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Modelling water resources and water demand in semi-arid areas: Data integration and analysis using a Geographic Information System

UNESCO-ITC demonstration programme

Geo-information for the environmentally sound management of natural resources

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International Hydrological Programme

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MODELLING WATER RESOURCES AND WATER DEMAND IN SEMI-ARID AREAS: DATA INTEGRATION AND ANALYSIS USING A GEOGRAPHIC INFORMATION SYSTEM

A case study in Samburu District,
northwestern Kenya, using the
Integrated Land and Water Information System
(ILWIS)

A demonstration program prepared for
the Unesco-ITC programme

"Geo-information for the environmentally
sound management of natural resources"

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UNESCO - ITC PROJECT

This is a publication of the UNESCO/ITC programme "Geo-information for environmentally sound management of natural resources". The objective of the programme is to demonstrate the usefulness of the application of modern technologies, especially GIS (geographic information systems) and remote sensing in the environmentally sound management of natural resources.

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1. *Water quality evaluation using remote sensing and a geographic information system: The Songkhla lagoon basin, southern Thailand, J.L. Palacio.*

2. *Modelling water resources and water demand in semi-arid areas: data integration and analysis using a geographic information system, G. Bocco, H. de Brouwer, F. Karanga.*

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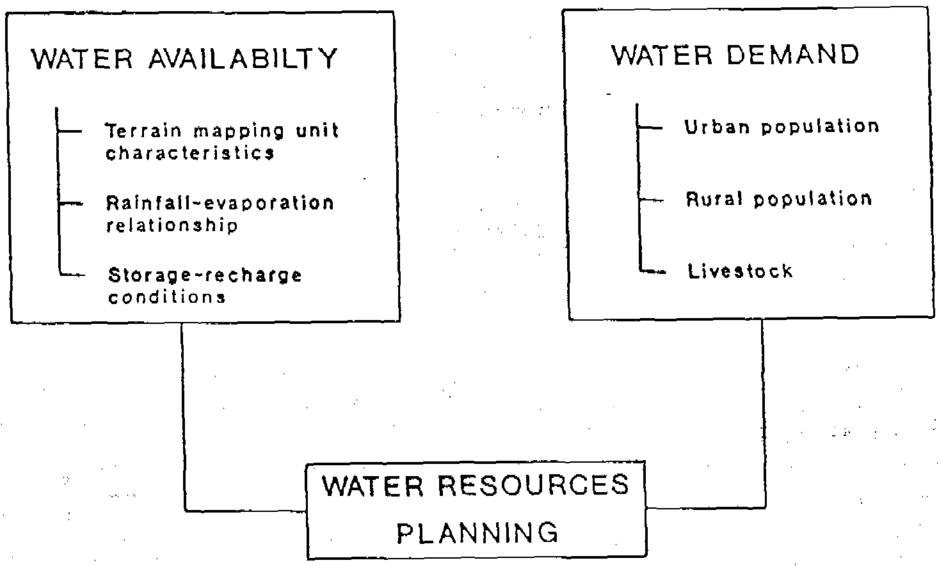
INTRODUCTION

INTRODUCTION

The following subjects will be dealt with in the introduction:

- the objectives of this demonstration program,
- general overview of the study area, and
- a definition of the problem that will be addressed.

GENERAL OBJECTIVES

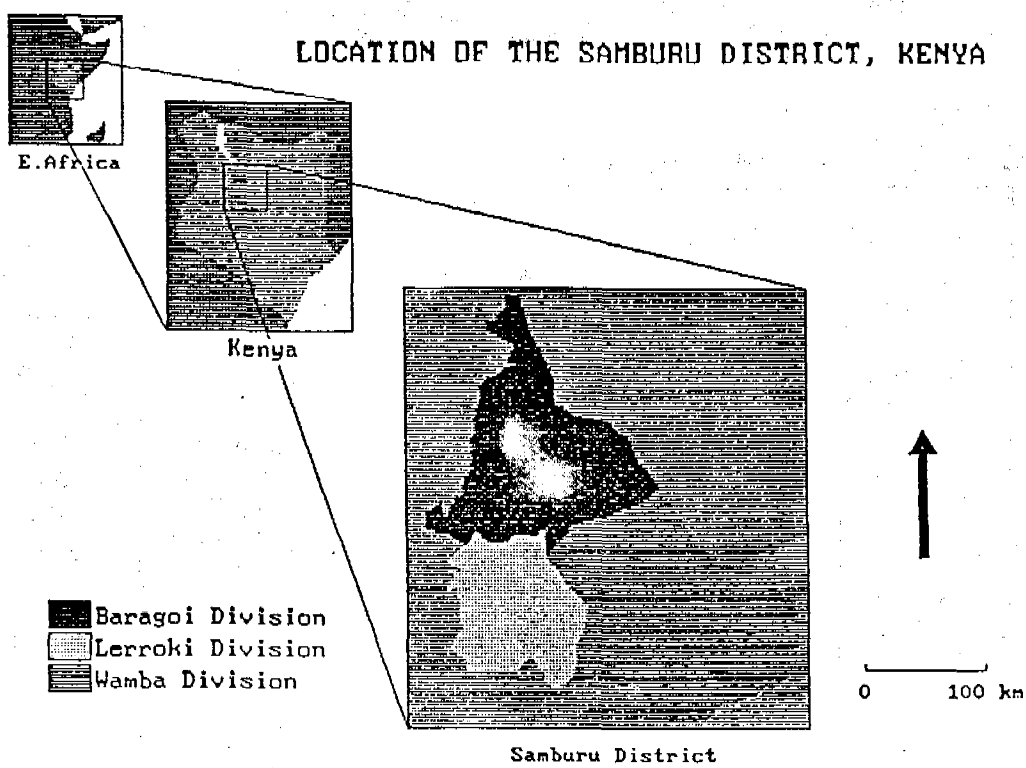


OBJECTIVES

This demonstration was prepared as part of the overall programme of the Unesco-ITC project "Geo-information for the environmentally sound management of natural resources". It also reflects the objectives of Phase IV of the International Hydrological Programme, in particular Theme M-2.3.

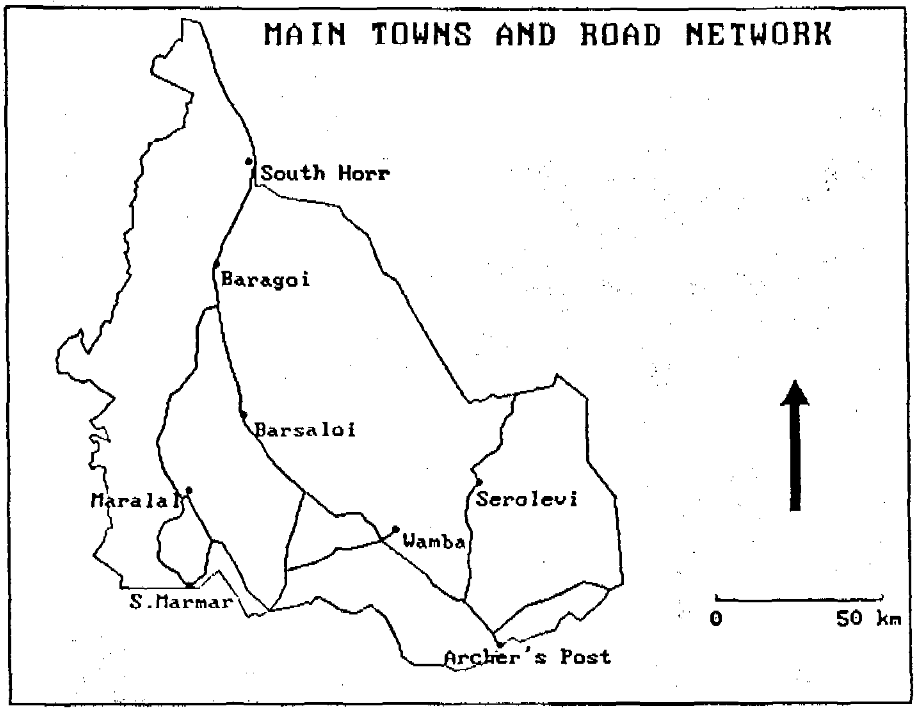
It illustrates the use of data integration and analysis techniques in a PC-based geographic information system (GIS) to assess the availability of and demand for water resources for Samburu District, Kenya.

Emphasis is given to the particular conditions found in this semi-arid region where data are often either inadequate or insufficient. In addition, the image processing capabilities available within the GIS (ILWIS) are used to integrate satellite data in the analysis.



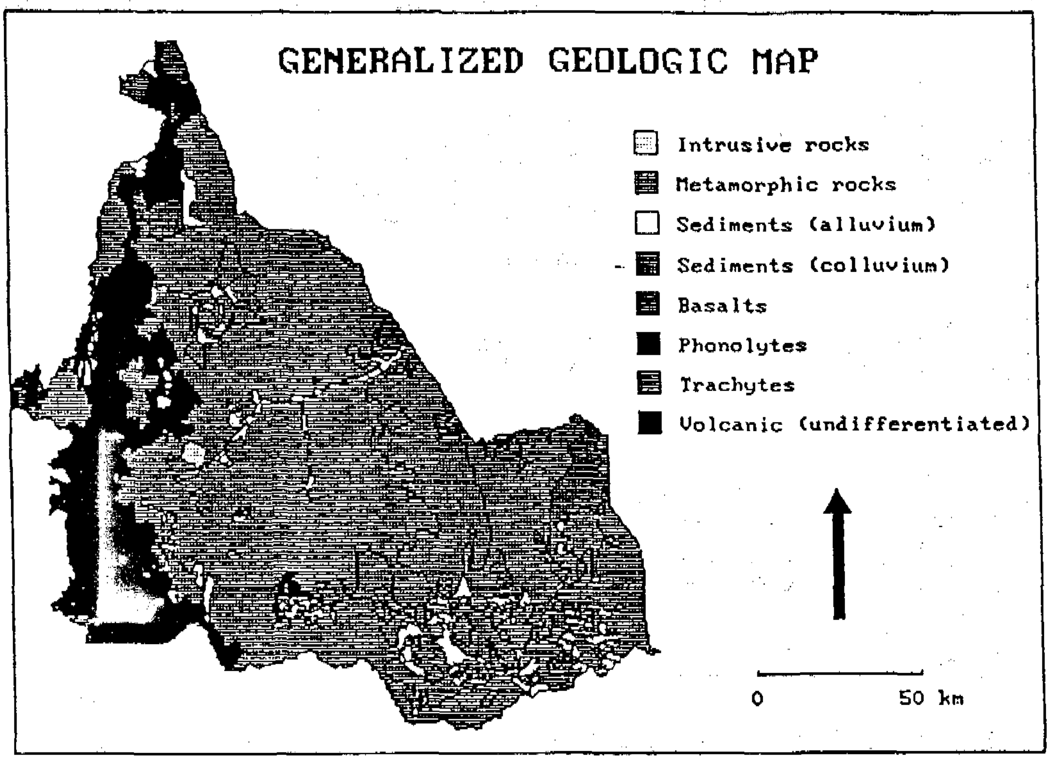
GEOGRAPHIC CHARACTERISTICS OF SAMBURU DISTRICT

Samburu District is located in the semi-arid northwestern part of Kenya. Its total area is approximately 20,000 km2. Seventy-six percent of the total population are indigenous Samburu. The rest are Turkana, other ethnic groups or immigrants from outside the district. The total population in 1979 was approximately 77,000. This number is expected to reach 160,000 by the beginning of the next century.



TOWNS AND ROADS

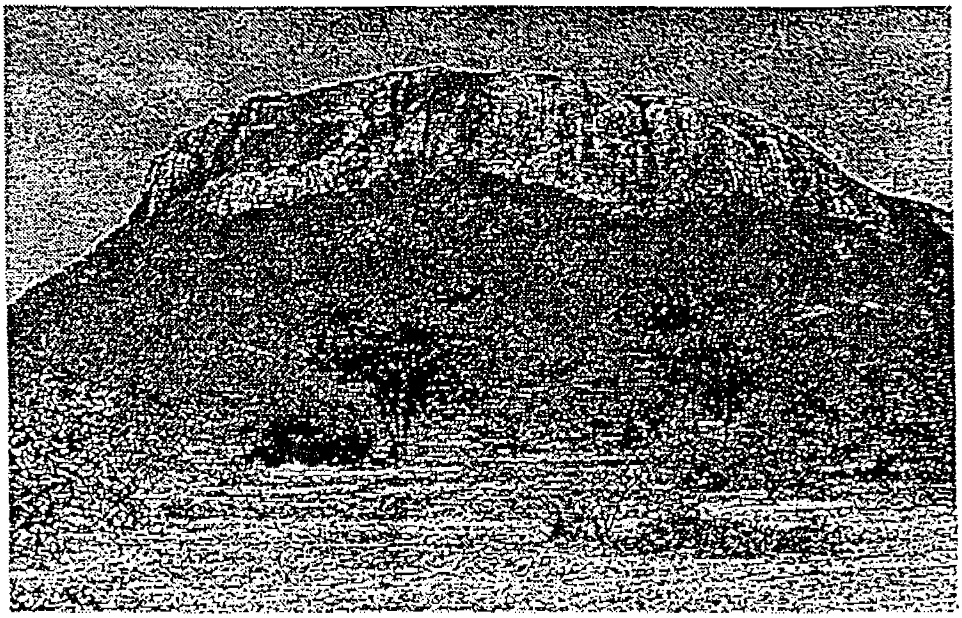
Most of the population is rural; the urban population is settled in several villages linked by a secondary road network.



GENERAL GEOLOGIC SETTING

The central and eastern parts of the district consist of low-lying grass-covered plains (average elevation is approximately 1000 m) on metamorphic basement rocks. A forested high mountain range, also of metamorphic origin, runs in a NW-SE direction, rising to more than 2400 m elevation. The western side of the district is a volcanic plateau that drops, in a series of escarpments, to the Rift Valley.

INSELBERG --BASEMENT OUTCROPS-- WITH COLLUVIAL SLOPES
(SCANNED FIELD PHOTOGRAPH)

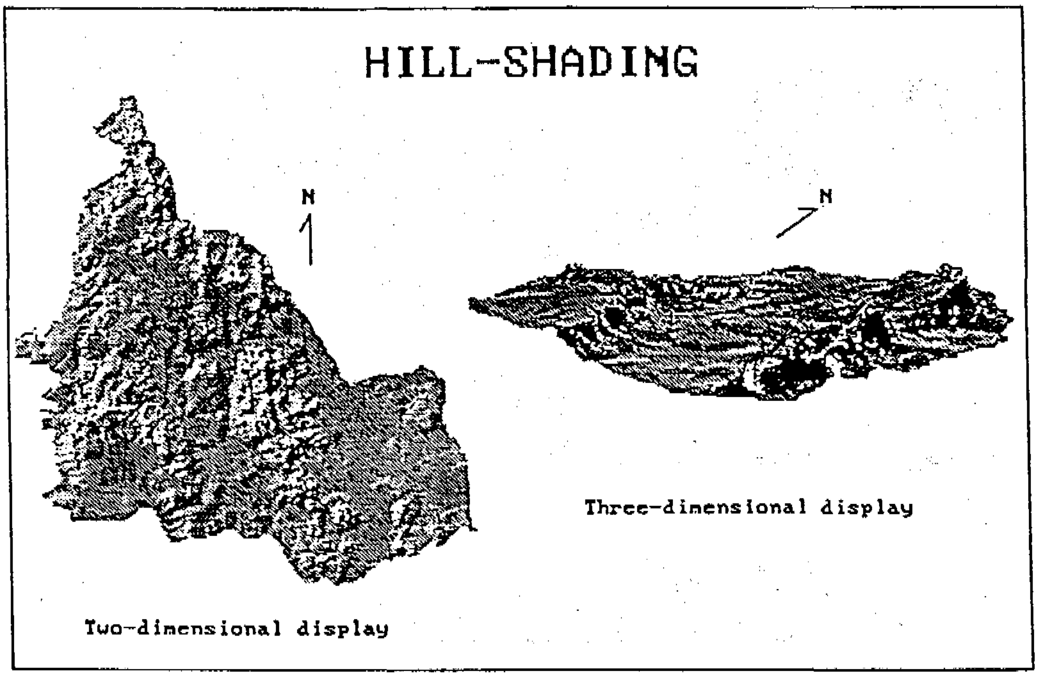


GENERAL CHARACTERISTICS

Although rainfall and evaporation records are generally inadequate, the data indicate that yearly precipitation is erratic and grouped into two rainy seasons: April and November. On average, annual rainfalls of 400 to 600 mm occur in the plains and as much as 1000 mm or more in the mountains. Evaporation rates of 1700 to 3100 mm have been recorded.

The only permanent river in the region is the Ewaso Ng'iro, which forms the southern boundary of the district.

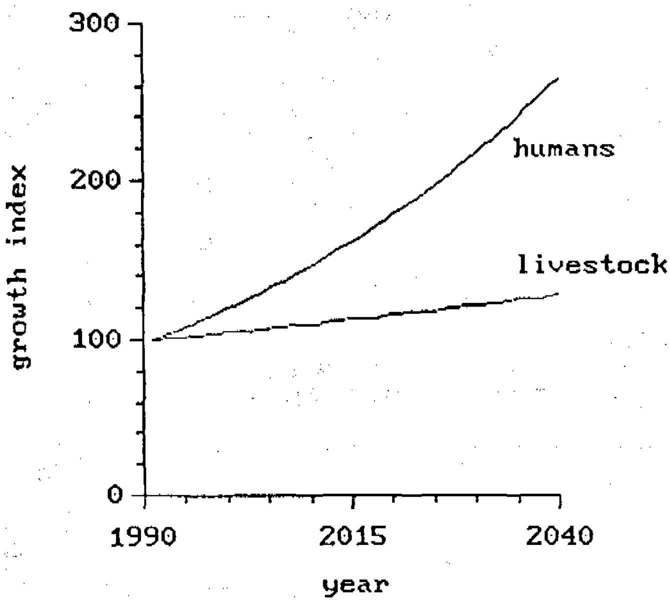
Soils are generally shallow, but in the footslopes of the mountain ranges they may exceed 100 cm in depth. Most soils are red, clayey and sandy if weathered from crystalline rocks, and brown to dark brown, well drained and loamy if weathered from volcanic rocks.



GENERAL GEOMORPHIC OUTLINE

Using a digital elevation model, the general geomorphic outline of the district becomes clear: mountains, hills and plains. Hill shading is produced by applying a directional filter to the digital elevation model.

PROJECTED GROWTH OF HUMAN AND LIVESTOCK POPULATIONS
(index 100 in 1990)

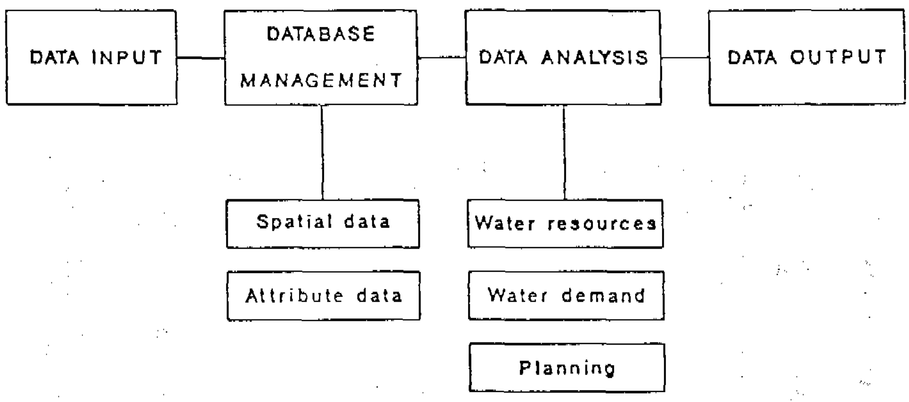


DEFINITION OF THE PROBLEM

The human population of Samburu District grows at an average rate of 2.7% per year. Because of their nomadic life style, people are still spread over the entire district, but there is a growing tendency for them to concentrate in towns and villages.

Most Samburu people are herdsmen and they follow their herds wherever water is available. Exact counts of the animal population are very important because livestock are the largest consumers of water.

The increase in both human and livestock populations and the tendency of people to concentrate in towns and villages will lead in the near future to problems of water supply. Another problem may occur if the spatial distribution of available water differs from the spatial distribution of the water demand.



DATA FLOW IN THE GEOGRAPHIC INFORMATION SYSTEM

DATA FLOW IN THE GIS

This demonstration reproduces the flow of data in a geographic information system. The program consists of the following parts:

(1) Data collection and input: satellite images, maps, tables and reports.

(2) Database storage and management: construction of the spatial databases (in vector (lines) and raster (cells) formats) and the attribute databases (in tabular format).

(3) Data analysis, modelling and development of scenarios: using GIS techniques to match water availability with different expectations of water demand.

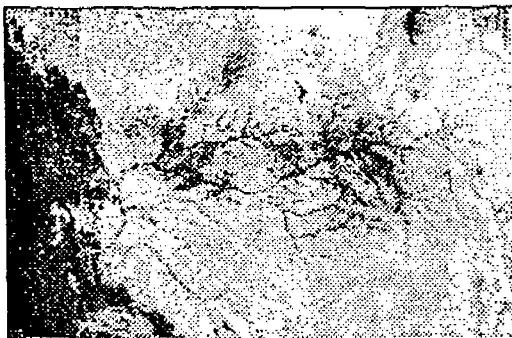
(4) Data output: newly generated information presented in maps, tables and reports.

DATA INPUT
&
MANAGEMENT

DATA INPUT & MANAGEMENT

The following subjects will be dealt with here:

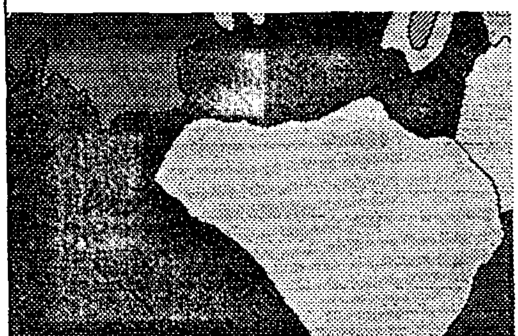
- data types and input,
- data management.



Satellite image data

Code	Descrip.	Lithology
BH1	Fluvial	Alluvium
BH2	Fluvial	Colluvium
BH3	Fluvial	Embayments
BP1	Fluvial	Pediment
IG	Intrusives	Acidic granites
IU	Intrusives	Ultramafic
B	Basement	Undifferentiated
V1	Volcanic	Basalts
V2	Volcanic	Trachytes
V3	Volcanic	Phonolytes

Non-spatial attribute data



Map data (vector-raster)

Station	X	Y	Rain	Elev.
Archer P.	351490	70065	864	304
Baragoi	254935	197026	1260	531
Barsaloi	263705	147024	1143	450
Bauwa	256931	114546	2103	626
Illaut	307071	205594	762	283
Kipsing	305030	70220	1306	456
Kirimun	263040	82052	1768	592
Lerata	332963	91038	914	453
Lesirikan	273881	196980	1551	447
Lodokejek	262808	94301	1676	702

Spatial attribute data

DATA TYPES AND INPUT

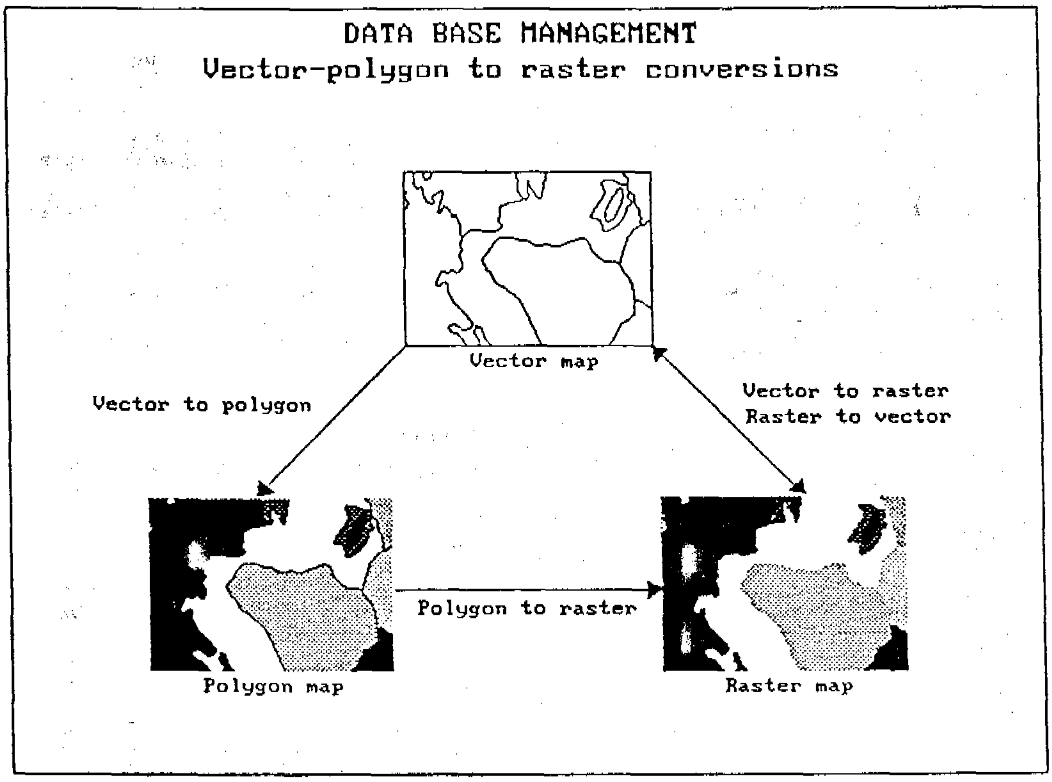
Spatial data:

Spatial data are collected from available analog and digital data sources, such as reports and publications, thematic and base maps, aerial photographs and satellite images.

Available thematic and base maps (such as topographic, geologic, soils, terrain mapping units (TMUs) and agroclimatic) are digitized and incorporated in the spatial database (in vector format). Satellite data are input directly to the raster spatial database. Aerial photographs are scanned and also stored in the raster spatial database. The images are geo-referenced to a desired coordinate system in order to integrate them with other spatial data. Point data, related to the data measured at points such as rainfall and evapotranspiration, are entered using the keyboard or by transferring digital files of existing databases into the tabular database of the GIS.

Non-spatial data:

Attributes of the spatial data (such as the hydrologic characteristics per terrain mapping unit) are stored in the tabular (non-spatial) database for further interaction with the related data stored in the spatial database.



MANAGEMENT OF SPATIAL AND NON-SPATIAL DATABASES

In a computerized GIS, digital databases act as a representation (model) of the real world. The spatial database has both vector and raster formats. Bearing in mind the limited storage capacity of a PC-based GIS, storage requirements can be optimized by keeping the maps in vector format. Arcs (lines or segments) and polygons are rasterized for analytic purposes--such as map overlaying--and combination with satellite images. Whenever needed, raster data can be converted to vector format.

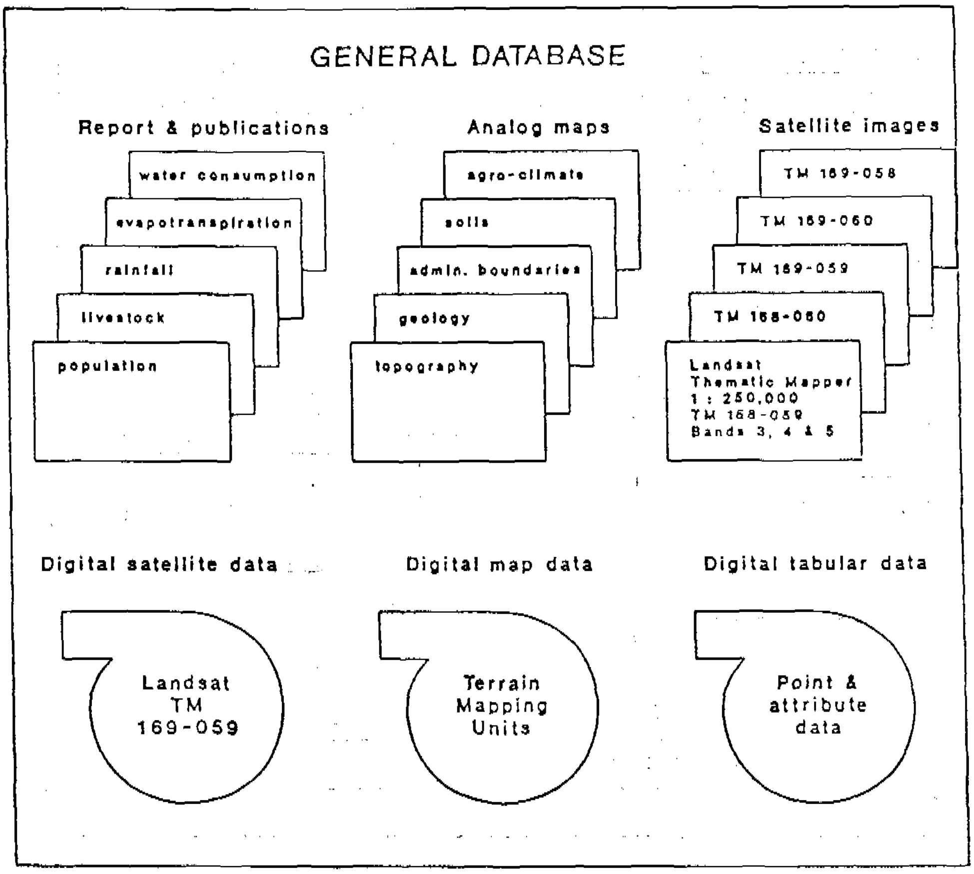
Attribute data stored in the tabular database are used either to analyze relationships among attributes (variables) or to interact with the spatial database to indicate spatial patterns in the data. The "map calculator" is used extensively for combining spatial data (in raster format) and attribute data (in tabular format).

DATABASES

DATABASES

The following subjects will be dealt with here:

- general database, and
- hydrologic database.

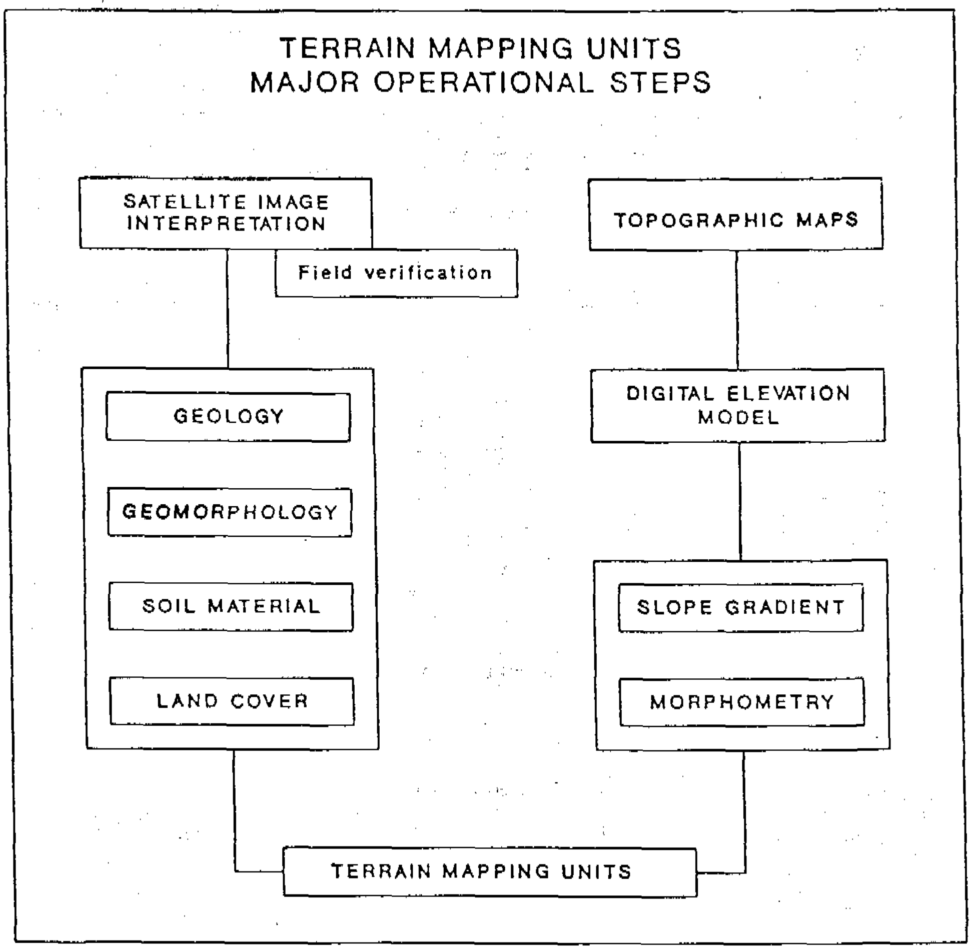


GENERAL DATABASE

A differentiation is made between a "general database" and a "hydrologic database". The general database contains the currently available data of different themes from various sources, such as topographic maps, geologic maps, census data, satellite images, etc.

For the analysis of water demand and water resources in the district, a selection was made of the available geo-referenced data sources. Decisions have to be made regarding the level of information to extract from topographic maps, the level of detail of geologic maps, the level of aggregation of the census data of humans and livestock, etc.

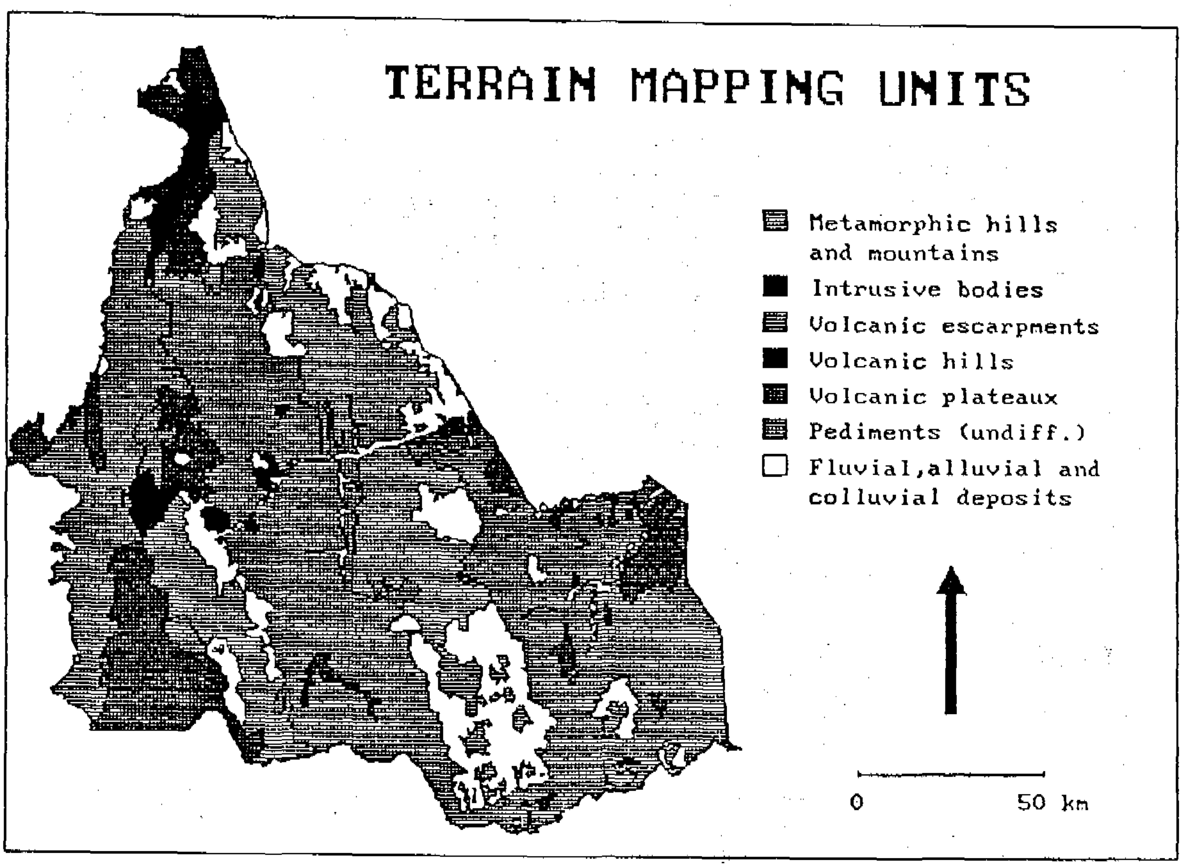
The data are often available in conventional formats: maps, reports and tables. The selected data have to be converted to a digital format. For the compilation of the database, some pre-processing may be required (for example, geometric corrections of satellite images, checking the consistency of rainfall records and making estimates for missing periods). The hydrologic database contains data with a level of detail which is usually not required for general users of a national or district GIS. The hydrologic data are essential for the water resources analysis.



TERRAIN MAPPING UNITS

Terrain mapping units (TMUs) are relatively homogeneous landscape units describing a natural division of the terrain that can be identified on the remote sensing images and verified in the field. TMUs group interrelated landscape characteristics, such as geomorphic origin, lithology, morphometry (slope, internal relief, etc), soil geography, land cover and land use.
A mapping unit (a polygon) may occur at more than one locality in a region (for example alluvial river beds, basalt plateaus, etc).

TMUs were delineated on photographic copies of Landsat TM false-colour composites enlarged to approximately 1:250,000 scale by Karanga (1990). Polygons were digitized and entered in the GIS. Each TMU was given a score for each different variable (columns of the attribute table) that plays a role in the hydrologic characteristics of the mapping unit (infiltration, water storage and recharge to groundwater bodies). After assigning these scores, the TMUs may be regarded as hydrologic response units.


TERRAIN MAPPING UNITS
Metamorphic hills and mountains
Intrusive bodies
Volcanic escarpments
Volcanic hills
Volcanic plateaux
Pediments (undiff.)
Fluvial,alluvial and colluvial deposits
0
50 km

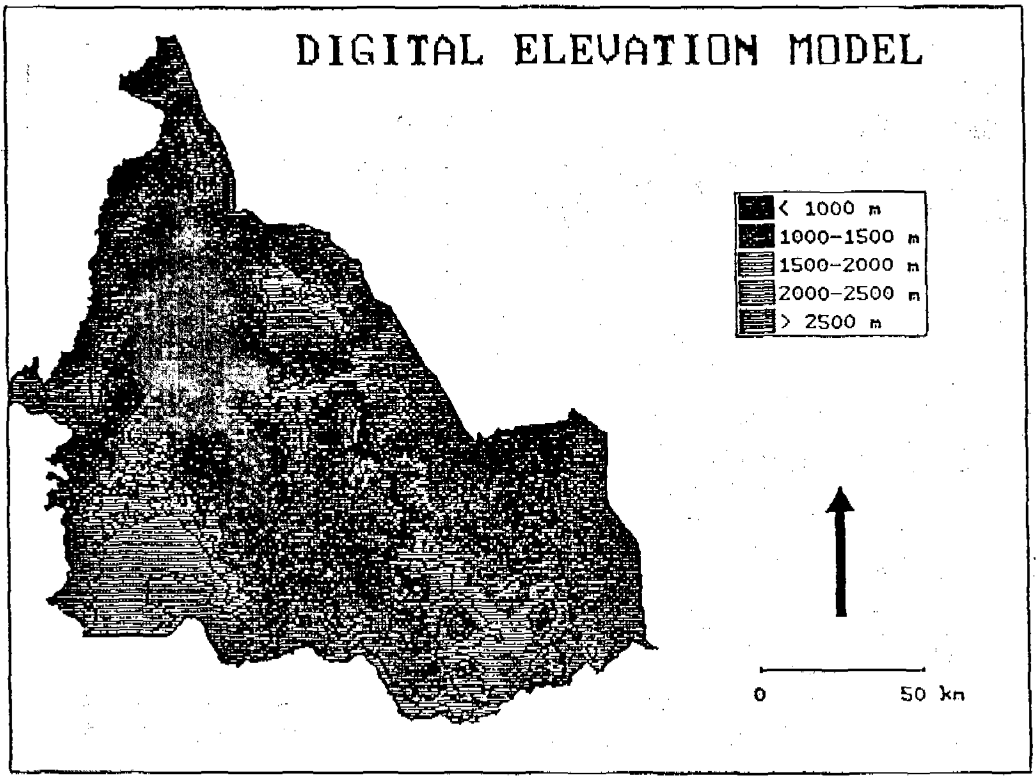
TMUs AND HYDROLOGY-RELATED VARIABLES: COMBINING SPATIAL AND ATTRIBUTE DATABASES FOR ANALYSIS AND MODELLING

Each TMU was assigned a value for several hydrologically-related variables: weathering stage, rock type, recharge capabilities, drainage and lineament densities. These data were stored in tabular format in which each column of the table corresponds to a given variable. The table was linked to the terrain map, i.e., to the spatial database, through the index number or terrain mapping unit number. This allowed the manipulation of the spatial data in terms of non-spatial (attribute) data obtained from the literature or from field observations and measurements.

The TMUs can be re-classified according to any desired attribute because the spatial and non-spatial databases are consistently linked in the GIS.

Such an attribute database will look as follow:

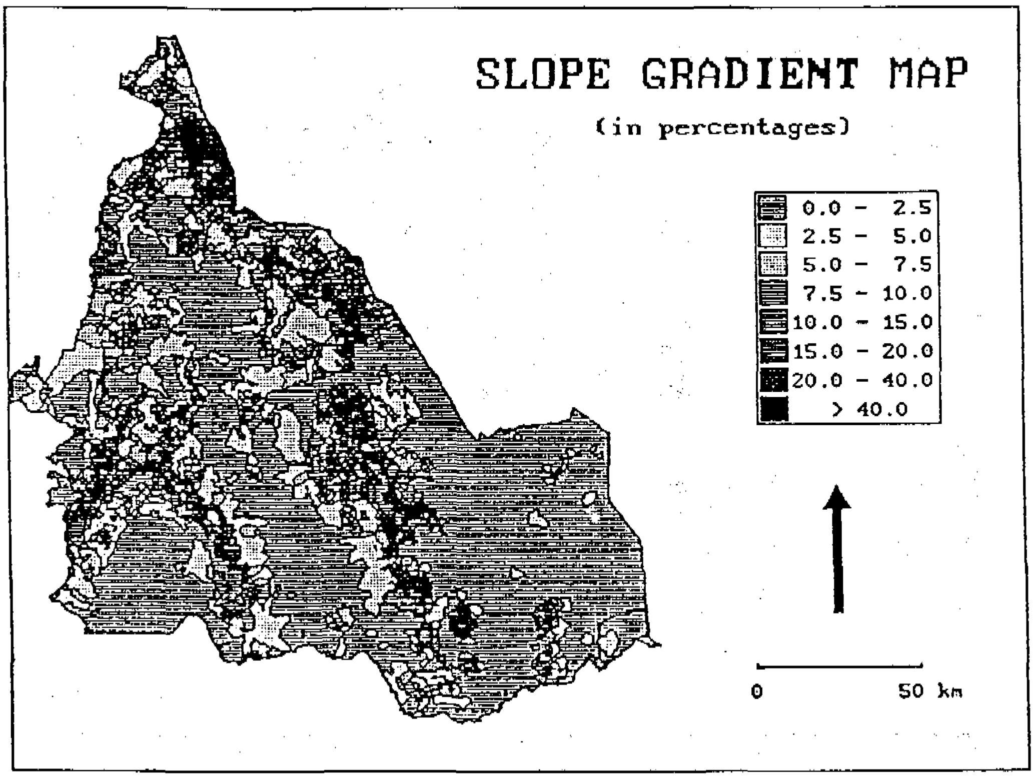
Unit Code	lineament density	recharge possibilities	weathering profile
bh1	1000 - 2000	poor	deep
bh2	1000 - 2000	poor	shallow
bh3	250 - 500	poor	deep
bh5	> 6000	poor	shallow
bp1	1000 - 2000	fair	deep
bp2	2000 - 3000	fair	deep
bp4	500 - 1000	poor	shallow
ig	< 250	fair	shallow
iu	500 - 1000	fair	shallow
q1	5000 - 6000	fair	deep
q2	3000 - 4000	fair	deep
q3	5000 - 6000	very good	deep
v2t1	< 250	poor	deep
v2t1l1	< 250	good	shallow



CREATING A DIGITAL ELEVATION MODEL: THE USE OF ELEVATION DATA

Digital elevation models (DEM) are raster maps in which each cell contains a value of elevation above mean sea level. This type of map models the elevation changes in a given area and may have several applications. For instance, the elevation is important in the morphometric characterization of the terrain mapping units.

A DEM of Samburu District was constructed on the basis of elevation data in vector format--contour lines--digitized from topographic maps. The contour data were transformed to raster format and an elevation value was calculated for each map cell by linear interpolation between contour lines.

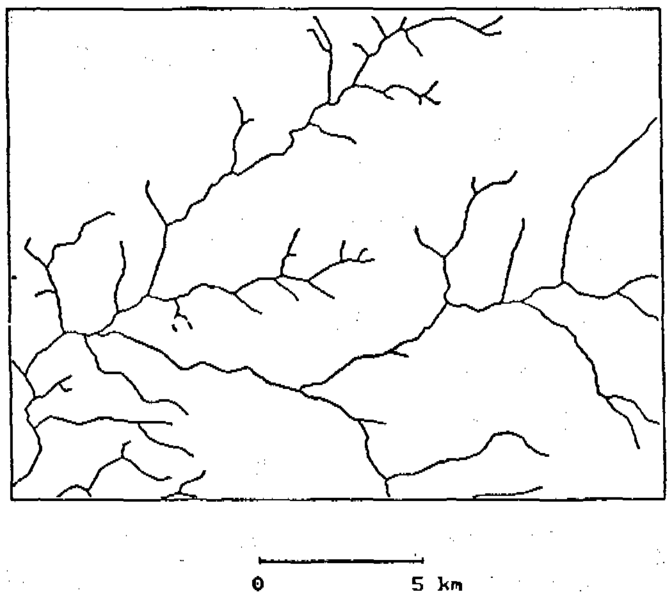


CONSTRUCTING A SLOPE GRADIENT MAP

Slope gradient is an important characteristic of the terrain mapping unit. The DEM was used to generate--by using directional filtering of the elevation data--a slope gradient map in which each cell contains a value for the maximum slope steepness.

Slope maps are useful in hydrologic analysis because the relationship between infiltration, water storage and hillslope runoff is partially controlled by slope gradient.

DRAINAGE NETWORK, BARAGOI REGION
(Source: topographic map)

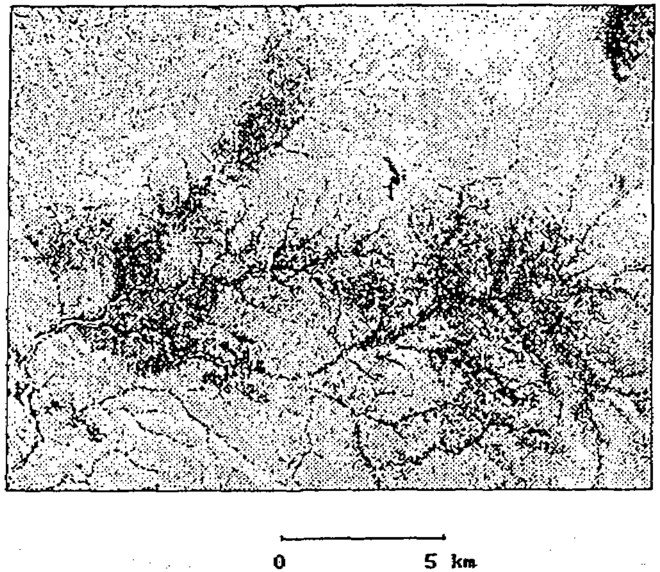


UPGRADING DRAINAGE NETWORKS

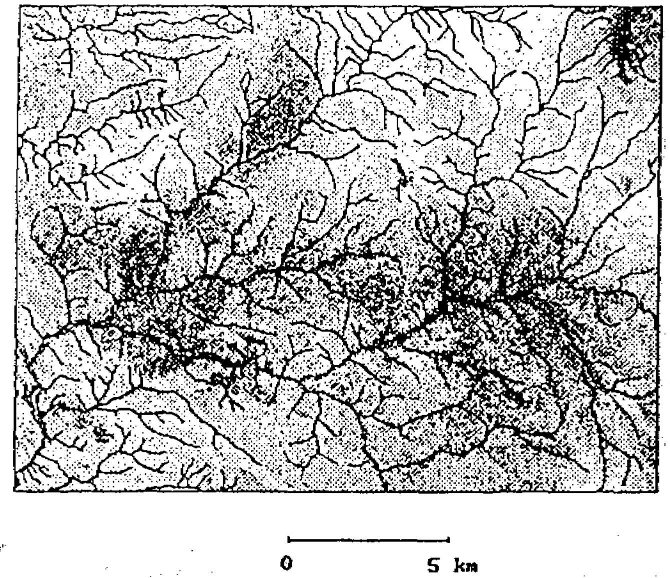
Drainage networks may not be properly represented on topographic maps. These networks are important in hydrology. The drainage density typifies runoff characteristics; river sand accumulations with groundwater are found along drainage lines; groundwater flow patterns may be affected by drainage lines. Some hydrologic models need stream orders which are determined from the drainage networks.

The drainage map can often be upgraded using enhanced satellite images, depending on the spectral contrasts between the drainage lines--or the vegetation patterns along the drainage lines--and the surrounding interfluves. These contrasts may vary seasonally. Aerial photographs, with their high spatial resolution and stereo capability, are of course extremely suitable for tracing detailed drainage. Making geometric corrections may be tedious, however, especially in areas with strong relief.

LANDSAT TM ENHANCED INFRARED BAND BARAGOI REGION



DRAINAGE NETWORK, BARAGOI REGION
(Source: screen-digitized enhanced satellite image)



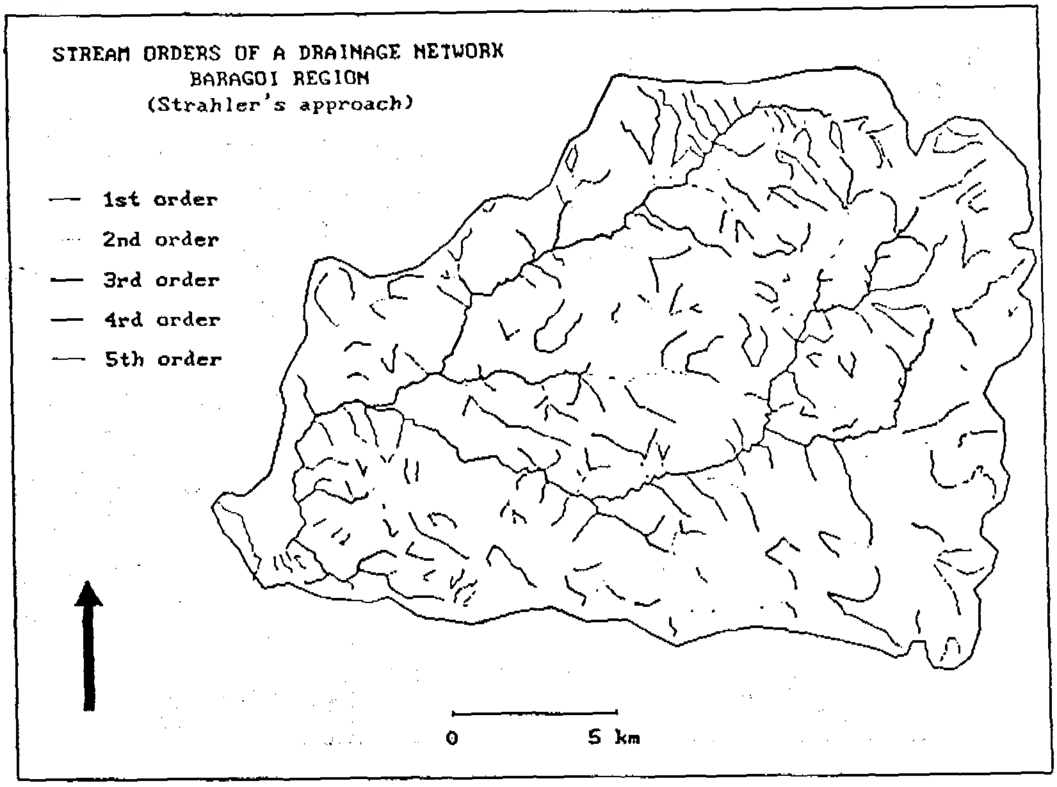
DIGITAL SATELLITE IMAGES FOR DRAINAGE NETWORK MAPPING

Landsat Thematic Mapper (TM) data of a portion of the Baragoi river basin (northwest of the study area) were geo-referenced using ground-control points obtained from topographic maps. The geometrically corrected image was enhanced by stretching (i.e., using all possible grey tones to improve contrast) and edge enhancement filtering (i.e., sharpening the boundaries between objects).

SCREEN-DIGITIZED ENHANCED SATELLITE IMAGES

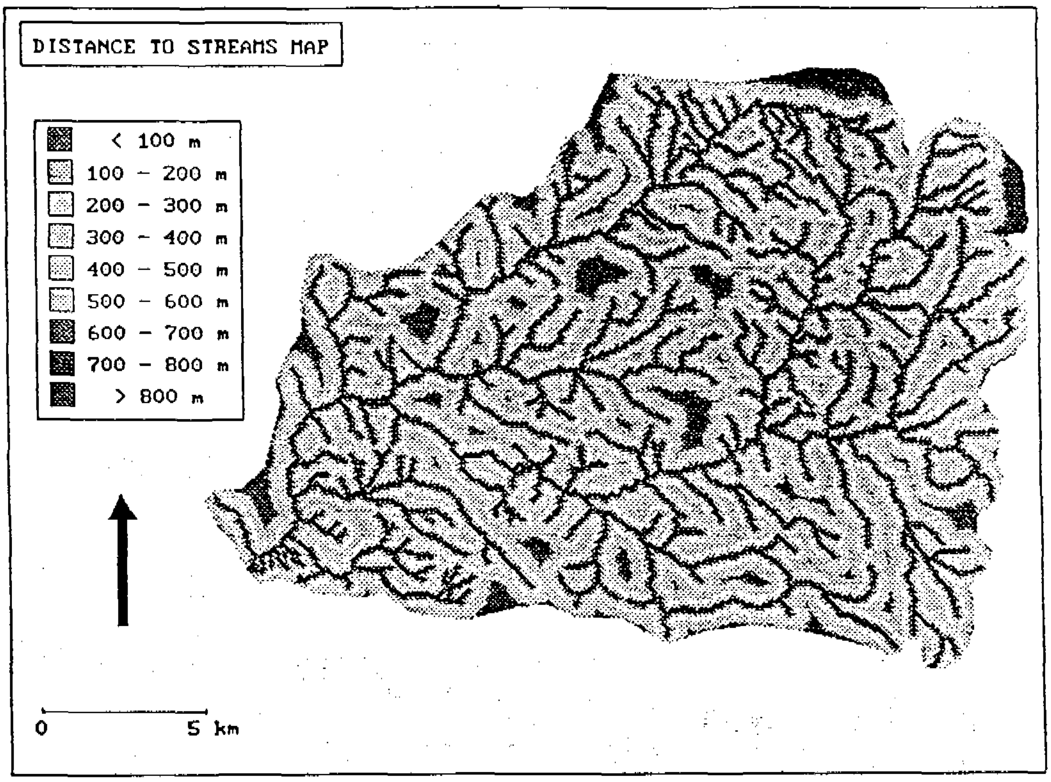
The enhanced image, as displayed on the high-resolution monitor, was used to trace the drainage lines directly ("screen-digitizing").

In a similar manner, hydro-geologically relevant linear features, such as lineaments, fractures and faults, can be digitized directly from the screen.



COMPUTING STREAM ORDERS

Research in Samburu District indicated that appropriate areas for shallow wells would include the alluvial deposits along the ephemeral channels--laggas--that are subject to flash-floods. The potential water storage capacity will be greatest in those streams receiving water from upslope channels, i.e, in streams of third and higher order. The stream order, in this context, becomes an indicator of (seasonal) water availability. Stream ordering is the result of a GIS counting/labelling operation in the vector domain. The streams of a basin near Baragoi were ordered according to the Strahler model.



DISTANCE CALCULATION TO RIVERS

The proximity to rivers or drainage lines may have hydrologic implications. The groundwater table may be shallow near streams and its area may expand during rainy seasons. Phreatophytes, causing high transpiration losses, may concentrate near channels.

The discharge of effluent rivers to the groundwater is also a function of distance. To demonstrate this effect, an operator is used to calculate distances from drainage lines, stored in vector format.

This operation involves a vector-to-raster conversion of the drainage network data and distance computations in the raster domain. The distance map can be reclassified into user-defined distance classes. It is also possible to select the drainage lines or streams for which the distance operator will be used.

CALCULATING DENSITIES OF LINEAMENTS

Lineaments play a major role in potential groundwater occurrences. Lineaments were interpreted on Landsat TM colour composites at 1:250,000 approximate scale. The features were subsequently digitized and stored in the GIS.

The density of linear features per area can be calculated in the spatial database, using vector maps of faults and fractures and a user-defined grid. The system measures the length of the linear feature per grid-cell. The results are stored in the tabular database. In this table the x and y coordinates of the grid-cell center uniquely identify a certain value of density.

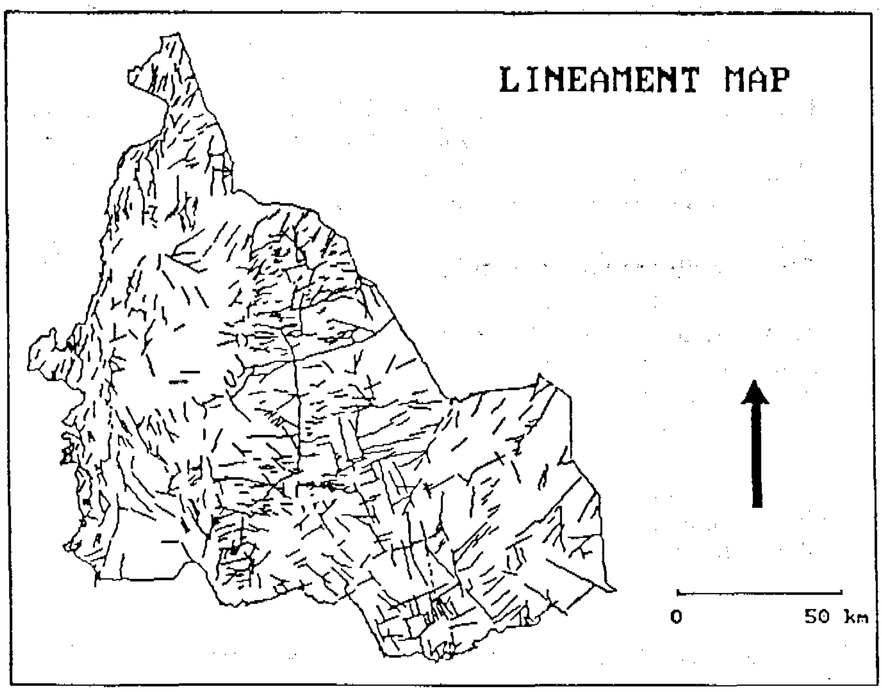
The analysis may include a differentiation according to the type of lineament (tensional fractures or faults), lineaments related to shear, directions of lineaments, etc.

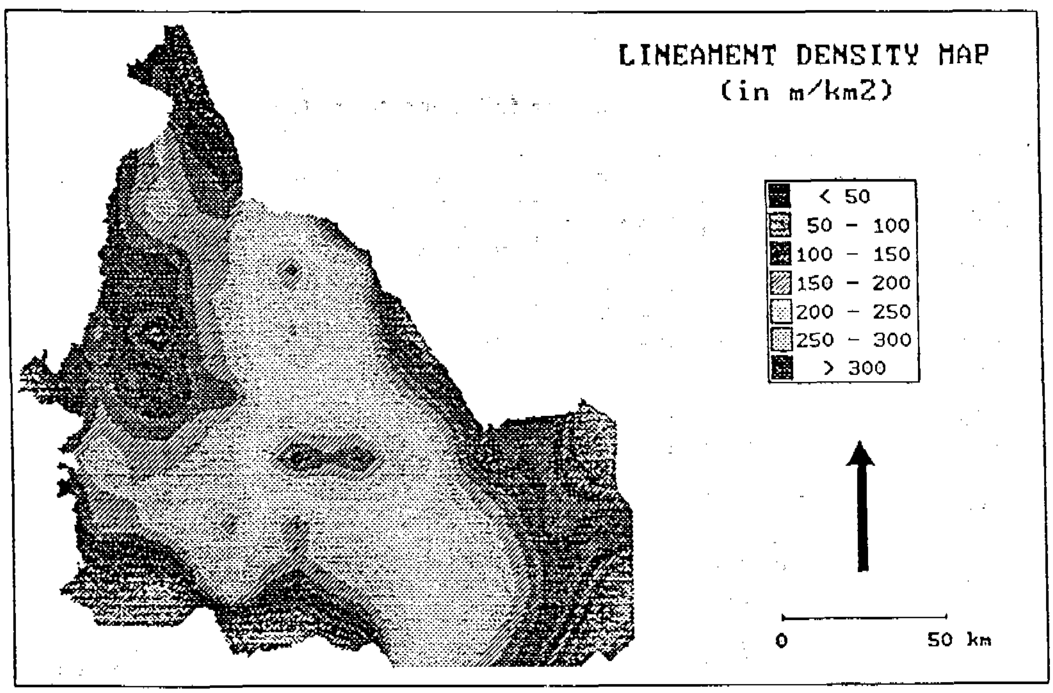
INTERPOLATING DENSITY DATA IN TABULAR FORMAT TO CONSTRUCT DENSITY MAPS

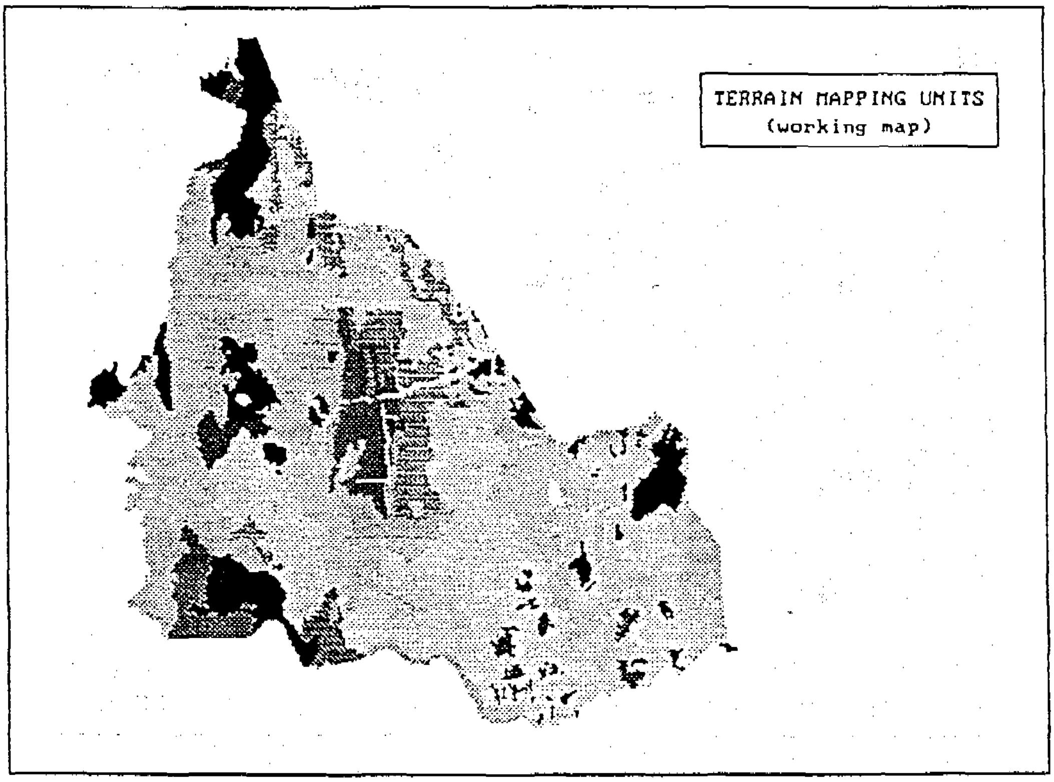
A tabular database has the following format:

Grid	X	Y	Density	Row	Col
1	207891	268225	0.0000000	01	01
2	227856	268225	0.0000111	01	02
3	247890	268225	0.0001722	01	03
4	267925	268225	0.0002322	01	04
5	287960	268225	0.0000850	01	05
6	307994	268225	0.0000600	01	06
7	328029	268225	0.0004433	01	07
8	348064	268225	0.0002854	01	08
9	368098	268225	0.0003211	01	09
10	388133	268225	0.0005380	01	10

These data can be interpolated and maps of lineament densities can be constructed


LINEAMENT MAP
0
50 km

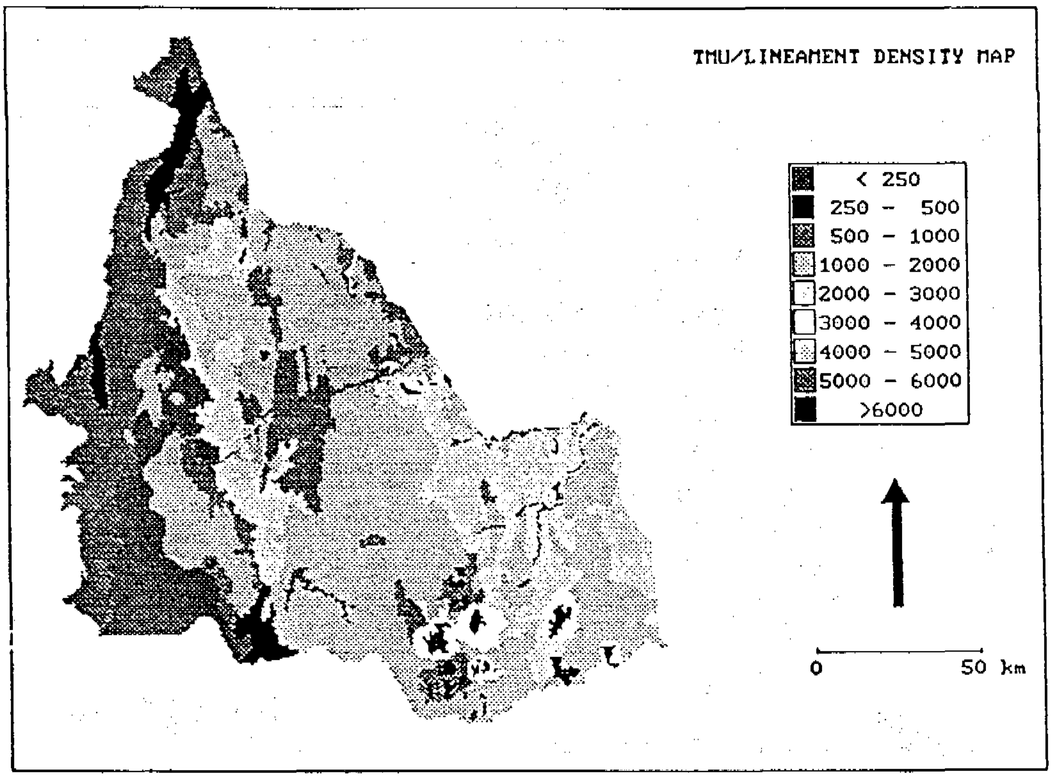

LINEAMENT DENSITY MAP
(in m/km2)
< 50
50 - 100
100 - 150
150 - 200
200 - 250
250 - 300
> 300
0
50 km



LINEAMENT DENSITY PER TMU

Computing lineament densities per terrain mapping unit--in terms of m of lineaments per km2 of each polygon--contributes to characterizing the hydrologic properties of those units. The results of this GIS measurement operation are stored in the tabular database as attributes of each TMU (lineament density classes).

However, this information should be regarded with caution. Certain parts of the regions have well developed soils and deeply weathered zones, in others the soils and weathered mantle have been stripped by erosion. In the latter, the lineaments are easier to detect and the apparent density will be higher. Lineament densities should therefore be analyzed in conjunction with data on weathering, given as an attribute of each TMU.



DISPLAY OF LINEAMENT DENSITY PER TMU

Each terrain mapping unit can be assigned a value for lineament density by combining the tabular and spatial databases.

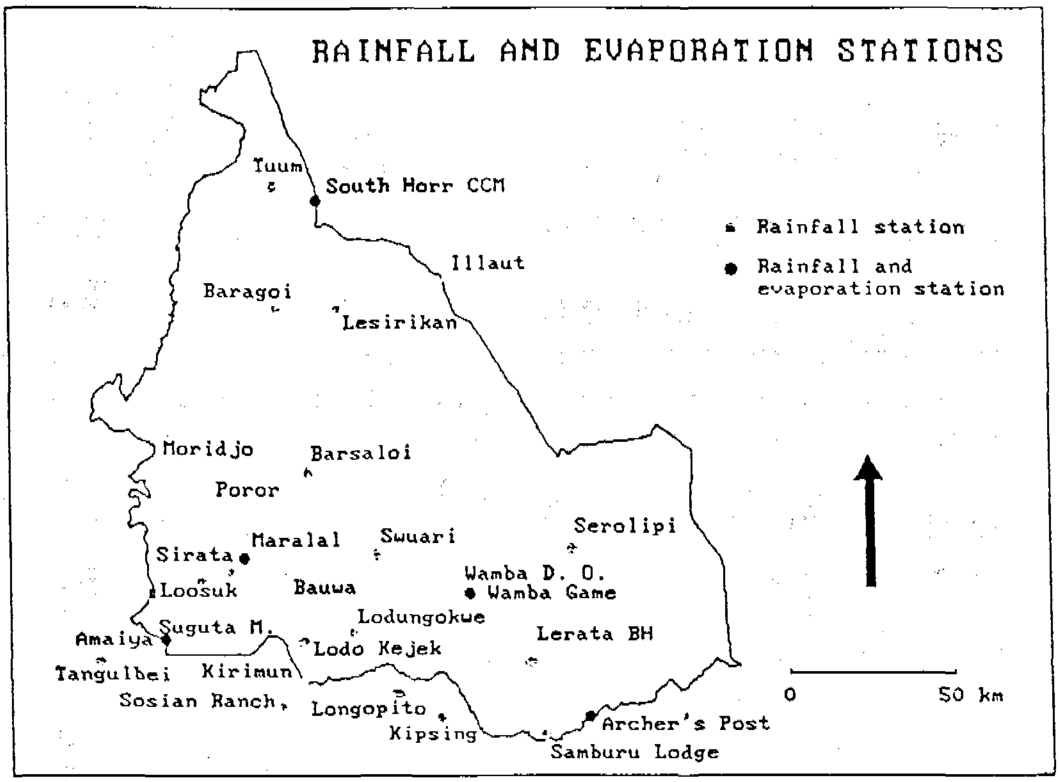
As an example, the TMUs will be re-classified, on the screen, according to the lineament density of each unit. The resulting lineament density map would contain a wide range of numerical values expressing the densities. In order to display the newly created map in a more readable manner, the densities are grouped in classes (see the legend of the TMU/Lineament density map on the colour monitor).

TABULAR DATA USED FOR RE-CLASSIFYING AND GROUPING

Table (a) was used for re-classifying the TMUs according to their lineament density (the table shows only part of the TMUs to be re-classified); table (b) was used to group the resulting lineament density map into nine distinct classes.

(a) To re-classify the TMUs: (b) To group the re-classified TMUs:

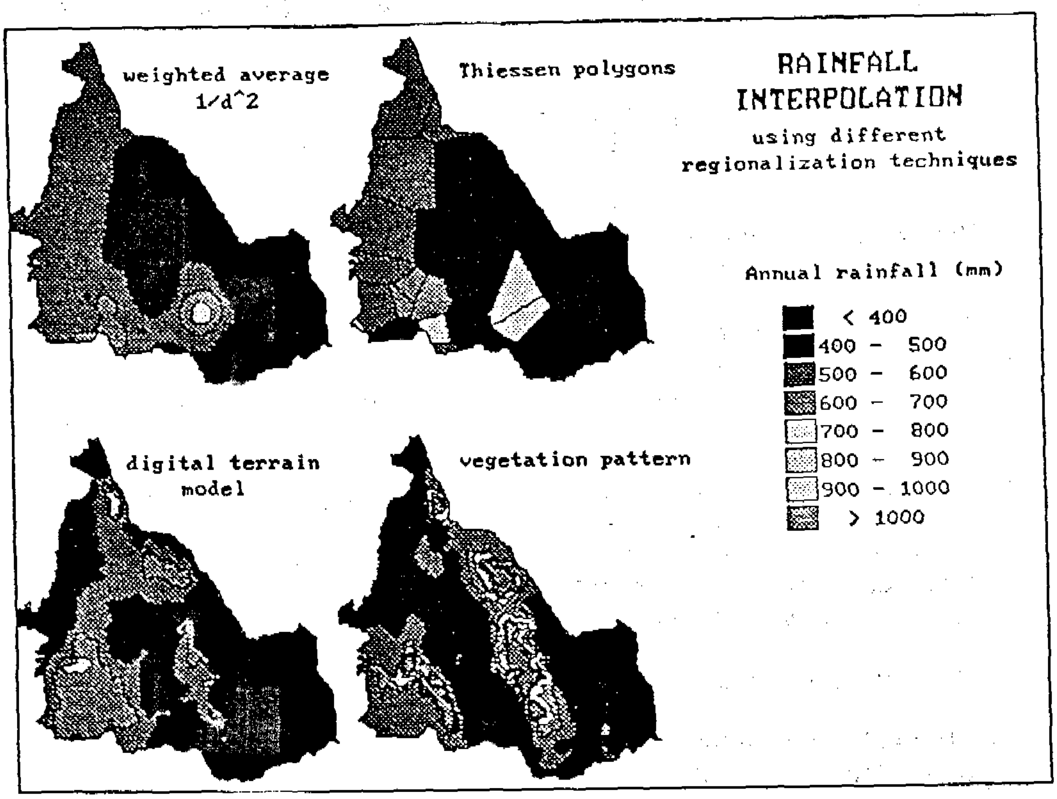
TMU code	Lineament density (m/km2)	Class boundary	Class No
bh1	1088	0	0
bh2	1831	250	1
bh3	299	500	2
bh5	8986	1000	3
bp1	1836	2000	4
bp2	2470	3000	5
bp3	1629	4000	6
bp4	879	5000	7
ig	166	6000	8
iu	607	>6000	9



RAINFALL AND EVAPORATION STATIONS

Twenty-seven rainfall recording stations are in operation in Samburu District or its immediate vicinity. Five of these stations have records exceeding 30 years. The stations are not well distributed over the area. Most are located in the south, and there are no stations in the mountains.

Five of the 27 stations also record evaporation. Only one station has records of more than 30 years. The other four stations started operating only recently.



USING DIFFERENT REGIONALIZATION TECHNIQUES TO MODEL THE SPATIAL DISTRIBUTION OF RAINFALL

Weighted average:
One of the most commonly used methods of finding the spatial distribution of rainfall is a straight-forward interpolation between points. In this case a limiting distance and a weighting factor are used. For every point P, rainfall is estimated by looking in a radius of 50 km for known rainfall values. The interpolation uses a weighting factor 1/d^2 (where d = distance between P and a rainfall station). The farther away a rainfall station is from point P, the less influence rainfall at this station has on the rainfall at point P. This method is not very reliable because topography is not taken into account: the expected higher rainfall in the mountains is not depicted.

Thiessen polygons:
One of the standard procedures in determining the spatial distribution of rainfall makes use of Thiessen polygons. A disadvantage of this method is that topography is not taken into account. A nearest neighbour operation can be used in a GIS to create Thiessen polygons automatically.

Digital elevation model:

In Samburu District, rainfall generally increases with elevation. Yearly rainfall data were compared with the elevation of each station, and a linear regression model was calculated.

The function obtained--yielding a correlation coefficient of 0.7--was applied to the elevation data stored in the DEM. This method is a substantial improvement on the two methods described above.

The expected influence of topography is obvious. However, the effect of "rain shadow" is not taken into account, and the relationship between rainfall and elevation is undefined at elevations above the highest rainfall stations. This is often indicated by type of vegetation at higher elevations.

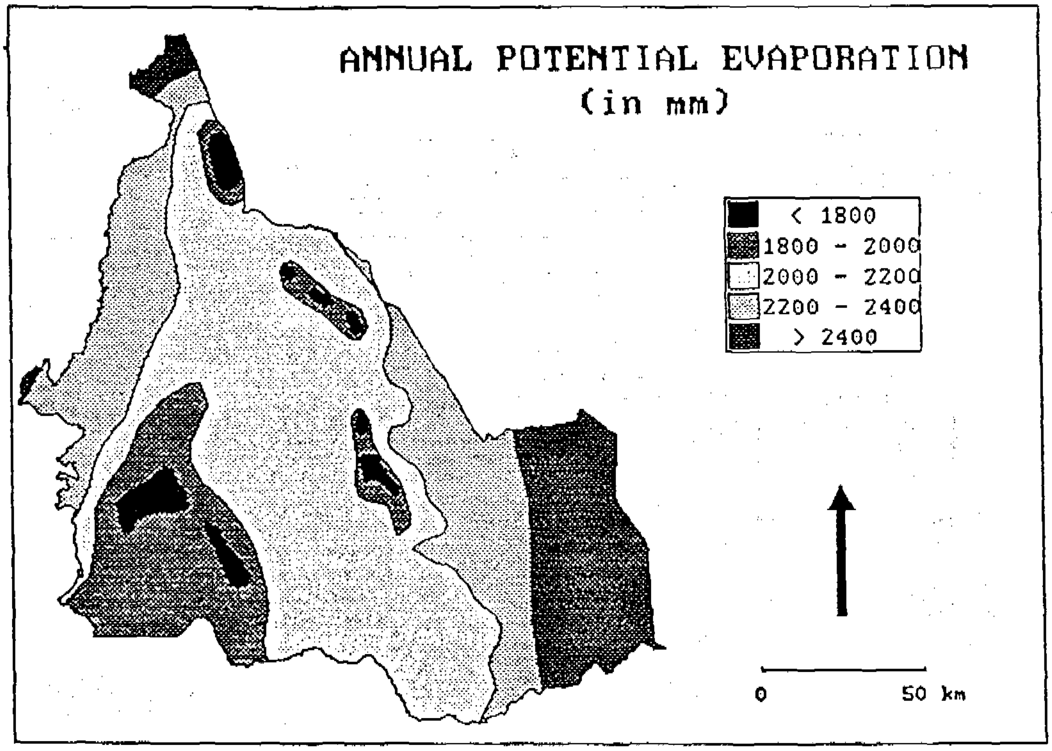
Vegetation patterns:

In semi-arid to sub-humid regions, vegetation density is related to rainfall. This relationship can be used for interpreting the vegetation density as it appears on a false-colour composite image or a "normalized difference (or green vegetation index)" image.

Visual interpretation is required because human disturbance of vegetation patterns caused by overgrazing and cultivation have to be taken into account when drawing lines of apparent equal vegetation density. These lines can be treated as isohyet lines. Areas with two classes of high vegetation density have been interpreted as well as undisturbed areas having very little vegetation.

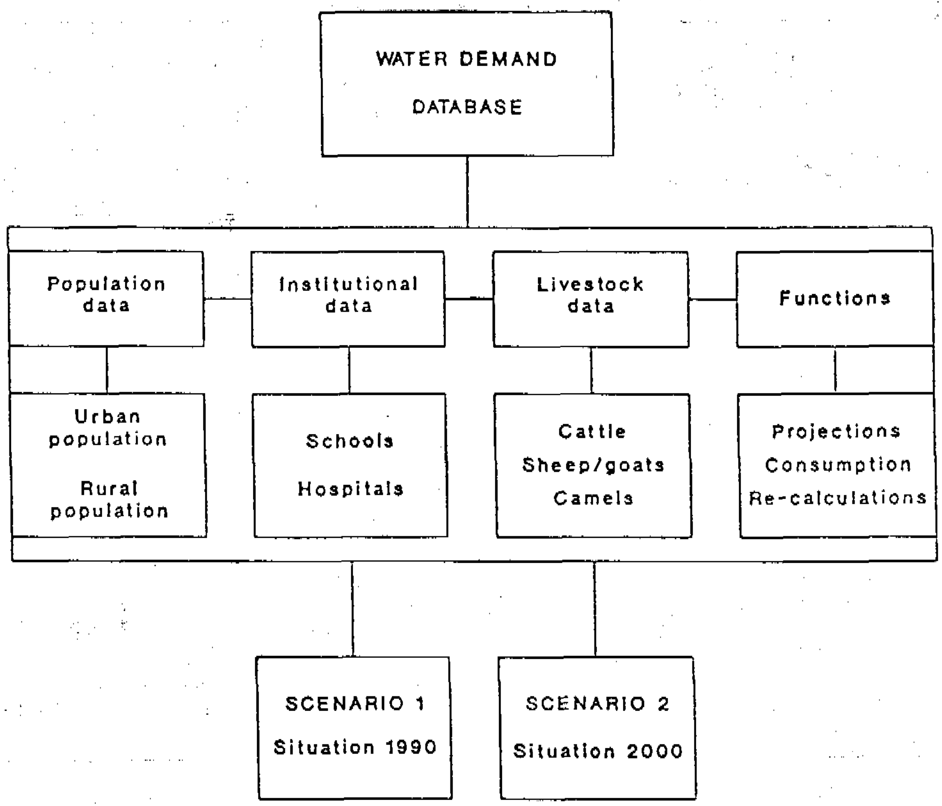
Agro-ecologic studies in the region indicated that the montane forests at higher elevation were likely to receive annual rainfalls of 800 to 1200 mm. In the areas with low vegetation density the rainfall could be less than 400 mm.

The ecologic information, the apparent vegetation density interpretation and the rainfall station data are merged to produce the map of areal rainfall.



REGIONALIZATION OF ANNUAL POTENTIAL EVAPORATION

The map of agro-ecologic zones of Kenya (Sombroek, 1982) was used to establish the spatial pattern of annual potential evaporation. The map was digitized and a vector database was created. The map was combined with the available evaporation data (Woodhead, 1968) to assign numerical values to the patterns. Data were rasterized and linearly interpolated to create an evaporation map in which each cell contained a value of potential evaporation.



BUILDING THE WATER DEMAND TABULAR DATABASE

A tabular database was prepared to describe the characteristics of the present water demand in Samburu District. Available data (WRAP, 1988; Karanga, 1990) included urban and rural populations, schools and hospitals and livestock categories. All data were referenced spatially and linked consistently to the spatial database.

Data on urban population and demand were stored as point data, together with the UTM x and y coordinates of each location. Data on rural population and demand were stored per administrative unit (sublocation). Data were organized systematically to increase consistency and minimize redundancy.

RETRIEVING SPATIAL AND ATTRIBUTE DATA DESCRIBING WATER DEMAND

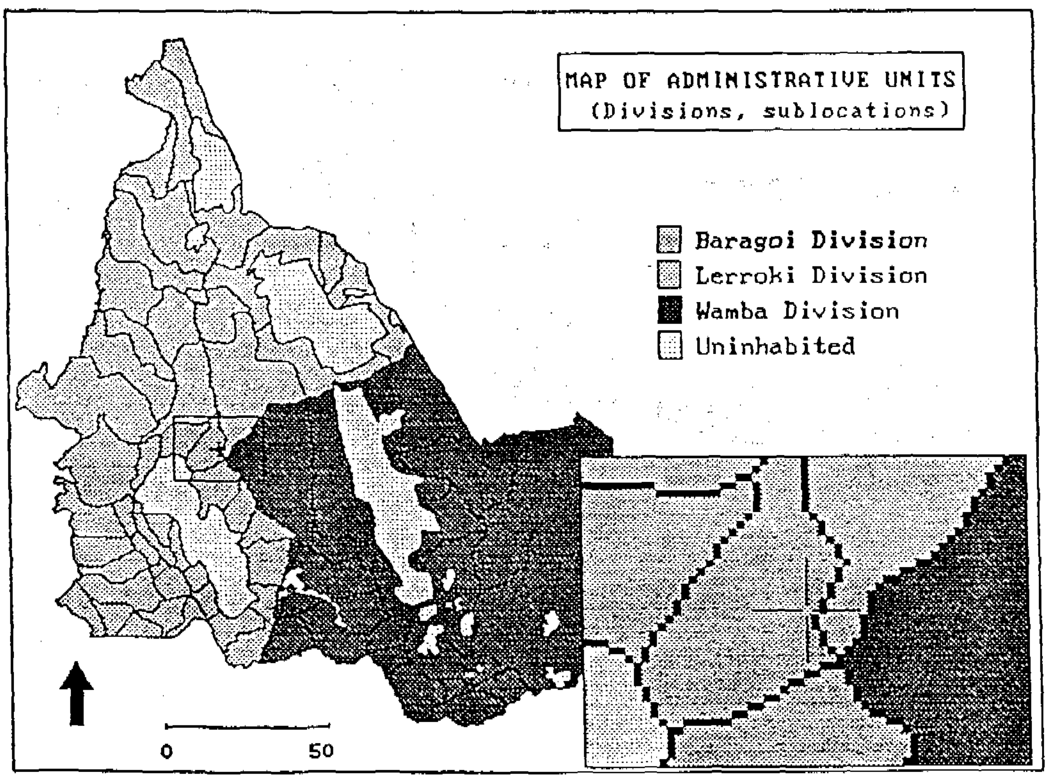
Tabular data describing water demand were linked to the administrative units (divisions, locations, sub-locations) of the district. Selective queries can be made to obtain combined information from both maps (spatial data) and tables (attribute data) about water demand: urban and rural populations, livestock, etc.

Areas without people or livestock (such as the inselbergs) were excluded from the analysis and are hereafter called "uninhabited". This exclusion improves the spatial pattern of population and livestock.

If desired, a query can be made to retrieve information on the administrative units by linking the value of the map with a table (pixelinfo).

Such a query will look as follow:

Location of the cursor on the map of analyzed area.	Row Col Pixel value 240 245 34 X: 315500 Y: 167000
Name of the map Value of the map on cursor location	1: admin Ngare narok
TABULAR DATA	Division : Wamba Location : Ngilai Sub_location : Ngare narok Rural_pop : 1926 Urban_pop : 0 Cattle : 1482 Shoats : 4160 Camels : 173 Donkeys : 137

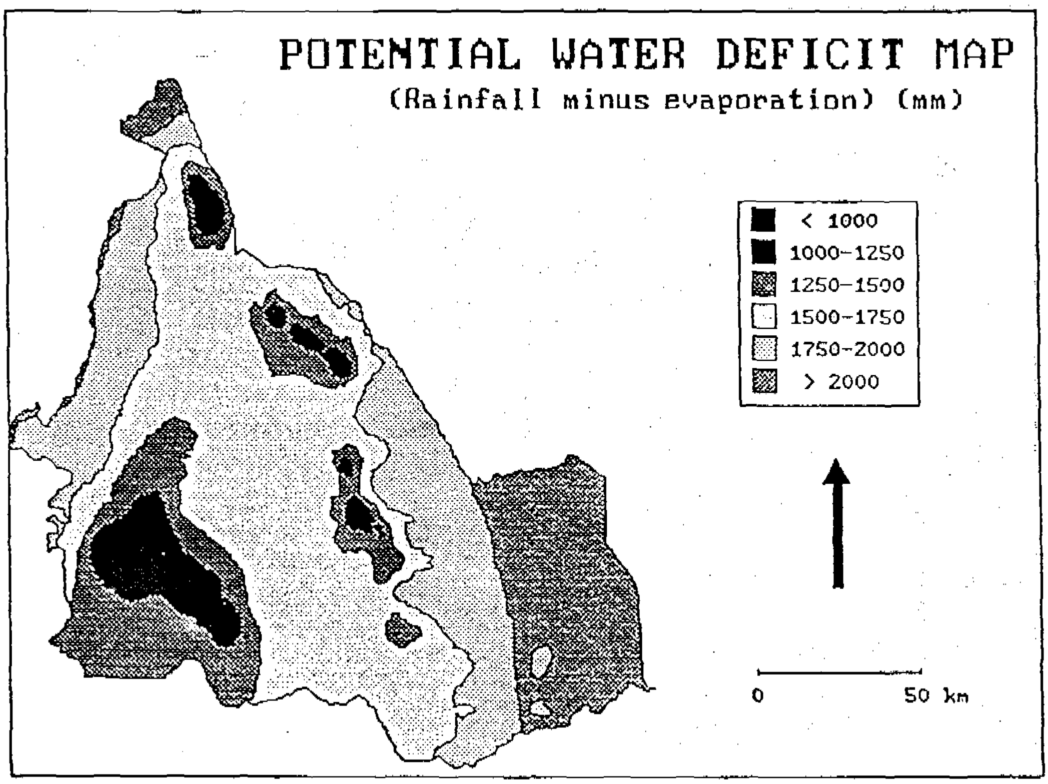


ANALYSIS

ANALYSIS

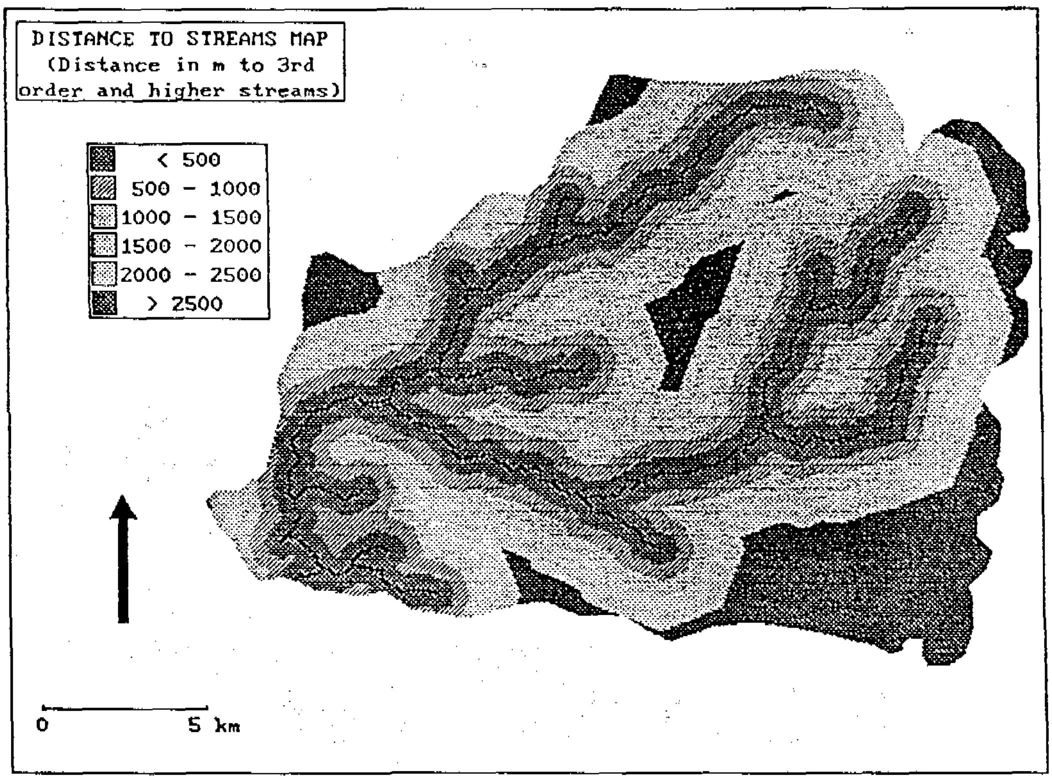
The following subjects will be dealt with in this section:

- an evaluation of the difference between rainfall and potential evaporation,
- an analysis of accessibility of limited seasonal water supply in laggas,
- a qualitative modelling of water availability in Samburu District,
- a prediction of the total human and livestock populations of Samburu District in the year 2000,
- an assessment of the total water demand for the year 2000,
- a comparison of water availability and water demand for the year 2000.



CALCULATING POTENTIAL WATER DEFICIT

The evaporation map was subtracted from the rainfall map in the raster domain to create a new map. Because potential evaporation exceeds rainfall in most of the district, this map shows spatial variation of the potential water storage deficit. The results obtained after this substraction were checked for consistency against agro-climatic zones digitized from an existing map.



ACCESSIBILITY OF SITES OF POTENTIAL LIMITED SEASONAL WATER SUPPLY

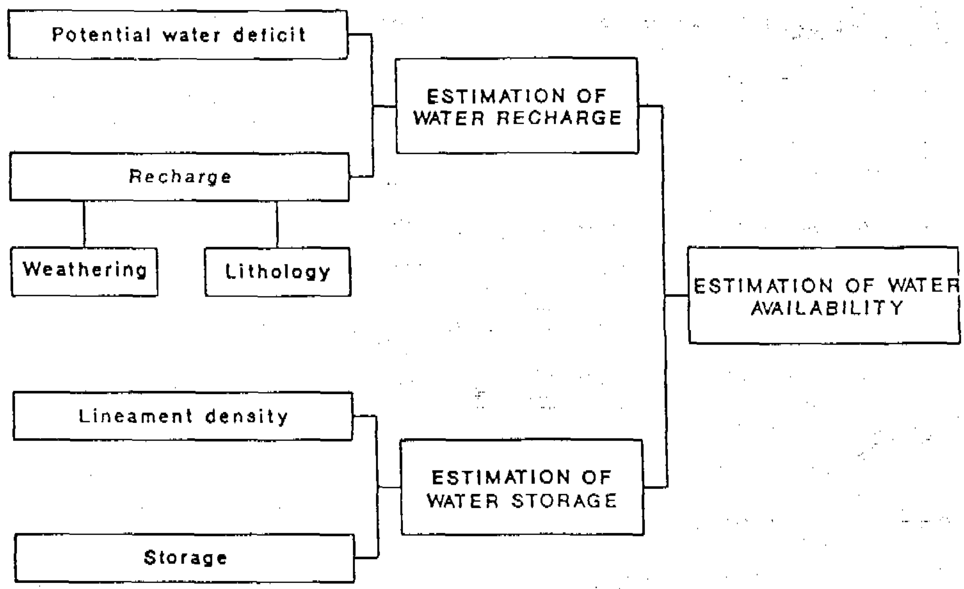
In the rural areas, water for domestic use is very often taken from shallow wells dug in the sands along the dry river beds (laggas). These shallow aquifers in the surficial deposits along the laggas are replenished by the erratic flash floods after heavy storms.

The Samburu take their water from the water points to their homesteads in small containers. Distances to the water source of 2 or 3 km are acceptable.

The smaller laggas--first and second order--do not have enough recharge to be productive. Thus only the streams of third order and higher are considered suitable for water storage and limited exploitation.

Distance computation is carried out in the raster domain and requires a vector-to-raster conversion of the ordered streams. The distance map is re-classified in intervals of 500 m.

ESTIMATION OF WATER AVAILABILITY PER TERRAIN MAPPING UNIT
using two-dimensional tables



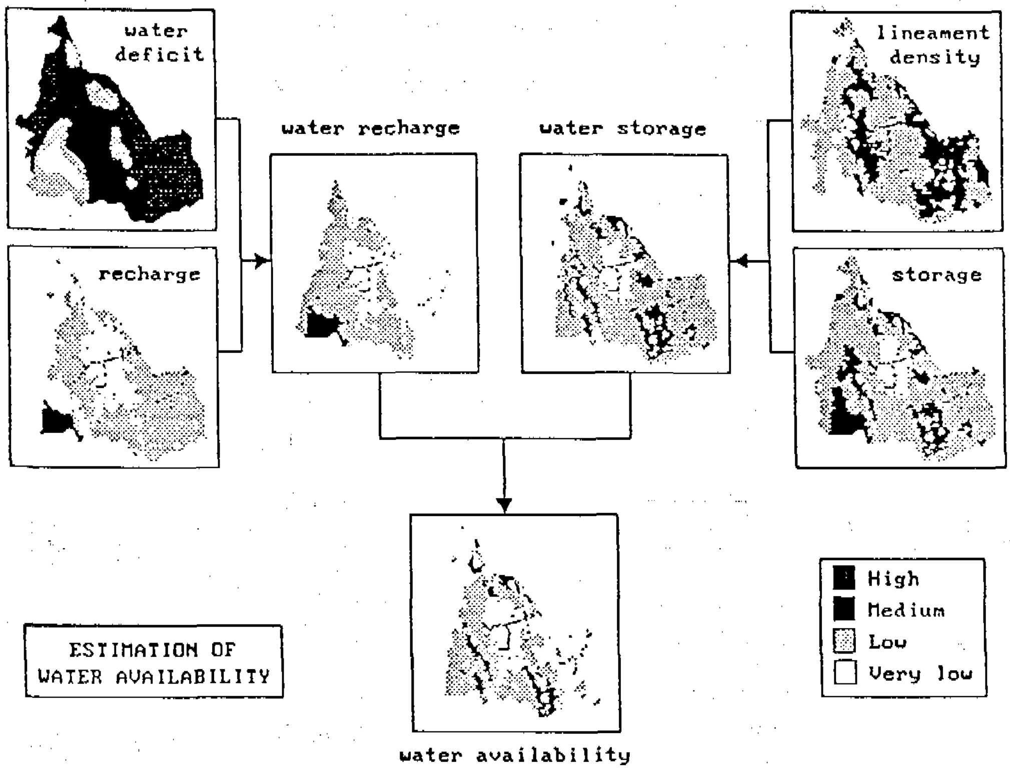
ESTIMATION OF WATER RECHARGE AND STORAGE

Estimation of water recharge

A first approximation of the water recharge for each TMU was made by estimating the recharge capability in qualitative terms: high, medium, low and very low. These estimates were based upon field experience and literature. The potential water deficit was used to refine the recharge. The lower the potential water deficit, the higher the contribution of rainfall to the water recharge will be; the higher the deficit, the lower the contribution of rainfall to the recharge.

Estimation of water storage

The lithology and depth of weathering for each TMU were used in a first estimate of water storage capacity. The TMUs were grouped according to rock types having a similar hydrologic response to storage: basement rocks, volcanic rocks and surficial deposits. In addition, the TMUs were rated according to the depth of weathering of their bedrock; more weathering implies a potential increase in the water storage capacity. As a second step, the lineament and drainage densities were included. A greater density (i.e., a close spatial distribution) suggests an increase in the potential water storage.

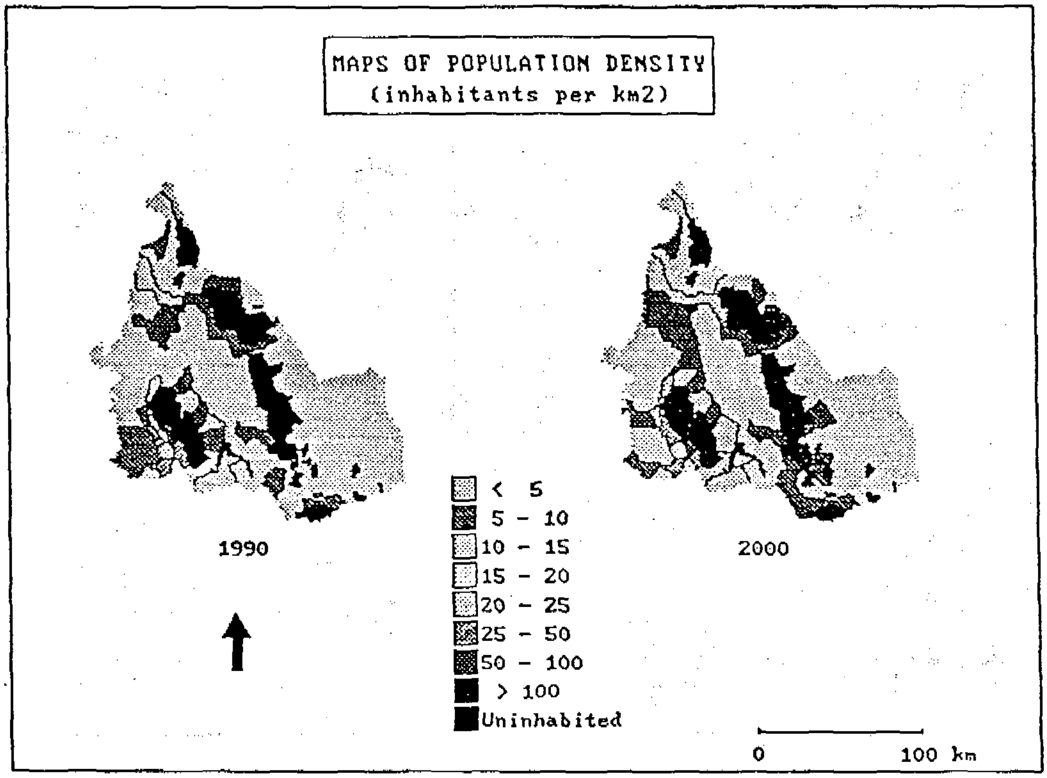


ESTIMATION OF WATER AVAILABILITY

The water availability is estimated by combining the final water recharge and water storage maps.

The water availability map therefore contains all variables influencing storage and recharge: lithology, weathering depth, recharge capability, drainage density and lineament density.

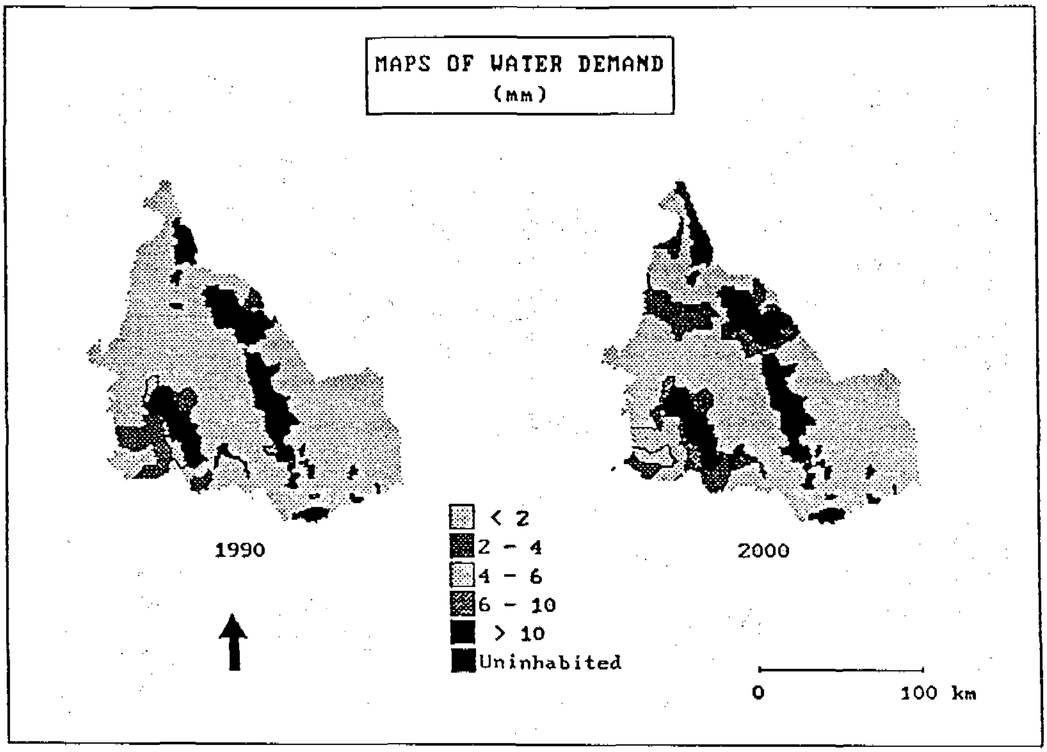
Because no data were available to quantify water storage and recharge, water availability is also expressed in qualitative terms.



PREPARING SCENARIOS OF WATER DEMAND

The first part of the analysis was carried out as a series of calculations within the tabular database. Estimates of human and livestock population growth established by Kenyan authorities (WRAP, 1988) were formalized in functions and also stored in the database. These functions were used to calculate projected human and livestock populations to the year 2000. A similar approach was used for schools and hospitals.

Scenarios of water demand were formulated, for conditions in both the present and the year 2000, on the basis of the projected population and demand coefficients estimated by government authorities (WRAP, 1988). The water demand per administrative unit includes the urban and rural populations, institutions (schools, hospitals) and livestock.

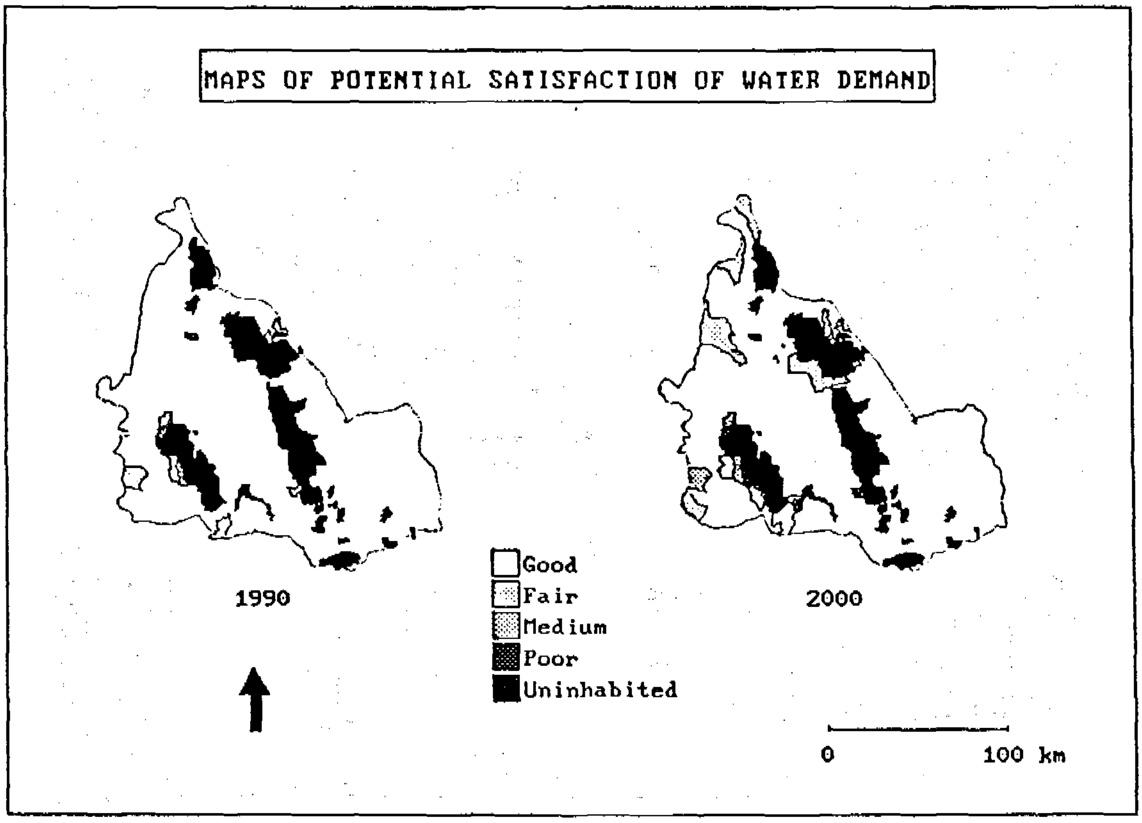


THE SPATIAL DISTRIBUTION OF DEMAND

The water demands for the two selected scenarios (1990, 2000) were analyzed spatially. The administrative units were grouped first according to their water requirements. This operation consisted of a re-classification of the map containing the administrative units according to the values of demand stored, per unit, as a column in a table. The results were grouped in ranges of demand, and areas with similar water demands were delineated.

To establish a fair comparison among the administrative units, the demand in cubic meters per day was divided by the area of the corresponding administrative unit and expressed as water requirement in mm per day.

These operations can be carried out only when the tabular data (in this instance the demand) are linked consistently to the spatial data (the administrative units).


MAPS OF POTENTIAL SATISFACTION OF WATER DEMAND
1990
2000
Good
Fair
Medium
Poor
Uninhabited
0
100 km

MATCHING DEMAND SCENARIOS WITH POTENTIAL WATER RESOURCES

The demand scenarios for 1990 and 2000 were combined with the map of storage/recharge that depicts the potential water resources in the district. A two-dimensional table was used in which one axis contained the storage/recharge map and the other the daily demand per administrative unit. The newly created map units, which expressed degrees of potential satisfaction of demand, were defined as follows:

STORAGE / RECHARGE

		Good	Medium	Poor	Very Good
D					
E	V. Low (<2mm)	good	good	good	good
M	Low (>2mm)	good	good	good	fair
A	Medium(>4mm)	good	good	fair	medium
N	High (>6mm)	good	fair	medium	poor
D	V.High (>10mm)	fair	medium	poor	poor

In other words, an area with very high demand and poor storage, for example, will be mapped as an area with a poor degree of satisfaction of demand. The maps created depict the probabilities of satisfying the demand estimated for the present and the year 2000.

THE ANALYSIS COMPONENT OF THE SAMBURU EXAMPLE

INTRODUCTION

This text was written for hydrologists with little--or no--experience in the use of geographic information systems. In the following, we will emphasize applications of GIS in practical hydrologic work, rather than in research.
A list of appropriate literature is included to assist the reader in extending his knowledge. Of the rapidly growing number of titles, a small selection has been made of currently available books, journals and symposium proceedings.

We will first take a closer look at the **G**, **I** and **S** of GIS.

Geographic

Hydrologists are committed to studying the effects of physical catchment factors including the hydrogeologic factors, on the flow and storage of water. Hence a multitude of spatially related (i.e., geographic) data concerning rainfall, evaporation, vegetation, geomorphology, soils and rocks have to be considered. Also of interest are social and economic data related to where the demand is for water for urban and industrial supplies, irrigation, etc. In addition, technical data are required, such as locations and types of tubewells, rain and river gauges, power supplies, etc. Thus the fast storage, retrieval, display and updating of map contents are important functions.

Information

Data may be described as "facts of any kind, or notes", whereas information is related to knowledge. Information may perhaps be described as data with knowledge added, or as data manipulated for a specific purpose. For example, lists of daily rainfall and recording station coordinates form a "databank", but the coefficient of variation of the annual rainfall, derived from these lists, may be regarded as "information".

A system that can store the data, select and classify the stations and perform mathematical and sorting operations is called a "database" and information can be extracted from it for a given purpose. If this information can also be displayed in the form of a map (screen, printer/plotter) we can speak of geographic information.

System

A soil map with a legend and report is in fact a quite complex geographic information document. When this map is evaluated in terms of infiltration (i.e., redrawn after classification) and overlayed with a transparency of a map showing the number of rainy days to prepare an infiltration estimate, a system operation has been performed by hand.

All GIS operations can, in principle, be done manually, but many tasks are so time consuming that they are performed only for very small research areas. By using computers and their graphics facilities and GIS software, the laborious tasks can be performed with ease.

Analysis

Apart from storing, retrieving and displaying data or information, the strength of a GIS (with emphasis on the I) lies in the ability to assist in the analysis and transformation of data into desired hydrologic information. A typical analytic GIS function is the intelligent comparison of spatial hydrologic data. Suppose there is a strong rainfall gradient in a hard rock area. We could combine a map of aquifers (as derived from a geohydrologic survey) with the rainfall maps and plot the locations for which well yields are known (using colour symbols) on the combined map (overlay), together with mapped fractures. Inspection of the patterns would clearly indicate whether there is an association between well yields and rainfall or distance to fractures. If topography is added, the association of well yields with recharge/discharge areas of flow systems could also be studied.

Similarly, for the study of surface water resources, it could be useful to prepare input data for a multiple regression study relating the direct runoff to rainfall and physical catchment factors. This would require overlaying a number of maps in the GIS: rainfall (isohyets); geomorphology (drainage densities, slope steepness, floodplains or valley bottoms); soils (texture, depth); geology (permeability). The aggregated values per catchment could be regressed (multiple regression) against direct runoff. Taking this example one step further, an isohyet map can be prepared showing the rainfall of a certain frequency and the multiple regression can be prepared using peak flows of the same frequency.

It will be evident that a wealth of methods of hydrologic analysis can be used. This increases the desirability of linking typical GIS operations--such as map calculations, interpolation and other geostatistical methods--with hydrologic methods, as well as interfacing with simulation models. The Samburu demo shows some basic operations.

Model Base

The model base may be considered as a collection of hydrologic models, selected or developed for handling hydrologic spatial data, with an interface to the GIS (file transfers) or to be executed within the GIS using the system's command language.

For example, the GIS can be used for the preparation of input for a finite element groundwater model or for a deterministic rainfall-runoff model. The data have to be transferred from the GIS to the model.

Depending on the versatility of the GIS and its software, however, mathematical modelling can also be performed within the system. For example, certain simple soil moisture models can be programmed in a GIS whereby full spatial processing takes place, taking into account the rainfall, potential evapotranspiration, soil moisture holding capacity and rooting depths. This can be done using either pixels or all logical combinations of units (polygons).

The Samburu demo shows the use of empirical modelling based on field experience and general hydrologic knowledge. Some details are described below.

An obvious component of the model base is the facility for common operations, such as checks for consistency of the data, frequency analysis, plots of hydrographs with corresponding rainfall and so on. The same is true for linkage with statistical packages and spreadsheets. This facility can be incorporated in special hydrologic database packages.

Most spatial (distributed) hydrologic models are deterministic, i.e., all processes are simulated by equations. This is deductive modelling. The procedures used in the Samburu demo are deductive.
A GIS is also a most suitable tool for inductive modelling. The basic philosophy is that a set of rules is developed from spatial input datasets to explain the (available) sampled spatial distribution of the characteristic (flow duration, well yields, etc.). The development of the rules makes use of various statistical techniques, numerical taxonomy and so on. This approach is expected to be increasingly applied.

A GIS can thus be considered as a versatile tool to assist hydrologic analysis and synthesis. It is nothing more than a tool, but there are a number of specific considerations related to spatial GIS processing that are briefly described below.

MODELLING WATER RESOURCES AND DEMAND, SAMBURU DISTRICT

Concept of the analysis of water availability

Essentially, the passage of water from rainfall excess to storage in aquifers is tracked by preparing three "information layers", as shown in figure 1.

First a map of the differences between precipitation and evaporation is made. Second, the recharge possibilities (not amounts) are estimated by considering the geomorphology, soils and vegetation (grouped in the so-called "TMUs"). The two products are combined using simple logic in what is called "the potential recharge".

Third, the storage possibilities in aquifers are considered by classifying the geologic units. "Potential recharge" is then combined with storage to produce the groundwater availability map. Dynamic aspects related to groundwater flow are not considered.

The meteorologic layer

Rainfall

The first and upper "information layer" is the meteorologic layer, consisting of rainfall and evaporation. Preparation of the spatial annual rainfall patterns was discussed in the demo. Although difficult to prove, the one using the vegetation responses, together with the station data, may come the closest to the (unknown) true isohyets, because the vegetation patterns are also associated with elevation.

Attempts were made to establish monthly and seasonal regressions for the precipitation-elevation relationships in various parts of the district: the southeastern part has a monsoon climate and the remainder a continental climate. An acceptable result was obtained only for the southeastern part. Bi-monthly rainfall maps for the entire district were made on a provisional basis, but it was judged wise not to include them in the demo.

Evaporation

As can be judged from the distribution of the stations in the demo, it was difficult to establish the spatial pattern of evaporation (E). Woodhead's (1982) regional map was therefore included, as well as an agro-ecologic map of Sombroek et al (1982). The data available were not sufficient to test the results of E estimates based on temperature, such as the formulas of Turc or Khosla, or Thornthwaite's method using the heat index. Also the elevation-temperature gradient(s) in Samburu District were unknown. Thus the elevation model could not be used with confidence for an improved estimate of the spatial evaporation. For a first rough estimate of the bi-monthly water budget (P-E), a theoretical gradient of temperature with elevation was assumed for the creation of provisional ET maps.

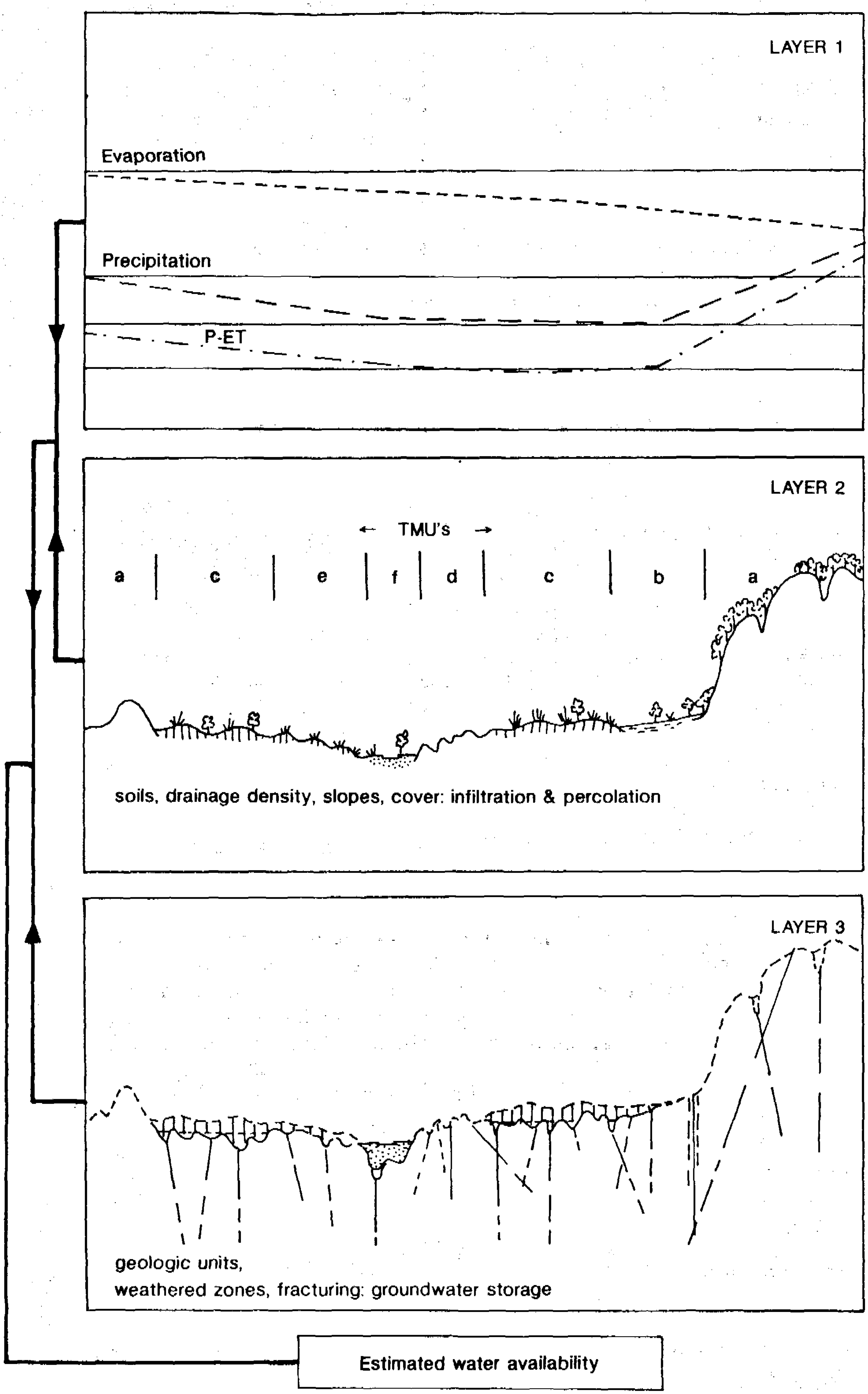


Figure 1. Scheme showing information contents of three layers used for the GIS procedures

Water deficit

The precipitation (P) map and the evaporation (E) map are not of equal spatial quality. However, the demo contains a map showing the subtracted values (P - E) because only the relative values were used.
On an annual basis there is nowhere a surplus. On the provisional bi-monthly (P-E) maps, there are a few places at high elevation where a small water excess may occur. All these areas fall in the class of the least deficit of the annual (P-E) map.

It was reasoned that where the deficit is lowest, there is a greater chance that water precipitated during wet periods of a few days will infiltrate, although on a averaged annual basis there is still a deficit. Estimation of the proportion of potential recharge would require an analysis of daily rainfall and groundwater rises in shallow wells. A sufficient number of records of the latter were not available for this study. Thus only a few relative classes of the (P-E) map were used.

The potential recharge map

Hydrologic responses, such as infiltration or runoff, cannot be determined from aerospace images, but it is possible to segment the terrain into units that group natural associations of geology, geomorphology and soils. These are known as mapping units. Vegetation patterns are often associated with such units.
The main problem that arises after the inventory/mapping stage is evaluating the hydrologic processes in each unit, particularly the recharge. The approaches are :
1. water level fluctuations and specific yield determinations
2. estimations using natural or other tracers
3. analysis of the base flow
4. estimations of relative recharge using field experience and data reported in the literature.

The first two approaches were unfortunately beyond the scope of the study. Flow data of one year for a medium-sized hard rock catchment became available during the study: the annual baseflow was approximately 1% of the rainfall during 1989. However, the recharge in some locations with favourable conditions can be much greater than this small quantity. The main reason is that many weathered and fractured zones, which contain the groundwater, have an imperfect connection with the stream network, as shown in the schematic illustration of figure 1.

Values for groundwater recharge reported in the literature for semi-arid hard rock terrain vary from some 20% to <1 % of the annual precipitation. This wide variation reflects the strong influence of local factors. Quantitative recharge rates therefore cannot yet be established in the district. For the evaluation, the units were classified according to estimated relative rates with the advice of local hydrogeologists.

Combination of maps

There are several ways to combine two or more maps in a GIS. For the chapter on analysis in the demo, so-called two-dimensional tables were used. The example of the combination of the water deficit map and the terrain unit map (TMU) will be used for explanation. In fact, information layers one and two were combined according to their hydrologic characteristics.

The annual water deficit was divided into six classes, D1..D6, covering the range of < 1000 mm to > 2000 mm, in steps of 250 mm. Four classes of estimated infiltration and percolation (I1 ..I4) were made for the many terrain units in the district. The low number of (relative) classes of course reflects the imperfect knowledge of the recharge conditions in this area. The class denoted I1 represents terrain units with poor recharge possibilities, such as sloping, dissected units with shallow soil cover and sparse vegetation. Units with the best infiltration and transmittance were grouped in class I4. Examples include units with fluvial sands or gently sloping, little-dissected units with well developed soils and good ground cover, etc.

A small matrix configuration (2-D look-up table) was made of both classifications , as shown below.

		DEFICIT					
REL. INFILTR. & PERLOCATION		<100 D1	100-125 D2	125-150 D3	150-175 D4	175-200 D5	>200 cm D6
good	I1	1	1	2	2	3	3
medium	I2	1	2	2	3	3	4
poor	I3	2	2	3	3	4	4
very poor	I4	2	3	3	4	4	4

For each combination of D and I classes, a figure was entered representing the potential recharge (R). Here only four values (1 .. 4) were used instead of a possible (4 x 6) 24 values. To use many values (i.e., new combination classes) would suggest a level of accuracy that did not exist. The fact that one of the classifications (recharge) had only four relative classes was a limiting factor.

As can be easily seen, the matrix is symmetric, giving an equal weight to each of the classifications of deficit and/or relative infiltration and percolation. Thus the combination of a deficit in the range of 1000 - 1250 mm (D2) and a low infiltration and percolation (I1) was judged to have the same potential recharge as the combination < 1000 mm (D1) deficit and low to moderate infiltration and percolation (I2). Similarly, the potential recharge was estimated to be the same for such combinations as D6/I2 and D4/I4.

The values resulting from the combination, i.e., the estimated potential recharge (R1..R4), can be shown on a map. The GIS algorithms sort out where such (logical) combinations occur and then assign the corresponding R-value. Instead of the 2-D table, the same result can be achieved by relational statements (e.g., IF D = 1250 to 1500 mm AND Iclass = 2 THEN classify R = 2 ,etc., or whatever syntax the system uses).

The new classification of potential recharge was combined with the classes of potential groundwater storage (aquifers - aquicludes), combining information layers two and three (see figure 1) in a similar fashion. The demo contains a flowchart of these steps as well as the resulting maps.

Discussion

Combination procedures

It is evident that these procedures are based on judgement, which should be replaced by procedures based on sufficient observations directly related to groundwater recharge and storage. At this stage, the look-up tables contain many arbitrary decisions. The procedure should consist of models or equations established by regressions. Unfortunately, there were no such data or tested models for application in Samburu District.

The demo contains an example of how regression results can be used, namely for the conversion of elevation (DEM) to isohyets.

For an initial evaluation in a more humid environment, the well-known Thornthwaite and Mather (T&M) soil moisture budget (a simple model) could be used, perhaps with a percolation extension. In several GISs, the T&M method can be programmed to operate either on a pixel basis or on all logical combinations of mapping units/ deficit-surplus classes (isolines). The rooting depths could be derived from cover classifications using remote sensing data, and the soil moisture-holding characteristics from soil maps or physiographic terrain unit maps.

Dynamic aspects

Dynamic aspects, such as groundwater flow, should also be considered. In the southwestern volcanic part of Samburu District, there are seasonally marshy areas which can also be identified on the satellite images. A considerable part of the water is believed to derive from groundwater discharge, because of the upward component of a flow system that has the intake area in the elevated part adjoining the Rift Valley.

The DEM, the geologic information and the upward discharge areas as derived by interpretation of the image could be used to prepare the input for a flow model. The results of groundwater modelling can be brought back into the GIS procedures. The flow (in mm) within the intake, transient and discharge areas could be presented on a map and this information can be mosaicked with the more local groundwater resources in the weathered crystallines.

The dynamic aspects were omitted in this demo, but they will be included in a demo pertaining to the Cibodas area in west Java (Indonesia) within the framework of IHP M-2.3.

Geostatistics

As the demo illustrates, interpolation procedures are required to convert point data into spatial information. This raises the question of which interpolation methods are appropriate for the various hydrologic aspects (groundwater tables, rainfall, etc.) The GIS should have a library of interpolation methods and the hydrologist must be able to select the appropriate method, considering the density of the dataset and the nature of the problem.

There may be important differences for given locations if two modelling approaches are followed:
(a) Model results are calculated for a number of locations for which the model input variables are known, as well as calibration data. The model results are then interpolated to the given locations.
(b) The input variables of the same model are interpolated to the given locations and the model results are obtained with the interpolated values.
Apart from such difficulties when using point data, there is an additional problem when model results are presented in raster format. Most combination operations (overlaying, etc) are performed in the raster domain for reasons of efficiency. Interpolation results are also shown as raster values. In fact, most interpolation procedures first calculate interpolated values on a grid basis, and then calculate the positions of the isolines with respect to the regular grid.

The size of the raster cells has an important effect on overall accuracy, as is evident by considering the problem of capturing sinuous boundaries by, say, 0.5 x 0.5 km. Matters are worse when intricate and complex terrain patterns have to be dealt with. The use of mapping units alleviates the problem because this forms an "object oriented" approach, but it does not solve it fully. The spatial variability of infiltration or soil moisture within soil types, even on 1: 20,000 scale soil maps, has been established in many studies.

It is therefore useful to analyze the effects of the selected raster size on the consistency of the data quality during data capture and transformation. There are various techniques that can be used for such an analysis, such as the evaluation of the semi-variogram or the coefficients of two-dimensional autocorrelation with varying raster sizes. In practical application, however, it is not the method but the quality of the dataset that hampers the use of rigid testing results. The conditions in Samburu are a good example.

Error propagation

The two-dimensional (combination) potential recharge table described above and the flowchart in the demo indicating various combinations contain sufficient examples of potential sources of error and the principal of error propagation. To illustrate error accumulation and propagation and various sources of error, we will describe a sort of "worst case scenario".

A site (or small area) is located in the rainfall shadow of a hilly complex, at low elevation, and behind a wide gap in the hilly range. This gap causes a higher wind velocity than at the few locations (at higher elevations) where evaporation data are recorded. There is colluvium of limited depth at the site, but below the colluvium the rocks are not weathered, little-jointed and have few fractures. Hence groundwater availability is poor.

Following GIS procedures, errors are introduced in each information layer (see figure 1) and in the contents of the combination look-up table. The latter is called here "transfer function error".

Layer 1

Assume the rainfall map is based on the regression of rainfall with elevation (the map based on vegetation patterns is probably preferable). The site lies in the rainfall shadow, and there will thus be an over-estimate of the rainfall in the map of 150 mm, as illustrated in figure 2. The error is caused by a deviation from the regression ($r=0.7$).

Assume that the real annual evaporation at the site is 2400 mm because of the high temperature and windy conditions. The value on the evaporation map is 2100 mm, however, because a linear interpolation technique was used with only recorded station data. No corrections for temperature and wind speed could be made because of lack of data. The error is caused by insufficient data for proper interpolation.

The first accumulation of error for the site occurs when the P-E map is prepared, resulting in a deficit of class D3, 1400 mm (700 - 2100 mm), whereas the real deficit is in class D5, 1850 mm (550 - 2400 mm).

Layer 2 and combination

The infiltration and percolation properties of the site were evaluated correctly as "good" (class I1; sandy colluvium with cover), but there is an error in the transfer function, expressed in the look-up table. The combination (I1 \ D3) should have resulted in a potential recharge class R2 (medium class, as shown in the look-up table above), but it was changed incorrectly to class R1 (I1 \ D3 = R1). The true combination for the site is (I1 \ D5 = R3).

Layer 3

Then errors caused by the effect of pixel size are introduced. The site (marked by a cross in figure 3) is located on rocks classified as having "poor storage", S3. When combined with infiltration, this results (according to the look-up table used) in a groundwater availability class of A3 ("poor"; R3 \ S3 = A3).
With the selected pixel size and using the majority rule during the vector-to-raster conversion, the full pixel is classified as S2, as illustrated on the map. The look-up table combining storage classes with infiltration and percolation classes (not shown) gives R1 \ S2 = A1, having the qualification "good".
The discrepancy with the real value is obvious.

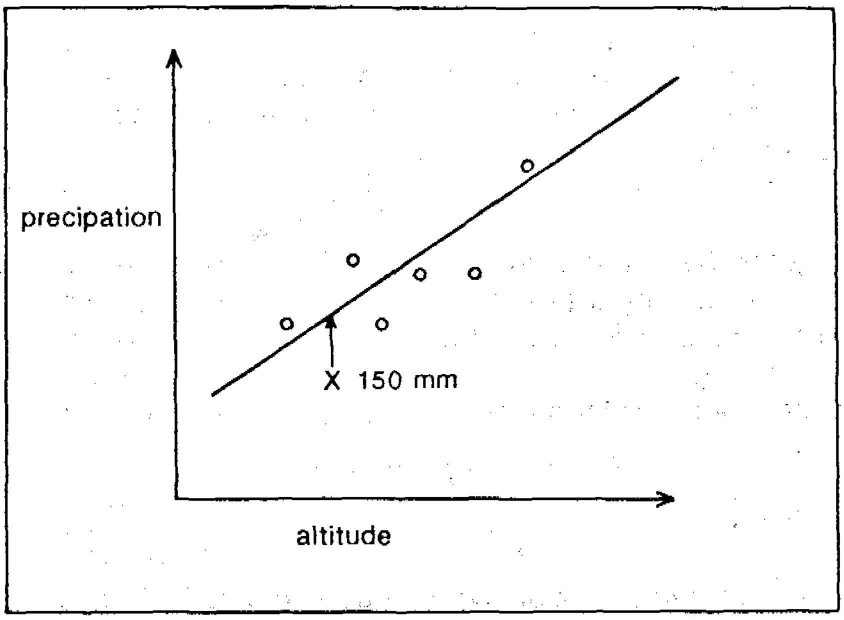


Figure 2. Difference of actual rainfall with regession value

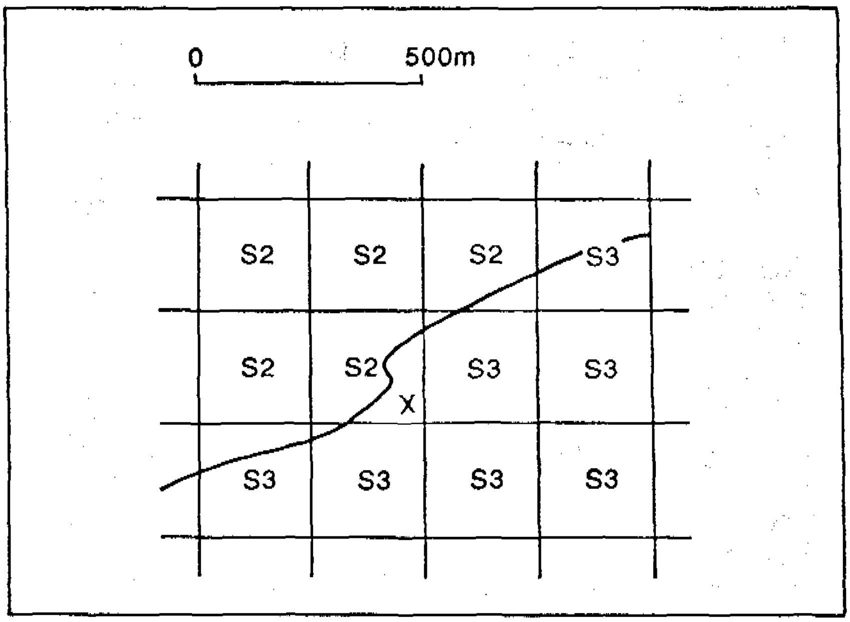


Figure 3. Sketch illustrating effect of classification of pixels during rasterization

Conclusion

The capabilities of a GIS in terms of hard- and software (including processing of satellite data) should not distract attention from the problems that may be encountered. These problems are usually at the human end of the user interface, and they are often related to a lack of relevant hydrologic data and the non-availability of appropriate transfer functions and applicable models for the region of study--in addition to insufficient insight into the various hydrologic processes of the area. There is obviously much scope for further development of the model and rule base for GIS procedures.

As illustrated by the Samburu demo, it is possible to proceed with a hydrologic study without deterrence by these obstacles. Local hydrogeologic experience and a combination of various data sources (remote sensing, station data, geologic maps and some geohydrologic data) are used to prepare the results. Their preliminary nature can be made explicit by considering accuracies and error propagation.

Summary

Emphasis has been placed on the analytic function of a GIS. This does not diminish its important function as an efficient system for storing, retrieving, editing/updating and displaying hydrologic data and information. However, the importance of the accuracy and dependability of the data processing results must always be emphasized.

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Responsibility for the content of this demo rests fully with us.

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