Chapter

# Remote Sensing and River Basin Management: An Expository Review with Special Reference to Southwest Nigeria

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## Abstract

This chapter is part of the focus on the development in river basin management, and its specific objective is to provide an expository review of drainage basin morphometry and the relevance of remote sensing technology, especially for locations in developing countries, where sophisticated remote sensing technology are either expensive or challenged by limited professionals. The chapter is divided into six subsections, treating issues on remote sensing, drainage density and presenting specific case study, among others. The study reveals that remote sensing technology is efficient for providing decision support system for both gauged and ungauged river basins, and that freely available remote sensing data can efficiently fill the data gaps in many developing countries. It however warned on the need to consider variations in sensors capacity and mission as important attributes that can generate different spatial radiometric issues which may negatively affect the quality of the results. It concluded that researchers on drainage basin analysis in developing countries will benefit immensely from the freely available remote sensing data in the region.

**Keywords:** remote sensing data, river basin studies, developing countries, decision support systems

## 1. Introduction

A river basin is any area of land where precipitation collects and drains off into a particular point along a channel network or depression [1]. The basin is the basic unit for a hydrological study, probably because the input and output can be quantified and accessed; the basic input is precipitation, and largely rainfall in the humid region while the output or response is the runoff. Rainfall-runoff relationship provides insights into a basin's input-output relationship, and consequently, a basin's behaviour and an indicator of the basin's status of health [2]. Being an open system, a river basin receives inputs (of wastes, seepages, debris, etc.) from anthropogenic and natural activities within the confinement of the basin that are capable of influencing the quality of the river. Also, landcover, topography, the shape and size of a basin are capable of posing significant influence on the basin response to rainfall input [3, 4].

Researchers and policy makers across countries have demonstrated interests in the study of river basins, catchment or watershed, mainly because of the importance of river basins to human's livelihoods. River basins are wetlands, and home for ecological resources. Adequate management of river basins are known to promote soil and water conservation, and control of soil erosion and resources management. River basins are also main source of freshwater for ecosystem's survival; humans, animals and plants within the drainage basin system often depend on the survival of river basins. Sivapalan [5] described the river basin 'as a fundamental landscape unit for the cycling of water, sediment and dissolved geochemical and biogeochemical constituents, which integrates all aspects of the hydrological cycle within a defined area that can be studied, quantified and acted upon'. Jackson et al. [6] argued that temporal and spatial assessment of land use change in a river basin is important for flood risk management in the area. In the Taw river basin in the southwest England, Williams and Newman [7] demonstrated how the knowledge of the chemistry of streams in the basin can be useful to set criteria for vulnerability zones, control pollution of streams and improve the understanding of biogeochemical cycles in the basin. Evaluation of studies across decades reveals different levels of concerns of methodologies for evaluation of the morphology and biogeochemical cycle in the river basins for the purpose of pollution control, water management and seeking understanding of the effects of landuse changes in hydrological basins.

Despite the importance of the drainage basins, studies have shown that that they are difficult to conceptualise [8], causing a global dedication to 'Prediction in Ungauged Basins (PUB) science programme (2003–2012), that urged a rethink about the different ways in which the form and function of river basin systems are conceptualized [5]. Many river basins in the sub-Saharan Africa are ungauged, probably because of poor access to appropriate technology. There is also poor information about their characteristics and changes that have taken place within them over the years. Except for the few large basins such as Niger that are gauged by international organisations, drainage basins have been poorly studied and understood. The main objective of this chapter, therefore, is to provide an expository review of drainage basin morphometry and the relevance of remote sensing technology, especially for locations in developing countries, where sophisticated remote sensing technology are either expensive or challenged by limited professionals.

## 2. Remote sensing and allied technologies for river basin investigation

Remote sensing is concerned with acquiring information about the earth's land and water surfaces with reflected or emitted electromagnetic energy. Sensors fixed to a platform detect and record electromagnetic energy from target areas in the field of view of the sensors' instrument. Remote sensing is one of the many methods (others are land and social surveys, extensive field and laboratory analysis, among others) of data acquisition for geographical information system—a computerised system of software, hardware and people (expertise and users) involving data acquisition, storage, manipulation, analysis, retrieval and information presentation aimed at solving a location-referenced problem. Areas of remote sensing application include agriculture, disaster monitoring and mitigation, surveying and urban planning and water resource management. Remote sensing image and geographical information are useful for land use-land cover classification, land degradation and soil erosion [9].

A review of studies on river basin management have shown that whereas earlier focus has been within the perspectives of engineering, extensive social and fieldwork activities, more recent studies have involved the application of remote sensing and geographical information system to link the numerous hydrological parameters, their relationships and other indicators within combined socio-physical and biographical context. Grohmann [10] also argued that recent advancement in computational power of remote sensing and geographic information system has accounted for development in hydrological models and computational (rather than descriptive) interests in morphometry analysis. Application of remote sensing and geographical information systems is often preferred for potential and capacity for customised production of outputs (in terms of resolution and data integration). Sarmah et al. [9], Rai et al. [11], Fenta et al. [12], among other studies argued that hydrological model inputs have successfully been derived from remotely sensed data and geographical information-based modelling activities. In all, remote sensing and geographical information system's applications to river basin often assume that the drainage basin is a system—that it actually is.

## 3. Drainage basin as a system

Bertalanffy [13] described the system as an interdisciplinary study of systems; for elucidation of the system's dynamics, constraints, conditions and principles. In the river basin, the purpose of a system theory is to achieve optimized equifinality in the explanation of functions and processes within a unit the hydrological system [14]. The systems approach provides a useful conceptual vehicle for the study of the drainage basin. Studies based on a system theory measure the inputs, outputs, transfers and transformations that characterize this system. The system analysis also serves useful purpose in organizing process studies into a framework that allows both qualitative and quantitative data-base modelling and prediction [15, 16]. A hydrological system will comprise a set of drivers of hydrological processes and their relationships with components of hydrological systems.

Until recently when remote sensing and GIS are integrated in hydrological models, existing typical hydrological models are either parametric, physically based or deterministic. Parametric models describe the component hydrological processes, and are made up of interconnected reservoirs representing the physical elements of a catchment; i.e., rainfall, infiltration, percolation, evaporation, runoff and drainage. They often adopt semi empirical equations, and model parameters are assessed from field data and calibration. Many conceptual models have been developed with different levels of complexity, including the Stanford Watershed Model IV (SWM) developed by Crawford and Linsley [17], and Hydrologiska Byrans Vattenavdelning (HBV) model [18]. In addition, physically based or mechanistic models provide mathematical representation of reality through the principles of physical processes. They use of variables that are measurable functions in both space and time. They can overcome the limitations of empirical and conceptual models because of the use of parameters that have physical interpretation [19]. Example includes the Systeme Hydrologique European (SHE/MIKE SHE) model in 1990, the Soil and Water Assessment Tool (SWAT) Model as well as Topmodel [20]. Beven et al.'s [20] topographical (TOP) model is a rainfall-runoff model that makes use of topographic information related to runoff generation for prediction in single and multiple basins. Other models were the empirical, metric models or data driven models that involve the use of information from the existing data without considering the features and processes of the hydrological system. The model involves mathematical equations derived from concurrent input and output time series but not from the physical processes within and over the catchment.

In river basins, parameterisation can be a major modelling challenge because they (parameters) are many. Common morphologic parameters in drainage basin stream order, number, length ratio, bifurcation ratio, drainage density, stream or channel frequency, texture ratio, form factor, circulatory ratio, elongation ratio, relief ratio and length of overland flow. The stream orders and stream number typically provide information on other parameters, suggesting complexity in the parameters [21]. Subsequently, major advancements in remote sensing technology are the availability of many high-quality drainage models or abstraction of reality.

## 4. Development in modelling drainage basins

The river basin concept aids the development and management of water resources in many countries, and consequently interests planners and engineers, and scientists, including agriculturists that are interested in the elucidation of hydrological processes. Improvements in water supply and demand enhance hydropower generation, flood control, water supply and irrigation; Recreation, aesthetic ammenities, ecosystem services pollution control are also justifications for scientific interests; especially among hydrologists, soil scientists, geologists, physical geographers and environmental modellers [22]. Concerns about basins probably became noticeable since 300 BC [23, 24], with improved focus on hydraulic infrastructure over flood basins and dams for flood disaster control, intensive agriculture, and industrialisation. Parameterisation of basins for explanatory and predictive modelling purposes later became popular with the thoughts of Horton [25] and Langbein [26], emphasising concerns on runoff regeneration mechanisms.

Digital elevation models (DEMs) are frequently explored for the morphometric analysis of river basins through the extraction of topographic parameters and stream networks, and their use presents many advantages over traditional topographical maps. DEM is a regular gridded matrix representation of the continuous variation of relief over space [27], and a digital model of the land surface form. The most important requirement of any DEM is that it should have the required accuracy and resolution and be stripped of data voids [28]. Recent increase in the application of DEMs can be attributed to their easy integration within a GIS environment. The Shuttle Radar Topography Mission (SRTM) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) are samples of advanced global DEMs. They have been adopted in a variety of studies where terrain and drainage factors play prominent roles because of convenience of users and open-access availability of the DEMs. The DEM approach is also useful for characterising stream basin because of its easy integration within the GIS environment. It is fast, precise, updated and it is an inexpensive method for drainage basin analysis [29]. The DEM will help to show the general topography of the area and the direction of flow of the streams.

In addition, studies have shown that the advantage of timeliness and ability to capture information on larger areas than in studies with traditional surveying methods [21, 30–33] are main strengths of remote sensing and GIS in river basin investigations. GIS is also a viable tool for establishing relationship between drainage morphometry and properties of landforms useful in the development and planning of drainage system. Results from remote sensing and GIS are known to provide decision support information for prioritization of basins, water conservation and natural resource management. Specific results of basin morphometry are also advantageous in the recognition of different terrain parameters and basin's health; measured in terms of runoff and sediment yield index from a basin, flow characteristics and fluvial processes [34, 35]. Malik [30] adopted drainage density and stream frequency to explain control of the runoff pattern, sediment yield and other hydrological parameters within the basin. In addition, Kulkarni [35] argued that dynamism of river morphology is the aftermath of natural processes as well as anthropogenic intervention, hence both causes can be explained by the changes observed in the basins. In general, good information about basin morphometry generally assists in making decisions for combating hydraulic structures to combat erosion [36] and to arrive at decisions regarding suitable sites for soil and water conservation structures [37]. In many basins, the remote sensing approach is the only option, especially in difficult or dangerous terrain especially in Congo and Amazon.

Most studies from the Nigerian environment have focused mainly on the drainage basin morphometry from the angle of landuse/landcover change [38–40]. Orunonye et al. [39] carried out morphometric studies on River Lamurde in Jalingo, Nigeria, and explained that lack of reliable hydrological data has been a major constrain for use by water resource managers and researchers in Nigeria, therefore, the only alternative was to resort to measures of appraising and evaluating the natural water resources potential of basins without stream gauge records using series of generalised regional relationships based on morphometric parameters.

## 5. Case study analysis

### 5.1 Precipitation input measures

Main precipitation input into the drainage basin in Nigeria is rainfall based on its location in the tropical region. Whereas the ground-based data has become rather expensive, despite being coarse (almost only available for locations around airports, which are often not representative of the large area that they are meant to represent), satellite-based data sources are poorly explored. This is probably because of the poor awareness and low capacity for remote sensing analysis among many climate experts in the country.

Meanwhile, satellite-based precipitation estimation algorithm use information from two primary sources; the visible and infrared channels from geosynchronous satellites. Many meteorological weather satellites have been launched in the last few decades and some of these satellite rainfall products are freely available in real time on the internet via the web or File Transfer Protocol (FTP). Some of the freely available spatially distributed satellite-based rainfall estimates are the Tropical Rainfall Measuring Mission (TRMM), EUMETSAT's Meteorological Product Extraction Facility (MPEF), and Multi-Sensor Precipitation Estimate-Geostationary (MPEG). Others include the Climate Forecast System Reanalysis (CFSR), the NOAA/Climate Prediction Center Morphing Technique (CMORPH), Climate Research Unit (CRU), and Global Precipitation Climatology Centre (GPCC), European Centre for Medium-Range Weather Forecasting (ERA-Interim), the Naval Research Laboratory's blended product (NRLB) and African Regional Climate (ARC) [41]. These satellites have different spatial and temporal resolutions, thus providing a stream of datasets in support of operational meteorology and many other disciplines. They are scaled to match rain-gauge measurements on land points where ground measurements are available. The TRMM, CRU, GPCC, GPCP, and ERA-INTERIM (Medium-Range Weather Forecasting Reanalysis-Interim) were commonly selected and chosen for use in many studies and have been shown to possess complementary capacity with ground based data based on their high spatial and temporal characteristics, free availability and accessibility online and minimal frequency of missing data. The centre for this is the latest global atmospheric reanalysis (third generation reanalysis) which computes synoptic hourly, daily and monthly means of precipitation by accumulating the available hourly forecast for each calendar month [41]. The ECMWF ERA-Interim reanalysis, provides global precipitation at gridded spatial resolution of 0.125° × 0.125° (i.e., 13 km). In addition, dataset from the Global Precipitation Climatology Project is made available from October 1996 to present. The GPCP provides daily, global horizontal resolution of 1 × 1° (i.e., 111 km) gridded fields of precipitation. The GPCP 1-DD draws upon several data sources such as GOES, Meteosat, GMS geostationary satellites and with NOAA AVHRR polar-orbiting IR satellite, given the different available input sources (GPCP-1DD v.1.2; [42]). The Tropical Rainfall Measurement Mission (TRMM) satellite, launched in November 1997 is a joint space mission between the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC), and the Japan Aerospace Exploration Agency (JAXA). It is a polar orbiting satellite, having a relatively high temporal resolution, designed to monitor rainfall over the global Tropics [43]. The satellite estimates rainfall and energy exchange on tropical and subtropical regions of the world based on the characteristics of cloud cover, cloud tops and temperature.

The great advantage of satellite-based rainfall records is their global coverage, providing information on rainfall frequency and intensity in regions that are in accessible to other observing systems such as rain gauges and radar. Through the aid of satellite weather observing technologies, the influence of viewing and understanding tropical rainfall systems has been greatly improved. In recent studies, several satellite-based rainfall products have been subjected to cross-validation tests over many regions to ascertain the accuracy of their rainfall estimations. The performance of satellite precipitation estimates over land areas has been reported to be highly dependent on the rainfall regime and the temporal and spatial scale of the retrievals [44].

### 5.2 River basin analysis: Opa River basin in Southwest Nigeria

Opa river basin is a tributary of River Shasha (one of the main tributaries of River Osun) located within latitudes 7°26′56′′–7°35′5′′ N and longitudes 4°24′53′′–4°

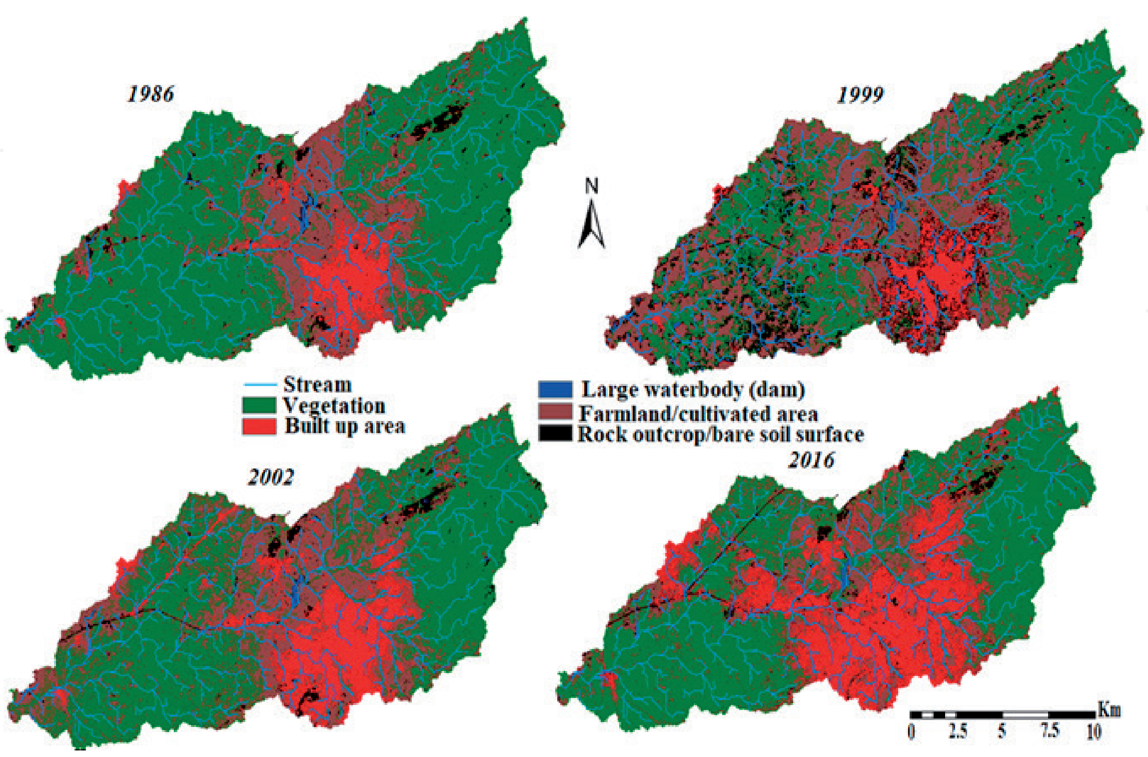


**Figure 1.**
*Landcover change over Opa river basin in Southwest Nigeria between 1986 and 2016 (see [45] for details of the methodology used to derive this).*

39′13′′E. The basin covers four local government areas and an important impoundment in the basin is the 68 km$^2$ Opa Dam that was established in a University (Obafemi Awolowo University, Ile-Ife, Nigeria) community in 1978 supply water for more than 10,000 students and staff in the University community. Satellite data used were freely available Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs) and Landsat imageries (mainly TM of December, 1986; ETM+ of December 1999; ETM+ of March, 2002 and OLI/TIR of January, 2016) to provide management decision support on river basins in the region. Main objectives were to examine landuse/landcover change over the river basin, characterize the basin, morphometrically and compare the morphometric characteristics from different sensors and resolutions.

Results showed that built-up areas and farmlands have increased in the study area by 262.71 and 7.15%, respectively, at the expense of vegetation cover that has reduced by 23.78% within the study period of 1986–2016 (**Figure 1**). Analysis of the DEMS classified the river basin as belonging to a fifth order class, with about 480 tributaries over the 236 km$^2$ area. When subjected to cluster analysis, results showed that the remote sensing data can be used to generate distinguishable sub-basins that can ease management and allow for creation of sub-basin plans based on each sub-basin's comparative advantage. To achieve the classification, important drainage parameters were investigated across selected (Opa) basin, and their results are presented in **Table 1**. Subsequently, the river basin was classified into five sub-basins (**Figure 2**) that can aid planning.

Despite the suitability of the remote sensing data, comparison of the results across geometric and radiometric differences indicate that 30 and 15 m resolution DEMs from ASTER sensor produced fewer contrasting results than what was obtained from different sensors (but same resolutions) analysis of 30 m ASTER and 30 m SRTM. It this can be recommended that it is better to adopt same product of a particular sensor rather than of different sensor for analysis. Nikolakopoulos et al. [46] had indicated that differences may occur due to variations in mission specifications of different sensors, and that whereas SRTM elevation data are unedited, and contained occasional voids, or gaps, where the terrain lay in the radar beam's shadow or in areas of extremely low radar backscatter, such as sea, dams, lakes and virtually any water covered surface, ASTER imageries can be influenced by weather conditions during the stereo-imagery acquisition.

| Morphometric parameters | CLUSTER | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| | S2, S5 | S1, S7 | S8, S9, S11 | S4, S6 | S3, S10, S12 |
| Basin length (m) | 8.56-9.62 | 4.5-6.3 | 6.45-9.56 | 8.9-13.1 | 4.9-7.07 |
| Basin Area (sq.km) | 23.7-28.6 | 7.6-9.2 | 15.8-20.6 | 34.7-39.4 | 10.7-14.27 |
| Perimeter (km) | 33.7-37.4 | 19.9-23.9 | 29.5-39.2 | 42.64-58.5 | 19.4-27.6 |
| Drainage density | 1.60-1.68 | 1.49-1.55 | 1.61-2.89 | 1.56-1.66 | 1.59-1.69 |
| Stream frequency | 1.68-2.07 | 1.45-1.75 | 1.77-1.94 | 1.65-1.79 | 2.03-2.24 |
| Texture ratio | 1.28-1.45 | 0.55-0.67 | 0.75-1.23 | 1.11-1.45 | 0.9-1.23 |
| Form factor | 0.32-0.33 | 0.23-0.37 | 0.17-0.41 | 0.23-0.44 | 0.25-0.52 |
| Circulatory ratio | 0.26 | 0.2-0.24 | 0.14-0.26 | 0.14-0.24 | 0.13-0.36 |
| Elongation ratio | 0.64-0.65 | 0.54-0.69 | 0.47-0.71 | 0.54-0.75 | 0.57-0.81 |
| Length of overlandflow (m) | 0.8-0.84 | 0.75-0.78 | 0.82-1.45 | 0.78-0.83 | 0.8-0.85 |
| Mean stream length (m) | 1.8-4.32 | 1.83-2.95 | 1.67-7.6 | 2.44-5.3 | 1.46-1.86 |
| Total Stream length (m) | 39.78-45.57 | 11.79-13.7 | 25.4-47.53 | 54.1-65.57 | 18.2-22.6 |
| Bifurcation ratio | 3.43-6.61 | 3.33-6.5 | 3.58-5.34 | 3.62-7.91 | 2.37-5.2 |
| Stream number | 48-49 | 11-16 | 28-39 | 62-65 | 24-29 |

**Table 1.**
*Selected morphometric characteristics of identified sub-basins from remotely sensed data. Details of the parameters and methods are provided in Eludoyin and Adewole [45].*

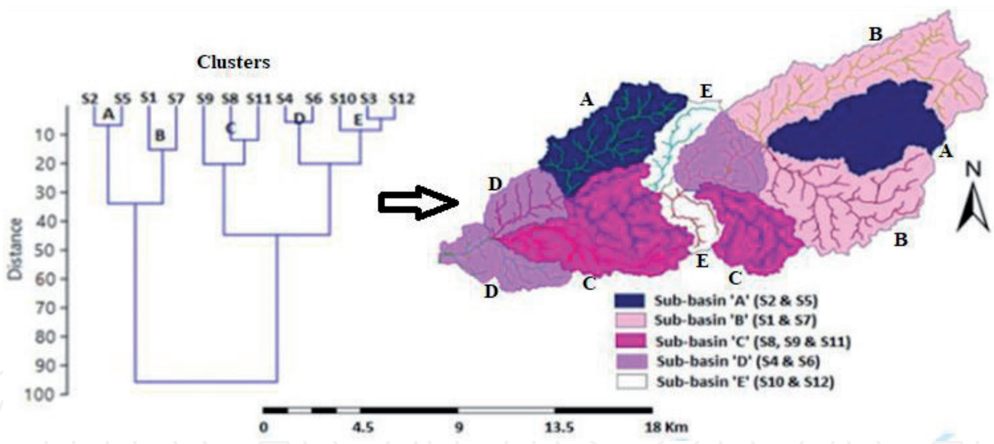


**Figure 2.**
*Delineated sub-basins from hierarchical clustering, and their corresponding locations (the methods are presented in detail in [45]). Specific characteristics of the sub-basins are in* ***Table 1****.*

## 6. Conclusion

This chapter reviewed different areas of application of remote sensing to river basin studies, with significant emphasis on and a case study in a part of Nigeria. The study used mainly an expository review and presented a case study. The chapter showed that huge potentials in some freely available remote sensing data in the developing country and considered that they are capable of bridging the gap of the coarse data. The case study presented was to indicate that decision support information can be generated from the freely available (only requiring downloading from the authorized archive) remote sensing data in many developing countries, where researchers have complained of significant data gaps. The review however warned that remote sensing data are prone to geometric and radiometric discrepancies that make them vulnerable to errors.



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