GROUNDWATER EXPLORATION USING REMOTE SENSING AND A LOW-COST GEOGRAPHICAL INFORMATION SYSTEM

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ABSTRACT: Now that personal computers (pc's) have become more powerful, portable, and affordable, geoscientists can make full use of developments in computer-aided mapping, particularly Geographical Information Systems (GIS). The *IDRISI* GIS was used to 1) carry out image processing on satellite images; 2) assess the reliability of the interpreted lineaments; 3) create maps showing individual lineament lengths, areal extent of interconnected lineaments, and targets for groundwater boreholes; and 4) incorporate socio-economic factors, by creating maps that show the proximity of villages to sites considered favourable for boreholes. The exact location of each site for drilling was decided on the basis of geophysical surveys over the areas that had been targeted by the remote sensing and GIS analysis. Most of the remote sensing and GIS work was carried out in Ghana in two weeks, during which the 'ground truth' of lineament maps was checked. The total cost of the hardware and software used in this project (16-colour laptop pc, portable colour printer, and *IDRISI*) was slightly less than US$ 2,600. The relatively low cost and ease of use of this system make it a technology that is readily transferable to developing countries.

RÉSUMÉ: Maintenant que les ordinateurs personnels sont puissants, portables et accessibles, les spécialistes des sciences de la terre peuvent profiter pleinement des développements en matière de cartographic assistée par ordinateur, en particulier avec les Systèmes d'Information Géographique (SIG). Le SIG *IDRISI* a été utilisé pour 1) traiter des images satellites; 2) tester la validité des linéaments interprétés; 3) créer des cartes donnant les longueurs de chaque linéament, l'extension des linéaments interconnectés et les implantations pour les forages; et 4) introduire les facteurs socio-économiques en créant des cartes montrant la proximité des villages par rapport aux sites considérés comme étant favorables pour les forages. La position exacte de chaque site de forage a été décidé sur la base de campagnes géophysiques sur les territoires qui ont été définis au moyen de la télédétection et de l'analyse du SIG. La plupart des études de télédétection et portant sur le SIG ont été menées au Ghana, durant deux semaines au cours desquelles a été vérifiée la réalité de terrain des cartes de linéaments. Le coût total de l'équipement informatique et des logiciels nécessaires au projet (PC portable 16 couleurs, imprimante couleurs portable et *IDRISI*) est un peu inférieur à 2600 Dollars américains. Le coût relativement bas et le type d'utilisation en font une technologic tout à fait applicable aux pays en voie de développement.

RESUMEN: Ahora que los ordenadores personales (pc) son cada vez más potentes, portátiles y económicos, los científicos pueden utilizar plenamente los desarrollos en generación de mapas por ordenador, particularmente, los Sistemas de Información Geográficos (SIG). Se utilizó el SIG IDRISI para 1) procesar

imágenes de satélite; 2) evaluar la confianza de los lineamientos interpretados; 3) crear mapas que muestren las longitudes de los lineamientos individuales, la extensión superficial sus interconexiones y los posibles lugares para sondeos hidrogeológicos; y 4) incorporar factores socio-económicos, creando mapas que muestren la proximidad de las poblaciones a los lugares que se consideren apropiados para la localización de los pozos. La localización exacta de cada perforación se decidió basándose en sondeos geofísicos sobre áreas previamente analizadas por teledetección y SIG. Gran parte de este trabajo se llevó a cabo en Ghana, a lo largo de dos semanas, durante las que se comprobó la veracidad de los mapas de lineamientos. El coste total del hardware y software usados en este proyecto (un pc portátil de 16 colores, impresora de color portátil y IDRISI) fue algo menor de US$ 2,600. El relativamente bajo costo y la facilidad de uso de este sistema, le convierte en una tecnología fácilmente transferible a países en vías de desarrollo.

INTRODUCTION

The central part of the Volta Basin, in the vicinity of Tamale in northern Ghana, is one of the most sparsely populated regions of Ghana. The reason for this is simple: a lack of both surface water and groundwater. Although this region has 1,000-1,300 mm of rainfall per year, virtually no rainfall occurs during six months of the year. Furthermore, up to 86 percent of the annual rainfall is lost to evapotranspiration, with about 10 percent remaining as surface runoff; only 2-4 percent of the rainfall recharges the regional aquifers (Tod, 1981). During the dry season, many villages are totally dependent on hand-dug cisterns and small (1-2 ha) reservoirs that are only a few metres deep. Both types of surface-water supplies are invariably contaminated with pathogens, notably Guinea Worm and Bilharzia, giving this region one of the highest mortality rates in Ghana.

Groundwater is rarely available near the centre of the Volta Basin, due to the predominance of mudstones and siltstones. Toward the margin of the basin, groundwater is more abundant, due to the presence of coarser sediments and a greater degree of rock fracturing. A 'successful' borehole is here defined as one that yields at least 20 litres of water per minute, sufficient for hand-pump installation. The success rates of water boreholes on the margins of the Volta Basin are 40-66 percent. Near the centre of the basin, the success rates decline to 13-21 percent (Tod, 1981; Iddirisu and Banoeng-Yakubo, 1993).

A recent programme of groundwater exploration in the region of fine-grained sediments west of Tamale (fig. 1) was designed to locate fracture zones that would increase the likelihood of drilling successful boreholes. Lineament maps derived from the interpretation of panchromatic aerial photographs were used to target sites for geophysical surveys. At each targeted site, VLF-EM and electrical resistivity surveys were carried out along three lines, 250 m long and 10 m apart, with readings every 10 m. Of the 38 sites that were drilled during that programme, only five (13 percent) were successful (Iddirisu and Banoeng-Yakubo, 1993). This lack of success was probably due to the presence of relatively few fractures in the fine-grained sedimentary rocks, and to the low, relatively featureless relief of the region; these conditions make lineament mapping from aerial photography extremely difficult. An additional problem was the relatively poor quality of the panchromatic aerial photographs that cover the study areas. The only ones available for interpretation were from 1960, 1961, and 1969, and the prints were old, worn and had poor contrast.

All 38 drilling locations were initially selected on the basis of aerial-photograph lineament mapping, with follow-up geophysical surveys to locate the best fracture zones for drilling. Most (87 percent) of the fracture zones targeted by the geophysics failed to yield sufficient amounts of water when drilled. A review of the aerial-photograph lineament mapping carried out for this initial project showed that, of the five successful boreholes, only two (5 percent of all 38 sites) were within 30 m of aerial-photograph lineaments; 95 percent of the aerial-photograph lineament maps failed to contain identifiable fractures that could successfully supply boreholes. The very low success rate of this initial groundwater exploration programme appears to have been due to the difficulties encountered at the aerial-photograph interpretation and lineament-mapping

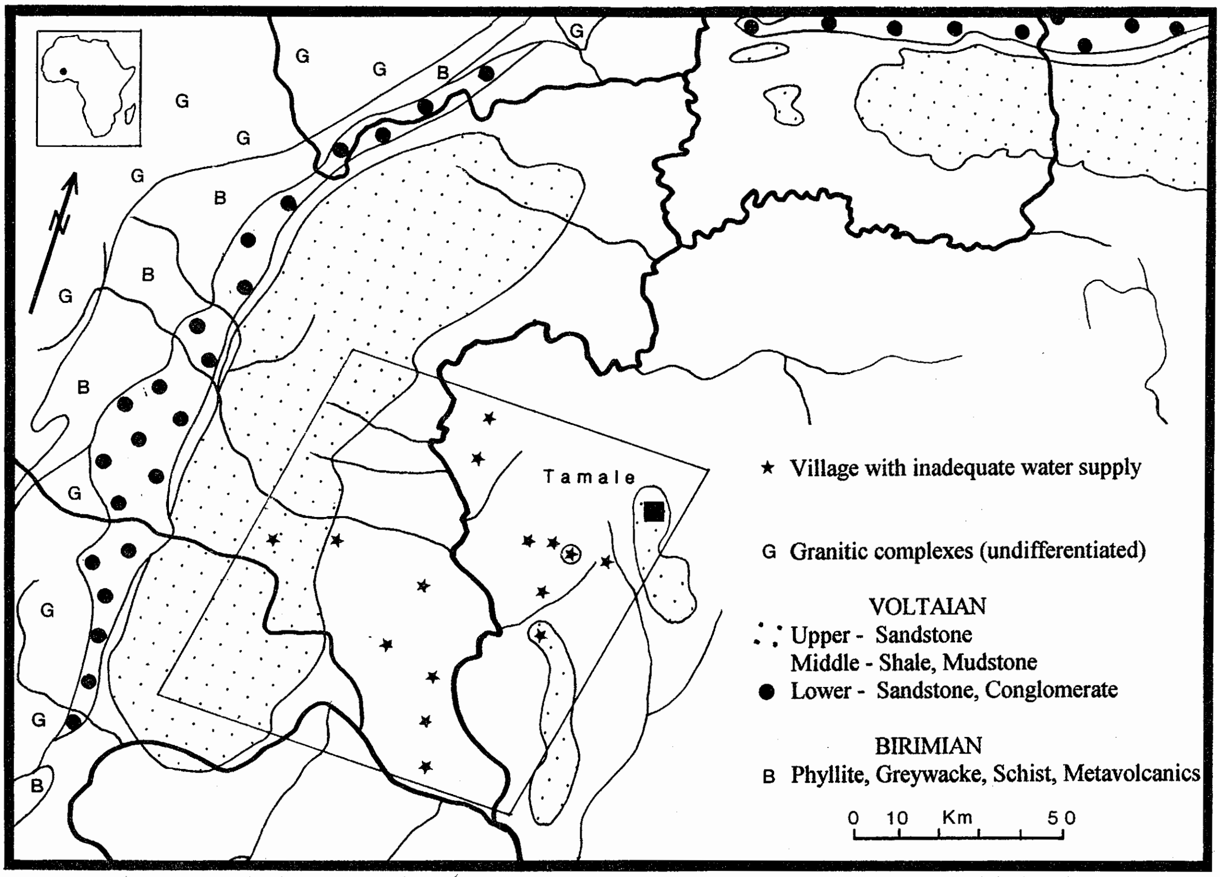

Figure 1. Geology of northern Ghanaa and location of the study area. Box indicates extent of Landsat Quarter Scene; open circle indicates village featured in figures 2, 3, and 4.

stage, rather than at the follow-up geophysical-survey stage.

The objectives of the exploration programme outlined below were to target probable sites of fracture zones for follow-up geophysical surveys and borehole drilling, using low-cost, computer-aided mapping techniques that could be transferred with relative ease to water-sector workers in Ghana.

SATELLITE IMAGE PROCESSING AND GIS

In an effort to improve the success rates of groundwater exploration in this region, a GIS with image-processing capabilities was used, along with satellite images in the visible and infra-red parts of the spectrum. The GIS software, IDRISI, was developed at Clark University, USA, with support from the United Nations Institute for Training and Research (UNITAR). Non-commercial organisations can purchase the DOS version of IDRISI for only US$ 320; a new, much-improved version running on Windows is now available for US$ 495. Within this low-price category, IDRISI is probably the most powerful integrated GIS and image-processing software available (Chuvieco, 1991). IDRISI is also relatively 'user-friendly' and can be used to produce maps from satellite images (or scanned-in aerial photographs) after a few days of working through its tutorial exercises. Furthermore, IDRISI does not require expensive computer hardware; it can run on computers of the 80286-generation and above, and it was used on a 16-colour 80386 laptop computer during fieldwork in Ghana.

A Landsat Thematic Mapper (TM) Quarter Scene was purchased, and IDRISI was used to produce images for lineament mapping. Unlike the single broad sector of the electro-magnetic spectrum observed with the panchromatic aerial photography, the Landsat TM data allow seven sectors, or Bands, of the spectrum to be examined. Simple contrast-enhanced (histogram-stretched) images of Band 4 (Near InfraRed, 0.76-0.90 μm), Band 5 (Mid InfraRed, 1.55-1.75 μm), and Band 6 (Thermal InfraRed, 10.4-12.5 μm), produced useful images, with minimal amounts of time spent in image processing. Band 4 was selected because it is the Band that best discriminates between different types of vegetation and soil. Bare ground, such as occurs in villages and along roads or tracks, stand out particularly well. Band 5 was selected because valleys, shallow surface depressions, and their associated soil and vegetation types show up most clearly. Band 6, which records differences in the temperature of the earth's surface, is useful for identifying major lineaments. These three Landsat TM Bands were used to examine the vegetative cover, soils, geology, and geomorphology around 15 villages that lacked adequate year-round supplies of water. The lineament mapping was carried out on 15-km x 10-km blocks centred on each village. Figure 2 shows the area around one village where contrast- enhanced images were used from Landsat TM Bands 4, 5, and 6.

LINEAMENT MAPPING

Discontinuities are defined here as elongate, often vertical, fracture zones that range from a few millimetres to kilometres in width and from a few centimetres to hundreds of kilometres in length. *Lineaments* range from 300 m to many kilometres in length: discontinuities that are shorter than 300 m are *fracture traces*. Lineaments that are longer than 10 km are likely to be important sources of groundwater, as are extensive networks of interconnected lineaments, owing to their greater subsurface 'catchment area'. The identification and mapping of discontinuities on the earth's surface has sometimes been criticised for being dominated by intuitive interpretation, rather than by rigorous scientific analysis. However, many groundwater exploration projects had higher success rates when sites for drilling or detailed geophysical surveys were guided by lineament mapping, based on both aerial photography (Lattman and Parizek, 1964; Sharpe and Parizek, 1979; Carruthers et al., 1991) and satellite images (Teme and Oni, 1991; Gustafsson, 1993).

To help avoid errors, a standard procedure was followed for each of the 15 villages. On-screen digitising, using the pc's mouse, was used to plot the locations of villages, roads, and reservoirs, using Bands 4 and 5 to identify associated areas of bare ground or water. These line, or *vector,* maps were then saved and later overlain on the various images in order to 1) orient the interpreter, and 2) avoid anthropogenic features, such as field patterns, being mistaken for geological lineaments. Where uncertainty existed about the natural or anthropogenic origin of linear features on the images, those features were omitted. No attempts were made to interpolate or extrapolate lineaments.

IDRISI's on-screen digitising facility also allowed *Lineament Maps* to be made for each of the three Landsat Bands cited above (Bands 4, 5, and 6). The lineament maps derived from each of the three Landsat Bands were treated as three layers of data. Each lineament-map layer was viewed either individually on the computer screen, or draped over any of the other Landsat Bands (or Band combinations). Figure 3a is a composite map that was produced by merging all three lineament-map layers derived from the three Landsat Bands. Because the subsurface dip of each lineament was not known, a buffer zone 45 m wide was created either side of each lineament, producing a 'zone of interest' that was 90 m wide for follow-up geophysical surveys to examine.

Of particular interest are lineaments that are located in virtually the same position as the images derived from each of the three Landsat Bands (fig. 3a). The GIS was used to generate a simple scoring system to highlight such areas. Each of the three lineament maps was modified to give all of the lineaments and their buffer zones a value of 1, with the background area having a value of 0. By adding these three lineament-map layers together, a composite-map layer was produced that highlighted areas where lineaments coincided. The resulting *Lineament Coincidence Map* for all three Landsat Bands contained scores of 0 where there were no lineaments, 1 where only one lineament

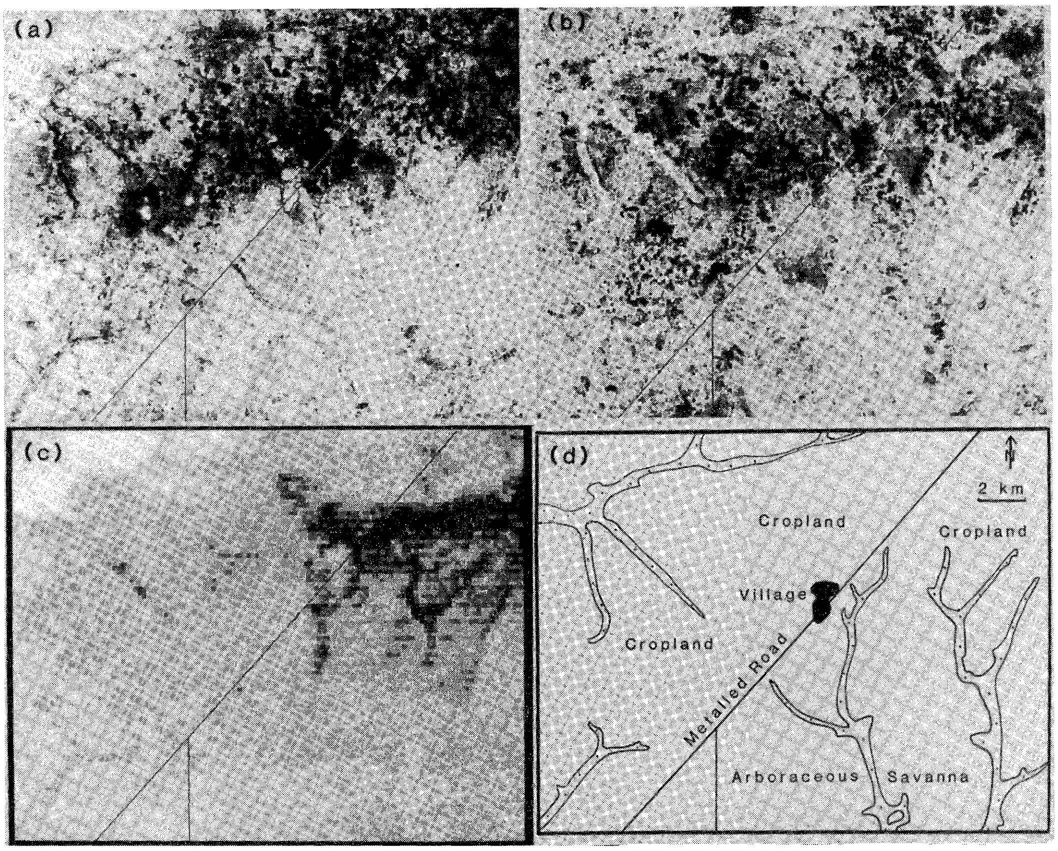

Figure 2. Contrast-enhanced (historgram-stretched) images from the three Landsat TM Bands utilised in this study: a) Band 4, Near Infra-red; b) Band 5, Middle Infra-red; c) Band 6, Thermal Infra-red: temperatures range from 17°C (black) through to 32° C (white) over 16 increments of grey scale; d) Summary site map. Note: The original images were interpreted using 16-colour images.

occurred, 2 where two lineaments coincided, and 3 where three lineaments coincided. To highlight the areas where coinciding lineaments occurred, this map was further modified by allocating a score of 0 to areas where only one lineament occurred; thus, only areas with two or three coinciding lineaments were plotted on the ensuing map (fig. 3b).

Because the length of a lineament is a key factor in determining the probable groundwater yield of a fracture system, a second set of maps was prepared using IDRISI's module for calculating areas and distances. Lineament-length maps were prepared, using the following scoring system: 0-0.3 km = 0; 0.3-1 km = 1; 1-3 km = 2; 3-10 km = 3; over 10 km = 4 (fig. 3c). In an effort to quantify and highlight the degree of inter-connectedness of the various fracture systems indicated by the lineaments, a series of *Lineament Network Maps* was produced for each study area. These maps are based on the lineament coincidence maps and show the areal extent of interconnected lineaments, or lineament networks. IDRISI's geographical analysis facilities were used to arrange the interconnected lineaments (including their 90-m-wide buffer zones) into groups, calculate the areal extent of each group, to remove groups with areal extents less than 1 ha, and to reclassify the remaining groups with the following scoring system: Less than 1 ha = 0; 1-3 ha = 1; 3-10 ha = 2; greater than 10 ha = 3 (fig. 3d).

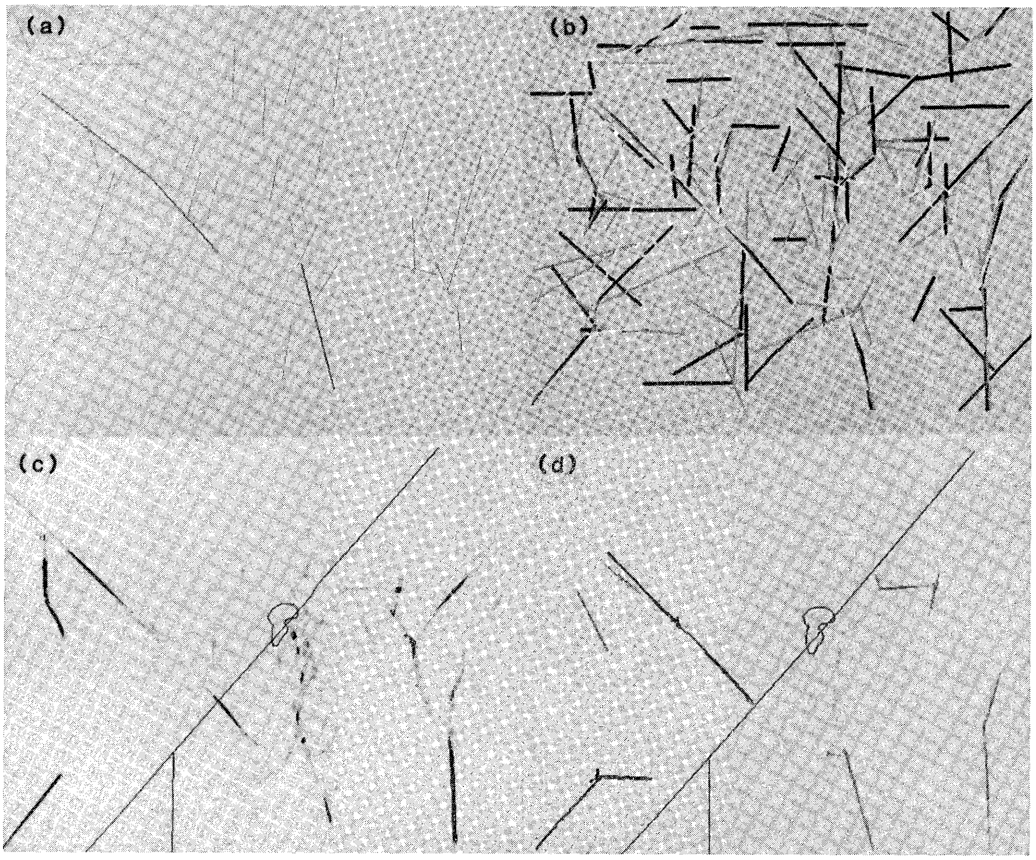

Figure 3. a) Lineament Length Map for Band 4: Black = 3 km to 10 km; Gray = 1 km to 3 km; White = 0.3 km to 1 km; b) Composite Map, Lineaments from all 3 Bands: Band 4 = White; Band 5 = Gray; Band 6 = Black; c) Lineament Coincidence Map: Black = lineament occurs on three Bands; Gray = lineament occurs on two Bands; d) Lineament Network Map: Black = > 10 ha; dark gray = 3 to 10 ha; light gray = 1 to 3 ha. Note: the original images were in 16 colours.

GIS ANALYSIS OF NON-GEOLOGICAL FACTORS

The final factor to be considered in the geographical analysis was the distance that villagers would have to walk to get to the areas that were targeted as favourable sites for boreholes. Research by rural planners in Northern Ghana has shown that villagers are unlikely to walk farther than 1 km to fetch water from a borehole and hand pump, if they can collect water from traditional cisterns or hand-dug wells near the centre of their village, even though those sources are probably contaminated with water-borne pathogens. A *Proximity Map* was therefore created for each village, with scores of: 3, for all pixels within 500 m; 2, for pixels within 500-1,000 m; 1, for pixels within 1,000-1,500 m; and 0, for pixels greater than 1,500 m from the village (fig. 4a). The proximity map was then merged with the lineament coincidence map. Sites with the maximum score of 6 had a lineament that had been identified in the same location on all three Landsat bands, and that occurred within 500 m of a village (fig. 4b). Merging the proximity map with the lineament length map allowed the targeting of sites with scores of up to 7,

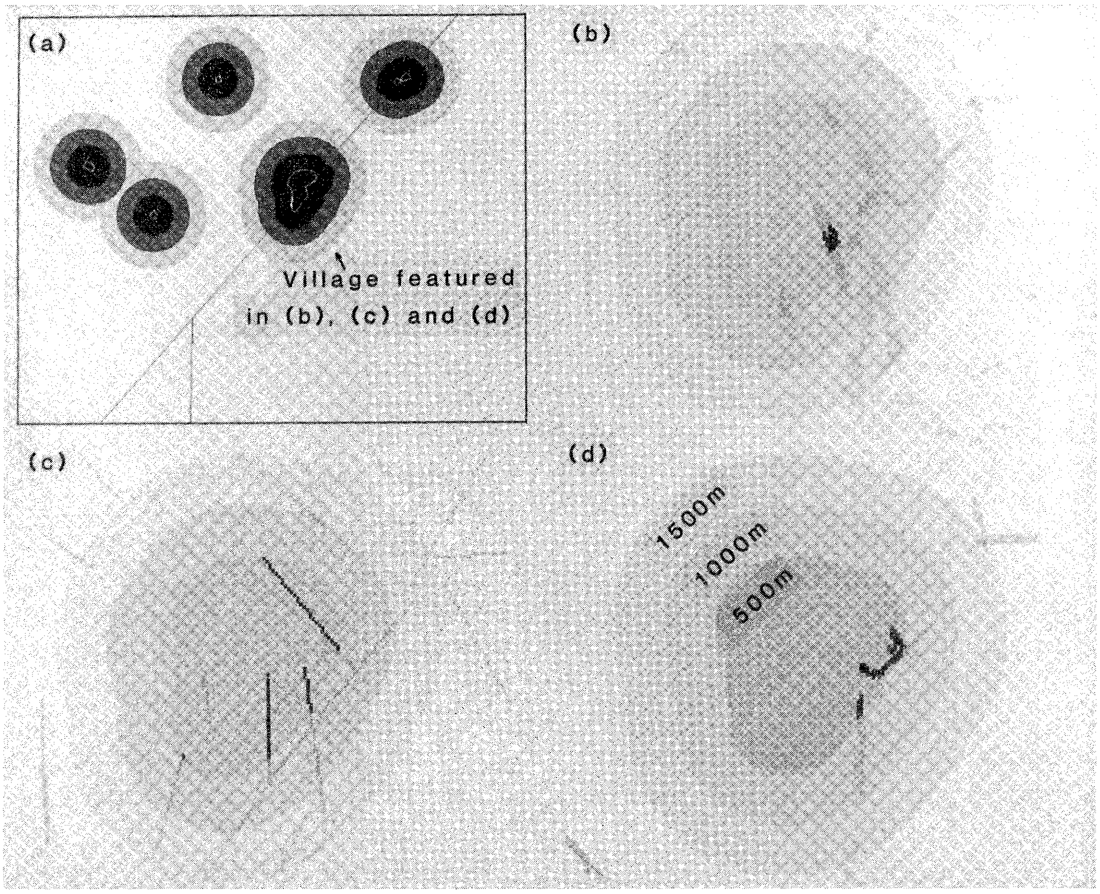

Figure 4. a) Scores for Proximity to Village; b) Lineament Coincidence and Proximity; c) Lineament Length and Proximity; d) Lineament Networks and Proximity. Note: the original images were in 16 colours.

where a lineament over 10 km long occurred within 500 m of the village (fig. 4c). A similar procedure was followed with the lineament network map, merging that dataset with the proximity map to give a maximum score of 6, where a lineament network with an areal extent greater than 10 ha occurred within 500 m of a village (fig. 4d).

The various GIS-generated maps linking village proximity with lineament coincidence, lineament length, and lineament networks were not merged further, because that might have put undue emphasis on one of the three sets of lineament features. Instead, all of the targetted areas from the three types of lineament maps were examined before the most suitable site for the follow-up geophysical survey was selected. Because of the poor spatial resolution of the Landsat data, relative to the aerial photographs, the Landsat-targeted VLF-EM geophysical survey was modified to cover a larger area (1 km x 1 km).

Numerous other non-geological factors exist that could have been analysed by the GIS, using the Landsat-derived topographic maps as base maps, for use by other agencies working in rural development. Spreadsheets and databases (such as *Excel* and *dBASE)* can be linked to IDRISI, if they use a compatible reference system to locate sample points, thereby allowing the merging of datasets, geographical analysis, and the rapid production of 'customised' maps. For the region covered in this study, future GIS-generated maps could extend beyond water exploration to water management, for instance, by highlighting relationships between census data, rates of water consumption, and incidence of water-borne disease.

SATELLITE VERSUS AIRCRAFT REMOTE SENSING

The 1:33,000-scale aerial photographs have two advantages over the Landsat data: 1) a higher spatial resolution, allowing the mapping of features as small as 2 m x 2 m; and 2) stereoscopic viewing, which can help detect lineaments with very subtle surface expressions, if stereopair sets are available. However, the Landsat TM images proved easier to interpret than the aerial photographs. This result was primarily because Landsat TM allows an area to be viewed in seven parts of the electromagnetic spectrum, from visible light to thermal infrared wavelengths, whereas the panchromatic aerial photography is limited to one broad swathe across the visible part of the spectrum.

The speed at which the digital-image processing and on-screen digitising could produce high-quality maps for colour printing was also much faster than the hand-drawn maps produced with the aerial-photograph interpretations. Furthermore, Landsat TM's ability to detect in the infrared parts of the spectrum gives the interpreter access to additional features, such as vegetation chlorophyll content, vegetation moisture content, soil moisture, and earth-surface temperature, all of which often indicate the presence of discontinuities in the underlying rocks. The Landsat TM images were also easier to interpret, because they could be viewed in either grey scale or in a variety of customised colour palettes, whereas the aerial photographs were limited to grey-scale ('black-and-white') prints.

A further advantage of using Landsat data is that a huge area can be viewed: 180 km x 175 km per scene. This regional overview allows major lineaments and regional lineament patterns to be mapped, while still maintaining the ability to 'zoom in' and map smaller lineaments at a local scale around villages. In contrast, the lineament mapping from aerial photography tends to be focused around each village at a local level, making the recognition of regionally important lineaments more difficult, particularly when aerial-photograph coverage of a region is patchy. Given the poor quality of the aerial photographs covering the study region, and the total absence of air-photo cover for some villages, the Landsat imagery proved to be far more useful than the aerial photography. The cost of 32 photographic prints, giving stereographic coverage of about 80 km^2 around 15 villages, was US$ 1,920, or US$ 1.60 / km^2. The Landsat TM Quarter Scene covered 7,560 km^2 (virtually all of the study region) and cost US$ 2,550, or US$ 0.34 / km^2.

TECHNOLOGY TRANSFER

Most of the remote-sensing and GIS work was carried out in the study region over a span of two weeks, during which the 'ground truth' of the lineament maps was checked. The total cost of the hardware and software used in this project (16-colour laptop pc with an 80386 processor, portable A4 colour printer, and IDRISI) was just under US$ 2,600. A few years ago, the equivalent costs would have been an order of magnitude greater, and running such a system in a remote part of a developing country would have been extremely difficult. More sophisticated GIS software could have been used, but it tends to cost thousands of dollars and requires more sophisticated (and, hence, more expensive) computers. It also tends to require high levels of computing expertise, reducing the potential for transferring basic GIS skills to technical staff. The transfer of basic skills in image processing and GIS analysis to technical staff was one of the objectives of this project, and IDRISI formed the basis of a five-day 'hands-on' training course for a dozen Ghanaians working in the water and health sectors.

DISCUSSION

A key feature of this study, made possible by the digital nature of the Landsat data, was the use of computer software for image processing, geographical analysis and map generation. The GIS was crucial to this project, because it enabled 1) the rapid creation of customised maps, such as vegetation cover, topography, and lineaments; 2) the highlighting of coinciding lineaments from two or three Landsat TM Bands; 3) the production of maps showing individual lineament lengths and the areal extent of lineament networks; 4) the utilisation of non-geological data, such as proximity to villages; and 5) the use of simple scoring systems that targeted the most suitable sites for follow-up geophysical surveys.

It is too early to assess fully the reliability of the GIS-generated target maps for the follow-up geophysical surveys and the ensuing borehole site locating, because drilling has not yet started. However, a comparison of GIS-targeted sites with the locations of wells or pre-existing successful boreholes, showed that 55 percent of the GIS-targeted locations were within 200 m of a well or borehole. Given that previous groundwater exploration programmes in this region have had borehole success rates of only 13-21 percent, the satellite-image processing/GIS techniques outlined above represent a major improvement. The only major problem associated with the satellite lineament-mapping techniques outlined above was the lack of lineament coverage close to villages, where many linear features had to be omitted because of possible anthropogenic origins. In some cases, lineaments that were probably formed by subsurface fractures could be followed to the farmed margins of a village and then picked up again, following the same orientation, on the far side of the village. This is a problem that impacts mapping lineament lengths and lineament networks, because some long, continuous, lineaments are not registered if they traverse villages or farmed areas.

Limitations exist for satellite remote sensing that is linked to a GIS to highlight features of interest to a groundwater exploration programme. Using Landsat TM, the accuracy of resulting maps is constrained by the 120-m pixel size of Band 6 and the 30-m pixel size of the other Bands. However, the aim of the various GIS-generated lineament maps outlined above was not to locate accurately the sites where boreholes should be drilled, but only to identify areas where detailed geophysical surveys could be used to locate fracture zones and sites for drilling.

An attempt was made at the start of this study to produce maps based primarily on image processing, using directional filtering, to highlight lineaments. Unfortunately, the low relief of the study region and the widespread distribution of rotational farming around villages produced images that were dominated by the major valley systems and by anthropogenic lineaments, such as field boundaries and tracks. Instead, this project relied on differences in the spectral properties of lineaments, based particularly on Landsat TM Bands 4, 5 and 6, and on the judgment of an 'expert' who had carried out ground-truth surveys of the study areas. A totally objective system that incorporates image processing with GIS analysis to produce lineament maps, without the need for human judgment to distinguish natural linear features, is not possible with the relatively limited spectral coverage and poor spatial resolution of the Landsat TM data. Future research will assess improvements in lineament mapping that result from using IDRISI to merge the Landsat TM data with: 1) a Digital Elevation Model (DEM) of the study region, 2) the aerial-photograph lineament maps, and 3) satellite radar imagery of the region. The radar is of particular interest because its sensitivity to soil-moisture content may highlight water-bearing lineaments.

CONCLUSIONS

The most expensive single item used in this study was the satellite data, costing thousands of dollars. Given the huge area covered by the Landsat image and its usefulness, not just for groundwater exploration but also for land-use mapping and rural planning, the use of IDRISI's image-processing and geographical-analysis facilities to create customised maps from the Landsat data represents real value for money.

This study has shown that although the Landsat TM images are limited in their locational accuracy, their spectral characteristics and digital nature make them better for lineament mapping than conventional aerial photography. Their digital format also allows each Landsat TM Band, or each corresponding lineament map, to be examined individually or merged with other datasets, using IDRISI's GIS operations. Overlaying lineament interpretations from different TM Bands highlighted lineaments that had coinciding locations. The lengths of lineaments were calculated, along with the areal extents of lineament networks, and simple scoring systems were used to eliminate unnecessary data and target areas of interest. The relatively poor locational accuracy of the Landsat TM data was not crucial to the exact siting of boreholes, because they were located by follow-up geophysical surveys.

Both the computer hardware and software that were used in this project are relatively low-cost and easy to use, turning the integration of satellite-image processing, field data and GIS analysis into a technology that can readily be transferred to hydrogeologists and rural planners in developing countries.

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The IDRISI software can be purchased from the following:

The IDRISI Project
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Worcester, MA 01610-1477, USA
Tel: +1 508 793 7526 Fax: +1 508 793 8842

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