Remote sensing applications in African erosion and sedimentation studies

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ABSTRACT Currently available remote sensing systems are evaluated for their usefulness in soil erosion and sedimentation studies in Africa. Pixel size and scale of the erosion process, timing of imagery, and vegetation cover relationships are thought to be important. A similarly orientated preview of future satellite remote sensing systems is made. Examples of the use of satellite data to monitor the relationships between sediment source areas and vegetation and of the interfacing of socio-economic, terrain and landcover data in an elementary geographic information system to provide predictions of future soil losses are drawn from West Africa. Some of the economic and technical constraints on the use of remote sensing in Africa are also discussed.

Les applications de la télédétection dans les études d'érosion et de sédimentation en Afrique

RESUME Les systèmes de télédétection couramment disponibles font l'objet d'une étude critique en ce qui concerne leur utilité dans les études d'érosion du sol et de sédimentation en Afrique. Les relations entre la taille des pixels et l'échelle des processus d'érosion, entre répartition dans le temps des images et la couverture végétale sont jugées importantes. On fait une prévision de systèmes de télédétection pour de tels buts conçus pour les futurs satellites. On utilise des exemples africains pour montrer l'utilisation des données prises par satellites pour surveiller les relations entre les régions d'origine des sédiments et la végétation et pour donner un système d'informations géographiques qui peut comprendre les relations entre données de terrain, l'utilisation du sol et les éléments socio-économiques en vue de fournir une prévision des pertes en sol dans l'avenir. Quelques contraintes économiques et techniques qui retardent l'emploi de la télédétection en Afrique sont aussi étudiées.

INTRODUCTION

With the exception of North Africa (Mitchell, 1981; Mitchell & Howard, 1978), little work has been done in Africa on the applications of remote sensing to erosion and sediment yield studies. This paper will examine some of the possible approaches in this area which utilize both remote sensing and geographic information systems,
briefly describe two case studies and consider future trends in remote sensing that may have potential applications in this general field.

WATER EROSION, SEDIMENTATION AND REMOTE SENSING

Remote sensing can provide useful information on the above topics in both a spatial and a temporal framework. However, only certain aspects of erosion and sedimentation within the landscape can, at the present time, be monitored using currently available remote sensing products.

When examining the spatial implications, identification of erosion is mainly a function of the scale of the process and pixel size (Table 1), the height of the platform on which the sensor is located, the wavelength of the imagery and the amount of vegetation cover. The latter factor is especially pertinent in the African context. In hyper arid and arid zones the general lack of cover allows direct observations of the land surface, and hence erosion phenomena. In fact in these areas vegetation cover could be advantageous since after rainfall events it may be possible to identify flow lines of water erosion by the "desert bloom" which occurs in response to increased sub-surface moisture levels. In the semiarid and savanna areas the patchy vegetation cover allows only partial direct observation of areas of soil erosion. In areas where erosion is relatively advanced the soil is often so degraded that the vegetation is much sparser than the surrounding, less degraded areas, or is absent altogether; the latter is usually the case with gullying and mass movements, the former with other types of erosion. In some areas topsoil is removed altogether, exposing less fertile subsoils and again reducing vegetation cover. In these areas direct observations of erosion phenomena can be made. Cloud cover is only a problem in these drier climatic zones during the short wet seasons, but the high particulate matter contents of dry season winds, such as the harmattan in West Africa, are effective in obscuring surface features.

In the humid tropical biomes (the tropical moist forest and seasonal deciduous forest) and wetter savanna vegetation complexes, the probability of direct observation of soil surface features is greatly reduced due to the more complete vegetation cover and more frequent, and often continuous, cloud cover in the wet season. In these areas the only opportunities for direct observation of surface erosion phenomena are provided in the late dry season and early wet season when vegetation is cleared and burnt for cultivation or to promote better cattle grazing and in severely degraded areas which are only sparsely vegetated. Areas of shifting cultivation in both the semiarid and humid zones are foci of erosion, but because of their relatively small size (only a few pixels), are difficult to identify.

Water erosion in the seasonal climates, which dominate most of Africa, is restricted by the incidence of the rains; however, wet season monitoring of water erosion phenomena is very difficult because at that time most vegetation "greens up". This provides not only a more extensive cover, but also more uniform spectral
### TABLE 1: Erosion and Sedimentation Identification from Various Remote Sensing Systems

<table>
<thead>
<tr>
<th>Type of Imagery</th>
<th>Aerial Photography</th>
<th>Landsat 1-3</th>
<th>Landsat 4</th>
<th>SPOT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(i) Slope Processes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Splash erosion</td>
<td>YES; small areas</td>
<td>FEASIBLE; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
</tr>
<tr>
<td>Sheetwash</td>
<td>YES; small areas</td>
<td>FEASIBLE; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
</tr>
<tr>
<td>Rilling</td>
<td>YES; individual rills if scale small enough</td>
<td>YES; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
<td>FEASIBLE; extensive areas</td>
</tr>
<tr>
<td>Gullying</td>
<td>YES; individual gullies</td>
<td>YES; areas only, not individual gullies</td>
<td>FEASIBLE; areas and large and small medium size gullies</td>
<td>FEASIBLE; areas and large and small medium size gullies</td>
</tr>
<tr>
<td>Mass Movement</td>
<td>YES; individual cases of all types</td>
<td>YES; individual cases of most processes</td>
<td>FEASIBLE; FEASIBLE; individual cases of most processes</td>
<td></td>
</tr>
</tbody>
</table>

| **(ii) Channel Processes:** | | | | |
| River channel erosion (other than bank erosion) | YES; individual occurrences of slumping etc. seen | YES; extensive areas | FEASIBLE; Extensive areas and medium and large scale features. | FEASIBLE; Extensive areas and medium and large scale features. |
| Bank erosion (channels, lakes and impoundments) | YES; individual occurrences | FEASIBLE; extensive areas only | FEASIBLE; relatively small areas and large and medium scale individual occurrences | FEASIBLE; relatively small areas and large and medium scale individual occurrences |

| **(iii) Sedimentation Processes** | | | | |
| Intra-channel sedimentation (point channel forms can be identified) | YES; individual larger forms and areas of sediment in flux can be seen. | FEASIBLE; larger and medium-scale forms could be identified as well as areas of sediment. | FEASIBLE; larger and medium-scale forms could be identified as well as areas of sediment. | |
| Sedimentation in lakes and impoundments | For all types of imagery, low water conditions are advantageous | YES; YES; | FEASIBLE; FEASIBLE; deltaic deposits and shallow water shelves can be seen in all types of imagery, although for Landsat 1-4 and SPOT the size of these identified is controlled by pixel size; sedimentation plumes can be seen in satellite imagery, again the scale is controlled by pixel size. | FEASIBLE; FEASIBLE; |

**YES** - indicates the type of imagery has been used for identification of the process.

**FEASIBLE** - indicates the type of imagery could be used to process identification; but to the authors' knowledge, has not been.

1. Landsat 4 is operational and its products will be available in early 1984.
2. Landsat 5 will have a similar spatial resolution, 30m.
3. SPOT is due to be launched in 1985.
reflectances in the visible and infrared bands. In addition late
dry season monitoring, whilst providing increased opportunities to
directly observe water erosion phenomena due to the die-back of
vegetation, is usually characterized by two broad environmentally-
based groups of reflectance spectra. These are green vegetation in
swamps and dead vegetation on upland (non-flooded) areas. Maximum
variability in spectral reflectances occurs in the early dry season
in response to the differences in water retention capacities between
soils and the differences in water usage between vegetation
communities. These differences in soil moisture are potentially
useful for land cover mapping which can indirectly be related to
soil erosion phenomena through a variety of mechanisms; for instance
ground observations and modelling strategies.

**TABLE 2** Landsat 1-3 imagery available for an area in
the Sahel (central Gambia and southwest Senegal; path 219:
row 51), with less than 50% cloud cover

<table>
<thead>
<tr>
<th>Date</th>
<th>Landsat satellites</th>
<th>Sensor(^{\text{§}})</th>
<th>Cloud cover (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29 September 1972</td>
<td>1</td>
<td>M</td>
<td>50</td>
</tr>
<tr>
<td>4 November 1972</td>
<td>1</td>
<td>M</td>
<td>10</td>
</tr>
<tr>
<td>10 December 1972</td>
<td>1</td>
<td>M</td>
<td>40</td>
</tr>
<tr>
<td>10 March 1973(^{\dagger})</td>
<td>1</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>3 February 1978(^{\dagger})</td>
<td>2</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>2 January 1979(^{\dagger})</td>
<td>3</td>
<td>M</td>
<td>10</td>
</tr>
<tr>
<td>2 April 1979</td>
<td>3</td>
<td>R</td>
<td>0-10</td>
</tr>
<tr>
<td>8 May 1979</td>
<td>3</td>
<td>R</td>
<td>0</td>
</tr>
<tr>
<td>22 November 1979</td>
<td>3</td>
<td>R</td>
<td>0</td>
</tr>
<tr>
<td>22 November 1979</td>
<td>3</td>
<td>M</td>
<td>10</td>
</tr>
<tr>
<td>23 September 1980</td>
<td>3</td>
<td>R</td>
<td>40</td>
</tr>
<tr>
<td>16 November 1980</td>
<td>3</td>
<td>R</td>
<td>30</td>
</tr>
<tr>
<td>4 December 1980</td>
<td>3</td>
<td>M</td>
<td>10</td>
</tr>
<tr>
<td>9 January 1981(^{\dagger})</td>
<td>3</td>
<td>R</td>
<td>10</td>
</tr>
<tr>
<td>27 April 1981</td>
<td>3</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>15 May 1981</td>
<td>3</td>
<td>M</td>
<td>0</td>
</tr>
<tr>
<td>2 June 1981</td>
<td>3</td>
<td>M</td>
<td>30</td>
</tr>
</tbody>
</table>

* Images that would definitely be useful for soil erosion
  mapping.
\(^{\dagger}\) Images that may have some use for soil erosion mapping.
\(^{\text{§}}\) M - multispectral scanner (MSS); R - return beam vidicon.

**SOURCE:** EROS Data Center; Ref. OLOOl-1, 12 May 1983

Problems relating to wet season cloud cover are important in the
humid tropical zones and, to a lesser extent, in the savanna zone.
In such cases visible and infrared spectral reflectances can be
replaced with microwave radar wavelength imagery which has a cloud
penetration capability. Radar imagery has been effectively used in
mapping forest resources in Nigeria and land resources in Brazil.
Radar imagery is much less available than visible and infrared
imagery since its availability is dependent on high-cost project specific monitoring events, but with the launch of ERS-1 in 1988 much more data will become potentially available, assuming that the necessary ground receiving stations exist.

The repetitive nature of satellite imagery is potentially useful in providing information on the evolutionary sequence of erosion in an area and also in monitoring the effectiveness of remedial and control measures. In reality, however, detailed multiple temporal sequences are difficult to establish due to the lack of available satellite imagery for many African countries. To illustrate the problems, a Landsat frame from the Sahel is analysed (Table 2). Seventeen images are available from the EROS Data Center for the period between 1972 and 1981: six of these are return beam vidicom images and are restricted in the amount of quantitative analysis, five have cloud cover over 30% and many were taken in either the late dry season or wet season. Only three images are definitely useful, a further two being of possible use. If the three very good images were chosen this would only give a temporal framework of four years.

At the present time then, mapping the spatial distribution of individual linear erosion features is restricted by the spatial resolution of the imagery, but areas with similar types of erosion on similar soils can be recognized by either their unique spectral reflectances or those of the vegetation community that has adapted to those edaphic conditions. Direct observation of erosion phenomena is restricted by vegetation cover, although the effects of vegetation can be reduced by the judicious timing of imagery acquisition. Similarly the problems of cloud cover are best overcome, at the present time, by critical timing of imagery rather than a search for available radar imagery. Temporal frameworks for the examination of changes in spatial patterns of erosion are restricted by product availability.

CASE STUDY 1: MULTITEMPORAL MONITORING OF SEDIMENT SOURCE AREAS USING VEGETATION MAPPING FROM SATELLITE DATA

It has been shown above that vegetation cover is an important control on surface erosion rates in Africa. Its importance is severalfold. Precipitation is intercepted by vegetation, thereby reducing the impact of rainsplash erosion. It also prevents the formation of sealed surface layers with lower infiltration capacities and higher rates of overland flow and sheetwash. The presence of organic matter due to leaf-fall and root decay tends to improve soil structure and raise infiltration capacities, reducing the probability of overland flow. Thus up-to-date depiction of surface cover is of considerable value in the identification of sediment source areas.

Although conventional aerial photography can provide data of considerable value for land cover mapping (Table 1), it is expensive, especially for the survey of large areas. Previously collected air photographs are often unreliable sources of land cover information in Africa because of the rapidity of vegetation change that has recently occurred.

Not surprisingly, therefore, satellite data have been appraised
as a source of timely information for vegetation survey. The principal source which has been used is Landsat data with a ground resolution of 79 m. Mitchell (1981) and Mitchell & Howard (1978) described how Landsat images were used for assessing soil degradation in Africa and the near East. One of the important characteristics extracted using these data were six categories of percentage vegetal cover. These were derived by photo interpretation of colour composites of Landsat MSS bands 7, 5 and 4 with the colours cyan, magenta and yellow being assigned to each band. Changes in colour from blues or greens through yellow-brown, yellow, brown-red and magenta corresponded to increasing vegetation cover.

One of the principal difficulties with Landsat MSS data, that of frequency of suitable imagery, has already been noted (Table 2). The repeat cycle for Landsat 4 is once every 16 days, although in the wet season, the actual frequency of cloud-free imagery is lower and it has been noted that, even in areas marginal to deserts, suitable dry season imagery is difficult to obtain. The acquisition of wet season imagery is useful for two main reasons. Firstly, late dry season imagery may not accurately depict the distribution of vegetation cover where the spectral response of dry vegetation matter is similar to that of bare ground. Secondly, if sediment sources are to be accurately identified, it is important to monitor changes in vegetation cover through the rainy season, because areas with low dry season vegetation cover can change rapidly with the onset of the rains. Thus, it is important to monitor changes in vegetation with time in individual years. The temporal frequency of data from Landsat MSS makes it an inappropriate source for such monitoring.

An alternative which should be considered is the Advanced Very High Resolution Radiometer (AVHRR) of the meteorological NOAA satellites, especially NOAA-7 (Townshend & Tucker, 1981, 1984). Despite the name, the spatial resolution of this system is much lower than that of the Landsat MSS (1.1 km cf. 79 m). Its advantage is that the data are potentially available on a daily basis. Provision of data at the 1.1 km resolution is dependent on the existence of a local receiving station or use of the satellites onboard recorders, but data at 4 km resolution are available globally on a daily basis. Extraction of vegetation cover information from these data is aided by deriving a ratio between the near infrared and red bands. This is useful since green vegetation has low values in the red due to absorption by chlorophyll and high values in the near infrared due to internal reflection within the open cells of the mesophyll layer. Thus high values of near infrared to red ratio will tend to correspond to areas with high green biomass.

Figure 1 shows a series of ratio images derived from the AVHRR during the 1982/1983 wet season in Senegal. This figure is a black and white image derived from a colour image, but, even with this restriction, the movement of the greenwave northward with the onset of the rains and the subsequent progressive die-back (browning) with the onset of the dry season can readily be detected. Work by Tucker et al. (1984) has shown a definite relationship between the ratio values and the green leaf biomass present.

It should be stressed that establishing relationships between vegetation properties and the spectral ratio is best achieved if one has previous knowledge of the vegetation type being observed. For
FIG. 1 Vegetation index images derived from NOAA-7 AVHRR data of Senegal. Note how the green-wave effect can be monitored with a high temporal frequency through the rainy season.

Example, savannas at any given time might have similar ratio values to tropical rain forest. Recent work using AVHRR data has indicated that by using spectral ratio data from two different seasons (Tucker et al., 1983), or better data from several dates throughout the year (Townshend et al., 1984), it may prove possible to identify
the land cover type that is present, instead of relying on existing maps produced by conventional means. As yet this has only been carried out at very small scales for the whole of Africa, but utilizing spatially aggregated data with a resolution of 15 km. Nevertheless, it seems likely that it will prove feasible to apply such methods to the data with the full 1.1 km resolution. Experiments along this line are currently underway in both Kenya and Botswana.

On the basis of these considerations it seems likely that AVHRR data can be used to provide a regular temporal source of information about vegetation cover. Its usefulness is predicted on the assumption that data of a resolution of 1.1 km will provide useful information about the spatial distribution of sediment source areas. Undoubtedly in some areas this will not be sufficient. However, if such data with high temporal regularity are combined with more infrequent but finer resolution data from Landsats 4 and 5 and SPOT or from aircraft, it seems likely that substantial improvements in our knowledge of the spatial and temporal variations in vegetation cover can be achieved. In this way information about sediment sources should be available on a much more timely basis than hitherto.

CASE STUDY 2: ACTUAL AND POTENTIAL SOIL LOSS MAPPING IN SIERRA LEONE

Both Hudson (1981a, b) and Blaikie (1982) have shown the extent to which soil erosion is dependent on cultural, economic and social factors which act as intervening mechanisms in the overall erosion process. Furthermore, whilst the potential exists to map the spatial distribution of erosion phenomena at the present time and in the recent past, an important consideration is the provision of indications of the future rates and spatial distribution of erosion. Of all of the factors which control soil erosion, those most susceptible to change over a relatively short time period are the demographic variables, which often result in dramatic changes in land use and hence rapidly alter erosion patterns. These are usually first recognized as vegetation changes, the monitoring of which has been considered above; however, the socio-economic factors controlling these changes have important implications for trend prediction. Models of soil erosion do not consider these variables and consequently modelling strategies cannot be adopted to predict future distributions of eroded land at the present time. A possible solution to this problem lies in the use of geographic information systems in which digitally analysed land cover data can be interfaced with digital terrain and socio-economic vector data.

This has been done in Sierra Leone where grid-square based maps of potential maximum and actual soil loss and erosion hazards were constructed for the entire country and also for an agricultural development project area, (it should be noted that in this study the land cover mapping was from 1:70 000 false colour infrared high flight aerial photography (FAO, 1979)). The best-fit distribution was one that combined the $p^2/P$ erosivity index, the erodibility
index* of all gravel free and slightly gravelly soils that were not
flooded in the wet season, slope angle and drainage texture. This
was done by combining the four sets of vector data in an additive
factorial scoring system. Other factorial scoring systems were
attempted as well as various types of combinations of standardized
values. The latter were calculated by dividing parameter vector
values for each grid square by the standard deviation of all of the
grid square values of the parameter; this system, however, could
only account for the simple linear or curvilinear relationships
between soil erosion and the parameter. Some variables have more
complex relationships with soil erosion which involve high erosion
rates at more than one value e.g. erodibility indices and population
growth rates. Socio-economic variables and land-cover types were
interfaced with the potential maximum erosion risk maps on the same
grid-square format using the additive factorial scoring system. The
best-fit distribution with present day erosion patterns was provided
by combining the four physical variables above with population growth
rates in the last intra-censal period, 1963-1974 (Fig.2). In
addition, population growth rates have an important role in predicting
future trends in land use and, consequently, the potential for
increased soil erosion. Theoretically in land-intensive economies,
the greatest rates of environmental degradation occur in areas of
high in-migration and out-migration (Levi, 1973), and this was found
to be the case in Sierra Leone. Without large-scale changes in
government economic policies, which are not foreseeable in the
immediate future in Sierra Leone, these areas are likely to continue
to experience high rates of in-migration and depopulation
respectively, thereby accentuating the already existing patterns of
soil erosion and increasing its severity in these areas. It will be
possible to test this hypothesis by repetitive satellite monitoring
of land cover characteristics in these areas and field monitoring
of soils.

Geographic information systems can therefore provide a number of
possible directions in which soil erosion and sedimentation studies
Can take. Firstly, they enable areally based relationships between
both digital land cover and vector physical and socio-economic data
which affect soil erosion to be studied. Secondly, they can provide
indications of future trends in soil erosion extent and magnitude in
an area to be predicted, and thirdly, they can be readily updated
with new land cover and socio-economic data as they are an easily
accessed computer-based information retrieval system.

PROBLEMS FACING REMOTE SENSING IN AFRICAN EROSION AND SEDIMENTATION
STUDIES

The problems facing the use of remote sensing systems can be divided
into two broad groups: technical and economic.

The major technical problems which currently restrict the wide-
spread application of remote sensing in this field have been discussed

*The erodibility index was calculated by multiplying the dispersion
ratio (Middleton, 1930) and the stone and gravel content (<2 mm) of
the upper 10 cm of the soil.
above. The first of these is the problem of the presently available coarse spatial resolution of images. Although in the next few years finer resolution systems will become available (e.g. Landsat 4 and 5, SPOT) these will still not enable some individual linear erosion features to be mapped (Table 1). It has, however, been shown that the most important applied task facing soil scientists and hydrologists in Africa, the mapping of sediment source areas, can easily and accurately be carried out using existing remote sensing systems. The second major problem, that of penetration through cloud cover in the wetter tropical areas will need to await the extensive use of radar sensors on board satellites; however, the acquisition of Landsat imagery at critical times of the year and the use of imagery from relatively rapidly repetitive weather satellites can obviate this problem.

The most difficult problems are economic in nature, because the acquisition and interpretation of satellite data can be costly. For the weather satellite systems a number of ground stations already exist in Africa and these can be relatively inexpensive to install. Earth resources satellite data are only received at a few
strategically located global stations which also act as distributors of the remotely sensed products for particular areas. Qualitative analysis of all types of satellite imagery can be done relatively cheaply but with the attendant loss of much information. More information can be retrieved using computer-based digital image processing systems and, in addition, these are also needed to allow interfacing with socio economic data in geographic information systems. These systems are costly to install, involve operators with relatively sophisticated computing skills and require system maintenance which is not readily available in most African countries. Cheaper micro-computer based systems could decrease some of the initial costs, but the acquisition of remotely sensed products and system maintenance would still involve high recurrent costs.

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