Photonirvachak
Journal of the Indian Society of Remote Sensing, Vol. 25, No. 2, 1997

Principal Component Transformation Method to Separate Active Discharge and Recharge Areas

C V SUNDARA RAJAN*, O BATELAAN° and F De SMEDT°
*Environmental Department, Consulting Engineering Services (India) Limited,
57, Nehru Place (5th Floor), New Delhi - 110019
°Laboratory of Hydrology, Faculty of Applied Sciences, Free University Brussels, Pleinlaan-2,
B-1050 Brussels, Belgium

ABSTRACT

A method is proposed to separate active discharge, recharge and intermediate zones from the digital Thematic Mapper TM data. A case study was carried out in a natural reserve Welenbos (Walen Forest) and adjacent areas in Belgium comprising a total area of 174.3 sq. km. A microcomputer based Geographic Information and Image Processing System have been utilised for the identification of the characteristic of Remote Sensing TM data favourable for hydrological applications. The histogram of remote sensing data showing the characteristics of discharge, recharge and intermediate zones are unique and can be utilised for mathematical modelling purposes. This has a large potential in hydrological applications.

Introduction

Recently remote sensing has developed into a most promising technique for regional analysis of both small and large scale hydrological system (Van de Griend and Engman, 1985). The basic concept is, in summer i.e. during relatively dry periods, drainage patterns are the predominantly linear patterns where ground-water find its way out. Most effective way to identify or to utilise digital remote sensing data in hydrological models, is to accurately delineate these zones. These zones are the swamps, marshes and seasonal or permanent wet areas. The TM data, with a resolution of 30 metre when suitably processed is found to be accurately identifying these areas. In this study digital TM data with a pixel size of 30m was utilised to delineate the recharge and discharge areas.

(Recd. Sept. '96; in final form July '97)

Physical Principles

The regional groundwater flow system concept proposed by Toth (1963) is a very useful tool for studying groundwater flow on a regional scale. The fundamental unit of such a concept is a vertical section in which groundwater regions are discharged. A flow system consists of flow lines in which any two flow lines adjacent at one point of the flow region remain adjacent at any point of the flow region and these can be intersected anywhere by an uninterrupted surface across which flow takes place in one direction only. The potential or energy gradients are the driving force of groundwater. Groundwater always tries to find its way-out to some point of discharge under the influence of gravitational force. The terminology of natural groundwater flow reported by Bobba *et al.*, (1992) explains that a local system has its recharge area at a topographically high and its discharge area the immediately adjacent to topographically low. An intermediate flow system has its discharge and recharge area separated by one or more local flow system. A regional flow system has its recharge area at the basin divide and its discharge area at the valley bottom. The discharge area is an area where the direction of the surface flow is towards the water table and an active source area for surface runoff. The recharge area is an area where the direction of subsurface flow is towards the water table and the transition area is an area between recharge and discharge areas.

Basic process underlying the application of satellite digital data can be explained by a conceptual model (Bobba *et al.*, 1992) of flow system in winter and summer (Fig. 1). During winter months, recharge water that is colder than the ambient surface temperature of the recharge area ultimately discharges at a temperature warmer than the ambient surface temperature of the area. In summer it is vice versa. The thermal gradients present in the subsurface flow systems are directly attributable to the presence of subsurface water. It is further assumed that the surface manifestations of these thermal gradients are inversely proportional to the depth of water table.

Most important elements for deciphering the groundwater systems from remote sensing data are vegetation (biomass), moisture content and drainage pattern. The principle is that under natural circumstances vegetation species are strongly adapted to the local hydrological conditions in terms of drainage conditions of the soil, variability of soil moisture content and groundwater depth. Under cultivated circumstances, vegetation reflects the local conditions if they deviate from growth conditions for the specific species. Therefore, a strong correlation between surface reflectance of vegetation and hydrological conditions can be derived in many cases (Van de Griend and Engman, 1985).

Geographical Setting of the Study Area

The study area is located between latitudes 50°50'28" and 50°59'02", longitudes 4°58'03" and 4°58'10", comprising a total area of 174.3 sq. km (Fig. 2). This area is covering an ecologically disturbed and significant natural reserve 'Walenbos'. The training site shown in Fig. 2 completely covers the Walenbos natural reserve (Walen forest) area. The Institute of Natural Conservation of Flanders, Belgium has taken up an eco restoration programme for this area. This region is characterised by large quantities of discharging groundwater in the form of springs and seepages. Revealing the groundwater flow system is important in managing the area in an ecologically stable way. The area receives an average rainfall of 80 cm per year. This is more or less equally distributed throughout the year with winter relatively wetter than summer.

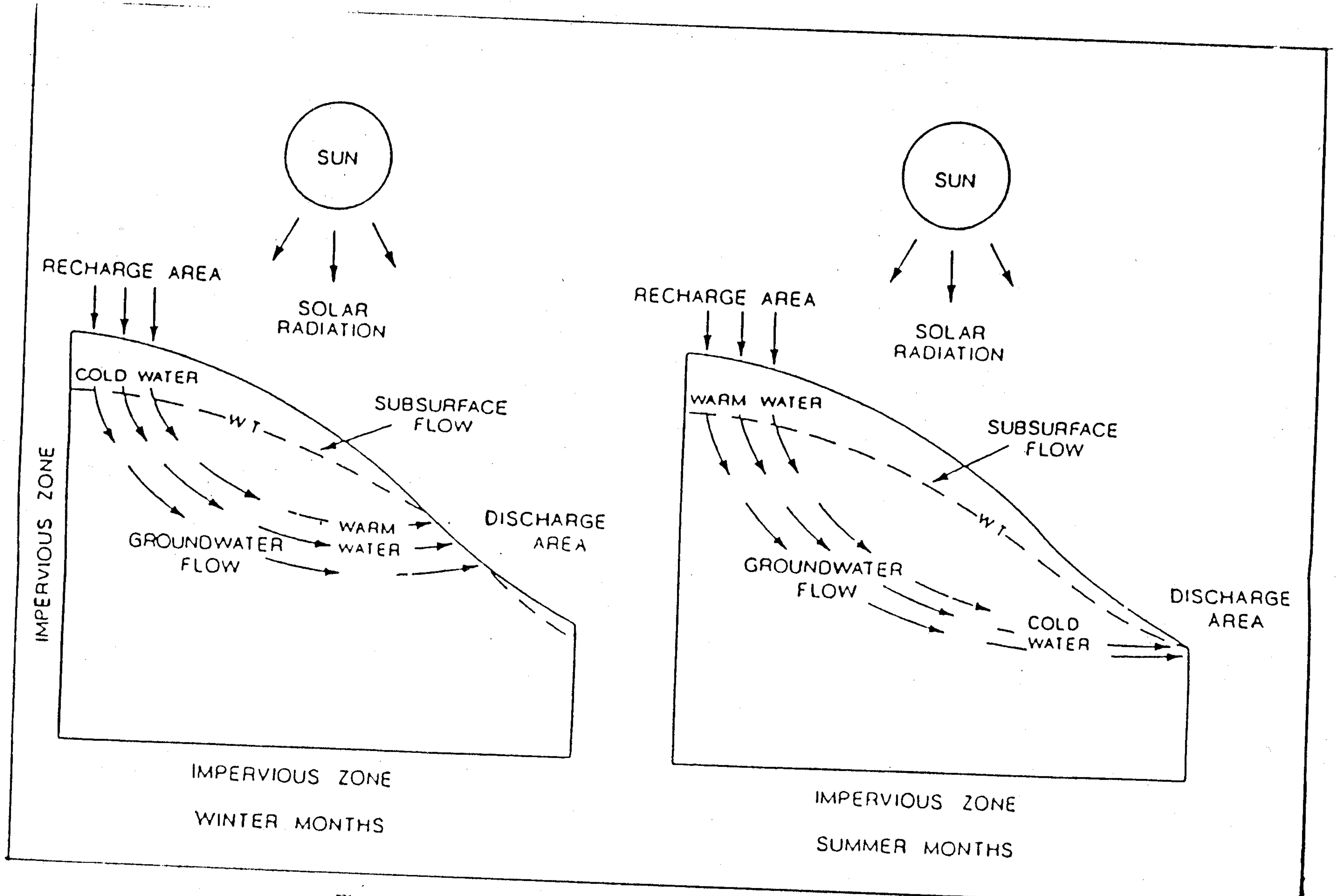

Fig. 1. Conceptual model of groundwater flow system in winter and summer.

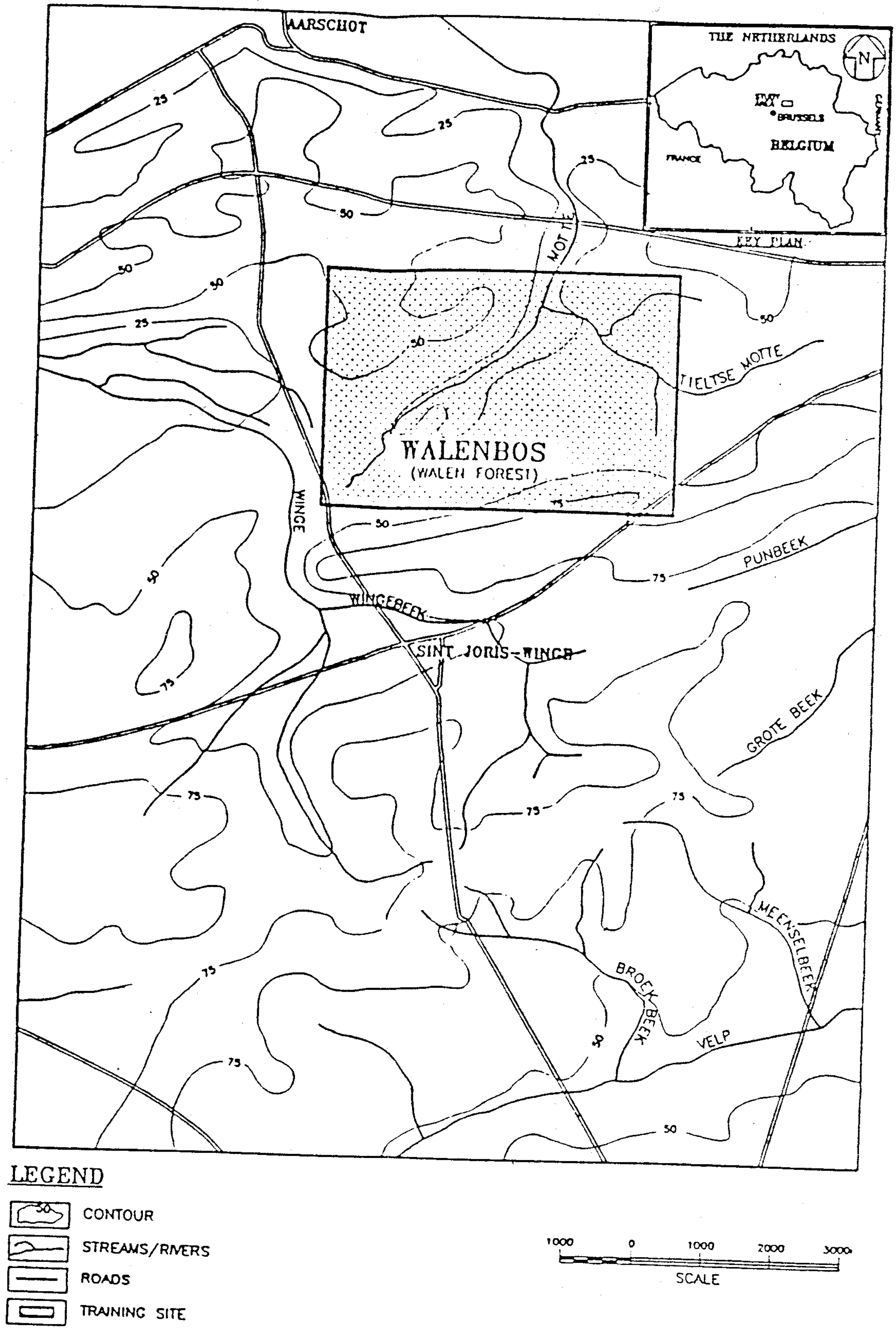

Fig. 2. Location map of study area.

Materials and Methods

This paper brought out strong correlation between surface reflectance and hydrological conditions using a Geographic Information and Image Processing System. In this work the GIS package IDRISI (version 4.0) has been utilised. This is a raster based Geographic Information and Image Processing System. The satellite Thematic Mapper (TM) data (Table 1) of the study area (174.3 km^2) have been analysed for winter and summer. It is a known fact that the TM data is superior to MSS data both in spectral and spatial resolution, hence the objective of the present study was to find out the discharge and recharge characteristics using TM data.

Table 1. Statistical parameters of the TM data used.

Landsat TM band	*Actual*		*Mean*	*Standard Deviation (SD)*
	Minimum	*Maximum*		
1	81	148	95.367	4.9297
2	29	69	40.322	3.5844
3	25	87	39.399	6.8851
4	32	138	81.217	14.0959
5	13	255	75.628	17.0071
7	5	255	31.892	12.7362

Degree of freedom = 193668

In this work the statistical technique Principal Component Analysis (PCA) has been used to separate discharge, recharge and intermediate zones. This technique reduces the number of spectral dimension in a given amount of information (e.g. discharge, recharge and intermediate zones). This results in specific features within data set having transformed values that more effectively describe the data (Lillesand and Keifer, 1987). It is worth emphasising that the signal variance in the first transformed picture is always increased by the transformation while the noise variance remains unchanged (Barry and Gillespie, 1980). Hence the first transformed picture has been utilised in this study.

The integral reflection or albedo is highest when the soils are dry. With increasing water content albedo decreases. The entire phenomenon can be explained by the Stefan-Boltzmann law,

$$Q = \sigma T^4$$

Q = Total rate (per unit area) of emission of energy

σ = Universal constant (the Stefan-Boltsmann constant)
(5.67×10^{-8} watt/meter^2) (°K^4)

T = Absolute temperature

It states that the total rate (per unit area) of emission of energy of all wave lengths is directly proportional to the fourth power of its absolute temperature. In fact, heat rays are emitted by all material bodies, no matter how low or high their temperature are, but according to the Stefan-Boltzmann law, their intensity falls very rapidly with the temperature.

Results and Discussion

Thus from the Stefan Boltzmann law it is clear that warm, dry and bright surface (Recharge areas) will emit more energy, since the emission of all wave lengths is directly proportional to the fourth power of its absolute temperature. This is evident from the fact that Digital Number in TM bands for these areas are relatively higher in any given region compared to discharge areas. In summer, discharge areas can be described as relatively cold, wet and fader, while that of recharge areas are relatively warm, dry, and bright. The comparative energy levels of different zones can be described as given in Table 2. In this table X, Y and Z are assumed as the quantitative terms and if X > Y > Z, then it can be seen that quantum of electromagnetic energy received on a cold, wet and fader surface (Discharge areas) is more than that received on a warm, dry and bright surface (Recharge areas).

Table 2. Representation of comparative energy levels in different zones.

Relative energy levels in terms of	*Recharge*	*Intermediate*	*Discharge*
i) Temperature	X	Y	Z
ii) Water content	Z	Y	X
iii) Albedo	X	Y	Z

where X, Y and Z are quantitative terms with a relation X>Y>Z.

Using the Principal Component Transformation (PCT) technique, a theoretical normal curve fitting can be obtained for the first transformed picture for representing discharge, recharge and intermediate zones (Fig. 3). The Table 3 shows the listing of the image statistics, eigne values (which gives in indication of decreasing variance in successive principal components) and eigne vector loadings (linear combination of weighted input images in the principal components) for a principal component transformation, using the covariance matrix, on three reflective bands of the study area.

Since the satellite data correspond to a single date only, in this work discharge zones are described as the active discharge zones. That is depending upon depth to water table the discharge area increases or decreases. Ac discharge zone varies throughout the year un the climatic extremes.

Table 3. Principal Component Statistics.

(i) Variance/Covariance matrix

	TM3	TM5	TM7
TM3	48.59	92.17	08.74
TM5	92.10	302.47	200.08
TM7	78.74	200.08	167.71

(ii) Correlation matrix

	TM3	TM5	TM7
TM3	1.00	0.76	0.87
TM5	0.76	1.00	0.89
TM7	0.87	0.89	1.00

(iii) Principal Component Summary

comp	PC1	PC2	PC3
% Variance	92.53	5.83	1.64
Eigenval.	480.02	30.22	8.53
Eigevec. 1	00.27	00.52	00.81
Eigevec. 2	00.78	−0.61	0.13
Eigevec. 3	0.57	00.6	−0.57

(iv) Component Loading Summary

	PC1	PC2	PC3
TM3	0.85	0.41	0.34
TM5	0.98	−0.19	0.02
TM7	0.96	0.25	−0.13

The active discharge zones in the first transformed component can be separated by the PCT method described in Fig. 3. From the figure it is evident that the pixels beyond the model Digital Number (DN) value of the discharge normal curve are doubtful pixels and the test results confirmed that this cannot be active discharge zones hence this category goes to the intermediate zones.

Further to get only two classes i.e. recharge and discharge zones for hydrological application in models, it is required to separate the Principal Component (PC) Digital Number (DN) into two classes. The first class representing the active discharge zones, i.e. all the values DN < DN mode value of the normal curve representing discharge zones and the second class representing DN > DN mode value. The second class will be consisting of both intermediate and recharge zones.

For the present study under the existing climatic set up, summer data after the chlorophyll peak is found to be the ideal time. Moreover, during summer months discharge water will be relatively colder than the recharge water. At this time the effects of thermal gradients are mixed. Winter data could not be considered since it is not as cool (snow) as it should be for such a consideration. Hence the satellite TM data used for this study is the summer after the chlorophyll peak collected during the satellite over pass of 20th September 1986. Four TM band combinations were tested viz., (1) 1 to 7 (only reflective bands), (2) 4, 5, 7 (3) 3, 5, 7 (4) 5 and 7. The thermal band could not be used since it has a resolution of 120 m.

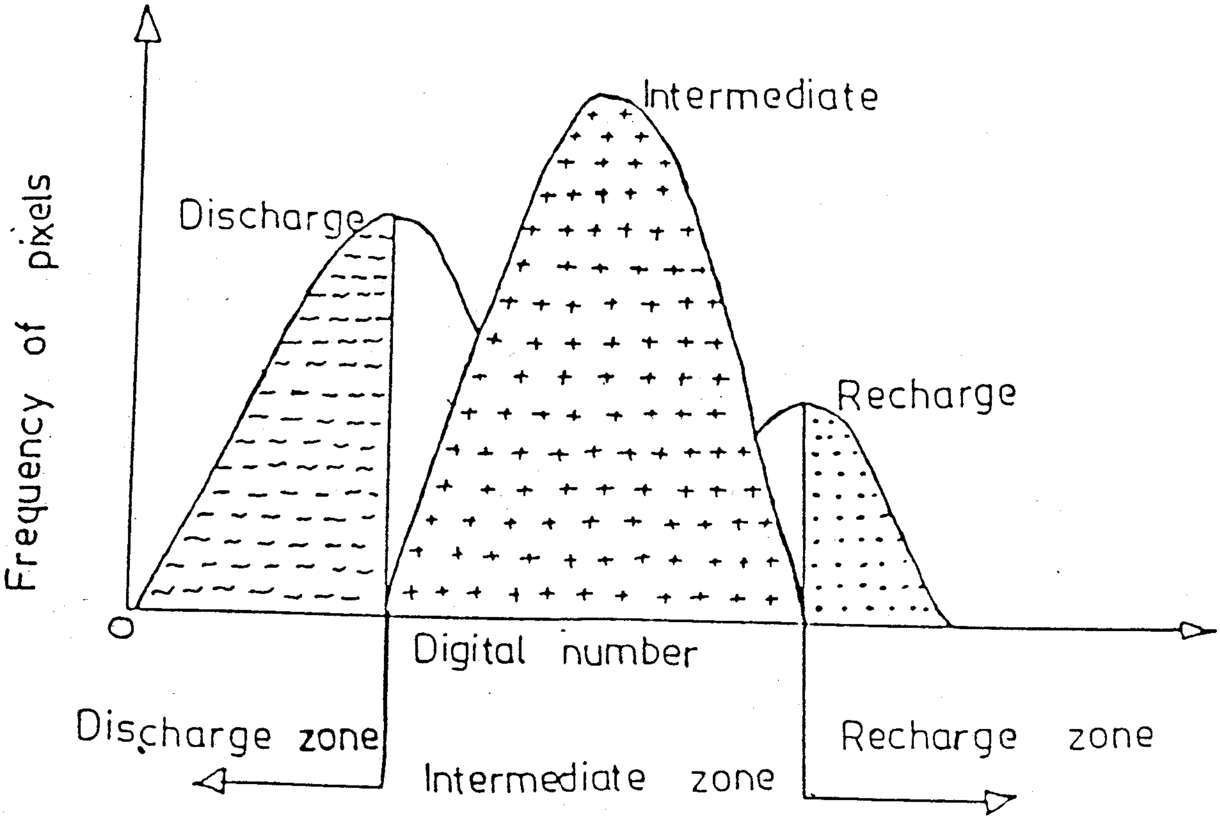

Fig. 3. A theoretical normal curve fitting for representing discharge recharge and intermediate zones by means of PCT method.

Test results indicate that

1. All the band combinations more or less successfully carried out the separation of discharge, recharge and intermediate zones by the Principal Component Transformation method.

2. However the separation of recharge and discharge areas have been most effectively carried out using TM band combinations (1) 3, 5, 7 and (2) 4, 5, 7.

3. Reason could be a homogenous mixing of the similar spectral signatures more or less clearly defining hydrological conditions. Wet bodies are a total absorber of incident Infrared Radiation (IR). In the Electromagnetic spectrum these four spectral bands are closely located to IR in terms of frequency and wave length.

In this part of the spectrum scattering is lesser and absorption and reflection are without much energy loss. The relevant spectral characteristics of these spectral bands are given in Table 4. A histogram output for the band combination 4, 5, 7 is given in Fig. 4.

For field control, a training site has been identified and studied by frequent visits in the area. This is in area of 16.97 km^2 completely covering Walenbos natural reserve. Training site is composed of about 80 percent discharge and intermediate zones represented by springs, seepage areas and streams in a thickly vegetated background. This is well represented by higher frequency of pixels in this category in a single TM band 7 histogram of training site. In comparison with the histogram of the study area the frequency of pixels lying in the intermediate zones are higher and frequency of pixels in discharge category is lesser (Fig. 5).

Table 4. Relevant characteristics of Thematic Mapper Spectral Bands.

Band	*Wave length (μm)*	*Nominal Spectral Location*	*Relevant Application*
3	0.63-0.69	Red	Designed to measure green reflectance peak of vegetation for vegetation discrimination and vigour assessment.
4	0.76-0.90	Near Infrared	Useful for determining vegetation types, vigour and biomass content for delineating water bodies, and for soil moisture discrimination.
5	1.55-1.7	Middle Infrared	Indicative of vegetation moisture content and soil moisture. Also useful for differentiation of snow.
7	2.08-2.35	Middle Infrared	Sensitive to vegetation moisture content.

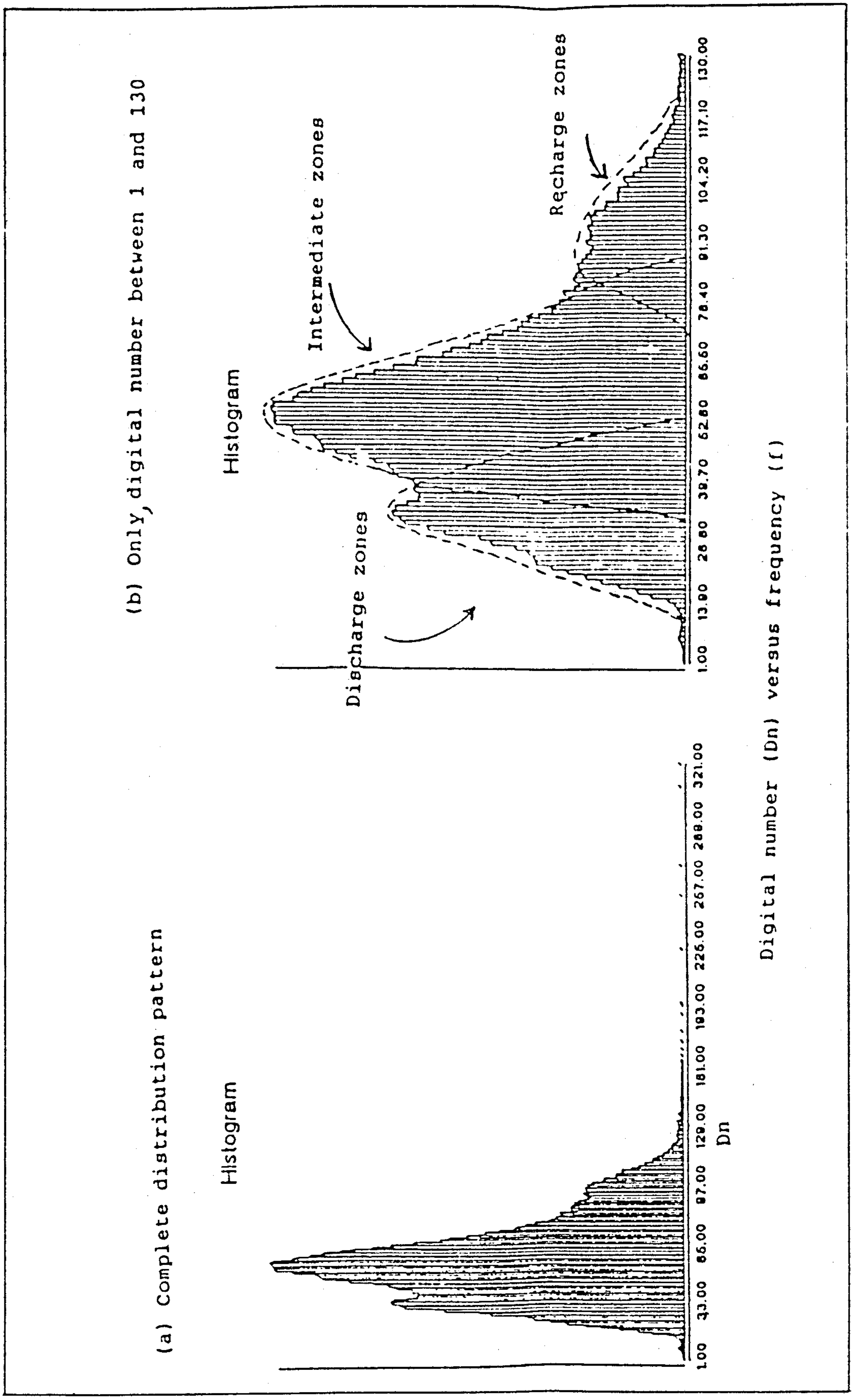

Fig. 4. Histogram of TM band 4, 5 and 7 combinations.

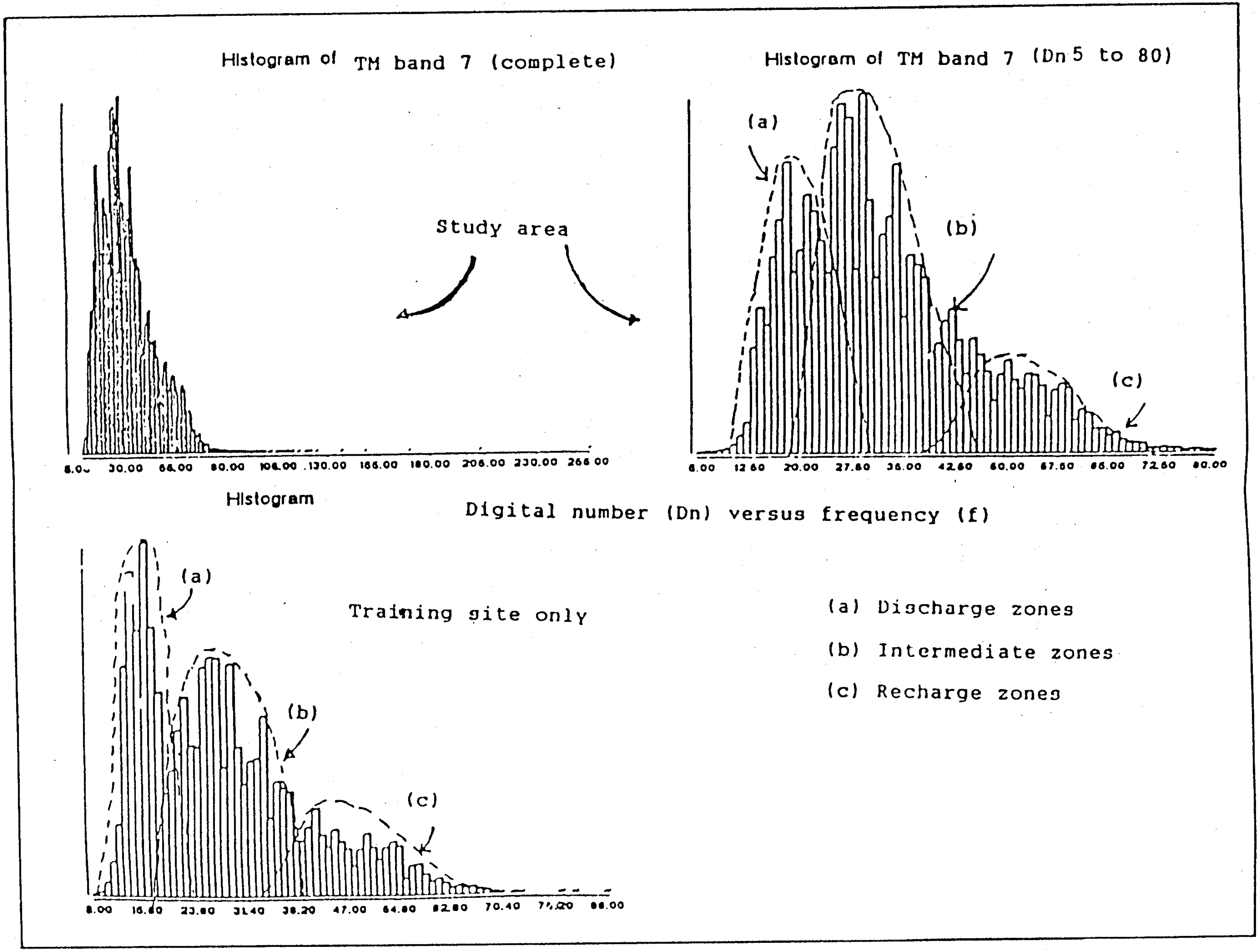

Fig. 5. TM band 7 histogram of study area and training site.

Conclusion

From this study it is evident that from the satellite data valuable information can be derived for hydrological applications. From the digital TM data the recharge, discharge and intermediate zones can be effectively separated by Principal Component Transformation (PCT) method using suitable data. PCT method is found to be more effective with TM band 3, 5, 7 and 4, 5, 7 combinations because of the closer spectral locations with respect to that of infrared radiation. It is also evident that at this part of the spectrum, energy exchange takes place with less scattering effect and absorption and reflection without much energy loss.

Acknowledgements

The authors acknowledges their sincere gratitude towards Prof. Dr. A Van der Becker for the constant encouragement provided throughout the work. The first author also acknowledges Belgium Administration for Development Cooperation (BADC) for giving necessary finance, to study and carryout the work in the Laboratory of Hydrology of the Faculty of Applied Sciences of the Free University of Brussels by awarding a fellowship.

References

Barry S S and Gillespie A R (1980). Remote Sensing in Geology. John Wiley and Sons. New York. 702 p

Bobba A G, Bukata R P and Jerome J H (1992). Digitally processed satellite data as a tool in detecting groundwater flow systems. J. Hydrol. 131:225-262.

De Smedt F and Bronders J (1985). A regional groundwater flow model based upon the variable source areas concept. IWRA. Vth World Congress on water resources. (June 1985). Brussels. Belgium.

De Smedt F and Betelaan O (1992). Simulative Van de geplande groundwater storming in het gebied rond Walenbos. Dienst Hydrology. VUB. Brussels. Belgium.

Lillesand T M and Keifer R W (1987). Remote Sensing and Image Interpretation (2nd Edition. John Wiley and Sons. New York).

Sundara Rajan C V (1992). Remote Sensing as an Aid to Regional Mathematical Modelling of Groundwater Flow Systems (using a GIS). MSc thesis. Laboratory of Hydrology, VUB. Brussels. Belgium.

Van de Griend A A and Engman E T (1985). Partial area Hydrology and Remote Sensing. J. Hydrol. 81:211-251.

Toth J (1963). A theoretical analysis of groundwater flow in small drainage basins. J. Geophy. Res.. 68:4795-4812.