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The Development of an Automated Watershed Management

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An automated watershed management system (AWMS) for Trinidad and Tobago was developed and tested in the Maracas and Santa Cruz watersheds. AWMS is developed using IDRISI™ GIS and image processing software. It embraces the use of the soils and land use/land cover data, since the problems in the watershed are land use related. This paper presents stages in the development of AWMS, its applications in examining the current and potential erosion in the Maracas and Santa Cruz watersheds and the assessment of the contribution of human-induced factors to erosion. Sensitivity analyses carried out on two human-induced factors showed that human settlements were more sensitive than agricultural activities and they accounted for 33% and 10% of the erosion of watershed respectively.

1. Introduction

Watershed management is the planning, implementation and operation of programmes, projects and practices relating to natural resources. It includes the physical, biological, social, economic and institutional aspects of a designated watershed (Fogle and Ffolliott, 1985). Watershed management is necessitated by the potential of the negative impact due to inappropriate human activities necessitated sometimes by conflicting demand for land. Inappropriate human activities in watersheds could lead in macro terms to deforestation, severe erosion, soil degradation, and flooding at low elevations and in micro terms to siltation of river courses and reservoirs, reduction in stream flow, blocking of drains, increase in runoff, poor water quality, and changes in land productivity.

There are two approaches by which watershed management can be implemented. These are, the process approach and the ecosystems approach. The process approach identifies individual system under degradation in the watershed and develops strategies to counteract intolerable effects at specific sites. On the other hand, the ecosystems approach recognises the intricate relationships of the living and non-living portions of the watershed. The use of the ecosystem approach demands knowledge of the entities, their positive and negative impacts on the watersheds and the interaction among the entities. The ecosystem approach is used as the design concept behind the development of an Automated Watershed Management System (AWMS). The approach demands that complex and disparate data be collected and updated on a regular basis in order to monitor and manage the watershed. Complexities in the data range from the mix of manual and digital data as well as multi-scale data. The handling of this data in a manual environment presents enormous challenges hence the non-popularity of the ecosystem approach.

The use of manual data analysis hinders efficient watershed management. Geophysical and socio-economic data are collected and stored in a fragmented manner by different state agencies. This has resulted in the collection of a vast amount of data that cannot be readily integrated for any useful analysis. Manual methods of analysing data, suffer from severe inefficiency due to tedious and time-consuming processes. An automated approach with a distributed database is one method increasing the efficiency of watershed management. The development of a Geographic Information System (GIS) for watershed management system provides an efficient method of storing, manipulating, analysing and presenting geophysical and socio-economic data that is needed for the development of watershed management programmes. The potential benefits to be derived from such a system are:

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- Ease and flexibility of integrating different data types for a more comprehensive analysis.
- Improvement in the quality of decision-making by providing a wider range of information with which to better manage land use conflicts.
- Integration of data inventory with analytical tools.
- Integration of data sets which in turn leads to data consistency and greater reliability.
- Fostering of interdisciplinary approach to watershed management.

The following sections of the paper describe the stages in the development of the AWMS and its application in the Maracas and Santa Cruz watersheds.

Geographic Information Systems were initially developed as tools for the storage, retrieval and display of geographic information, however these have since been moving towards integration with spatial analyses tools. Most of the literature reviewed however, highlights the success of integrating early simulation models with GIS, the merits to be derived, obstacles to be overcome and use of object-oriented technology.

Lee (1985) suggested the use of a GIS for efficiently compiling input data for complex distributed hydrological models. It was recommended that the development of GIS be independent of a specific model so that the data can be retrieved to meet the requirements of different geometric configurations of watershed models. A further advantage cited was that the sensitivity of various delineation and hydrologic processes in a watershed can be evaluated.

Nyegres (1993) supported the concept of integrating GIS and spatial process modelling. In so doing, he saw the combination of the principal benefit of modelling (the ability to deal with large volumes of spatially-oriented data the geographically anchor processes across space) with the principal benefit of GIS (the in-depth injection involving temporal and attribute issues to make the model more realistic). Areas of concern he noted relate to the model structuring functions, i.e., the design trade-off for integrating and/or linking spatial process models into a GIS external spatial and statistical software using a software bridge and the use of an object-oriented hierarchy of spatial knowledge about hazard conditions.

Brimicombe and Bartlett (1996), while acknowledging that the strengths of GIS lies in the ability to synthesise complex data, argued that their analytical capabilities must be extended to include in dynamic modelling of spatial phenomena such as "what if" types queries. They suggest the inclusion of deterministic of stochastic type simulation to provide multiple, optional outcomes as a sound basis for decision-making. From a civil engineering perspective, the authors saw the capability for mathematical and statistical modelling that GIS provide by the use of macro languages or internal functionality as inadequate. More sophisticated tools they claim, are often required and hence the reason that proven and benchmark proprietary software used by this group despite their graphic limitations when compared with GIS.

Depinto et al (1996) undertook the development of a loosely coupled modelling support system to integrate GIS with watershed analysis models. They demonstrated the feasibility and utility of GIS as a tool for developing and applying surface water quality model on a site specific basis in the Buffalo Watershed. The resulting prototype, Geographically-based Watershed Analysis and Modelling System (GEO-WAMS) highlighted the significant utility of GIS data for modelling the environement behaviour or watershed. In the system, ARC/INFO™ was the GIS chosen.

2. General Characteristics of the Project Sites

In the Northern Range of Trinidad, Gumbs and Lindsay (1982) noted that 55 tons of soils per acre have been lost from bare soil over a three-month period in the rainy season. The Maracas and Santa Cruz watersheds were selected as the project sites for the development of AWMS. These watersheds form part of the northern range of Trinidad and are located in the high rainfall belt of the island. The sites lie between latitude 10°.6144N and longitude 61°.4978W; and latitude 10°.7519N and longitude 61°.4208W. The sites receive an average annual rainfall of 1,800 mm and an average annual runoff of 350mm. **Figure 1** shows the project site in relation to the other watersheds in the northwestern area of the northern range.

These watersheds cover an expanse of approximately 12,500 hectares of land. Its highest peaks are Mount El Tucuche (932 metres above msl) in the Maracas watershed and the St. Ann's Peak (560 metres above msl), in the Santa Cruz watershed. A network of roads, water pipelines, electricity, and telecommunication services traverses the sites. Other urban infrastructure includes schools, health services, commercial and residential centres.

The landuse of the watersheds consist of residential developments, farmsteads, forestry and quarries. The valleys and flat lands on the lower slopes are used mainly for the production of cocoa, coffee, fruit crops and horticultural

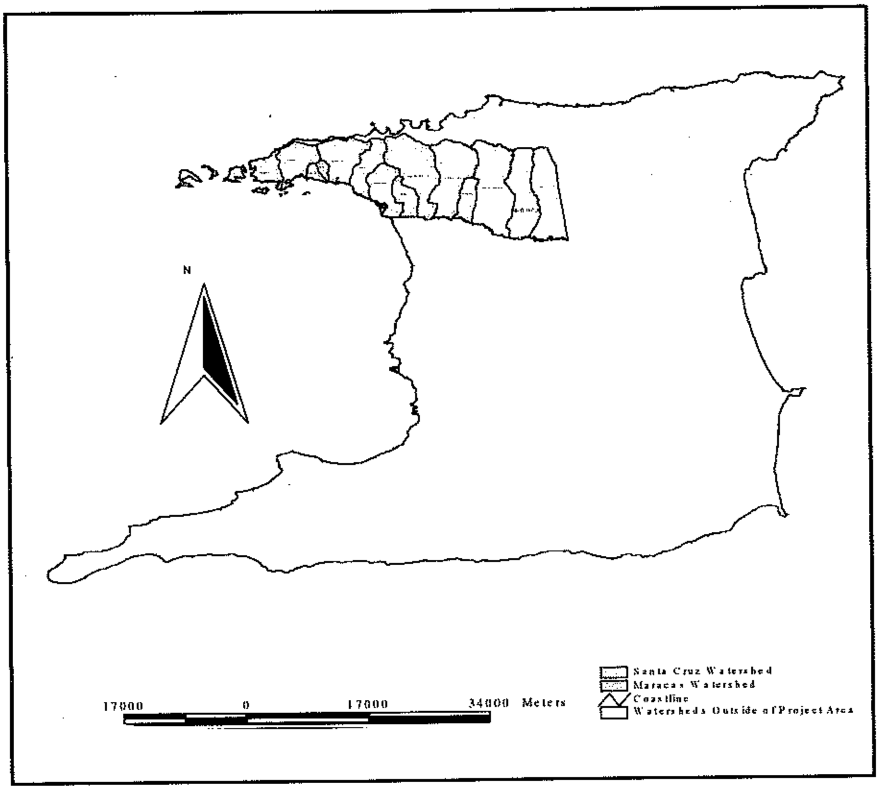

FIGURE 1: *Location Map of the Maracas/Santa Cruz Watersheds of Trinidad*

crops. On the sloping lands, small farmers grow cash crops such as sweet pepper, pimento, watermelon, cabbage and pigeon peas under shifting cultivation. The practices of shifting cultivation and squatter settlements are most prominent on State lands with steep slopes. Residential and commercial activities are concentrated in the southern portion of the watersheds. Degradation in the Santa Cruz and the Maracas watersheds is caused mainly by agricultural and residential squatting, unsound residential and quarrying practices, uncontrolled forest and bush fires; effluent and garbage dumping in river courses (Gumbs, 1996). The watersheds are characterised by steep slopes and v-shaped valleys with relatively flat lands closer to the rivers. Although 16 soil series have been identified in the area, the Maracas and River Estate soil series dominate with over 70% coverage. The Maracas soil series is classified under the USDA soil classification system as Orthoric Tropudults while the River Estate series as Fluventic Eutropepts. The ultisols are the older soils occurring on the steeper slopes whereas the inceptisols are young soils located on the lower slopes of the valley. **Figure 2** shows the soils of Maracas and Santa Cruz watersheds.

3. The Development of AWMS

The AWMS was designed and developed to perform the following aims and functions:

- To develop a spatial database that is capable of exploiting GIS analytical tools.
- To determine the current erosion status of the watersheds.
- To determine the inherent susceptibility of the watersheds to erosion occurrences.
- To determine the extent of erosion caused by human-induced factors.
- To conduct sensitivity analyses on factors that cause watershed degradation.

AWMS is a low cost GIS application developed using the IDRISI™ GIS and image processing software. It provides geophysical data that can be used to aid the

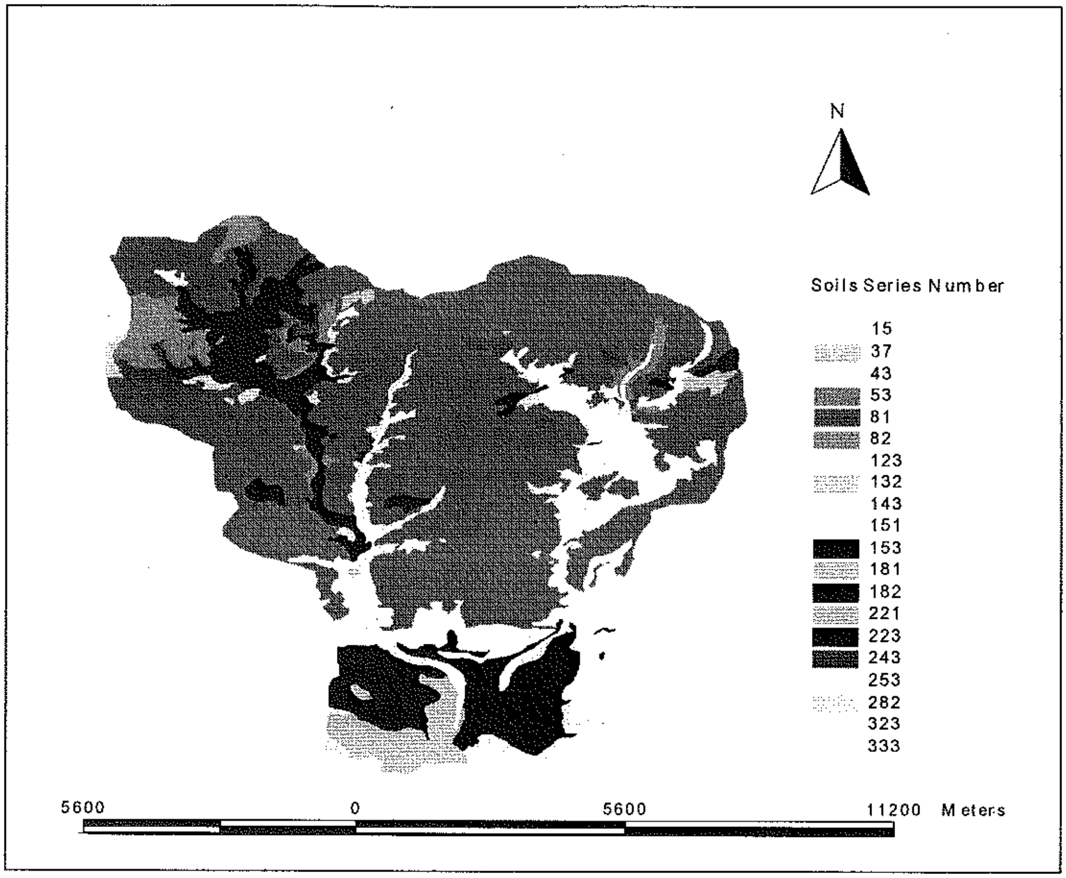

FIGURE 2: *The Soils of the Maracas/Santa Cruz Watersheds*

management of the watersheds. Although several factors contribute to the degradation of the watersheds, the main data sets used by AWMS at this time are soils and land use/ land cover. This watershed management framework is similar to that proposed by Vohra (1985). The majority of the problems in the northern range of Trinidad are landuse-related problems and the surface water problems are spin-offs from them. Therefore, if the landuse-related problems are given priority attention, then there would be a significant reduction of the surface water problems. Each mapping unit of soil database contains a wide variety of data relating to land and land use that makes it convenient for the AWMS database to analyse. These include soil erosion, soil erodibility, soil slope, soil texture and soil series classification. The land use and land cover data capture both human activities and naturally occurring vegetation.

There are four stages involved in the development of AWMS. These are:-

- Data automation,
- Preparation of raster images and documentation files,
- Development of applications, and Sensitivity analyses.

The database development procedure IDRISI™ is shown in **Figure 3**.

3.1 *Data Automation*

This stage is concerned with the conversion of existing spatial databases in native ESRI ArcINFO™ format into Digital Line Graph (DLG) file format. The DLG files are imported into IDRISI vector file format, the associated ARC/ INFO attribute database (dBase Format) is imported into IDRISI database format (Microsoft ACCESS). Incompatible real number field formats are modified by exporting the database to Microsoft ACCESS™ and changing the format to integer.

3.2 *Preparation of Raster Images and Documentation Files*

This involves the development of the IDRISI raster database, deriving the soils and land use layers required for analysis and updating the documentation files by the addition of the legend categories.

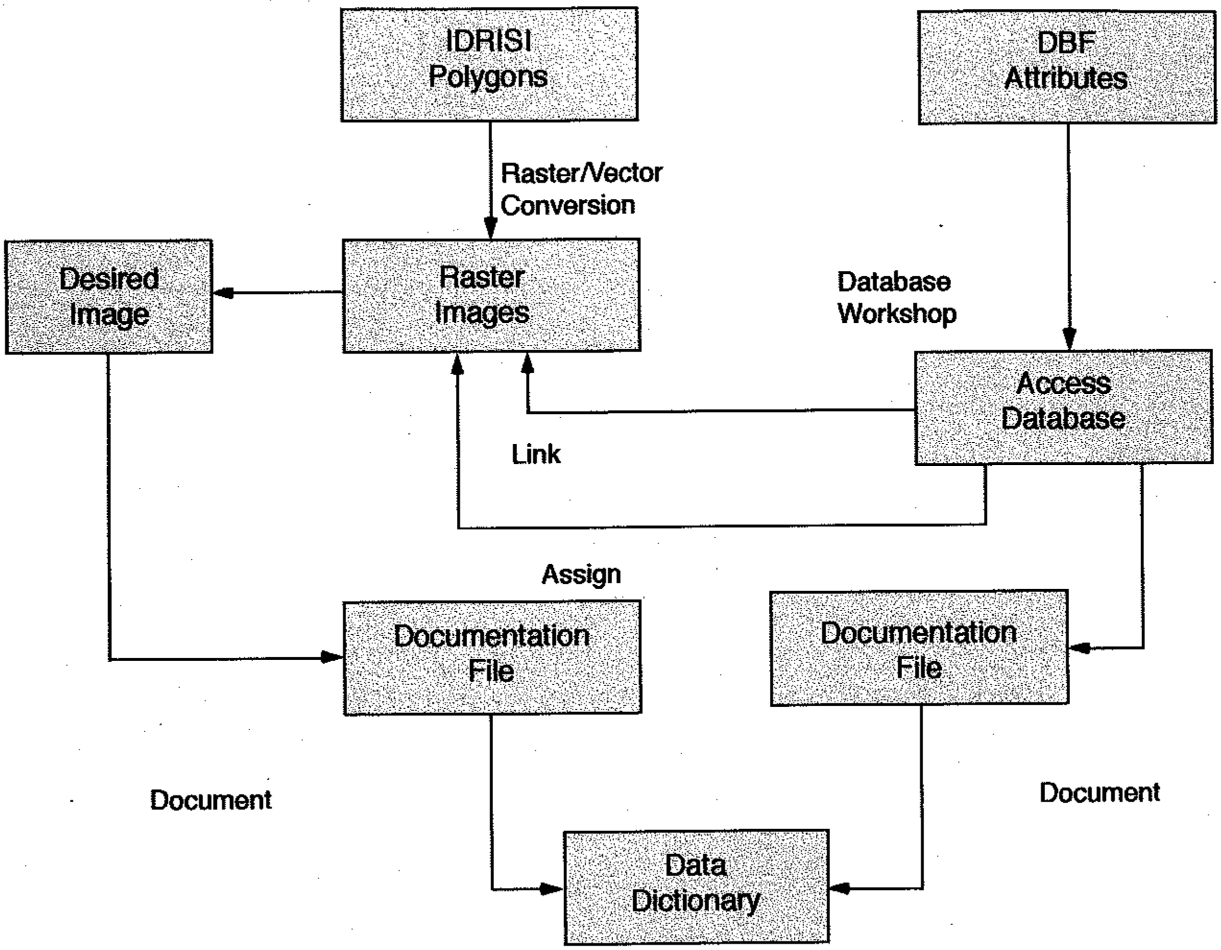

FIGURE 3: *Database Development Procedure IDRISI™*

3.3 *Development of Applications*

This involves the development of related GIS applications as well as cartographic and tabular presentation of the results of the application.

3.4 *Sensitivity Analysis*

This final stage involves the conduct of sensitivity analyses on the human-induced factors impacting on the watershed so as to determine the impacts of the factors in the whole ecosystem.

4. Applications of AWMS

AWMS was used to develop three watershed management applications. These are:

- Mapping the current status of erosion and susceptibility to erosion.
- Mapping incident of erosion attributed by human-induced factors.
- Estimating the impact of human-induced erosion.

4.1 *Mapping the Current Status of Erosion and the Susceptibility to Erosion*

Based on crop performance on eroded soils, the Soil Survey Reports of the soils of Trinidad and Tobago have adopted the following Erosion Status Classification as shown in **Table 1** (Brown & Bally, 1966). If no erosion has occurred and all of the topsoil is in place, crop performance will be maximum, the erosion class will be "no erosion" and the erosion code will be "0". At the other extreme, because the topsoil of many West Indian soils is thin, a loss of 50% of the topsoil severely affects crop growth. In this case, the erosion class is "severe erosion" and the erosion code is "3". In between these two classes, two other classes are recognised. If up to 25% of the topsoil is lost, the erosion class is "slight erosion" and the erosion code is "1". If

TABLE 1: *Erosion and Slope Classification Schemes*

Erosion Class	Erosion Code	Slope Degree	Slope Class
No erosion	0	0 - 2 deg	A
Slight erosion	1	2 - 5 deg	B
Moderate erosion	2	5 - 10 deg	C
Severe erosion	3	10 - 20 deg	D
Very severe erosion	4	20 - 30 deg	E
Extremely severe erosion	5	< 30 deg	F

between 25% and 50% of the topsoil is lost, the erosion class is "moderate erosion" and the erosion code is "2". Where between 50% - 75% of the topsoil is lost, the erosion class is "very severe erosion" and the erosion code is "4". Where over 75% of the topsoil is lost, the erosion class is "extreme severe erosion" and the erosion code is "5". The classification is broad-based because of the heterogeneous nature of soils and variations in crop performance.

Inherent susceptibility of soils to erosion is largely determined by slope percentage. Other physical soil factors like aggregation, cementation and permeability also affect inherent susceptibility to erosion but their influence can be variable and not as dominant as soil slope percentage.

The Soil Survey Reports of Trinidad & Tobago recognise six slope categories which influence the susceptibility of the soil to erosion, i.e., the erosion class. These are shown in **Table 1**.

This application is developed to map the current status of erosion in the watersheds and the inherent susceptibility of the watersheds to erosion, using routine GIS procedures of reclassifying and overlaying of map themes. The soils spatial and attribute databases were interactively linked so as to allow the values contained in the erosion and erodibility fields to be assigned to the soils theme, thereby creating two new themes (soil erosion and soil erodibility). Spatial analysis is then performed to determine the land coverage of the different categories of erosion and the erodibility of the land. **Table 2** and **Figure 4** contain the result of these analyses and manipulations in respect to the erosion status.

About 30% of the land is subjected to moderate and severe erosion, while 60% have undergone slight erosion. A mere 11% has been spared from soil erosion. The analysis of the current inherent susceptibility to erosion shows that 60% of the soils are vulnerable. The results of this analysis are presented in **Table 3**. The very severe and extremely severe categories account for 47% of the erodibility.

TABLE 2: *Soil Erosion Status of the Project Area*

Erosion Class	Description	Area (Ha.)	% of Land Covered
0	No erosion	1409.76	11.35
1	Slight erosion	7517.04	60.51
2	Moderate erosion	2613.96	21.04
3	Severe erosion	881.72	7.10

TABLE 3: *Inherent Susceptibility of the Project Area to Erosion*

Erodibility Class	Description	Area (Ha.)	% of Land Coverage
0	No erosion	4758.03	38.30
1	Slight erosion	433.98	3.49
2	Moderate erosion	191.78	1.54
3	Severe erosion	1198.63	9.65
4	Very Severe erosion	3264.40	26.28
5	Extremely Severe erosion	2575.50	20.74

4.2 *Mapping of Human-induced Erosion*

Human-induced factors can be defined as social, recreational, and economic activities that lead to changes in the natural state of the topography and constituents of land. The mapping of human-induced erosion was accomplished using a similar GIS reclassification and map overlay functions on the data themes. The land use categories in the project area that are known to be associated with human activities are used to represent human-induced factors (Gumbs, 1996). These categories are shown in **Table 5**. The land use theme was reclassified into natural land cover and human-related activities. The result of overlaying the human-induced land use activities with the erosion theme is presented in **Table 4**. About 40% of the erosion in the project area is human-induced. Of this amount, less than 3% is severe erosion.

4.3 *Sensitivity Analyses on Human- induced Factors degrading the Watershed*

Two sensitivity analyses were conducted to determine the extent to which the selected categories of human-induced activities can detect variations among all the elements making up this unit of land use. The first analysis excludes

TABLE 4: *Human-induced Erosion in the Watershed Project Area*

Erosion Class	Description	Area (Ha.)	% of Land Covered
1	Slight erosion	3100.20	29.95
2	Moderate erosion	898.94	7.24
3	Severe erosion	312.38	2.51

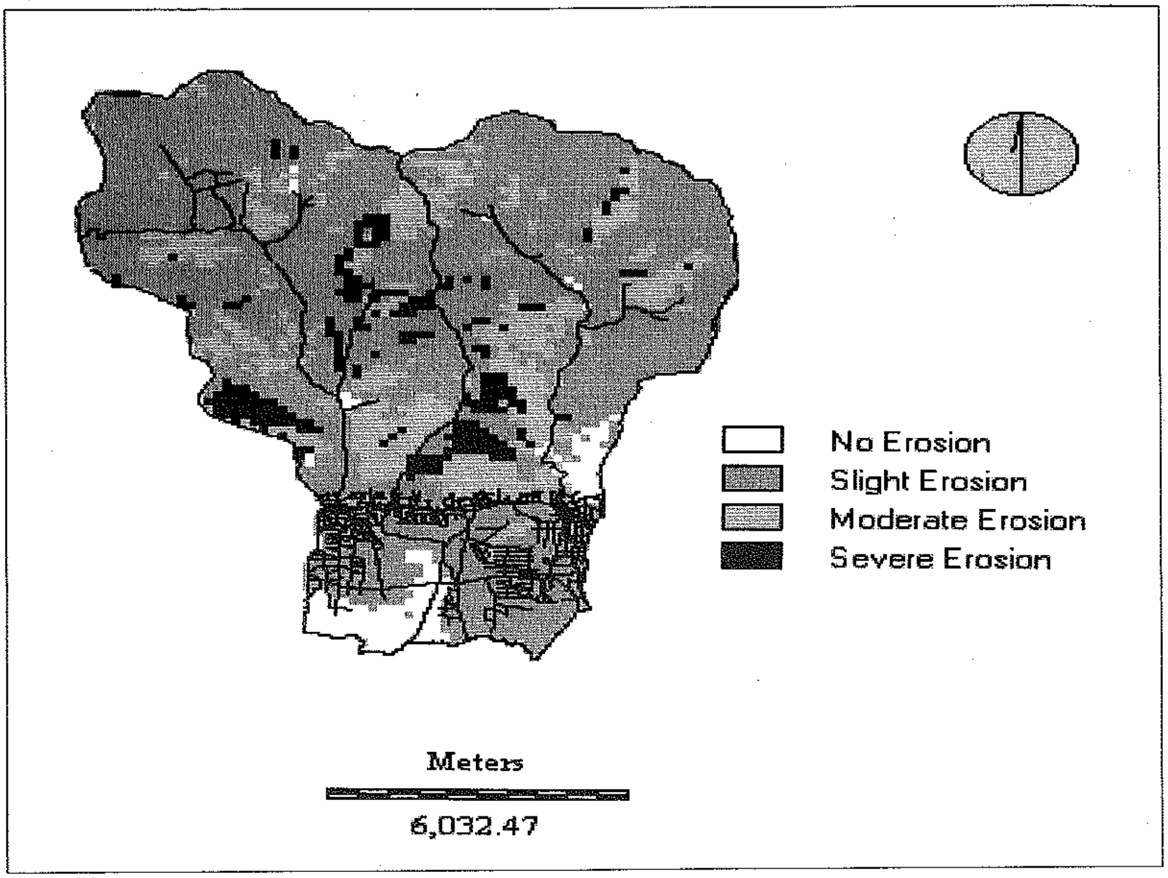

FIGURE 4(a): *Soil Erosion Status of the Project Areas*

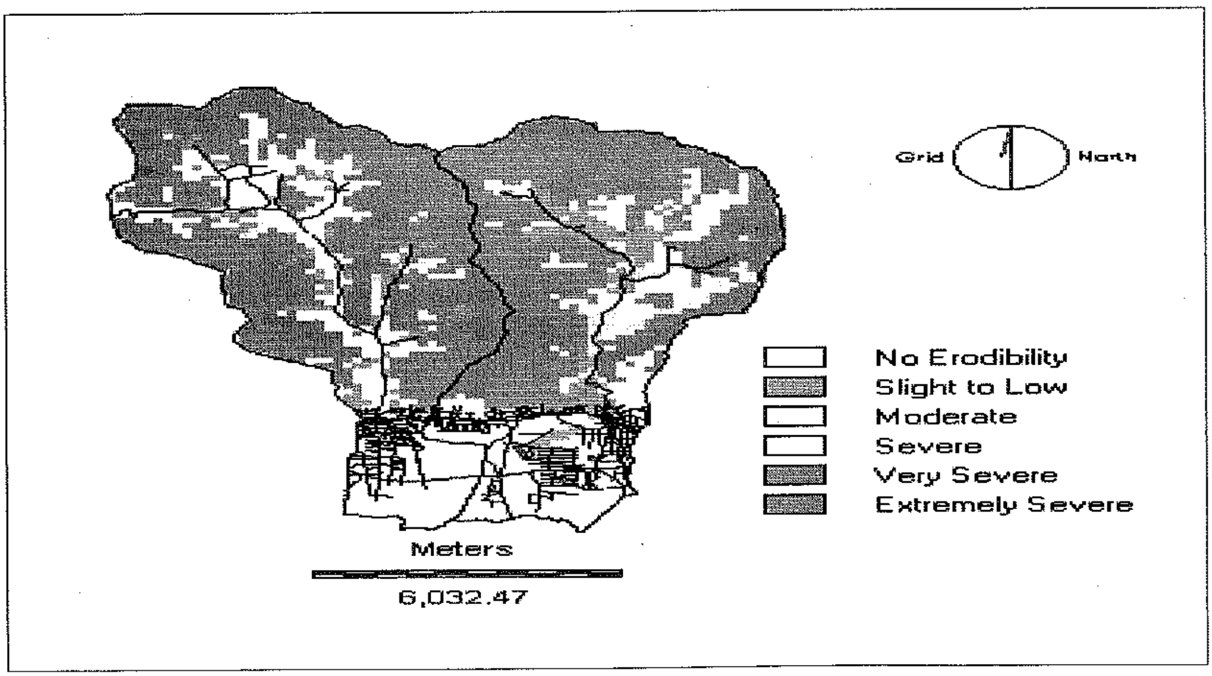

FIGURE 4(b): *Erodibility Map of the Project Areas*

TABLE 5: *Human-induced Land Use Categories used in the Spatial Analyses*

Land Use Code	Human-Induced Land Use	Natural Land Cover
100		Forested areas
200	Broken forest	
300		Scrub
400		Grassland
500	Cleared/felled areas	
600	Pine plantation	
700	Built-up areas	
800	Agricultural lands	
900		Savannah grass
1000		Bamboo forest
1100	Non-forested areas	
1200	Disorganised	
1400		Grassland & Bamboo forest
1600		Grass & shrubs
1700	Recreational parks	
1800	Airports	
1900		Stone
2000		Swamp & mangrove forest
2100	Landfill	
2200	Sewage plant	

agricultural areas from the human-induced factors, while second excludes built-up areas. The results of this sensitivity analyses are presented in **Table 6**.

When agricultural areas were excluded from the list of human-induced landuse, it was found that about 29% of the erosion is caused by human-induced activities. This represents a decline of 11% of the human-induced erosion in the watershed. On the other hand, when built-up areas were excluded, 7% of the erosion was found to have been caused by human-induced activities. This represents a decline of 33%. It can therefore be concluded that built-up areas have higher impacts than agricultural areas in the watersheds. Built-up areas account for about 33% of the human-induced erosion, whereas agricultural activities account for only 11%.

Although sensitivity analyses were conducted for only two categories of human-induced activities, these were done to demonstrate the utility of AWMS in assessing the contribution of each land use category to erosion, either individually or in combination. The ability to interactively link the spatial and attribute data has made it possible to view the geographic location of the various erosion categories. The visual display of the spatial data shows that most of the areas experiencing erosion is easily accessible via the road network that traverses the area.

5. Conclusions and Recommendations

The development of an Automated Watershed Management System (AWMS) will lead to an efficient alternative method to the traditional manual methods of building inventories of geophysical maps. This system has the capacity to store and analyse data relating to watersheds and the database has the flexibility to grow and adapt over time. AWMS shares the basic paradigm of GIS, in that its chief components are a

TABLE 6: *Human-induced Erosion Excluding Agricultural and Built-up Areas*

Erosion Class	Description	Area (Ha.) (Agriculture Excluded)	% of Area	Area (Ha.) (Built-up Areas Excluded)	% of Area
1	Slight erosion	2553.43	20.56	555.60	4.47
2	Moderate erosion	763.48	6.15	203.13	1.64
3	Severe erosion	265.91	2.14	64.76	0.52
	Total	3582.82	28.85	823.49	6.63

spatial database and a relational attribute database integrated to allow spatial manipulations and graphic display of data.

AWMS utilises GIS functions to overlay various spatial data for analysis. The most time-consuming aspects of this study are data conversion, database design and database development. These account for more than 70% of the total development time. Watershed areas can be selected for analyses by updating existing data themes with data contained in specific field in the relational database. AWMS has its strengths in data inventory, retrieval, overlay and analysis and presentation. These features are typical functionalities of GIS.

The level of detail contained in the database makes it more suitable for general-purpose watershed management. The flexible design of the database lends itself to expansion to accommodate a higher level of detail for special purpose planning. More information relating to each mapping unit in the watersheds can be added to the attribute database and this in turn can be used to update the existing data themes.

AWMS' strength lies in its ability to significantly reduce the time taken to collect and analyse watershed data. Graphical presentation of results using AWMS is faster and more flexible than manual drafting. By having data relating to the watershed in digital form, numerous analyses can be done by simply regenerating the data set. The interactive link in AWMS, which allows several maps to be derived from the attribute database, reduces the number of spatial data themes that has to be stored. The successful utilisation of AWMS is dependent on how well the system is managed and the organisational context in which it operates rather than on the technology. AWMS is technology driven. More work is needed to turn AWMS into a decision support system.

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