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Tree Planting Index for Watershed Health Restoration in Ramsar Lake Maladumba, Nigeria

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Abstract

Ramsar convention supports the sustainable use of all wetlands including the outward landscapes drained by Ramsar Lake Maladumba and its tributaries. The research paper proposes an optimization approach for identifying degraded landscapes for tree planting and forest restoration in the catchment area of the Lake. The concept of neighbourhood sub-basin concatenation or Primary Catchment Area (PCA) was established and retained in the study for forest cover analysis. The ratio of the lake's surface area to the PCA is 0.0236. A deficit in forest presence was recorded from 25.17% to 6.39% in the period 2001-2019, amounting to a cumulative loss of about 13.2sq.km of forestland or 69.40ha of forestland per annum. The fifth order attribute of the lake alludes to the all-year water retention potentials of the reservoir. The low drainage density (1.66km/sq.km) and unsustainable forest clearance within the basin allow for accumulation of overland flow and inundation of the reservoir's fringes after an intense and prolonged precipitation. However, the water seepage potential of the basin is enhanced by its geology as indicated by the bifurcation ratio (5.82). The tree planting index is a reflection of watershed vulnerability to sediment yield and was calculated from few hydrologic parameters including the Normalized Difference Vegetation Index (NDVI) for the later image. 40% of the 200m disk and hotpots created as the centroid of second and first order stream network inlets to the Lake were designated as highly vulnerable and capable of inducing ageing and biodiversity losses in the aquatic system. ML3, ML5, ML6, ML2, and ML10 are therefore nominated as potential restoration sites requiring urgent reforestation and other integrated water and soil conservation measures.

Keywords: Forests; NDVI; Ramsar lake; Conservation; Primary catchment area; Hydrology; Freshwater

Introduction

Lakes of natural origin influence earth's energy budget and cycles and are sources of freshwater significant to the well-being and resilience of the local people. Every ecosystem takes part in this circulation [1], however, the value per ha of wetland ecosystem services ranks first among all kinds of ecosystems, and the total values of wetland ecosystem services account for 47% of the values of the global ecosystem [2,3].

Anthropogenic eutrophication is one the most prevalent environmental problems in freshwater ecosystems [4-6]. The eutrophication of aqueous systems is often the result of land degradation in the catchment areas of reservoirs which also impacts the quality of ecological services derived.

Lake ecosystems face threats arising from multiple pressures, related to nutrient runoff [7,8]. According to [9,6], eutrophication has deteriorated the possibilities for domestic water use and recreation through its effects on water quality and biota in a large number of lakes. This is often due to haphazard land-use and land-cover changes around the lakes. [10] in his work attributed four major impacts on hydrological cycle as a result of LULC changes. These includes flooding, droughts, changes in river and groundwater regimes, and impact on water quality. Forest clearance for fuelwood and shifting cultivation attended with chemical additives within catchment areas have the likelihood of increasing aquatic systems susceptibility to pollutants and desiccation. Misau LGA benefited from the World Bank Fadama III assisted watermelon production subproject due to the its vast Fadamaland [11]. Simple geomorphic analyses can aid decision makers to align adopted conservation measures with policy objectives on FADAMA projects, wetlands conservation and catchment area management. Morphometric descriptors represent relatively simple approaches to describe basin processes and to compare basin characteristics [12,13] and enable an enhanced understanding of the geological and geomorphic history of a drainage basin [14,13]. Simple characterization of the catchment area will aid land use allocation within the sub-basins of Lake Maladumba.

The location of Lake Maladumba (ML) in the semi-arid ecosystem, its shallow depth coupled with the intensification of non-forest land uses in the catchment area are potentially capable of increasing the vulnerability of the system to bedload and nutrient deposition. The problem of water management in the country is the fact that wetlands, which naturally recharge and protect both the surface and groundwater resources, are being unscrupulously degraded at a rather alarming rate [15,16]. The key point of watershed delineation is the determination of river network and raster flow direction matrix [17]. However, the size attributes of watersheds delineated from elevation data are unrealistically too large to guide practical soil and water conservation approaches, especially in countries with small budgets and limited technical capacities. It therefore imperative to develop a pragmatic guide that is consistent with local hydrologic principles and simplified enough to be adapted by managements of wetlands in developing countries.

We, therefore, in our research, undertook a geomorphometric, forest cover and terrain analyses of Lake Maladumba with the aim of identifying vulnerable land units within the catchment's sub-basins where forest restoration activities are expected to yield the maximum impact. In our study, the concept of primary catchment area was simplified by amending topographically delineated catchment area into realistic land units to ensure its early adaptation for aquatic system management at all levels in view of scarce economic resources. This is in recognition of the fact that, lakes that have degraded to an undesirable state can be very difficult to restore [8].

Materials and Method

Study area

Lake Maladumba (ML) is a significant part of Maladumba Lake and Forest Reserve (MLFR) - located in Misau LGA, Bauchi State, Nigeria. It geographically lies between Latitudes: 11.219036° N-11.24177°N and Longitudes: 10.34029°E-10.38124°E - in the semi-arid zone and Sudan savannah vegetation belt of Nigeria. The climatic conditions in Bauchi State vary with the southern areas experiencing more volumes of rainfalls than the northern parts of the State. The Lake (Figure 1) is situated in the northern part of Bauchi State. The average annual rainfall is 700mm in the northern part and 1300mm in the southern parts [18]. The vegetation is characterized by mostly short trees and grasses typical of the Savanna zone due to the short rainfall window, which is usually between May and September. The Lake is a hotspot for biodiversity conservation and supports a large number of migrant birds, fishes and other aquatic life forms, thus providing supports to rural livelihood and economy. It is an international wetland of importance with Ramsar designation No.: 1756.

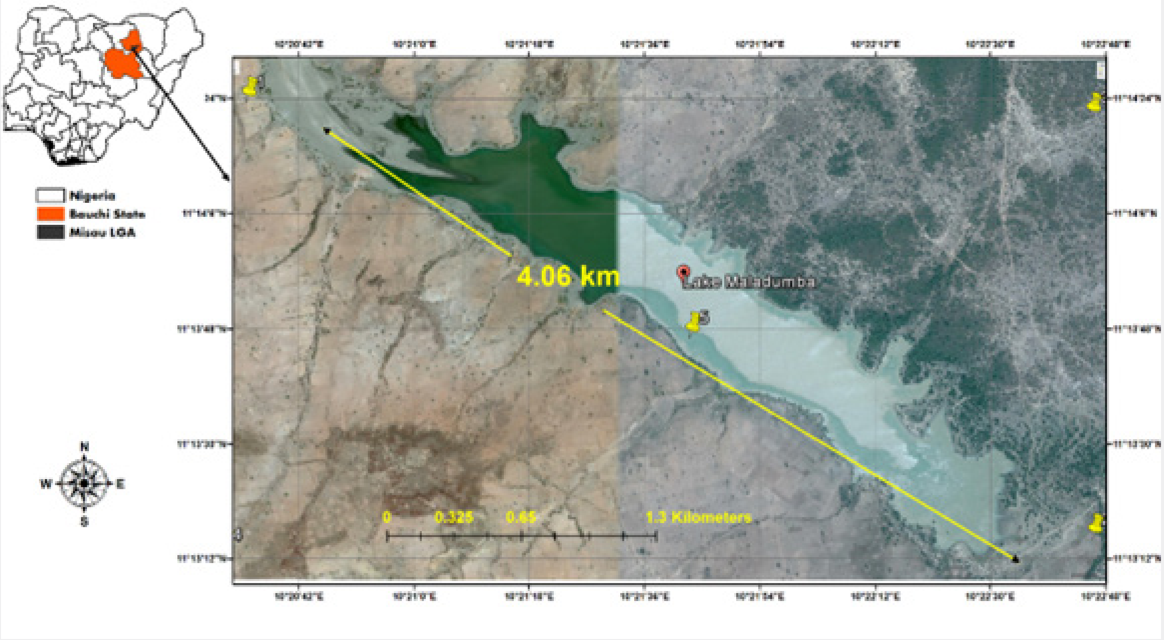

Figure 1: Panoramic view of Lake Maladumba processed from Google Earth (GE).

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Data processing and analyses

The datasets used include: (I) Landsat 7 (EMT+) (II) Sentinel 2A and (III) Digital Elevation Model (DEM). The imageries were processed with geospatial tools for the watershed delineation, forest cover analysis and landscape vulnerability assessment. Catchment area delineation was accomplished with the deterministic eight-node (D8) algorithm. This approach uses a digital elevation model (DEM) as the source data to simulate the overland flow between the grid cells and then determine the watershed boundary, river networks, and sub-watersheds associated with each river segment [19].

Geomorphic parameters, namely; bifurcation ratio (R_B), drainage density (D_D) and elongation ratio (R_E) were employed as shown in Eq. 1 [20], Eq. 2 and Eq. 3 [21] to characterize the catchment area.

$$D_D = \frac{\sum L_U}{A} \qquad (1)$$

$$R_E = \frac{2\frac{\sqrt{A}}{\Pi}}{L_B} \qquad (2)$$

$$R_B = \frac{N_U}{N_{U+1}} \qquad (3)$$

Where, D_D – Drainage Density; R_E – Elongation ratio; R_B – Bifurcation ratio; L_U – Mean stream length of all order; A – Basin area; L_B – Basin length; N_U – Total number of stream segment of order “U”; N_{U+1} - Number of stream segment of the next higher order.

Forest cover mapping

The Normalized Difference Vegetation Index (NDVI) outputs from Eq. 4 and Eq. 5 enabled comparison of the forest vegetation cover, in terms of gains/losses, between the periods 2001 - 2019. The near infra-red (NIR) and red (RED) bands for the Landsat data were reconstructed to the top-of-atmosphere reflectance and further resampled to 10m spatial resolution for correspondence with the level-2A Sentinel data.

$$NDVI\ 2001\,[ETM+] = \frac{NIR(B4) - RED(B3)}{NIR(B4) + RED(B3)} \qquad (4)$$

$$NDVI\ 2019\,[Sentinel\ 2A] = \frac{NIR(B8) - RED(B4)}{NIR(B8) + RED(B4)} \qquad (5)$$

Tree planting index

The following land surface parameters (Figure 2), namely; NDVI, Slope, Length-Steepness Factor (LS Factor), Slope and Digital Elevation Model (DEM) – were constructed and values extracted to assess catchment area vulnerability and prioritize forest restoration in selected sites. Hydrologic zones created as 200m circular buffers around the discharge or pour points where the networks of the first and second order streams drain into the Lake (Figure 3) are the target restoration sites. The 200m circular buffers were reduced to varying sizes of convoluted disks overlapping only the Lake’s outer edges. 10 random points were generated within each of the 10 sample disks to aid values extraction from the land surface parameters as illustrated in Figure 2. The hotspots were, subsequently, ranked according to the compound influence of the land surface parameters on the hotspots.

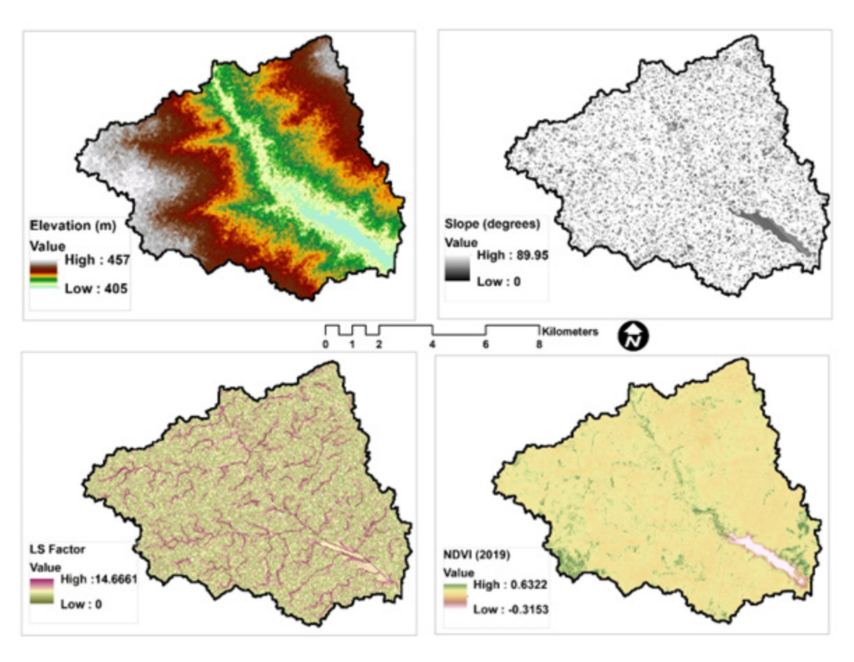

Figure 2: Land Surface Parameters influencing peak flow and sediment yield in ML.

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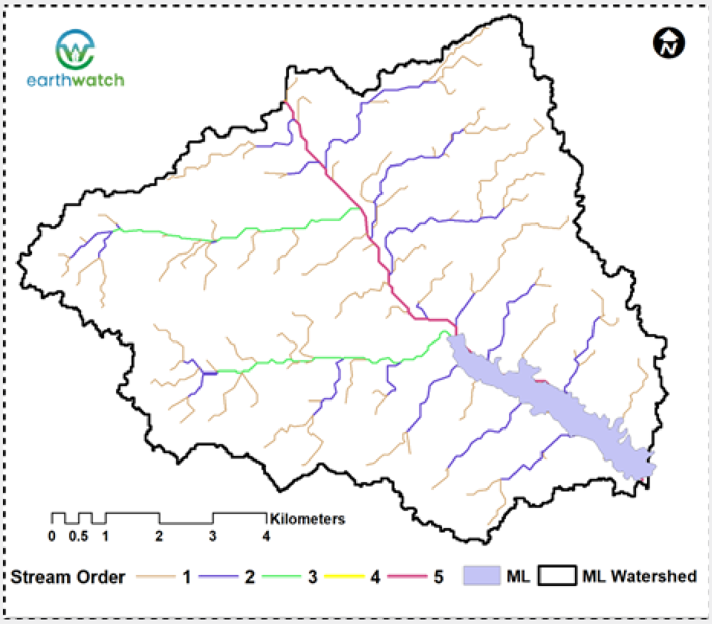

Figure 3: Primary Catchment Area for Lake Maladumba (ML).

Results

The outcomes of the analyses portray the attributes of the catchment area in terms of its resilience to material movement, permanence of the aqueous system and the loss of forest cover. The delineated drainage basin (Figure 4) of ML covers a landmass of 387.145sq.km and extends across three (3) administrative areas, namely; **Misau**, **Shira** and **Giade** Local Government Areas (LGAs). The ratio of the Lake's basin to the ratio of the Lake's surface area is about 198, an indication of size differential. Theoretically, an area about 200 times larger than the Lake is required for its effective management. The nine (9) sub-basins as shown in Figure 4 were further subdivided into Primary Catchment Area (PCA) and Secondary Catchment Area (SCA) – where the PCA or Area of Interest (AOI) is the sub-basin containing the Lake's main feature.

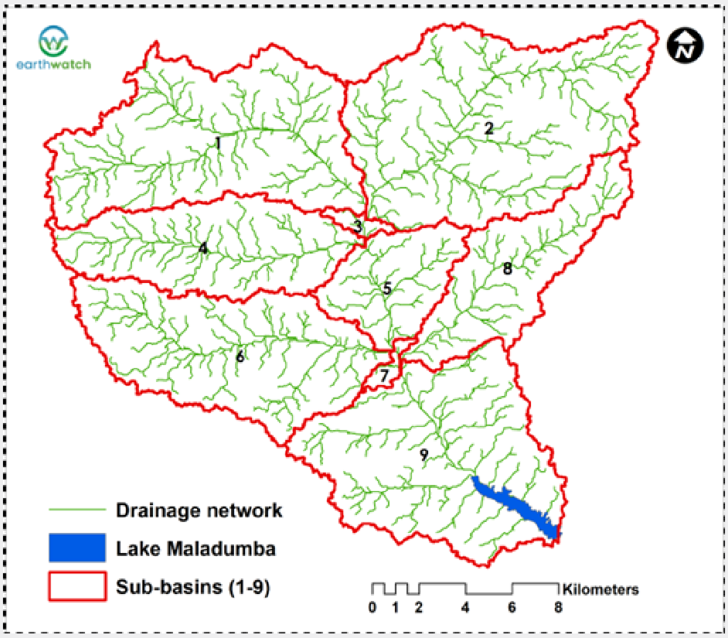

Figure 4: The Drainage basin, sub-basins and networks of Lake Maladumba

The PCA comprises approximately an area of 70.23sq.km; and its ratio to the surface area of the lake is approximately 36. Other sub-basins are categorized as the SCA. The PCA is a fifth (5th) order stream with a mean bifurcation ratio of 5.82 and R_E of 0.16. The D_D of the PCA is 1.66km/sq.km, an indication of the length of stream required to drain a unit area of the PCA. The D_D is low and typical of areas with low rainfall. More details on the estimated geomorphic parameters are included in Table 1.

Table 1: Geomorphic parameters for Lake Maladumba.

S/N	Morphometric Parameters	Values
1	Stream Order {I (86), II (36), III (19), IV (1), V (30)}	5th (Strahler Ordering)
2	Mean Bifurcation Ratio	5.82
3	Total Stream Length	116.297km
4	Basin Area	70.23sq.km
5	Stream Number	172
6	Basin Length	59.99km
7	Drainage Density	1.66km/sq.km
8	Elongation Ratio	0.16

Forest cover change in the catchment area

The NDVI values (Figure 5) for the Landsat ETM+ and Sentinel 2A images for 2001 and 2019 range from -0.4634 to 0.5696 and -0.3153 to 0.6322, respectively. Images for the PCA in the period 2001-2019 showed a forest cover of 25.17% and 6.39%, respectively. The PCA lost about 18.76% or 13.2sq.km of forestland in the period 2001-2019. The estimated rate of forest loss per annum is 69.40ha, an equivalence of about 0.52% of the AOI per annum.

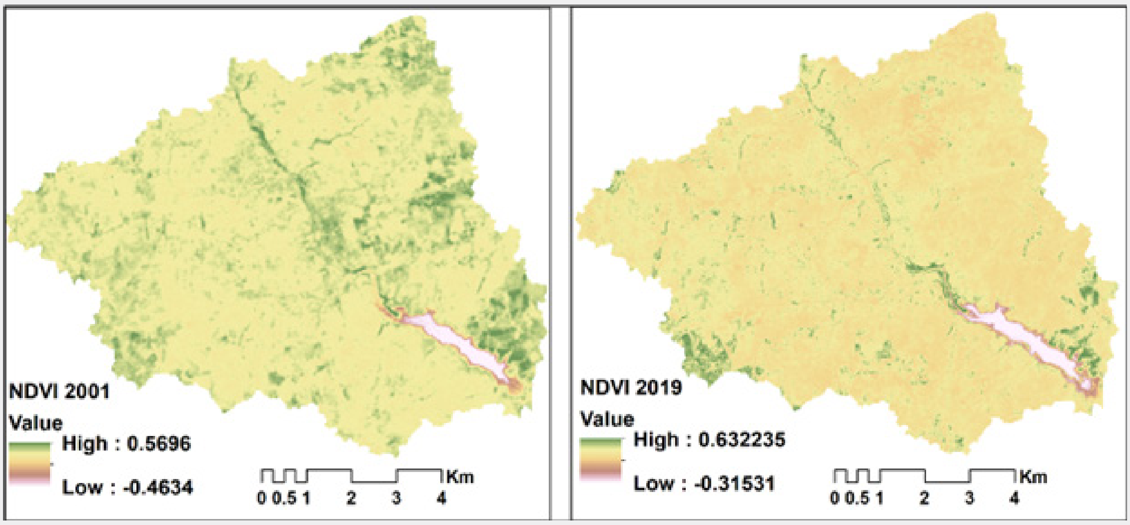

Figure 5: NDVI images of Lake Maladumba and watershed. Left (2001) Right (2019).

Watershed restoration index

Enclosed in paratheses are the range of values on the raster images for elevation (405m-457m), LS factor (0-14.67), slope (0°-89.95°) and NDVI 2019 (0.3153-0.6322). The circular sample plots with the highest values are ranked most vulnerable and areas to be prioritized for tree planting programmes. Restoration plots ML1- ML5 are inlets for the second order streams. Plots ML6-ML10 are inlets for the first order streams. The final ratings for the watershed restoration index nominated ML3, ML5 ML6, ML2 and ML10 (in that order) as hotspots with high erodibility potentials; ML1, ML4, ML7 and ML8 with medium vulnerability and ML9 with the lowest vulnerability. Plot vulnerability was assessed using ranked values of the arithmetic means estimated using the random values extracted from the geomorphic parameters.

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Discussion

Land degradation in the catchment areas of aquatic systems is influenced by factors of human and natural origins. These factors are examined to help with future plans for the sustainable use of the aquatic system and wetland. The fifth (5th) order stream attribute of the lake provides evidence to support water permanence year-round in the natural reservoir. The resilience of the lake to drought in the semi-arid agroclimatic zone of Nigeria serves to the advantage of communities dependent on the lake. However, current regimes of perturbations could compromise this advantage of wetland land use/land cover. R_B reflects the complexity and degree of dissection of a drainage basin [22]. According to [23], R_B value greater than 5 indicates structural control over the drainage networks. Since the MRB for ML is slightly greater than 5, the geology of the watershed had undergone transformation sufficient to influence water movement with higher likelihood for higher sediment yield within the watershed. The PCA's form is an extreme deviation from circular form ($R_E = 0.16$) which makes peak flow elastic and deferred in terms of travel time. According to [14], flood flows within elongated basin are easier to manage than those of the circular basins. Overland flow which results from precipitation in excess of evapotranspiration and the seepage potentials of the soils are received and drained through the channel networks into the reservoir.

However, in the case of Lake Maladumba, draining of overland flow is diminished due to the number of drainage inlets feeding the Lake and the lower forms of their stream order. One of the noticeable features of elongated basins mostly omitted in modern literatures is the possibilities for lateral delivery of sediments. The reservoir is highly probable to sediment depositions from its flanks. D_D is a key indicator of landscape dissection and runoff potentials in ML basin. The D_D of the PCA is 1.66km/sq.km, indicating the length of stream required to drain a unit area of the PCA. The D_D is low and typical of areas with low rainfall. Peak flow at the Lake's outlet is expected to be delayed due to the permeability of the subsoil in the PCA. [24,25] concluded in his work on Maladumba Lake and Forest Reserve (MLFR) that the soils in the area are deep sandy clay and loamy sands. However, inundation is expected immediately after a prolonged and intense downpour due to the weak ratio of stream networks to the overland and the intense impacts of agricultural practices and patterns on the soils.

Watershed restoration index

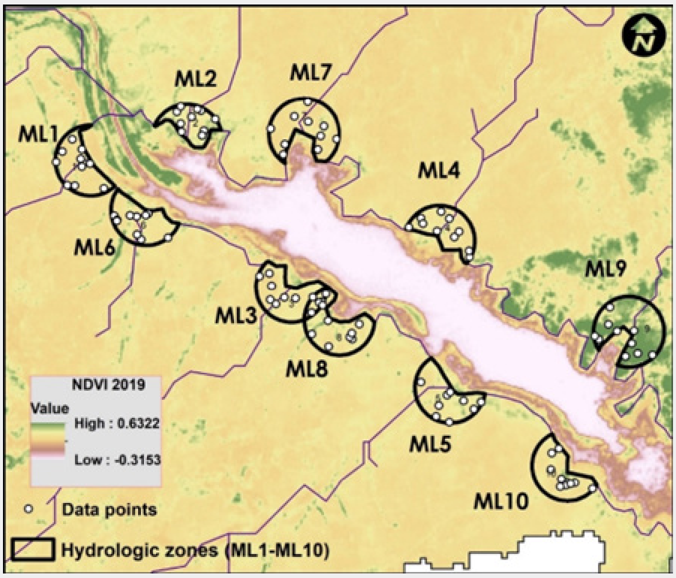

Figure 6: Data extraction points within the potential restoration sample plots/disks.

The estimated rate of forest clearance in the period 2001-2019 which stood at 69.40ha/annum provides strong conclusion about the existing unsustainable forest management regime in the study location. Forest degradation and losses with its potential influence on streamflow patterns and annual soil loss will impact freshwater quality and quantity in the Lake. According to [26-31], there is now broad scientific agreement that removing tall vegetation (trees and forests) from the landscape will result in (greatly) increased volumes of streamflow due to correspondingly reduced evaporative losses, with the bulk of the increase in flows manifesting itself during times of baseflow. The exaggeration of non-forest uses is an index of unhealthy watershed management practices would produce significant effects on freshwater availability in the Lake. Forest restoration and tree planting exercises are therefore to be prioritized in Plots ML3, ML5, ML6, ML2, and ML10 (particularly in plots ML3, ML5 and ML2 with the second order stream networks) to reduce ageing of the Lake. The optimization approach implemented is underpinned by the first law of geography where the consequence of human activities on the target lake is a function of proximity. Other plots (Figure 6) are secondary candidates for restoration activities. With this approach, tree planting and other restoration strategies can be prioritized where resources are scarce and limited.

Conclusion

The degradation and loss of wetlands is more rapid than that of other ecosystems [31]. The findings of our paper highlight efficient forest restoration design for Ramsar Lake Maladumba (ML) catchment area. The high rates of forest clearance in the fringes of ML calls for an expanded approach where land users are organized into support zone groups for ease of sensitization and evaluation of future restoration efforts. The adoption of the methodology outlined in our research on forest restoration in the lake's catchment area will serve towards planning sustainable land uses in the watershed and as model for other significant systems in Nigeria. ML supports the livelihoods (Figure 7) of several families across more than 20 communities in Misau LGA of Bauchi State and therefore requires flexible terms and approaches to promote participatory approach for its management.

Figure 7: Rice farming along the banks of Lake Maladumba.

Acknowledgment

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Conflicts of Interest

The appearance of authors in the publication, in addition to the concepts and findings presented are products of our mutual decisions to which declaration is now made to the non-existence of any conflict of interest.

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