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Spatial and Temporal Dynamics of Non-Point Source Pollution

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Summary

Despite extensive and increasing investment by the USDA since 1987, agricultural non-point source (NPS) pollution remains the leading cause of water quality problems in the United States and a serious concern for policy makers, scientists, and the residents who rely on impacted waters. The Upper Big Walnut Creek (UBWC) watershed in central Ohio provides drinking water for approximately 600,000 residents of Columbus and surrounding communities. The majority of headwater streams in this watershed are impaired by nutrient enrichment, pathogens, and habitat degradation stemming from agricultural management practices. Existing pressures on the watershed may also be exacerbated by local impacts of global climate change.

Global climate change is predicted to increase climate variability, altering the distribution of environmental variables that influence agricultural and hydrological processes (e.g. longer growing seasons, more frequent extreme precipitation events, and increasing periods between events). Under an uncertain climate future, it is critical to understand how all linked processes—biogeochemical, hydrological, and land management—could accelerate and exacerbate the impacts of NPS pollution in the UBWC Watershed.

The overarching goal of this research is to identify the hydrologic and land surface characteristics that influence the spatial and temporal dynamics of NPS pollutants (nitrogen and phosphorus, in particular). To achieve this objective the following activities will be undertaken for the UBWC watershed: (i) Assessment of a suite of existing indexing methods used to identify critical source areas (CSAs); (ii) Application of the Soil and Water Analysis Tool (SWAT) to quantify pollutant load for comparison of SWAT derived CSAs to those identified by existing methods.

By developing relationships that link hydrologic, biogeochemical and land management characteristics to the spatial and temporal dynamics of NPS pollutants, the identification of chronic and acute CSAs will be achieved for the UBWC watershed. This methodology is generalizable and applicable to any agricultural based watershed with NPS pollution issues. The CSAs developed by this research will aid water resource managers by providing a method to prioritize the deployment of conservation measures and monitoring equipment.

Spatial and Temporal Dynamics of Non-Point Source Pollution

1 Statement of Regional Water Problem and Research Benefits

The August 2014 drinking water emergency in the City of Toledo, Ohio affecting over 400,000 residents was largely triggered by non point source (NPS) pollutants, namely phosphorus and nitrogen, originating from agricultural lands. This event has sparked the Great Lake Region to address the issue of nutrient runoff with the Ohio Lake Erie Phosphorus Task Force (2013) recommending a 37% reduction from the 2007-2012 spring averages and a 41% reduction in dissolved reactive phosphorus for the Maumee Basin which is the principal Ohio watershed draining into Lake Erie. With region being poised to invest heavily in order to meet these targets the need for an understanding of the spatial and temporal dynamics of NPS pollutants is critical for the efficient use of these resources.

Pollutant loading into surface waters varies in space and in time. This variability originates from the need for hydrologic transport mechanisms such as surface runoff (Dunne and Black, 1970; Horton, 1940), subsurface and tile drainage (Freeze, 1972) and erosion (Lyon *et al*., 2006) to intersect and mobilize a pollutant sources from the land surface to surface waters (Heathwaite *et al.*, 2000). This variability creates a disproportionate contribution of pollutants to surface waters, driven by differences in source and transport mechanisms across a watershed and is central to the concept of Critical Source Areas (CSAs).

Several studies focusing on CSAs have observed that a relatively small fraction of a watershed can generate a disproportionate amount of pollutant load (Pionke et al., 2000; Gburek *et al.*, 2000; Yang and Weersink, 2004). A study of Oklahoma watersheds, reported that just 5% of the land area yielded 50% of the sediment load and 34% of the P load (White et al., 2009). Similarly in a Vermont river basin, about 74% of the annual P load was estimated to come from just 10% of the land area (Winchell *et al*., 2011). In the Upper Scioto Watershed of Ohio Xie (2014) calculated that 50% of the phosphorus came from 32% of the land. The identification of CSAs in a watershed offers an opportunity to prioritize and tailor conservation practices that will better protect water quality and reduce costs and transform a purely NPS problem into a quasi-point source problem.

Often neglected in these studies is the temporal nature of hydrologic transport mechanisms, primarily driven by seasonal variability in precipitation and land cover. For example, precipitation falling on fields prior to planting in early April would result in very different regions of the watershed contributing pollutant loads to if the same precipitation event where to occur just after fertilizer application or late in the growing season. As the land surface characteristics change through the course of a growing season, so too will the location of the CSAs. From a monitoring and management perspective, an understanding of these temporal dynamics may improve targeted short term mitigation efforts.

On a longer timeframe, global climate change is predicted to increase weather variability, altering the distribution of environmental variables that influence agricultural and hydrological processes (Mendelsohn *et al.,* 1994). Longer growing seasons, more frequent extreme precipitation events, and increasing periods between events are among the numerous ways in which environmental drivers of land management are anticipated to change under an altered climate. Under an uncertain climate future, it is critical to understand how all linked processes—biogeochemical, hydrological, and land management—could accelerate and exacerbate the impacts of NPS pollution and alter the spatial and temporal dynamics of NPS pollution and CSAs. Changes to hydrological flow paths could impact the transport of NPS pollutants, while changes to soil moisture dynamics and soil temperature could affect the biogeochemical cycling of pollutants within the soil column. It is critical to quantify how the fate and transport of pollutants are impacted by the current land use and how local impacts of global climate change manifest and combine with other pressures. A sound understanding of the interactions between NPS pollution and global climate change will allow for better long term policy-making and management of agricultural lands and water resources in central Ohio.

This study used the Upper Big Walnut Creek (UBWC) watershed in central Ohio as a case study. The UBWC watershed is comprised of approximately 60% agricultural cropland and provides drinking water for approximately 600,000 residents of Columbus and surrounding communities. It was identified as a priority impaired watershed by the Ohio Environmental Protection Agency (EPA) in 1998, 2000, and 2003 (King *et al*., 2008). The majority of headwater streams in the watershed are impaired by nutrient enrichment, pathogens, and habitat degradation stemming from agricultural management practices (King *et al*., 2008). In addition, current pressures from agricultural intensification (increases in tile drainage and fertilizer application) and rapid urbanization within the UBWC Watershed may be exacerbated by local impacts of global climate change (Melillo *et al*., 2014).

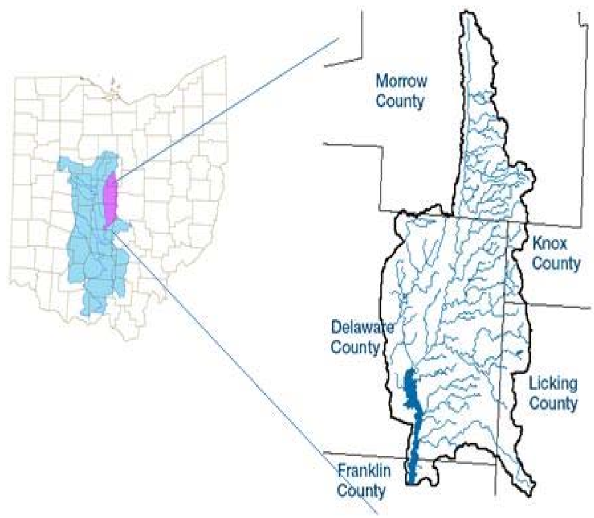

Figure 1: Left - Scioto River Watershed (blue) and Big Walnut Creek Watershed (magenta); Right - Upper Big Walnut Creek

2 Objectives

The overarching objective of this research is to:

Identify the hydrologic and land surface characteristics that influence the spatial and temporal dynamics of NPS pollutants (nitrogen and phosphorus, in particular).

To achieve this objective the following activities will be undertaken:

(i) Assessment of a suite of existing indexing methods (eg topographic Index, phosphorous index) that can be used to identify CSAs in the UBWC watershed and to compare these results with pollutant load quantifications observed by the USDA.

(ii) Application of the Soil and Water Analysis Tool (SWAT) model to explicitly represent the linked interactions between biogeochemical, hydrological, and land management to quantify pollutant load for comparison of SWAT derived CSAs to those identified by the methods listed above.

3 Methods

3.1 Site Description: The Upper Big Walnut Creek (UBWC) Watershed

The UBWC watershed is an 11-digit watershed (HUC 05060001-130) located in central Ohio (latitudes 40°06’00 to 40°32’30”, longitudes 82°56’00” to 82°42’00”, Figure 1). It covers 492 km^2 (190 mi^2) and contains 686 km of perennial and intermittent streams that drain into Hoover Reservoir.

The UBWC watershed is one of the twelve benchmark watersheds in the United States that are being evaluated as part of the Agricultural Research Service’s (ARS) component of the Conservation Effects Assessment Project (CEAP) (Mausbach and Dedrick, 2004). UBWC is unique among ARS watersheds because it involves the combined evaluation of the hydrological, chemical, and ecological responses of channelized and unchannelized headwater streams to conservation practices.

Agricultural cropland comprises the largest land use classification in the watershed (approximately 60%). The primary agricultural crops are corn, soybeans, and wheat. Management practices include conservation tillage, fertilization, and herbicide applications. A substantial portion of the watershed used for agricultural production is systematically tile-drained. In addition to crop production, approximately 15% of the watershed (in the southwestern portion) is transitioning from agriculture to urban land use that is composed of single- and multi-unit dwellings, parks, and golf courses. Additionally, soils in the watershed are clayey, poorly drained.

Current agricultural intensification (increase in tile drainage and fertilizer application) and rapid urbanization within the UBWC Watershed provides a unique opportunity to examine the impact of different land uses, agricultural management and conservation practices on NPS pollution by leveraging a paired watershed study conducted by the USDA ARS (King *et al*., 2008).

3.2 Existing Index Methodologies

In order to assess the utility of our propose model based identification of CSAs an assessment of an the existing methods used for the identification of CSAs will be undertaken for the UBWC watershed. The following methods were examined:

- Topographic index (TI) approach (Beven and Kirkby, 1979), and
- Curve number (CN) model (Arnold *et al.*, 1998),

The results obtained from these methods will be validated using pollutant loads observed by the USDA (data from 8 sub-basins from 2006-present). These methods rely on observed correlation between land surface characteristics and the generation of runoff to implicitly identify CSAs. Their advantage is in their simplicity, but consequently they lack the ability to predict and quantify runoff and nutrient generation processes and pollutant load (Srinivasan *et al.*, 2005; White *et al.*, 2009). Precipitation characteristics, which are projected to alter significantly under a changing climate, are noticeable absent in any of the methods listed above.

3.3 SWAT and Identification of CSAs

SWAT is a process-based, river basin-scale model developed by the USDA Agricultural Research Service (Arnold *et al.*, 1998) to predict the short- and long-term impacts of land management practices on aquatic water, sediment, and nutrient fluxes in large complex watersheds with varying soils, topography, land use, and management conditions. It explicitly represents the key hydrological, biophysical, and biogeochemical processes in both terrestrial and aquatic ecosystems, as well as management practices. A wide array of nonlinear biological and environmental processes are captured across all of the major model components, including crop and other vegetation growth patterns, temporal patterns in precipitation inputs and resulting interception by plant canopies, subsequent estimation of surface runoff, evapotranspiration, other hydrologic components, and estimation of soil erosion and transport of sediment, nutrients, and other pollutants.

Numerous studies have reported successful applications of SWAT for reproducing observed hydrologic and/or pollutant loads across a wide range of watershed scales and environmental conditions, as well as its applications, in assessing impacts of conservation practices, land use, water management, and other scenarios (Gassman *et al.*, 2007). SWAT has been widely evaluated for simulating streamflow and in-stream water quality constituents, such as water temperature, sediment fluxes, dissolved oxygen, nitrogen, and phosphorus (e.g. Daloglu *et al.*, 2012; Ficklin *et al.*, 2012; Jang *et al.*, 2012; White *et al.*, 2012; Palao *et al.*, 2013), and applied to assess effects of cropland management practices, wetland restoration, and reservoir construction and operations on water quality (e.g. Garg *et al.*, 2012; Michalak *et al.*, 2012; Comin *et al.*, 2013; Zhu *et al.*, 2012).

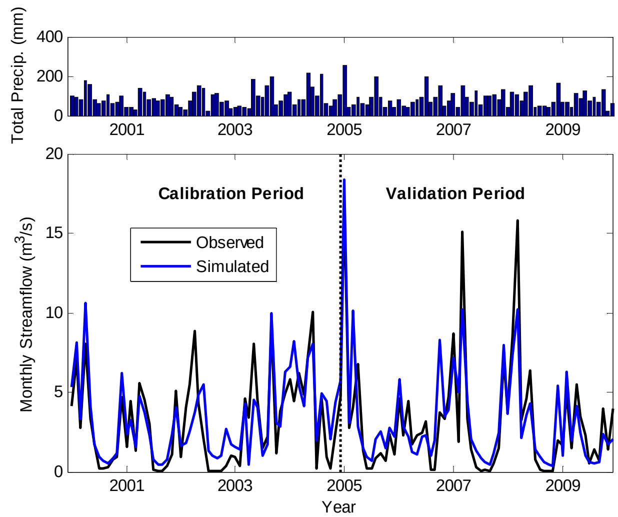

Figure 2: Flow calibrated SWAT Model for UBWC Watershed. Comparison of mean monthly observed streamflow to simulated streamflow at USGS Gauge 03228300 (Sunbury, OH) for the model calibration and validation periods of 2000-

As a semi-distributed model, SWAT requires a suite of spatially-explicit inputs, primarily including topography, soil properties, land use/cover, weather/climate data, and management practices. For our modeling analyses, a 10m digital elevation models will be used for topography; soil parameters will be retrieved from USDA's SSURGO database; annual land-use maps at a 56-m resolution, with crop-specific land classes, will be obtained from NASA's Crop Data Layer; weather data, such as precipitation and temperature, will be collected and extrapolated from NOAA's weather stations (or national re-analysis data) for historical periods and from downscaled GCM projections for future scenarios; management data, such as fertilization, tillage, planting, harvesting, and other field operations will be derived from survey data obtained directly from operator interviews from the National Resources Inventory (NRI) CEAP Cropland Survey.

This study will used the latest release of SWAT, SWAT2012, which includes a synthetic weather generator and improvements to simulation of nutrient cycling (nitrogen and phosphorus). We will focus on the UBWC Watershed in order to take advantage of the USDA datasets available at the site and the existing modeling efforts the Sivandran Lab has in the watershed.

3.3.1 Chronic and Acute CSAs

It is critical also to make a distinction between chronic or persistent sources of NPS pollutants which may result from the slow release of nutrients through leaching through the soil column into tile drainage, and the more acute or episodic NPS pollutant fluxes which may arise from fields susceptible to the generation of episodic surface flows from high intensity precipitation events. These two sources are of equal importance to the total load accumulating in receiving water bodies, even though at present the use of the Total Maximum Daily Loads (TMDL) thresholds by the EPA tends to neglect these chronic sources. By explicitly making this distinction, operational land management decisions can be made to focus conservation efforts to address local watershed issues.

To identify CSAs, we will utilize a calibrated and validated SWAT model for the UBWC watershed flow (Figure 2). SWAT model simulation output will be analyzed at the hydrological response unit (HRU) level. Monthly aggregated NPS pollutant loads will be synthesized to identify chronic CSAs subsetted for each pollutant, following an approach similar to Niraual *et al.* (2013). HRU-level yields will be ranked in terms of yields from the highest to lowest and then functionally related to the land surface characteristics and management practices at each HRU.

In order to capture the temporally variable component of NPS-pollutants, high NPS pollutant yielding events will be analyzed at the HRU-level to determine the location of acute CSAs. These events will be analyzed to determine what hydrologic or land surface conditions resulted in the episodic events occurring. Focus will be given to antecedent watershed conditions, particularly soil moisture conditions prior to the event, vegetation phenological state, and the precipitation event characteristics (intensity, duration and interstorm period). By combining relationships between acute CSAs and antecedent conditions with relationships linking land surface characteristics and land management practices with chronic CSAs a real time spatial risk index can be created.

4 Research Outcomes

4.1 Critical Source Areas

SWAT simulations of watershed were conducted and the subbasins (depicted in Figure 4-2) were ranked in terms of their load contributions. The top sextile, which aggregates the contribution of the top sixth of subbasins, was responsible for contributing 52% of the total nitrogen and 55% total phosphorous (Figure 4-2).

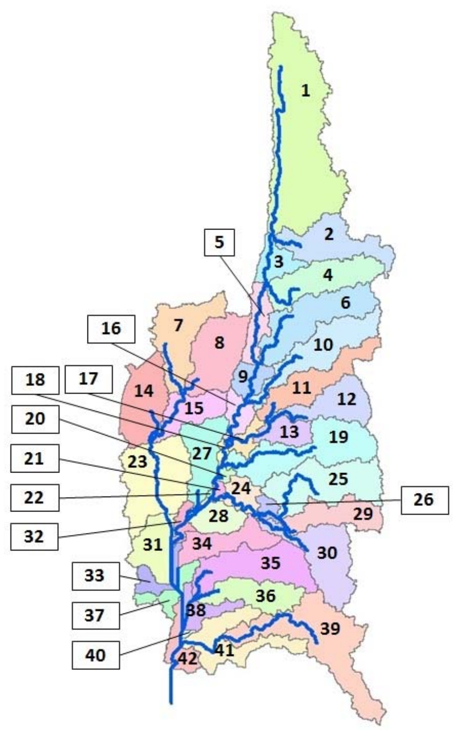

Figure 4-1. Subbasins in UBWC.

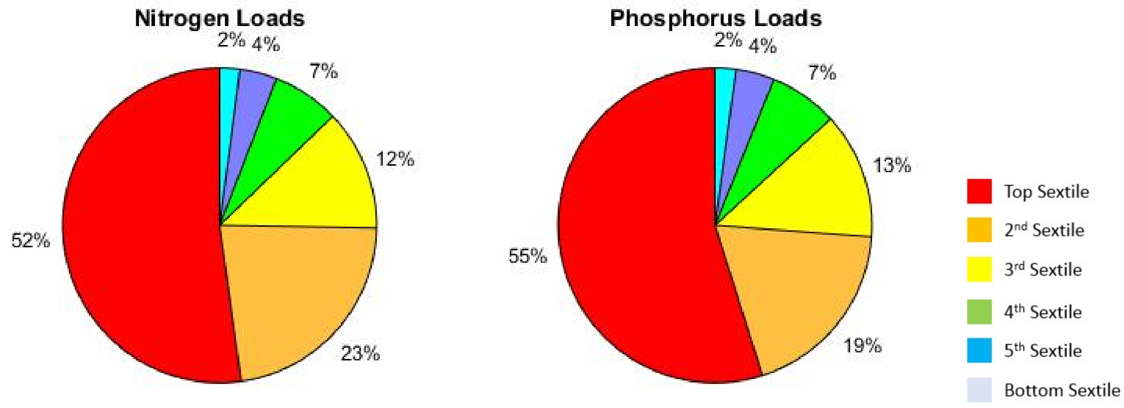

Figure 4-2. Percentage of Load for Each Sextile of Subbasins in UBWC

4.2 Critical Source Times

Rather than focusing exclusively on area, variation in loadings over time were examined to determine if they could possibly be a source of this variation. Over the 60-months of the study, the Top Sextile would be represented by the 10 individual months that had the highest loads (months Feb [50], Dec [24], Feb [14], Mar [3], Feb [26], Mar [15], Jul [55], Oct [58], Apr [52], and Oct [10]). This sextile (Critical Source Times) represents 54% total nitrogen and 58% total phosphorous of the nutrient load (Figure 4-3). Three months, February (50, 14, and 26), March (3 and 15), and October (58 and 10) account for seven of the top ten contributing months.

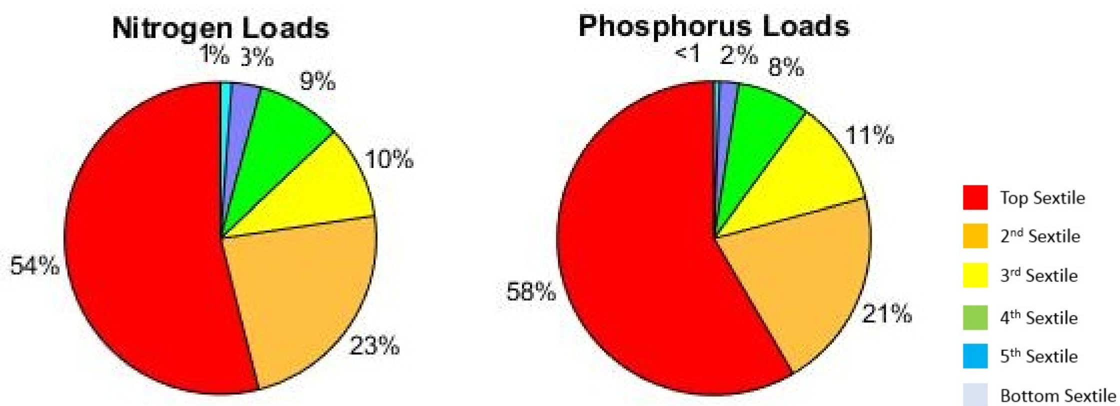

Figure 4-3. Percentage of Load for Each Sextile of Time (Month) in UBWC

4.3 Critical Source Junctures

When examining the spatial-temporal interactions (subbasins and time), the top sextile represents 62% (Nitrogen) and 65% (Phosphorus) of the nutrient load, and an even higher percentage than CSAs or CSTs individually. Therefore, it can be hypothesized that addressing the CSJs will have a greater impact than CSAs independently.

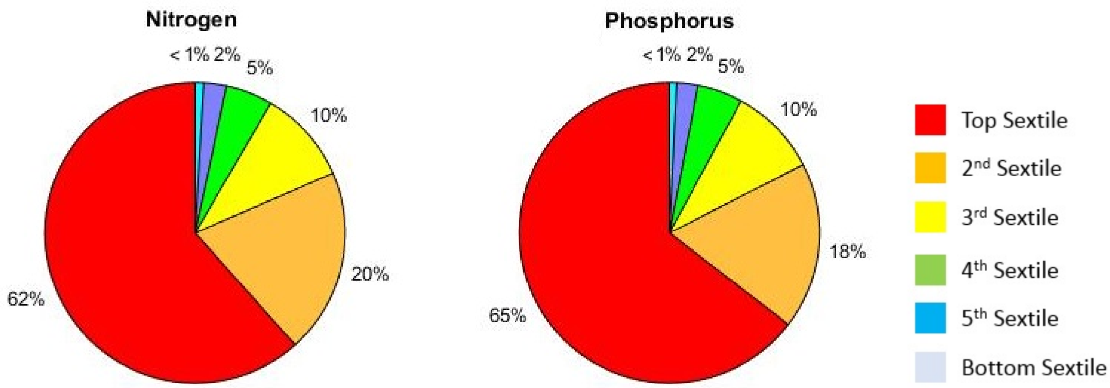

Figure 4-4. Percentage of Load for CSJ sextiles.

4.4 Discussion and Conclusions

Both time (Critical Source Times) and space (Critical Source Areas) can be used to determine contributors for the highest nutrient loads. However, by examining both time and space, a greater percentage of Nitrogen and Phosphorus loadings can be explained. Implementing BMPs that address both spatial and temporal issues could be a more efficient method of addressing nutrient pollution.

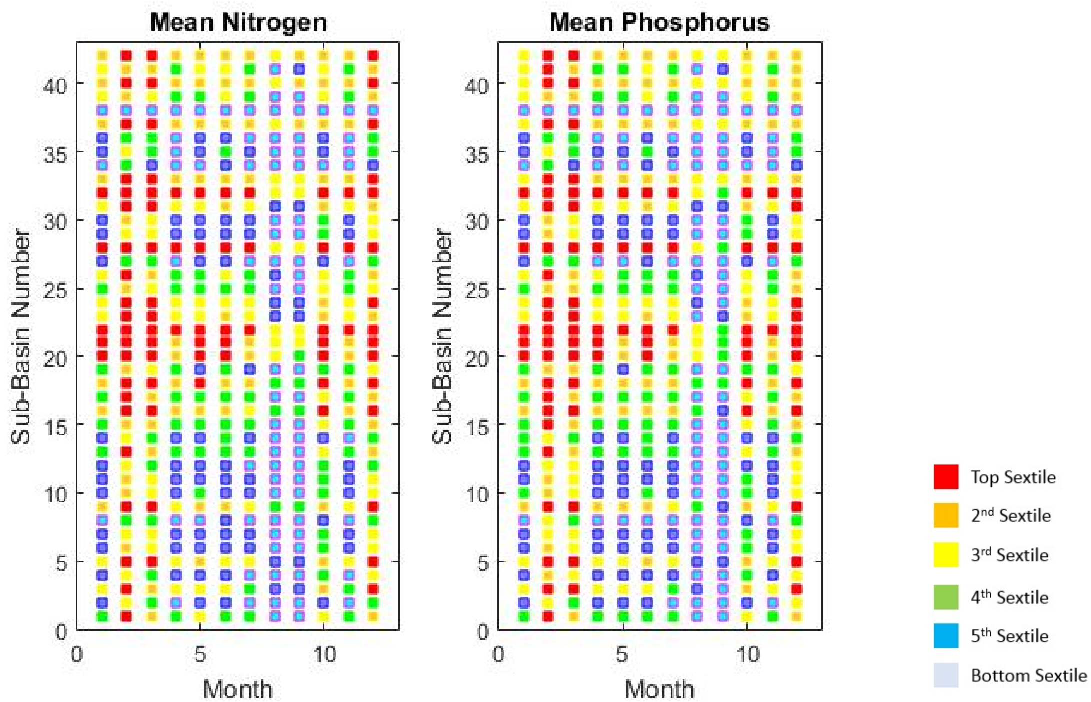

Figure 4-5. Monthly Mean Nitrogen and Phosphorus Load among 42 Subbasins and 12 Months in UBWC. Vertical features indication times of year of interest whereas horizontal features indicate areas within the catchment that consistently contribute to NPS.

Figure 4-5 indicates the interaction of both time and space. Vertical features on these plots indicate consistent spatial response at a given time. February, March, October, November and December all show stronger contributions across all subbasins. Horizontal features indicate a givens subbasins contribution to NPS across time. Subbasins 20,21,22 and 32 all show high levels of contribution regardless of time.

This form of temporal and spatial analysis could prove useful in determining the timing of intervention, the duration of that intervention as well as which subbasins would result in the greatest overall reduction in contaminate load. With mitigation resources limited, the ability to prioritize regions where long term conservation measures would greatly improve the ability to reduce the overall transport of nutrient load into Hoover Reservoir.

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