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USING SATELLITE IMAGES TO STUDY DRAINAGE PATTERN ANOMALIES IN SAUDI ARABIA

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Drainage systems follow patterns of water flow and network connection that are influenced mainly by geologic structures, surficial processes, terrain properties and rainfall behavior. These patterns often reflect a normal stable condition of the terrain surface on which they developed. However, in many instances, drainage patterns exhibit anomalies in their orientation as a result of subsequent events and processes. Drainage pattern anomalies are seen in many regions of the world, including the Arabian Peninsula. The development of remote sensing techniques, notably satellite images with a variety of optical properties and image resolutions, can now show terrain features that were not seen before. The analysis of three types of satellite images (Landsat 7 ETM+, IKONOS and STRM) in this study revealed unique features of drainage patterns and anomaly types in the Saudi Arabia region and its surroundings. Patterns were analyzed at different scales using different image processing approaches for 136 drainage systems in the Arabian Peninsula. They represent 10 drainage patterns, of which 12 anomaly types exist. Out of the 12 anomalous drainages, there are 6 newly recognized types according to known classifications. These anomalies are found to reflect many structural and geomorphological processes, which were difficult to identify directly from geomorphologic and geologic maps, and in field surveys. A new classification for drainage patterns and their anomalies is presented in this study. The mechanism for each anomalous pattern is also interpreted. The methods used in this study can help improve analysis of drainage systems for application in hydrological and engineering practice.

INTRODUCTION

The drainage network is probably the most important single identifier of landforms (Way, 1978). It is described as the aggregate of all terrain surfaces adapted to water flow and accumulation. These surfaces include wet and dry channels, valleys, depressions, flat basins and lakes. They have an essential role in governing the components of the hydrologic cycle and can be viewed from different aspects of terrain channelling systems. From a hydrologic point of view, the morphometric characteristics of drainage networks reflect the surface water regime, and they have been characterized by linear, areal and relief indices (Yamada, 1999).

Drainage systems are important not only to hydrologists, but also to geologists, geomorphologists, agricultural engineers and other environmental professionals. They can be considered as the synthesis of many landscape properties, such as climate, topography, soil and lithology, geologic structures and vegetation (Gracia and Camarasa, 1999).

Usually, drainage systems are studied according to their type, pattern and density. Several approaches of analysis are followed to provide geomorphologic information on the behavior of a drainage network. The information obtained characterizes the drainage texture and is utilized in several different hydrologic disciplines, such as watershed management and flood studies, as well as in water supply and engineering practices. Moreover, the hydrologic characteristics of drainage systems reflect elements of different surface geologic features and terrain surface properties. They can be used to identify subsurface geological structures as a aid in hydrogeological studies. In natural resources assessment, such as for petroleum and metallic deposits, these characteristics are always prerequisite components for any analysis.

Drainage properties can be well diagnosed by several methods. Detailed classification and categorization of drainage patterns can attribute each pattern to specified terrain settings. However, there can also be many distortions in expected drainage patterns. These distortions, the so-called drainage anomalies, are widely observed in many regions of the world. The Kingdom of Saudi Arabia has many of these anomalies as shown by remotely sensed data.

This study is an analytical approach to categorize these drainage anomalies by processing different satellite imageries for the Saudi Arabia region. The recognized anomalies will be also be interpreted in terms of subsurface terrain properties.

Saudi Arabia encompasses a miscellany of topographic aspects as well as different climatic regimes. It has a total area of about 2.15 million km^2 and is by far the largest country in the Arabian Peninsula. (Figure 1). It comprises four major physiographic units (FAO, 1999). These are:

- Western Mountains, called the Arabian Shield (2000 m), crossed by deep valleys,
- Central Hills, which run close to the western mountains and lie in the center of the country (900-800 m),
- Desert Regions, which lie to the east of the Central Hills (200-900 m),
- The Coastal Regions, which include the coastal strip along the Red Sea with a width of 16 to 65 km. The important part is the Tahama Plain in the south. The plain on the eastern side overlooks the Arabian Gulf and is generally wide and includes the region of oases.

The Arabian Peninsula lies in the tropical and subtropical desert region. The winds reaching the country are generally dry, and almost all the area is arid with great extremes of temperature

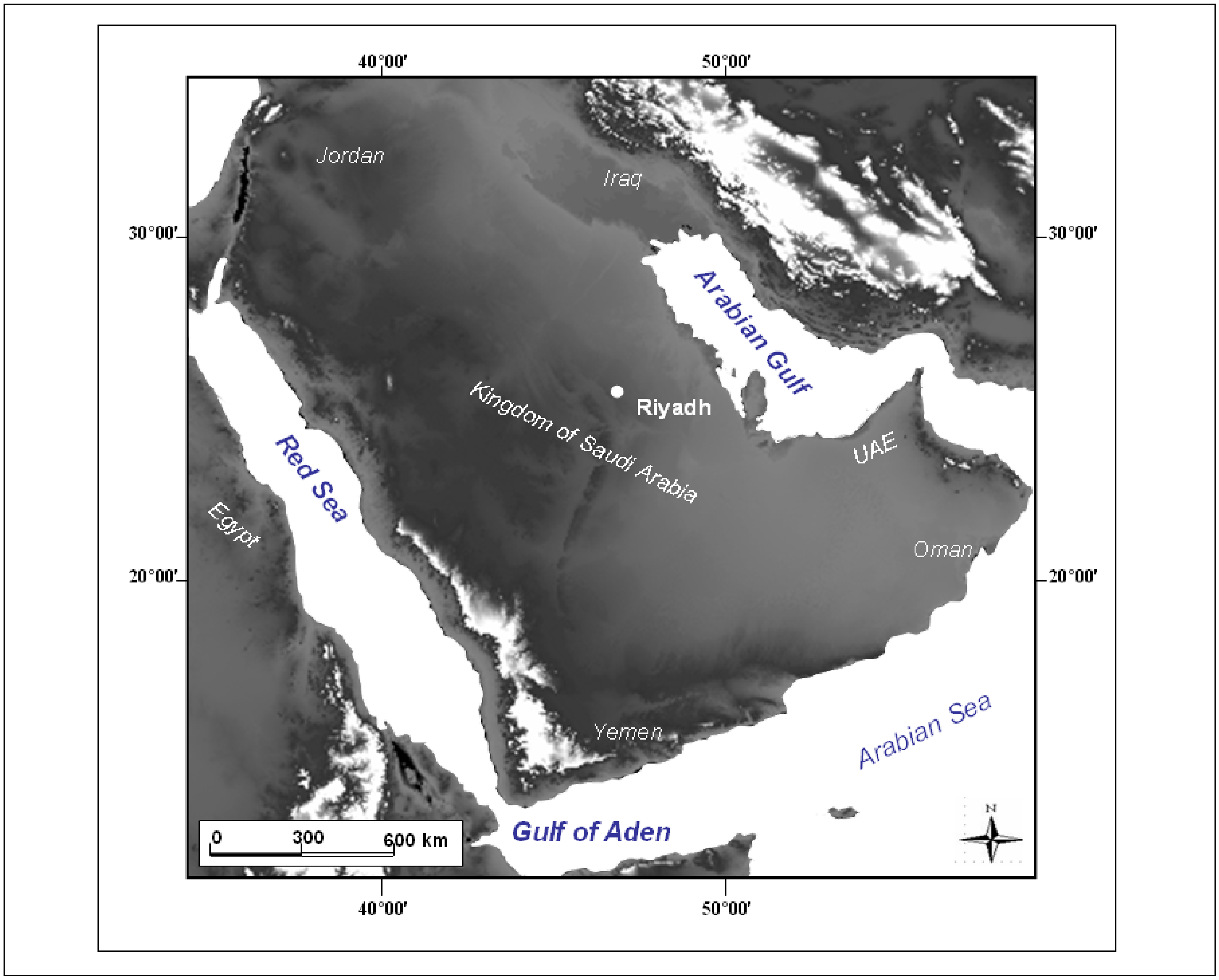

Figure 1. Location map of the Kingdom of Saudi Arabia.

(42-50°C), but there are also wide variations between the seasons and regions. Commonly, over the whole country, annual rainfall drops below 200 mm, except over the high parts of the southwestern region. Annual rainfall varies between 200-500 mm (El-Sherif, 2002). The total precipitation has been estimated at 126.8 km³/year, which is equal to 59 mm/year over the whole country (FAO, 1999).

In the Arabian Peninsula, intensive rainfall sometimes results in flash floods of short duration. However, river beds remain dry for the rest of the time. Part of the surface runoff percolates through the sedimentary layers in the valleys and recharges the groundwater and some is lost by evaporation.

MATERIALS AND METHOD

There are several methods and tools to identify, delineate and interpret drainage networks. Conventionally, topographic maps are used for this purpose, but often errors exist due to scale limitations, dates of acquiring aerial photos, as well as changes that may have occurred on the drainage tributaries. However, new approaches of drainage pattern extraction and analysis have been developed. Basically, these approaches depend mainly on remotely sensed data and, in some instances, combination with a Geographic Information System or GIS. Consequently, research in this field must include an evaluation of the utility of these techniques for drainage basin analysis.

In this study, several steps for drainage pattern analysis were used to reveal different drainage anomalies. The analysis of satellite images as a first step was followed by comparison with the Howard catalogue of drainage patterns (Howard, 1967). Recognition of unknown or new abnormalities in drainage patterns was conducted and the mechanism behind their distortion was interpreted. Drainage patterns in this study were analyzed by delineating all obvious drainage systems from the higher order towards the lower order. In the area of interest, this was carried out for all types of drainage systems and for all existing scales on different geologic formations.

Concept of drainage patterns

The arrangement of streams in a drainage system constitutes the drainage pattern, which in turn reflects mainly structural or lithologic controls of underlying rocks (Easterbrook, 1969). Normally streams are connected with each other and to anoutlet finally in an endpoint, except in the case of karstic terrain. Moreover, the direction of water flow can be induced from stream ordering. The higher order streams flow to lower order streams.

The terrain properties (e.g. slope, land cover, roughness, etc.) have a role in shaping different streams. Some studies were used based on drainage patterns to infer the subsurface topography (Gupta and Jindal, 2000). In other studies patterns are used for tectonic analysis (Deffontaines and Chorowicz, 1991). Normally, analysis of drainage patterns is conducted to predict the following (Shaban, 2003):

1. Infiltration potential of the underlying soil and lithology.
2. Homogeneity and distribution of different types of bedrock.
3. Prevailing slope degree and direction.
4. Headwater zones and catchment boundary.
5. Abrupt structures, mainly faults, joints and escarpments.
6. Dissolution effects of carbonate rocks.

A number of drainage patterns were categorized by several authors, and catalogues were produced for this purpose, such as those by Zernitz (1932), Howard (1967) and Gagnon (1974). In these catalogues however, no link in general was established or even an order of rank between different network patterns. They are just descriptive catalogues rather than a true classification. An improved description by Way (1978) catalogued 34 drainage patterns. Eight of them are the major and most common ones. These are: dendritic, angular, rectangular, multi-basinal, contorted, trellis, centrifugal, and parallel drainages. All types were utilized in this study to describe schematically different drainage patterns.

Distortion of drainage patterns

In a simple expression, straight drainage is the easiest path on a terrain surface, and it can be smoothly curved and connected with other reaches of a drainage system. Mankind has long been interested in the pattern of watercourses, and early geomorphologists, for example, have noted the existence of abnormally straight watercourses (Daubree, 1879). However, the effect of geologic structures and terrain movement (e.g. subsidence, uplift, etc.) can influence the behavior of drainage patterns (Figure 2). In addition, drainage patterns are affected by tectonics, which are deformations the geologic structures.

Most recognition of drainage distortion lies in identifying any abnormal deviation from the straight stream. The following are typical distortions:

- Abrupt change in drainage direction,
- Existence of meanders, notably compressed type,
- Trans-cutting of different drainage lines,
- Abrupt termination of drainages,
- Level variation in stream beds.

Various morphological factors affecting the origin and development of drainages must be considered in order to analyze drainage patterns. These include:

- Internal factors (rock lithology and geologic deformations and neo-tectonics),
- External factors (climate, vegetation and land use),
- Composite factors (topography, surficial processes and hydrologic regime).

Drainage patterns can occur as syn-processes (i.e., at the time of drainage development), or post-processes, after drainage has developed and often long after development. Post-processes change the pattern of stream networks. In some instances, the effect of these factors, notably complex influences, create distortions in the pattern of a stream channelling system. In this respect, Howard (1967) defined the so-called perturbation of networks, which combines genetic analysis in relation to anomalies or local perturbations, and created a descriptive classification of drainage network anomalies (Table 1).

Analysis of satellite images

Three types of satellite images were used in this study. They have different resolution (ability of discrimination) and optical properties. The variation in the resolution of the selected images

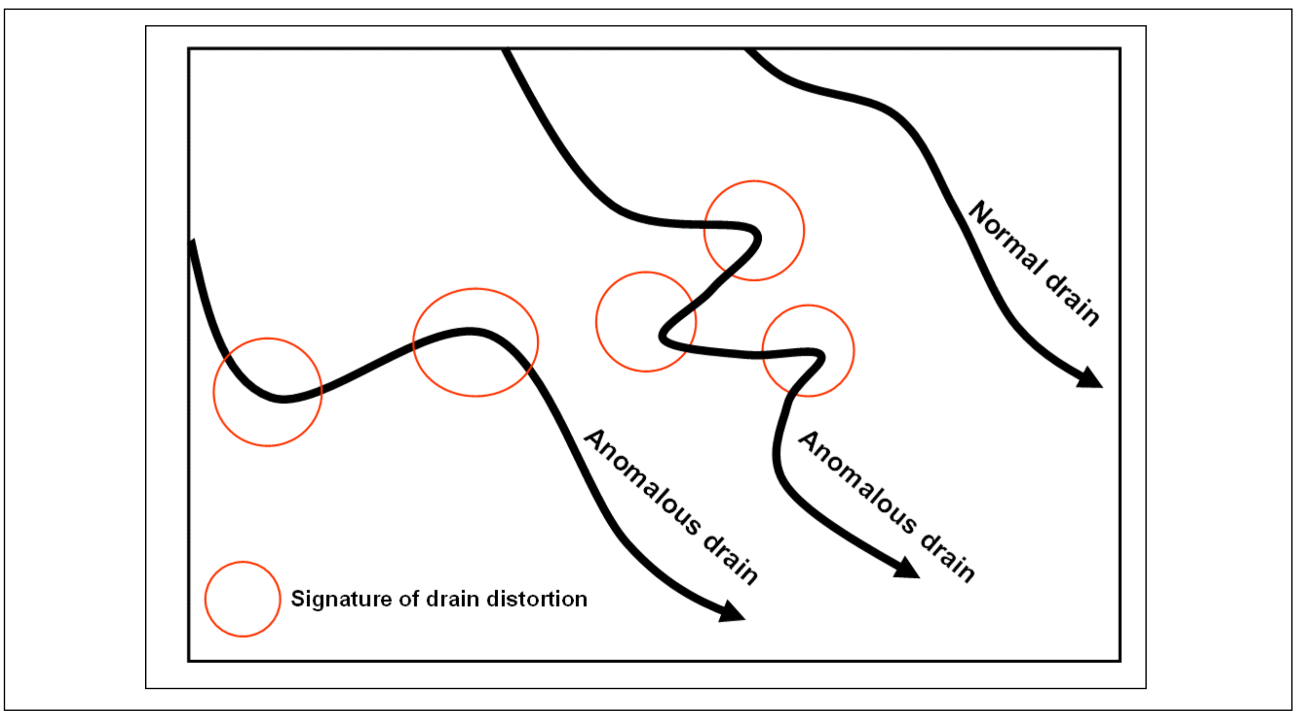

Figure 2. Example showing the identification of drain distortion.

was necessary to enable the capture of features in drainage patterns utilizing the optical properties of the image and its resolution. The processed images are: IKONOS, Landsat 7 ETM + and STRM.

IKONOS Satellite is a high-resolution satellite operated by Geo-Eye, and has four bands: Panchromatic, blue, green, red, and near IR. Its capabilities include capturing a 3.2m multispectral and 0.82m panchromatic resolution. It has a swath width of 11.3 km at nadir and 13.8 km at 26° off-nadir, with a revisit time of 3 days.

The Landsat 7 ETM + image has a repeat time of 16 days and swath width of a 185 km x 185 km, has eight spectral bands, in which bands 1-5 and 7 have 30m resolution and wavelength range from 0.45 to 1.75 µm. While band 6 is thermal and has a special spectral resolution of 60m and wavelength ranges from 10.4 to 12.5 µm, the last one, band 8 is panchromatic with 15 m spatial resolution and wavelength from 0.52 to 0.90 µm.

STRM (The Shuttle Radar Topography Mission) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of the Earth. It consisted of a specially modified radar system. There are three resolution outputs available, including 1 kilometer and 90 meter resolutions for the world and a 30 meter resolution for the US. GLCF serves the main USGS editions, plus has 'enhanced' editions as well as provides editions in WRS-2 tiles to approximate Landsat scenes.

For the above three types of satellite images, two image processing software packages were applied for each image separately (Figure 3), ENVI-4.3 and ERDAS Imagine. Both are capable of discriminating terrain and tracing drainage systems. However, digital image data requires several preprocessing steps. These commonly comprise data preprocessing with a series of sequential operations including, but not limited to, atmospheric correction or normalization, image registration, geometric correction, and masking geo-referencing. These applications are necessary to increase the accuracy and interpretability of the digital data during the image processing phase.

Table 1. Descriptive classification of drainage network anomalies (Howard, 1967).

Type	**Morphology**	**Causes**
Rectilinearity	Long rectilinear segments of streams are anomalies if regional pattern is not rectangular, angular or fault trellis	A fracture, an easily erodable vein or dyke
Local meandering	Abrupt and local appearance of meanders, a straight and simple channel gives two meander-like curves	Structural anomaly dome: subtle upstream change in stream gradient
Compressed meander	Stream pattern of which meanders are normal and in continuous series, squeezed, compressed and incised	Structural anomaly (dome)
Abrupt and localised braiding	Abrupt and localised braiding. It could be indicated by variations in drainage density	Braiding indicates inability of a stream to transport its bed load
Flaring in valley	Local widening or narrowing of valleys or channel	Local structure, shallow upwarp
Anomalous ponds, marshes	Isolated ponds and marshes	Subsidence or uplift
Anomalous breadth of levees	Abandoned channels are locally narrow	Subsidence, levees wider
Flying levees	Levees locally preserved	Subsidence or buried structural features
Anomalous curves and turns	Varieties and legion	Piracy, domal upwarp and strike slip fault

The software packages for image processing have different digital applications for image analysis and are dependant on the visible contrast between terrain elements. These applications are the color, directional filtering, contrasting, sharpening, tone, texture, and enhanced stretching. In addition to the above, single band and multiband enhancements were carried out by interrelating each three bands as one set.

Even though the higher resolution satellite images expose obvious figures of the developing drainage systems, the lower resolution satellite images can give a better idea about the geologic structure that relates to these systems. Therefore, a combination of both types is favorable in the analysis (Figure 3). Moreover, the application of thermal bands in this analysis served to delineate buried channels and even hidden structures.

RESULTS AND DISCUSSION

According to many definitions, distortions in drainage (a drainage anomaly or perturbation) are a local deviation from regional drainage and/or stream pattern, which elsewhere conforms to the known regional structure and/or topography (Howard, 1967). The expected pattern is regarded as the norm (Deblieux, 1949) and deviations are anomalies. These anomalies have been recognized in several regions of the world and are found to be at different scales and behaviors, and their assessment has followed many approaches. The use of remotely sensed data in recent approaches can clarify many facts about drainage pattern anomalies.

The analysis of all obvious drainage systems and their patterns in the Arabian Peninsula provides a detailed understanding about the type of drainage patterns at all scales in the area. In addition a comprehensive classification for drainage distortion types was developed. These distortions in the channel systems, which mainly result from tectonic activities, show the unique hydrologic and climatic regimes the area has been subjected to. In addition, the diversity and sharp contrasts of different lithologies has increased the number of drainage anomalies.

The level of anomalous effects on drainage patterns varies from one area to another. It was found that distortions in drainage patterns are often concentrated in specific regions of the Arabian Peninsula, which reflect local factors that have resulted in drainage anomalies. Moreover, some of the physical processes were abrupt, while others developed over the long term.

The influence of physical processes (i.e., internal, external and composite factors) was clear and was found to have taken effect after the initial channel pattern was established. These processes showed different episodes of effect on the drainage network. In other words, some processes were seen to have originated over a long time period and paleo-channels were observed, while others were recent processes.

In the Arabian Peninsula, the existence of sand dunes in many cases hindered identifying the complete delineation of drainage networks. The traces of hidden drainages were extracted using digital applications on satellite images, notably edge detection and sharpening plus thermal applications for some localities. The selection of networks depended on sampling a representative variety of streams on a miscellany of lithologies, structures, topography, and land cover as well as areas of different climatic conditions. This approach comprises all physical parameters that might affect the behavior of drainage patterns in the Arabian Peninsula.

In this study, 136 drainage systems (considered as a site for each system) were analyzed from different regions of the Arabian Peninsula. The sampling of these systems for drainage pattern

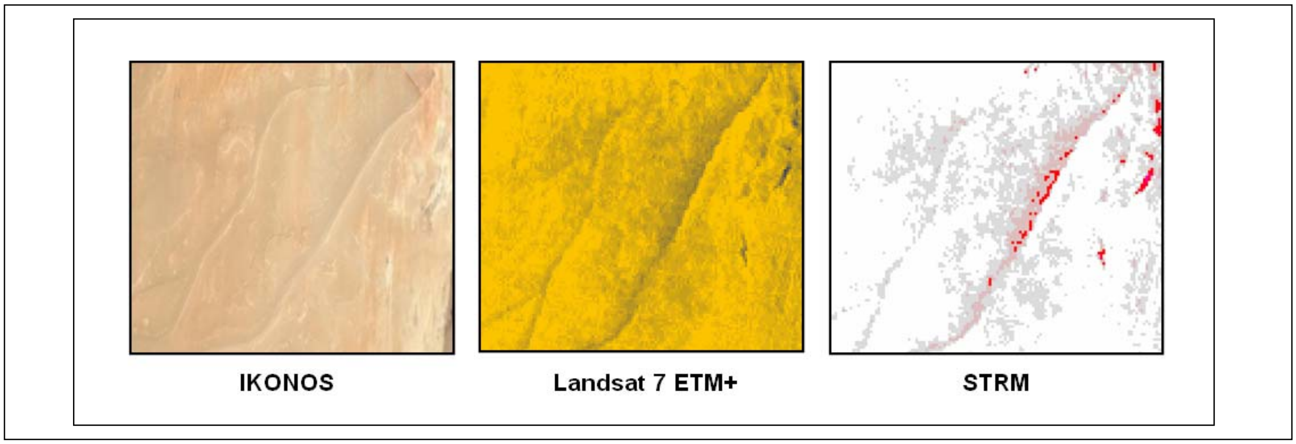

Figure 3. Example showing the three used satellite images of different resolution.

analysis started with the large-scale tributaries (branches), in which the analysis focused on small-scale drainages within the unique system. For each drainage system delineation to find anomalous drainages was applied for each system separately.

Out of the 136 investigated drainage systems, 10 major drainage patterns were identified (Table 2). They are 29%, 14%, 12% and 10% for the dendritic, sub-dendritic, angular and centripetal type respectively. Each pattern was found in a unique rock formation, thus indicating the homogeneity of the exposed formations. Some other types of drainage patterns were also observed. The use of different satellite images with different resolution helped to identify all types of drainage patterns in the areas of concern.

In many cases, the same drainage system encompasses more than one pattern type, notably when it crosses different rock formations. For the same drainage pattern, different scales were found in terms of drainage length and channel width. However, these patterns, which are developing in sloping areas, are characterized by relatively narrow width and deep channels. Those drainages existing in flat areas have relatively large width and shallow depths, like those in braided and anastomatic patterns, as well as drifted edges.

The data reveal several drainage distortion types or anomalies. These were found to be distributed among all pattern types, lithologies and geomorphologic units. Some new drainage anomaly types were observed which have not been identified before. The mechanism of distortion for the recognized anomalies was postulated. Figure 4 shows some examples of these anomalies and their interpretation.

The identification of anomalous drainages, in many instances, was not directly derived from the stream delineation (e.g., an abrupt meander or deviation), but morphologic characteristic were utilized as elements for identification. This was applied using low resolution satellite images (e.g. STRM), which are capable of detecting hidden or unclear geomorphologic features that are difficult to recognize through the analysis of high resolution satellite images. For example, an abrupt change in stream (drainage) depth is not easily detectable from IKONOS images. The processing of STRM images, which provides a digital elevation model, helps identify depth changes. Figure 5 shows an example of direct and indirect recognition of drainage anomalies.

During the analysis of different data, a unique drainage anomaly was identified and found to be especially abundant in the Arabian Peninsula. This is the transition between paleo-channels and recent drainage systems, which indicates regional tectonic activity has affected the area and made

Table 2. Dominant drainage pattern in the Arabian Peninsula according to the 136 investigated sites.

Drainage pattern	**Occurrence (%)**	**Geology**	**Topography**	**Climate**
Dendritic	29	Carbonate rocks and volcanic tuffs	Remarkable sloping terrain with uniform relief	Regular rainfall and temperature, with torrential episodes
Sub-dendritic	14	Abundant with impermeable rocks	Slightly sloping terrain with rough surfaces	
Angular	12	Carbonates with influencing structure	Moderately sloping terrain with jointed surfaces	
Centripetal	10	Impermeable rocks with dome structure	Sloping terrain, almost directed to depressions	The same as above with increased rainfall
Rectangular	9	Carbonates with jointed structure	Moderate to high sloping surface	Regular rainfall and temperature
Pinnate	8	Almost soil deposits with silt and sands	Highly sloping surface with local fissured and eroded surfaces	Regular rainfall and temperate areas, almost dry
Trellis	7	Structure-controlled carbonates	Moderately sloping terrain with jointed surfaces	
Braided	5	Alluvial and fluvial deposits	Flat and smooth terrain	Traces of torrential rain even (palaeo-climatic indications)
Radial	4	Dome-structure in volcanic rocks	Domal, volcanic crater and depressions	Almost temperate areas with decreased rainfall
Anastomatic	2	Almost eroded materials	Flat surface with dunes	Torrential rain and high temperature

changes in the geomorphologic and hydrologic aspects of terrain (Figure 6). Paleo-channels can be observed to often carry no water, because recent channels capture surface runoff. Many paleo-channels are potential sites for groundwater recharge, such as in the great Sahara of Libya, Egypt and Arabian Peninsula (El-Baz, 2000).

Of the 136 drainage systems, 12 major types of drainage anomalies were recognized in the Arabian Peninsula (Table 3 and Figure 7). Four types are new. This might be a phenomenon limited to the study region, since this region encompasses a variety of unique influencing factors, which were mentioned earlier. Most of these anomalies exist in the dendritic and sub-dendritic drainage type, as these were found to be the most common among the selected systems (43%).

In general the number of anomalous drainage patterns in the Arabian Peninsula is high if compared with other regions. Also, it is obvious that most of the drainage anomalies are structurally controlled (Table 3). The common type is local meandering in drainage courses, which may include one or more curved channels as a result of structural compression. This indicates active tectonic processes. These structures can be ancient or recent. Topographic controls on these anomalies are primarily influenced by structure. The density of these anomalies differs from one region to another, but is normally found to concentrate in the mountainous and coastal regions. In addition, some anomalies have a common drainage distortion property such as that of the anomalous flow trends in the case of returned and opposite direction types (Figure 7). Both have different mechanisms and causes of drainage pattern shaping.

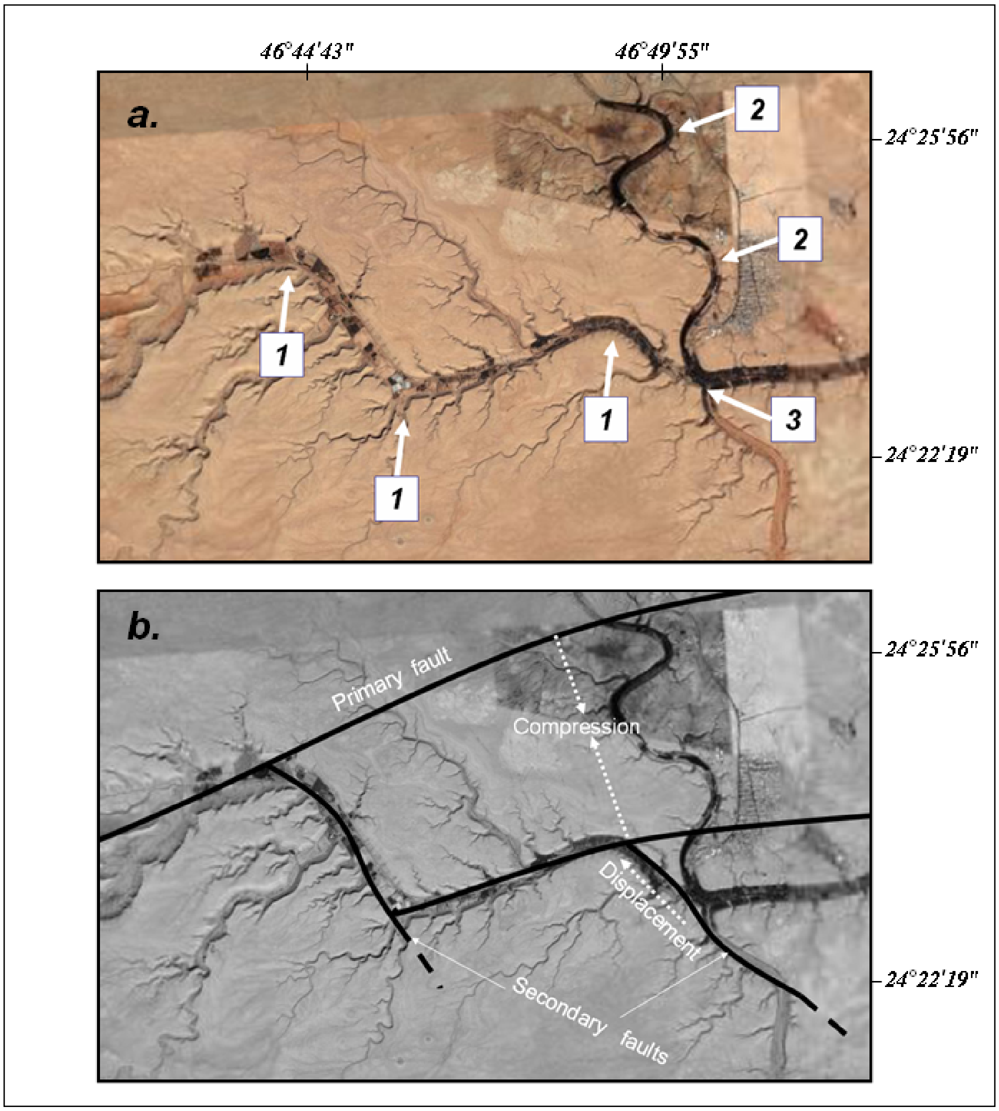

Figure 4. Drainage anomalies as observed in IKONOS satellite images for Jabal Hafahaf (28 km south of Riyadh). a) 1-Abrupt meander, 2-Compressed drainage and 3-Acute drainage connection. b) Interpretation of structure influence for the same area.

There are six newly identified drainage anomalies (Figure 8). They represent unique anomalies, but not are not necessarily limited to the Arabian Peninsula. They are prominent in the study area and found to be clearly identifiable from satellite image interpretation.

The identification of these anomalies and understanding their mechanism helps geomorphologists, geologists and hydrologists interpret many topographic and hydrologic phenomena. For example, the direction of the local meanders indicates a compression force has influenced the site. Also, from the orientation of these meanders along specific trend lines the direction of the presumed compression can be determined. The existence of anomalous drainages helps identifying buried rock structures (Shaban et al., 2006), which are often covered by sand dunes or alluvial deposits, as is common in the Arabian Peninsula. Correlating drainage anomalies with structural and geomorphic criteria will serve to be useful in many hydrological and engineering studies applied in these regions.

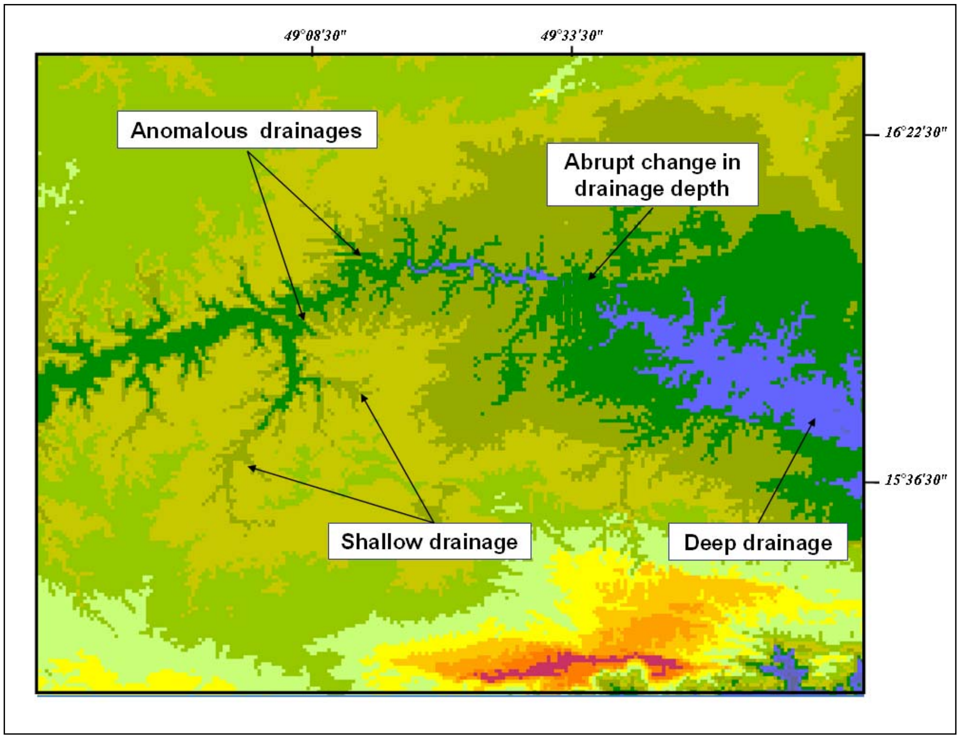

Figure 5. STRM image showing the identification of drainage anomalies from direct and indirect observations (Wadi Sidarah area at Saudi-Yemeni border).

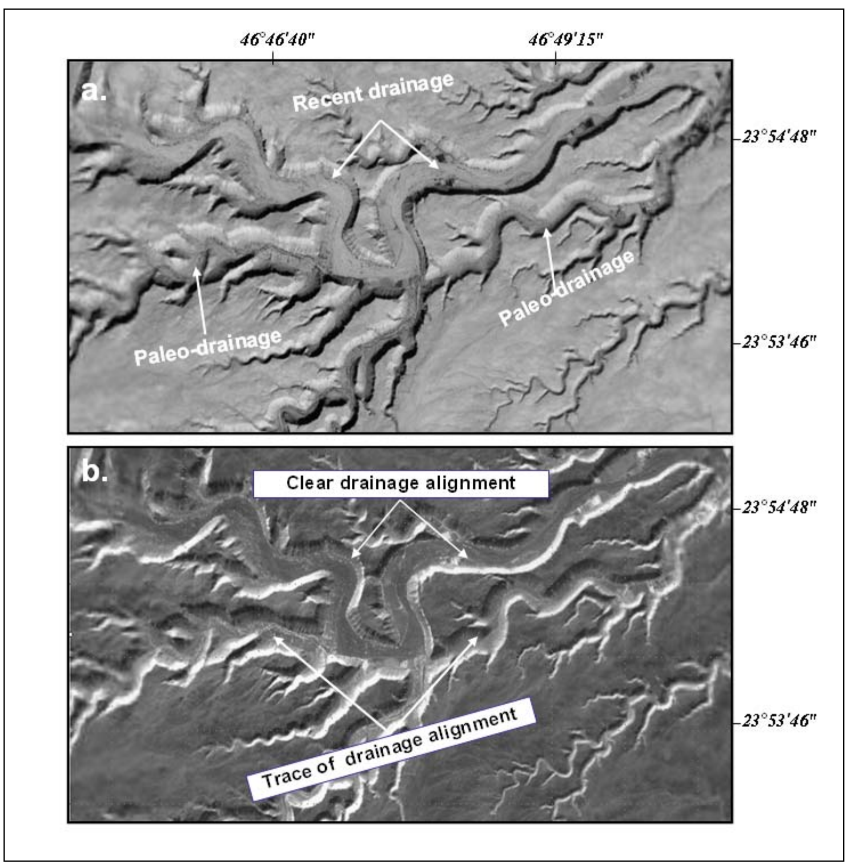

Figure 6. Identification of the intersection between recent and paleo-channels near Al-Harq (85 km south east of Riyadh).

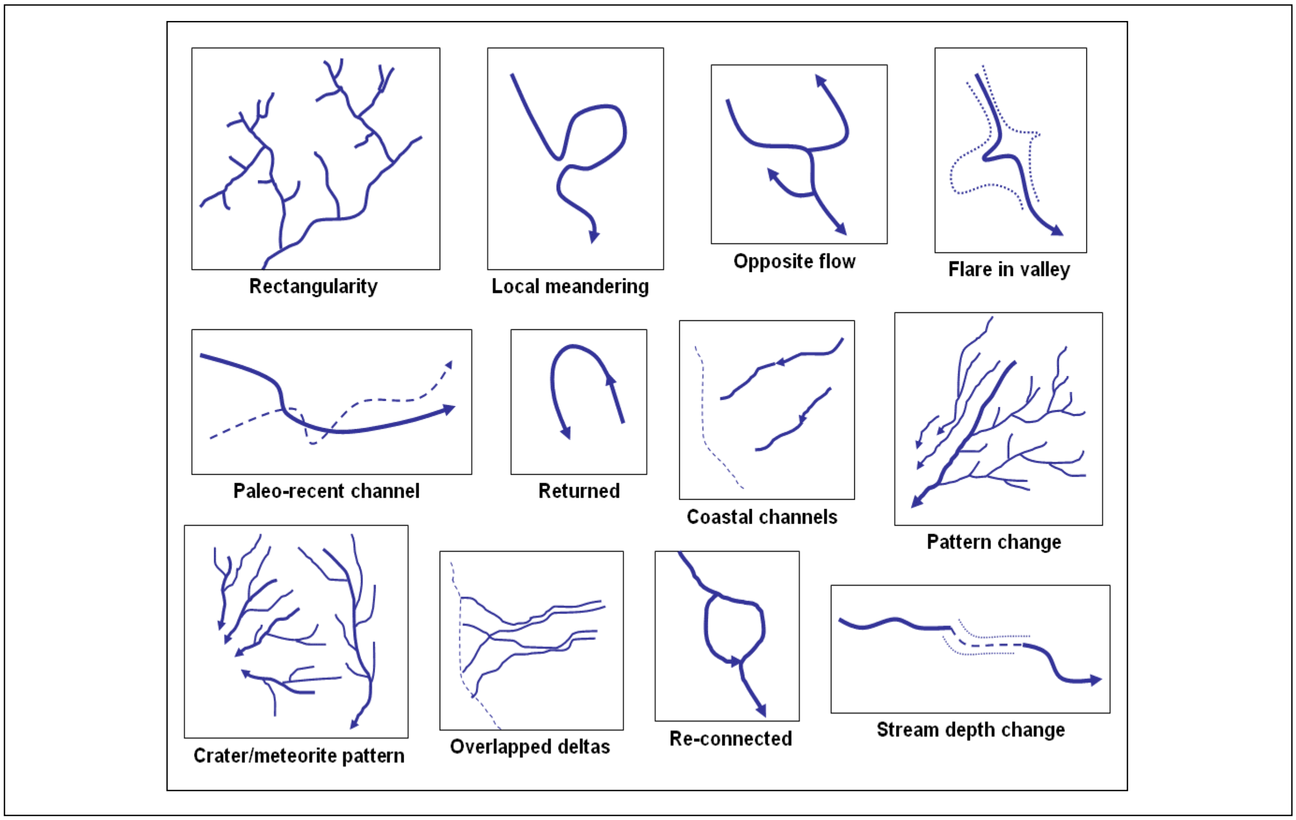

Figure 7. Sketches of the identified drainage anomalies in the Arabian Peninsula.

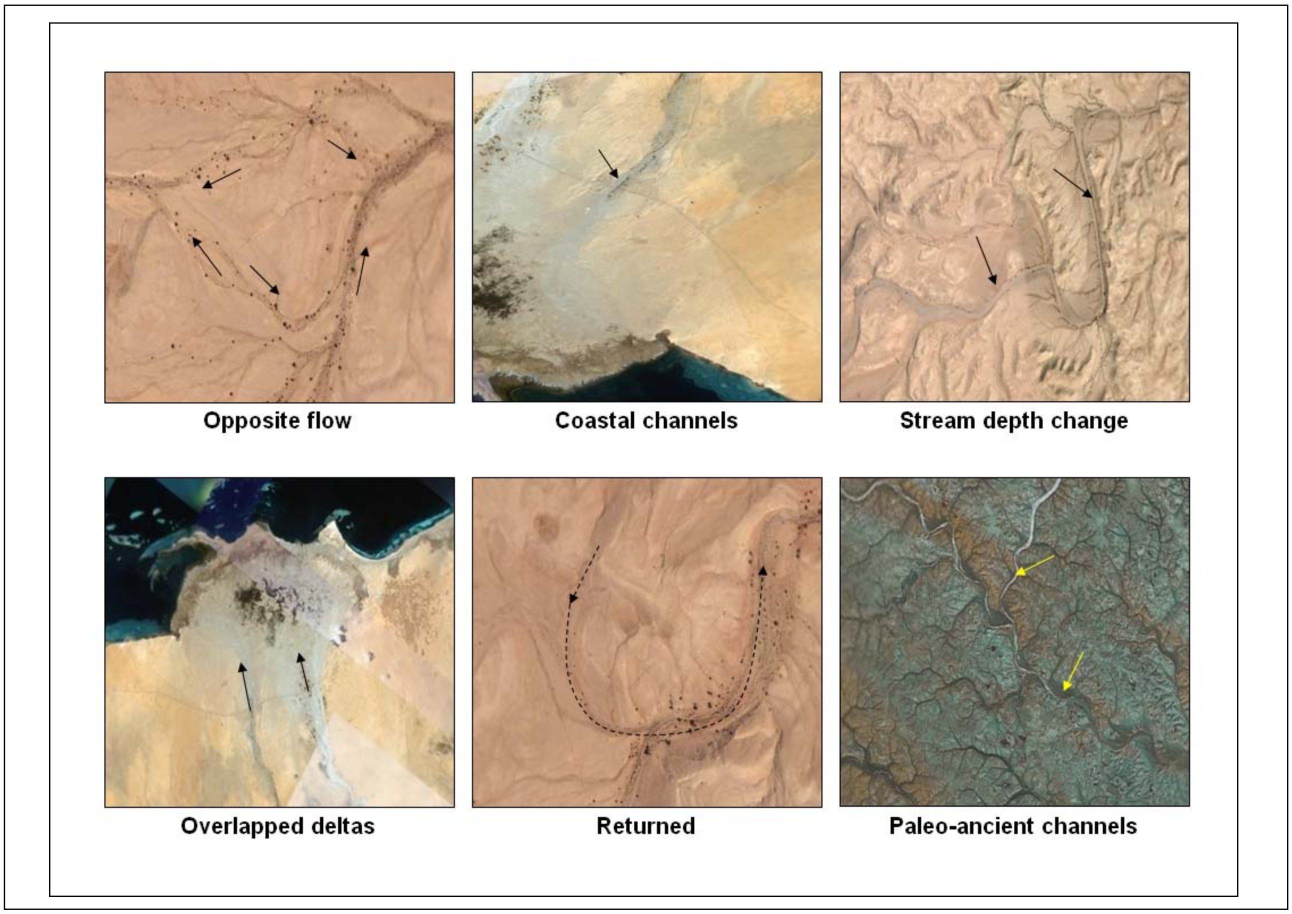

Figure 8. Examples of the new types of drainage anomalies identified in the Arabian Peninsula.

Table 3. Identified drainage anomalies from satellite imageries in the Arabian Peninsula.

Anomaly type	**%****	**Common morphology**	**Presumed causes**
Local meandering	41	Abrupt meandering in channel. Sometime, several ones exist as compressed meandering	Structural anomaly caused compression forces, which often a of the tectonic type
Rectilinearity	11	Long, rectilinear segments of streams, almost at right angles	A fracture, an erodable vein or dyke, as well as fault-controlled
Pattern change	9	Two different drainage patterns along the same primary course	Existence of primary watercourse exactly on fault line, thus separated two different lithologies
*Stream depth change**	8	Decrease in stream depth for certain distance of the channel and thus return to the original depth	Recent structure-controlled that cuts along the drainage course
*Returned**	7	Return in flow direction within the same drainage	Acute change in topographic units within a parallel direction
Flare in valley	6	Local widening or narrowing of valley or channels	Local structure and shallow up warp
*Paleo-recent channel**	6	Overlapping between ancient and recent channels	Almost regional tectonic activity
Re-connected	5	Separation within a channel course, then re-connected around a domal/or depression terrain	Existence of dome or depression-like shape topography
*Opposite flow**	3	Two/or more opposite flow direction, but almost at right angles	Jointed, faulted terrain with different topographic slopes
Crater/meteorite patterns	2	Two neighbouring pattern systems. First, directed to depression and second move around	Existence of crater or meteorite cones
*Coastal channels**	1	Coastal channels terminate before reaching the coastline	Termination of channel system before reaching the coast as a result of uplift or sea level drawdown
*Overlapped deltas**	1	Two, or more delta system overlapped	Regional activity affected the geomorphology of the area

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