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Saheed A. Raji (raji.saheed@fupre.edu.ng)
Federal University of Petroleum Resources Effurun https://orcid.org/0000-0002-5890-5414
Shakirudeen Odunuga
University of Lagos https://orcid.org/0000-0003-4307-9428
Mayowa Fasona
University of Lagos https://orcid.org/0000-0002-7876-7397

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Spatiotemporal Modeling of Nutrient Retention in a Tropical Semi-Arid Basin

Saheed A. Raji*[1 2], Shakirudeen Odunuga[2], Mayowa Fasona[2]

[1] *Federal University of Petroleum Resources Effurun, Department of Environmental Management and Toxicology, Delta State NIGERIA, raji.saheed@fupre.edu.ng*

[2] *University of Lagos, Department of Geography, Akoka-Yaba, Lagos, NIGERIA.*

ABSTRACT

The Sokoto-Rima basin defines the natural and socioeconomic lifeblood of northwestern Nigeria. Its agrarian nature is an indication of significant dependence on the supply of ecosystem services from its various rivers, streams, and wetlands. However, nitrogen (N) and phosphorus (P) constitute a great portion of chemical fertilizers used to enhance crop yields and poor management of these portend great threats for water quality. The overarching objective of this study was to examine the extent of spatial variation of nutrient dynamics in the Sokoto-Rima basin between 1992 and 2015 using the nutrient delivery ratio (NDR) model of InVEST (Integrated Valuation of Ecosystem Service and Tradeoffs) software. Landcover, precipitation, digital elevation, and biophysical variables were the principal datasets employed as software input. The result of the study showed that the surficial N load is almost 15-fold of P in the Sokoto-Rima basin. Over the period of study, cultivated areas and rivers were spatially detected as nutrient sources and sinks respectively. The subsurface nutrient load is dominated by P while the amount of N load is insignificant. The trend of nutrient export is linearly defined: with 0.87% and 1.7% increase in N and P export respectively during 1992-2015. N and P exports vary spatially with a north-south increase-decrease index. Critical length and threshold are highly sensitive to changes in the parameterization of the NDR model. Thus, synergistic cultivation practices such as agroforestry should be extended to existing crop cultivation complexes to curtail nutrient enrichment in the Sokoto-Rima basin and ensure environmental sustainability.

Keywords: *Ecosystem services, InVEST, Nutrient modeling, Semi-arid, Sokoto-Rima basin, Spatial variation.*

INTRODUCTION

One of the numerous ways in which anthropogenic activities alters the natural nutrient cycling of any ecosystem is through land use changes particularly agricultural expansion [1-6]. Given that nutrient flow is a vital ecosystem service that regulates ecosystem integrity, changing pattern of land use and landcover can alter this natural pathway leading to distortions in ecosystem functioning and by extension ecosystem intactness. Point sources of nutrient discharges particularly industrial effluent and non-point sources from domestic and agricultural activities constitute a high proportion of human-induced distortions to the natural nutrient flow in any ecosystem [1, 7]. Within tropical systems particularly in semi-arid areas of the world where agriculture determines the lifeblood of the local economy, this scenario persists such that rainwater flows over the cultivated landscape washing away animal manure, chemical fertilizers and wastes from domestic sources into abutting streams and rivers [8]. This causes a great threat to both human health and welfare [9] and the associated aquatic life in the water bodies with restricted capacity to adapt to accumulative eutrophication and possible pollution [10, 11].

In controlling non-point source nutrient discharges particularly in areas of intense application of chemical fertilizers to enhance maximum outputs, ecosystems provide natural measures for amelioration such that vegetation can remove pollutants via tissue storage or aiding natural cycling in another form [12, 13]. In addition, non-polluted soil as well as wetlands provide suitable pollution-mitigation by providing nutrient storage prior to in-washing into hydrological systems [13-15]. In the engagement of pollution control measures particularly within agrarian circles, nutrient loads are often assessed by estimating the proportion of specific nutrients that are present within identifiable non-point sources across the landscape. Two of the most common pollutants in virtually any landscape is nitrogen (N) and phosphorus (P) from different environmental sources [12-14]. Studies across the semi-arid hydrologic basins suggests that N and P driven nutrient load exists in higher proportion within crop cultivation dominated areas than any other discernible landcover class. For instance, [12] specified that 68% of the pollutants within the agricultural region of Fenhe River are N compounds. [16] conducted a study across the expanded urban terrestrial ecosystem across the agrarian area of the Mississippi River in the Capitol Region Watershed (CRW) of the United States and results showed that 22% and 80% of net P and N inputs from cultivated regions were retained in the basin while the difference were washed downstream. With respect to semi-arid areas, [15] asserted that such areas with less dense vegetation tend to erode nutrients more than forested regions, consequently emphasizing the high propensity to stimulate eutrophication and nutrient-filled stream flow rivers.

Geochemical characterisation of semi-arid water bodies such as lakes, streams and rivers have been studied showing heavy nutrient loads with little or no focus on retention capacities making it difficult to analyse the impact of such on river hydrology [3, 5, 6, 8, 10]. [10] stressed that semi-arid soils of the Basara region of India has been polluted by nitrates and phosphates affecting the ability of water users' reliance on it for domestic and agricultural purposes. [12] underscored that sediment characterisation of agrarian landscapes of the Shanxi Province of China had altered some features of the local hydrology. Within the context of Nigeria, studies such as [14, 17-20] suggest that the country is not invulnerable to the realities of this problem particularly to water quality and river eutrophication.

Studies have also shown that the water quality of the surface water and groundwater ecosystem of the Sokoto-Rima basin of north-western Nigeria has been altered by series of anthropogenic activities ranging from local industrial effluent discharge into streams [18, 19] as well as manure and fertilizer in-washing into water bodies [14, 18, 20, 21]. Specifically, [14] used the point-based sample collection method to analyse to affirm the temporal variations of N and P derivatives of the Kware Lake in within the Sokoto-Rima which is traceable to human-induced sedimentation of the freshwater ecosystem. Similarly, [18] analysed physicochemical parameters of water samples collected along defined points along the Sokoto River to determine seasonal variations of its water quality. [20] examined surface water and groundwater characterisation of the Sokoto-Rima basin focusing on isotopic and geochemical characterisation determining only the nutrient loads of the identified groups. [21] investigated the level of certain anions of the Argungu River using in situ sample collection and direct analysis methods while the results showed that the river low pollution status of the nutrient loads.

The underlying assumption employed in these previous studies within the Sokoto-Rima basin refused to consider the complete phase of nutrient flow which consists of nutrient import source, uptake by plants and animals, export and other dispersal modes which are vital ecosystem services [5, 6, 11]. In addition, spatial distribution of these characteristics and variation overtime remains critical so as to identify location of these dispersion and utility pathways across the semi-arid landscape [7-8]. In this study, an attempt is made to spatially characterise the nutrient delivery conduit of the Sokoto-Rima basin focussing on the surface, and subsurface layers as well as to examine the variations in export mechanisms of N and P using a geographic information system (GIS) oriented model. This approach thus provides a cost-effective fashion and synoptic visualization of the nutrient flow and its variation across the landscape of the Sokoto-Rima basin while guaranteeing sustainable environmental assessment.

2. MATERIALS AND METHODS

2.1 The study area

The study was conducted in the Nigerian section of the transnational hydrological basin referred to as Sokoto-Rima basin. It is bounded in the north by Niger Republic, and in the west by Benin

Republic while in the east and south by Katsina and Niger States of Nigeria. Its geographical location is defined by Latitudes 10˚32'35" N to 13˚32'55" N and Longitudes 3˚30'30" E to 8˚1'15" E and the total land area is 94,026.5 km^2 (Fig 1). The semi-arid climate of tropical savanna of West Africa dictates the environmental condition of the study area. Precipitation (mostly rainfall) is typically seasonal, quasi-monsoonal in nature; confined to the wet season. Annual rainfall ranges between 350 mm to 895 mm in the northern and southern ends typifying a north-south rainfall increase index. Through the year, diurnal temperature averages 30^0 C with significant seasonal variability. Vital to nutrient flow is the hydrological network which flows westwards from the eastern highlands and ends southwards into the River Niger. The rock typology is dominated by the basement complex that is spatially restricted to the east. The sedimentary basin of the central and southern axis activated by the hydrologic and hydraulic activities of the Sokoto and Rima Rivers with several spots of rolling hills (Fig 1). Small-scale and climate-dependent agriculture is the mainstay of the Sokoto-Rima basin. Rice, tomatoes, beans, sorghum, maize, groundnut and millet are the key crops cultivated. Settlement pattern is mainly rural typified by crop production and rearing of cattle, ram, goats and sheep.

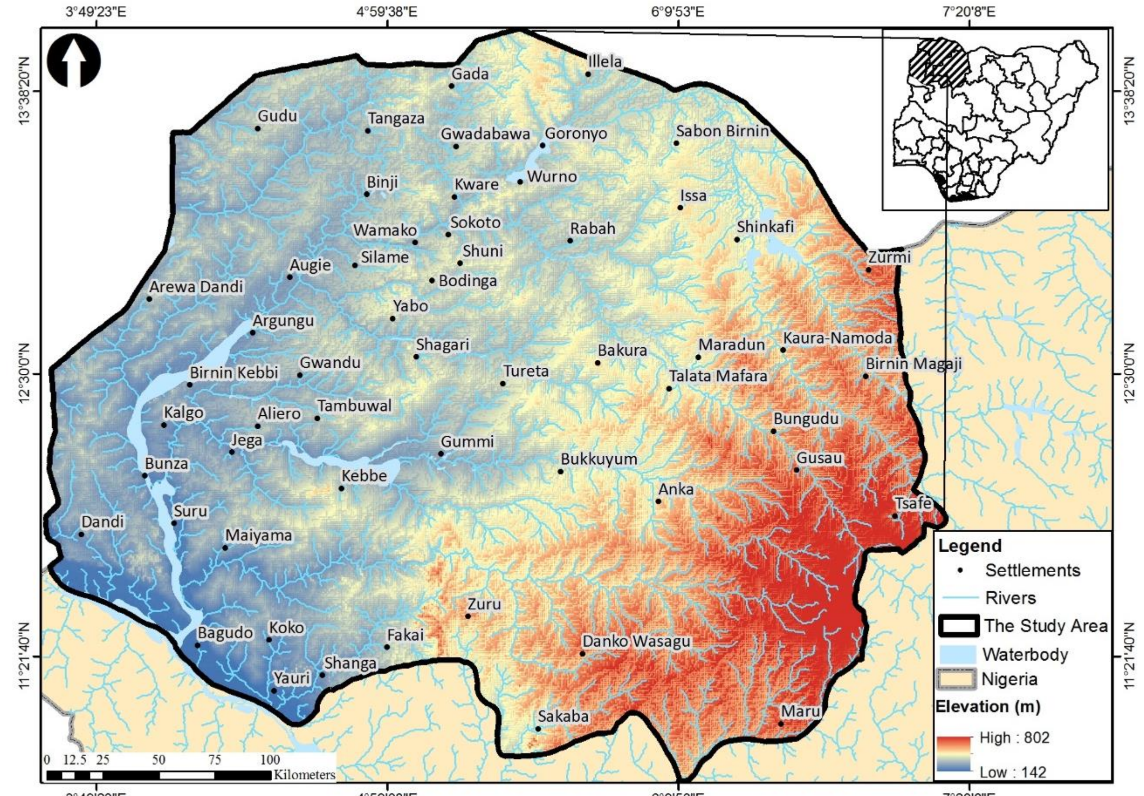

Fig 1. Geographical location of the Sokoto-Rima basin in context of northwestern part of Nigeria with the hydrological network and relief

2.2 Data sources

The landcover data from the Climate Change Initiative (CCI) of the European Space Agency (ESA) was used as data spine for landcover characterization of the study. The pre-classified data has 300 meters spatial resolution with auto-rectified benefits nullifying further image registration and rectification tasks. It has a dynamic range of 32-bit which is wide enough for detection of homogenous landcover classes. It also has regional coverage thus preventing edge-matching errors and continuous phenomenal assessment; an advantage it possesses over existing remotely sensed data sources such as Landsat and Sentinel. Data for the years 1992, 2002, 2015, and 2015 were sourced based on availability at http://maps.elie.ucl.ac.be/CCI/viewer/profiles.php.

Nutrient runoff proxy data was based on mean annual rainfall which acquired from climate synoptic stations within and outside the basin to permit proximate geographic coverage. The data were acquired from Sokoto, Yelwa, Birnin Kebbi, Argungu, Gusau, Goronyo, Wurno, Kano, and Kaduna in Nigeria and Malanville in Benin Republic and Niger Dabnou in Niger. Data for the years 1992, 2002, 2012 and 2015 were to match the previously explained landcover datasets extracted for the study. The data was acquired from the Nigerian Meteorological Agency (NIMET).

Digital Elevation Model (DEM) data was extracted from the West African grid of the ALOS World 3D Digital Surface Model (DSM) version 2.2 data obtained from the digital libraries of Japan Aerospace Exploration Agency (JAXA) through https://www.eorc.jaxa.jp/. The data has a 32-meters spatial resolution resampled to 300 meters resolution for data consistency with the landcover data. Its respective radiometric resolution of 32 bit also ensure fitness for feature detection consistency.

2.3 Quantifying nutrient retention

In this study, the Nutrient Delivery Ratio (NDR) model an integrated module in the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software package was employed to spatiotemporally quantify nutrient retention. InVEST is a free and open-source software package with extensive utility for modeling and assessing diverse ecosystem services principally based on landcover dynamics in conjunction with other environmental variables [1, 11]. The NDR model employs a mass-balance approach to spatially simulate the flow of nutrients as influenced by the inherent natural vegetation and other nutrient constraining and stimulating factors. The outcome of the model generates raster datasets that provides spatial information about nutrient loads (nutrient sources), exports, and the actual NDR for each of N and P. Data inputs into the NDR model include the prior described data on DEM, landcover, and nutrient runoff. The associated biophysical parameters are classified into tabulated data which include nutrient loads, retention efficiency, and subsurface proportion for N and P respectively (see Table 1). The software default value of 2.4 for Borselli K parameter (calibration function between hydrologic and sediment flow) was retained while threshold flow accumulation value was set at 10,000 which corresponds to 300 m data resolution. Three outputs were thus modeled from the NDR simulation.

Table 1. Landcover based biophysical variables used for nutrient modeling

Landcover description	Load (N)	Efficiency (N)	Critical length (N)	Proportion subsurface (N)	Load (P)	Efficiency (P)	Critical length (P)	Proportion subsurface (P)
Cropland	89	0.5	25	0.3	3.57	0.48	15	0.01
Agroforestry	89	0.6	50	0.25	2.48	0.54	15	0
Shrubland	8	0.75	150	0.47	0.93	0.6	25	0
Grassland	8	0.75	150	0.47	0.93	0.6	30	0
Waterbody	2	0.05	10	0.66	0	0.4	15	0
Settlements	10	0.1	10	0.2	2.1	0.26	15	0
Bare surface	5	0.01	10	0.47	0.79	0.26	15	0
Woodland	2.8	0.8	300	0.47	1.4	0.67	20	0

Adapted from [1, 11, 22]

Surface NDR focusses on the surficial traits of the basin defined by the multiplication delivery factor (downstream nutrient transportation excluding retention) and topographic position of the landscape. Mathematically, this is expressed as:

$$NDR_I = NDR_{0,I}\left(1 + exp\left(\frac{IC_i - IC_0}{k}\right)\right)^{-1} \quad (1)$$

where: IC_0 and k are calibration parameters, IC_i is topographic index computed from the DEM data, and $NDR_{0,I}$ is the ratio of retained nutrient by pixels downstream the lanscape.

Subsurface NDR which is the second output is based on geographic function of distance decay or the first law of geography which states that closer events are spatial connected than distance events. The subsurface NDR relates with distance to stream and the utmost subsurface nutrient holding and it is defined in equation (2) as:

$$NDR_{subs,1} = 1 - eff_{subs}\left(1 - e^{\frac{-5.l}{l_{subs}}}\right) \quad (2)$$

where: eff_{subs} is the maximum retention efficiency traceable through the subsurface patwhay in the multispectral space, l_{subs} is the subsurface flow retention length detected at soil maximum capacity, l_i is the distance from the pixel to the stream.

Nutrient export from a given multispectral location is a function of the nutrient load and the NDR, this is further explained in equation (3) as:

$$x_{expi} = load_{surf,1}\left(NDR_{surf,i} + load_{subs,i}\right)NDR_{subs,i} \quad (3)$$

At the basin level, equtaion (3) aggregates all the pixels within the multispeatral space to give:

$$x_{exp_{tot}} = \sum_i x_{exp_i} \quad (4)$$

where: $load_{surf,1}$ is the surface load at the first pixel, and $NDR_{surf,i}$, $load_{subs,i}$ and $NDR_{subs,i}$ is surface NDR, subsurface nutrient load and subsurface NDR loads respectively while x_{expi} is the specific nutrient export, aggregate of which generates the $x_{exp_{tot}}$.

2.4 Sensitivity Analysis and Uncertainties of the Nutrient Export

As a test of model performance, sensitivity analysis was conducted on the vital NDR model parameters particularly on critical length, threshold flow accumulation, Borselli *k* value, load and efficiency functions of each of the landcover classes. This was performed by increasing and decreasing parameter values by 50%, precisely: Borselli *k* parameter varied from the default of 2.4, to 1.2 and 4.8, the critical length was varied from the default value of 90 m to 45 m and 180 m while the threshold flow accumulation was varied from 10,000 (default) to 5,000 and 20,000. The load and efficiency values stated in Table 1 where adjusted ±50% for each of the landcover values.

3. RESULTS AND DISCUSSION

3.1 Nature and Dynamics of Surface Nutrient Load of the Sokoto-Rima Basin

Surficial nutrient loads of the Sokoto-Rima basin as defined by the temporal distribution of N and P is displayed in Fig 2. During the period of study, N rises from 1992, peaks at 2012 and plunges slightly in 2015. This shows a linear relation with increasing mean annual load of 5,667 tons increasing at 9.56 tons/year. Over the period of assessment, surficial N load increased from 51,736 million tons to 513,070 million tons.

Spatially, Fig 3 shows that high N loads of roughly 8.22 kg per kilometer are directly connected to headwaters of the Sokoto-Rima basin throughout the years. The outline of Rivers Sokoto and

Rima shows that they water bodies contribute the least amount of surficial N loads. The baseline year (1992) showed that tributaries of these main river networks in the eastern and northern axis channels high N loads downstream. In addition, wetlands of the southern axis which are mainly lowlands constitutes the highest N loads. By 2002, areas of high were observed in part of central areas with roughly 50% increase in N load while most areas remain unchanged. This observation changed slightly as notable spatial loads were detected around wetlands around the major rivers as well as wetlands in the east. Slight changes were detected in 2015.

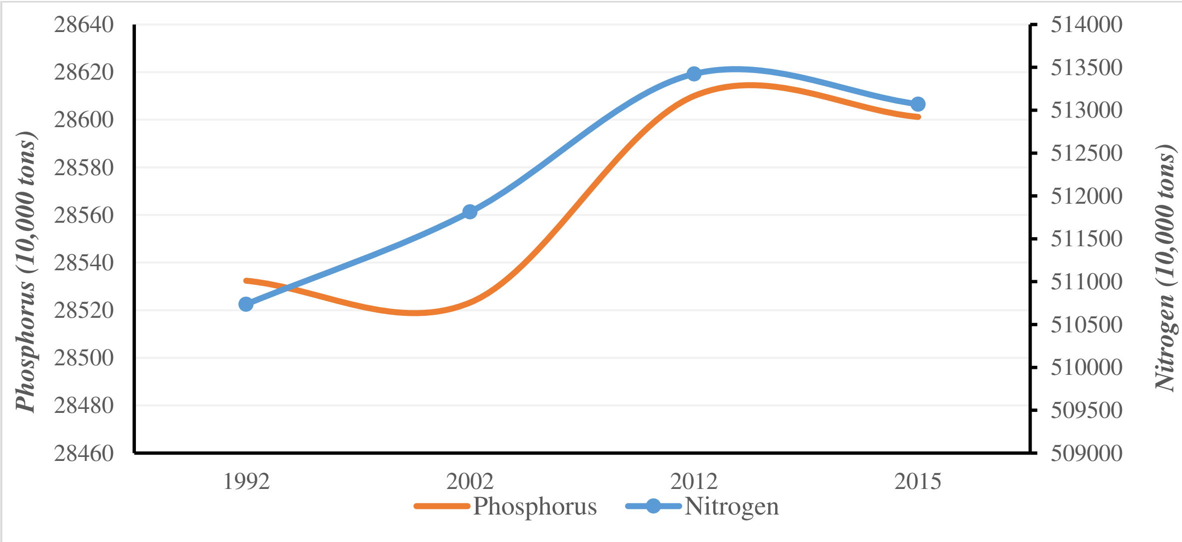

Fig 2. Temporal trend of surface loads of nitrogen and phosphorus of the Sokoto-Rima basin

Surficial P load within the Sokoto-Rima basin increased annually with a mean annual load of 26,103 tons per unit area, increasing at a rate of 32 tons for every km (Fig 2). Precisely, the baseline value of 28,532 million tons increased to 28,601 million tons. Its semi-sinusoidal curve pattern showed the level of consumption and the extent of landcover of the Sokoto-Rima basin, an area that is dominated by crop production.

Changes in spatial distribution of surficial P load showed pattern that is similar to that of N where headwaters of the major streams that define the basin were detected as major sources (Fig 4). On the eastern axis where most of the rivers takes their source accounts for over 70% of the 5.86 million tons per km^2 of P. Areas at the lowest range of P with roughly 0.89 million tons are directly proportion to areas of high intense crop production.

These results concurred with the findings of [14, 18 and 20]. Explicitly, [14] claimed that low quantities of nitrate, nitrite, and ammonia (derivatives of N) and orthophosphates in Kware Lake is an indication of fitness of the surface water for multipurpose uses especially during the dry season. [18] stated that seasonal variation of N and P in surface water of the Sokoto River lies between 1.77 mg/litre and 19.7 mg/litre which is suitable for crop cultivation but slightly above the required fitness for domestic consumption purposes. [20] indicated that the isotopic classification of the surface water classified that of Sokoto-Rima basin in Group IV and V with direct linkage to rainfall input and elevated values are directly connected to the presence of gypsum in some parts of the Sokoto-Rima basin.

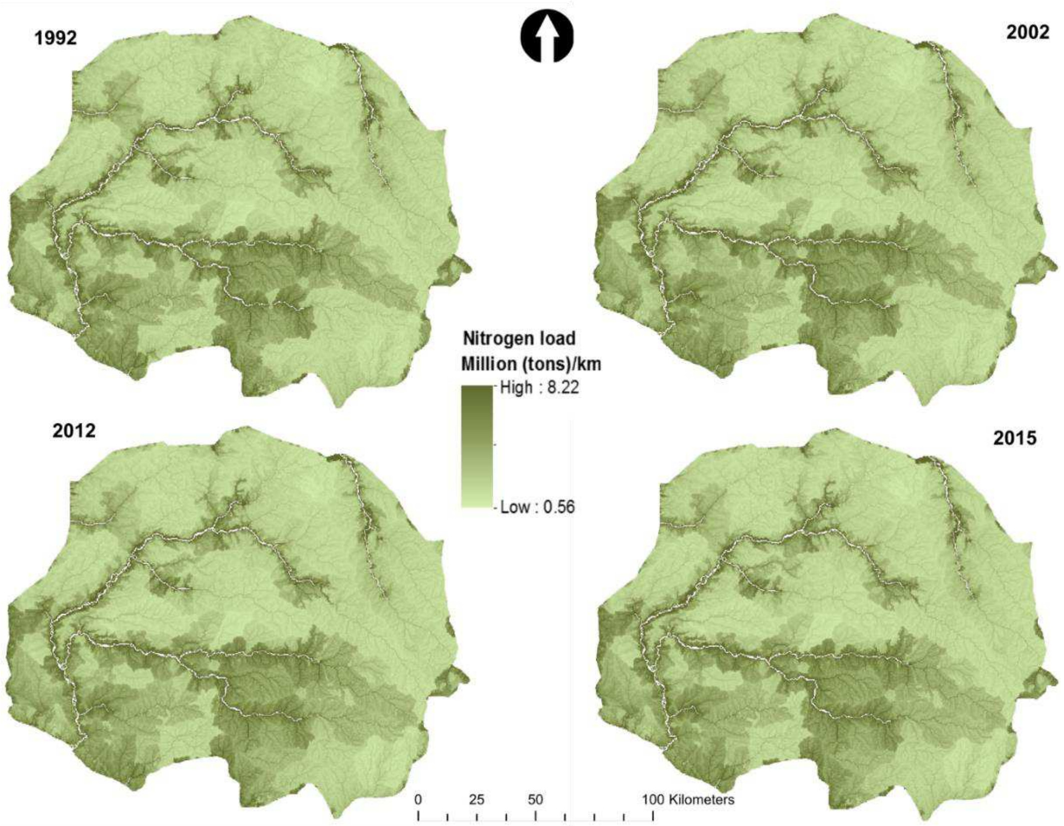

Fig 3. Spatial distribution of surficial nitrogen load in the Sokoto-Rima basin for the years 1992, 2002, 2012 and 2015.

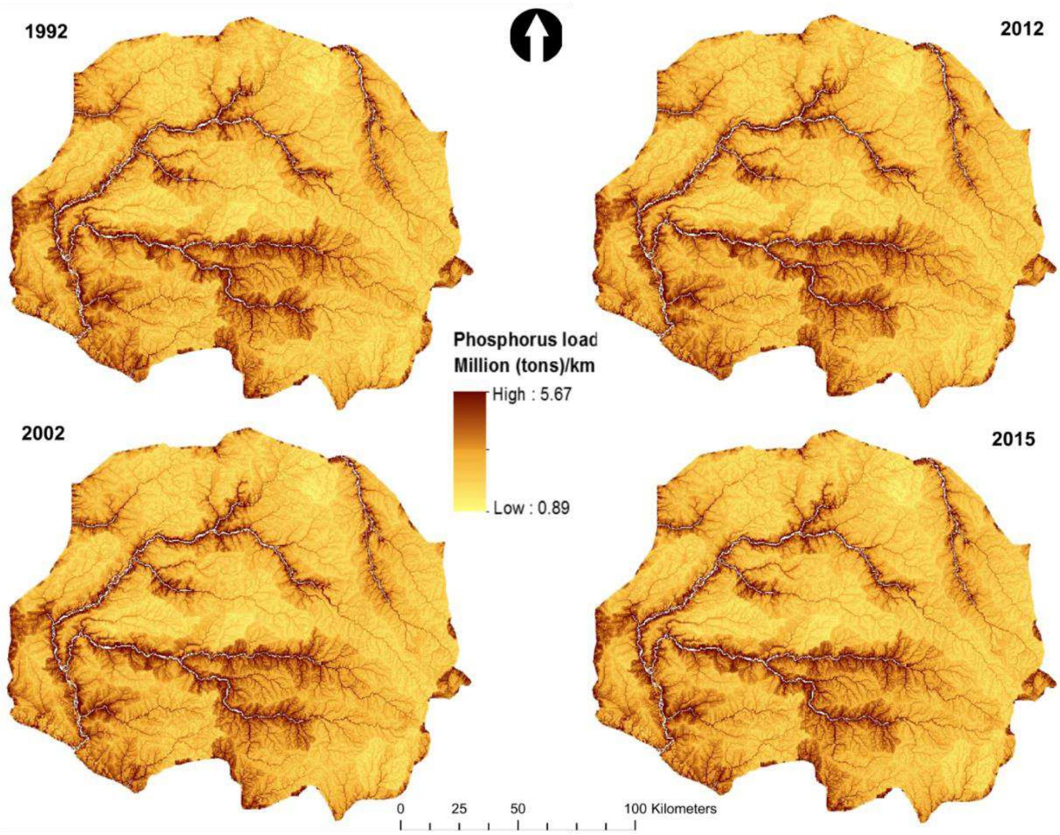

Fig 4. Spatial distribution of surficial phosphorus load in the Sokoto-Rima basin for the years 1992, 2002, 2012 and 2015.

3.2 Nature and Dynamics of Subsurface Nutrient Load of the Sokoto-Rima Basin

The outcome of subsurface nutrient load returned contrasting results as spatiotemporal dynamics returned differing characterization for each of N and P. First, subsurface load of N in the Sokoto-Rima basin returned no value. This is consistent with the deductions of [22 and 14] who affirmed that N is a surficial nutrient element for driving crop productivity in the semi-arid zone of northern Nigeria with low or no value at the subsurface level. These have been further asserted by [8, 10] in China and India respectively where geochemical analysis of derivatives of N yielded paltry outcomes.

According to [23] accumulated study of P over the centuries has showed a direct correlation with human activities and its impacts on freshwater eutrophication in China. This shows that there are latent chances of subsurface trend of P in an agrarian milieu such as the Sokoto-Rima basin. Fig 5 showed that that P load increased from 2,128.7 million tons in 1992 to 2,150.5 million tons in 2015, 0.36% increase with a difference of 7.62 million tons. Despite this trend, no spatial variation of subsurface P was detected an evidence of strong surface load forcing.

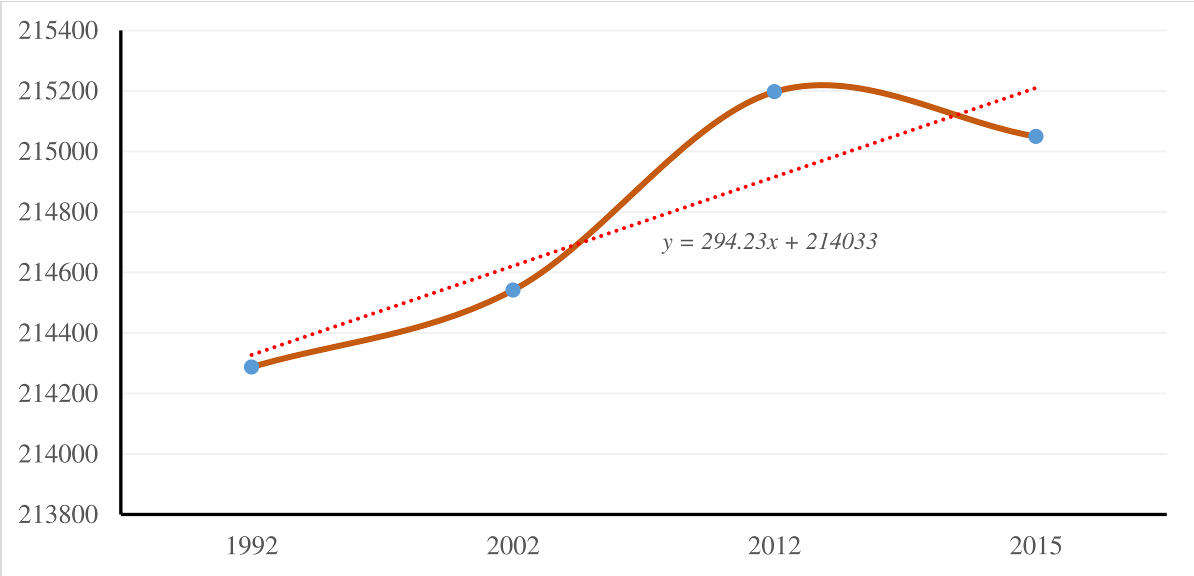

Fig 5. Trend of subsurface phosphorus load of the Sokoto-Rima basin from 1992 to 2015

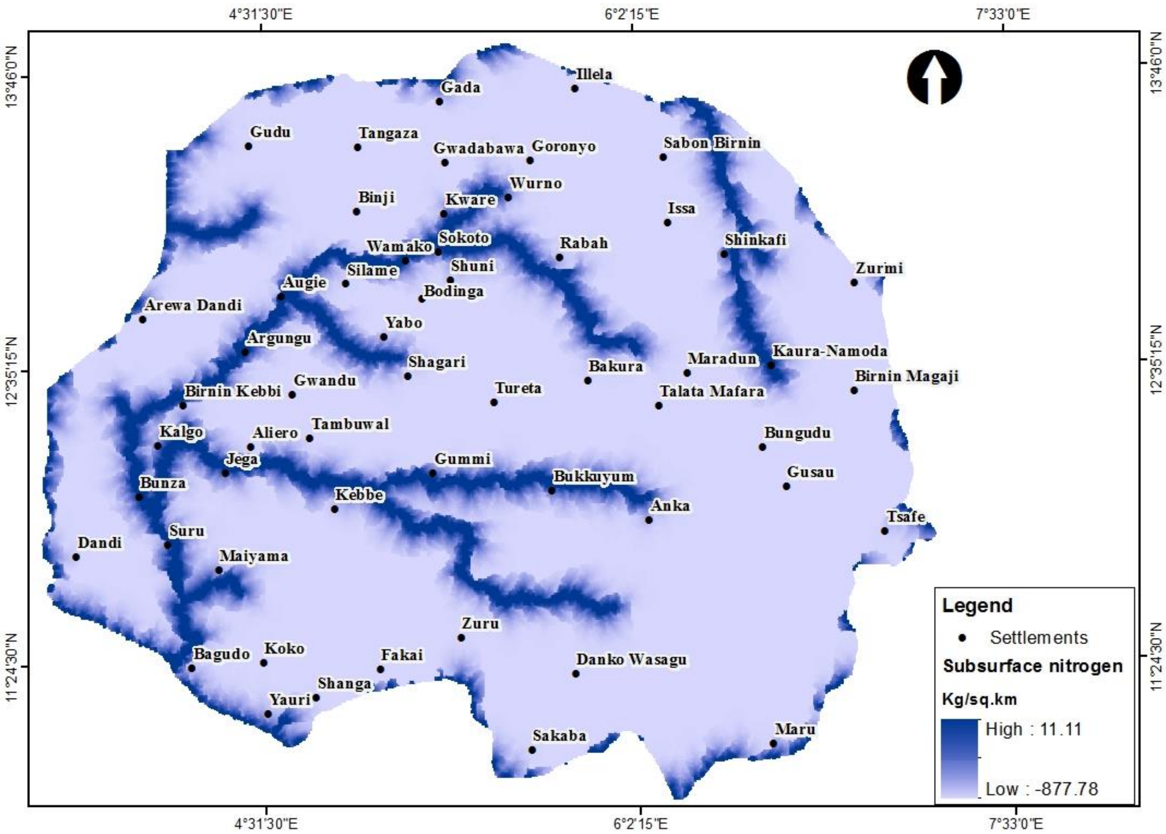

Fig 6. Spatial distribution of subsurface nitrogen loads of Sokoto-Rima basin (1992-2015)

Within the time of this study, no specific spatial variation was detected in the amount of subsurface N loads in the Sokoto-Rima basin, hence the extent of spatial distribution for the year 1992 returned the same as 2015. However, Fig 6 showed that subsurface N loads were spatially restricted to water bodies – rivers, streams and freshwater lakes, with highest values

11.11 kg/km^2. This was followed by the adjoining wetlands with 1.09 kg/km^2. Largely, subsurface N loads are directly influenced by water-bearing landcover classes. This is because N is a vital chemical component of aquatic ecosystems as it contributes extensively to the growth and sustenance of aquatic organisms as part of their essential feedstock hence performing a vital ecosystem service [6, 12]. The deficit range of loads observed in the other areas can be attributable to high uptake of the nutrient as distinguished by crop consumption rates [13, 16 22].

3.3 Trend of Nutrient Export in the Sokoto-Rima Basin

3.3.1 Temporal dynamics of nutrient export

It has been established that nutrient export contributed to the increasing evidence of eutrophication and sedimentation evaluated within frashwater bodies of the Sokoto-Rima basin particularly Lake Kware [14]. It was noted that N exports accounted for over 65% of the nutrient yields observed in the lake [14]. This could be directly associated with increasing intensity of economic and social activities which has resulted in adjustments of the previous natural conditions of the area. Cumulative cultivation of crops and animal domestication around the wetlands and upland areas have led to introduction of nutrients such as herbicides, pesticides, solid wastes from various domestic sources, sewage, chemical fertilizer runoff from cultivated fields have been acknowledged in the Sokoto-Rima basin [19-21]. Over the course of this current study, N export outweighs P as shown in Table 2 even though the proportionality of increase overtime is low. The magnitude of change showed that from 1992 to 2015, N export increase slightly by 0.87% with the greatest increase compared to baseline in 2012. Similar pattern was detected for P with 1.7% increase. The trend is could be related to previously acknowledged human activities.

Table 2. Nitrogen and phosphorus export in 1992, 2002, 2012, and 2015.

Year	**Nutrient export ('000 ton)**		**Percentage Change from baseline**	
	Nitrogen	Phosphorus	Nitrogen export	Phosphorus export
1992	15,179.64	4.59	-	-
2002	15,278.19	4.62	0.65	0.74
2012	15,319.76	4.66	0.92	1.70
2015	15,311.09	4.66	0.87	1.70

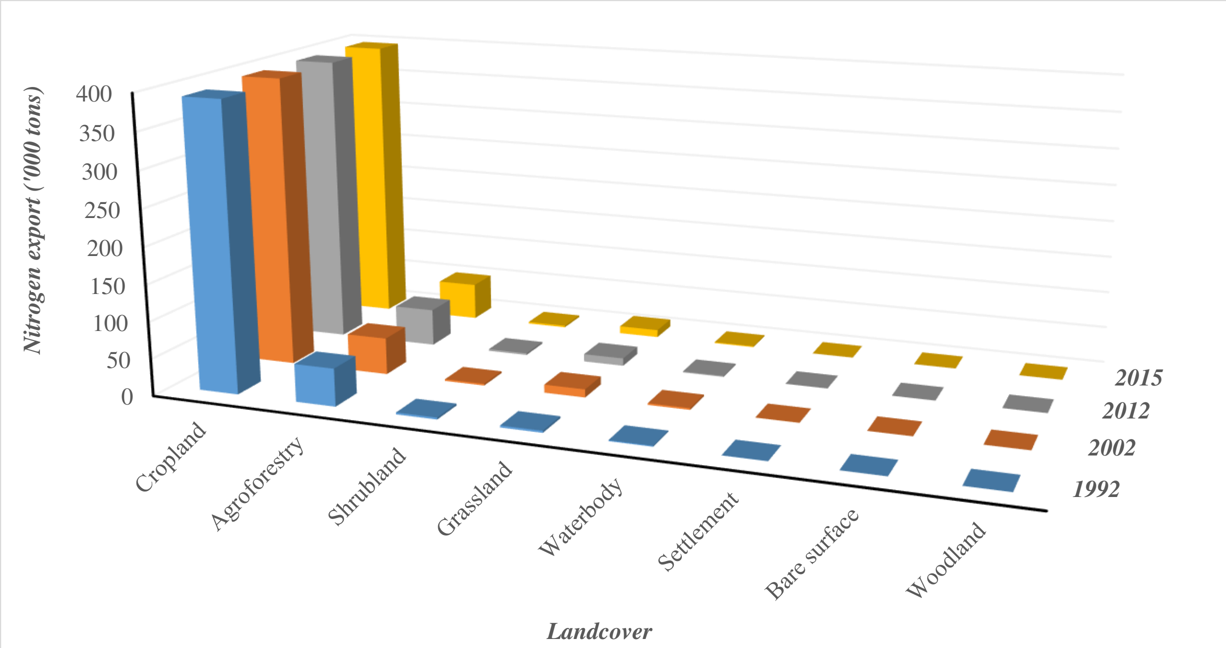

Fig 7. Nitrogen export of the Sokoto-Rima across the different landcover classes from 1992 to 2015

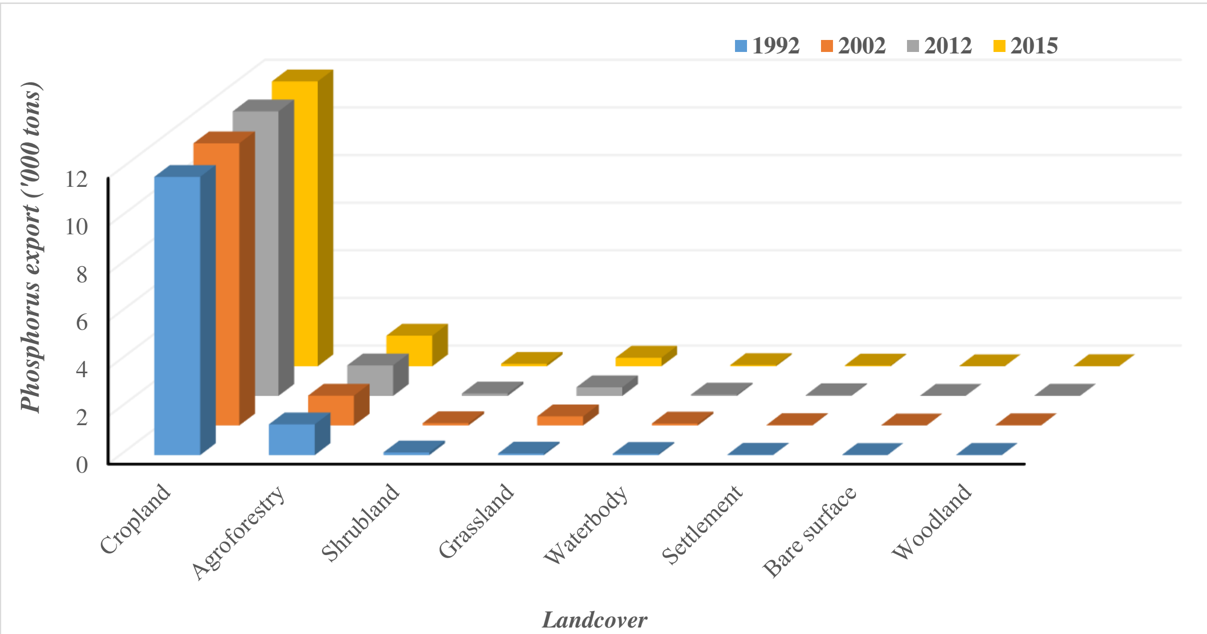

Fig 8. P export of the Sokoto-Rima across the different landcover classes from 1992 to 2015

Fig. 7 and Fig 8 showed that cropland influenced nutrient export in the Sokoto-Rima basin with almost 85% of the overall amount of nutrient exported. This is immediately followed by agroforestry (which is mosaic of cropland and woodland) and grassland while bare surface contributes the least nutrient export. Infinitesimal proportion of nutrients were also exported from settlement. [26] had shown that Sokoto-Rima basin is cropland dominated and the trend and proportionality is anticipated to persist in the future. This is expected to inhibit the associated ecosystem services and possible nutrient export. Roughly 90% of N exported is from cropland while few amounts exported originated from grassland, shrubland, woodland, and waterbody. This describes the basin N cycle in which cultivated areas determines the nature and pattern of N with respect to low tree density forested areas.

Fig 8 specified that the proportion of P exported from the Sokoto-Rima basin is roughly 3-fold less than the magnitude of N. This is also directly related to the anthropogenic activities and limited P storage by the dominant landcover themes [23]. [25] argued that available N inputs in a given terrestrial ecosystem could trigger a coupled increase in other related nutrient elements thereby boosting nutrient cycling. However the scenario in a semi-arid environment such as the Sokoto-Rima basin where biomass response to increased N is very low, P export is high and co-related to anthropogenic forcing. This justification is proven by Fig 8 where natural landcover contributes the least to P export as the landscape is dominated actively by agrarian influences.

3.3.2 Spatial variation of N and P export

The spatial context of nutrient export of the Sokoto-Rima basin over the period of study showed dissimilar traits that explain the extent of place-based and location specific variations. In particular, spatial distribution and variation of N export as displayed in Fig. 9 showed that N export is generally unchanged within the period of study (1992-2015) typical justifying the temporal observations. Interval variation however depicts some explicitness. From 1992 to 2002, spatial decreases in exported N were detected around wetlands and agroforestry of the north.

Spots of decreases were also detected in some parts of the east and the southern swath of the Niger plain where River Sokoto confluences with the Niger River. Local increases can be observed throughout the area with exceptions from the cultivated areas where there are no changes. The period 2002 to 2012 had slight changes as large decreases in N export were detected in areas with increases especially around the south and wetland areas of the north while other areas remain relatively unchanged. Large decrease in N export within the 2012-2015 period could be related to the short space of spatial comparison. Overall, spatial difference in N exports of the Sokoto-Rima basin remain largely constant with more decreases than increases and this is analogous to the nature of landcover.

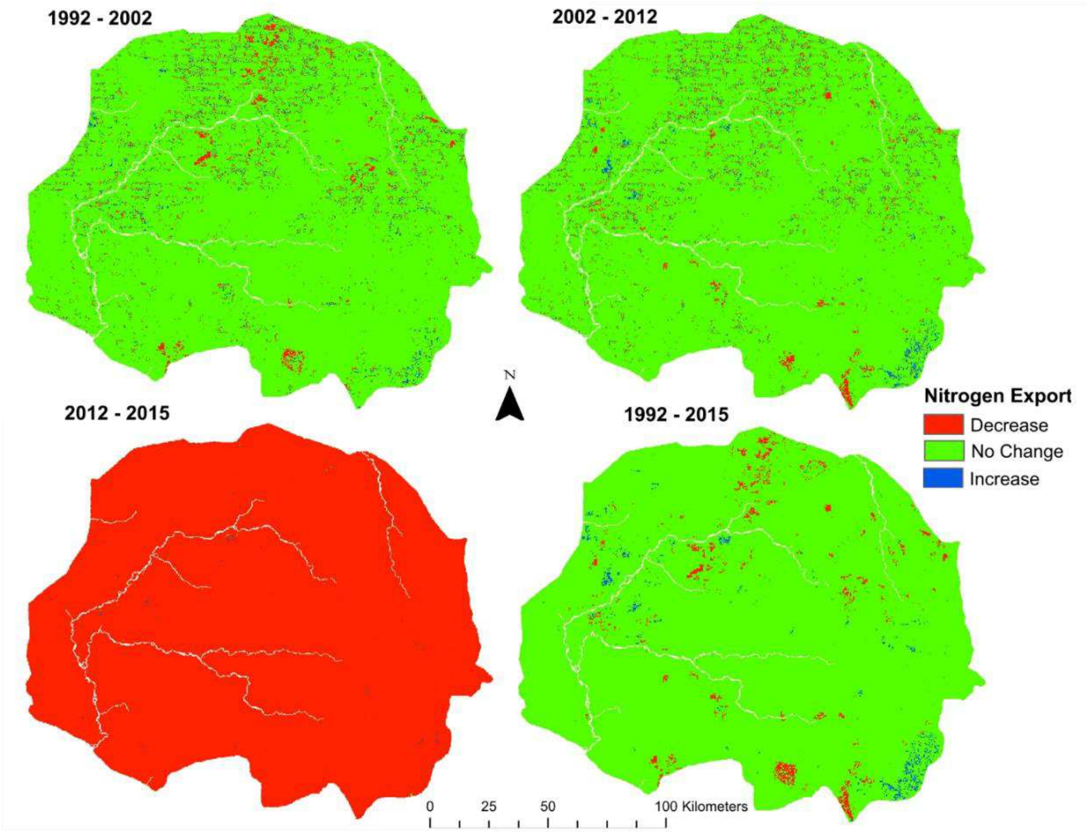

Fig 9. Spatiotemporal variation of nitrogen export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and cumulative spatial difference)

P export across the landscape of the Sokoto-Rima basin for the study period (1992 to 2015) showed fluctuating decreases and increases (Fig 10). Largely, P export remained unchanged in the fashion as that of N export. However, there are locational differences across the period of study. The decade (1992 to 2002) had increase in P export in certain areas around the north, central and the east while spots of decreases where noted in minuscule portions. Similar variation was observed in the period 2002 to 2012. The period 2012 to 2015 had quasi-constant P export. Overall, there were indication of increase in P than decrease particularly in areas of agroforestry of the north, wetland plains of the south.

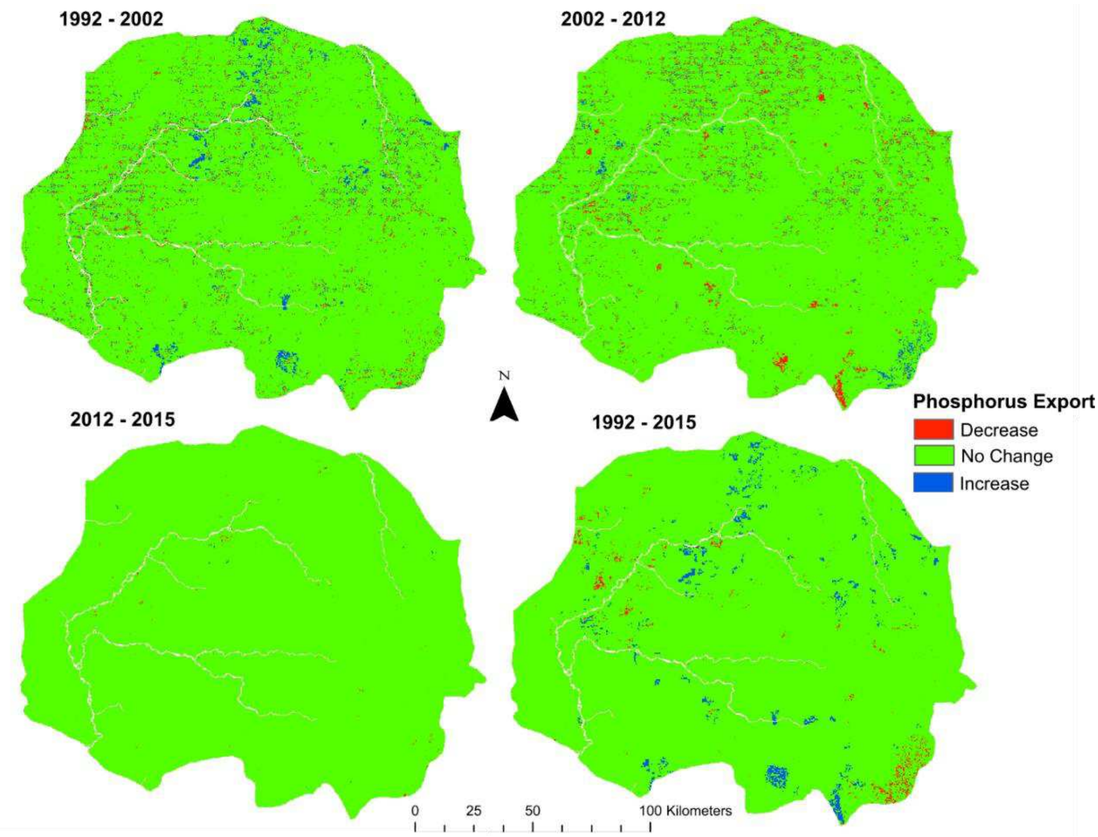

Fig 10. Spatiotemporal variation of P export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and accumulative spatial difference)

3.4 Sensitivity Analysis of Nutrient Export

The linearity function of the equations utilised in deriving the spatial relationships between nutrients and associated parameters suggests a high degree of sensitivity. This has been justified and substantiated in Fig 11 which showed the aggregate nutrient export varied considerably with the parameters in the Sokoto-Rima basin. The sensitivity of the nutrient export was greatest for critical length (*Crit len*) showing the extent of elasticity such that a ±50% adjustment triggers a corresponding 94% decline and 108.76% upsurge in nutrient export. Threshold value (*Threshold*) demonstrates a converse sensitivity to nutrient exports with a quasi-co-equal influence in which a 50% reduction leads to increase in nutrient export while +50% increment yields a reduction up to 95.93%. Load parameters attached to each of the landcover revealed a direct level of sensitivity out of which cropland returned the highest nutrient export with +50% increment leading to 110.09%. Similar sensitivity pattern was observed for loads for agroforestry and woodland in which positive adjustment in parameter value leads to direct change in nutrient exports. Nutrient efficiency factor across the landcover spectrum largely have direct influence on change in nutrient export where cropland and woodland possesses the most dynamic influences (Fig 11).

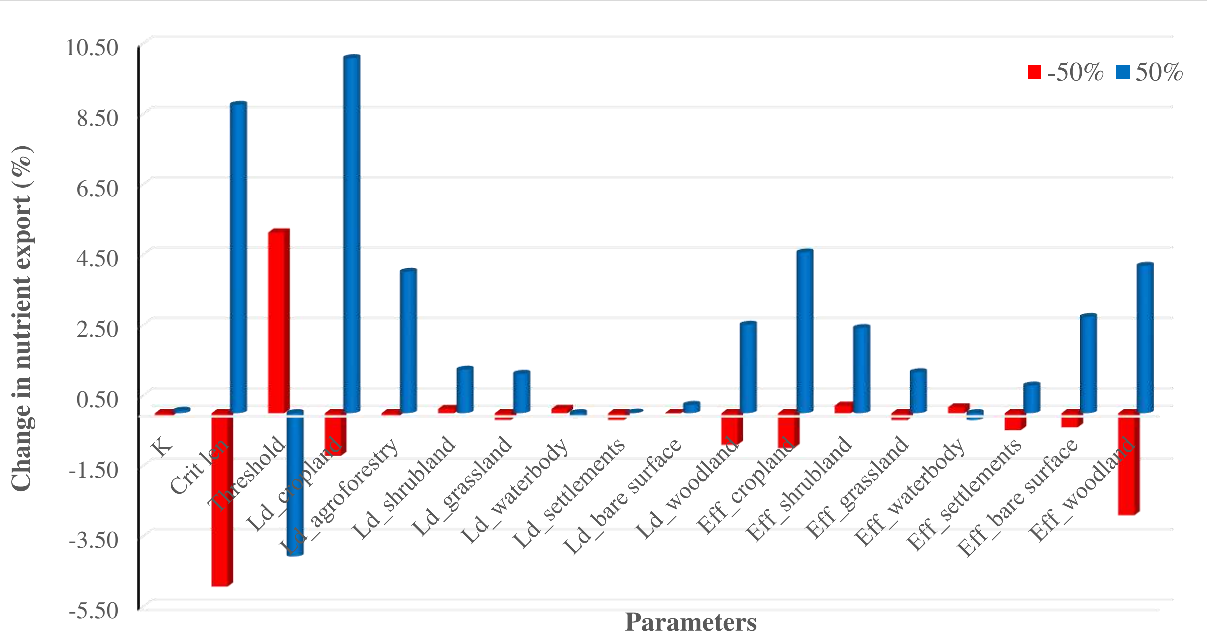

Fig 11. Sensitivity as depicted by response of the aggregate nutrient export to a ±50% change in selected input parameters for the entire Sokoto-Rima basin. K depicts Borselli factor, crit len (critical length, in Table 1), Ld and Eff stand for loads and efficiency for respective landcover classes.

3.6 Localized Context for Nutrient Cycle

Nutrient cycling pathway is place-based and context-specific significantly influenced by dynamics of nature and anthropogenic forcing. Given that the Sokoto-Rima basin is predominantly agrarian interspersed with dispersed settlements. The spatial organization of settlements is such that it is buffered by crop production complexes which stretches to wetlands and plains throughout the area. Accordingly, farmland fertilization accounts for N and P enrichment in the Sokoto-Rima basin. Related factors such as weathering of farm wastes, domestic wastes and sewage from townships and bucolic communities as well as animal droppings can be related. These are usually washed into rivers and streams via surface runoffs off cultivated fields and animal production fens as well as open grazing fields where animals freely roam and animal wastes directly enrich the soil or used as compost manure for cultivation. Often these are washed into open water bodies leading to eutrophication problems which have been recorded in the Sokoto-Rima basin [17-20]. Low woodland and forest cover which is not uncommon for semi-arid ecosystems some vital natural landcover drivers of these as forest cover aids nutrient uptake and curtail the extent surface delivery of nutrient elements.

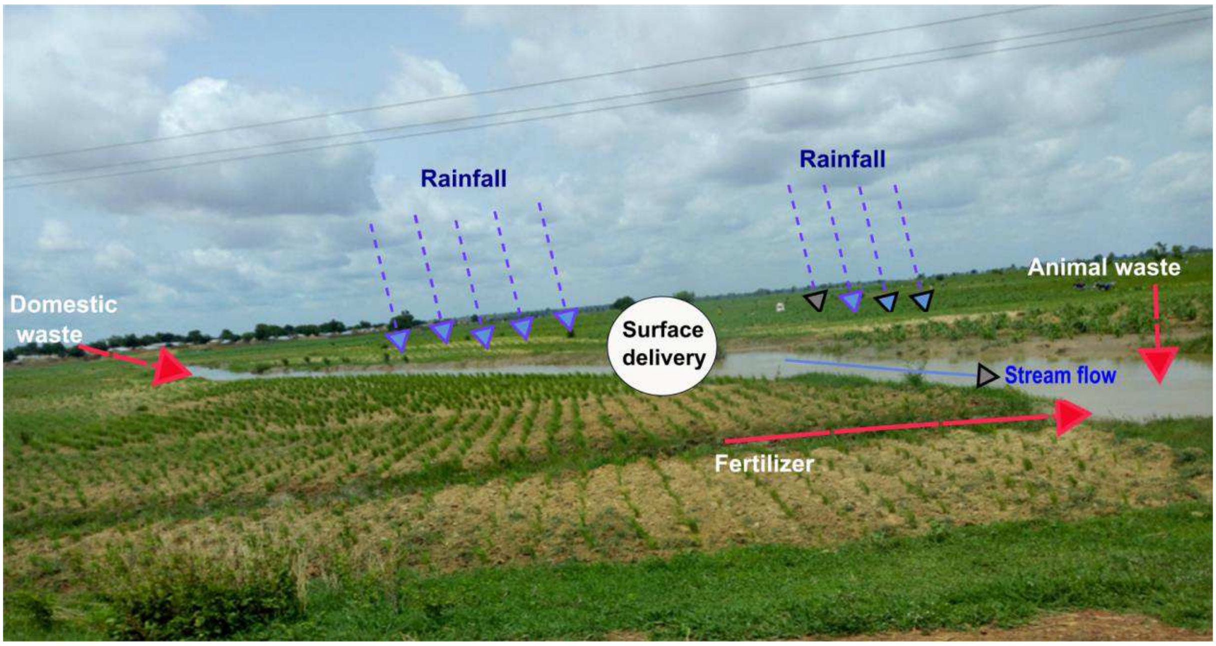

Fig 12. Pathway of nutrient flow and cycling in the along the section of River Zamfara a vital water body of the Sokoto-Rima basin. The blue arrow and feature shows natural input source while the red arrow indicate the anthropogenic source of both nitrogen and phosphorus.

4. CONCLUSION

This study has shown that amounts of surficial N outweighs P in the Sokoto-Rima basin by almost 15-fold with linear increment trend from 1992 to 2015. Also, spatial distribution showed that both nutrients were directly proportional to crop cultivation areas while water bodies particularly the major rivers were identified as sinks. Subsurface nutrient loads of N and P loads produced different output in which N returned no trend and no value P returned linear increasing trend. Spatially, N loads were restricted to water bodies and P retuned no spatial characterisation and variation. Nutrient exports also showed spatiotemporal variations with large amounts of N exports were observed compared to P. Cropland and agroforestry influenced roughly 90% of the amount of nutrient exported thus establishing a firm human-nature nexus in the amount of nutrient exported.

Management of this emerging nutrient enrichment of the landscape of the Sokoto-Rima basin require a synergistic approach whereby intensity of crop cultivation is integrated with nutrient sink approach. For instance, agroforestry and woodland advancement schemes will aid the control of the direct influence of cropland on nutrient adjustment at the local space. This approach will engender managed nutrient cycling close to reality. For instance, the Nigerian section of the West African Great Green Wall programme aimed at curtailing the impact of the Sahara desert encroachment can be locally adjusted as community-based approach to enhance natural ecosystem services and by extension improve environmental resource appraisal within the Sokoto-Rima basin [20, 21].

Sensitivity analysis of the InVEST model adopted for this study revealed some level of uncertainties in the predictive abilities of the model despite its innovative theory and simplified approach. This shows that more extensive studies on model calibration processes, consideration of high-resolution landcover datasets, influence of parameterization should be considered vital. These are needed in the context of emerging science of nutrient modeling within the series of natural and anthropogenic factors and forcing.

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Figures

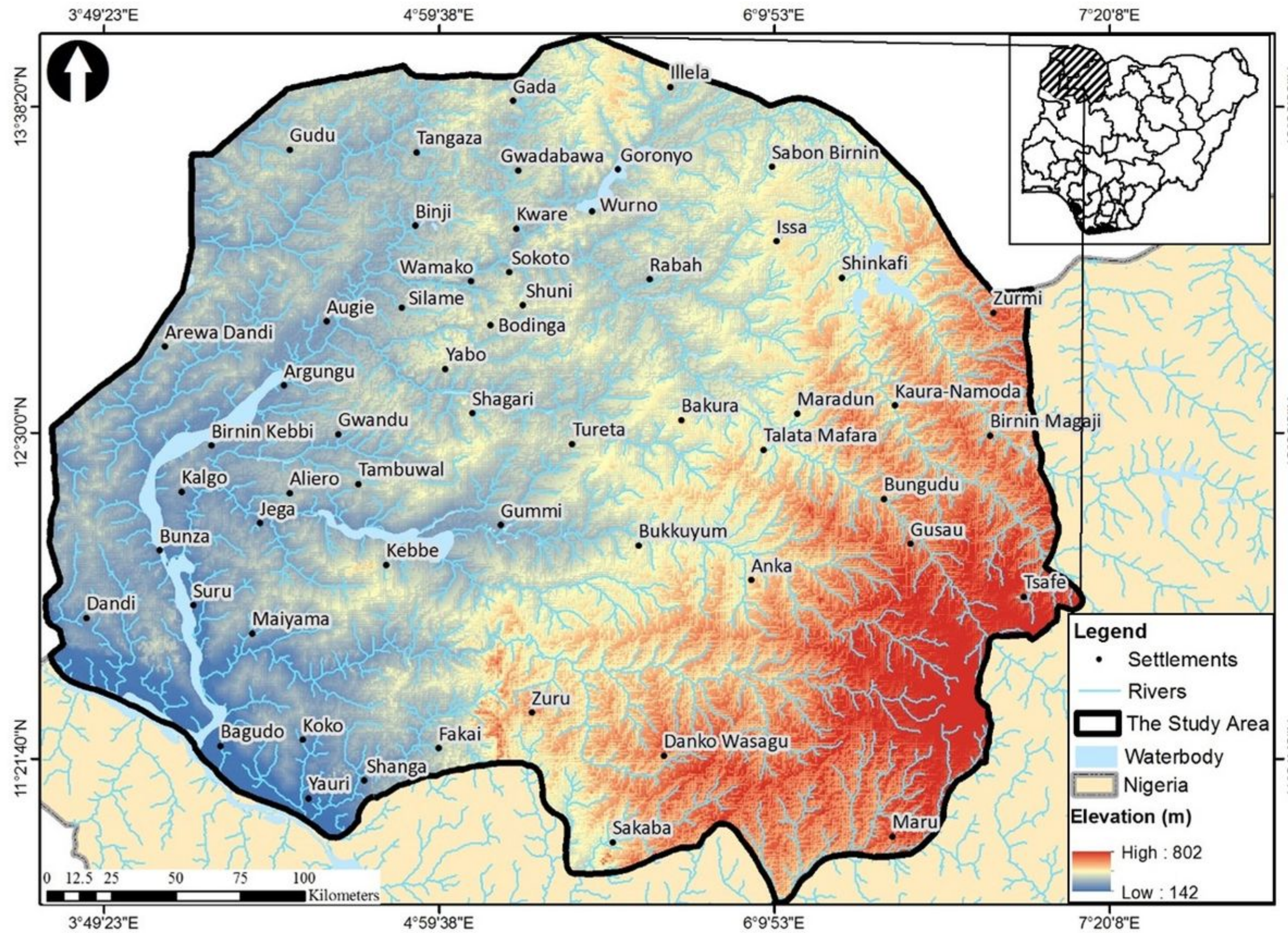


Figure 1

Geographical location of the Sokoto-Rima basin in context of northwestern part of Nigeria with the hydrological network and relief

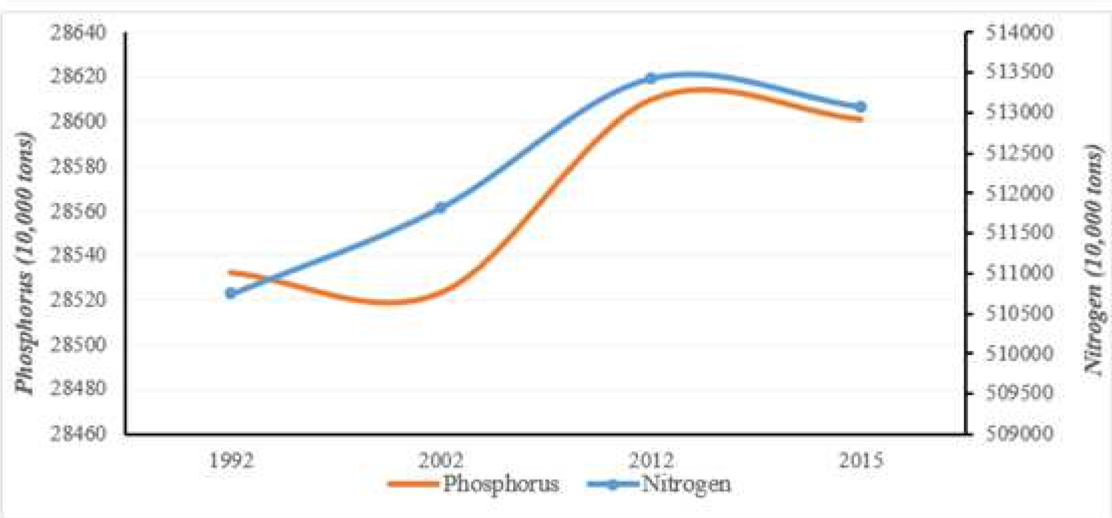


Figure 2

Temporal trend of surface loads of nitrogen and phosphorus of the Sokoto-Rima basin

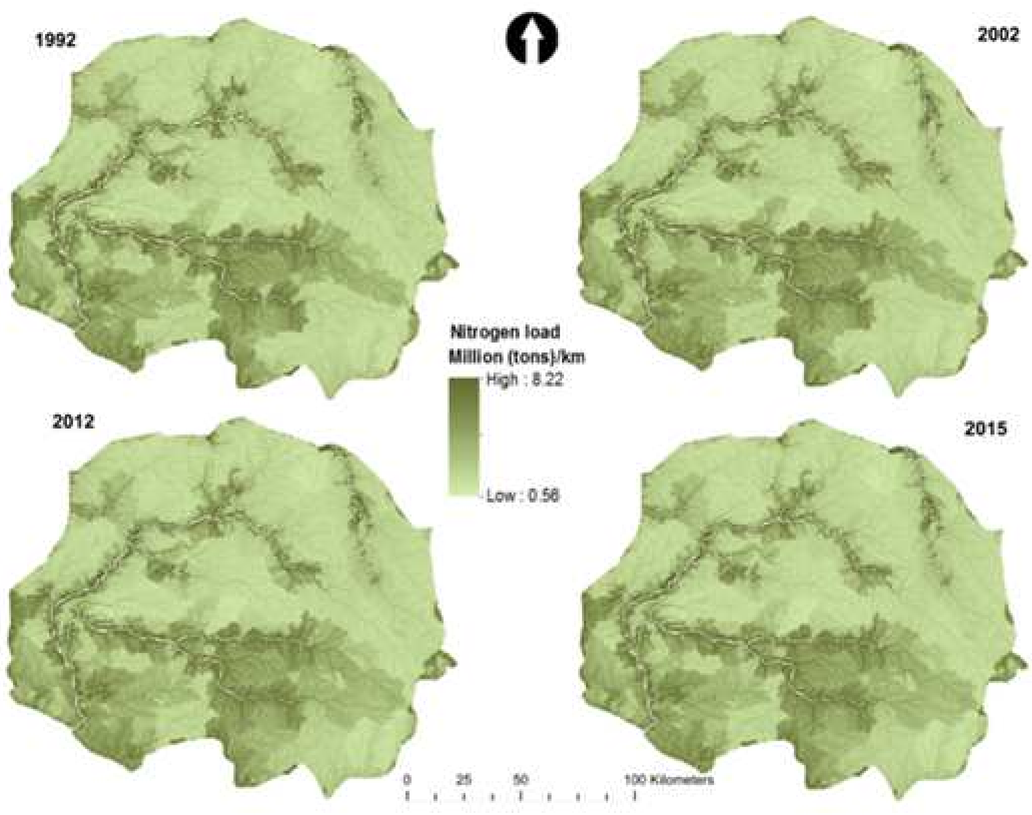


Figure 3

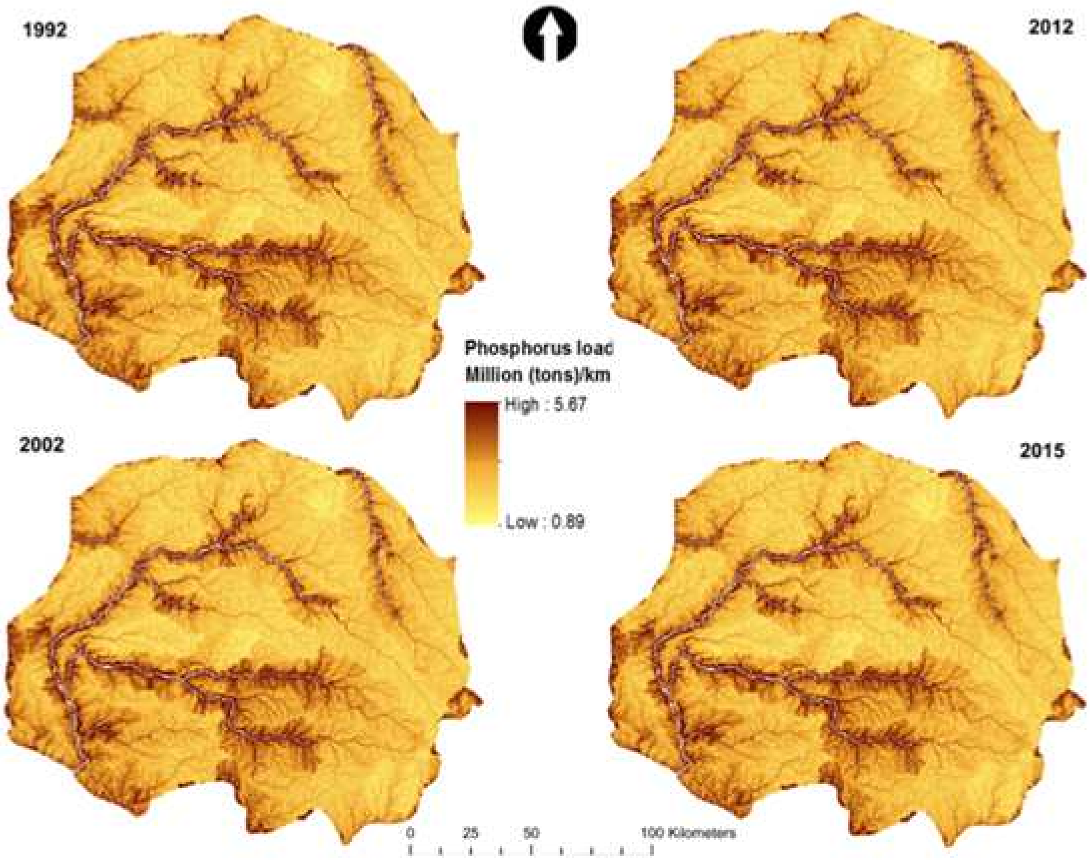


Figure 4

Spatial distribution of surficial phosphorus load in the Sokoto-Rima basin for the years 1992, 2002, 2012 and 2015.

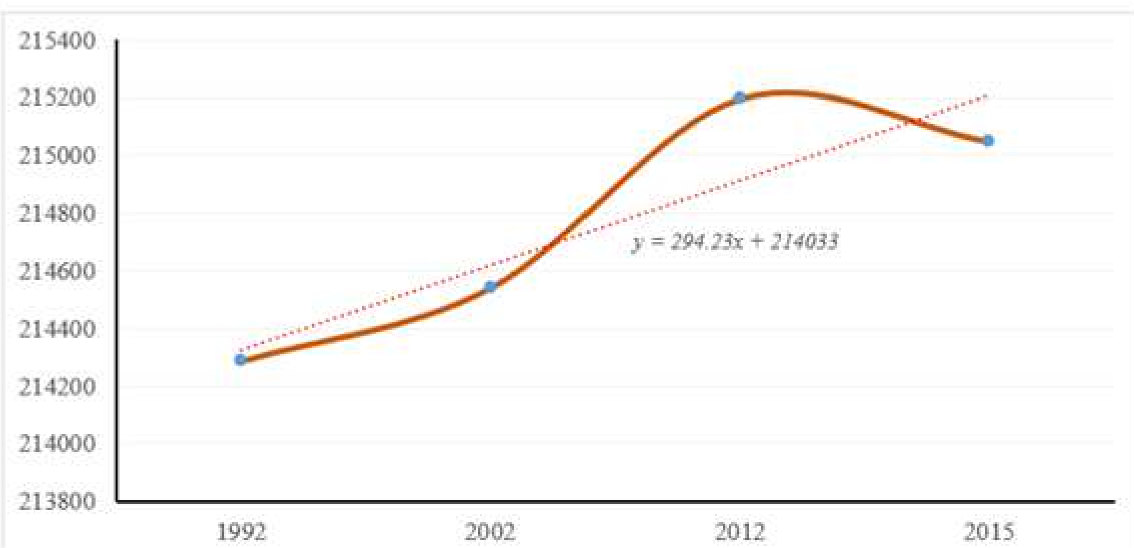


Figure 5

Trend of subsurface phosphorus load of the Sokoto-Rima basin from 1992 to 2015

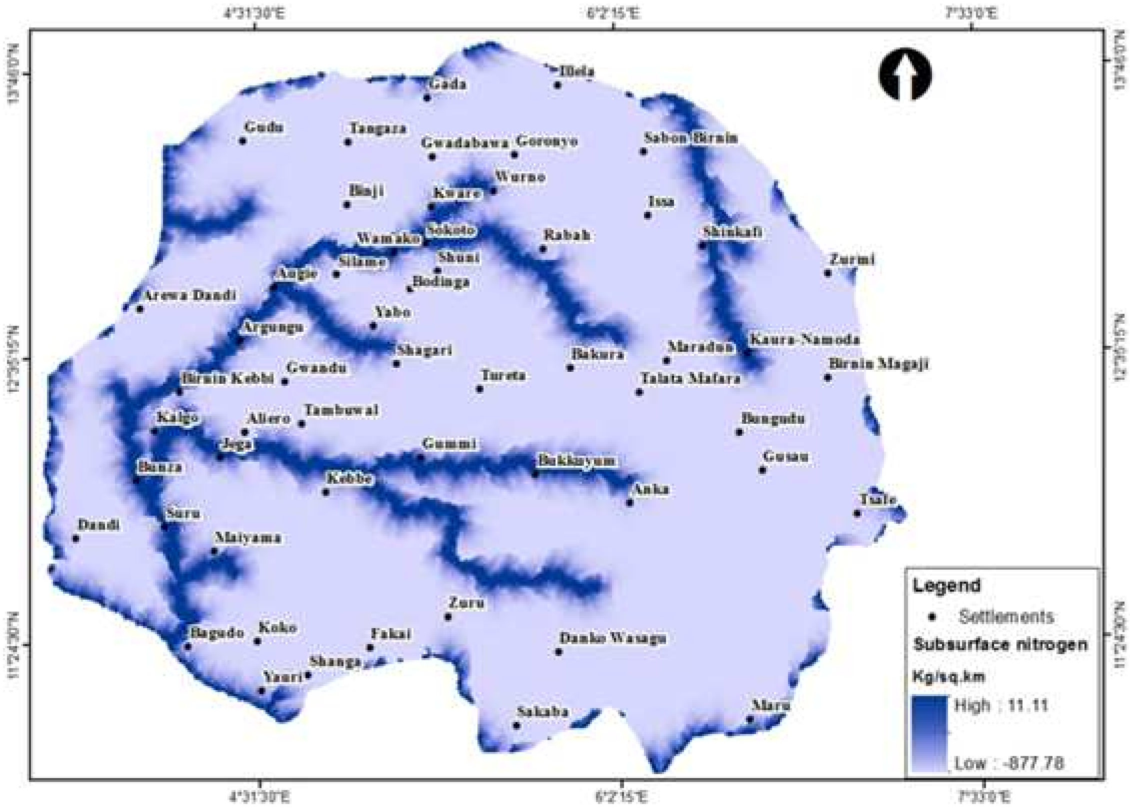


Figure 6

Spatial distribution of subsurface nitrogen loads of Sokoto-Rima basin (1992-2015)

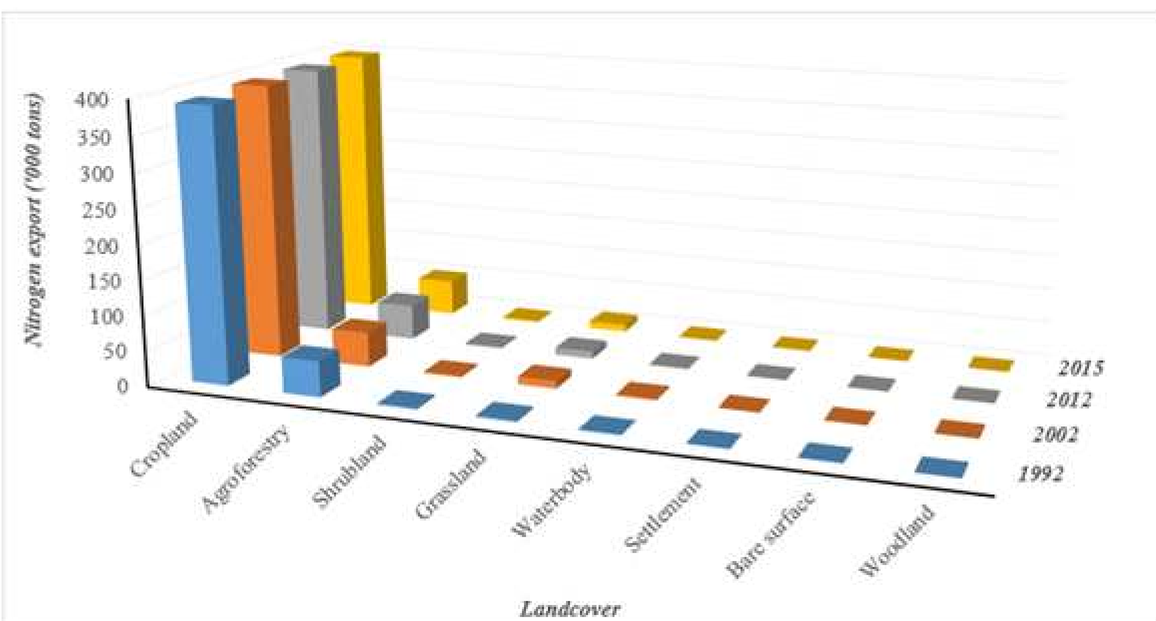


Figure 7

Nitrogen export of the Sokoto-Rima across the different landcover classes from 1992 to 2015

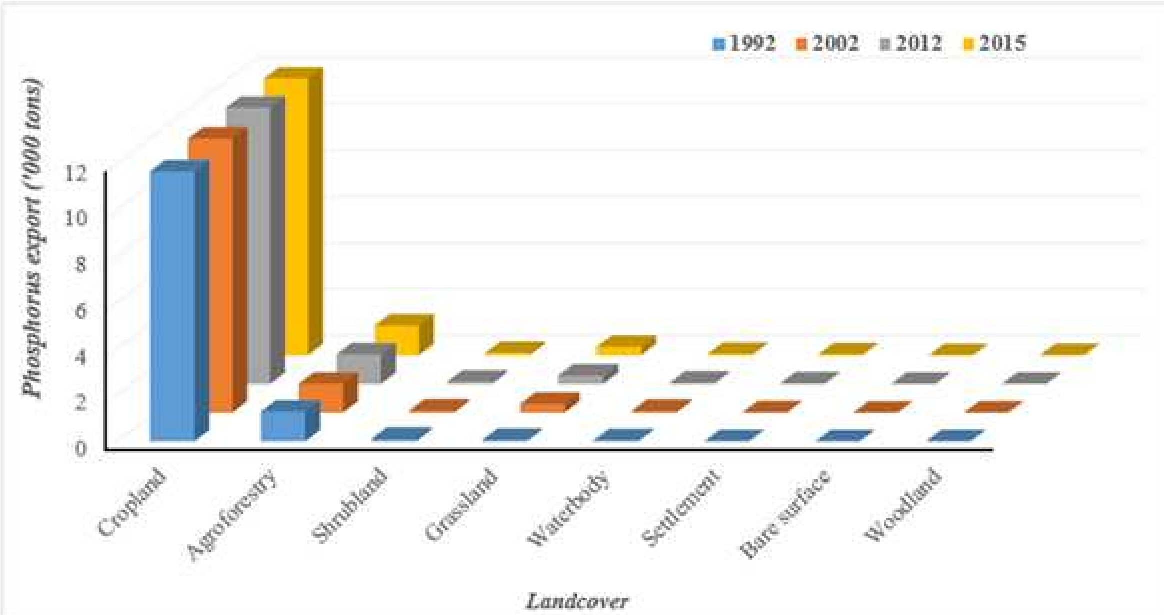


Figure 8

P export of the Sokoto-Rima across the different landcover classes from 1992 to 2015

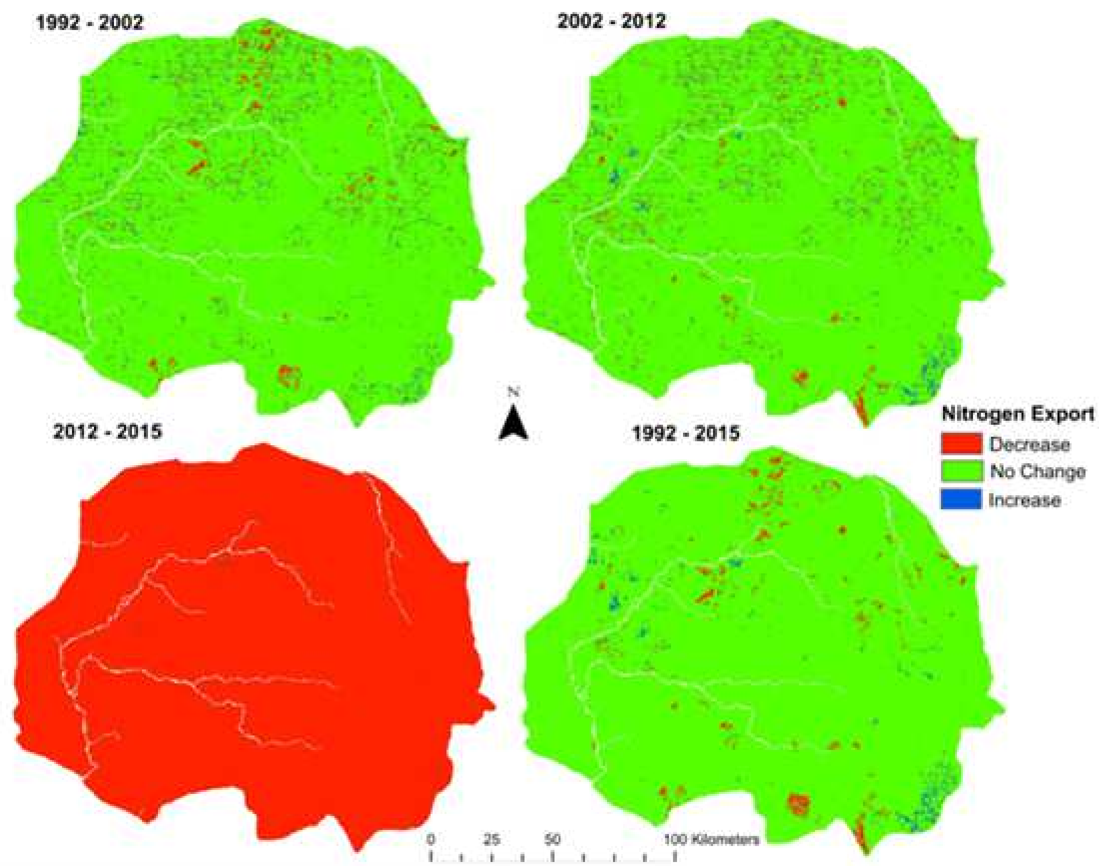


Figure 9

Spatiotemporal variation of nitrogen export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and cumulative spatial difference)

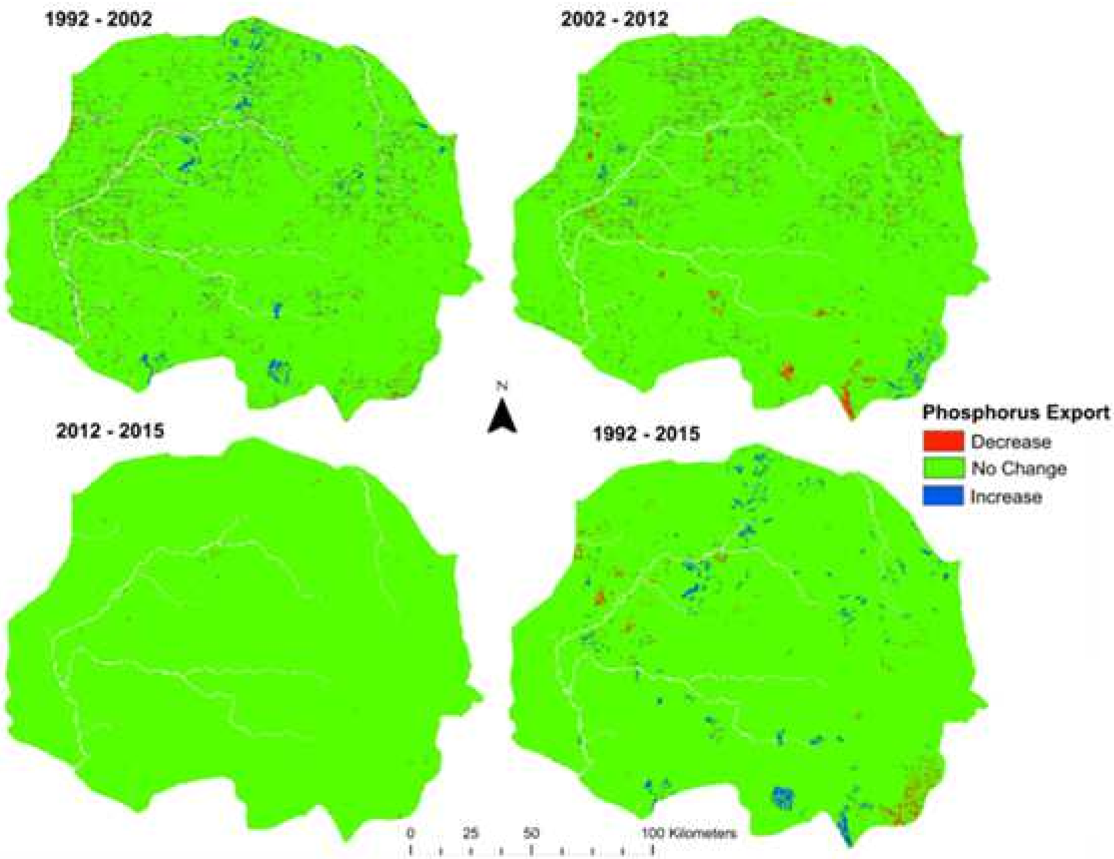
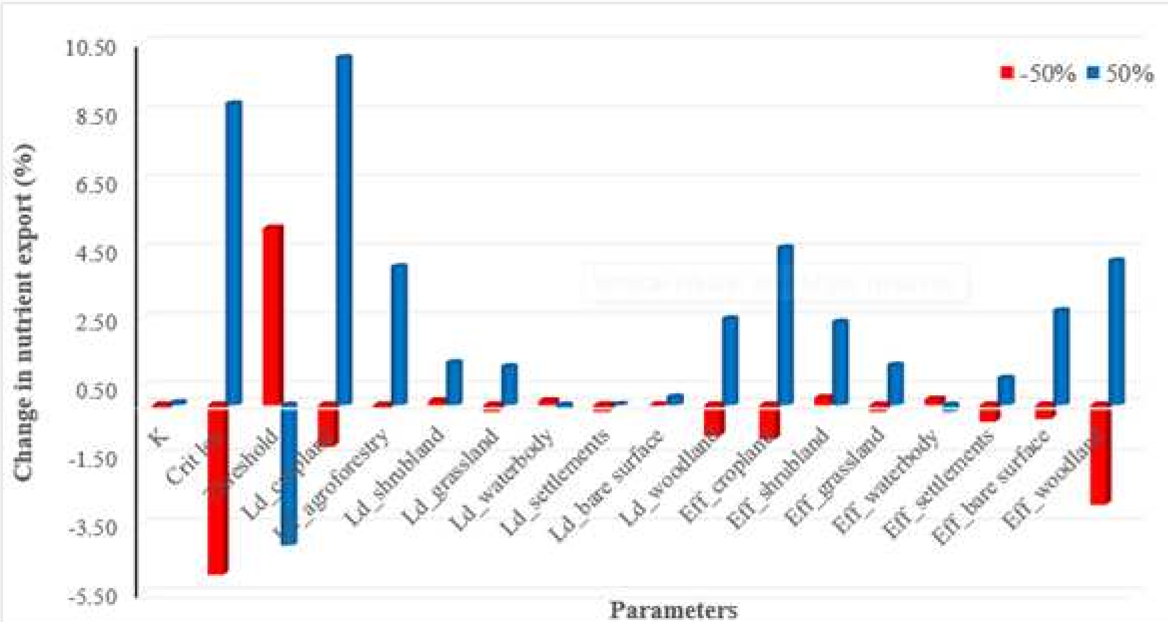


Figure 10

Spatiotemporal variation of P export in the Sokoto-Rima basin from 1992 to 2015 with specific interval differences (1992 to 2002, 2002 to 2012, 2012 to 2015 and accumulative spatial difference)



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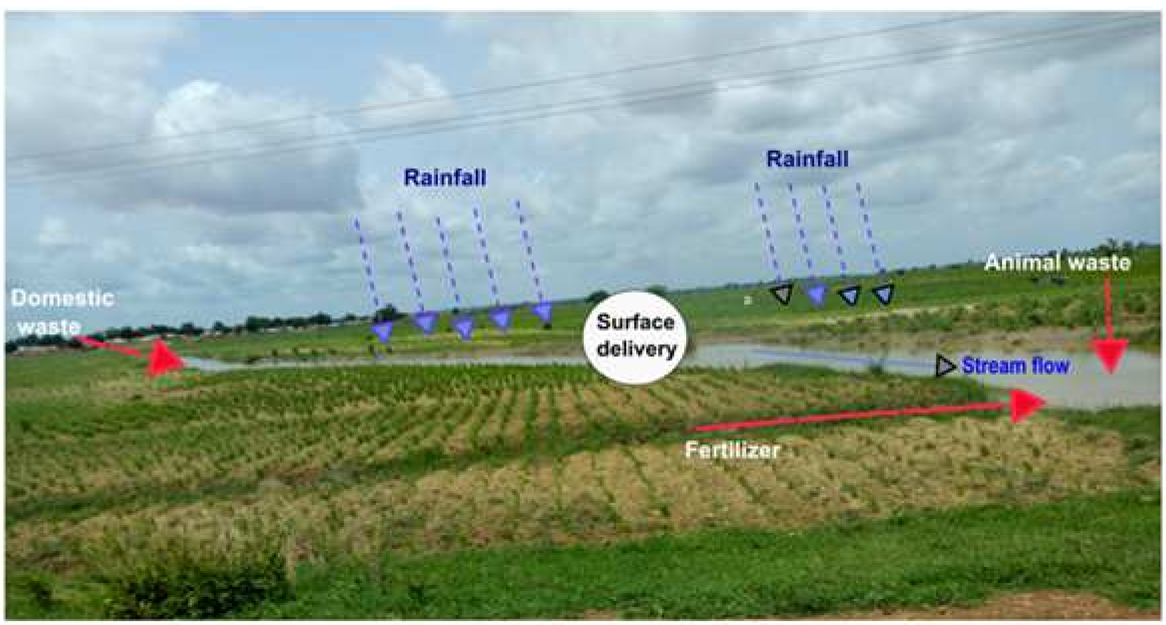

Figure 12

Pathway of nutrient flow and cycling in the along the section of River Zamfara a vital water body of the Sokoto-Rima basin. The blue arrow and feature shows natural input source while the red arrow indicate the anthropogenic source of both nitrogen and phosphorus.