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DETERMINING SOIL MOISTURE CONDITIONS OF SALT CRUSTS BY USING LANDSAT TM DATA

a qualitative and quantitative approach

P.B. Roeters

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instituut voor cultuurtechniek en waterhuishouding, wageningen

C O N T E N T S

List of figures

List of tables

List of appendices

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1. INTRODUCTION

1.1 Background of the research

Several groundwater reservoirs are known (EUROCONSULT/PACER CONSULTANTS 1983) in the Saharan Belt. A widespread opinion is that the last relevant recharge took place some 11,000 years ago, but there is no definite proof and no overall estimation of its extent (MENENTI 1985).

As mean annual rainfall in the Western Desert of Egypt is very low (see figure 1), the small lakes that can be found in many parts of the Sahara are the result of a continuous efflux of fossil groundwater. This implies that, because of the hydrological connection with the regional aquifer system, lake levels give accurate and direct information on the water balance of the groundwater reservoirs (KUIPERS & MENENTI 1986).

Groundwater losses occur as a result of evaporation from either open water surfaces or from areas with a shallow groundwater table (sebkha). The location of areas where changes in grondwater level occur can be identified and mapped by using Landsat TM data.

The Qattara and Siwa Depressions of the Western Desert of Egypt form two areas where groundwater of the regional aquifer system, viz. the Nubian sandstone aquifer system comes close to or at the surface.

1.2 Research objectives

The objectives of the research were:
- to establish the combination of Landsat TM bands that are most suitable for the determination of changes of soil moisture conditions in arid areas;
- to locate units in the terrain that show changes in soil moisture conditions and related features of the soil surface (e.g. various types of salt crystals), considering the locations of the various permeable layers in the Qattara and Siwa Depressions;
- to describe the dynamical changes in both characteristics and areal extent of salt crusts in the Qattara Depression by Landsat digital and photographic information and derived products (topographic and geological maps).

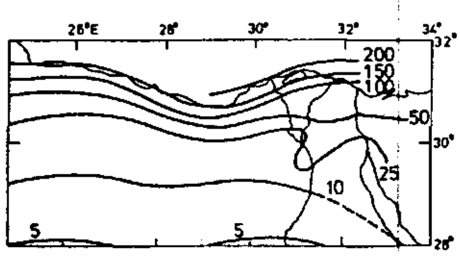


Fig. 1. Distribution of the mean annual total of rain in Egypt (after GRIFFITHS 1972)

2. ENVIRONMENTAL CHARACTERISTICS

2.1 Location

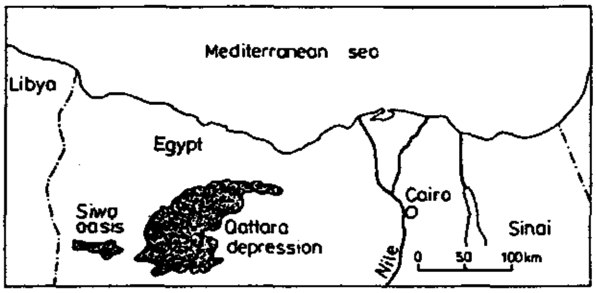


Fig. 2. The location of the Qattara and Siwa Depressions (after MENENTI 1985)

The Qattara Depression is a large continental depression that is located in the northern part of the Western Desert of Egypt (see figure 2). The northern and western boundaries of the Depression are formed by steep escarpments that rise to more than 250 m above sea level; the average depth of the Depression is some 60 m below sea level; the deepest point being 134 m below sea level. To the south the floor of the Depression rises gradually to the general desert level (BALL 1933).
The largest part of the Qattara Depression consists of salt marshes or sebkha, partly covered by eolian sands. The remaining soils consist of sands, gravels, clays and outcropping shales and limestones.

2.2 Geology

The Western Desert of Egypt stretches westwards from the Nile Valley to the borders of Libya and embraces an area that is more than two thirds of the whole area of Egypt. The Western Desert is essentially a plateau desert with vast flat expanses of rocky ground and numerous extensive and deep closed-in depressions (SAID 1962).
The northern part of the Desert consists of a great plateau of Tertiary rocks, about 200 m high, which extends north-westward to the Mediterranean Sea. The Qattara Depression is excavated in the horizontally bedded layers of these rocks that were deposited as fluvio-marine sediments in the transition zone from stable to unstable shelf (SAID 1962).

Two rock units are important considering the development of the Qattara Depression: the escarpment consists of hard limestone of the Middle Miocene Marmarica Formation. The thickness of this formation increases from a few meters at the Qattara escarpment to several hundreds of meters near the Mediterranean coast, where it is covered with younger deposits.
The escarpment wall of the Qattara Depression consists of Lower

Miocene clastic sediments of the Moghra Formation. Sediments of this formation vary from calcareous clayey to silty-sandy materials. Generally, the bottom of the Qattara Depression consist of Upper Eocene-Oligocene shales of the Dabaa Formation.

The origin of the Qattara Depression has been the subject of controversy for a long time (SAID 1962). It is assumed that, amongst others, the Qattara Depression is formed as a result of wind erosion, mainly during the Pleistocene (BALL 1933). Other factors, as erosion starting at boundaries between geological formations, as well as tectonic events and structural conditions, should be considered important in facilitating deflation (LINNE & MEISSNER 1983).

The sandy constituents of the eroded formations have been blown by wind south south-eastward and have been deposited in the form of great chains of sand dunes (SAID 1962).

2.3 Salt crusts

The northern part of the Western Desert can be considered as a low altitude rocky platform that has been characterized throughout its recent history by arid climatic conditions. Geomorphological features are primarily due to wind action: the depressions being recent features, imposed upon the region due to erosion. The depth of the floors of the depressions is governed by the groundwater level which forms a base level for wind action (SAID 1962).

In the Qattara Depression shallow groundwater tables have largely determined the characteristics of the soil surface. A large part of the floor of the Qattara Depression is covered by salt marshes or sebkha: a mixture of sand and salt, generally with more or less water. Parts of the sebkha are covered by a sheet of eolian sands of varying thickness. The salt marshes do not form a single continuous expanse, but occupy several detached areas of the Depression floor. BALL (1933) notices that the marshes do not lie at a constant level, 'even within the continuous tract of it'. According to BALL (1933) the water in the sebkha is the result of a continual seepage of underground water from the Nubian sandstone through the overlying Miocene rocks into the Depression. Hence, the location of sebkha at various levels can be related to a lateral and vertical variation of lithological characteristics (e.g. porosity) of the rocks of the bottom of the Depression. These lithological characteristics have a considerable influence on groundwater movement and efflux.
High evaporation rates in the low lying depression results in the development of salt crusts. Salt polygons may or may not grow, depending on the relative concentration of salt (GLENNIE 1970).

Within the sebkha in the Qattara Depression older and younger salt crusts can be distinguished. Older ones are characterized by a slightly higher level (0.5 - 1 m) in contrast to the younger ones and by hardness and wind erosion features. The youngest crusts are

situated in the deepest parts of the wet sebkha. Polygones are not yet developed, the salt crust is soft and covered by wet clay. The different levels can be explained as temporary standstills during a general decrease of the groundwater level (JVQ 1981).
The older crusts are found in the central part of the sebkha; the younger crusts are situated in the marginal parts where less saline groundwater has been observed. At the contact of hard crust in the centre and soft crust at the margin, often a narrow zone of open water with snow-white salt floes has developed (JVQ 1981).

The salt marshes are not uniform in appearance, but can be subdivided in several types (JVQ 1981) considering the depth of (present) groundwater level:
Salt crust, dry (mapping unit 13)
These dry salt crusts, that are found only in the south-western part of the Qattara Depression, have no connection to the groundwater level of today. There are low areas of soft to hard crusts, continuing from 'wet' crusts to the dry depression margin, or also plateau-like crusts that may represent former groundwater stages.

Solid salt crust (mapping unit 14)
The type of solid salt crust is widespread in the western and southern part of the Qattara Depression. The salt is thicker than 0.5 m and the surface is not as rough as mapping unit 15.
The groundwater is found directly below the crusts.

Rough salt marsh (mapping unit 15)
This salt marsh has the aspect of a recently ploughed field. The salt crust is thin (up to some 30 cm), but hard. The margins of the polygons (diameter 1.5 - 2 m) are warped up.
The groundwater is situated directly below the crust.
This rough salt crust is uniformly developed in the centre of the eastern part of the Depression. The hardness, the high salinity of the groundwater and traces of wind erosion on top of the salt polygons make it probable that this marsh type is older than mapping unit 16.

Soft salt marsh (mapping unit 16)
This type is characterized by a thin, soft salt crust and high groundwater level. It is developed mainly at the northern and southern margin of the Depression, where often a groundwater efflux of proportionally low salinity is met. In the western part of the Depression a scarce vegetation of halophytes is found on this salt marsh.
In the depression of Siwa Oasis and at the western edge of the Qattara Depression (Qara, Tibaghbagh) a rough salt marsh is developed tending to the mapping unit 15. This rough salt marsh, however, tends to be softer because of higher groundwater inflow.

Salt marsh, undivided (mapping unit 17)
This comprehensive mapping unit means multiform salt crusts which could not be separated in the small scale map presented by JVQ

(1981). The type of salt marshes generally correspond to those described before.

3. METHODOLOGY

3.1 Working materials

The following Landsat products and maps were available for the research:

- Landsat MSS colour composites (band 4, 5 and 7):
  - . 192 - 39 6JAN73
  - . 193 - 39 12FEB73
  - . 192 - 40 7JAN73

  The scale of these colour composites is 1: 500,000
- Landsat TM B/W transparencies, scale 1: 1,000,000
  - . 178 - 039 13MAY84 bands 3, 4, 5, 6, 7
  - . 178 - 039 1AUG84 bands 2, 4, 5, 6, 7
  - . 179 - 039 12NOV84 bands 3, 4, 5, 6, 7
  - . 179 - 040 12NOV84 bands 3, 4, 5, 6, 7
- Landsat TM Computer Compatible Tape 180 - 40 28JUN84, quadrant 1, 2
- Geological sketch map of the Egyptian Western Desert, scale 1: 1,000,000 (after JVQ 1981; reduced to ± 1: 1,618,000)
- Egypt 1: 250,000 - Working Sheet (POEHLMANN et al 1983):
  - . sheet Bir Fuad
  - . sheet Bir Khalda
  - . sheet Siwa
  - . sheet Qaret Agnes

  The Working Sheets are the result of plotting all topographic information from available maps and fieldwork descriptions on the Landsat MSS band 5 mosaic.

3.2 Colour additive viewing

Data on reflection characteristics of the surface of the Earth are sensed by Landsat TM in a number of spectral bands simultaneously. Processing of data by means of optical, photographical and digital techniques is carried out to make them suitable for qualifying, quantifying or mapping features on the surface of the Earth.
One of the non-digital data processing techniques is colour additive viewing.

Colour additive viewers are devices designed to assist in the interpretation of multispectral photography. These devices normally incorporate four projectors (LILLESAND & KIEFER 1979) that are aimed at a single viewing screen (see figure 3). Each projector has a variable brightness and colour filter control.
For operation of the viewer black and white (B/W) multiband images are used. Both positive and negative format transparencies can be applied. The transparency for a particular spectral band is placed in a projector and projected through a colour filter.
The optical superimposition of multiple bands with different (primary) colours results in the production of colour composite images.

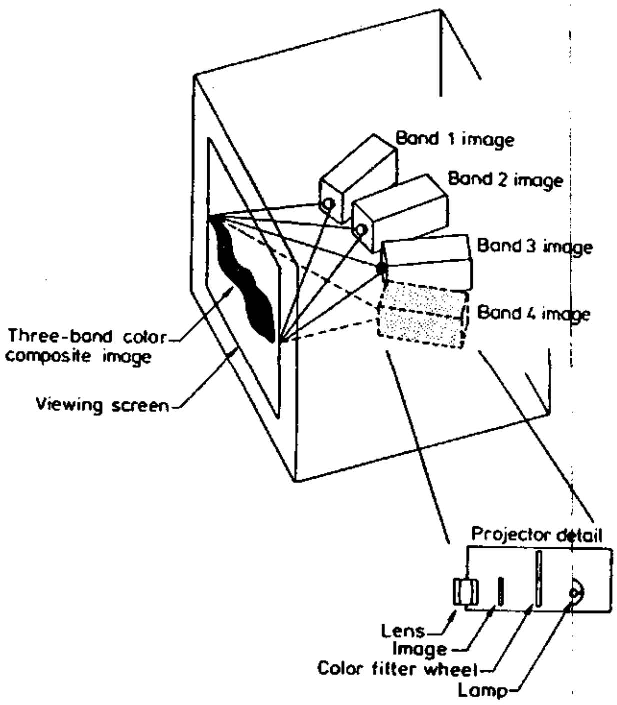


Fig. 3. Colour additive viewer schematic (after LILLESAND & KIEFER 1979)

3.3 Colour Additive Viewing In Agriculture

On request of the Agricultural University, the Technical and Physical Engineering Services (TFDL) in Wageningen have developed a device for making colour composites: Colour Additive Viewer in Agriculture (CAVIA).
One of the advantages of CAVIA in comparison with other CAV-systems is that the projection of the B/W-transparencies shows (almost) no distortion. The lack of distortion makes interpretation easier.

CAVIA also offers the possibility for varying the order of colour filters assigned to the respective channels. It is also possible to use filters of the same colour, but with different transmittance characteristics.
In this research the following KODAK WRATTEN colour filters were used: blue (no. 47B), green (no. 58) and red (no. 25). Appendix 1 shows the transmittance charateristics of these filters in both graphical and tabular form.

The combination of colour filters and channels of CAVIA that were used during the research are presented in table 1.

Table 1: The combination of channels and colour filters in CAVIA

FILTERS	CHANNELS 1	2	3
3	B	G	R
4	R	B	G
5	G	R	B

From this table it is clear that filter combination 3 3 3 means blue in channel 1, green in channel 2 and red in channel 3; filter combination 5 4 3 means green in channel 1, blue in channel 2 and red in channel 3.

CAVIA is not equipped with a means for direct and automatic registration of the colour composites (CAVIA-composites) on photographic film yet. CAVIA-composites need to be registered indirectly and manually with a camera placed on a tripod in front of the device.

3.4 Working methods

To determine the location of units in the terrain that show changes in surface reflection due to changes in groundwater efflux of the Miocene rocks in both the Qattara and Siwa Depressions, the Landsat MSS colour composites are compared with the Landsat TM B/W transparencies. Once the location of these units has been established, negatives of the B/W transparencies are used for making colour composites with CAVIA.
It should be borne in mind that using negatives of B/W transparencies implies that instead of reflection characteristics absorption of the various terrain features is presented.

The absorption characteristics of various terrain features in the different bands are qualitatively described. Subsequently, variations in absorption characteristics of single features are compared with spectral absorbance curves of land cover types, thus enabling to interprete variations in absorption in different bands.
CAVIA-composites are made using various combinations of Landsat TM bands and various combinations of colour filters. The CAVIA composites are recorded on photographic film. The photographic products are compared to determine the combination of Landsat TM bands most suitable for the drawn up objectives. Subsequently, the combination of colour filters that gives the best results for visual distinction is established.

The final stage of the research is the processing of a Landsat TM Computer Compatable Tape (CCT). The goal of this data processing is to quantify the absorbance pattern of various terrain features and to use the absorbance pattern to draw conclusions on the relative height of the units in the terrain.

4. INFORMATION IN THE LANDSAT TM B/W TRANSPARENCIES

4.1 Introduction

The interaction of electromagnetic energy with any given earth surface feature results in a partial reflectance of energy. The reflectance characteristics of earth surface features may be quantified by measuring the portion of incident energy that is reflected. This is measured as a function of wavelength, and is called spectral reflectance (LILLESAND & KIEFER 1979). In figure 4 typical spectral reflectance curves for various land cover types are presented.

One of the most distinctive characteristics considering the spectral reflectance of water is the absorption of energy at reflected infrared wavelenghts (LILLESAND & KIEFER 1979). The reflection characteristic does not only count for bodies of open water (lakes and streams), but also for water contained in vegetation or in soil. Thus, the location and delineation of water bodies with remote sensing is done most easily in reflected infrared wavelenghts.

When using Landsat TM data for locating water surfaces and determining soil moisture conditions, best results will be obtained by using bands 5 and 7. Different reflection patterns in the lower bands, especially bands 3 and 4, provide the possibilities for an additional differentiation in water covered or containing surfaces.

Variations in reflection form the basis for a distinction between three major geomorphic units in the Qattara Depression (LINNE & MEISSNER 1983):
- open water areas
- permanently dry areas
- areas with a (relatively) high groundwater level

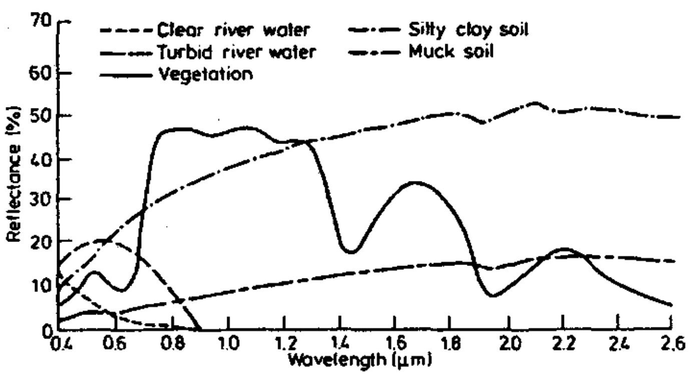


Fig. 4. Spectral reflectance curves for various land cover types

Open water areas:
Even with higher salt contents water absorbs almost all energy in the total Landsat TM range. Therefore, the open water surfaces resulting from the effluxes of groundwater appear as white in the B/W negatives. Only with extreme salt contents, water will show reflections in the visible range.

Permanently dry areas:
Moistening of soils of geomorphic units in the Qattara Depression is restricted to non-consolidated sediments. Decreasing the groundwater table results in a minimal degree of consolidation of the sediments at the surface. Subsequently, wind action may be important in shaping superficial forms. This implies that all areas that show relief-controlled structures at the surface can be considered as recently 'permanently dry' (LINNE & MEISSNER 1983).

Areas with a (relatively) high groundwater level:
The areas that are characterized by clayey or sandy surfaces with a relatively shallow grondwater table can show considerable variations in reflection due to the presence of salt crystals of varying size. Within each unit, however, the relations 'low reflection = wet/moist' and 'high reflection = dry' are still valid.

4.2 Qualitative description of the B/W negatives

The use of B/W negatives of Landsat TM images in CAVIA will cause a reversed effect on recognition of water and related soil moisture features: open water will appear as white, decreasing soil moisture contents can be interpreted by a shift from light to dark grey tones. The description of grey tones in the B/W negatives will be related to variations in absorption characteristics.

One of the areas in the Qattara Depression where changes in groundwater efflux and soil moisture conditions can be easily recognized is near Sitra. Here several lakes are found with a varying salt crust environment. The four lakes in this area are numbered (see figure 5) from 1 to 4 (from east to west) and are qualitatively described hereafter. Figures 5, 6, 7 and 8 are the photographic products of bands 3, 4, 5 and 7 respectively.

Lake 1:
In band 3 (see figure 5) the lake does not show any particular differences in absorption values. Near the eastern tip of the lake some small variations in absorption are visible. The most striking features are dark lines, appearing on both southern and northern lake shores.

In band 4 (see figure 6) the overall view on absorption intensities is similar to band 3. However, to the outsides of the dark lines absorption intensities appear to be lower.

Fig. 5. Sitra Lake and adjacent salt lakes, band 3

Fig. 6. Sitra Lake and adjacent salt lakes, band 4

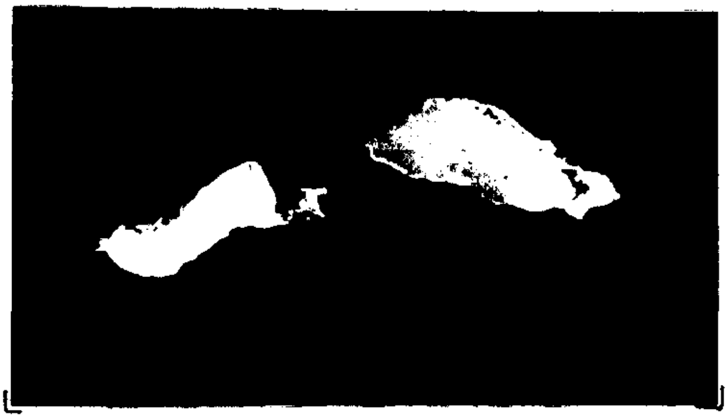


Fig. 7. Sitra Lake and adjacent salt lakes, band 5

Fig. 8. Sitra Lake and adjacent salt lakes, band 7

In band 5 (see figure 7) a clear division between two units can be made: a central unit that appears to be somewhat less absorbing; and an outer unit (=boundary unit) that appears more whitish. The dark lines have disappeared; only at the boundary between central and outer unit (in the east of the lake) a dark line is still visible. It is striking that this dark line can be observed in bands 3 and 5 (and 7), but is almost absent in band 4.

In band 7 (see figure 8) the differences in intensities between central and outer unit are less distinctive than in bands 5. No dark lines are visible, except in the eastern lake tip.

Lake 2:
In band 3 (see figure 5) a clear distinction can be made between several units. Along the northern lake shore two units can be distinguished, different in grey tone. The southern shore also (faintly) shows a different unit. Within the lake an increase in intensities can be observed when going from W to E. One unit stretches along the faintly observable unit at the southern lake shore. The eastern tip of the lake shows greatest differences (grey and dark grey). The most eastern tip is similar in reflection to the surrounding landscape.

In band 4 (see figure 6) the overall pattern has not really changed, except for some important details on the southern shore. Here, a W-E stretching unit has become clearer than in band 3. Within the lake the intensities show a sudden change from white to dark grey.

In band 5 (see figure 7) the intensity appears to be the same throughout the lake environment. The northern shore shows more distinct units.

In band 7 (see figure 8) the units at the northern shore can be best distinguished. No real differences with band 5 seem to appear.

Lake 3:
In band 3 (see figure 5) three units can be distinguished easily. To the east two units with lower absorption intensities; the southern shore shows a faintly distinguishable unit.

In band 4 (see figure 6) one of the units in the north has a higher absorption now, whereas the western part is now somewhat more grey.

In band 5 (see figure 7)only the eastern tip of the lake is still faintly absorbing. Some faint units can be observed.

In band 7 (see figure 8) differentiation is almost impossible.

Lake 4:
In band 3 (see figure 5) four units can be readily observed. Two units have similar medium absorption intensities, while the third (to the west) and the fourth (in the middle) increase in absorption

intensity.

In band 4 (see figure 6) the distinction of the units has become difficult.

In band 5, however, the same observations as for band 3 can be made (compare figures 5 and 7).

In band 7 (see figure 8) the four units can still be observed, although differences in reflection intensities have become smaller.

4.3 Absorbance versus soil units and soil moisture content

The salt crust of lake 1 shows a rather good differentiation between a central and a boundary unit in band 5. In band 7 the differences are less distinctive, but in bands 3 and 4 almost no distinction can be made. This can be explained by the absorption of energy by soil moisture in the lower bands 3 and 4, while in the bands 5 and 7 the absorption by soil moisture becomes more important. The differences in reflection of various salts in bands 5 and 7 is presented in figure 9.

In the environment of lake 2 the area that appears white due to the absorption of energy in bands 3 and 4 can be identified as open water. The small units that are visible near both the southern and northern shore might be slightly higher grounds that rise from the open water. The lower absorption of these soil surfaces may be similar to the low surface absorption in the eastern part of the lake. As bands 5 and 7 are suitable for determining soil moisture conditions and the areas just mentioned appear white in both bands, it can be concluded that these areas are located sligthly higher than the water surface. The different absorptions of the two salt crust units that are known to the north of the lake can be related to a general decrease in groundwater level. The northernmost unit will be more consolidated than the one adjacent thus causing different surface absorption conditions. In band 7 the various salt crusts units can be distinguished relatively well. This might be related to the varying soil moisture conditions that are detected very well in this band.

No open water surfaces are known from lakes 3 and 4. The variations in surface absorption patterns are relatively well distinguished in bands 3 and 4 and almost absent in bands 5 and 7. Hence, it might be concluded that these variations are caused by different soil moisture conditions.

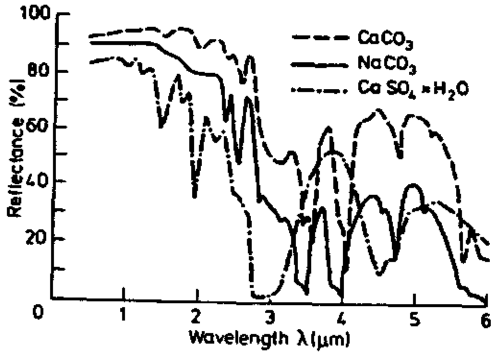


Fig. 9. Spectral reflectance curves for various salt types (after HOVIS 1966)

5. INFORMATION IN THE CAVIA-COMPOSITES

5.1 Introduction

Four Landsat TM bands are available, viz. band 3 that covers part of the visible (VIS) range of the EM-spectrum, and bands 4, 5 and 7 that show the reflected energy in the near infrared (NIR) part of the EM-spectrum. As can be seen from figures 5 to 8, bands 3 and 4 show more detail than bands 5 and 7. Therefore, the B/W negative transparencies are used to compile colour composites of three bands in two main combinations:

- bands 3 and 4 with either band 5 or band 7;
- bands 5 and 7 with either band 3 or band 4.

Considering the spectral reflectance characteristics of different phenomena in the study area, differentiations in the CAVIA-composites of these phenomena in the two main combinations can be expected.

A comparison of composites of each of the mentioned main combinations made with various filter combinations reveals a distinct differentiation in colours. Basically, the differentiation is the same, a change in colours is merely caused by a varying filter combination. Therefore, the differentiation discussed below will refer to the filter combination 3 3 3, which means that the respective filters blue, green and red are assigned to the first, second and third channel of CAVIA.

Colour description is a rather subjective matter. To prevent confusion, colours have been quantified using the ITC-COLOUR CHART (ITC 1982).

5.2 Qualitative description of the CAVIA-composites

5.2.1 Bands 3 and 4 with either band 5 or 7

The composite described hereafter is of bandcombination 3 4 5 (see figure 10).
Lake 1 is characterized by a light greyish-blue (ITC colour code:001) central unit that appears to have some internal variation in colour when going from W to E. The eastern edge of lake 1 shows an orange-yellow (660) to light-reddish (330) colour. At some point between these two units a dark greyish-blue (102) line can be observed. Near the western tip of the lake an orange-red (650) line unit is visible.

Going from W to E, lake 2 shows a transition in colour from whitish (100) via light yellow (200) to orange (650) to red (660). Just south of the orange part of the lake a magenta (040) unit is visible. Adjacent to this unit (at the water side) a faint yellow (200) unit can be observed. North of the lake two units of greyish-blue (102,323) are distinguished. The northern lake shore is visible as a thin reddish (660) line.

Fig. 10. CAVIA-composite of Sitra Lake and adjacent salt lakes, bands 3 (blue) 4 (green) and 5 (red)

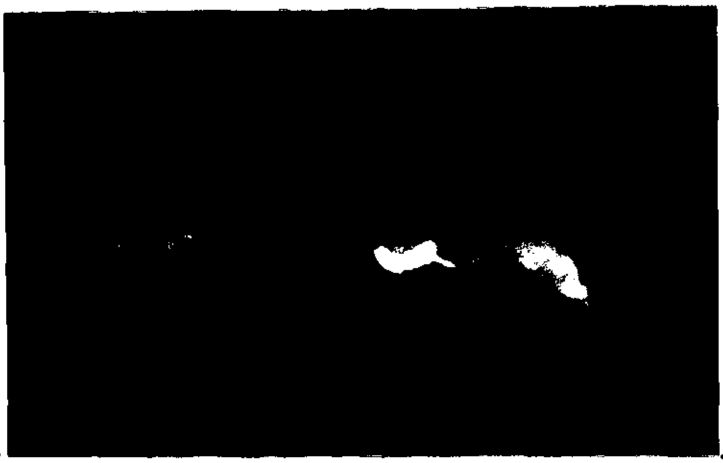


Fig. 11. CAVIA-composite of Sitra Lake and adjacent salt lakes, bands 3 (blue) 4 (green) and 7 (red)

The eastern tip of the lake appears in the same colours (553) as the surrounding landscape.

Lake 3 largely consists of a magenta (250) unit with an orange (640) unit at its eastern side. Some small bluish-grey (102) units can be seen. The eastern tip of the lake appears in the same colours as the landscape surrounding the lake (553).

Lake 4 consists of two magenta (150) units and two units of a brownish (332) colour.

In the combination 3 4 7 the overall view in colours is similar to the combination described above (see figure 11). Most striking however, is the colour of the central unit in lake 1 that appears as a light magenta (121). This colour can also be observed in the units directly north of the water of lake 2.

5.2.2 Bands 5 and 7 with either band 3 or band 4

The colour composites of the combination 7 3 5 are not really suitable for a qualitative description of colours because of the inaccuracy by which the composite has been made: only two of the composing B/W negatives fit together, the third is shifted eastwards. Despite this inconvenience an attempt has been made to describe the colours. As the overall view of the colour composite of combination 7 3 5 is similar to that of combination 7 4 5 the description of colours is based on the latter combination (see figure 12). Differentiating characteristics in the 7 3 5 combination will be mentioned as well.

The central unit of lake 1 consists of a light bluish-grey (001) colour, while the outer unit has a magenta (030) colour. A dark (244) colour is observed between the eastern part of the outer unit and the adjacent part of the central unit.

In lake 2 the water surface shows a quick transition from white (000) to magenta (060) via a light magenta (030) colour. The complete eastern tip of the water is characterized by magenta (030) colours.Along the south-eastern shore a magenta (030) unit is visible. The northern shore of the lake shows some greenish (412,622,632) units.
In band combination 7 3 5 (see figure 13) the SE-stretch along the lake shore is visible as a whitish (000) colour. Directly north of this unit (in the water) a magenta (040) coloured unit is visible.

Lake 3 appears to consist of four units: an eastern unit that is in colour equivalent to the surrounding landscape (543); adjacent to this unit is a light magenta (130) unit. The western part of the lake seems to be magenta (040) with parts of a fourth unit appearing in a dark colour.
In band combination 7 3 5 (see figure 13) a magenta (060) unit appears adjacent to the eastern tip of the lake; a light coloured/whitish (001) unit is visible throughout the rest of the

Fig. 12. CAVIA-composite of Sitra Lake and adjacent salt lakes, bands 7 (blue) 4 (green) and 5 (red)

Fig. 13. CAVIA-composite of Sitra Lake and adjacent salt lakes, bands 7 (blue) 3 (green) and 5 (red)

lake.

Lake 4 shows two different types of units: a magenta (040) unit comparable to the magenta unit that is described in lake 3 as well, and a unit of a dark (332) colour.

5.3 Interpretation of the CAVIA-composites

Interpretation of the colour composites described above is based on the combination of knowledge on the location of various soil units and their characteristic reflectance-absorbance patterns. Hence, the various distinctive colours can directly be related to the distinguished soil units. Variations of colours, or transitions from one colour via an intermediate to another colour will be related to varying absorption intensities in different bands. The colour composite described hereafter is of band combination 3 4 5, with colour filter combination 3 3 3 (= B G R).

Lake 1:
The salt crust of the central unit of lake 1 appears as cyan colours. This is caused by the relatively high absorption in bands 3 and 4 respectively: a high transmittance of blue and green results in cyan. The lowest absorption values will thus be found in band 5. The orange-yellow colours of the boundary units are the result of combining green and red light of the respective bands 4 and 5. The high absorption values in these bands can be explained by a relatively high soil moisture content in this unit.

Lake 2:
The whitish colour in lake 2 is the result of combining relatively equal amounts of blue, green and red light. The high absorbance of energy by water thus results in white in the colour composite. Features related to the open water area are found in the eastern part of the lake environment and along the southeastern shore of the lake.

The yellow colours indicate moist or wet soils, whereas the red colour forms an indication for the largest extent of soil moisture in this area.
Considering the relative absorption intensities that can be observed in the B/W transparencies, the soils in the eastern tip of the lake are not comparable with the salt crusts. This might be the result of the absence of salt crystals in a clastic sedimentary environment.
The salt crust north of the open water unit appears in cyan colours. The combination of blue and green light (band 3 respectively 4) forms an indication for a relatively high absorption in these bands.
The southern shore of lake 2 shows a second feature related to the open water surface: in combination 3 4 5 (with filter combination 3 3 3 - B G R) a magenta unit (ITC-colour code: 040) unit can be observed along the southern shore of the lake. As magenta is a mixture of blue and red light, this forms an indication for a feature related to low absorbance in band 4. A land cover unit that can be related to a relatively low absorbance in band 4 is vegetation.
The presence of vegetation as concluded from the magenta coloured units form an indication for groundwater levels close to or at the surface. LINNE & MEISSNER (1983) describe the 'competition' between vegetation, that reflects highly in the NIR-range on one hand, and the strongly absorbing characteristics of open water on the other: a minimal amount of water is required to initiate the development of vegetation. The concentration of vegetation will have a considerable influence on the recorded reflection compared with the relatively low reflection of the surface, resulting in a 'vegetation-zone' in the colour composite. In combination 3 4 7 the magenta is similar in appearance.
The two combinations of 1 VIS + 2 NIR show a clear distinction in appearance of the 'vegetation' unit. In combination 7 3 5 this unit appears as whitish adjacent to a magenta unit that is located in the water of the lake, whereas in combination 7 4 5 the unit in the water cannot be observed and the vegetation unit appears as magenta. The reasons for this, of course, are differences in absorption characteristics in the bands 3 and 4.

Lake 3:
The orange unit in lake 3 is the result of combining light of band 4 (green) and band 5 (red). This means that a relatively high absorption in bands 4 and 5 is an indication for wet soil.
The magenta coloured units in lake 3 can be compared with the magenta unit of lake 2. This indicates that in lake 3 a vegetation unit can be found. The presence of vegetation is surprising, since no open water surface has been interpreted near the vegetation unit. Hence, it might be concluded that vegetation is the result of shallow groundwater tables.

Lake 4:
In lake 4 two magenta units can be observed. In this lake the presence of vegetation can be interpreted from these composite colours.

In band combination 3 4 7 the overall view in colours is similar to that in 3 4 5. An important differentiation is the light magenta colour of the salt crust of the central unit of lake 1 and the magenta colours in the salt crust of lake 2. This might be due to a higher absorbance of the salt crusts in band 7 as compared with band 5.

5.4 Conclusions

Various land cover types have been distinguished (LINNE & MEISSNER 1983) within the Qattara Depression in general and the Sitra area in particular. To find the combinations of Landsat TM bands that are most suitable for determining changes of soil moisture conditions colour composites are made with CAVIA. The availability of the Landsat TM bands 3, 4, 5 and 7 enables to distinguish between two important combinations in the colour composites: 1 VIS + 2 NIR and 3 NIR. Each of these combinations is more or less suitable for the distinction of specific land cover types. The combination most suitable for distinction of all land cover types seems to be 1 VIS + 2 NIR. As some specific land cover types can be distinguished only in either band 3 or band 4, a combination of these bands with band 7 of the NIR-range appears to be the best combination for distinction of all land cover types.

6. COLOUR COMPOSITES AND VISUAL DISTINCTION

6.1 Introduction

It has been concluded that a combination of Landsat TM bands 3, 4 and 7 is most suitable for determining geomorphic units, groundwater levels and related soil moisture conditions (see chapter 5).
The combination of colour filters assigned to the respective channels of CAVIA was 3 3 3, which stands for channel 1 = blue, channel 2 = green and channel 3 = red. The use of this filter combination, however, does not allow an easy distinction of all features in the study area, while with other filter combinations better results are obtained.

As the most important features that need to be distinguished are theW-E elongated soil units in the open water area of lake 2 and the W-E elongated soil units in the open water area of lake 2 and the adjacent vegetation unit, there is no use for an extensive qualitative description of the soil units of all lake environments.
In table 2 an overview of the colours of the important units in the lake 2 environment using various combinations of colour filters is presented. Both a qualitative description of composite colours and a quantitative description, using the ITC colour code, is given.
The following combinations of colour filters have been used:
3 3 3 (B G R); 4 4 4 (R B G); 5 5 5 (G R B); 5 4 3 (G B R).

Table 2: Colours of some soil units in various colour filter combinations

	3 3 3	4 4 4	5 5 5	5 4 3
open water	white/yellow 000	white 000	faint magenta 010	faint magenta 010
soil units	faint yellow 520	faint cyan 102	magenta 050	magenta 050
vegetation	magenta 040	faint orange 430	light cyan 202	faint orange 310
clastic sed	orange >red 660	cyan >green 603	magenta >blue 066	magenta >red 660

Since the variation of colour filters assigned to the respective bands appears to be important for the distinction of all features in the study area, the best combination of colour filters needs to be established considering the sensitivity of the human eye for various colours.

6.2 Colours in the human visual system

Light forms the input for the human visual system. In figure 14 the ocular optical system of a human is seen to produce a transformation of the light energy of the visual input stimulus impinging on the eye to an output which is similarly a high-energy signal (LEVINE 1985). The conversion of one energy signal into another takes place in the retina.

One of the ocular media, viz. the lens, has an important influence on the kind of light that will reach the retina. In figure 15 the absorbance spectrum of the human lens is presented. It can be seen that the amounts of green and red light that will be transmitted by the human lens are relatively small as compared with the amount of blue light.

In the retina, the electro-optical transduction of energy is accomplished by light receptors of two different types, namely rods and cones. Both receptors have a different task: rods provide scotopic vision or night viewing; cones provide photopic vision or day viewing. Furthermore, the cones are occupied with colour processing.

Each of the photoprocessors possesses photopigment that responds to energy stimuli. The photopigment in rods basically operates within the VIS part of the spectrum, between approximately 400 and 700 nm (see figure 16). In contradistinction to the rods, the cones possess three different kinds of photopigments, each of which responds differently to a stimulus wavelength (LEVINE 1985), as shown in figure 16. Here, it can be observed that each photopigment in the cones fully absorbs light at a specific wavelength.

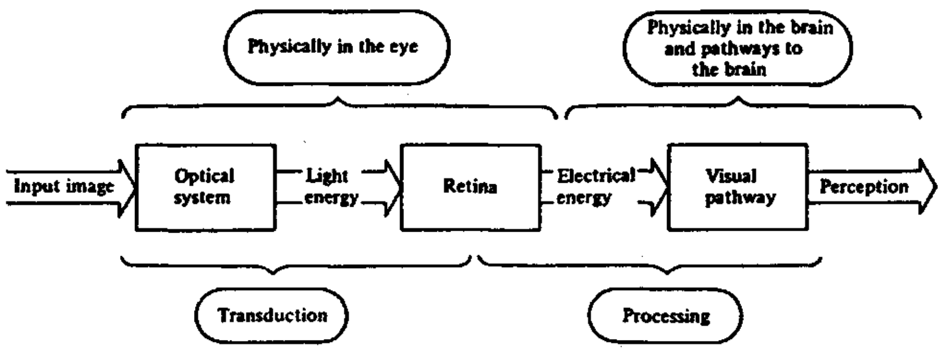


Fig. 14. The human visual system viewed as consisting of a camera and a computer, providing for transduction and processing respectively (after LEVINE 1985)

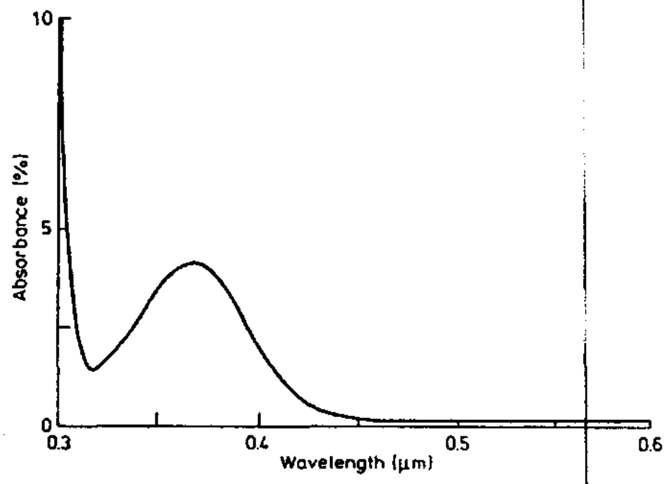


Fig. 15. The absorbance spectrum of the lens of the human eye (after LEVINE 1985)

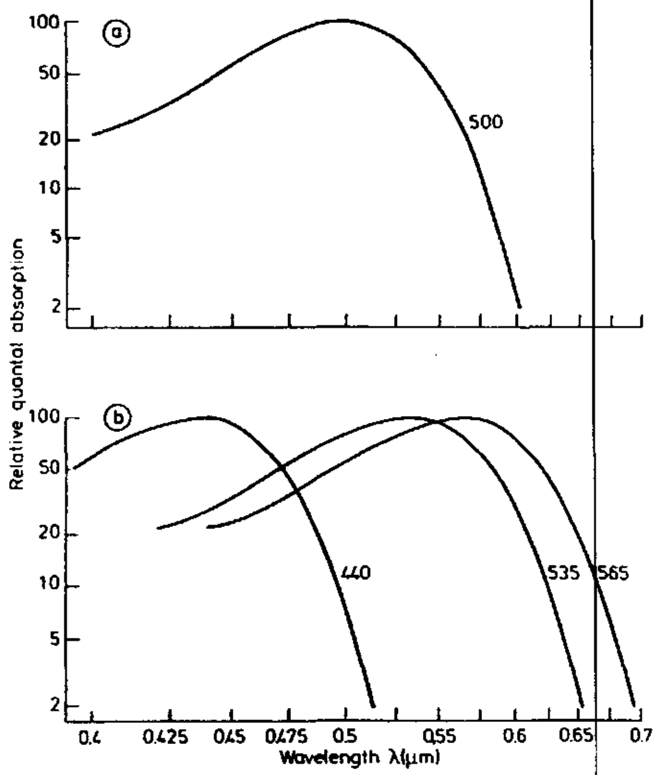
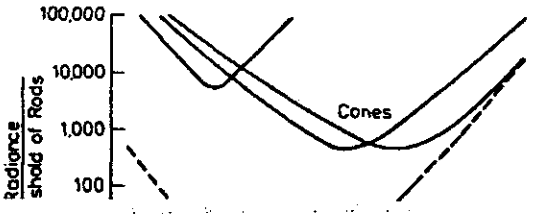


Fig. 16. A representative set of absorption spectra
a. rod photopigments
b. cone photopigments
(after LEVINE 1985)

6.3 Visual distinction of composite colours

The elucidation of differences in visual distinction of phenomena occurring when different combinations of colour filters are applied to a given set of Landsat TM bands, should be explained by absorbance characteristics of specific elements of the human visual system. The factor that determines visual distinction might be related to the difference of level of radiance that stimulates the various types of cones: the cones that are sensitive for green and red light are stimulated at a lower radiance level than the blue cones (see figure 17). This difference might induce that a combination of blue and either green or red in bands 4 and 7 results in a better visual distinction than the combination of green and red in these bands.



7. COMPARISON OF SATELLITE IMAGERY: 1973 LANDSAT MSS VERSUS 1984 LANDSAT TM

7.1 Introduction

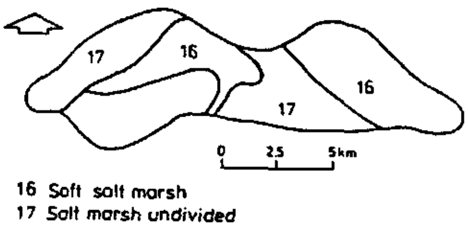


Fig. 22. Soil units of Sitra Lake and environments (scale approx. 1: 250,000 after JVQ 1981)

Various Landsat imagery and derived products are available at this stage of the research. Except for differences in origin (either MSS or TM), differences in scale and processing occur.
A comparison of the available materials on the various scales seems justifiable to determine differences and resemblances in the presentation of the terrain situation and to find out whether any differences are the result of changes in environment or due to the increased accuracy of the Landsat TM.
JVQ (1981) indicate several mapping units in the Sitra Lake and environments. These mapping units are presented in figure 22.
A description of these mapping units is given on page 4.
Landsat MSS and Landsat TM imagery and related products of Sitra Lake and environment are compared at three scales, namely 1: 500,000; 1: 250,000 and 1: 100,000.

7.2 Comparison of satellite imagery at various scales

7.2.1 Scale 1: 500,000: 1973 Landsat MSS colour composite versus CAVIA-composite

Since the Landsat MSS colour composite is processed from Computer Compatible Tape (CCT) and the CAVIA-composites by using B/W negative transparencies and coloured light it is not easy to compare these composites on the same grounds.
The major difference between both composites can be found in the presentation of the westernmost units of the Sitra Lake environment. Here, the MSS composite only shows three units that can easily be delineated (see figure 23), while the CAVIA-composite shows at least five units (see figure 24). South of these units the CAVIA-composite shows a white unit, indicated as open water (see chapter 5). Here, a transition can be observed when going to the east. In the MSS colour composite this transition cannot be indicated easily.
It can be concluded here that on a scale 1: 500,000 the CAVIA-composites show better possibilities for delineating soil units than the 1973 Landsat MSS colour composite.

Fig. 23. Sitra Lake in the 1973 Landsat MSS colour composite (scale 1: 500,000)

Fig. 24. Sitra Lake in CAVIA-composite (scale 1: 500,000)

7.2.2. Scale 1: 250,000: Sitra Lake (after JVQ,1981) versus Landsat TM band 4

The delineation of the geomorphic units of the Sitra Lake as presented by JVQ (1981) in figure 22 is based on the interpretation of satellite imagery. Some of the units that are distinguished here are rather similar in extension to the units that can be recognized in the TM images, while others are completely different (see figure 25). E.g. the salt lake of Sitra Lake does not show any important differences between MSS and TM, but in figure 22 the eastern tip of this lake is assumed to belong to the same soil unit as the one north of the salt lake.
However, all bands of the Landsat TM show variations in absorption in these points. These variations form an indication for a difference in both surface morphology and soil moisture content. This implies that instead of presenting one salt marsh unit two units should be distinguished.
To the north of the salt lake the TM images show considerable difference in soil units as compared with the delineation of units by JVQ (1981). In the TM images the area that is designated as mapping unit 16 seems to have extended as compared with the map of JVQ (1981). It can be concluded that the 1984 Landsat TM images show more detail than the map of JVQ (1981) that is based on 1973 Landsat

Fig. 25. Sitra Lake in
1984 Landsat TM band 4
(scale 1: 250,000)

MSS imagery.

7.2.3 Scale 1: 100,000: Sitra Lake (after LINNE & MEISSNER,1983) versus Landsat TM band 4

When comparing the map of Sitra Lake (LINNE & MEISSNER 1983 p.69) and the 1984 Landsat TM bands several differences in delineation of soil units can be observed.
At the north side of the salt lake LINNE & MEISSNER indicate one single unit (see figure 26) that is designated as 'dry lake bottom'.

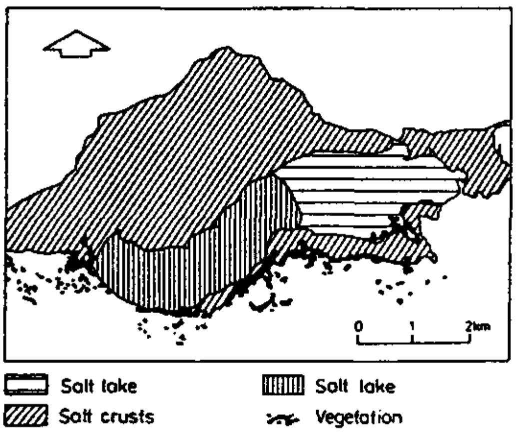


Fig. 26. Terrain units of Sitra Lake (scale 1: 100,000; after LINNE & MEISSNER 1983)

Fig. 27. Sitra Lake in 1984 Landsat TM band 4 (scale 1: 100,000)

In the TM images this unit appears as consisting of at least five subunits (see figure 27).
The area that LINNE & MEISSNER indicate as 'salt lake' is divided into two subunits: the western subunit does not differ from the 1984 Landsat TM image; the eastern subunit is considered a single unit. The Landsat TM images (especially bands 3 and 4)show at least four subunits in the eastern part of the salt lake. The sebkha along the southern shore of the salt lake is uniform in appearance in both types of Landsat imagery.
Especially on a scale 1: 100,000 much detail of the salt lake environment of Sitra Lake can be presented. The map based on 1973 Landsat MSS data only shows major units, while the 1984 Landsat TM band 4 can be used to distinguish several subunits in all major units. Thus, the 1984 Landsat TM data are preferred for delineating soil units.

7.3 Conclusions

The comparison of satellite imagery of different origin - either 1973 Landsat MSS or 1984 Landsat TM - and at various scales (1: 500,000; 1: 250,000; 1: 100,000) of the environments of Sitra Lake serves a dual purpose.
Firstly, it can be used to establish whether any major changes in groundwater efflux and soil moisture content in the environment have occurred over a 10 year period.
Secondly, it might be established whether the improved accuracy of the Landsat TM as compared with the Landsat MSS results in delineation of more mapping units.

As described above, the environment of Sitra Lake can be distinguished into two major units, namely the salt lake itself and the dry lake bottom directly north of the lake. From the comparison of the Landsat products at a scale 1: 100,000 it is clear that no major changes have occurred in the extension of the salt lake.
This is an indication that between 1973 and 1984 the efflux of groundwater of the Nubian sandstone into the lake has not changed.
The units of the dry lake bottom to the north of the salt lake can be delineated differently in both Landsat products. The mapping unit 17 seems to have become smaller in the 1984 Landsat TM images. From this image it can be concluded that an increase in soil moisture content has occurred in mapping unit 16.
This increase in soil moisture content is in contradiction with the observation that the efflux of groundwater has not changed.
Therefore, it is assumed that the possibility for delineating more soil units in this area from the 1984 Landsat TM, is the result of the improved accuracy of the Thematic Mapper as compared with the Multi Spectral Scanner.

On a small scale (1: 500,000) the CAVIA-composites, originally 1984 Landsat TM B/W negatives, show more detail than the 1973 Landsat MSS colour composite. Except for the improved accuracy of the Landsat TM this is also described to the use of negatives instead of the original B/W positive transparencies. It is observed that transitions of soil moisture content can be determined more easily with negative transparencies.

Originally, the map of JVQ (1981) was meant to present units that serve as a base to calculate the evaporation of several salt crusts in the Qattara Depression assuming that groundwater would remain at a constant level. It is observed that changes in soil moisture content have occurred at several locations in the Depression. These locations are (1) El Kish; (2) El Arag; (3) Qattara. Because of these changes in soil moisture content the base for calculating evaporation has vanished and thus the map appears not te be suitable for its purpose.

8. SPECTRAL ABSORBANCE PATTERN OF SALT CRUSTS

8.1 Introduction

The qualitative absorption aspects of the various soil units in the Sitra area have been described by means of the Landsat TM B/W negative transparencies (see chapter 4 and 5). In order to quantify the relative absorption values and thence to distinguish between various soil units based on the spectral absorbance pattern a Landsat TM Computer Compatible Tape is processed.
Since no Computer Compatible Tape (CCT) of the Sitra area was available, an area with comparable soil units to that of Sitra was selected in the Landsat TM CCT 180/40 28JUN84. The location of the area, west of Siwa Oasis, is indicated in figure 28, presenting the soil units distinguished by JVQ (1981) as well. Three soil units are distinguished: a central and an outer salt crust unit and a 'vegetation' unit.
JVQ (1981) describe the central unit as a 'solid salt crust with high groundwater level' (mapping unit 14, see also page 4) and the outer salt crust as 'soft salt marsh with high groundwater level' (mapping unit 16, see page 4). The 'vegetation' unit is found at the northern edge of the salt lake. Most probably, this vegetation unit is closely related to the efflux of groundwater as has already been described on page 15.

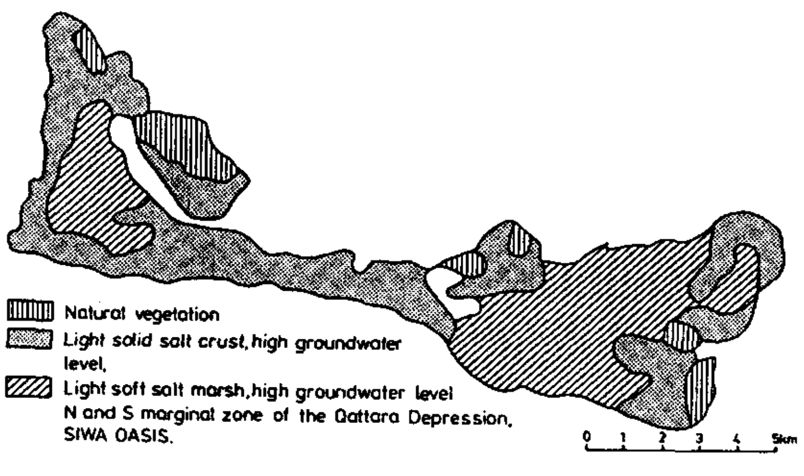


Fig. 28. Siwa Oasis, western part (scale 1: 250,000; after JVQ 1981)

8.2 Processing of CCT

The Landsat TM CCT applied contains radiance values in arbitrary units within the range 0 - 255. A specific pair of gain and offset values apply to each scene as indicated in table 3 and according to the equation

$$R_i = (R_{X,i} - R_{N,i}) . \frac{DN_i}{255} + R_{N,i} \qquad (W.m^{-2}.sr^{-1})$$

where R_i is the total radiance measured by the TM in the seven spectral bands, i.e. i = 1, 2, 3, 4, 5, 6, 7; $R_{X,i}$ respectively $R_{N,i}$ the maximum respectively minimum radiance in each band; DN_i the digital value corresponding with a particular pixel in each band.

The R_i -values are applied next to calculate the reflectance of the earth-atmosphere system, termed planetary reflectance, by means of the equation

$$\alpha_{p,i} = \frac{\pi . R_i}{\cos \phi_{su} . R_{out,i}} . d^2 \qquad (-)$$

where $\alpha_{p,i}$ is the planetary reflectance, d is the sun-earth distance in Astronomical Units (AU), ϕ_{su} is the sun zenith angle at the time of acquisition of each image and $R_{out,i}$ is the exo-atmospheric radiance in each band. The reflectance $\alpha_{p,i}$ is an emispherical reflectance under the hypothesis that the surface is a Lambertian reflector.

Table 3: Specific data for processing CCT 180 - 040 28JUN84

band	gain coeff.	offset coeff.
1	0.6024 E-01	-0.1500 E+00
2	0.1175 E+00	-0.2805 E+00
3	0.8060 E-01	-0.1194 E+00
4	0.8144 E-01	-0.1500 E-00
5	0.1081 E-01	-0.3700 E-01
7	0.5698 E-02	-0.1500 E-01

sun elevation 61.00
sun azimuth 94.00

To make comparison of the data of the CCT with qualitative description of absorbance of soil units in the B/W negatives and the

CAVIA-composites easier, the data of the CCT were made negative by reversing the Look Up Table.
The planetary absorbance can be calculated from the planetary reflectance by using the equation $\gamma_{p,i} = 100 - \alpha_{p,i}$

where $\gamma_{p,i}$ = absorbance and $\alpha_{p,i}$ = reflectance in band i.

No data were available to properly correct the R -values for atmospheric effects to obtain surface reflection values $\alpha_{0,i}$ from the $\alpha_{p,i}$ -values. Since, however, the research is not meant to be a multitemporal atmospherical effects are neglected.

8.3 Spectral absorbance of various salt crusts

Figure 29 shows the absorbance values of band 4. It can be seen that in contrast with the soil units of JVQ (1981) more than three units can be distinguished. It might appear, however, that some of these units are similar on grounds of absorption percentages. To determine whether this assumption is correct several sampling points are selected in the various units and subsequently absorbance characteristics are calculated in all bands. The spectral absorbance curves that thus can be drawn for each sampling point can be used to establish whether or not sampling point belong to the same soil unit. The curves can also serve to establish whether units that appear different should be distinguished separately or can be collectively grouped in a major unit.

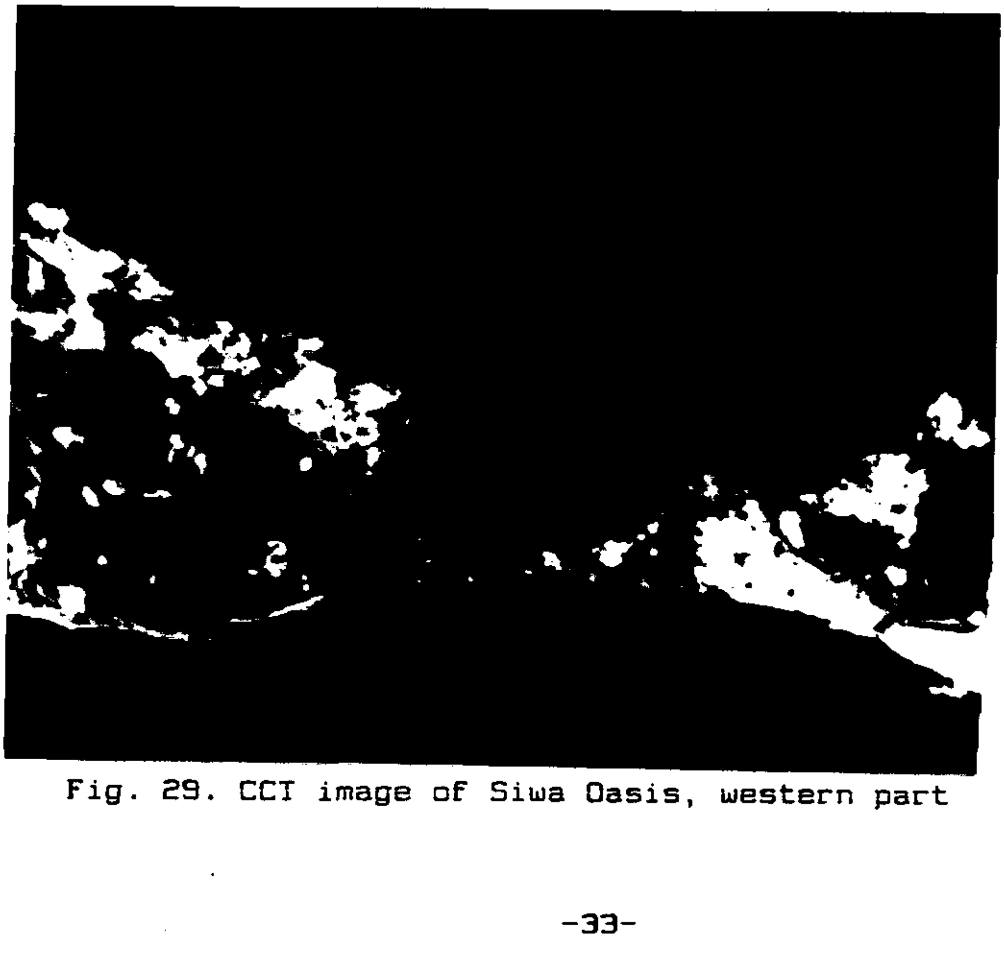


Fig. 29. CCT image of Siwa Oasis, western part

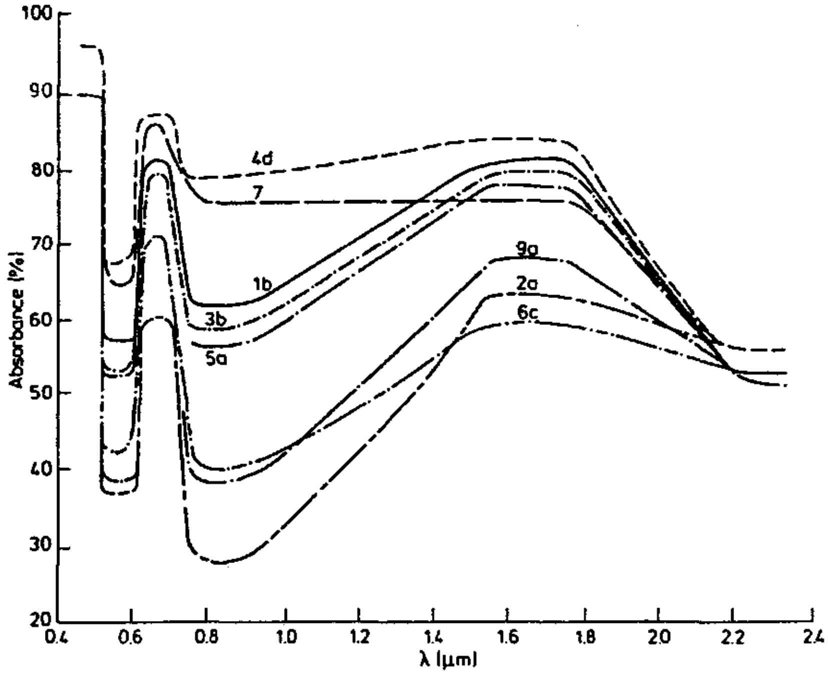


Fig. 30. Spectral absorbance pattern of several soil units in Siwa Oasis, western part

In figure 30 the spectral absorbance pattern is presented of several soil units in the area west of Siwa. When comparing the absorbance pattern of the units it is striking that all curves are similar in appearance with only quantitative differences. The resemblance of the curves might point towards a gradient that exists between the units that are represented by the lowest respectively the highest curve.

In some units the spectral absorbance curves show deviations from the overall pattern. This is the case with the curves of units 4 and 7 (see figure 30). In comparison with the other units the curves of units 4 and 7 show similar absorbance percentages in bands 4 and 5.

8.4 The location of salt crusts in the terrain

The observations described above can serve as a base for conclusions on the relative height of the various units in the area.
The salt crusts in the area west of Siwa can be divided into three soil units: a solid salt crust (salt crust thicker than 0.5 m) with high groundwater level; a soft salt marsh with high groundwater level and a 'vegetation' unit.
The spectral absorption of the various units that are sampled show quantitative differences in curves. MENENTI (1984, p.85) shows that with increasing soil moisture content of a soil unit the absorption increases as well (see figure 31). Hence, it can be concluded that in figure 30 the lowest curves represent units with a low soil moisture content and the highest curve represent units with a higher soil moisture content.
This means that, considering the groundwater to be at a constant

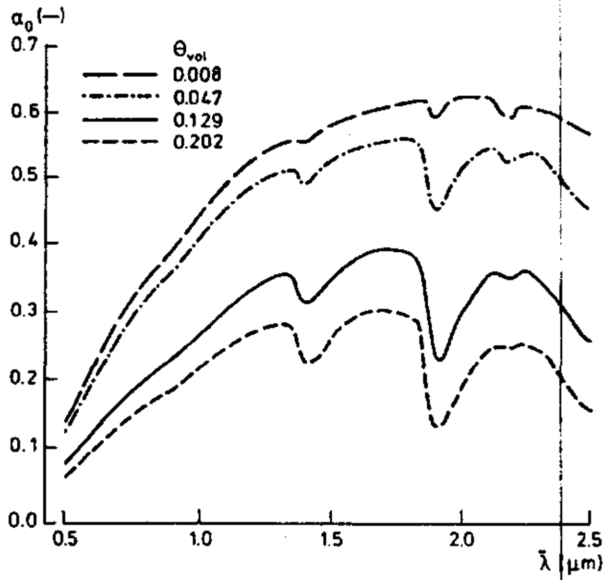


Fig. 31. Reflectance versus wavelength for different moisture contents as indicated for each curve (after MENENTI 1984)

level, the spectral absorbance curves can be used to establish the relative height of the various soil units in the area.
The lowest spectral absorbance curves are thought representative for units with a relatively low groundwater level: the units with a solid salt crust will thus be located in the highest position. The higher the spectral absorbance curves the higher the soil moisture content will be and consequently the lower the position of the respective soil unit in the terrain.

Since the spectral absorbance curves of units 4 and 7 show deviations from the curves of the other units, it is assumed that these units show specific features.
The location of the spectral absorbance curves of units 4 and 7 in a high position in the graph indicates that these units are in a low position in the terrain. The similar absorbance percentages in bands 4 and 5 might indicate the presence of a sheet of water on top of the salt crust. Minor variations in the curves of the sampling point are described to changes in water depth.

In figure 32 the relation between terrain situation, absorbance and soil moisture content is presented.

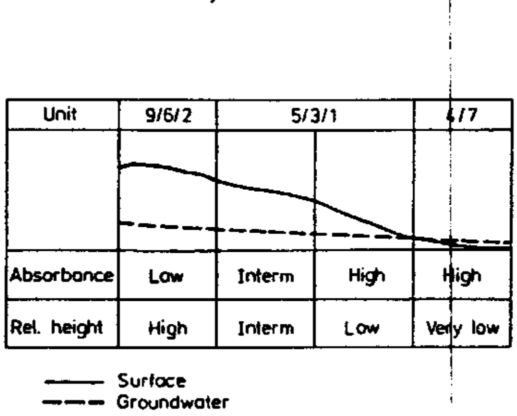


Fig. 32. The relation between terrain situation, absorbance and soil moisture content

8.5 Conclusions

When the spectral absorbance curves of the various units are compared several features can be observed.
Firstly, it is striking that the difference between a high absorption in band 3 and a low absorption in band 4 becomes smaller when going from a unit with a relatively high location to a unit that is located relatively low. This feature can be ascribed to the levelling influence of soil moisture that absorbs more radiation in band 4 in the lower situated units.

Secondly, it can be observed that absorbance values of all units in band 7 are in the same, small range. This is rather strange because a distinction between a relatively dry unit and a relatively moist unit should be fairly easy in band 7 (see also chapter 4).
The bad quality of these band 7 data seems to indicate that the available CCT is not entirely correct.

Thirdly, the curves can be divided into three groups: one group consists of the curves of units 4 and 7; a second group comprises the curves of units 1, 3 and 5; the third group consists of the curves of units 2, 6 and 9. These groups respectively represent the moist to wet units, the intermediate units and the dry units.
This implies that units that look slightly different on the image appear to be in the same group on grounds of similarities in spectral absorbance pattern.

The division of the units into three groups resembles the one made by JVQ (1981). Although minor changes may have occurred in the terrain situation the overall view is the same: the central unit is a relatively highly located dry salt crust; the encircling unit comprises salt crusts with an intermediate groundwater level, while the third unit is a salt crust with a high groundwater level or perhaps in some cases a sheet of water on top of the salt crust.
So far, it has not been possible to find out whether the wet unit resembles the vegetation unit that was indicated by JVQ (1981).

9. SUMMARY AND GENERAL CONCLUSIONS

9.1 Summary

This research was aimed at establishing the most suitable way of using Landsat TM data to determine soil moisture conditions of salt crusts in arid areas.
The Qattara Depression of the Western Desert of Egypt is an area where groundwater of the regional aquifer system comes close to or at the surface. Here, several types of salt crust are found that can be used for the above described aim.

The environmental characteristics of the Qattara Depression are described in chapter 2.
The Qattara Depression is excavated in Tertiary deposits (Lower Miocene clayey to silty-sandy deposits and Middle Miocene limestone deposits). It is assumed that excavation by wind action, mainly during the Pleistocene, has resulted in the development of the Depression. The depth of the excavation was governed by the level of fossil groundwater that formed a base level for wind erosion.

The continual seepage of groundwater of the regional aquifer system into the Qattara Depression and high evaporation rates have induced the development of salt crusts or sebkha: a mixture of salt and clastic deposits. These sebkha are found at various levels as a result of a lateral and vertical variation in lithological characteristics of the rocks of the bottom of the Qattara Depression.

The salt crusts can be distinguished into older and younger types. Distinctive characteristics are relative height of various salt crusts, considering the depth of present grondwaterlevel; hardness; and wind erosion features.

The relative soil moisture content of varios salt crusts in the Qattara Depression can be determined qualitatively and quantitatively by using Landsat TM data.
One of the qualitative ways is to describe the grey tones of the Landsat TM B/W transparencies. In this research negatives of the original positive B/W transparencies are used in order to present open water or areas with a shallow groundwater table as white. A decrease in soil moisture content will be shown as a transition from lighter to darker grey tones.
The Landsat TM B/W transparencies that are used cover the southern part of the Qattara Depression, especially the area arond Sitra Lake. It is observed that bands 3 and 4 show most variation in terrain features, while bands 5 and 7 only show features that are related to the environment of the salt lake.

The negatives of the Landsat TM B/W transparencies are also used for colour additive viewing, the second qualitative determination of salt crusts and soil moisture content. Here, different colour filters are assigned to the various bands that are subsequently projected on a

single viewing screen. A specially built colour additive viewer, namely CAVIA (= Colour Additive Viewer In Agriculture) is used to compile the multiband images. The colours of the multiband image (CAVIA-composite) that is created, form an indication for the location of specific soil units and thus for a relative soil moisture content of the various units.
The availability of the Landsat TM bands 3, 4, 5 and 7, that all show different aspects of the area of Sitra Lake, enables to distinguish between two main combinations of CAVIA-composites. The first combination is bands 3 and 4 with either band 5 or band 7; the second combination is bands 5 and 7 with either band 3 or band 4.
The combination of bands that is considered most suitable for distinction of soil units is 3 4 7.

Since CAVIA enables to vary the order of colour filters assigned to the respective bands, the combination of colour filters that shows the best visual distinction between the various soil units in band combination 3 4 7 is determined. It appears that, considering the sensitivity of the human eye for various colours, band 3= green, band 4= red or blue and band 7= blue or red, is the combination of Landsat TM bands and assigned colour filters that enables a rather good visual distinction of all soil units.

From a comparison at various scales of 1984 Landsat TM images with 1973 Landsat MSS satellite imagery, it is concluded that at all scales the negatives of the Landsat TM B/W transparencies are better for delineating soil units than the products derived from 1973 Landsat MSS.

A quantitative way of determining the relative soil moisture content of salt crusts is described in chapter 8. A Computer Compatible Tape (CCT) is processed and absorbance characteristics of salt crusts in Siwa Oasis, western part, are calculated. The spectral absorbance pattern of various salt crusts enables to draw conclusions on the relative soil moisture content and the relative height of these crusts in the terrain.

9.3 General conclusions

At the end of the research considerable insight has been obtained into the possibilities of the various Landsat TM satellity imagery products considering the determination of relative amounts of soil moisture of salt crusts in the Qattara Depression, Egypt.
A qualitative description of negatives of Landsat TM B/W transparencies can only result in preliminary conclusions on the absorbance characteristics of salt crusts and their relative amount of soil moisture.
The qualitative description of the information contained in the CAVIA-composites, together with the information on absorbance characteristics of various land cover types can lead to conclusions on the characteristics of specially indicated units in the terrain.

The only quantitative analysis of specific units in the terrain has been by the use of a processed CCT. This has only resulted in the quantitative determination of absorbance characteristics. Subsequently, conclusions were drawn on the relative height of the various units in the terrain.

Here, the method of using CAVIA-composites and the method of using a processed CCT seem to give acceptable results for the drawn-up objectives. No analysis is made of the financial aspects of both methods. Therefore, it is difficult to indicate which method should be propagated. The availability of processing facilities, either a colour additive viewer for the CAVIA-composites or a computer for the CCT, is important when deciding on the method that should be followed.

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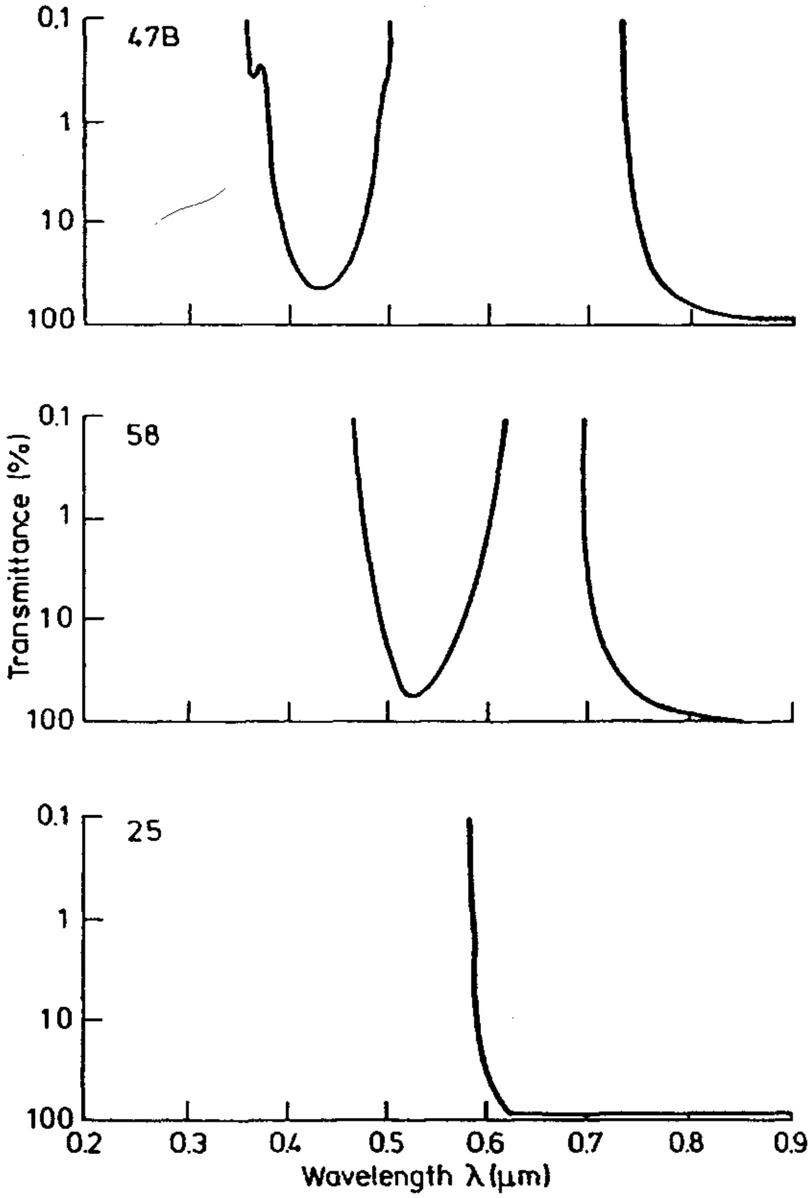

Transmittance characteristics of three KODAK WRATTEN filters (after EASTMAN KODAK COMPANY 1970)