Assisting the Exploration of Groundwater near Refugee/IDP Camps using Remote Sensing and GIS

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Zusammenfassung: Zur Versorgung von Flüchtlingslagern mit Trinkwasser benötigen humanitäre Hilfsorganisationen wie Ärzte ohne Grenzen eine effiziente hydrogeologische Bewertung. Im Projekt EO4HumEn werden dafür Methoden auf Basis von Fernerkundungsdaten entwickelt. Je nach Aquifertyp (Porenaquifer/Kluftaquifer) stehen unterschiedliche Fragen im Fokus. Für Porenaquifere ist die Kartierung von Sand- und Tonkörpern, Gewässernetz und Quellhorizonten anhand von Vegetation und Bodenfeuchte von besonderem Interesse. Für Kluftaquifere soll ein Algorithmus zur automatischen Extraktion von Lineamenten mit Hilfe von objekt-basierter Bildanalyse entwickelt werden. Grundlage sind Daten der Sensoren Landsat, ASTER und TerraSAR-X. Die Ergebnisse werden an ausgewählten Standorten validiert und sind Ausgangspunkt für weitergehende Untersuchungen im Gelände.

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1 Introduction

According to the United Nations High Commissioner for Refugees (UNHCR), by the end of 2012, 10.5 million refugees and 28.8 million internally displaced persons (IDP) were forcefully displaced worldwide as a result of persecution, armed conflict, generalized violence and/or human rights violations (UNHCR, 2013). Following the outbreak of armed conflict, refugee/IDP camps can form spontaneously in remote areas, turning existing rural settlements into densely populated agglomerations, and often exceeding locally available resources. A key concern for humanitarian organizations providing relief actions like Médecins sans Frontières (MSF) is the provision of sufficient water with reasonable quality. While the short-term water demand may be met by delivering water by trucks or by purification of surface waters, the exploitation of groundwater resources is usually the best option to supply the camp population on the longer term. This requires an assessment of the local hydrogeological situation even in the case that basic data like geological maps or borehole logs are not existing or unavailable. The current project EO4HumEn (*EO-based services to support humanitarian operations: monitoring population and natural resources in refugee/IDP camps, FFG-ASAP 9, Nr. 840081*) aims at mitigating this gap by providing basic information using remote sensing and GIS for systematic ground water exploration.

2 Hydrogeological situations and remote sensing

Recent hotspots of refugee and IDP movements have been the Democratic Republic of Congo, Afghanistan and Syria as well as Eritrea, Somalia (UNHCR, 2013) and currently Sudan and South Sudan. This list illustrates that any generalized approach towards a hydrogeological assessment has to cope with a wide variety of climatic and geological environments. Depending on the basic type of aquifer, consisting either of unconsolidated sediments, consolidated sedimentary rocks, volcanic rocks or crystalline basement, a different approach has to be taken towards the assessment of the aquifer, which in turn dictates different questions that may be investigated using remote sensing. Fig. 1 shows a general overview of the distribution of the basic aquifer types in Africa. Approximately 22% of the land surface of sub-saharan Africa (SSA) is comprised of unconsolidated sediments, 32% of sedimentary rocks, and 40% of basement rocks. Volcanic rocks make up 6% of the surface (MACDONALD et al., 2008).

2.1 Unconsolidated sediments

Unconsolidated sediments form the most productive aquifers in Africa (MACDONALD et al., 2008) and consist of clays, sands and gravels that have been deposited as alluvial or lacustrine sediments, in coastal basins or dunes in the recent geological past. Being exposed directly at the surface and easy to excavate without motor-operated tools, aquifers of this type are usually well known and exploited by the local population. Remote sensing can contribute in several ways in assessing this type of aquifer. First, the spatial distribution of the different types of sediments (clays, silts, sands and gravels) can be assessed. This is important as the conductivity and transmissivity of unconsolidated sediments is mainly governed by the grain size, with large grain sizes resulting in higher permeability. Optical sensors such as Landsat TM and ASTER imagery with their spectral bands in the short wave infrared can be used to map the spectral absorption of clay minerals, which in turn act as a proxy for the permeability. Although the distribution of clays, sands and gravels can form a highly complex pattern, which changes laterally and vertically within meters, the view from above can provide a general idea of the sedimentary body as a whole and the likelihood of boreholes intersecting a coarse-grained deposit at a given location. Another approach is to determine the rock type of the source rock of the sediments, using satellite imagery. Shales, schists and basic rocks tend to produce more clay-rich sediments upon weathering, while acidic rocks, sandstones and limestones produce sands and gravels and only little clay (DRURY & DELLER, 2002). Remote sensing data may also be used to identify recharge areas of the aquifer by mapping current or abandoned surface water courses. Coarser, more permeable sediments are usually deposited in the channels of a drainage network and not in the only occasionally flooded plains, where the lower flow velocity leads to the deposition of clays. As these deposits can be infiltrated by surface waters, wells in proximity of a river or lake are likely to produce fair amounts of ground water that has been filtered as it passed through the banks of the sediment body.

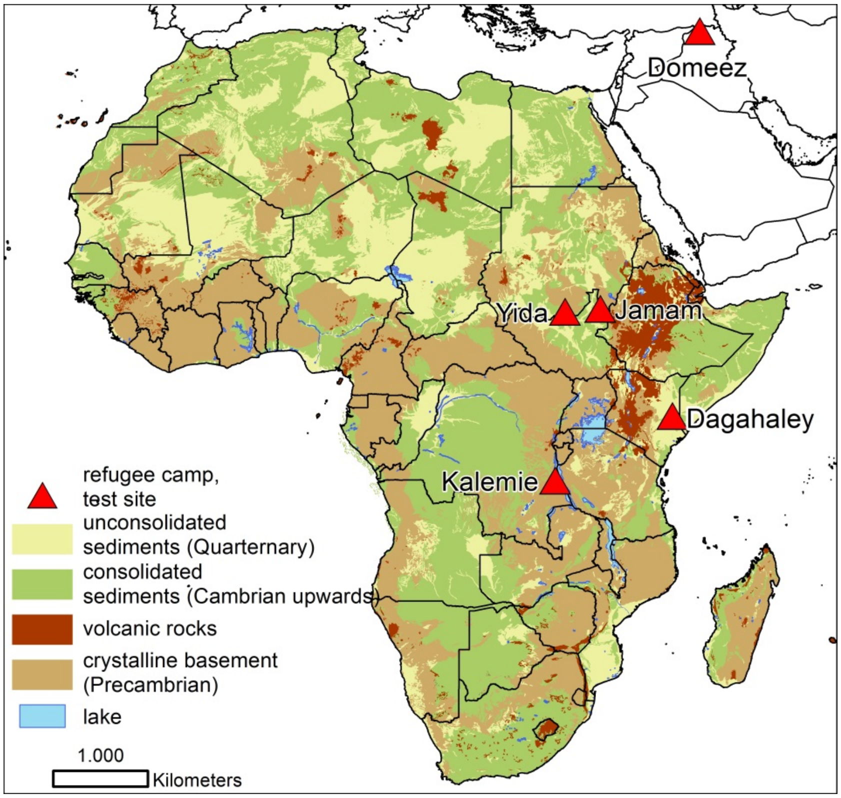

Fig. 1: Hydrogeological zones of Africa and test sites of the EO4HumEn project. (after MACDONALD AND DAVIES, 2000; data from USGS, 2002). Three test sites (Yida, Jamam and Dagahaley) are located within unconsolidated sediments and porous aquifers. Fractured aquifers within crystalline basement and consolidated sediments, respectively, are represented by the test sites Kalemie and Domeez.

The direction of groundwater flow tends to be parallel to surface waters. Mapping the surface water body therefore helps to identify borehole locations upstream of settlements, camps or other potential sources of contamination in order to extract groundwater fit for human consumption. Discharge zones, where the ground water table is close to the surface and thus easy to access may reveal themselves by active vegetation and a higher amount of soil moisture during the dry season, which can be localized in remote sensing data as well.

Active sensors such as Radar can complement the identification of sand and clay bodies in three ways. (1) The magnitude of the backscattered signal depends on the surface roughness and its permittivity. The former is related to the grain size, the latter is mainly controlled by the water content and in part by the clay content of the soil. Although the two effects can cancel each other out, making quantitative estimations difficult, they help mapping local grain size variations. (2) The signals in the longer wavelength bands (P-band, L-band) can penetrate dry sediments and thus reveal buried channels, which are not visible in optical imagery due to surface cover. (3) The emitted radar signal hits the surface at a very shallow angle. Therefore, even subtle surface structures such as paleodrainages produce variations in the reflected signal, making these structures visible in radar imagery.

2.2 Consolidated sediments and volcanic rocks

In consolidated, bedded sedimentary rocks, the flow of groundwater occurs within the rock layers having a relatively high permeability, such as limestones and sand stones parallel to the bedding. Medium-resolution optical remote sensing imagery (e.g. Landsat, ASTER) can be used to map the spectral characteristics of these rocks or their specific texture, where these rocks are outcropping at the surface. Especially limestones can have a high conductivity if they are karstified. Together with digital elevation models (DEM), these outcrops can be used to extrapolate the continuation of the aquifers underneath a possible surface cover in order to estimate the depth at which it may be penetrated in a borehole. The boundary of an aquifer and an aquiclude often reveals itself by a line of springs and increased vegetation cover. These areas are also favorable spots for wells. Within volcanic rocks, groundwater flows within the rough-textured and porous sections at the top and bottom of individual lava flows, giving them similar hydrogeological characteristics to bedded sedimentary rocks.

Radar data can complement the distinction of rock types, as differences in surface roughness indicate variations in resistance to weathering of different rock types. Rock units can also be discerned using polarimetric information. The sensitivity of the radar signal to surface moisture can be used to identify springs and zones of groundwater seepage.

2.3 Crystalline basement

Crystalline rocks have no primary porosity in their pristine state. The only conduits for groundwater are fractures, joints and other zones of weakness. Under favorable conditions, these structures can be widened by weathering and erosion to extend several hundred meters into the subsurface and provide formidable permeability. Thus, mapping of these features, often seen as lineaments in satellite images, is a crucial step in the investigation of hard rock aquifers. However, SANDER (2007) points out that any groundwater exploration project has to take the tectonic history and local lithology into account, instead of focusing only on image-processing to extract lineaments. The reasons for this are manifold. Lineaments can be zones for enhanced conductivity, but they can also act as a barrier for groundwater, for example if they are formed by dykes or as results of ductile deformation. The tectonic stress field also plays a role, as open fractures tend to form parallel to the main compressional stress, whereas fractures perpendicular to the direction of stress are more likely to be closed. Whether a given fracture or fault is a good conduit for water yet also depends on the rock type it has developed in. Schists or metabasalts with a high content of biotite readily form clay minerals, clogging the fractures, while rocks rich in quartz and feldspar tend to form very little clay, leaving fractures open. Finally, the best groundwater conditions exist when deep, open conduits in the basement interact with storage in overlying unconsolidated material, which conceals the lineaments, meaning that the largest and best visible linear structure identified in a satellite image may not be the optimal target for a production borehole. Thus, the mapping of lineaments has to be accompanied by a thorough geological assessment. Here, Landsat and ASTER imagery are most suitable to determine the local lithology in absence of geological maps.

The ability of radar sensors to observe even subtle terrain variations due to the shallow angle of the emitted signal with the surface further supports identifying lineaments. However, is has to be kept in mind that structures oriented perpendicular to the incoming electromagnetic wave produce a large shadow, whereas lineaments parallel to the looking direction can be underrepresented. The same effect holds for optical images, where structures in the direction of the sunlight will also be barely visible.

3 The Project Setup

The purpose of the EO4HumEn project is to develop a workflow for groundwater exploration in the vicinity of refugee/IDP camps based mainly on freely available Earth observation (EO) data, GIS technology and integration of auxiliary data (e.g. geological/hydrogeological maps, drilling logs, vegetation, soil types) to meet the mid-term needs for potable water of the inhabitants. The interpretation of EO data is especially valuable in situations where hydrogeological field data, borehole profiles or even basic data like topographic and geological maps are missing or not available. To this end, we selected five refugee/IDP camps as test sites (Fig. 1) in a variety of geological and climatic conditions. With MSF being a partner in this project, it is assured that the project meets the specific requirements of a refugee camp situation, and that results can be validated against data collected in the field or actual drilling campaigns at the camp sites. Further test sites will be defined on demand of MSF.

The information need regarding the hydrogeology and the possibilities of remote sensing differ according to the basic type of aquifer present in the area of interest. In the case of a pore aquifer, the questions regarding the distribution of permeable sandy and less permeable clay-rich deposits, the recharge and discharge areas, and the direction of groundwater flow require a high level of human interaction and interpretation of remote sensing products. Automated procedures may be used to preprocess the data and to assist in the delineation of the drainage network. In crystalline basement terrain, where the groundwater flow is confined to linear structures such as faults and fracture zones the automated extraction of lineaments has the potential to produce objective and reproducible results in a short time frame. Therefore, one of the project aims is to develop an automated procedure to map linear structures in crystalline basement terrain on remote sensing data employing object-based image analysis (OBIA).

3.1 Lineament mapping: previous work/approaches

The mapping of lineaments, defined by O'LEARY ET AL. (1976, p. 1467), as "mappable linear features of a surface whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differ from the pattern of adjacent features and presumably reflect a subsurface phenomenon", is a common procedure in geological remote sensing. Two general approaches may be distinguished: Manual/visual mapping of lineaments, and automated or semi-automated attempts. Manual procedures have been criticized as being subjective to the interpreter's experience and skill. Existing automatic approaches on the other hand, while being objective and reproducible, require a post-processing step to discern natural features from man-made structures like roads, overland power lines or field boundaries, which depends on additional data or human interaction. This lead RAMLI ET AL. (2010) in their review on lineament extraction to the conclusion that automated approaches were still in their infancy.

Lineaments have been mapped based on a variety of data sources, including geophysical data, digital elevation models, SAR and optical imagery (ZEIL ET AL., 1991, DRURY ET AL., 2002, SOLOMON AND GHEBREAB, 2006, SANDER 2007, DHAKATE ET AL., 2008, RANGANAI ET AL., 2008, CORGNE ET AL., 2010, AL-MUQDADI ET AL., 2012). The most commonly used satellite images in this regard are from Landsat, ASTER, SPOT and IRS missions. Most researchers working with optical imagery make use of various false color combinations, Principal Component Analysis (PCA) and edge filtering methods like Canny or directional filters to make linear features more apparent in the data, rendering them easier to map either by a human interpreter or an automated algorithm. Automated lineament mapping algorithms usually produce binary images from the edge-filtered data or make use of segment tracing procedures. The extracted edges or segments are then linked to more continuous lineaments during an edge-linking step. This step often employs the Hough transform to link edges in close proximity with similar orientations using a set of thresholds previously determined manually on a subset of the data (RAGHAVAN ET AL, 1995, HUNG ET AL., 2005, MOSTAFA & BISHTA, 2005, MARGHANY ET AL., 2006, MASOUD, 2006, HASHIM ET AL., 2012, SOTO –PINTO ET AL., 2013).

Lineament mapping with radar data mostly follows analogous approaches, consisting of contrast stretching and filtering to remove speckle. Consequently, edge filtering or directional filtering techniques are applied to extract lineament segments, which are then linked to form lineaments. (BRUNING, 2008, MADHAVAN ET AL., 2010, LEPAGE ET AL., 2000).

3.2 Object-based image analysis for lineament mapping

The common approach of object-based image analysis (OBIA; LANG, 2008) relies on segmentation of the image into homogenous objects and classification of these objects using not only the spectral information, but also the shape and size of the objects and their spatial relationship to neighboring objects. OBIA has become increasingly popular since around the year 2000 and has been used in a large number of remote sensing applications. A recent summary is provided by BLASCHKE (2010). Despite many successful applications of OBIA, this methodology has rarely been employed for geological remote sensing purposes. SHRUTHI ET AL., (2011) used OBIA for the extraction of gullies in high spatial resolution imagery, MARTHA ET AL. (2010) and AKSOY & ERCANOGLU (2012) identified and classified landslides. GLOAGUEN ET AL. (2007) used a combination of Radar and DEM data to extract faults based on texture, MALLAST ET AL. (2011) combined lineament filtering and object-based classification from DEMs. The aim of this project is to develop an automated, object-based approach for lineament extraction and to integrate different data sources. The capability of OBIA to take context and shape information of the image objects into account bears the potential to overcome limitations of previous attempts of automated lineament extraction, as it allows an implementation of the intrinsic knowledge of human interpreters about the objects of interest into the classification procedure (LANG, 2008).

Raw optical data, data transformed with principal component analysis, edge-enhanced image products, DEM data and its derivatives (shaded relief, slope, curvature) as well as corresponding products based on radar data will be used individually and in combination as input data. Thereby the optimal data combinations, processing steps, and parameter settings should be explored to reliably extract lineaments under a wide range of climatic and geologic conditions. The entire work flow of the lineament extraction in crystalline basement terrain is shown in Fig. 2.

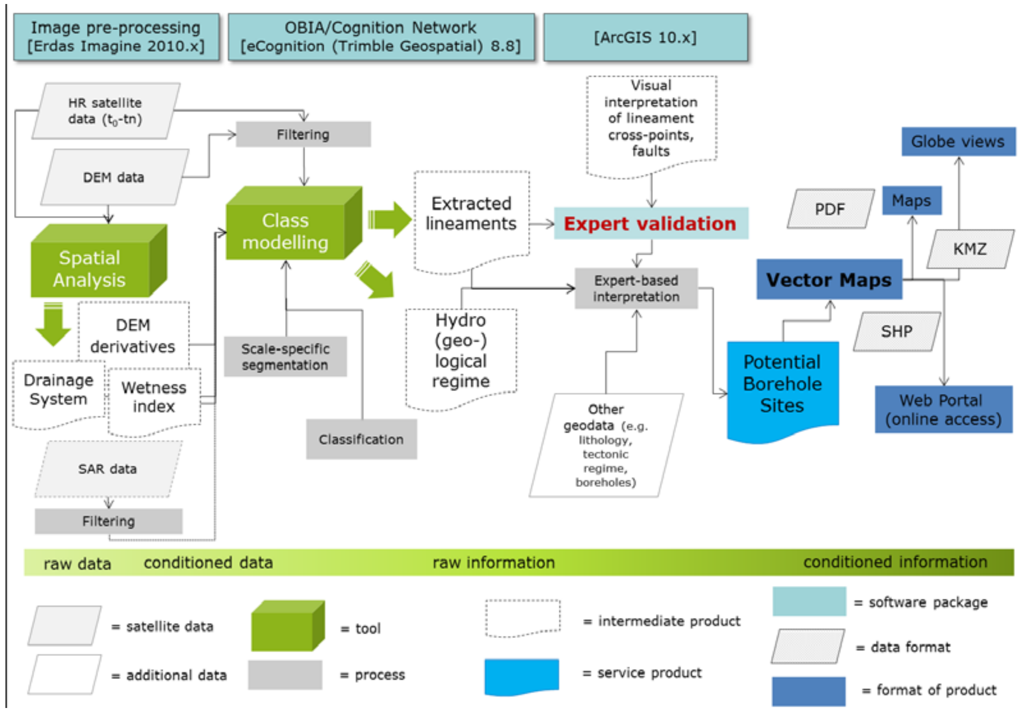

Fig. 2: Planned service architecture for the exploration of potential groundwater sites in crystalline basement terrain and consolidated sedimentary rocks. Optical satellite imagery, filtered data, DEM derivatives and SAR data products are produced in a preprocessing phase. Then, lineaments are extracted in an object-based image analysis environment. The most effective combination of input data and extraction rules is determined. The extracted lineaments are evaluated by experts, and finally, maps are produced.

4 Summary

The overall aim of this project is to develop workflows to provide humanitarian organizations with hydrogeological information using on EO data and auxiliary data to facilitate targeted groundwater exploration by conventional field methods in the vicinity of refugee/IDP camps. The nature of the aquifer at the site dictates the approach for the information extraction from remote sensing data. In unconsolidated sediments, the distribution of sedimentary bodies with different grain sizes, the recharge areas, flow directions and discharge areas of the groundwater system have to be investigated. In consolidated sedimentary rocks and crystalline basement aquifers, the mapping and characterization of lineaments as the main conduits for groundwater flow plays a decisive role. The applicability of automated approaches will be tested in both hydrogeological settings. In particular, the optimal combination of input data, preprocessing steps and methods for automated detection and mapping of lineaments in hard rock terrain will be explored.

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