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Remote sensing applications to hydrology: groundwater

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Abstract The traditional use of remotely sensed image interpretation lies in the qualitative characterization of hydrogeological mapping units and the detection of specific features. Most applications pertain to crystalline basements, limestones and Quaternary volcanic terrain. More recent developments pertain to groundwater emergence in the discharge areas of groundwater flow systems, using thermal and multispectral imagery, and to the management of groundwater. For the latter, spatial recharge patterns and contamination assessment will focus attention on defining the parameters of vegetation and terrain mapping units and on monitoring hydrogeologically relevant surface features embedded in spatial groundwater models.

Applications de la télédétection à l'hydrologie: les eaux souterraines

Résumé Habituellement l'interprétation des images de télédétection a consiste à caractériser de façon qualitative les unités cartographiques hydrogéologiques, et à détecter certaines caractéristiques spécifiques. La plupart des applications s'intéressent aux sous-sols cristallins, aux calcaires et aux terrains de type volcanique quaternaire. Des développements plus récents, utilisant des images thermiques et multispectrales, étudient l'émergence des eaux souterraines dans les zones de décharge des systèmes d'écoulement ainsi que la gestion de ces eaux. En ce qui concerne cette dernière, les modèles de recharge spatiaux et d'évaluation des pollutions s'attachent particulièrement à la définition des paramètres de la végétation et des unités cartographiques de terrain, ainsi qu'au suivi de caractéristiques hydrogéologiques de surface, intégrés dans des modèles spatiaux des eaux souterraines.

INTRODUCTION

This paper attempts an overview of the application of remote sensing to groundwater studies. Groundwater is by definition subterranean. Most remote sensing techniques, with the exception of airborne geophysics and radar, have no penetrating capabilities beyond the uppermost layer. Geophysical techniques are not discussed here, but the synergism of satellite imagery and airborne geophysical data can be a valuable asset in the early stages of groundwater exploration and in groundwater modelling.

In the physical applications of imaging sensors, long wave radar can sometimes detect groundwater levels at depths of a few metres and other

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subsurface features, such as buried channels (McCauley *et al.*, 1982), but only if all conditions are suitable, i.e. coarse-grained deposits, dry vadose zone without vegetation and some *a priori* knowledge of the geology. Radar imagery has its general use in hydrogeology for the interpretation of geological structures (Koopmans, 1983; Drury, 1993).

Thermal imagery depicts the long wave radiation emitted from the surface. Its use pertains to temperature anomalies in water bodies, whereas other applications relate to a more complex interpretation of the imagery, with some promise for conceptual groundwater modelling.

The surface features contained in the imagery of the reflected shorter wavelengths relate to the surface expression of geological and geomorphological features and land cover. Hence, indirect hydrogeological information is obtained.

Rango (1994) reviewed the use of remote sensing in hydrology but did not list groundwater among its operational applications, possibly because "most approaches use surficial indicators of the underlying groundwater reservoir and require considerable skill and knowledge on the part of the interpreter". This is true, but it does not prevent an operational use by many hydrogeologists in certain types of shallow groundwater systems.

IMAGE INTERPRETATIONS

Exploration for groundwater using photogeology was a major field of interest in the past and still is in areas covered inadequately by geological maps. The classic work of Ray (1960) has assisted many beginners. Photogeology reached a state of maturity during the 1960s (e.g. Miller & Miller, 1961). Satellite imagery is included in the work of Sabins (1987). The development of physiographical and geomorphological interpretations followed later. The use of stereo aerial photointerpetation was described by Goosen (1967) for soil mapping, by Verstappen (1977) for geomorphology and by Way (1978) and Townshend (1981) for terrain analysis and physiography. For groundwater studies the general physiographical type of interpretations assist the mapping of surficial materials for indexing methods of groundwater pollution and for estimating recharge and evapotranspiration components of a groundwater balance.

Visual interpretations should make use of imagery that contains an optimal display of the terrain information. To achieve this the colour and intensity information of the multispectral data can be manipulated by image processing techniques, such as histogram operations, filtering and decorrelation methods for the preparation of colour coded imagery. Meijerink *et al.* (1994) discussed the techniques and gave examples and further references. Discussions and examples of visual hydrogeological interpretations appear chiefly in manuals for training courses, but some examples have been discussed by Kruck (1976; 1990). Most interpretations need experience and familiarity with the terrain. Hence criteria for objectivity and repeatability do not apply in *sensu stricto*. However, image interpretation is the most frequent use of remote sensing in groundwater studies.

In certain cases the imagery contains features which have a direct link to the groundwater discharges, such as the extent of the fresh water swamps in a saline lacustrine plain in south Kenya (Fig. 1). A hydrometric survey showed that the groundwater discharge is approximately equal to the area of swamp vegetation times the potential evapotranspiration (Meijerink & van

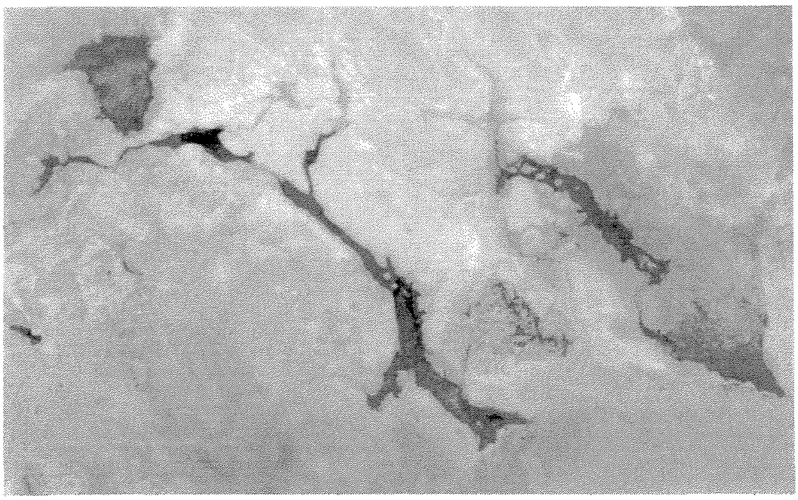

Fig. 1 Marshes (dark elongated areas) fed by springs in dry saline lacustrine plain of Amboseli Park, Kenya. Thematic Mapper, band 3 with histogram manipulation for contrast enhancement.

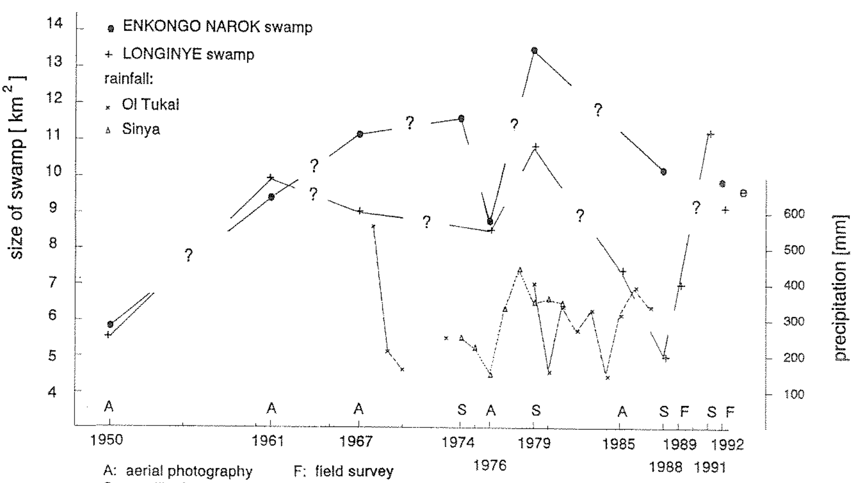

Fig. 2 Variation of the size of the two major swamps shown in Fig. 1, based on aerial photography and satellite imagery, for the reconstruction of past discharges. Available rainfall data of two local stations added.

Wijngaarden, 1996). Hence, past imagery can be used for an estimation of the fluctuations of the past discharges, as is shown in Fig. 2. Such direct links are exceptional. Generally the interpretations give more circumstantial evidence or surrogate hydrogeological information.

GROUNDWATER FLOW SYSTEMS

The appearance of groundwater at or near the surface is caused by either the intersection of topographic depressions (blow-outs, dolines, silicate karst depressions, backswamps, etc.) and the static phreatic groundwater level, or the discharge zone of a groundwater flow system. In the latter case the groundwater table is shallow and there is a pressure gradient which causes upwelling of groundwater. Such conditions are found in the area shown in Fig. 3(a) and (b), band 7, Landsat Multi-Spectral Scanning (MSS). The example pertains to an alluvial area in north India, which has low relief and most of the area is fallow at the time of recording. Therefore there are spectral contrasts with the surrounding higher groundwater intake areas. Often, the exfiltration areas are less obvious and have to be interpreted from the vegetation patterns. The theory of the flow system must be credited to Toth (1962) and it provides a framework for hydrogeological interpretations of three-dimensional imagery for the differentiation of phreatic or perched water tables from the ones in exfiltration areas.

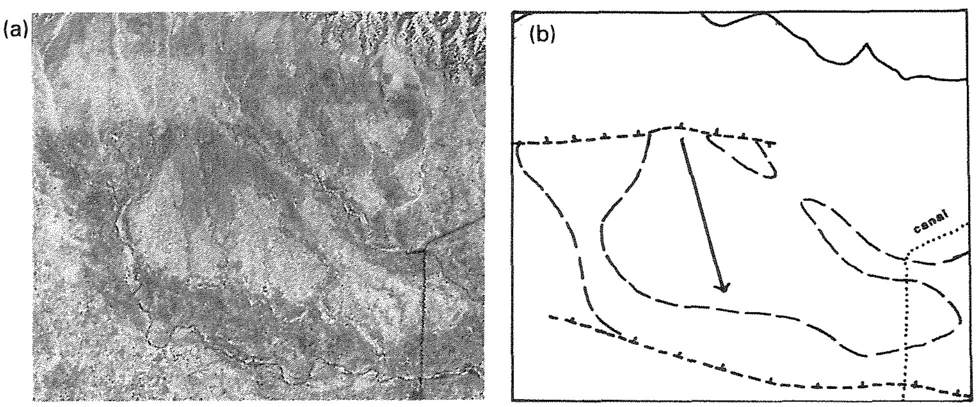

Fig. 3 Example of data extraction by visual interpretation aided by some field observations: (a) MSS image, band 7, after image sharpening, of a mainly alluvial area with deposits of different age and nature, north India; and (b) interpreted exfiltration zones, partly influenced by faults and tilting.

Peters & Stuurman (1989) used Thematic Mapper (TM) imagery for a detailed cover-type classification in an area in The Netherlands with unconsolidated rocks for which a systematic inventory of flow systems was made. It was found that the category 'wet grasslands' corresponded to both shallow stagnant groundwater areas and upwelling discharge areas. To separate the two, band 6 (the thermal band of TM) of a winter scene was subtracted from band 6 of a summer scene to enhance the contrasts in what the authors considered to be temperatures, but in fact were contrasts in emissivity, which is only indirectly related to the groundwater temperature. The wet grasslands in the cold and intermediate thermal class were related with moderate success to the discharge areas, but there was confusion in the spectral class 'broadleaf forest', which may occur on both infiltration and exfiltration areas.

Local flow systems are usually superimposed on regional ones and the result may be complex patterns of discharge areas. Bobba *et al.* (1992) identified areas with relatively warm groundwater on aircraft thermal imagery recorded during the winter in Ontario, Canada, and related them to either shallow aquifers or discharge areas of deeper flow systems. Sample sets taken from recharge, transition and discharge areas formed corresponding clusters on a feature space of the MSS spectral bands 7 and 5, 0.8-1.1 μm and 0.6-0.7 μm respectively, of a late March image. By using a simple linear segmentation of the feature space, the three parts of the flow system could be mapped, although visual editing of the product seemed to be required.

Batelaan *et al.* (1993), in studying an area in Belgium, used principal component (PC) analysis to classify vegetation related to groundwater exfiltration. The histogram of the first PC was composed of three Gaussian curves, following Bobba *et al.* (1992), and the image of the first one (in fact a density slice of PC 1) was in good agreement with the modelled discharge areas. For a nearby similar area it was found (Donker & Mulder, 1976) that the first principal component was strongly related to the spectral intensity information, rather than to the colour information. The association of moist soils and low spectral brightness may hold true for only certain seasons; in others the empirical relationships may be different and other classification techniques may be used, depending on local knowledge of the vegetation responses.

The synergism of various types of imagery – such as multitemporal short wave reflection, active microwave and thermal imagery – can increase the discrimination power for the mapping of specific vegetation types and wet soils in exfiltration areas. In addition, the classifications may be superimposed on a digital elevation model (DEM) of the groundwater level, since the flow systems are driven by the potentiometric surface, or by a DEM of the ground surface with detailed drainage added because the groundwater level more of less follows the topography.

There can be a close relationship between groundwater depth and streamnet characteristics in permeable lowlands. The stream system can be considered an outcrop of groundwater flow systems if there is a rainfall excess, enabling the development of a theoretical model on the basis of flow formulae that interconnect groundwater flow and stream runoff (de Vries, 1994). This type of approach offers new possibilities in similar terrain of placing detailed streamnet interpretations on imagery in a quantified context.

HYDROGEOLOGICAL EVALUATION AND MAPPING

The traditional objective of a hydrogeological map is to present cartographically the hydrogeological properties of the mapping units in a systematic manner, with symbols added for hydrogeological features. Various studies have shown how imagery can contribute to the mapping and qualitative evaluation (Meijerink, 1974; Moore & Deutsch, 1975; Sahai *et al.*, 1985; Dutartre *et al.*, 1990a,b; Waters *et al.*, 1990; Jeyaram *et al.*, 1992). The Quaternary is often poorly differentiated on the existing maps. This is regrettable because recharge, shallow flow systems and water quality are related to these often non- or little - consolidated deposits. Mapping of such deposits using satellite imagery has been described by many (Obyedkov, 1990; Li Botao *et al.*, 1990; Kruck, 1990). For the Quaternary volcanic terrain in Java, for example, the degree of dissection relates well to the relative age, which is associated with the degree of compaction, which in turn influences permeability, base flow and overall recharge. (Anon., 1990). Hydrogeological image interpretation can be very cost effective. El Hadanai *et al.* (1993) showed an important reduction of the number of drillholes and thus drilling costs (about half) for groundwater development in Morocco by using image interpretation. There was also a sharp reduction of the costs for geophysical work in terms of a reduction of the number and lengths of profiles (more than half).

More recently, attempts have been made to present also the hydrogeological *behaviour* of the units, requiring simple conceptual modelling and GIS operations for merger with other data (Civita, 1995). An attempt was discussed by van der Sommen *et al.* (1990) who applied two-dimensional groundwater flow modelling along sections to differentiate the effects of flow systems in the upper, middle and lower parts of volcanoes for hydrogeological mapping. With some baseflow observations, a large variation of the effect of the upper part on the groundwater flow to the lower parts could be assessed (5-30% of the rainfall), depending on the details of dissection, i.e. relative age and degree of compaction, and geology of the volcanoes.

The use of expert systems is another avenue for assessment of the hydrogeological units. Poyet & Detay (1989) presented such a system for west Africa where some of the initial observations were based on image interpretation. Furthermore, for a hard rock area in Sri Lanka probabilistic modelling offered an objective way of combining in a GIS geohydrological data with measurements made on imagery to provide the probabilities of striking high-yielding wells (Hansmann *et al.*, 1993). The method is quite suitable for evaluations of a more general type, provided that a good geo-referenced database of well data is available.

THERMAL IMAGERY

Considering the pressure distributions in the saturated zone, it is most likely that if upward flow of deep groundwater occurs, it will emerge in valleys or rivers. It can be detected by large scale (1:1000 or 2000) thermal imagery because of the thermal inertia of relatively warm groundwater emergence in cold rivers in mountainous terrain. Strong head differences of the groundwater surface and the presence of fracture conduits contribute to the ease of detection. Burger *et al.* (1984) described examples, using enlargements of airborne thermal imagery at a scale of 1:2000, in mountainous terrain.

The vast fossil groundwater reserves in parts of northern Africa are likely to leak out partially in the sebkhas (playas) which are important evaporative sinks. Menenti (1984) used various remote sensing platforms and field measurements to determine the evaporation rates of sebkhas in north-central Libya. He remarked that "not a single one of the fluxes appearing in the surface energy balance equation can be calculated directly from satellite data only". Using imagery in the visual and thermal ranges, with some meteorological ground measurements, the actual evaporation in the central zone of the sebkhas was 2 mm day^{-1}. The total annual loss of 220 mm over an area of 3800 km^2 is about ten times an estimate made by conventional methods.

A third field of application is the detection of groundwater escaping to the sea (Guglielminetti *et al.*, 1982). For detection, the conditions must be suitable, i.e. a temperature difference between the fresh and salt water and a sufficient amount of outflow to overshadow mixing effects in the path between the sea bottom and the surface. The author was engaged in a study of airborne thermal imagery of the coasts of the island of Malta. Apart from one well-known spring, no other temperature anomalies could be detected, probably because the heads of the fresh water lenses in the island's limestones are not sufficient to maintain substantial springs in the sea. However, several winter NOAA images of the Tunisian coast near Djerba show a strong anomaly. The temperature difference of the Mediterranean surface (about 14°C) and the groundwater (>18°C) may explain the contrast, in particular because thick permeable beds dip north below the sea and normal – tensional – faults traverse the beds, parallel to the coast, through which groundwater can escape. Hence all the suitable conditions are present.

HARD ROCK TERRAIN AND LINEAMENTS

Vast areas of the world consist of hard rocks (basement complexes), or limestone terrain, where water is restricted to secondary permeability, and thus to the fractures and the weathered zones. Most such areas have a shortage of water. As the success ratio of drilling in hard rock terrain may be low, and the use of geophysics is often judged as too expensive, the study of lineaments on imagery is an attractive proposition. Larsson (1984) wrote a comprehensive text on groundwater in hard rocks, with ample references and case studies. The study of fractures on imagery of limestone terrain has attracted early attention (Bouche & Poulet, 1971; see also a discussion in Waters *et al.*, 1990). A method for lineament analysis in hydrogeology has been described by Waters

(1988). Greenbaum (1992) reviewed remote sensing applications to groundwater exploration in basement and regolith.

Photo-lineaments can be described as linear structural elements which are thought to have developed over fracture zones, and which are visible on remotely sensed imagery. Interpreted lineaments can pertain to fractures of a different tectonic nature, with or without intrusive or secondary clay fillings. Low topographic corridors of some straightness, formed by denudation initiated by open fracturing, have been identified as lineaments, as well as sharp linear features in outcrop areas. Because of their varied nature the hydrogeological significance of a lineament remains to be proven by drilling and well testing.

The statistical study of the hydrogeological significance of lineaments has been hampered by the difficulty of making a proper stratification of the hydrogeological situation around the lineaments. In some studies high yields have been associated with short distances from lineaments; in others this was not true. Waters *et al.* (1990) give a review and discussion and Carruthers *et al.* (1993) report a field study of photo-lineaments, supported by an assortment of geophysical exploration methods and drilling.

The simple global relationship of well yield-distance to lineament may be of little diagnostic significance. First of all, a segmentation according to directions should be made, and specific capacity (l h^{-1} m^{-1} drawdown) rather than yield (l h^{-1}) should be used if data permit, to incorporate the influence of the surroundings of a lineament. The information of conventional rose diagrams can be supplemented (Brière & Razack, 1982) by directional variograms and by relating the results to the tectonic history of the area (e.g. Djeuda Tcapnga & Ekodek, 1990).

There is general agreement that the most promising water bearing directions originate from brittle deformation caused by tensional stress related to normal faulting and strike-slip faulting (Larsson, 1984; Baweja & Raju, 1984; Greenbaum, 1986; Castaing *et al.*, 1989; Du Wencai & Ye Deliao, 1993). Different rocks respond to the same overall stress field with different fracture densities. Grouping such rocks as gneisses, which do not fracture easily, with granites will therefore cause much unnecessary variation in the statistical analysis.

Finally, the recharge conditions are of considerable importance, in some cases more so than the lithology. This was shown by an analysis of variance incorporating lithology, size of potential recharge area and size of irrigated areas of single open wells and well clusters, as determined from aerial photographs (Meijerink, 1974). Recharge characteristics can be further differentiated by physiographical image interpretation, merged with geohydrological data.

GROUNDWATER QUALITY

In specific areas, valuable information on groundwater quality can be derived from imagery by making use of relationships between water quality and vegetation. Kruck (1976, 1990) presented well-illustrated examples of the adjustment of vegetation to the salinity of the shallow, phreatic waters of the inland Okavango delta in Botswana and the pampas in Argentina. The local effects of hydrocarbon contamination on the vegetation have been described by Svoma (1990) and Svoma & Pysek (1983).

The general use of remote sensing for assessing possible groundwater pollution is an indirect one, by way of spectral land use mapping. The loading by agrochemicals must be estimated by stratified sampling. Physiographical interpretations could supplement the information required by approaches such as DRASTIC (Aller *et al.*, 1985), or the related SINTACS method (Vrba & Civita, 1995).

FUTURE DEVELOPMENTS; GROUNDWATER RECHARGE AND MANAGEMENT

Imagery contains information for planning. In certain cases, not only the likelihood of groundwater occurrences and risk of contamination and salt water intrusion, but also of the characteristics of the terrain for groundwater use, such as suitability for small-scale irrigation, location and size of settlements, and so on, are contained in the imagery. Castaing *et al.* (1989) and Dutartre *et al.* (1990b) described such applications from the viewpoint of a hydrogeologist. The merger of image interpretations and GIS operations for the planning of groundwater development in a data scarce district in Kenya was described by Karanga *et al.* (1990) and doubtless many more studies of this kind have been done or will follow.

Attention is increasingly paid to the management of groundwater. Zonation of and intervention in the recharge process and the need for distributed groundwater balances will focus the interest of the hydrogeologist on remote sensing applications in studies of soil moisture, evapotranspiration and snowmelt runoff. Rango (1994) has reviewed these subjects.

For the study of groundwater balances in dry regions, it is common practice to use multispectral land use classifications to determine the size of areas irrigated by groundwater. The net drafts are estimated from approximations of the consumptive use and evaporation loss from conveyance, generally by using empirical methods. Information from old aerial photographs, taken at a time when the drafts did not exceed the recharge in many aquifers, can be used for steady state groundwater modelling. The expansion of the irrigated areas can be detected on more recent photographs or on satellite imagery and used for transient state modelling.

The well known simple Thornthwaite and Mather monthly soil moisture water balance method, with some adjustment for reaction time of the system, was used in a mountain catchment in Indonesia to estimate the baseflow (Meijerink *et al.*, 1994). The procedure with monthly time steps was embedded in a GIS. Imagery was used for the mapping of soil units to estimate waterholding capacities and for mapping vegetation to estimate rooting depths. A close fit for the monthly baseflow discharge was obtained, but more studies are needed to have confidence in its application in ungauged catchments. Van Dijk *et al.* (1996) applied a similar method to a semiarid area to prepare input for groundwater modelling.

A more sophisticated approach using thermal and multispectral imagery was adopted by Thunnissen & Nieuwenhuis (1989) to determine the effect of groundwater extraction on crop evaporation. A comparison was made of the results obtained by remote sensing and by one-dimensional soil moisture modelling for areas in The Netherlands. However, for parts of the study area the results did not match and it was difficult to determine which of the two methods represented the true evapotranspiration.

Finch (1990) used vegetation indices from Thematic Mapper data and the probability of rainfall derived from Meteosat data to study the recharge of a sand-covered area in Botswana. Changes in the indices were ascribed to the response of the vegetation to the availability of subsurface water, but no actual recharge data were presented. It is to be expected that remotely sensed vegetation indices will play an increasing role in recharge studies, considering the developments in the research concerning spatial evapotranspiration using weather satellite data (Bastiaanssen, 1995; Choudhury, 1994; Kustas *et al.*, 1994). Until the more physically-based monitoring methods become common practice, the use of remote sensing in groundwater balance studies will rely on image interpretations followed by empirical transformation of land cover and terrain characteristics in estimated recharge.

CONCLUSIONS

There are few physical remotely sensed measurements (temperature, backscatter of active microwaves from saturated zones) of direct relevance to groundwater studies, and if so they pertain to specific conditions and thus have limited application as yet. The general application of remote sensing in hydrogeology has been, and still is, in the domain of image interpretation, whereby interaction takes place between what can be observed on the imagery and what is expected on the basis of a conceptual model of the hydrogeology of a given environment, in particular groundwater flow systems. The use of imagery for qualitative studies in certain types of terrain is well described in the literature, particularly the crystalline basement and limestone areas, where attention is directed to the study of lineaments.

The interest of hydrogeologists in remote sensing is shifting to the dynamic aspects of water balances and contamination, for which the appropriate instrument is provided by combining image processing, GIS procedures and numerical modelling. The upper boundary of shallow groundwater is strongly influenced by the features at and near the surface, which are recorded on imagery. There is need for further development of simple and robust methods to transform the interpreted physiographical or geomorphological units in distributed parameters. A challenge is the development of affordable, physically-based use of satellite data with a high temporal resolution for monitoring recharge and emergence of groundwater driven by flow systems.

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