A Strategy for Estimating Nutrient Concentrations Using Remote Sensing Datasets and Hydrological Modeling

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ABSTRACT

This paper presents a methodology for estimating nutrient concentrations of total phosphorus (TP) and total nitrogen (TN) through the use of hydrological modeling, remote sensing datasets, and nutrient export coefficients. The strategy is applied to the Upper Tombigbee watershed, located in the northern region of the states of Mississippi and Alabama, USA. USGS GIRAS (1986), NASA MODIS MOD12Q1 (2001-2004) land use datasets, and USGS-DEM topographical datasets were used to characterize the physiography of the watershed. TN and TP concentration values estimated using the methodology were compared to values reported in the literature.

Keywords: *GIRAS, HSPF, Hydrological Modeling, Hydrological Simulation, MODIS, Nutrients, Remote Sensing, Water Quality, Watershed Modeling*

INTRODUCTION

The absence of water quality monitoring stations that would provide updated data on nutrient concentrations for establishing water quality regulation strategies (such as Total Maximum Daily Loads, TMDLs, or Best Management Practices, BMPs), creates the need for innovative data estimation methods. In areas of the world where the land use coverage is predominantly agricultural lands and forest lands, remote sensing data can provide opportunities for making educated estimations of nutrient concentrations.

For example, the United States of America (USA) has a land area of approximately 900 million hectares, from which about 28 percent is covered by forest land, 26 percent permanent grassland pasture and range land, and 20 percent cropland. The total land used for agricultural purposes in 1997 was about 485 million hectares; that accounts up to over 52 percent of total U.S. land area (Vesterby & Krupa, 1997). Cropland, grassland pasture, and range land accounted for most of the land used for agricultural purposes, but land used

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for agricultural purposes also included forest land used for grazing and land in farmsteads, farm roads, and farm lanes (Vesterby & Krupa, 1997). Land use in the Southeastern United States is predominantly covered by forests and agricultural lands.

Water quality and flow regime (quantity, temporal variation, and spatial distribution) influence the ecological "health" of aquatic biota (Allen, 1995; Karr & Chu, 1999). In watersheds such as the Upper Tombigbee (located in northeastern Alabama and northwestern Mississippi, USA), where agricultural land use can comprise 50% or more of land cover, sediment and nutrient runoff can seriously degrade the ecological quality of aquatic environments (Allen, 1995).

Data on nutrient loads to rivers from non-point sources (characterizing the water quality of a watershed or a river) are particularly difficult to find because setting up field surveys for collecting these data and performing additional laboratory analysis require extensive use of personnel and resources, making it an impractical alternative. A technique for estimating nutrient loads that would combine remotely sensed land use data and export coefficients seems to be particularly attractive given the geographical extent that is covered by land use maps. There are several recent examples of this type of approach for estimating nutrient loads in watersheds located outside the United States (Ierodiaconou, 2004; Liu et al., 2009; Liu, He, & Wang, 2008), but there are no recent studies of this type in the USA.

This paper details a strategy that combines hydrological modeling, geo-processing of physiographic data (land use, topography), and export coefficients for estimating stream flow, runoff, and nutrient concentrations throughout the Upper Tombigbee watershed. The Hydrological Simulation Program Fortran (HSPF) (Bicknell, Imhoff, Kittle, Jobes, & Donigian, 2001) is used for estimating water quantity. Export coefficients and geo-processing of land use datasets are used for calculating nutrient concentrations.

METHODOLOGY

Watershed Under Study

Water bodies in the Southeastern USA are subjected to loads of pollutants resulting from urban development, agriculture, and other human activities. Impairment of rivers in the region is related mainly to sediment and nutrient loads. Monitoring of water quality in the region's water bodies, however, does not take place in a frequent basis due to costs associated with water quality surveys.

The Upper Tombigbee watershed is located in the states of Alabama and Mississippi in the Southern USA (Figure 1). The watershed drains approximately 13900 square kilometers and it is a main contributor of flow to the Mobile River, with an approximate average stream flow of 169 m^3/s.

Physiographic Datasets

Topography and land use datasets were used to characterize the physiography of the Upper Tombigbee watershed. The topographical dataset used in this research was the United States Geological Service (USGS) Digital Elevation Model (DEM), which corresponds to the 3 arc-second (1:250,000-scale, 300 m spatial resolution) USGS topographic map series. A seamless topographical mosaic was produced by using several DEMs that cover the area. ArcInfo (GRID) was used to fill grid cells with no-data values (con, focalmax, and focalmean commands were used). Figure 2 shows a flowchart of the processing steps and the resulting topographical dataset.

From the several digital land use maps that are available in the USA (NLCD, GIRAS, MODIS, etc.), two land use datasets were used in this study (Figure 3): USGS GIRAS, and NASA MODIS MOD12Q1. The USGS GIRAS consists of set of maps of land use and land cover for the conterminous USA, delineated

Figure 1. Watershed under study. Upper Tombigbee watershed, located in the northern Mississippi-Alabama region (USA).

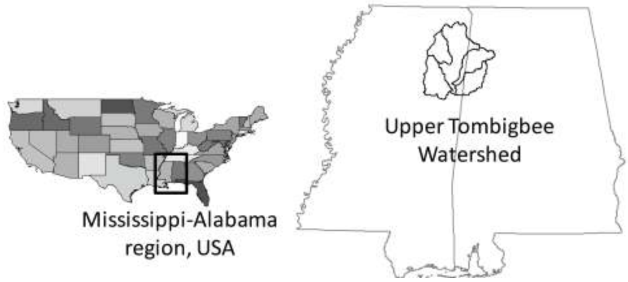
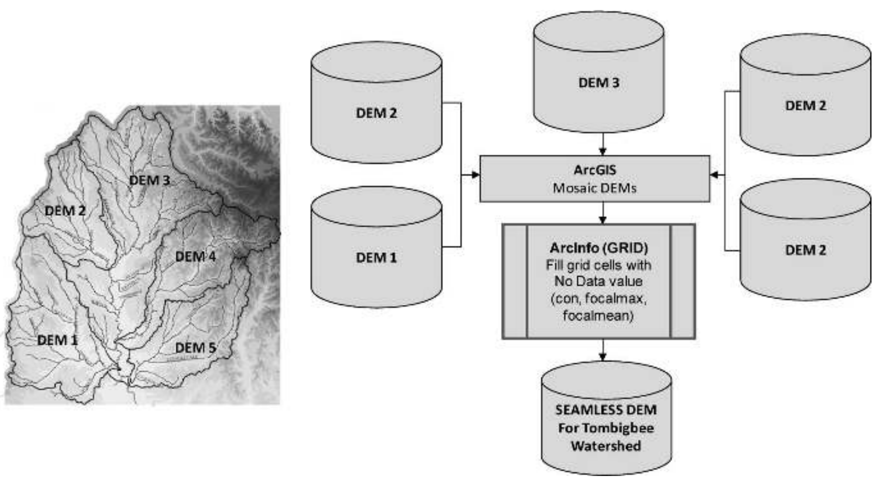


Figure 2. Generation of a seamless topographical dataset for the Tombigbee watershed

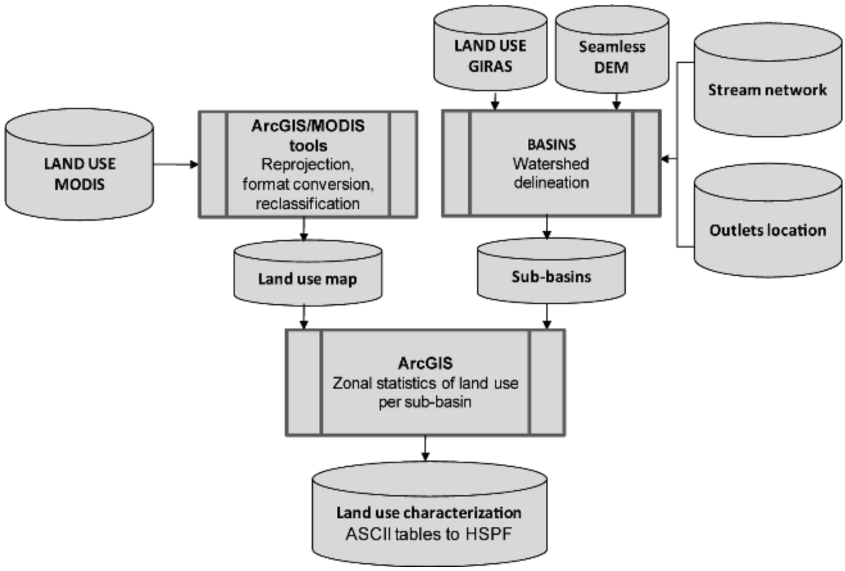


with a minimum mapping unit of 4 hectares and a maximum of 16 hectares (equivalent to 400 m spatial resolution). The NASA MODIS MOD12Q1 Land Cover Product (MODIS/Terra Land Cover, 1000 m spatial resolution) (Hodges, 2002) is provided by NASA through several internet portals. The MODIS land use map is classified in 21 land use categories, following the International Geosphere-Biosphere Program (IGBP) land cover classification. The map covers most of the globe and is updated every year.

The software Better Assessment Science Integrating Point and Nonpoint Sources, (BASINS, 2010), is a GIS program that provides tools for downloading the basic meteorological and physiographic data required for setting up a number of water resources models. The USGS GIRAS dataset was downloaded using the BASINS system. BASINS reclassifies automatically the raw USGS GIRAS into major categories more amenable for hydrological modeling: urban, forest, agricultural, barren land, rangeland, water, and wetlands. The MODIS MOD12 Q1 data, however, had to be geo-processed for the dataset to be consistent with the USGS GIRAS dataset.

A flowchart with the geo-processing steps followed to generate a MODIS land use dataset with the same number of land use categories as the USGS GIRAS is shown in Figure 3. NASA provides MODIS land use data in Inte-

Figure 3. Extraction of land use statistics for the Tombigbee watershed



gerized Sinusoidal (ISIN) map projection and Hierarchical Data Format (HDF). NASA also provides a suite of tools (MODIS Tools) for re-projecting and re-formatting these dataset to more common contexts. The data downloaded for this research were initially converted to .tiff format and re-projected to geographical coordinates. Then, ArcGis was used to re-project the datasets to UTM coordinates and also to the more common GRID dataset format. This new format allowed a re-classification from the 21 IBEP MODIS land use categories to the USGS-GIRAS-HSPF categories.

ArcGIS was also used to extract land use characterization tables per sub-watershed and per land use datasets from the MODIS dataset. These tables were further processed to be in ASCII format and in a data structure amenable to the hydrological model (HSPF).

While the higher-resolution land use maps of the National Land Cover Dataset (NLCD) may have been used in this study (e.g., NLCD 1992 or NLCD 2001), these land use maps are outside the time intervals of interest for this study (2002-2004 and 1977-1982). Another option would have been using raw LANDSAT reflectance data and producing land use maps for the time intervals of interest (trying to replicate the process of producing NLCD maps) but this was unachievable since those maps would have required ground-truthing in large geographical regions.

Watershed Delineation

The seamless DEM for the Upper Tombigbee watershed, in conjunction with the US National Hydrography Dataset (NHD) for the region, and outlet locations around the area were used to delineate the watershed in 97 sub-basins.

The digitized stream network resulting from the geo-processing of the seamless DEM was burned to the NHD stream network to ensure connectivity of stream polygons. All the delineation process was performed using BASINS. Figure 3 illustrates the geo-processing involved.

Hydrological Modeling and Nutrients Estimation

Hydrological modeling of the Upper Tombigbee watershed was performed using the Hydrological Simulation Program Fortran (HSPF). HSPF is a computer model designed for simulation of non-point source watershed hydrology and water quality.

In general, HSPF uses time-series of meteorological/water-quality data, land use and topographical data to estimate stream flow hydrographs and polluto-graphs. With these data, HSPF is capable of simulating interception, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapo-transpiration, and ground-water recharge.

Simulation results are provided as time-series of runoff, sediment load, and nutrient and pesticide concentrations, along with time-series of water quantity and quality, at any point in a watershed. Additional software (WDMUtil and GenScn) is used for data pre-processing and post-processing, and for statistical and graphical analysis of input and output data.

HSPF offers two options for setting up a hydrological model. The simplest configuration summarizes land use and topography for the whole watershed, disregarding the delineation of the watershed in sub-basins. Although that type of hydrological model could be useful for small watersheds or watersheds where the physical geography is homogeneous, it would not be applicable to the Upper Tombigbee basin because of the big geographical area it covers and the heterogeneous distribution of land use.

For this reason, the HSPF hydrological model for the upper Tombigbee was set up using the other alternative offered by HSPF, i.e., the configuration in which land use and topography are specified per sub-basin. This type of conceptual model represents the hydrological processes more realistically and provides hydrological estimations that take into account the particular characteristics of each sub-basin. Needless to say that the generation of HSPF input files when using the MODIS land use dataset required additional pre-processing, as detailed in Figure 3.

Total nitrogen (TN), and total phosphorus (TP) export coefficient for the region (Lin, 2004) were used to estimate nutrient concentrations. Table 1 shows minimum, average, and maximum export coefficient values used in this research. Although HSPF could have been used for this estimation, the lack of measured nutrient concentrations for the study area did not allow water quality modeling.

RESULTS

The results of the geo-processing of MODIS MOD 12Q1 land use data are shown in Figure 4. For the purposes of comparison the figure includes the USGS GIRAS land use dataset for the region of study.

The land use categories to which the MODIS datasets were reclassified (same categories as in the GIRAS dataset) are also shown. Although MODIS land use images for years 2001 through 2004 were produced, the figure only shows resulting datasets through 2003.

At first glance, the images in Figure 4 show that land use in the region changed (from 1986 to 2001) in detriment of forests (represented in dark green color) with evident increase in agricultural lands (depicted in yellow color).

Changes from 2001 to 2003 are also evident although not as dramatic as the change identified for the period 1986 - 2001. Interestingly, the increase in agricultural lands takes place with more intensity at the western portions of the Tombigbee watershed (State of Mississippi) where agricultural activity has increased during the last decade.

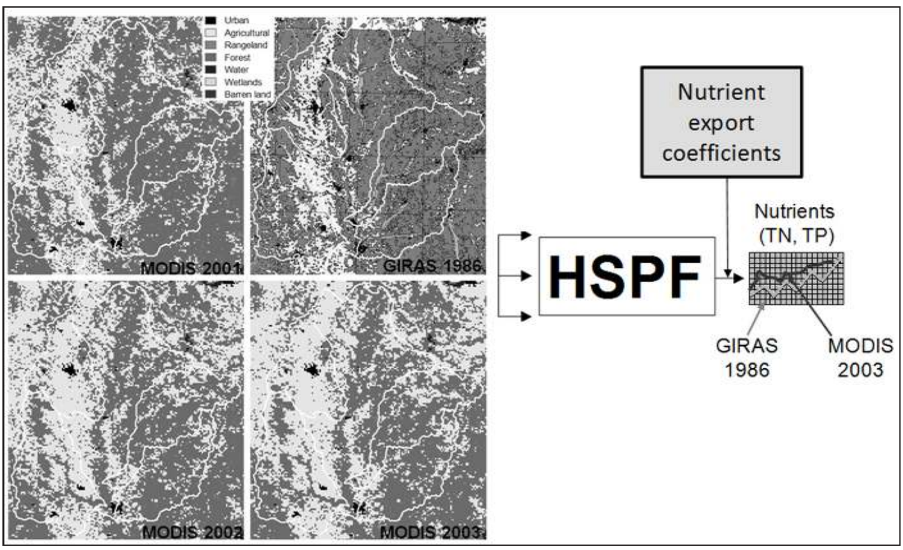
As can be observed in Figure 5 and Table 2, from 1986 to 2003 agricultural lands increased in almost 34%, forest lands decreased in 16%, and range-land almost quadrupled in size. Interestingly, urban areas decreased in 50%, as well as water bodies. However, due to the coarse spatial resolution of MODIS land use data (1000 m), the land use area values for categories rangeland, water, wetlands and barren should be taken as coarse approximations.

Within the context of this research (non-point source hydrological and water quality processes) the percent-change values associated with forest and agricultural lands are the

Table 1. Range of nutrient export coefficients for the area of study, in kg/ha-year (Lin, 2004)

	Total Phosphorus (Kg/Ha)			**Total Nitrogen (Kg/Ha)**		
	Min.	Average	Max.	Min.	Average	Max.
Row Crops	0.26	4.46	18.6	2.1	16.09	79.6
Non Row Crops	0.1	1.08	2.9	0.97	5.19	7.82
Forested	0.019	0.236	0.83	1.38	2.86	6.26
Urban	0.19	1.91	6.23	1.48	9.97	38.47
Pasture	0.14	1.5	4.9	1.48	8.65	30.85
Feedlot/Manure Storage	21.28	300.7	795.2	680.5	3110.7	7979.90
Mixed Agriculture	0.08	1.134	3.25	2.82	16.53	41.5

Figure 4. Diagram showing the use of MODIS and GIRAS land use datasets, HSPF output, and export coefficients for nutrient concentration estimation



most important. This is consistent with previous research results (Haobo, Wang, Jia, Bo, & Wang, 2008), which reported that the accuracy of the MODIS land cover type for croplands is higher than other categories when cropland is one of the dominant land cover types.

Considering that the accuracy of the MODIS MOD12 Q1 land cover product is relative to the spatial distribution of features of the land cover patches (Haobo et al., 2008), and that the vast geographical areas associated with agriculture and forests are dominant in the Upper Tombigbee watershed, the estimations of land use coverage from MODIS datasets for the study area are useful and consistent with the objectives of this research.

Once an optimum watershed delineation was achieved (Figure 6), HSPF was launched from within BASINS to initialize the HSPF model application. To each of the sub-basins shown in the left hand side of Figure 6, the HSPF model assigns a Reach/Reservoir (RCH/

Figure 5. Comparison of re-classified MODIS MOD 12 Q1 land use datasets for years 2000-2003 to the 1986 GIRAS land use dataset

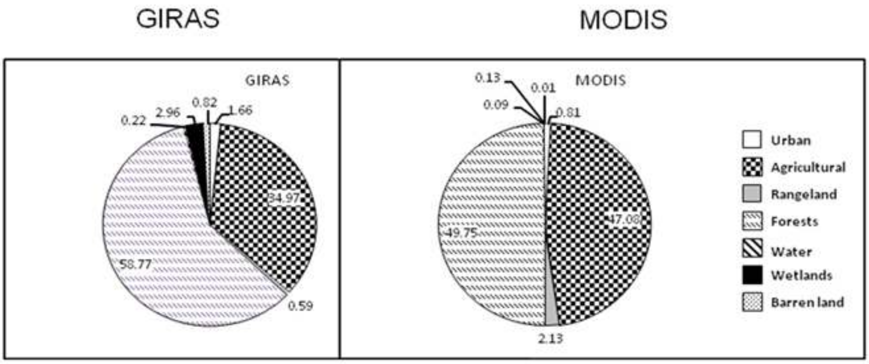


Table 2. Predominant land use classes in the Upper Tombigbee watershed and percent change in land use from 1986 to 2003

Land Use	GIRAS 1986 (Ha)	MODIS 2003 (Ha)	% Change 1986-2003
Agricultural	479521.47	642173	33.91
Rangeland	8029.43	29108	262.51
Forests	805819.88	678665	-15.77

RES) unit (represented by boxes at the right hand side of the figure). HSPF is a lumped parameter hydrological model, meaning that physiographic information is summarized for each of the RCH/RES units.

Two hydrological models were set-up with two different time periods of simulation: 1980-1990, and 1996-2006. Figure 6 shows the location of the stream flow gauge station used for hydrological calibration (Luxapallilla Creek, USGS 2443500).

Results of the hydrological calibration of the HSPF model for the Upper Tombigbee watershed are shown in Figure 7. Scatter plots of measured versus simulated stream flow data for the two hydrological models are depicted. Correlation coefficient (r^2) values of 0.94 and 0.63 were calculated for the models corresponding to 1995-2007 and 1977-1982 periods of analysis, respectively. The r^2 values show good agreement between measured and simulated stream flow data.

The stream flow and run-off time-series estimated by the two calibrated hydrological models for the watershed under study were used in conjunction with export coefficients (reported in the literature) to calculate concentrations of total nitrogen (TN) and total phosphorus (TP).

These estimations were initially performed only for selected sub-watersheds to explore the range of values achieved by the methodology.

Figures 8 and 9 show estimated total nitrogen (TN) and total phosphorus (TP) concentrations. Table 3 presents nutrient concentration values for sub-basins 43, 51, and 54 (common sub-basins for the GIRAS and MODIS analyses). Average and third-quartile total phosphorus (TP) concentrations were not found to differ greatly when using either land use dataset (GIRAS or MODIS). Only maximum concentrations are shown to have increased from 6% to 16% (Table 3).

Figure 6. Relationship between the delineated Tombigbee watershed and the corresponding HSPF model

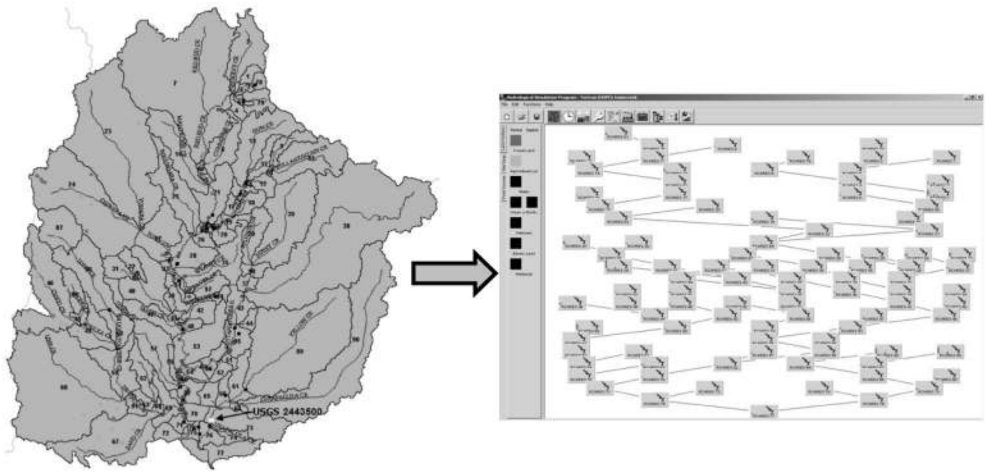
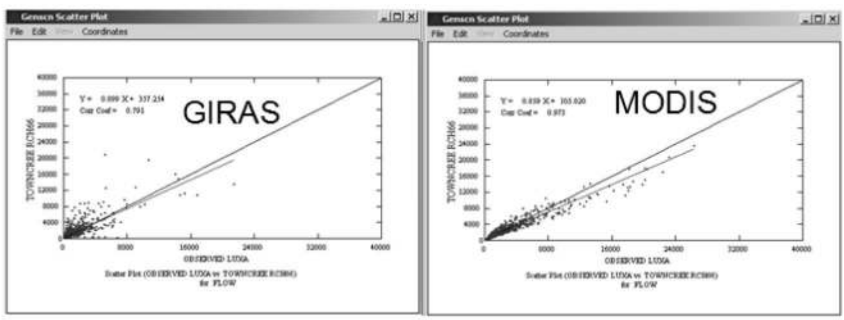


Figure 7. Comparison of measured and HSPF-simulated stream flow after the hydrological calibration step



Total nitrogen (TN) concentrations for sub-basins 43, 51 and 54, follow the same trend as those of phosphorus (Table 3). Only maximum TN concentrations were found to have increased when using MODIS land use data (with respect to TN concentrations estimated using GIRAS land use data). Percent increments in TN concentration values are in-between 5% to 15%.

When taking into account all sub-basins (Table 4), average TP concentrations estimated using the GIRAS dataset range from 0.31 to 1.23 mg/L, while maximum concentrations range from 1.51 to 5.66 mg/L. Concentration values calculated using the MODIS dataset are not noticeably higher. Average values are between 0.07 to 1.2 mg/L, and maximum values from 0.5 to 7.78. While average values did not seem to show an overall increase, maximum TP concentrations seem to have increased in about 37%.

Correspondingly (Table 4), average TN concentrations range between: 1.88 – 4.72 mg/L (when using GIRAS), and 0.9 – 4.48 mg/L (when using MODIS). Maximum TN concentrations are between: 8.96 – 21.58 mg/L (when using GIRAS), and 6.15 – 28.94 mg/L (when using MODIS). Again, the increase in maximum

Figure 8. Estimated total phosphorus concentrations (using GIRAS and MODIS land use)

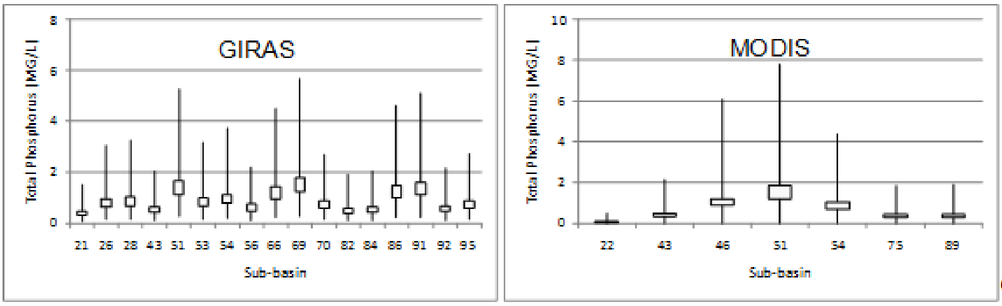


Figure 9. Estimated total nitrogen concentrations (using GIRAS and MODIS land use)

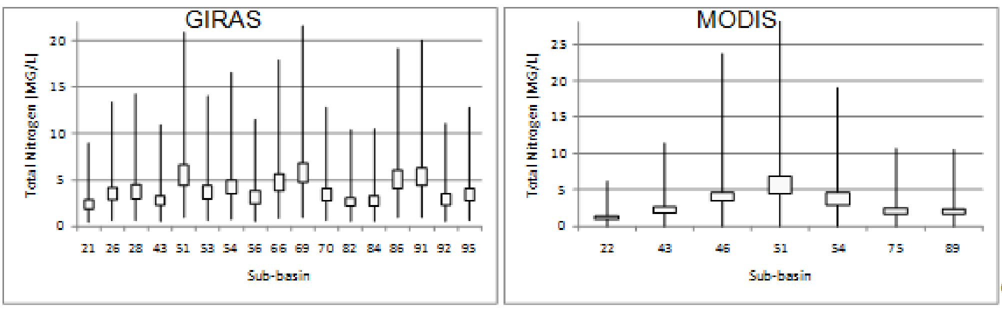


Table 3. Estimated nutrient concentrations in (mg/L)

Total Phosphorus				Total Nitrogen			
Sub-Basin	Average GIRAS	Maximum GIRAS	Third quartile	**Sub-Basin**	Average GIRAS	Maximum GIRAS	Third Quartile
43	0.43	2.04	0.62	**43**	2.30	10.91	3.32
51	1.11	5.26	1.66	**51**	4.40	20.94	6.61
54	0.80	3.75	1.12	**54**	3.53	16.65	5.00
Sub-Basin	Average MODIS	Maximum MODIS	Third Quartile	**Sub-Basin**	Average MODIS	Maximum MODIS	Third Quartile
43	0.33	2.17	0.51	**43**	1.76	11.42	2.69
51	0.88	6.09	1.17	**51**	3.42	23.7	4.55
54	0.68	4.36	1.06	**54**	2.98	19.07	4.62

Table 4. Average and maximum nutrient concentrations for all sub-basins, in (mg/L)

Total Phosphorus		Total Nitrogen	
Average GIRAS	Maximum GIRAS	Average GIRAS	Maximum GIRAS
0.31-1.23	1.51-5.66	1.88-4.72	8.96-21.58
Average MODIS	Maximum MODIS	Average MODIS	Maximum MODIS
0.07-1.2	0.5-7.78	0.9-4.48	6.15-28.94

Figure 10. Total Phosphorus concentrations measured in the study area during 2009 (Ortega-Achury et al., 2009)

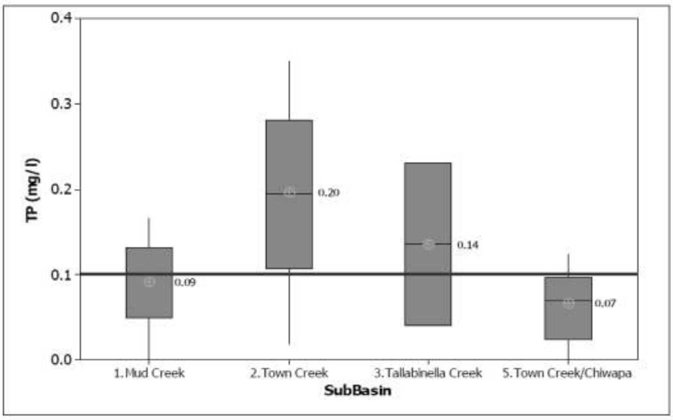


Figure 11. Total phosphorus and nitrogen concentrations measured in the study area during 2001 (ADEM, 2001)

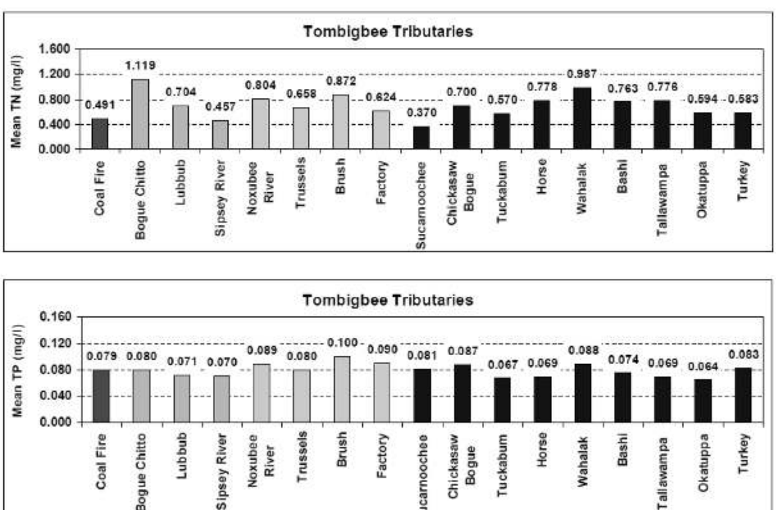


Table 5. Comparison of mean and median total phosphorus concentrations in (mg/L)

Total Phosphorus				
	GIRAS	MODIS	Ortega et al., 2009	ADEM, 2001
Mean	0.31-1.23	0.07-1.2	0.07-0.20	0.064-0.10
Median	0.16-0.60	0.015-0.29	-	-

Table 6. Comparison of mean and median total nitrogen concentrations in (mg/L)

Total Nitrogen				
	GIRAS	MODIS	Value Range ADEM, 2011	Single value ADEM, 2001
Mean	1.88-4.72	0.90-4.48	0.37-1.2	0.522
Median	0.16-0.60	0.015-0.29	0.37-1.2	0.496

TN concentrations seems to be of about 34%. This increase in maximum concentrations seems to correlate with the increase in agricultural areas from 1986 to 2003 for the Upper Tombigbee watershed, showed in Table 2.

In order to indirectly assess the methodology presented in this paper, measured nutrient concentrations from water quality surveys in the Upper Tombigbee watershed were reviewed. Figures 10 and 11 show mean values of total phosphorus and total nitrogen from water quality surveys performed during years 2001 (Ortega-Achury, Ramirez-Avila, McAnally, Martin, & Davis, 2009) and 2001 (Alabama Department of Environmental Management [ADEM], 2001).

A comparison of ranges of mean values of total nitrogen (TN) and total phosphorus (TP) concentrations is presented in Tables 5 and 6. Although the years for which the estimated values were produced in this study (1986, 2001-2003) do not fully coincide with the years of the water quality surveys (2001 and 2009), it is reasonable to compare ranges of average values in the absence of measured data. Median values for estimated concentrations using either GIRAS or MODIS land use data are also included.

The range of mean values for total phosphorus (Table 5), estimated using the MODIS land use data, seem to be in the same order of magnitude to those reported by Ortega-Achury et al. (2009) and ADEM (2001). Maximum mean estimated values seem to be slightly greater than measured values but median estimated values of total phosphorus almost overlap with measured values. TP estimated values using the GIRAS dataset are higher than measured TP concentrations in either water quality survey but are of the same order of magnitude.

In the case of total nitrogen (Table 6) the range of estimated median values corresponding to the MODIS dataset almost coincide with measured TN values reported by ADEM (2001). Mean estimated values are slightly higher than measured concentration values but are of the same order of magnitude. Estimations made using the GIRAS land use dataset are higher than those reported by ADEM (2001), although median values are closer to the measured concentration values range.

CONCLUSION

The methodology for estimating nutrient concentrations combining hydrological modeling, remote sensing data, and export coefficients is shown to be successful. A comparison of ranges of mean and median values of total nitrogen (TN) and total phosphorus (TP) concentrations shows that total phosphorus concentrations estimated using the MODIS land use data (0.07-1.2 mg/L) are of the same order of magnitude to those reported by the literature (0.07-0.2, and 0.064-0.1 mg/L). Maximum mean estimated values seem to be slightly greater than measured values but median estimated values of total phosphorus (0.015-0.29 mg/L) almost overlap with measured values. TP estimated values using the GIRAS dataset (mean: 0.31-1.23 mg/L, median: 0.16-0.60 mg/L) are higher than measured TP concentrations in the literature but are of the same order of magnitude.

For total nitrogen, the range of estimated median values corresponding to the MODIS dataset (0.19-1.08 mg/L) almost coincide with measured TN values reported in the literature (0.37-1.2 mg/L). Although mean estimated values (0.9-4.48 mg/L) are slightly higher than measured concentration values, they are of the same order of magnitude. Estimations made using the GIRAS land use dataset (1.88-4.72 mg/L, median 0.95-2.31 mg/L) are very similar to those reported in the literature although mean values are slightly higher.

This research also identified that from 1986 to 2003 agricultural lands increased in almost 34%. This increase in agricultural lands is similar to an increase in maximum TP and TN concentrations (37% and 34%, respectively).

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