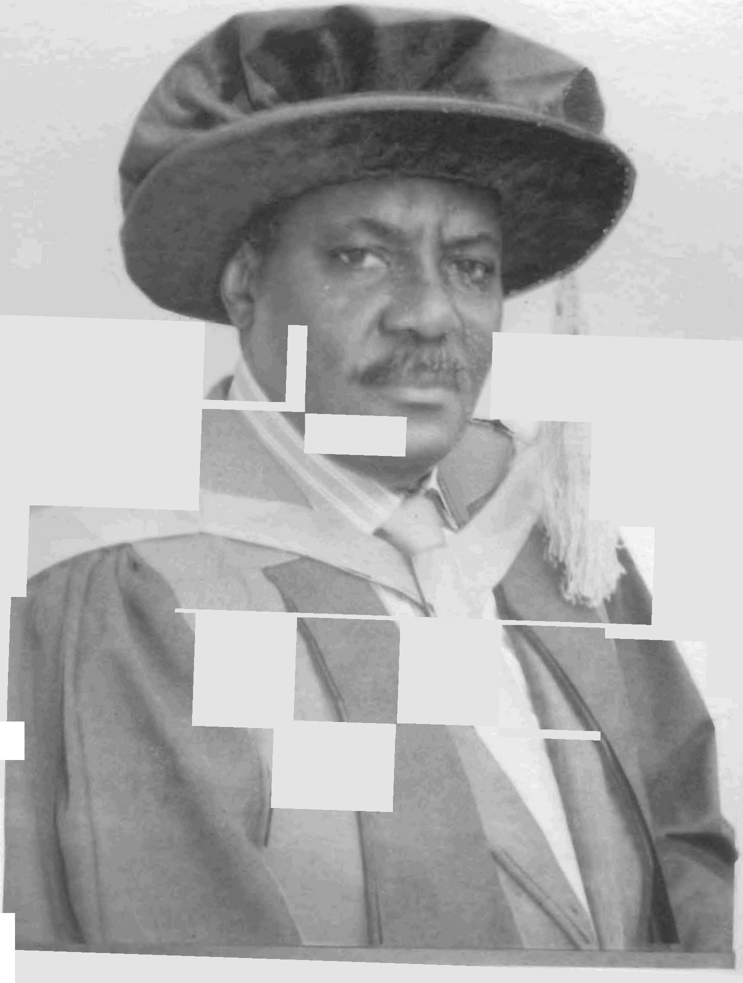
INAUGURAL LECTURE SERIES 256

'ALL RIVERS RUN INTO THE SEA; YET THE SEA IS NOT FULL...'

By

Olayinka Olatokunbo OGUNKOYA

Professor of Geography



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INTRODUCTION

Mr Vice Chancellor, distinguished ladies and gentlemen, I stand before you this evening, on this inaugural lecture event, to provide an update of my research effort thus far in my sojourn in the academia. It could be noted, as a background, that an inaugural lecture is a celebration and a way of informing colleagues in the Department, the University at large, and the public about the past and current research activities of a holder of an established Chair, and future research directions to which he or she might aspire. The lecture is intended to emphasize both the significance of his/her research and its implications for his/her discipline. This 256th Inaugural Lecture will therefore highlight advances in my main area of research in Fluvial Geomorphology and my contributions to its advances. It will also focus on the results of a research that should be of immediate concern to the University, and provide an insight into yet to be explored themes in my area of research.

The biblical King Solomon in an era that was entirely nomothetic (i.e. concerned with the formulation of general statements or laws *as opposed to the study of individual events – idiographic*), and from a perception of the cyclical patterns of phenomena including life on earth, stated that

> *'All rivers run into the sea; yet the sea is not full;*
> *unto the place from whence the rivers come, thither*
> *they return again'* (Eccl. 1: 7).

Issues that derive from this general statement include:

- ⇒ Where do rivers come from and return to?
- ⇒ How does water move from this location into rivers?
- ⇒ What happens to rivers on their 'run' to the sea?
- ⇒ How does man influence the process and what are the implications?

These issues, which were not resolved by King Solomon and other great 'thinkers' of the nomothetic era, most probably due to a lack of appropriate methodology and instrumentation, have constituted study themes and engaged man's attention over the ages. Initial studies yielded equally cryptic philosophical speculations on the occurrence, and processes associated with the movement of fresh water on the earth's surface. Attempts to elucidate the issues only became fruitful when researchers began to adopt methods of observational science. Thus for instance, Pierre Perrault in the 1670s measured precipitation and evaporation in the catchment of R. Seine in France and clearly proved for the first time that streamflow and groundwater are generated from the precipitation falling on catchments. By 1750, Carl von Linne was able to present some advanced understanding that:

> *'Rainfall gets its contribution from evaporating vapours that are carried around in clouds until they unite into drops and are brought to the earth. The origin of springs is rainwater that percolates through the soil. Rivers in their turn start from springs. They bring the water back to the sea, from where it initially rose'* (Biswas 1970).

It was hitherto believed that springs emanated from sea water that was driven through the subsurface by powerful spirits. Subsequent to von Linne, it was established that streamflow comprises the movement of water in channels under the influence of gravity and represents the excess of rainfall over evapotranspiration and catchment storage. These and other more recent studies have shown King Solomon's statement to be a description of the Hydrologic Cycle, a concept that depicts the occurrence, circulation and distribution of fresh water on and within the earth's surface and its atmosphere.

The Hydrologic Cycle has a number of aspects:

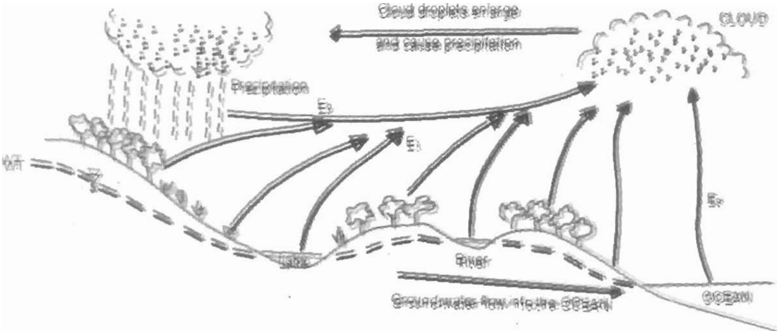
(i) the various storages of water in the different phases of matter
(ii) the processes through which water moves from a phase and/or storage to another

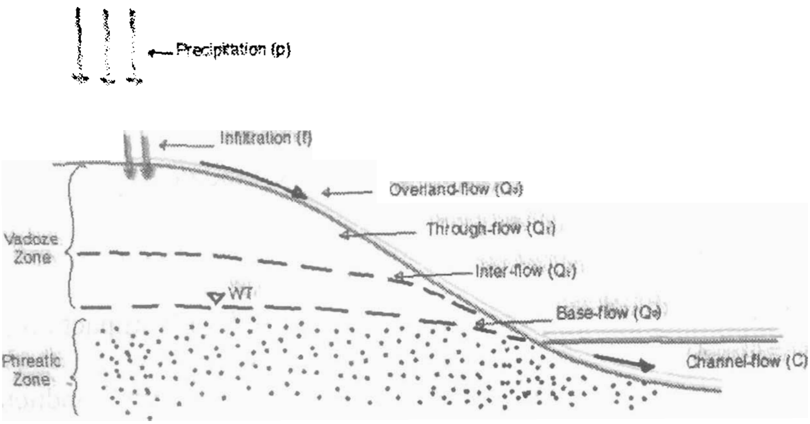
(i) the interrelationships between the processes and the storages, and

(ii) the influence of man on these interrelationships.

The storages include precipitation, interception storage on leaf surfaces, surface storage in lakes, ponds, puddles and channels, soil moisture storage in shallow soil layers and groundwater storage in deeper soil layers and rock. The processes include evapotranspiration, through fall, stem flow, drip, infiltration, percolation, overland flow, interflow, base flow, and channel flow (Figure 1). Modern day studies of the hydrologic cycle have been a purview of Fluvial Geomorphology, a sub-discipline of Geography concerned with the study of running water, and the associated processes and landforms they engender.

Figure 1: The hydrologic cycle





Studies of the hydrologic cycle are usually based on the catchment (also referred to as drainage basin or watershed), hence catchment studies or as defined by Hatton (2001), catchment science. The catchment is the entire area that provides runoff to, and sustains part or all of the flow of a main stream and its tributaries. It has a boundary (drainage divide), which encapsulates the catchment's physical and human attributes - rocks, soil, relief, channel network, vegetation, and human cultural practices and their artifacts. By totally encapsulating the hydrologic cycle, the drainage divide facilitates its evaluation. The catchment is at different scales micro (< 20 km^2), macro (< 10000 km^2) and mega (> 100000 km^2). Micro-catchments are usually of scales ranging from the first to the fourth 'order'. A first order river or stream[1] is the fingertip or headwater segment that derives directly from the source (e.g. a spring head), and thus has no tributary. The area drained by the first order stream is a first order catchment. Two first order streams converge to form a second order stream. The combined area drained by the second order stream and its

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[1] There is some ambiguity concerning the terms **stream** and **river**. It is however generally accepted that all natural flowing water channel segments of 'order one' to 'order four' should be designated as streams while channel segments of higher orders are rivers.

tributaries constitute a second order catchment, etc. My research has focused more on micro catchments.

CATCHMENT STUDIES

Catchment studies have been along four main themes:

- ✓ Physical Hydrology
- ✓ Representative Catchment Studies
- ✓ Process Studies
- ✓ Experimental Catchments Studies, and Man's impact on the hydrological cycle

I have singly and in collaboration with other scientists conducted research in the four themes, and particularly within the context of the Humid Tropics.

PHYSICAL HYDROLOGY

This is concerned with the investigation of the basic components of the hydrological cycle and their interrelationships. It is epitomised by the assessment of the parameters of the 'catchment water balance' equation (see Hudson et al. 1997):

$$P = Q + E + \Delta S + L \quad \ldots \text{(i)}$$

where P is precipitation, Q is streamflow, E is actual evapotranspiration, ΔS is the change in catchment storage, and L is seepage loss to deep ground water.

The catchment water balance has been described as one of the most satisfactory ways of studying the components of the hydrological cycle, particularly for a watertight catchment (Edwards and Rodda, 1972). It elucidates the manner of disposition of precipitation into the other main components of the hydrological cycle. Its drawback is the black box nature of the studies and the simplifying assumptions associated with the method due to the difficulty in accurately determining or measuring the terms of the equation. For instance, the balance is for a given time period, usually, a year over which ΔS and L are assumed negligible though without any full knowledge of the subsurface flow system (Beven and O'Connell, 1983). Further, semi-empirical methods are used for estimating evaporation.

Physical hydrological studies commenced in Nigeria with the need for the colonial government to provide potable water for urban and rural areas, water to raise steam for the then rail transport, and hydroelectric power. The first river gauging station in Nigeria was established at the end of the 19th C. at Jebba, in connection with the construction of a railway bridge across the R. Niger. Subsequently in 1914, the Nigerian Marine Department (a predecessor to the National Inland Waterways Authority) erected gauges at Baro, Lokoja, Idah and Onitsha along the Niger, and at Yola, Ibi and Makurdi along the Benue. The Irrigation Department of the Ministry of Agriculture and Natural Resources of the defunct Northern Nigeria regional government began erecting gauges in 1947 at locations on the R. Kaduna. In 1964, and with the assistance of the United States Agency for International Development (USAID), the effort was expanded to include a systematic survey of the surface water resources of the Hadejia-Komadugu-Yobe catchment (Area: >100000 km^2). This led to the establishment of many hydrological stations. Similar exercise started in the 1930s in the defunct Western Region of Nigeria with the construction of the Ibadan Water Supply Scheme at Eleiyele, but activities gathered steam only in the 1950s. Information in a Quarterly Hydrological Bulletin of the Western Nigeria Water Corporation published in 1969 indicates that many stations were built in response to the awareness for the need for water resource assessment created by the UNESCO-sponsored International Hydrological Decade (1965-74). All the same, most of the efforts of the then regional governments were not geared at holistic 'catchment studies' but were aimed at knowing 'what is where' and utilizing available resources for water supply and irrigation schemes. Thus for instance in Western Nigeria, river gauging stations were located only on river sections which, and in places where such rivers could be conveniently monitored and later exploited for urban and rural water supply schemes.

Real catchment studies commenced with the work by NEDECO (1959) on R. Niger and its main tributaries (Benue, Kaduna, Gongola, Taraba, Donga and Katsina Ala), though the interest was mainly on runoff and river potentials for Hydroelectric Power. The first Nigerian university-based research is that of Okechukwu (1974) who evaluated factors that contributed to variations in peak discharges and runoff of 75 (seventy five) catchments (> 500 km^2). A finding is that runoff coefficients are higher in the north than in the south of Nigeria (Table 1). Influencing factors evaluated are the catchment area, catchment shape, slope, length of main channel, storage capacity of the catchment, and time lag between rainfall and runoff.

Through our efforts in Ife, Adejuwon et al. (1983), Ogunkoya (1983, 1988, 1989), and Ogunkoya et al. (1984) presented information on annual, seasonal and peak runoff, runoff duration characteristics, runoff coefficients, and stream response of 15 micro (0.44 km^2 – 18.1 km^2) catchments to rainfall in southwestern Nigeria. Ogunkoya et al. (1984) observed that runoff coefficients range from 1 - 40%, the magnitude depending on catchment soil and geology with catchments draining fractured rocks and permeable soils having the highest values. Variations in annual rainfall among the catchments did not significantly explain variations in runoff response neither did the depth of saprolite. Rather, it is the water bearing and yielding properties of the saprolite and rocks that are of importance. Data from these studies generally confirm the relevance of the 'Engineer's Coefficient' (0.35 - 0.45) widely adopted in water resources development in Nigeria, but suggest the need for caution in the choice of values applicable to each zone of the nation. It should be noted that the use of the coefficients may continue given the continuing parlous state of the nation's economy and the reduced probability of judicious allocation of funds for procurement of water resources data.

Table 1: Runoff coefficients (%) of 75 catchments in Nigeria presented as zonal means

Zones in Nigeria	Runoff coefficient (%)
West	22.1
[1]Kwara	34.1
[2]Benue - Plateau	39.6
North Central	33.6
North west	53.8

[1] 8° – 9° N, 4° – 6° E

[2] 8° – 11° N, 8° – 10° E

Source: Okechukwu (1974, p 144)

We also conducted studies on the methodology and instrumentation appropriate for evaluating river discharge. Thus, Ogunkoya (2000a) assessed the accuracy of data obtained using three types of water level monitoring equipment, namely: the staff gauge, the crest-stage indicator and the water level recorder. The staff gauge, a graduated scale secured to a suitable structure within the channel, is inexpensive both in acquisition and installation. It is monitored at regular intervals, usually, twice daily (8.00 AM and 6.00 PM) to read and record the water level. A result of this systematic manner of observation is that most short-term extreme events e.g. flash floods which occur outside observation times are missed. The crest-stage indicator is a staff gauge to which a transparent open-ended tube is attached, with the bottom of the tube set below the lowest water level. A small quantity of saw-dust washed down into the tube is lifted up to the maximum water level attained during a flood wave where it is left clinging, and from where the level can be read. The saw-dust is washed down to the water line after each observation. This equipment thus indicates the maximum water level attained during the period between observations of the staff gauge. Self-recording equipment continuously monitors changes in water level over time, which it records on a chart, data logger or an appropriate record storage device. Though expensive in acquisition, installation and maintenance, it provides an objective and continuous record of stream water level. Ogunkoya (2000a) used data from five streams (catchment area = 0.44 – 9.50 km^2), and tested two data-collection scenarios (once daily, 8.00 AM; twice daily, 8.00 AM and 6.00 PM). Under- and overestimation of rainy season and annual runoff (procured using the water level recorder) by data from the other items of equipment range from –0.9% to 4.0% for the staff gauge, and 1.0% to 20.9% for the staff gauge-crest stage indicator. Two staff gauge observations per day tend to give a reasonably accurate estimate of runoff (+/- 0.3%). The results show that though the crest-stage gauge is no doubt valuable in monitoring peak discharges, its use in combination with the staff gauge detracts from accuracy of estimated daily runoff. The staff gauge is shown to be relatively efficient for the estimation of daily, seasonal and annual runoff, but cannot facilitate an accurate description of the storm hydrograph. This is very critical in the monitoring of low order rivers whose hydrographs are usually characterized by short lag times, with flood peaks occurring within the duration of causative rainfall. There are also problems of availability of dedicated observers, and maintenance, as it is readily defaced by algal and sediment encrustation, and damaged by floods. The crest-stage indicator used in conjunction with the staff gauge improves the quality of the description of the stream flow hydrograph. However, there is still a poor appreciation of the timing of flood events and consequently, some flood hydrograph parameters. A result is that its use promoted over-estimation (as compared to the water level recorder data) of rainy season and annual runoff of up to 21%. Use of such data will promote gross inefficiency in water resources planning and management. The staff gauge is the standard equipment utilized in the evaluation of river water level in Nigeria.

Ogunkoya (2000b) drew an annual and a three-year water balance for a small catchment (0.44 km^2) in Ile Ife (7° 31' N, 4° 32' E). The equation $P - Q - E - \Delta S = 0$ was not resolved. The residuals were negative and ranged between 4% and 5% of total rainfall, a probable source of error being the use of Thornthwaite's potential evaporation in estimating catchment evapotranspiration.

Potential evapotranspiration is higher than actual evapotranspiration in the study area due to the limited evaporation opportunity during the approximately four-month dry season. The computed water balance indicated that approximately 37% of annual rainfall becomes runoff with the variation in runoff coefficient being mainly due to the intensity of the dry seasons.

Ogunkoya and Jeje (1987), Ogunkoya and Adejunwon (1990), and Jeje et al. (1991, 1999, 2012) are other physical hydrology studies, but with focus on sediment and solute load and their dynamics in south-western Nigeria. Ogunkoya and Jeje (1987) presented information on the suspended and solute yields of fifteen third order catchments. Suspended sediment yield ranged from 0.4 to 29.5 tonnes/km^2/yr while solute yield ranged from 1.5 to 77.9 tonnes/km^2/yr. Statistical relationships that were established between the sediment and solute yields and catchment physiography indicate that the hydrological parameters reflected the then limited human impact on the catchments, the high infiltration capacity of some of the soils and Basement Complex rocks underlying the catchments, and the relatively insoluble nature of the rocks. Ogunkoya and Adejuwon (1990) on catchments with areas ranging between 100 km^2 and 160 km^2 went further to show that river water chemistry reflected rock chemistry and rock susceptibility to weathering.

Jeje at al. (1991, 1999, and 2012) presented information on suspended sediment and solute concentration dynamics in response to storms of various magnitudes in three small catchments draining quartzite and quartz-schist. Six types of responses were identified based on observed chemographs and hysteresis loops. Sediment/solute availability, exhaustion, and flushing effects were found to account for variations in the response types, while catchment slope and channel erosion were the sources of sediment.

Though physical hydrology studies generally aim to elucidate the operations of the catchment, and as noted by Whitehead and Robinson (1993) have proved invaluable for engineering design purposes, they do not provide adequate scientific understanding of catchment processes. Thus for instance, the catchment water balance approach provides only a crude approximation of the hydrological regime and no information on the dynamics of precipitation over time or that of streamflow or evapotranspiration. It does not yield any information on time dependent effects and areal variation in the parameters of interest. It is a lumped-parameter approach. The studies have at the best been 'grey box' studies from which detailed understanding of the internal functioning of the catchment could not be obtained (see Richards 1990).

REPRESENTATIVE CATCHMENT STUDIES

Representative catchments studies involve the evaluation of the relationships between catchment physical and land use attributes and the hydrological response patterns of catchments having known and specific indigenous attributes, which may not vary during the period of study. Given the impracticality of monitoring all catchments in an area, representative catchments serve to provide indices to the behaviour of similar catchments (in terms of climate, landform, geology, land use and vegetation) they were selected to represent. Accurate data from representative catchments could be extrapolated to and used to predict the behaviour of similar catchments.

Our studies in this area have therefore attempted to provide hydrological information that could be considered representative of 'hydrological regions' in south-western Nigeria. They have involved evaluation of catchment factors/parameters that determine hydrologic response patterns. Results from our studies in this area were presented in Adejuwon et al. (1983), Ogunkoya (1983), Ogunkoya et al. (1984) and Ogunkoya (1989). The hydrological response parameters considered include runoff regime, monthly, seasonal and annual runoff, and runoff variability and recession characteristics. The observed rapid hydrologic response and generally erratic flow (rapid response to rainfall events and runoff abating quickly), and other runoff characteristics were shown to be dependent on the water retention and yield capacity of catchment saprolite and rocks. Catchments underlain by fractured rocks have the highest groundwater contribution to stream flow, and lowest discharge variability and recession characteristics. The results were used to classify the studied catchments into hydrological regions (Ogunkoya, 1988). The constituent catchments of each of the regions were observed to share similar geology, implying that geology could be adopted as a factor in the prediction of hydrological response patterns in south-western Nigeria and by extension, the humid tropics. It was also revealed that catchments having at least 50% of their area underlain by quartzite have the most optimal hydrologic response patterns, optimality being in terms of perennial discharge, low discharge variability, and large ground water contribution to stream flow. Catchments underlain by granite gneisses, schists and amphibolites have much poorer response patterns.

Using surface hydrological information, we also conducted studies on the yield of the aquifers in the Basement Complex (Ogunkoya 1987). The studies adopted an approach based on the Unicell model (see Mandel and Shiftan, 1981) and Meyboom's (1961) Total Potential Groundwater Discharge (Q_{TP}) model, which utilize long term base flow of rivers as an index of aquifer yield. Results confirm the poor aquifer characteristics of most rocks of the Basement Complex suite and the saprolites developed on them. The results however also indicate that well fissured rocks and coarse grained saprolites e.g. quartzites and the weathered mantle on them have significant aquifer yields.

Another approach we adopted in the elucidation of aquifer yield in the Basement Complex area of south western Nigeria involved the use of chemical quality of base flows and their residence time within the soil and rock matrix. The hypothesis is that where the saprolite and rocks are of low transmissivity, base flow will have a longer sub-surface residence time and aquifer yield will be low. Residence time influences the chemical quality of water emanating from aquifers. Tritium (^3H) (a radio-active environmental isotope) was used to date the base flows, and provide information on residence/travel time and thus aquifer yield. Results of the study (Ogunkoya 1986) indicate that base flow discharge and therefore aquifer yield was directly related to the tritium content of the waters, and that tritium content of base flows may be used to estimate aquifer characteristics in south-western Nigeria. Base flows from quartzites and other well-fissured rocks have the highest tritium content, while those from amphibolites, schists and other such rocks that are associated with fine grained saprolite have the lowest.

Ogunkoya and Efi (2003) examined the veracity of a statement credited to the World Bank (1995) that:

> '*Speculations are widespread that gas flaring may have contributed to acidification of soils and corrosion of metal roofs. However, no evidence of acidification causing such damage has been found. With Nigeria's petroleum having some of the lowest S levels in the world and* NO_x *generation during flaring being insignificant, it is extremely unlikely that gas flaring is causing acid rain* [in the Niger Delta]'.

For this purpose, rainwater in the Warri area was collected and analyzed for a suite of determinants including organic and inorganic acidic anions. Among others, Warri rainwater pH was found to be as low as 3.6. Also, the SO_4^{2-} contribution to free acidity in rainfall was high (76%) and much greater than for non-anthropogenically impacted regions. Organic acidity (CH_3COO^-), most probably sourced from non-methane hydrocarbons in gas flare products, contributed 23%. NO_3^- was not a significant contributor to acidity in the area. In the much-impacted NW Europe and north-eastern USA, H_2SO_4 contributed 70% and 60% respectively, to mean annual precipitation acidity (Seip and Tollan 1985). The SO_4^{2-} contribution to rainfall acidity in Warri appears too high than could be suggested by the low S content of our natural gas (largely 0.04 – 0.27 %/weight; only Amenan-Mass has a higher S content at 0.97 %). But a cumulative emission through gas flaring of >40,000 t/y of SO_2 into the relatively calm air of the

Niger delta, could promote such contribution. However, biogenic emission of S from the peaty, sulphide-rich 'chikoko' soils of the Delta could also contribute to the high acidic anion content of the atmosphere. It was concluded that the magnitude of rainfall acidity in the Warri area would be the cause of accelerated weathering of outdoor metallic structures.

We received some impetus to our catchment studies between 2005 and 2007 through a grant from the United Nations University – Institute of Natural Resources in Africa. This supported a collaborative research with colleagues in the Department of Chemistry titled '*Land use, hydrological pathways and soil degradation implications in southwestern Nigeria*'. A number of graduate students benefitted from the grant. However, though the research was designed for Process Studies, only the Representative Catchment Studies aspect have been concluded due to some of the graduate students jumping ship to seek greener pastures.

One of the concluded studies (Ogunfowokan et al. 2009) elucidated the physico-chemical and trace metal characteristics of rivers draining different land cover/land use types and the levels of impairment to water quality the cover types have induced. Results indicate that while rivers draining forests are expectedly 'pristine', those draining lands under local farming techniques were more polluted than those under modern farming techniques. For instance, the river draining the University Research Farm (River Amuta) though more loaded during storm runoff events with suspended sediments than any of those studied, suffered only moderate level of pollution compared with R. Agbogbo draining the Hill 3 area. This may be due to the slower flow of the latter; the lack of knowledge of the application and timing of appropriate quantities of farm inputs by local farmers, and the use of the river to ferment and process various farm products.

Ogunfowokan et al. (2013) also examined the suitability of the rivers for irrigational purpose. This was in view of the increased probability of agricultural expansion and dependence on irrigation in southwestern Nigeria. Water salinity and particularly

Na^+ content relative to Ca^{2+} and Mg^{2+} (i.e. Sodium Adsorption Ratio, Sodium percentage (%Na), Permeability Index, Potential Salinity) affect infiltration rates and thus availability of water to plants. The waters were found not to exhibit toxicity problems with regards to salinity and sodium hazards.

Notwithstanding the significance of the information that have emanated from our research in this study theme and the valuable insight they have given into the nature of processes that operate within catchments, a main challenge remains the criticism levelled against Representative Catchment Studies with regards to the 'representativeness' of representative catchments (Riggs 1970). No one catchment is really representative of the other given that hydrologic responses of two catchments to the same input are not the same no matter the similarity of their physical components.

PROCESS STUDIES

The increasing intensity of hydrological problems e.g. acid rain, and catchment and stream water acidification, which have affected the industrialized nations of the world, prompted a shift in the main focus of scientific enquiry from systematic studies (Black and Grey Box, lumped parameter) and their essentially isolated single discipline interest to more complex multidisciplinary (white-box, distributed-parameter) catchment studies. The aim of these studies is to fully elucidate and provide rational explanations for the processes, interactions and interrelationships occurring in a catchment, to the point of making informed generalizations on catchment processes and responses. The studies have involved detailed investigations of, and the response of catchments to precipitation, and the influence of catchment land use, soil and geology (e.g. Fowler et al. 1989; Hornung et al. 1987, 1990).

Process studies were initiated in the early 1970s in Nigeria. Thus, Kowal and Kassam (1975, 1977) in their studies of the process of soil erosion at the Institute of Agricultural Research, Samaru highlighted the relevance of rainfall erosivity. They presented information on raindrop size, drop number, energy load and instantaneous intensities of rainstorms and evaluated their effect on erosion processes. They reported that 59% of all raindrops had diameters greater than 3 mm (mean = 3.4 mm), short duration high intensity storms had drop diameters up to 5.9 mm, and, 49% of the increase in rainfall intensity was due to increase in drop size while 41% was due to increase in drop number. Further, only storms greater than 20 mm resulted in runoff and concomitantly, soil loss, the degree of runoff depending on rainfall duration and intensity. A model was presented by which rainfall kinetic energy could be estimated from intensity or amount.

Okali (1980) examined interception by a teak (*Tectona grandis*) plantation at the University of Ibadan, Ibadan. Data on gross precipitation, through fall and stem flow were collected over one year. Transpiration loss was calculated based on some assumptions about seasonal variation in teak canopy resistance to vapour transfer, and meteorological data. Total water use by teak was estimated through summing up interception and transpiration loss. Interception and stem flow were found to be 21% and 2% of gross rainfall, respectively, while transpiration water use by the plantation was estimated to be 78 mm.

Jeje et al. (1986) documented subsurface flow from a 10% forested slope in Ile Ife. Information obtained includes those on timing of subsurface flow, seepage frequency, and amount at various soil horizons. The main percolation impeding layer was observed to be at the 90-120 cm horizon, but the largest relative contribution to total subsurface flow was not from the zone immediately above this horizon, rather, most subsurface flow was generated within the 0-30 cm horizon. Observed trends were explained using bulk densities, relative permeability, and intensity of the preceding dry season. The study highlights the key role of subsurface flows in the movement of rainwater to stream channels.

Ogunkoya et al. (2000, 2003) investigated the spatial and temporal dynamics, respectively, of soil water within a small catchment. Parameters investigated include moisture characteristics, moisture variability, field capacity and dynamic storage capacity of the various soil horizons in the catchment, and soil moisture response to rainfall, and short- and long-term drought. It was observed that the spatial dynamics of soil moisture and soil physical properties did not facilitate development of saturation to the surface, especially at the footslope. Thus, neither a surface identifiable dynamic source area, nor overland flow developed in the catchment.

Our studies noted above though indeed provided significant information, they could not, in many instances, adequately proffer the detailed answers required to fully solve the questions 'how' and 'why' to which process studies aim at finding solutions. Our next area of research aimed at providing such answers to a long-standing research concern in storm runoff studies summarized by Betson (1964) in the title of his paper:

'*What is watershed runoff*'?

It may be noted that runoff comprises the water that moves on/and within hillslopes and in natural channels under the influence of gravity, the water generally representing the excess of precipitation over evapotranspiration. Storm runoff is the runoff elicited by, and which occurs during and immediately (usually <72 hours) after a storm event in headwater catchments. These are catchments of such dimensions (usually less than 2.0 km^2) that their hydrological response to storm events is not influenced by channel storage characteristics. Betson's question requires answers with regards to the sources (i.e. end-members) of storm runoff; the processes/mechanisms by, and pathways through which precipitation reaches the river channel; the role of water stored in the soil prior to 'event' storm; and, the role of factors such as topography and soil. Attempts at resolving these issues have within the past fifty years, involved significant and heuristic field experimentation.

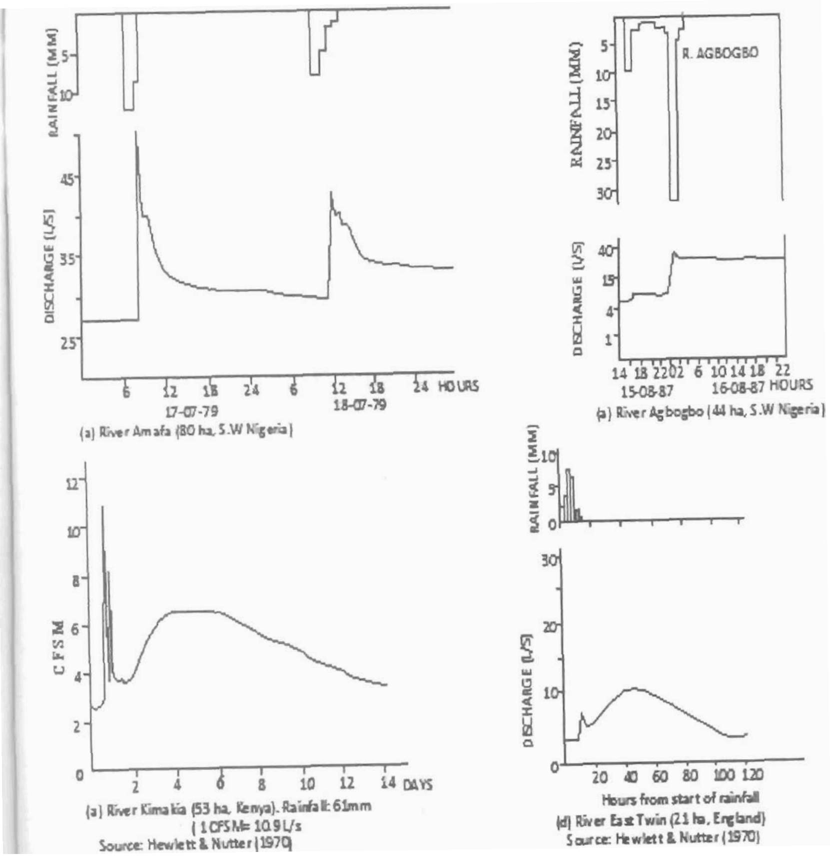
Research findings have been definitive with regards to the component waters or end-members of storm runoff:

(i) direct precipitation on riparian areas and channels;
(ii) waters which flow over the soil surface to reach the stream channel;

(iii) waters that flow laterally within the upper soil layers (<150 cm), and

(iv) groundwater discharge into stream channels.

There however continues to be no steadfast consensus on the prevailing processes/mechanisms of how the contributions from the various sources reach the channel to account for the observed magnitude and temporal variation of storm runoff. Outstanding issues includes accounting for the rapid response of stream flow to incident rainfall with lag time of less than thirty minutes; and the unusual large volumes of runoff a few days after the cessation of rainfall (see Figure 2; Burt and Butcher 1985).



(a) River Amafa (80 ha, S.W Nigeria)

(a) River Agbogbo (44 ha, S.W Nigeria)

(a) River Kimakia (53 ha, Kenya). Rainfall: 61mm
(1 CFSM= 10.9 L/s
Source: Hewlett & Nutter (1970)

(d) River East Twin (21 ha, England)
Source: Hewlett & Nutter (1970)

Fig. 2: Selected storm runoff hydrographs.

Various models including the ‘infiltration-excess overland flow model’ (Horton 1933, 1945); ‘partial source area concept’ (Betson 1964; Ragan 1968; Dunne and Black 1970); ‘subsurface flow (throughflow) model’ (Whipkey 1965,1967; Weyman 1973; Brown et al. 1999); ‘saturation overland flow’ model (Hewlett and Hibbert 1967; Kirkby 1969); and the ‘variable source area’ concept (Hewlett and Hibbert 1967) have been presented to explain these phenomena. Also, various mechanisms have been proposed to describe the pathways and modes of water transmission. These include the ‘pipeflow’ or ‘macropore flow’ pathway for the rapid transmission of water from ‘disjoint and distal contributing areas’ (Jones 1979, 1997; Germann 1990); the ‘transmissivity feedback’ (Zaslavsky and Sinai 1981; Bishop et al. 1990; Kendall et al. 1999); and the ‘piston flow’ (Hortons and Hawkins 1965; Zimmermann et al. 1966; Sklash et al. 1986) or ‘translatory flow’ (Hewlett and Hibbert 1967) or ‘shunting effect’ (Anderson and Burt 1982). Others are the ‘ground-water ridging’ (Sklash and Farvolden 1979); and ‘return flow’ or ‘exfiltration’ (Dunne and Black 1970), i.e. throughflow forced to the surface in the footslope due to water pressure from upslope and inability of soil to continue transmitting the water.

A detailed review of the various runoff generation models, concepts and mechanisms (see Ogunkoya 2012) suggest that a range of processes could generate runoff from specific parts of the catchment depending on the topography, land use, soil type, antecedent catchment wetness and incident rainfall intensity. There could also be a continuum of mechanisms in both space and time within individual catchments under different environmental conditions, though there could be zones in which specific processes/mechanisms are dominant for some part of or throughout the year.

Our research in this area, based on tracer hydrology, and conducted when I was a Royal Society Fellow at the then Institute of Hydrology, Wallingford, UK provided clarification on prevailing processes given extant environmental conditions. Tracer hydrology was adopted because each runoff end-member has its distinct chemical signature. We could note for instance that the prevalence of Horton's overland flow and saturation overland flow mechanisms would imply that storm runoff will comprise mainly of incident rain water (event water). Pre-event water may attain some significance if saturation overland flow, through contributions from return flow, were the dominant process. With the prevalence of through flow processes, storm runoff should comprise antecedent or pre-event water except where 'blow holes' in macropore network drain 'disjoint' overland flow source areas (Jones and Crane 1984; McGuire and McDonnell 2010). If runoff generation conformed to the variable source area model, there should be a mixture of water in varying proportions over time and space from a number of sources: direct precipitation onto saturated areas including the stream channel, pre-event soil water and by-pass event water, and shallow ground water in riparian areas. With these various sources, instantaneous relative contributions and mixing proportions will depend on the catchment antecedent wetness, catchment topography, timing of mixing and mixing ratios at source areas and in transit, and the order of entry of the waters into the channel. Elucidation of runoff generation could therefore be attained through a partitioning of storm runoff into its end-members (i.e. incident precipitation, soil water, and ground water both in tension-saturated and phreatic zones) and determining relative contributions at any point in time during the storm runoff.

Early attempts adopted a simplified two-component hydrograph separation model (e.g. Sklash and Farvolden, 1979; Rodhe, 1987; Bonell et al., 1990), which conceives storm runoff as having only two distinct sources: pre-event water (or 'old' water i.e. ground water and soil water in catchment storage) and event water (or 'new' water i.e. channel precipitation and direct precipitation onto saturated surface, and associated overland flow, Horton's overland flow and rapid by-pass flow of incident rain water). Most results indicate that old water is the dominant component of storm runoff; is the initiator of stream flow response and that new water contribution, even to instantaneous peak discharge, is less than 20% (Christophersen et al. 1984; Bishop and Richards, 1988). Thus for example, Pearce et al. (1986) on a 4 ha catchment with short steep slopes (34%) and thin soils (< 1m) in New Zealand, showed that the total new water contribution to storm runoff was 3% and this was apparently only through direct precipitation into the stream channel and a limited source area in the riparian zone. Ogunkoya and Jenkins (1991) on a 10 km^2 northeastern Scotland catchment also observed that old water dominated storm runoff. For an autumn (September) storm runoff (rainfall = 9.5mm; runoff coefficient = 37%), old water contribution was 87% on the rising limb, 91% at the peak and 70% on the recession limb of the hydrograph. Total old water contribution was 88%. Initial rise in the hydrograph appeared to be due to direct precipitation, but with continued precipitation and increase in stream flow, water chemistry shifted towards that of old water. Response to the storm was initially slow, but became rapid after a period of catchment wetting. Further, it appeared that with each renewed wave of precipitation, pre-event water contribution increased but declined during lulls. Each pre-event water peak was followed by an increased contribution of new water. For a summer (June) storm runoff (rainfall = 26 mm; runoff coefficient = 13%), instantaneous pre-event water contribution was 91% on the rising limb, less than 50% at the peak, and 36% towards the end of recession. Total pre-event water contribution was 54%. Ogunkoya (1999) also observed a large ground water contribution even during peak discharge, with solute concentration peak lagging behind peak discharge. These were explained using the concept of ground water ridging and time required for equilibration in the flushing out of nutrients concentrated in the draw-down zone by seepage water and ground water. The consequences of leaching of surface 'deposits' by overland flow for water quality in catchments, particularly where chemicals are applied to farms and overland flow paths connect direct to channels, were also noted.

However, Bonell et al. (1990) for a 3 km^2 catchment in New Zealand observed a rather high event water contribution of 54% at peak discharge and 80% on the recession limb. The highest ground water contribution (100%) was at the initiation of storm runoff response. The storm runoff occurred at a time of below average catchment wetness, and the high event water contribution was attributed to high rainfall intensity, which promoted a quick satisfaction of surface storage capacity and release of large volumes of incident rainfall to the channel.

A clearer picture was given by the three-component two-tracer hydrograph separation model. The model incorporates a detailed spatial and temporal sampling that captures all potential contributors to storm runoff that may originate from the three end-members: incident precipitation, soil water, and ground water. Ogunkoya and Jenkins (1993), the first in the literature to present a three-component two-tracer hydrograph separation model, showed that instantaneous contributions at the north eastern Scotland catchment were 8 – 30%, 3 – 46% and 30 – 87%, respectively. Contributions at peak discharge were 30%, 40% and 30%, respectively. Highest rain water contributions were at peak discharge, and during periods of peak rainfall intensities. The lowest contributions were during lulls in rainfall and at the end of storm runoff. Soil water (i.e. through flow) contributions also directly reflected rainfall intensities. The highest ground water contribution (87%) was on the rising limb of storm hydrograph, at a time when the water table showed an initial response to the storm event. Low ground water contributions coincided with periods of peak rainfall intensities (see also Jenkins et al. 1994).

The results of Ogunkoya and Jenkins (1993) appear to fit the Variable Source Area model. When catchment soils are wet, infiltrating water readily displaces old water into the stream channel (piston flow/groundwater ridging), and as saturation builds up to the surface, saturation overland flow is initiated. Other reasons for the delay in the delivery of new water to the channel include the low topographic gradients in the riparian zones, and the probable high hydraulic resistance to flow and the tortuous flow-paths through the dense vegetation in such zones.

It thus appears therefore that storm runoff consists initially mainly of old water (ground water, and unsaturated and saturated through flow) and with time, the old water is diluted by incident precipitation. Subsequently, stream flow becomes dominated by rain water and through flow until at the end of recession when stream flow reverts back to being ground water and through flow. It should however be noted that stream flow analysis using the two – or three – component hydrograph separation model only reveals the proportion of mixing in the streamflow. The uncertainty as to the synchronization of mixing on and within catchment slopes and entry of such mixture into the channel continues to preclude the drawing of firm conclusions about pathways. Thus, a main future research focus for us is the elucidation of pathways, and it is believed we may be able to attain this through the analysis of storm runoff water quality hysteresis.

EXPERIMENTAL CATCHMENTS AND MAN'S IMPACT ON THE HYDROLOGICAL CYCLE

Man, in the course of exploiting earth's resources, has over time impacted the hydrological cycle through activities such as deforestation, agriculture, road and dam construction, urbanisation, and waste disposal. A consequence is that processes, such as soil erosion that had been occurring at geologic rates have become highly accelerated resulting in massive gullying and high sediment yields that have promoted disequilibrium in receiving aquatic bodies.

A major theme in catchment studies has thus been the elucidation of the effects of cultural practices on catchment dynamics (see Whitehead and Robinson 1993). The studies have usually involved a deliberate modification of catchment characteristics and relating resulting changes in hydrological response to the degree of catchment modification. Only few of the studies conducted in this research area in Nigeria fall into the class of such as were conducted between 1958 and 1974 in East Africa (Kenya, Tanzania and Uganda) on the evaluation by means of controlled experiments, of the hydrological effects of changing land use/land cover from natural forest to tea plantations and exotic conifers (Blackie, 1972, 1979; Edwards and Blackie, 1981;

McCulloch and Robinson, 1993). Results from the East African paired-catchment (area: 36-702 ha) experiments indicate that replacement of rainforest by tea estates in Kenya resulted in an overall reduction of water use, combined with no significant increase in surface runoff and sediment loss. Similarly, replacement of bamboo forest by pine softwood plantations initially decreased the water use, but once the pine canopy had closed, no significant differences in water or sediment yield could be detected. The replacement of evergreen forest by small-holder cultivation (maize, vegetables) on very steep slopes in Uganda resulted in a large increase in water yield. Annual crops use considerably less water than indigenous forest. Long-term average increases in stream flow of the order of 50% were recorded compared with the forest control. However, due to the remarkably stable, porous nature of the volcanic ash-derived soils, only marginal increases in surface runoff and sediment loss are recorded though dry season base flow was doubled. It was therefore concluded that where surface storage opportunities are small, rational catchment management must aim at maintaining the maximum infiltration rates to reduce runoff and also minimize soil erosion particularly during the period of establishment of the new land cover. More recent and high-scale process studies have since confirmed that small stature vegetation use considerably less water than higher stature vegetation. This is due to the lower aerodynamic resistance and the consequent higher interception and evapotranspiration losses of higher stature vegetation (Roberts et al. 1990).

Rattan Lal and his colleagues at the International Institute of Tropical Agriculture, Ibadan in the 1970s and 80s conducted a similar scale of studies on the hydrological impact and soil erosion effects of land use changes (see e.g. Kang and Lal 1981; Lal 1981; Lawson at al. 1981).

Our own work in this area, Adediji et al. (1995) and Jeje et al. (1997), are plot-based erosion studies, which have examined soil loss from erosion plots on different slopes cultivated to early maize. The soils are Ultisols developed on granite gneisses and the studies have involved manipulation of land cover density (crop rotation and multiple plot studies) and documentation of associated runoff and soil loss. It was observed that soil loss was a function of rainfall amount, antecedent precipitation index and other erosivity parameters. The results were used to obtain the coefficients of a locally applicable Universal Soil Loss Equation, which was further calibrated using data obtained from other parts of southwestern Nigeria. The results indicate that the severity of soil erosion is more a consequence of rainfall erosivity rather than soil erodibility, and should be useful in determining optimal slope, crop management, and erosion control practices in the country.

Imevbore et al. (1986) reviewed the effects of soil erosion and attendant sediment transport on receiving aquatic ecosystems including those on channel morphometry, physico-chemical characteristics, and biological processes. Sedimentation in rivers causes changes including reduction in channel depth through formation of such features as braiding, extensive point bar deposits, and formation and growth of deltas particularly where rivers debouch into seas, lakes, ponds and reservoirs. Other effects include increased channel curvature through lateral channel migration in connection with development of point bars. Reduction in channel depth promotes flooding, a recurring factor in many urban areas in Nigeria, where poorly managed urban development (unpaved roads, open and un-lined sewers, and bare open spaces) and the attendant massive production of sediment coupled with the further blockage of channels by wantonly-disposed waste matter, have led to disastrous floods. Also, sediment-induced channel changes hamper navigation. NEDECO (1959) at a time when man's impact was still relatively minor, had shown that this was a problem with River Niger into which tributaries, including Sokoto, Malendo, Kaduna, Gurara, and Anambra bring such huge quantities of sediments that vast stretches of the river are not navigable for most parts of the year. This may signpost the issue that given the current continuing high rate of land degradation in most parts of River Niger's catchment, the current dredging exercise to stabilize River Niger's channel and facilitate navigation may be fruitless and may have to be continuous.

Man particularly impacts the run of a river to the sea through creation of reservoirs or artificial lakes by construction of dams, barrages and weirs across river valleys. Reservoirs store rainfall and runoff and guarantee water availability for agricultural, domestic, municipal and industrial use. Generally, the building of dams leads to submergence of established quasi-stable land surfaces, and the impoundments provide temporary base levels for deposition of sediments. Specific factors causing the sedimentation include the increased cross section of flow at the entrance into the reservoir, and the consequent decrease in flow velocity, and thus river competence and capacity (transporting potential). If the incoming sediment load consists of coarse grained materials, maximum deposition occurs in the headwater section of the reservoir, where the transport capacity is subjected to an initial reduction. Sands and gravels are the first to be deposited, while progressively finer materials are deposited with distance into the reservoir. Other substances (including toxic matter) entrained in inflows also get sequestered in the reservoirs. Clay and other colloidal matter that remain in suspension for longer periods of time are transported greater distances into the reservoir. But when the detention time of water in the reservoir is inadequate for such materials to become completely deposited, a portion of the fine grained sediment may be carried out of the reservoir with the outflow. Sedimentation does not just promote changes in reservoir morphology leading to decrease in water storage capacity; it also detracts from water use potential.

The ultimate fate of any reservoir created on a sediment-transporting river, is therefore to become silted up, though this process may take a long time (>100 years) before actualization. Such long reservoir life may however only be facilitated by appropriate catchment management upstream of the reservoir. But current environmental changes through continuing deforestation, agricultural expansion and urbanization ensure sediment delivery far in excess of natural rates, and a consequent reduction in reservoir's life.Many reservoirs and ponds have been so destroyed in Nigeria. Typical examples include the R. Ogunpa flood-control reservoir ($7^0$24'N $3^0$54'E) at the Secretariat in Ibadan, Oyo State; and the defunct Ilesha water supply reservoir at Effon Alaye ($7^0$43'N $4^0$56'E), Ekiti State. Annual dredging exercise on the latter has proved futile and the reservoir has since been totally obliterated by sediment save for the weir structure.

OPA RESERVOIR STUDIES

These observations led us to conduct some studies between January 2010 and December 2012 on our beloved Opa reservoir, the supplier of our domestic water, and pepper soup fish (and sometimes lobster) to the Ife community. The reservoir was created when the University constructed within its estate in 1978, an earth-fill dam with a concrete un-gated spillway on the River Opa. The dam axis abuts the Road 1, at a distance approximately 0.5 km from the University Main Gate.

The River Opa drains a catchment with an area of 110 km^2 that includes most of the Obafemi Awolowo University Research farm, the whole of the University Staff Quarters, part of the central campus, and a large part of Ile Ife Township. One of the main tributaries and the main contributor of dry season flow to the Opa reservoir, River Ogbe-Esimirin, drains more than half of the town, including More, Idita, Sabo, Mokola, Igboya and Oja Titun areas. It is in reality, the town sewer and 'land fill' site. Other tributaries drain rural areas. The main river of the catchment, the River Opa (also known as Obubu, Amuta), has its source in the hills around Osu. The catchment lies between Latitude $7^0$25' N and $7^0$35' N and Longitude $4^0$25' E and $4^0$40' E (see Figure 3).

At formation, the reservoir was about 2.5 km long and 0.80 km at its widest point, with an area of 0.66 km^2 (66 ha). The reservoir's depth ranged from <1.0 m at the reservoir head to 7.5 m along the thalweg at the dam axis. The as-built storage capacity of the reservoir at full pool elevation of 241 m a.s.l. is 1.5 MCM. The reservoir annually attains a maximum pool elevation of c. 241.5 m, but attained 242.5 m in 1987 following very heavy rainfall.

Reservoir outflow at 241.5 m is 1.3 MCM/day. The reservoir thus has a peak pool hydraulic residence time (HRT) or lake retention time of 1.17 days. Water level is lowest in March and highest between July and October reflecting annual rainfall pattern. The topography of the lake is dominated by a narrow 'dead storage' (reservoir zone proximate to the dam axis and below 236 m a.s.l.) formed within the incised old river channel. The valley-side slope is however much wider such that a one-meter increase in lake depth from the pool elevation of 241 m to 242 m equates to a change in storage from 1.5 MCM to 2.7 MCM.

Changes in Opa catchment

The catchment, within Ile Ife, has witnessed rapid urbanization since dam completion though with mostly unpaved roads, poor urban planning, and randomly located farm produce processing operations and mechanic yards. Effluents from these establishments drain ultimately into the reservoir. Further, the landscape of the University has been heavily denuded within the last three decades through cultivation, construction activities, tree felling, and bush fires facilitated by the droughts of the 1980s and 1990s. Before a poorly monitored 'blanket ban' was effected circa 1988, the area around the reservoir was intensively cultivated, with the result that the area contributing direct run off to the reservoir was exposed to intense rainfalls.

Figures 3 and 4, based on 1986 LANDSAT (TM), and 2011 ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) imageries, show the land use/land cover within, and the direction and magnitude of change in the human use of the Opa catchment between 1986 and 2011. Table 2 shows the percent changes in the land use/land cover classes (determined from satellite imageries) over the time period. Before 1978, the impoundment zone and the slopes abutting it were thickly forested and a main regional roost of the straw-colored African fruit bat (*Eidolon helvun*). But by 1986, the slopes abutting the lake were already deforested and covered by farms, fallow or bare ground, though most of the catchment, including the river valleys and adjoining wetlands was still covered by vegetation (forests and agro-forests). The Human Use index of the catchment (a sum of the proportions of cultivated, bare, and urban land use; see EPA 2001), which was 14.6% in 1986 had by 2011 increased to 32%. It could also be observed that the city had grown towards the lake and the University, with the growth terminating along the University estate's boundary. The area between the reservoir and the city limits have however been covered by farms, which tend to leave the area bare at the beginning of the year and the rainy season. Also, most of the University's estate within the catchment had been built up or become bare or cultivated. This promoted maximized sheet erosion with the eroded matter contributing to beach material and causing a narrowing of the reservoir. The poorly developed urban environment of Ile Ife, with the routing of storm runoff through open unlined sewers, facilitate sheet and rill erosion and thus constitutes a major source of sediment entering the reservoir. A more invidious issue is that the populace cursorily disposes waste in drains and river channels, which due to the direct linkage of township drains and streams to the reservoir, ensure that the reservoir is the repository of all manner of refuse.

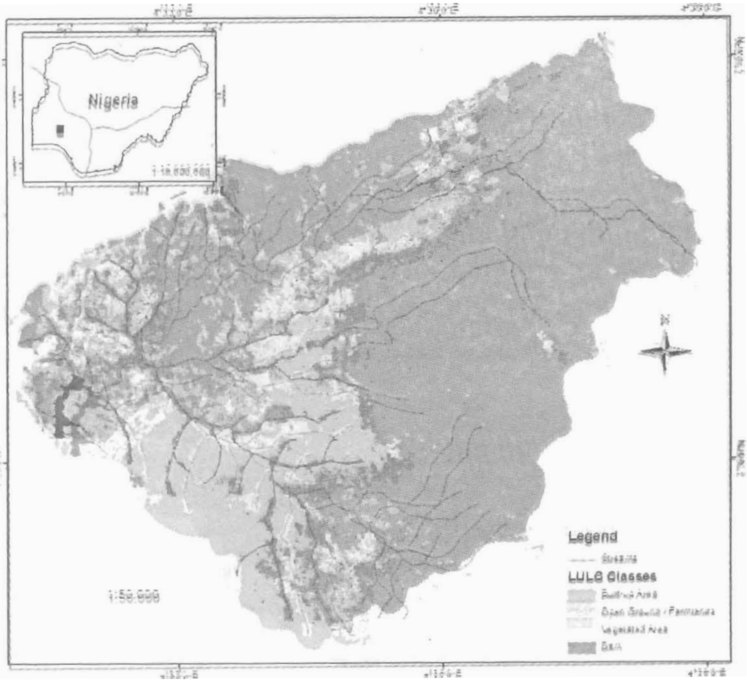


Figure 3: Opa catchment showing 2011 land use/land cover

Table 2: Changes in land use/land cover within the Opa catchment

Year	1986	2000	2005	2011
LULC TYPE	% Cover	% Cover	% Cover	% Cover
Vegetated	85.6	79.7	69.1	67.0
Built-up Area / Open Ground	7.2	10.1	12.2	13.7
Bare/ Cultivated Lands	6.9	9.8	18.4	18.9
Human Use Index	14.1	19.9	30.6	32.6

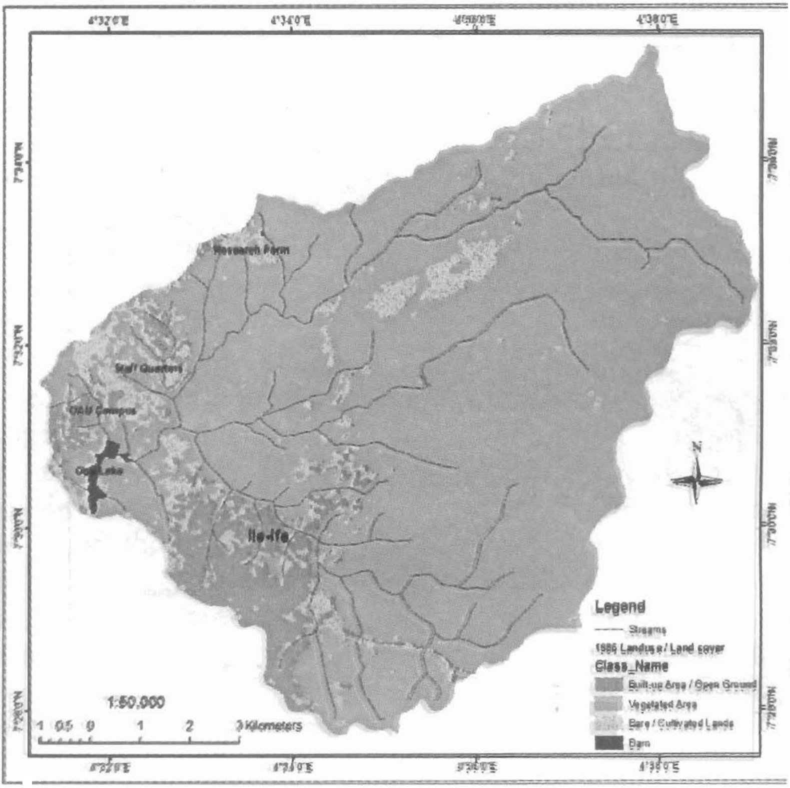


Figure 4: Opa catchment's land use/land cover in 1986

Changes in Opa reservoir morphology

Following the closure of the dam's sluice gates in August 1978, a 'pristine' lake was created, but this condition persisted for only a few weeks. First, though the impoundment zone was cleared of vegetation, many felled trees (cut into logs) and other detritus were not removed prior to closure of the dam's sluice gates. These became bouyant and were pushed by flood currents towards the spill way, where their movement was stalled except during spate flow. The logs in turn trapped hydrophytes washed downstream into the reservoir. The hydrophytes were subsequently concentrated along lake shores by wave action, thereby facilitating the colonization of shallow zones of the reservoir by weeds.

Hydrophytic weed species and their locational distribution and areal coverage on the surface of the reservoir have changed over the years. *Pistia stratiotes* (water lettuce) was the first water weed to be observed covering parts of the reservoir surface. The following have since successively been dominant in terms of areal coverage and occupation of various niches/locations previously filled by the preceding species:

Sedge (*Scirpus brachyceras*, *Rhynchospora corymbosa*, *Cyperus*) ⇒ Grass (*Typha australis*, *Coix lacryma*) ⇒ Fern (*Cyclosorus dentatus*) ⇒ Shrub (*Alchornea cordifolia*)

Currently, ferns, *Typha australis,* and *Scirpus* are the dominant species at and near the dam axis. *Alchornea* constitutes the dominant shrub along the shoreline, while ferns so covered the reservoir head area (before a 2011 channel clearing exercise) that water flowed into the reservoir only through a narrow channel (approximately 2 m wide) except when flood currents were able to dislodge the weeds. Fern density in the area indicated virtual total siltation. Vegetation has an important effect on water flow and sediment transport. It increases flow resistance, reduces velocity and sediment transport capacity, and thus induces deposition. The roughness coefficient increases as the number of plants per unit bed area increases (Bridge, 2003). The plants enhance the stilling effect, and their roots anchoring them to the reservoir bed act as filters stalling the movement of sediment.

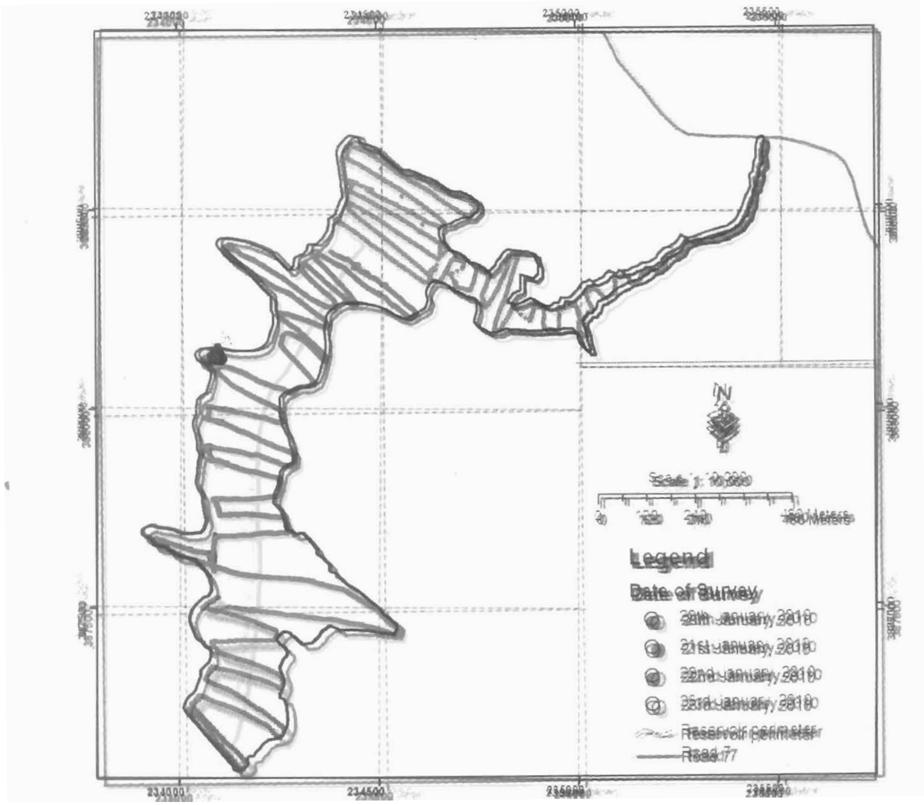
Believing that it must have undergone significant morphological changes, we deployed the contour survey method to construct a bathymetric map of the Opa reservoir. The contour survey method involves the determination of current reservoir bed elevation at many known locations along several tow (transect) lines across and along the reservoir (see Figure 5). The measurements, involving determining the water depth beneath a boat (depth measurements) and the exact location of the boat on the reservoir's surface (position measurements), were made using the *VALEPORT* DGPS Echo-sounder '*MIDAS* (Multi Input Data

Acquisition System) *Surveyor*'. The survey was conducted at reservoir pool elevation of 241 m a.s.l. (the spillway crest elevation) in January 2010. This was during peak dry season, a period characterized by very limited inflow, and wave and wind activity that could make the water turbid, and water depths unstable. Overflow across the spill way was also very marginal (< 1.0 cm deep) throughout the three-day survey exercise. Data derived from the bathymetric survey, consisting of water depths and locations, were interpolated to create bathymetric contours. The (2010) map was compared to a 1978 map (at inception of the reservoir) to determine changes in reservoir morphology between the time periods (Figure 6).

Figures 6 and 7 show changes in bed configuration, while Table 3 presents data on the morphology (area enclosed by specified bathymetric contour and volume between successive contours) of the Opa reservoir and the percentage change between 1978 and 2010. Reservoir area and volume losses were most prominent at those zones where tributary rivers draining Ile Ife and the more recently exposed parts of the university debouch into the reservoir. There also was a large decrease in depth and volume of the reservoir, particularly along the thalweg close to the 'dead storage' zone. This was the deepest part of the reservoir at inception but a part of it has become shallower by more than 2.0 m. Loss at the head of the reservoir was in terms of both area and depth. The data indicate that reservoir surface area decreased by 27%, equating to a loss of 18 ha out of the original 66 ha, while 41.4% of storage volume was lost over the 32 years.

The current capacity loss should be much greater given recent development (2011) in the catchment including a clearing of clogged tributary channels right to the reservoir to forestall flooding in the city. This has opened the reservoir to massive influx of all manner of refuse, including plastics (see Plates 1& 2);

the break-down products (including phthalate esters) of which are toxic[2].



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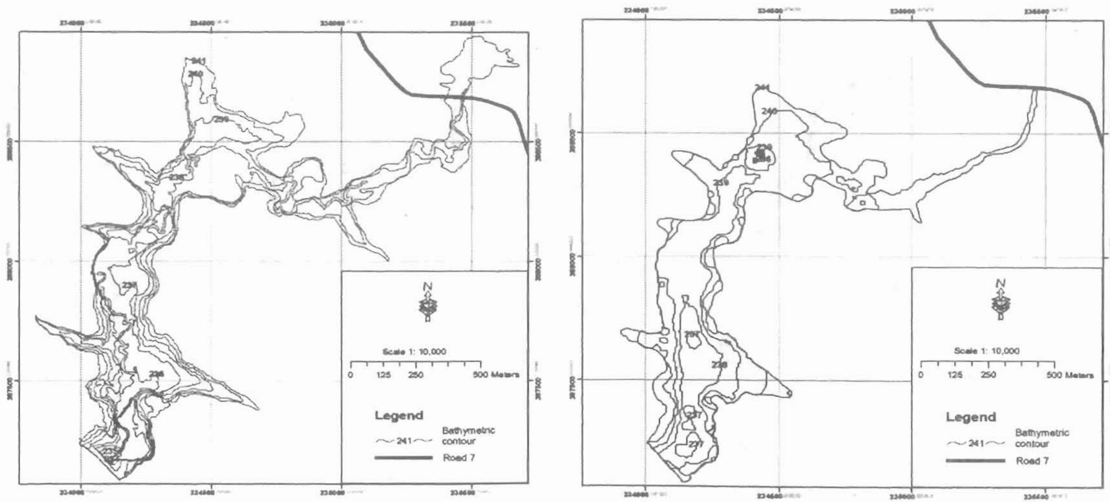
[1] As noted by Fatoki and Ogunfowokan (1993), phthalate esters are among the most common industrial chemicals, and are required in the manufacture of various plastics (including PVC), insect repellants, and lubricating oils. They are suspected to be carcinogenic and tend to concentrate along the food chain. They enter rivers through direct dumping of plastic and chemical wastes (including spent engine oil) into tributary rivers, or leaching from refuse dumps.



1978 **2010**

Figure 6: Opa reservoir bathymetric morphology

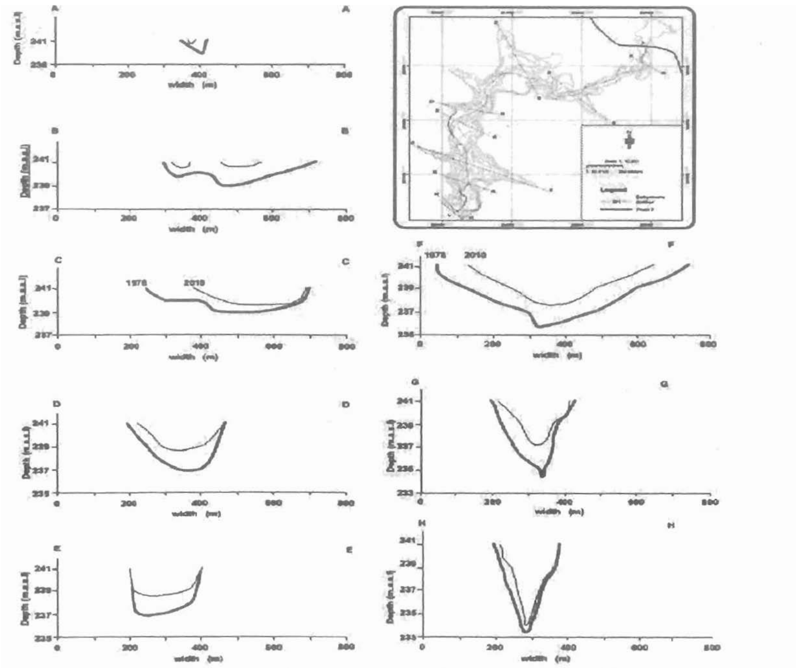


Figure 7: Bathymetric cross sections across Opa reservoir

Table 3: Changes in reservoir morphology between 1978 and 2010

Bathymetric contour (m)	**Area** enclosed by contour (m^2) **1978**	**Area** enclosed by contour(m^2) **2010**	**Volume** enclosed between successive contours (m^3) **1978**	**Volume** enclosed between successive contours (m^3) **2010**	**% Change between 1978 and 2010**
241	656861	479650			
240	478499	350924	567680	415287	26.8
239	323576	198212	401038	274568	31.5
238	194238	73253	258907	135733	47.6
237	119203	10918	156721	42086	73.1
236	38243	130	78723	5524	93.3
235	5289		21766	65	99.7
234	1561		3425		100
Total volume			**1489040**	**873263**	**41.4**

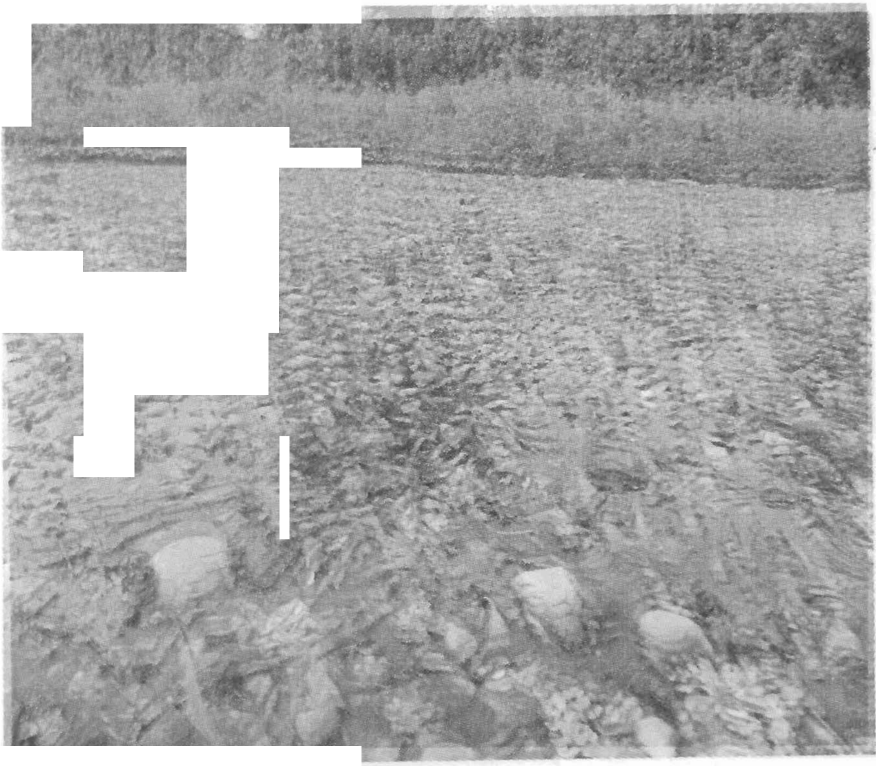


Plate 1: Refuse at location ~150 m downstream of Rd 7 bridge

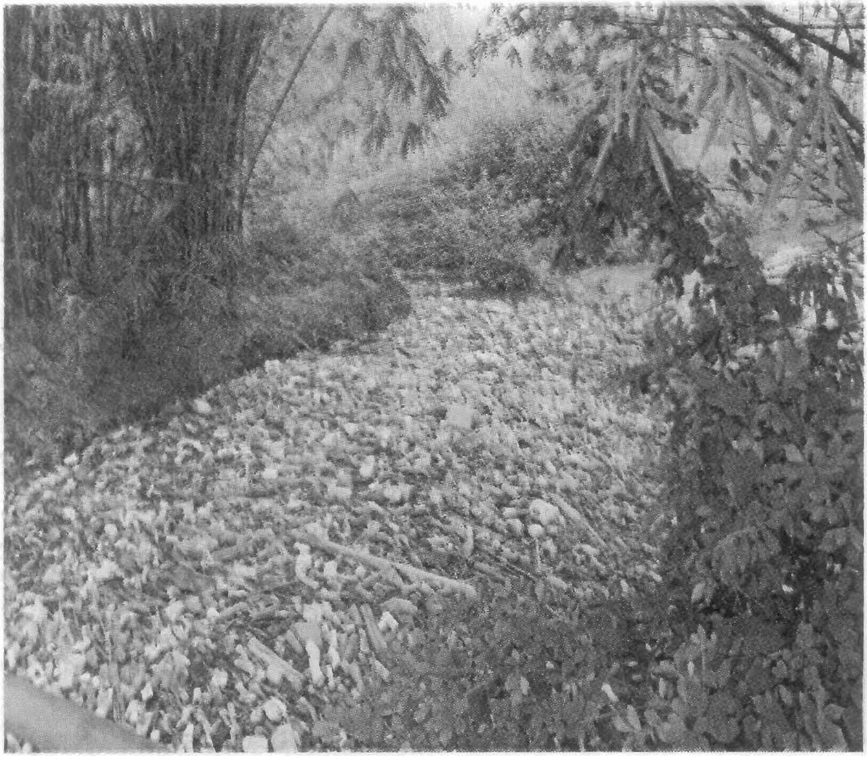
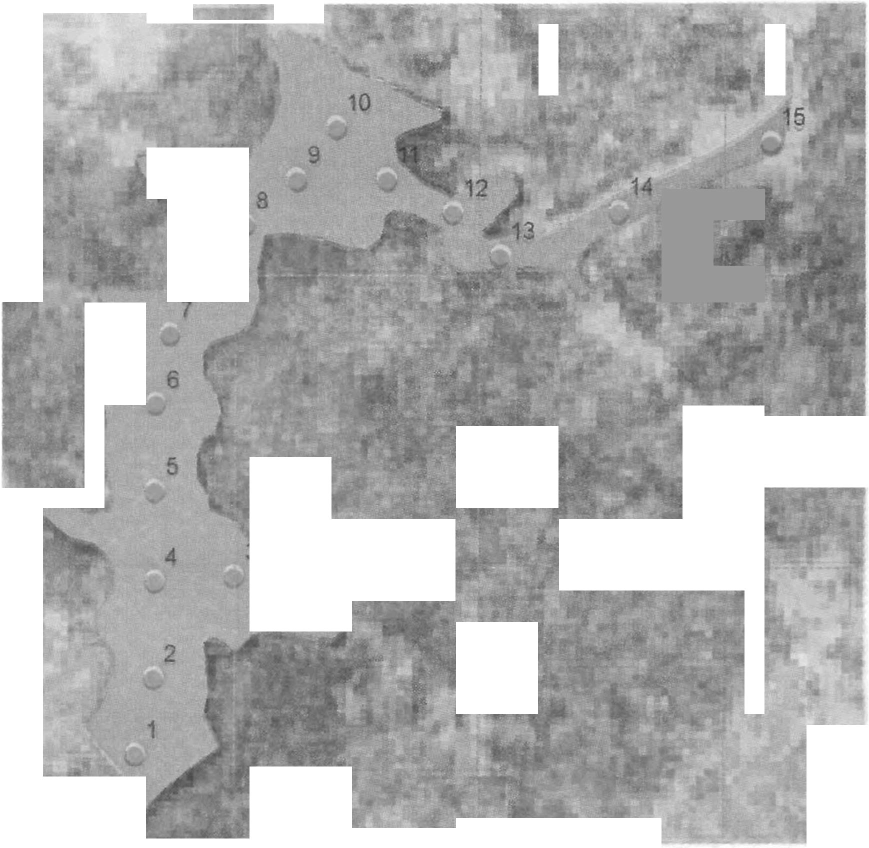


Plate 2: Refuse at location just upstream of Rd 7 bridge.



LEGEND

▨ Reservoir	▨ Vegetation	▨ Built-up/Bare Area	● Sampled Point

Figure 8: Water sampling stations on the Opa reservoir

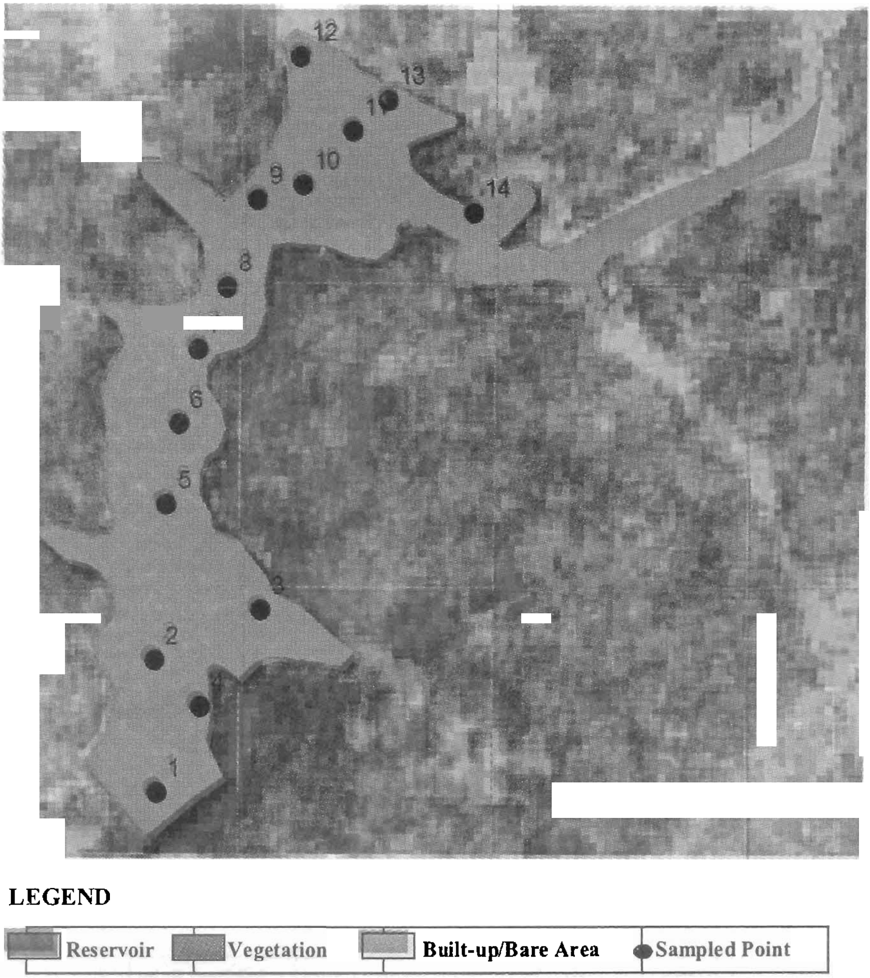


Figure 9: Bed sediment sampling stations on the Opa reservoir

Opa reservoir water quality

We sampled the reservoir's water at several locations (1-15; Figure 8) along and across the thalweg. The samples were subsequently analyzed for a suite of determinants including heavy metals at the CERD, OAU, Ile-Ife. The concentrations of the determinants in the surface water of the reservoir and at the various stations are presented in Table 4. When compared with fresh water quality standards and the W.H.O.'s and other international drinking water quality standards, the concentrations of cadmium (Cd) and lead (Pb) at some locations in Opa reservoir are significantly higher than the maximum allowable (.003 mg/L). These locations, marked as 12 and 15, are near the reservoir head, and the outlet of a river draining the Mbabi Mbayo area.

It should be pointed out that processes at standard water treatment plants such as ours cannot remove all impurities from water before delivery to the public. That means that drinking water derived from sources containing obnoxious chemicals will continue to contain most of them even after treatment. This explains and justifies the rationale behind a cardinal rule in water supply engineering that drinking water must always be taken from the best quality source. Anything less could result in unnecessary risks to public health (Akhionbare 2009). We may wish to consider that heavy metals such as lead and cadmium cause very serious harmful effects to man if ingested, even in very minute quantities (Ngaha 1980). A main symptom of chronic exposure to $\mathbf{Cd^{2+}}$ is renal tubular impairment followed by extensive proteinuria. It is also believed that it is involved in hypertension as highly elevated urinary and renal $\mathbf{Cd^{2+}}$concentrations have been found in hypertensive subjects. $\mathbf{Pb^{2+}}$ interferes with various biochemical and physiological systems in the body. Acute lead toxicity is manifested by its presence throughout the body and the effects are mainly seen as anaemia, kidney dysfunction, central nervous system damage leading to mental retardation and even death.

We did not analyze for the effect of plastics flushed into the reservoir on its water quality. But Fatoki and Ogunfowokan (1993) examined waters from water treatment plants in SW Nigeria, including the OAU Water Treatment plant for the presence of phthalate esters. They found among others that dimethyl phthalate ester (DMP) had a concentration in the Opa reservoir of 462 mg/L. DMP in rivers sampled ranged from 18 – 462 mg/L. The results also showed that DMP in tap waters ranged from 91 – 323 mg/L, and that there is no marked difference between DMP in tap water and river water, implying that water treatment does not remove this very harmful substance from the feed water. Similarly, most of the toxic matter in river/reservoir waters are not sequestered or removed by the treatment process. The DMP values reported by Fatoki and Ogunfowokan (1993) for the Opa reservoir and water from the OAU Water Treatment plant are from water samples collected between 1990 and 1991. This was when Ile Ife had relatively little negative impact on the reservoir, and long before 2011 and the opening up of the weed chocked R. Esimirin channel into the Opa reservoir. Even then, the values are much higher than those reported for polluted rivers in western industrialized countries and 10^5 higher than the 3 µg/L US EPA standard criteria for protection of aquatic life.

We also cored the bed of the reservoir at 14 different locations (see Figure 9) to obtain bed sediment samples, which were analyzed for heavy metals, among others using the Nuclear Accelerator at the CERD. The results are presented in Table 5. $\mathbf{Cd^{2+}}$was not detected in any of the bed sediment samples, while $\mathbf{Pb^{2+}}$ was only in trace quantities (lower than the level of detection) at two locations (4 and 5 on Figure 9) though there were heavy loadings of K, Mn, Fe and Zr at some locations. All these locations are not near the Opa Treat Plant's intake chamber. This is a major advantage to the University if the reservoir is to be desilted through dredging to restore storage capacity, and clean out sequestered muck. This is because accumulation of trace metals, radionuclides, organic matter and toxic material on colloidal interfaces being reversible; materials adsorbed on bed sediments may be released into the water column (Stumm and Morgan 1981; p672) through re-mobilization of contaminants during bed perturbation caused by dredging activities. The potential for integration of re-mobilized contaminants into drinking water would be very high duration such perturbations since water will continue to be pumped from the reservoir into the treatment plant.

But if the reservoir is to be desilted and cleaned out, there would be need to ensure that sediments and city refuse are permanently kept out through the construction of check dams across the channels of those tributaries that bring the most sediment and refuse into the reservoir. This could be readily achieved through the use of gabions. These will filter the water and keep the sediment and refuse on the city side. But the impoundment and backwater created by such dam on the Esimirin may flood sections of the town. This may effectively stall any construction since EIAs for such deleterious check dams may not be approved. The size of the dams will therefore have to be carefully considered. Further, there will be need to regularly remove chocking polyethylene matter from the upstream faces of the gabions to enable continuing filtration of river water. The sediment sequestered behind the check dams will also have to be routinely dredged out so that the dams will not be obliterated. The university may make some gains from the sale of the dredge spoil if the cost of removing the trash embedded in the sands is not prohibitive.

A solution to non-removal of objectionable matter during standard water treatment process is the recourse to water treatment technologies such as the Ion Exchange Membrane Bioreactor (IEMB), which incorporates pollutant transport through an ion exchange membrane by Donnan dialysis with biological removal of toxic heavy metal and other pollutants (Oehmen et al. 2006). These are however very expensive.

The situation in the Opa catchment is rather ubiquitous in Nigeria, and most probably in the developing world. Akoto et al. (2008) examined the As, Cr, Cd, Ni, Pb, Mn, Co, Cu, Fe and Zn concentrations in the waters of the Owabi reservoir, Kumasi, Ghana. This reservoir provides drinking water to Kumasi metropolis and its environs. Human activities found within the area include metal fabrication, auto garages, residential, farming, road construction as well as municipal waste disposal. The results showed that the water of the Owabi reservoir was unfit for drinking purposes though it continues to be so utilized. Tijani et al. (2007) found high concentration of trace metals such as Pb, Zn, Cd and high degree of anthropogenic contamination of water and bottom sediments of the Eleiyele reservoir, Ibadan.

During the colonial era when many water supply dams and reservoirs were constructed, the urban space was small and limited. Further, the catchments of the reservoirs were protected by forests. Since the end of that era, population increase and re-distribution have pushed city limits in the direction of the reservoirs, and in many cases, encircled the reservoirs. Zoning controls that were enacted during the colonial era appear to have been ignored. Thus for instance, the catchment of one of Ibadan city's water supply reservoirs (Eleyele; $7^0 26'$ N $3^0 52'$ E) built in 1942 was virtually covered with planted forests protected and managed by the State Forestry Department. But protection controls have either been abandoned or are unenforced. Consequently, most of the catchment is now covered by poor urban environment with absolutely ineffective waste management. Un-enlightened urbanites even dispose trash into an arm of the reservoir abutting the Eleyele-Polytechnic Road (Tijani et al. 2007; Olubode et al. 2011).

mg/L

Sample location	pH	EC	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe	Mn	Cd	Pb	Zn	Cl^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
1	7.3	722	1.02	0.16	1.12	0.04	0.136	0	0.006	0.002	0.019	61.1	47.02	2.89	57.3
2	7.5	661	0.55	0.17	0.13	0.024	0.081	0.001	0.005	0.001	0.024	79.91	19.51	2.12	91
3	7.9	1000	1.06	0.13	0.23	0.03	0.127	0	0.01	0.002	0.036	89.9	30.88	2.9	45.8
4	8.2	772	2.08	0.09	0.43	0.02	0.129	0.001	0.005	0.004	0.043	91.52	35.12	5.47	88.5
5	7.2	1009	1.06	0.1	0.33	0.02	0.088	0.004	0.008	0.008	0.049	78.82	31.39	3.34	65.2
6	6.5	922	0.47	0.21	0.15	0.02	0.025	0.004	0.011	0.01	0.039	260.83	21.81	4.23	113.4
7	8.2	1005	1.21	0.09	0.12	0.02	0.018	0.006	0.006	0.003	0.045	61.9	46.56	2.99	179.7
8	7.4	1116	0.64	0.13	0.07	0.02	0.017	0.005	0.008	0.004	0.125	76.65	40.45	4.7	245.1
9	8.5	788	1.1	0.18	1.02	0.02	0.125	0.003	0.003	0.01	0.099	241.12	41.82	2.35	251.05
10	7.9	953	1.09	0.18	0.53	0.02	0.052	0.01	0.005	0.002	0.048	176.71	33.2	3.04	100.1
11	8.1	1123	0.29	0.07	0.23	0.02	0.028	0.01	0.006	0.003	0.023	98.55	20.78	3.33	165.2
12	6.5	788	0.21	0.19	1.81	0.04	0.034	0.008	0.015	0.013	0.17	282.81	54.54	5.06	307
13	7.4	881	3.24	0.11	0.21	0.03	0.043	0.003	0.005	0.006	0.14	233.53	52.27	2.03	171.15
14	8.6	800	1.1	0.1	0.42	0.03	0.033	0.007	0.003	0.01	0.114	281.5	54.03	3.02	186.15
15	7.4	1201	1.09	0.19	0.43	0.03	0.042	0.009	0.007	0.009	0.115	254.91	51.58	2.73	288.5

Table 4: Opa reservoir's surface water chemistry

Table 5: Opa reservoir's bed sediment chemistry

Location	Al	Si	P	S	K	Ca	Ti	V	Cr	Mn	Fe	Pb	Cd	Zn	Cu	Zr
2	60720	105405	T	2468	3989	2708	5607	T	T	1548	86144	ND	ND	122	T	T
4	73096	136996	T	4680	4589	1907	5105	T	T	1984	92503	120	ND	150	ND	T
5	83862	143411	T	2458	5619	2132	5530	T	163	1483	91997	160	ND	180	ND	T
6	14953	47952	ND	ND	11943	1993	13441	T	T	1112	50776	ND	ND	T	ND	771
8	46146	109761	T	T	11752	2664	7607	T	T	3813	66570	ND	ND	144	T	T
9	46966	142234	ND	ND	18811	3017	12098	T	203	2916	54314	ND	ND	T	T	1060
10	272109	614099	ND	T	20781	3979	13758	T	T	5906	78792	ND	ND	124	T	258
13	165061	718337	ND	ND	51352	2790	5508	T	ND	360	17459	ND	ND	T	T	T
14	193327	477301	T	T	20322	4064	13257	T	T	3611	68659	ND	ND	214	T	1382
Basement Complex background[3]										229	15555	68	0.2	71	12	

T -Trace

ND – Not detectable

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[3] The reference background employed is that of average concentration of basement rocks of southwestern Nigeria, as compiled by Tijani et al. (2006). This reference background constitutes the average composition of weathered regolith over the different rock types and its application as reference background is based on the fact that such weathered regolith are source materials of the erosional wash-out and runoff sediments transported from the catchment area into the drainage system and the lake environment.

Reservoirs being sinks for upstream sediments and other detritus are naturally ephemeral features on the earth surface. But even before the total loss of the reservoir storage, water treatment costs could become so prohibitive as to outstrip the benefits derivable from the continued use of the waters of the reservoir. It has therefore become apparent that so long as urban expansion occurs and engulfs water supply reservoir catchments; urban landscapes remain poorly developed and managed, urban and state authorities do not have the capacity to or do not concern themselves with environmental and waste management, and the populace cursorily dispose waste of all types in drains and river channels, reservoirs such as our beloved Opa are inexorably on their way to an accelerated demise.

The University should therefore begin to seriously consider the development of alternative sources of water supply within its estate, such as the Shasha River. The river however drains the Osu area and part of its catchment within the University Estate has been designated as industrial park and housing zone. There is therefore need for appropriate catchment management to facilitate sustainability of any new reservoir's integrity. Such management will incorporate strict zoning controls. If such controls are not urgently established, as urbanization engulfs the catchment of the new reservoir, it too like the Opa reservoir will inexorably be on its way to an accelerated demise.

But, given the need to forestall a continuous case of 'build and abandon', it would be essential that specific land use zoning controls are built into the development of the river's catchment. These controls describe the restrictions on land uses in specific locations and deter or segregate emergent land uses that may not be compatible with desired ones. The goals are environmental sustainability and protection of the integrity and sustainability of desired land use e.g. water supply reservoir. A continuing successful example of the application of this type of policy is that of New York City's water supply reservoirs, which has enabled the city to have a low cost filtration-free water supply system. It should be noted that the city's water supply is based on a system of well-protected catchments and reservoirs built in them. The city has 90% of the catchments covered with forests and seeks to restrict development in them. A consequence is that the city has the largest unfiltered surface storage and supply system in the USA, which supplies drinking water to 9 million people in the greater New York City area, plus another one million tourists and commuters (EPA 2001; Germain et al. 2007).

CONCLUSION

Our discussions thus far have been on a major part of my research activities. There are others that have not directly been on catchment studies. There are also a few that had to be suspended for lack of equipment. A most painful one is on 'an isotope study of the natural waters along two SW-NE traverses in SW Nigeria'. The study aimed at assessing the contribution of local evaporation to incident rainfall and the significance of 'local' water recycling, and water samples had been meticulously collected. We needed environmental isotope data of the waters, and the equipment required for analysis is the Mass Spectrometer, which was then not available anywhere in Nigeria, nor in English-speaking West Africa. Efforts to secure analysis overseas elicited conditions that would impede attainment of study objectives, but provide general data to the laboratory owners. The university may therefore need to augment the capacity of our Central Laboratory as already canvassed by a number of Inaugural lecturers.

Mr. Vice Chancellor, please permit me at this juncture to express my gratitude to the One and the others who have ensured and worked that I attain this present status. First, all gratitude goes to the Lord God through whom and in whose support and grace I have been able to get thus far. Next, I need to note the contribution of my late father Mr. Thomas O. Ogunkoya who in 1975 travelled to Abeokuta where I was teaching after NYSC, to show me the University of Ife Post Graduate School advert and did all to encourage me to apply. It is the success of that application that led to my being a member of this great University community since

1975. I also need to particularly acknowledge the prayerful support of my late mother, and the encouragement of my brother and sisters in getting my life in order more so at times of imminent derailment. I also take this opportunity to express profound gratitude to my mentors, academic and spiritual, Professor J.O. Adejuwon, Prof. L.K. Jeje, and Prof. A.M.A. Imevbore.

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Mr. Vice Chancellor, Principal Officers, distinguished ladies and gentlemen, thank you very much for your attention.

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