Application of Remote Sensing and GIS in Water Resources Management

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Abstract

This paper discusses the application of remote sensing and geospatial information systems (GIS) in the management of water resources. As users and applications are diverse in a hydrologic community, a common data model that defines the structure, semantics and syntax of the database is crucial. This paper adopts a conceptual hydrologic data model to create a water resources database. The conceptual data model was translated to a relational database structure and implemented using sample hydrologic datasets from parts of Nigeria and proprietary GIS software.

Key words: Remote sensing, GIS, Ecosystems, Water resources, Data model

Introduction

The crucial role of water in accomplishing the socio-economic goals and environmental needs of a community is widely recognised. The African countries, for instance, have a shared vision of a society "where there is an equitable and sustainable use and management of water resources for poverty alleviation, socio-economic development, regional cooperation, and the environment". Sustainable water resources are needed to meet man's increasing water needs for drinking and sanitation, food and energy security, ecosystem and biodiversity, among myriads of other needs.

However, the most endangered "species" today is our environment (including water resources) because recent interaction of man with his immediate environment has been that of "getting what I need from the land" attitude without giving a thought to what happens thereafter. The "natural world" is now in great conflict with the "human-managed world", resulting in unsustainable natural resources. The present state of our ecological regions, especially in Nigeria (where there is a remarkable evidence of progressive change of the rainforest into savannah grassland), is the consequence of definitive occurrence in our socio-economic environment, which encourages depletion of these very important resources without appreciable plan for their replacement.

If we must guarantee the future, there is therefore an urgent need to protect the fragile environment with its vital strategic resources such as water, soil, and biodiversity (Skouri and Fezzani, 2002).

Finding optimum solution to these problems require accessible and adequate geospatial information to know, appreciate and resolve what is happening in the ecosystem, which can be achieved through a spatial data infrastructure (SDI) at national, regional and global levels. Parts of the essential tools for this are Remote Sensing and GIS technologies, which are the focus of this paper. The paper discusses remote sensing as a data acquisition tool for GIS application in water resources management and presents a database structure for achieving this.

Remote Sensing as Data Acquisition Tool for Management of Water Resources

Remote sensing is the science of measuring the geometric and thematic properties of objects in the environment without coming in contact with such objects, using various devices carried in the air or space. The major medium of contact or vehicle of communication is the electromagnetic energy. It enables an instantaneous view of very large regions of the earth's surface thereby making it possible to learn more about the physical structure of the earth's crust, to assess and monitor water, forests, crops, minerals, etc. and to predict some phenomena (climate, desertification, harvests, etc.). Although aerial camera can also be used to view and record the earth scene (i.e. aerial photographs), however, only satellites give a global, systematic and repetitive vision of large parts of the earth.

For example, Landsat satellite collects and archives a vast quantity of high-quality multispectral data each day, which enables us to monitor agricultural productivity, urban growth, and land-cover change, as well as volcanoes, glacier dynamics, and coastal conditions and providing data needed for oil, gas, and mineral exploration. While NASA's other EOS instruments: Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-angle Image Spectroradiometer (MISR) acquire frequent, coarse views of land-cover change, the spectral resolution of data from the Enhanced Thematic Mapper Plus (ETM+) instrument on Landsat-7 allows researchers to determine the actual causes of observed land-cover changes (NASA, 2002).

Applications of Remote Sensing

These can be grouped into the following five broad applications:

- Exploration and updating of the inventory of natural resources (geology, hydrology, land cover, mineral and oil exploration, etc.)
- Surveillance of dangerous natural activities or phenomena: seismology, volcanology, floods, droughts, etc. (e.g. Fig 1**)**

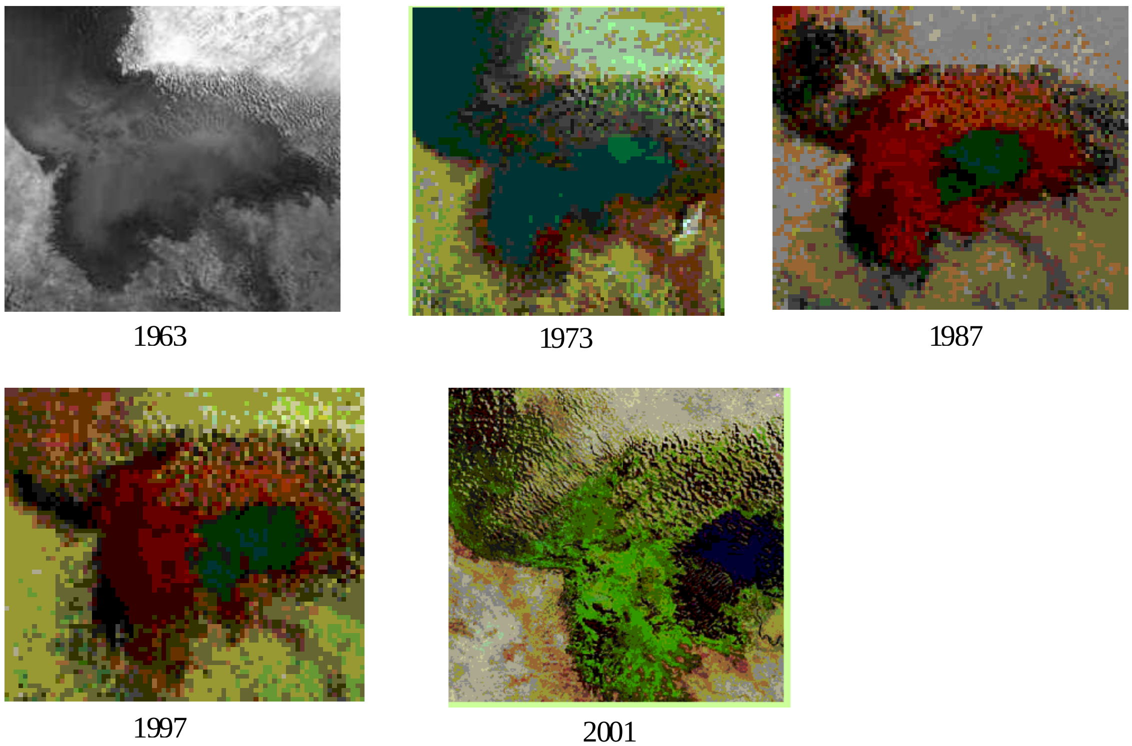

Fig. 1: Monitoring the gradual disappearance of Lake Chad (Source: Kufoniyi *et al.*,

- Detection of lineaments, faults and fractures for underwater recharge site identification (Figure 2)
- Observation and monitoring of the natural and man-influenced ecological processes (agriculture, forestry, grazing, land use, hydrography, oceanography, fuel, wood management, etc.)
- Detection and forecasting of the evolution of phenomena associated with climatology, soil erosion, pollution, desertification, etc

Fig. 2: Detection of lineaments, faults fractures for underwater recharge site identification. Some Characteristics of Satellite Sensors (Source: Kufoniyi *et al.*, 2003)

Table 1 shows the list of some sensors with their spatial resolutions while Table 2 shows the general applications of different spectral bands.

Table 1: Satellite Sensors and their Spatial Resolution (Source: Kufoniyi et al., 2003)

Sensor	Ground Resolution (m)
Landsat MSS (185 by 185 km)	80
Landsat TM (185 by 185 km)	30
SPOT XS (60 by 60 km) SPOT PAN (60 by 60 km)	20 10
SPOT 5 PAN	2.5
SPOT 5 XS	20
ERS SAR (100 by 100 km)	30
Japanese JERS-1 (SAR & OPS) (75 by 75 km)	18 by 24
European MOMS-02 X S	13.5
European MOMS-02 PAN (HR)	4.5
Indian IRS 1B LISS-1	36
Indian IRS 1B LISS-2	72
Indian IRS 1C LISS PAN (70 by 70 km)	10
Russian KFA-1000 (80km by 80 km)	5-10
Russian TK-350 (190km by 280 km)	7-10
Russian MK-4 (160 by 160 km)	10
Russian KFA-3000 (27 by 27 km)	2-3
Russian KVR 1000	1-2
NigeriaSat 1 (600 by 600 km)	32m

Table 2: Satellite Spectral Bands and Applications (Carlo, 1988)			
Channel (Basic)	Nominal Central wavelength (µm)	Nominal Spectral Band (µm)	Applications
VIS	0.6 0.635	0.56 - 0.71	Good for cloud detection, cloud tracking scene identification, aerosol observation vegetation monitoring.
VIS	0.8 0.81	0.74 - 0.88	For cloud detection, cloud tracking scene identification, aerosol observation, vegetation monitoring.
IR	1.6 1.64	1.50 - 1.78	Discriminates between snow and cloud, ice and water clouds and gives aerosol information.
IR	3.9 3.92	3.48 - 4.36	Good for low cloud, fire and fog detection; measurement of land and sea surface temperature at night.
IR	8.7 8.70	8.30 - 9.10	Aid in quantitative information of thin cirrus clouds and discrimination between ice and water clouds.
IR	10.8 10.8	9.80-11.80	For measuring of earth surface and cloud top temperatures. Aid in detection of cirrus and inference of total precipitable water vapour over sea.
IR	12.0 12.0	11.0-13.00	For measuring of earth surface and cloud top temperatures. Aid in detection of cirrus and inference of total precipitable water vapour over sea.
For Air mass			
UV	6.2 6.25	5.35 - 7.15	For observing water vapour and winds as being applied in the current MTP.
UV	7.3 7.35	6.85 - 7.85	For observing water vapour and winds as being applied in the current MTP.
IR	9.66 9.7	9.38 - 9.94	For tracking of ozone.
IR	13.4 13.40	12.40 -4.40	CO_2 absorption channel. To give vertical temperature profiles.
HRV	0.75	0.5 - 0.9	Limited data

GIS and Water Resources Management

As discussed earlier, there is a rising concern over the degradation of the environment, and subsequently, this has resulted in increased research on the identification of mitigating factors and study of environmental problems. Unfortunately, much of this work has been speculative and theoretical and, at least until recently, not well supported by adequate GIS databases. This can be attributed to lack of adequate knowledge of the potential of GIS technology as a tool for environmental application; hence, its usefulness has not been fully realised until 1990s. However, this situation is changing: in parallel to a rapid rise in the quantity of data collected through the processes discussed in section 2, massive changes in technical capability has facilitated the development of GIS to handle the diversity of information involved (Mounsey, 1991).

Water resources management requires multi-spatial, multi-temporal and multidisciplinary data, thus, the development of a functional GIS that will be relevant to these applications will certainly require a well-structured geospatial database. Various environmental data from diverse sources and resolution, designed for different purposes and in a variety of formats, can be easily integrated in a GIS to derive environmental information for water resources management. For large databases such as those needed in water resources management, remote sensing will be the sole data acquisition subsystem. In this case, the GIS software should preferably be raster-based, which usually have modules that perform the various processes indicated in figure 3. The initial inputs into the system are the relevant satellite images on CCT and ground control points (GCP) for geo-referencing.

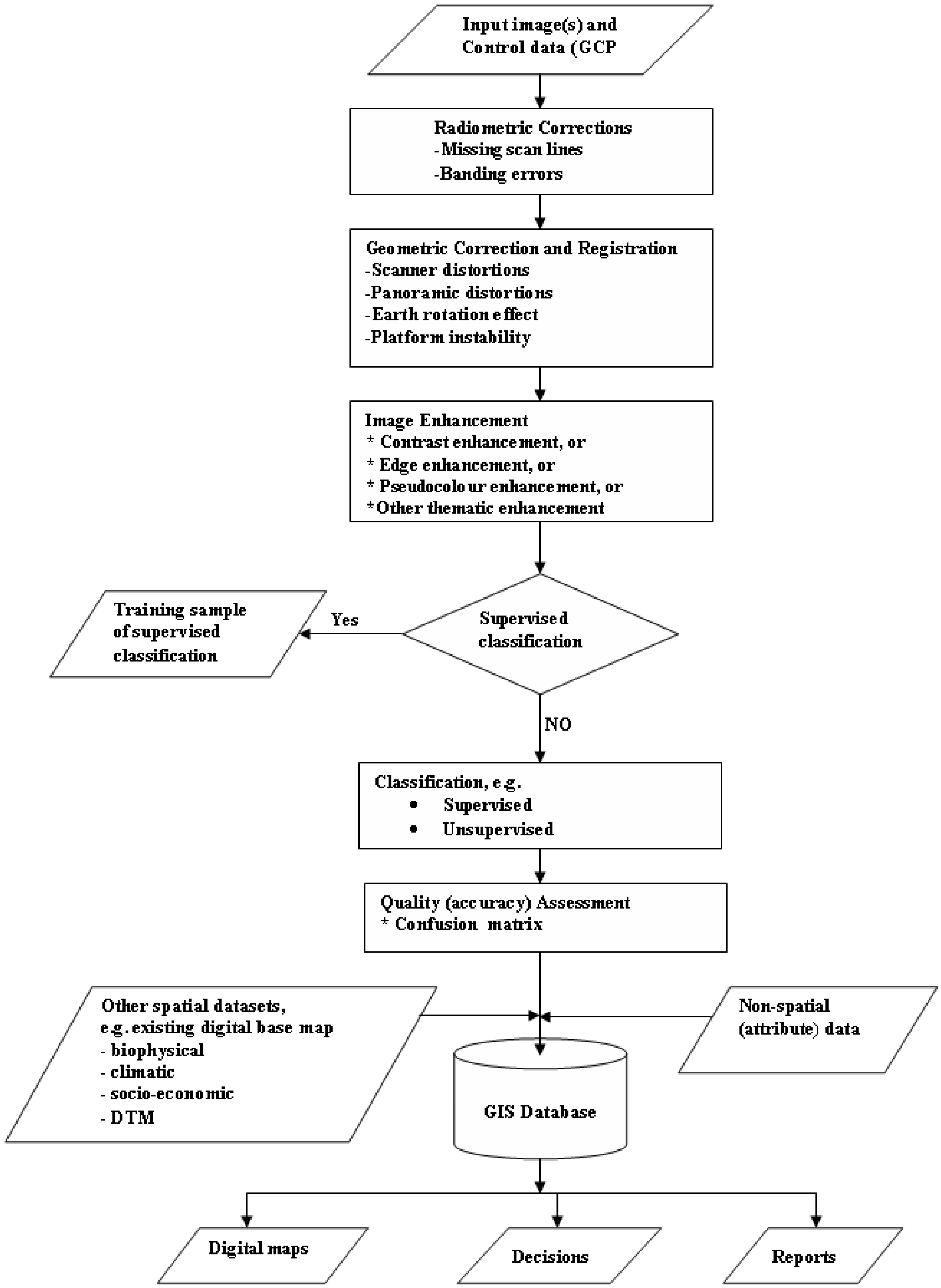

Fig. 3: Process Model in a GIS with Remote Sensing Data Acquisition (Kufoniyi, 1998)

In a geospatial community such as hydrology, users and their intended applications are very diverse. As a result, data collected and structured in an application-specific way is always difficult to re-use. A common data model that defines the structure, semantics and syntax of the database (i.e. entities and associated attributes) is an imperative tool in a geospatial community to ensure interoperability of data.

A Data Model for Water Resources Application

4.1 Hydrologic Data Model

Figure 4 depicts a hydrologic data model that can be used by a hydrologic community to abstract water resources information in a GIS.

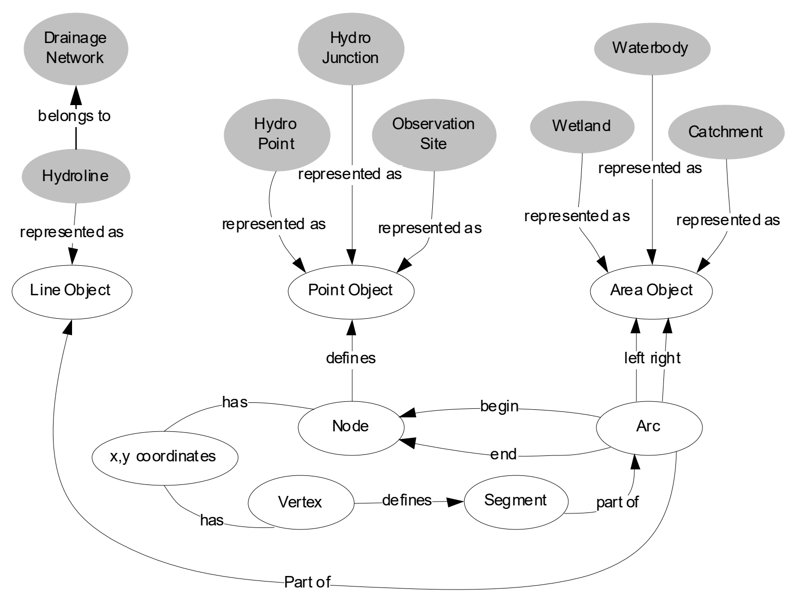

Fig. 4: Hydrologic spatial data model (Aboyeji, 2006)

The conceptual hydrologic data model recognises three types of terrain objects – point, line and area objects. These, the hydrologic features which are instances of the object types, together with the geometric primitives (arc, node, vertex and line segment), which determine the geometry of the objects, are depicted in ellipses in the model diagram (Figure 3). The instances are linked to the terrain objects by an arrow, indicating a many-to-one relationship in the direction of the arrow. The geometry of the object types are described by their linear characteristics using two topologic primitives – node and arc. A node is a point location defined by x, y coordinate pair on a planar map. A line segment is formed by a non-looping link between two vertices. Chains of two or more vertices (polylines) form an arc. An area object is formed in the enclosure formed by closed polylines (polygon).

In the model, a node may represent a point object as well as part of the geometry of line and area objects. However not all nodes play these roles. Some nodes define only point objects, while others only define the geometry of line and area objects. For line and area objects, the nodes and vertices contain the location information while the shape information can be derived from the arcs and line segments of the object. The segments are linked to the line/area objects through the arcs (one or more line segments form an arc). Two arcs may intersect at a node such as water line confluence node (HydroJunction). An arc can play a dual role of forming part of a line objects or boundary between two area objects, or both. The geometry of an area object is given by the polygon formed by the chains of arcs around it. Partitions of area objects are separated by directed arcs, which have one area object at the right side and another area object at the left hand side. See Aboyeji (2006) for full details on the conceptual hydrologic data model.

The entity-relationship (E-R) diagram for the model is presented in Figure 5. Entity names are in the top of the box with their attribute information below them. Relationships are shown by pointed arrows (indicating a many-to-one link type in the direction of the arrow) and non-pointed arrows (representing a one-to-one relationship between the entities). Figure 6 illustrates the entities depicted in the Entity – Relationship diagram.

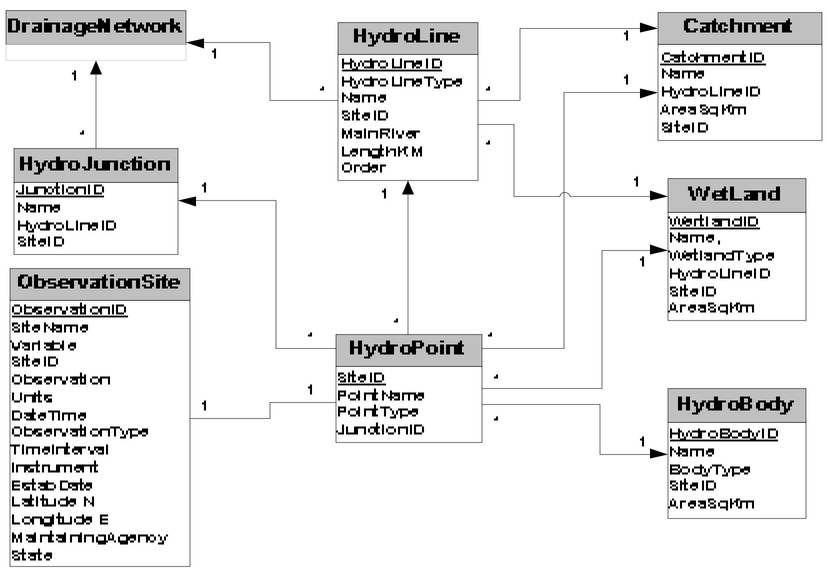

Fig. 5: Entity-Relationships diagram for hydrologic data (Aboyeji, 2006)

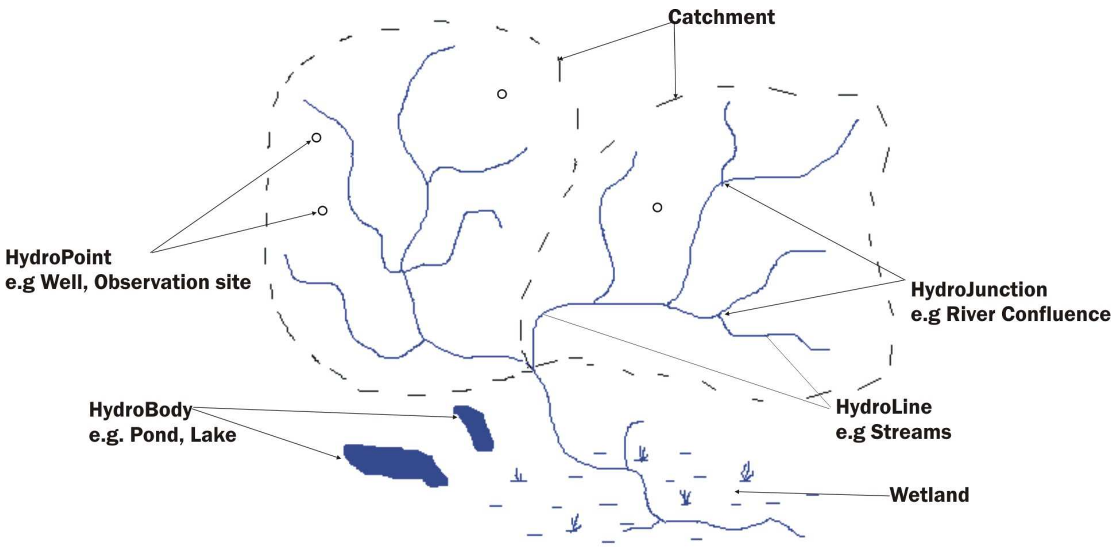

Fig. 6: Typical hydrologic spatial objects

The Logical Data Model

In geospatial database design and implementation, after the terrain situation have been conceptualised and modelled, the next step is a translation of the data model into a logical data model. A logical data model is the database structure that can be used to represent the data in an information system. Examples include network data structure, hierarchic data structure, relational data structure, object-relational data structure, object-oriented data structure, etc (Date, 1990; Burrough, 1986; Kufoniyi, 1995). For this work, the relational data structure was used to implement the hydrologic data model presented in sub-section 4.1.

In a relational data structure, the data are organised in the form of relations (tables). Each table consists of tuples (rows or records) and attributes (column or field). The rows contain values related to a particular entity. The intersection of each row and column in the table contains an attribute value relating to a particular record. For further details on relational database modelling and the normalisation approach, see Date (1990). In this paper, normalisation was restricted to the first normal form (1NF).

The conceptual data model and the Entity – Relationship were translated into the hydrologic relational data structure indicated in figure 7. To give an example of the implementation of the structure in this paper, seven tables were created (table was not created for the 'DrainageNetwork' in the diagram as its attributes are derivable from the aggregation of tables 'HydroLine' and 'HydroJunction'; also attributes of the entities 'HydroDataTypes', 'Hydrodata' and 'HydroSite' were combined in the table 'Observationsite').

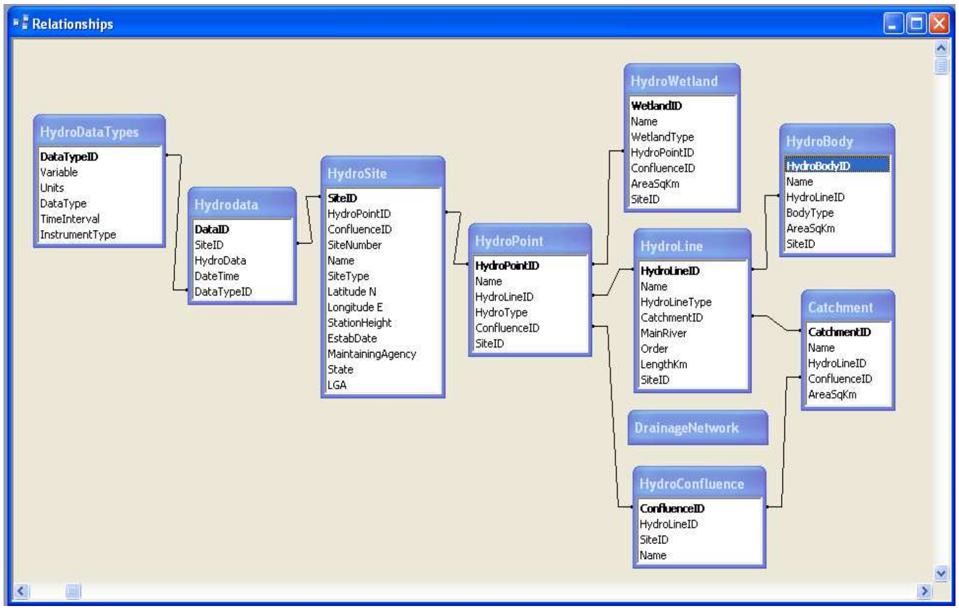

Figure 7: Hydrologic Relational Data Structure (Aboyeji, 2006)

OBSERVATIONSITE *(ObservationID, SiteName, Variable, SiteID, Observation, Units, DateTime, ObservationType, TimeInterval, Instrument, EstabDate, LatitudeN, Longitude E, MaintainingAgency, State)*
HYDROJUNCTION *(JunctionID, Name, HydroLineID, SiteID)*
HYDROLINE *(HydrolineID, HydroLineType, Name, SiteId, MainRiver, LengthKm, Order)*
HYDROPOINT *(SiteID, Pointname, PointType, JunctionID)*
CATCHMENT *(CatchmentID, Name, HydroLineID, AreaSqKm, SiteID).*
WETLAND*(WetlandID, Name, WetlandType, HydrolineID, AreaSqKm)*
HYDROBODY *(HydroBodyID, Name, BodyType, SiteID, AreaSqKm)*

In the structure, table names are in bold upper case with the table's attributes within parentheses and the primary keys underlined.

Implementation of Hydrologic Spatial Data Model

It is impossible to implement the hydrologic data model in Figure 4 in most of the existing proprietary GIS software. This is because the model conceptualises the spatial objects (point, line and area objects) as occurring in an integrated manner as it is in the real world (that is, point, line and area features are captured and presented in a single integrated spatial layer in the computer system). In the existing software on the other hand, terrain objects are captured in separate point, line and area layers. Moreover, objects belonging to the same geometric types are often further segregated into different layers. These are then overlaid to have them viewed and analysed as occurring in space. This is the approach adopted for this work, using ArcView 3.2a – a GIS software with layered data structure.

System configuration (Hardware and Software)

To implement the hydrologic data model, a computer system and relevant software were used for data acquisition, data management and information presentation in an integrated manner. The computer system consisted of Pentium IV processor with 256MB RAM, 40 gigabyte HDD, full multimedia and other peripheral devices. The software component consisted of Microsoft's Windows XP Operating System, Microsoft Office 2003, ArcView 3.2a (vector GIS – for data analysis) and ILWIS 3.0 (raster GIS – for image processing).

Input data

The input data for the work consisted of an analogue hydrological base map of Yobe Drainage Basin and hydrological observation data such as runoff, rainfall and evapotranspiration data. These are analogue historical data collected at hydrologic observation sites within and around the basin.

Database creation

Using River Yobe drainage basin in northern Nigeria as a case study, a sample spatial database of the basin was created. The terrain objects were digitized into distinct point, line and area layers. The point layers consist of HydroPoint, HydroJunction and ObservationSite; while the line layer consists of HydroLine. The area layers consist of Wetland, Waterbody and Catchment. (The aggregation of HydroPoint, HydroJunction and HydroLine form DrainageNetworks). Each of the spatial features was given unique identification numbers (ID) in the geo-table generated by the system.

Results of sample queries applied to the Yobe Basin hydrologic database

The whole essence of building a database such as the hydrologic database is to put in place in an enterprise, a central pool of data that can be accessed and shared by multiple users. Each user extracts specific portion of the stored data for specific application. In other words, a specific data can be extracted concurrently by different users for different uses. To extract information from the database, the Structured Query Language (SQL), a comprehensive database language is commonly employed. The SQL queries posed by the users are executed by the Relational Database Management System (RDBMS) software such as Microsoft Access, Oracle, Ingres, etc. Microsoft Access was used for this work. For the Yobe Basin hydrologic database, the following queries were posed to extract specific information from the database:

Query 1: This query was posed to select observation data from a particular hydrologic observation site (Yau) for a year. The SQL command syntax (Microsoft Access version) is

Select *(DateTime, Observations, Variable, Unit, SiteName, MaintainingAgency)*
From *ObservationSite*
Where *'ObservationSite`Year ([DateTime])=1963 AND 'ObservationSite'([SiteName]) ='Yau'*

For the system to realise this query, it selects the required data from columns: DateTime, Observations, Variable, Unit, SiteName and MaintainingAgency, from table ObservationSite. The information selected fulfils the conditions specified in the 'where' portion of the syntax.

That is, the system selects the data that has date/time = '1963' in table 'ObservationSite' under column 'DateTime', and which variable type (in column 'Variable') of the table is 'Stage Height' ; and site name (in column 'SiteName') of table 'ObservationSite' is 'Yau'. See figure 8 for the result.

Query 2: This is a spatial query made in the ArcView 3.2a graphic user interface (GUI) to select all hydrologic observation sites that fall within Kano State. Result is shown in Figure 9.

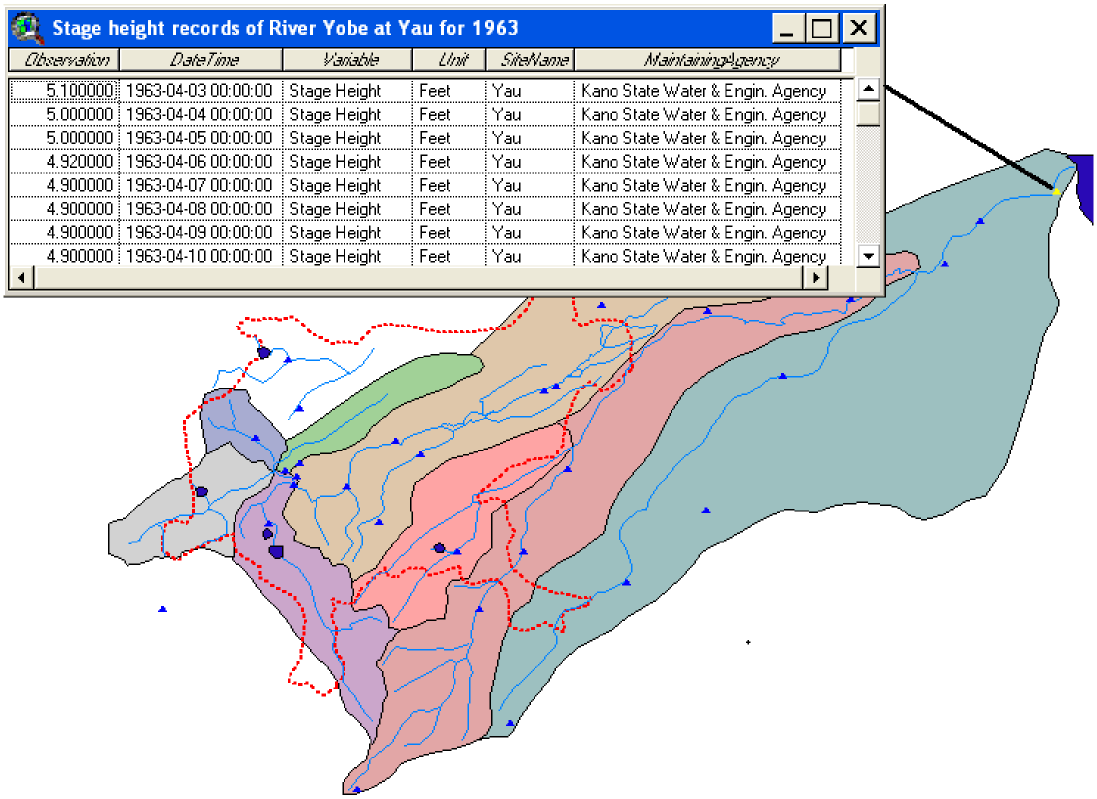

Fig. 8: Stage height records of River Yobe at Yau for 1963

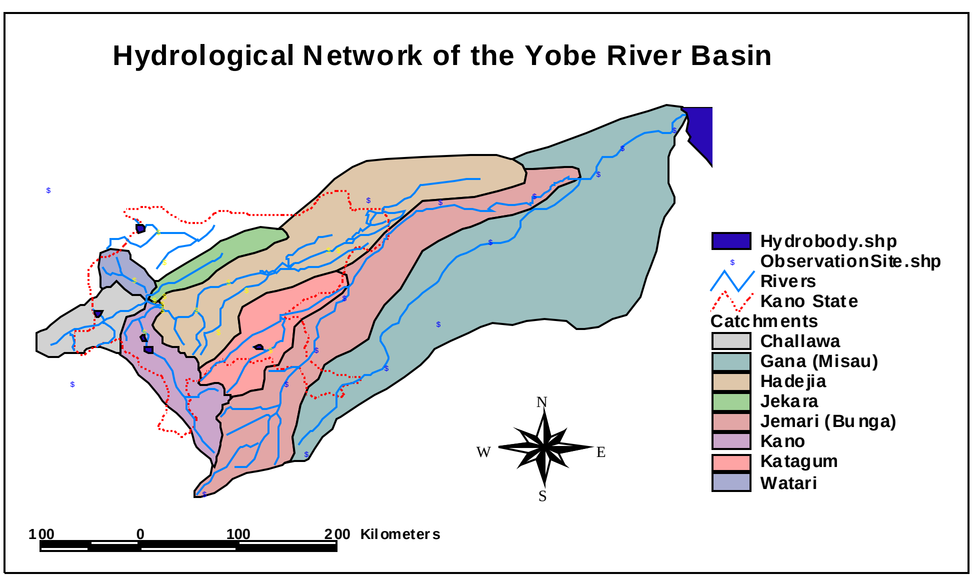

Fig. 9: Result of query showing hydrologic observation stations in Kano State

Contribution to Knowledge

Advances in science and technology in recent times have resulted in a significant increase in the volume of and quantity of water resources data. The task before policy makers and researchers now is how to employ the data to alleviate water related crises that face man and his environment. GIS technology offers a spatial framework to support decisions for the intelligent use of earth's resources and to manage the man-made environment. The development of a functional GIS to integrate and analyse disparate datasets require a well-structured geospatial database. While generic data models are available in GIS literature, a dedicated vector-structured generic data model with its accompanying database structure has been lacking. The hydrologic data structure presented in this paper provides a generic tool that any hydrologic community can use to capture and store water resources datasets in a GIS database.

Conclusions

Remote sensing provides a rapid inventory of natural resources on the earth's surface, which can then be extracted, processed, stored, analysed, retrieved and presented in various forms with the aid of GIS technology. When properly implemented, therefore, remote sensing and GIS technologies can facilitate a rapid sustainable development of the country and an efficient management of the natural resources and environment at the national and regional level.

The design and implementation of a generic vector-based data structure were presented in this paper with examples of information that can be derived from the database. While the designed hydrologic data model supports the integration of objects of different geometric structure in a single layer, it however does not support spatial coincidence, a situation in which objects of the same geometric type can occur on a single map layer. Also, the model can only be used to capture 2.5D vector data (i.e. spatial objects represented by 3D position and 2D topology). Further work is therefore needed to design a full 3D hydrologic data model that can also combine both vector and raster data structures since some hydrologic data can be captured in raster format. This can best be achieved using object oriented data modelling.

The need for a user-requirements study before the implementation of any GIS project was emphasised. In the same vain, rigorous and consistent training and retraining of staff is necessary for capacity building and to keep abreast with technological developments. And having trained the staff in the modern technology, they must be adequately motivated for maximum performance.

With the successful revolutions of Remote Sensing, GPS and GIS technologies in the mapping sciences, coupled with the expected availability of sub-metre (spatial) resolution satellite images in the next few years, the sustainable development of countries with economic and political stability is assured.

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