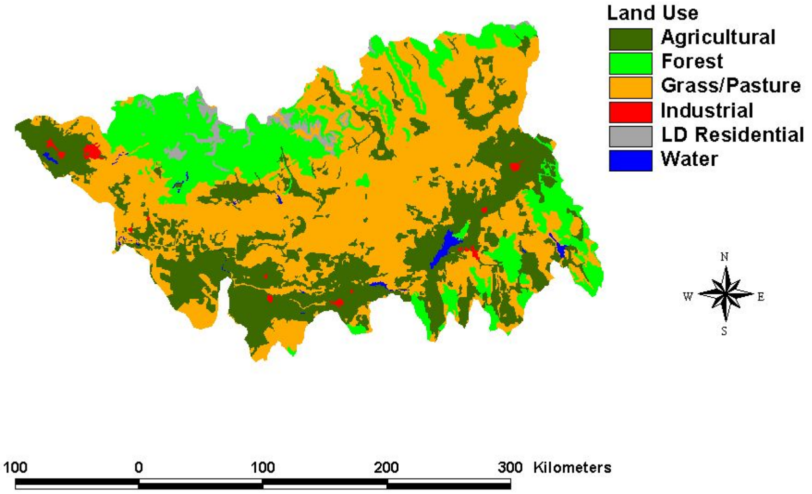

Figure 2: Classes of land use in the Snake River Basin (Agriculture, forest, and pastureland are the main categories)

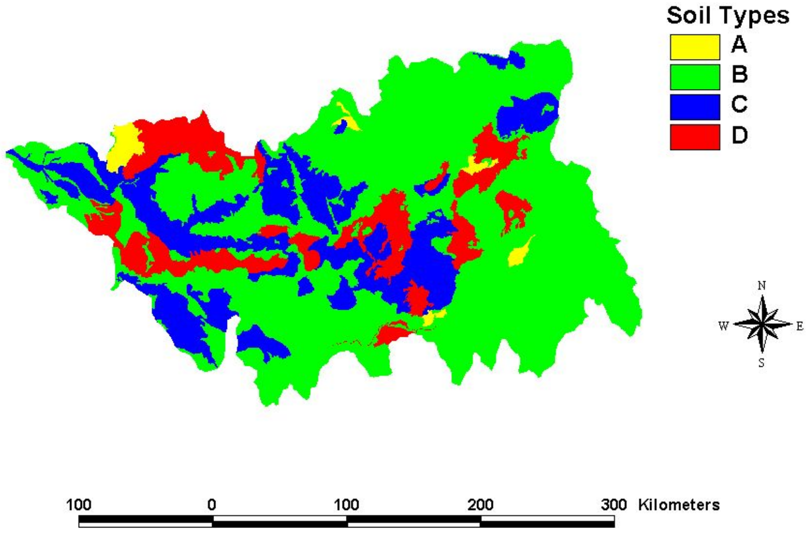

Figure 3: Hydrologic soil group in the Snake River Basin (Group A soils have low runoff potential and high infiltration rates, group B soils have moderate infiltration rates, group C soils have low infiltration rates, and group D soils have high runoff potential)

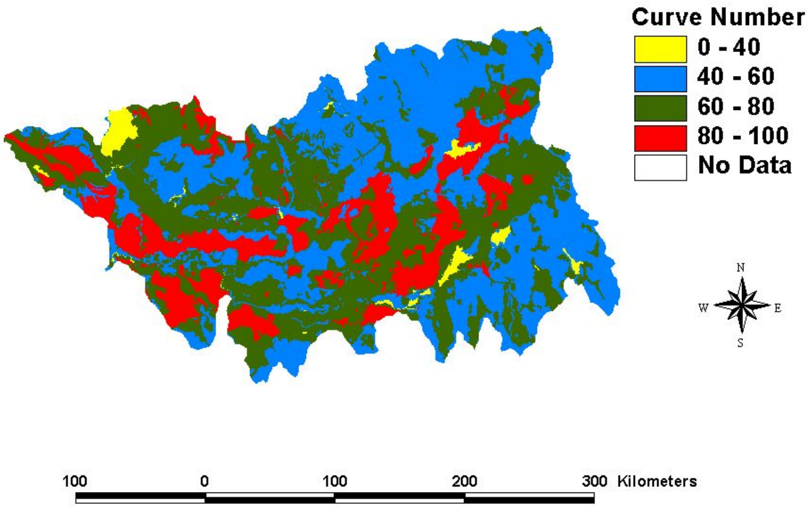

Figure 4: Curve number in the Snake River Basin. This GRID theme is a direct result of Equations 1 and 2 and based on land uses and soil types.

Model Modification

Precipitation as a text file can be obtained from the database linked to the L-THIA model and can be used as an input for small-scale applications. However, for the L-THIA model to be applied at a regional scale, as in the case of the Snake River Basin, it must first be modified. This modification allows the model to deal with precipitation as a GRID theme rather than as a text file. The precipitation GRID theme for the Snake River Basin is shown in Figure 5.

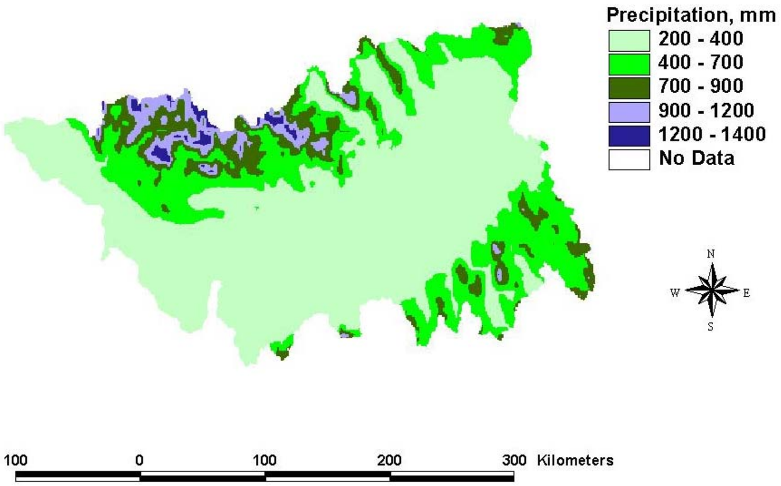

Figure 5: Precipitation in the Snake River Basin

The event mean concentration (EMC) of nitrogen and phosphorus depends on each land use area; and these values were used as input to the L-THIA model. High values are expected in agricultural systems, followed by residential, commercial, grass/pasture, and forest land uses (Favaretto 2000). The EMC values inserted in the model, representing the Indian Pine Watershed, were replaced by other values given by Loehr (1974). Loehr gave ranges of TN and TP concentrations from different non-point sources. Table 1 shows the average of these ranges that were used as EMC in this study.

Table 1. Event Mean Concentration (EMC) of TN, TP, and TN/TP in Each Land use Class

Nutrients (mg/L)	Agricultural	Grass/Pasture	LD Residential	Forest
TN	3	0.68	2.56	0.7
TP	1.14	0.035	0.5	0.035
TN/TP	2.63	19.43	5.12	20

Model Calibration

Calibration commonly is achieved by plotting the model results against the field measurements. The precision of the model can be expressed using one or more calibration statistics. Using data of median concentration for at least five analyses for the period 1980 to 1989 (Clark, 1994), the coefficient of determination was found to be acceptable ($R^2 = 0.84$), as shown in Figure 6, and no parameters have been changed to match field observations.

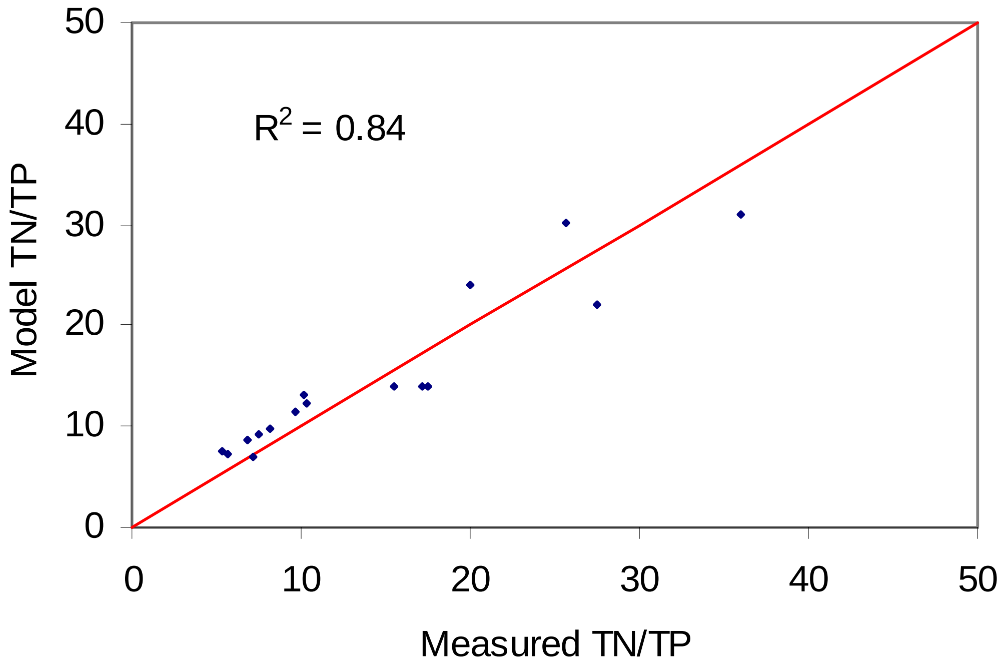

Figure 6: Model calibration

Statistical Approach

In addition, regression equations were used to calculate the TN or TP and thus, TN/TP in the Snake River Basin and its tributaries. Water quality and nutrients data used are examined for different watersheds in the Snake River Basin (Clark 1994). A comparison was performed between the calculated and measured nutrient concentrations using the results obtained from the L-THIA model and the regression equation.

Results and Discussion

L-THIA Model Results

The amount of nutrients carried by the surface water depends on the event mean concentration and the runoff volume. Agricultural land use has the highest EMC, but the highest runoff rates are present in the commercial and residential area. This generates a high loss of nutrients per area in commercial and residential land use classes. In spite of commercial and residential land use having a low EMC (Table 1), they may have a high average nutrient loss. The land use of the Snake River Basin, however, is basically agricultural; consequently, the amounts of nutrients coming from the entire watershed originated from the agricultural areas. Figures 7, 8, and 9 demonstrate model results using GIS maps. Table 2 shows the estimated loss of nutrients in the Snake River Basin. The agricultural and industrial activities give the highest values of both EMC and runoff volume, followed by the residential areas and urban runoff, which give medium values, and forests, which give the minimum values.

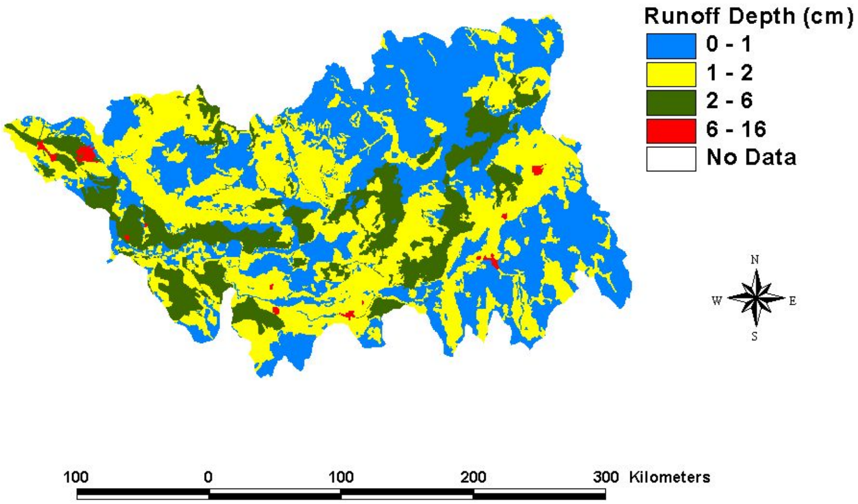

Figure 7: Annual runoff depth (cm) from the Snake River Basin

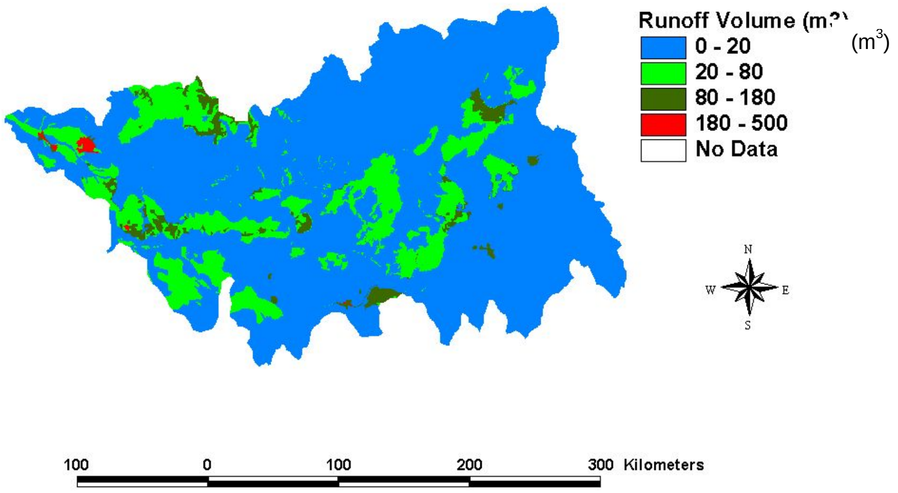

Figure 8: Annual runoff volume (m^3) from the Snake River Basin

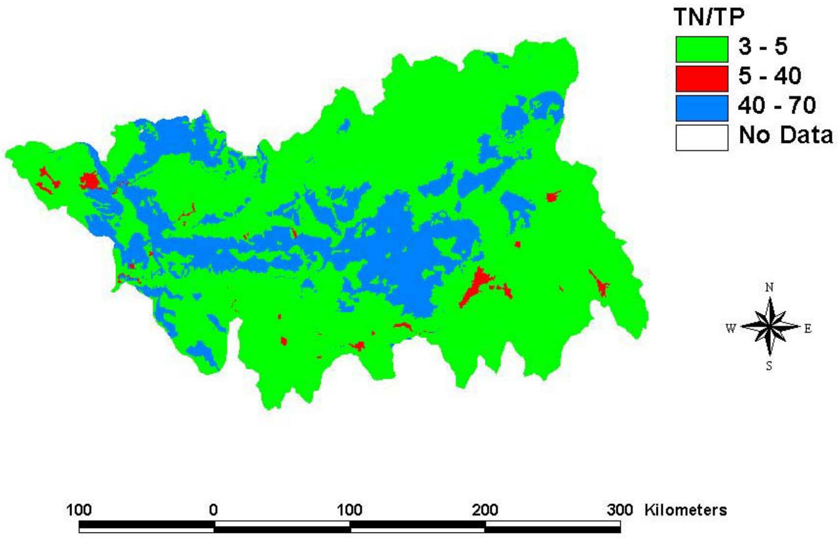

Figure 9: TN/TP ratios in the runoff of the Snake River Basin

Table 2. Weighted Average of Nutrient Losses (kg/ha/year) in Each Land Use Class from the Snake River Basin

Weighted average (kg/ha/year)	Agricultural	Grass/Pasture	LD Residential	Forest
TN	1.1	0.07	2.6	0.28
TP	0.201	0.0021	0.26	0.0011
TN/TP	5.47	33.33	10.00	72.73

Regression Equation

There is a strong relationship between the presence of total nitrogen and total phosphorus in fresh waters bodies. Most of the sources of both are the same. The relationship between total nitrogen and total phosphorus based on 15 degrees of freedom has a coefficient of explanation (R^2) of 0.75 when regressed against measured data as shown in Figure 10 and is given by Equation 3:

$$\text{Total Phosphorus (mg/L)} = 0.0998 \times \text{Total Nitrogen (mg/L)} + 0.0081 \qquad (3)$$

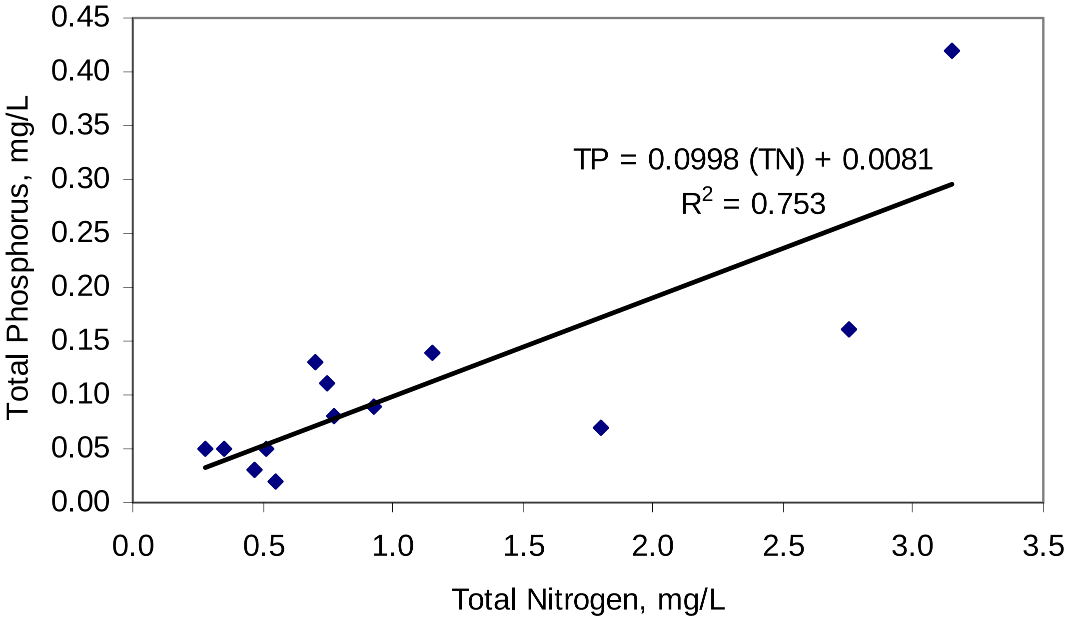

Figure 10: TN and TP relationship in some watersheds in the Snake River Basin (Data from Clark, 1994 and Clark, 1997)

A number of stream gaging stations on the Snake River Basin has been selected to compare the estimations obtained using the L-THIA NPS model with those obtained from the statistical approach. Table 3 (data from Clark, 1997) shows the selected stations and their land use distribution and Figure 11 shows that the TN/TP ratios for the selected stations are in the range of 7.4 to 27.5, which indicates phosphorus limited stream flows.

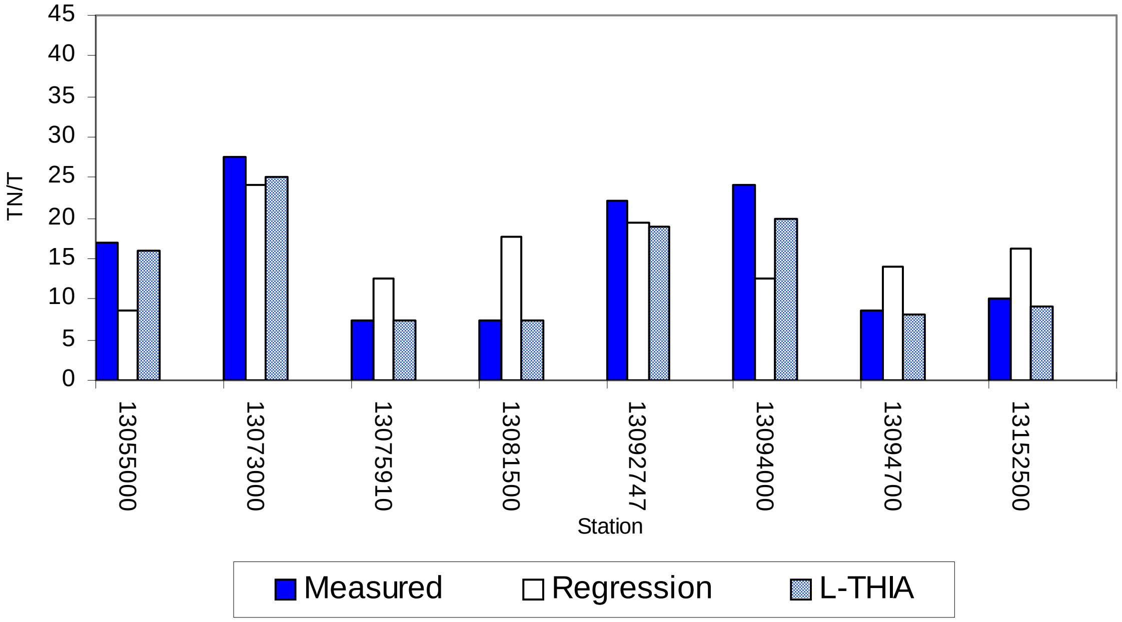

Figure 11: TN/TP ratios for the selected stations

Table 3. Land Use Distribution for Selected Water Quality Stations (Data from Clark, 1997)

Station Number	Station Name	% Land Use Agricultural	Pasture	Forest	Residential
13055000	Teton River near St. Anthony	42	12	40	6
13073000	Portneuf River at Topaz	35	54	10	1
13081500	Snake River near Minidoka	23	38	34	5
13092747	Rock Creek at Twin Falls	24	52	24	0
13094000	Snake River near Buhl	22	46	26	6
13152500	Malad River near Gooding	14	64	13	9
13037500	Snake River near Heise	6	26	61	7
13056500	Henrys Fork near Rexburg	26	19	49	6
13060000	Snake River near Shelley	19	25	51	5
13075000	Marsh Creek near McCammon	52	38	9	1
13088000	Snake River at Milner Dam	23	39	31	7
13090000	Snake River near Kimberly	23	39	30	8
13154500	Snake River at King Hill	21	50	23	6

Phosphorus Absorbance

The behavior of phosphorus in the soil is different than that of nitrogen. Phosphorus is strongly adsorbed on the soil particle and has a low solubility. Phosphorus in streams that run through the Snake River Basin is bound to sediment transported to streams. Clark (1997) showed that, typically, dissolved phosphorus only accounts for a small portion of the phosphorus present in streams. Total phosphorus and suspended sediment concentrations increase as sediment is washed into streams

and retained in suspension at elevated stream velocities (Clark, 1997). In addition, phosphorus could be absorbed under alkaline conditions when the pH of the rainfall is high (greater than 7).
However, it is expected that TN/TP will get higher in the streams than in the runoff for the same land use; therefore, the amounts of phosphorus measured in the streams are less than the amount calculated by the model (Table 4, TN and TP concentrations from Clark, 1997). Since the model estimates the phosphorus in runoff, the differences lie in the amounts that are adsorbed on the soil particle during the runoff process. Table 4 shows the concentration of these amounts present in the sediment within the selected stations areas of the Snake River Basin.

Table 4. Loss/gain of phosphorus at selected stations in the Snake River Basin from 1993-1995

Station (area, ha)	TN mg/L	TP mg/L	Measured TN/TP	Stream flow Bm^3/year	Stream P Load ton	Non-point P ton	P Gain/(Loss) ton
13037500 (1,489,761)	0.38	0.01	38	5.279	52,792	46,893	5,899
13056500 (756,277)	0.42	0.02	21	2.063	41,264	52,030	(10,766)
13060000 (2,535,598)	1.21	0.02	61	4.435	88,697	132,551	(43,854)
13075000 (91,427)	0.98	0.08	12	5.846	4,677	98,76	(5,198)
13090000 (870,928)	1.57	0.08	20	1.707	136,581	59,379	77,202
13154500 (9,272,157)	1.53	0.07	22	7.661	536,245	548,105	(11,860)

Point and Non-Point Phosphorus Loading

Water quality in the upper Snake River Basin is affected by a wide variety of nonpoint and point sources (Clark, 1994). Stream flow in the middle part of the Snake River (stations 13090000 and 13154500) is augmented by discharge from the Snake River Plain aquifer (Whitehead, 1986). The Snake River intersects the aquifer downstream from Milner Dam and remains below the regional water table for a significant length of the middle Snake reach (Clark, 1997). For example, in 1995, the aquifer discharged 150 m^3/s to the Snake River, or about 60 percent of the total stream flow at station 13154500 (Rupert, 1994). Table 4 shows the loss or gain of phosphorus loading due to point sources, ground water recharge, or filtration of runoff by riparian vegetation.

The estimation of phosphorus using L-THIA model and regression can help to differentiate between total phosphorus loads and the loads from runoff, which can be considered as the non-point source loads. The difference results from the fact that the phosphorus comes from other sources, which are the point sources and ground water discharge. Table 4 shows the estimated loads from these sources for the period 1993-1995.

Only Stations 13037500 and 13090000 present a net gain (the runoff phosphorus load estimated by L-THIA model is less than the measured stream flow load); all other stations present a net loss. However, station 13090000 has a higher gain due to ground water discharge and an effluent point source from industrial and commercial trout farms (Clark, 1994). While station 13154500 can be affected by the same activities, it presented a loss of phosphorus load. This may be attributed to the existence of riparian vegetation along river banks, to ground water discharge, or to dilution from spring inflows having low phosphorus concentrations.

Limiting Nutrient

The TN/TP ratios (EMC in Table 1) in the runoff from different land uses are 2.63 and 5.12, for the agricultural and residential land uses, respectively. For forest and pasturelands these ratios are higher. Figure 11 shows that the TN/TP ratios for the selected stations are in the range of 7.0 to 27.5 for the residentially dominated stations and higher for the stations subjected to intensive forest and pastureland. To calculate the ratios at the selected stations, land use distributions from Table 3 should be multiplied by TN/TP ratios shown in Table 1.

The use of TN/TP ratio can be illustrated by the following example: at station 13075000, the measured TN was 0.98 mg/L. Since land use distribution at this station is 52% agriculture + 38% grass/pasture + 9% forest + 1% residential (Table 3), the TN/TP = $5.47 \times 0.52 + 33.33 \times 0.38 + 72.73 \times 0.09 + 10 \times 0.1 = 24.1 > 7.2$, which means that phosphorus is the limiting nutrient and the estimated TP = 0.98/24.1 = 0.04 mg/L. The resulting estimate of the TN/TP ratios shows that the ratios are close to the measured values.

Summary and Conclusions

In this study, two estimation methods have been applied on the Snake River Basin for obtaining TN/TP data and phosphorus loads. The first method used the L-THIA NPS model to estimate the TN/TP in storm water runoff, while the second was a statistical regression for the TN/TP ratios in stream water. The comparison between these methods was used to demonstrate the accuracy of the model. The measured concentration and results from the L-THIA model were used to determine the phosphorus loads from point sources, non-point sources, and ground water discharge. The L-THIA NPS model gave more accurate results (i.e., closer to the measured values) than the simple regression. In general, the TN/TP ratios are higher than 7.2, which indicate that the limiting nutrient in the Snake River Basin is phosphorus as it is in most freshwater ecosystems. The ratios can change, however, due to land use change with respect to time (especially for agriculture). The TN/TP ratios in the Snake River Basin runoff are lower than those measured in the individual streams. The differences between the phosphorus concentrations in the storm water runoff and those measured in the streams (i.e. gain and loss) indicate that some amounts of phosphorus are adsorbed on the soil particle and do not contribute to the phosphorus concentrations that are measured in the streams. In addition, the pH of the rainfall can lead to phosphorus absorbance under alkaline conditions. The study estimated the gain and loss for stream flow stations within the study area. Some stations presented a high gain due to ground water discharge and an effluent point source from industrial and commercial trout farms. However, other stations presented a net loss that may be attributed to phosphorus absorbance, to the existence of riparian vegetation along river banks, to ground water discharge, or to dilution from spring inflows having low phosphorus concentrations.

The results of this study can help in managing the generation and application of nutrients and in providing a consistent description of general water quality conditions and long-term trends.

References

Bhaduri, B., J. Harbor, B. Engel, and M. Grove, Assessing watershed-scale, long-term hydrologic impacts of land use change using a GIS-NPS model. Environmental Management 26(6), 643-658, 2000.

Borah, D. K., and M. Bera. Watershed scale hydrologic and nonpoint source pollution models: review of mathematical bases. Transactions of the ASAE 46(6):553–1566, 2003.

Brusven, M.A., D. J. Walker, K. M Painter, R. C. Biggam. Ecological-economic assessment of a sediment-producing stream behind Lower Granite Dam on the lower Snake River, USA. REGUL. RIVERS: RES. MANAGE. ; (10)3-4, p. 373-387, 1995.

Chapra, S., Surface-Water Quality Modeling, Civil Engineering Series, 844 pp., McGraw-Hill International Editions, Singapore, 1997.

Clark, G., Assessment of selected constituents in surface water of the upper Snake River Basin, Idaho and western Wyoming, water years 1975-89, Water-Resour. Invest. Report 93-4229, U.S. Geol. Surv., Boise, Idaho, 1994, 49 pp.

Clark, G., Assessment of nutrients, suspended sediment, and pesticides in surface water of the Upper Snake River Basin, Idaho and Western Wyoming, Water Years 1991-95, Water-Resources Invest. Report 97-4020, U.S. Geol. Surv., 1997, 45 pp.

Engel, E., L-THIA NPS (Long term hydrologic impact assessment and non-point source pollutant model), Purdue University, available at: http://danpatch.ecn. Purdue.edu /~spawl/L-THIA7/, 2001, 2001.

Favaretto, N., Nitrogen and phosphorus losses in surface water from the Indian Pine watershed, Watershed System Design, Final Project, available at: http://danpatch .ecn.purdue.edu/~sprawl/LTHIA7/lthia/lthia_index.htm, 2000.

Grove, M. Development and application of a GIS-based model for assessing the long-term hydrologic impacts of land-use change. Unpublished MS Thesis, Purdue University, West Lafayette, IN 47907-1397, 1997.

Grove, M., Harbor, J., Engel, B. and Muthukrishnan, S. Impacts of Urbanization on Surface Hydrology, Little Eagle Creek, Indiana, and Analysis of LTHIA Model Sensitivity to Data Resolution. Physical Geography.135-153. 2001.

Harbor, J., A Practical method for estimating the impact of land use change on surface runoff, ground water recharge, and wetland hydrology, Journal of American Planning Association 60 (1), 95-108, 1994.

Idaho Department of Water Resources (IDWR), 2004. Available at: http://www.idwr.state.id.us.

Lima, K.J., B.A. Engela, Z. Tanga, S. Muthukrishnanb, J. Choic, K. Kimc. Effects of calibration on L-THIA GIS runoff and pollutant estimation, Journal of Environmental Management, 78(1), p. 35-43, 2006.

Lombardo, L. A., G. L. Grabow, K. L. Tweedy, D. E. Line, D. L. Osmond, J. Spooner, Section 319, National Monitoring Program Projects, National Nonpoint Source Watershed Project Studies, NCSU Water Quality Group in Cooperation with U.S. Environmental Protection Agency Raleigh, North Carolina, 1999..

Loehr, R. C., Characteristics and comparative magnitude of non-point sources, Journal of Water Pollution Control Federation, 46(8), 1849-1863, 1974.

McKillop, R., N. Kouwen, and E. D. Soulis. Modeling the rainfall-runoff response of a headwater wetland. Water Resources Research 35(4):1165–1177, 1999.

NRCS, Nutrient management for better crops, more profit, and clean water, the Iowa Soybean Promotion Board and U.S. Environ. Prot. Agency, Region VII. Natural Resources Conservation. Survey, Urbandale, Ia., 1995.

Pandey, S., Gunn, R., Lim, K., Engel, B. and Harbor, J. Developing a web-enabled tool to assess long-term hydrologic impact of land use change: Information Technologies Issues and a Case Study. Urban and Regional Information Systems Journal. 12(4), p.5-17. 2000.

Rupert, M.G., Analysis of data on nutrients and organic compounds in ground water in the upper Snake River Basin, Idaho and western Wyoming, 1980-91. Water-Resour. Invest. Rep. 94-4135, U.S. Geol. Surv., Boise, Idaho, 1994, 40 pp.

SCS, Estimation of direct runoff from storm rainfall, chapter 10, in National Engineering Handbook, Soil Conservation. Survey, 1972.

The Fertilizer Institute, The fertilizer handbook, available at: http://www.tfi.org, 2000.

Wang, Y., Choi, W., Deal, M. B., Long-Term Impacts of Land-Use Change on Non-Point Source Pollutant Loads for the St. Louis Metropolitan Area, USA. Environmental Management, 35(2), p.194-205, 2005.

Whitehead, R.L., Geohydrologic Framework of the Snake River Plain, Idaho and Eastern Oregon: U. S. Geol. Surv. Hydrologic Invest. Atlas Sheets, Scale 1:1,000,000, 1986.