Optical satellite pictures - The up to date source for discharge determination in arid countries

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Abstract

Many arid countries suffer severe water scarcity. Often lacking knowledge about hydrologic features like discharge prohibits the utilisation of valuable water resources. In this paper the basic approach is described to derive information about runoff water in arid landscapes by using optical satellite images. Wadi systems are highly sensitive regarding fluviomorphologic changes which are induced by rare flood events. Changes of river pattern, river width, sinuosity and so on correspond to duration and intensity of discharge events. These changes can be observed from space by comparing satellite data from different moments. Changes of river patterns are extracted from the satellite data and analyzed by visual comparison and fractal analysis. Finally the findings are correlated with discharge data from the two test sites in Jordan and Oman to calibrate the model to be transferable to other arid environments. First comparisons of satellite data before and after a flood event in Oman 2003 show exemplarily promising potential of this research project.

Keywords

Discharge Estimation, Remote Sensing, Fluviomorphology, Arid Areas

INTRODUCTION

Due to climate and geographic circumstances, the distribution of water is extremely unbalanced (Baumgartner & Reichel, 1975). Especially in large parts of northern Africa, the Middle East and western Asia not enough potable water is available (Simonis, 2001). At the same time, water demand increases because of the sharp population growth, the expansion of agricultural areas and in some countries also because of the fast development of the economy (United Nations, 2001). Already today, depletion of water resources leads to a drawdown of the water table, salinisation and proceeding desertification of great districts (Sharma, 1998). To ease water scarcity many innovative techniques like artificial groundwater recharge are being developed or already state of the art (Bouwer, 2002). But missing hydrological information (for instance discharge data) often prevents design and efficient operation of such measures. Especially in poor countries hydrological measuring devices like gage stations are often missing (Fakete & Vörösmarty, 2007), in a bad status or professionals of the water sector are absent (Belz, 2000). This leads to the paradox situation that in many arid areas water resources are indeed available but they cannot be utilised. Therefore innovative methods for discharge investigation with a sufficient spatial resolution are needed.

Up to date innovative methods intend to derive information about discharge from remotely sensed data. Alsdorf et al. (2000) observed interferrometric radar measurements to monitor water levels in reaches of the Amazon basin. Combined with information about river bed geometry and flow velocity the discharge can be estimated. Radar altimeter data were used to monitor sea level heights by Birkett (2000). Meinel et al. (2003) derived information about maximum flow depth and flow width from optical sensors of high resolution to calculate discharge of the river Elbe whilst the flood. Also Bjerklie et al. (2005) estimated discharges in rivers by using remotely sensed hydraulic information like river width from air photos and airborne SAR imagery. Promising efforts to derive information about river channel geometry delivered Legleiter & Roberts (2005) by using hyperspectral images.

Attempts to derive discharge information from structural components of the river and fluviomorphologic changes due to changing flow regimes are in the focus of recent research. For example Bryant & Gilvaer (1999) observed the change of river morphology after flood events. With the help of hyper spectral data, which were taken airborne, relocations of gravel bars and river bed material could be recognized. Lane et al. (2003) determined changes of river morphology by comparing digital elevation Models (DEM) which were computed from aerial photos. These DEM with a theoretical height resolution of less decimetre enabled a quantification of river bed material after a flood event. Smith et al. (1995) used Synthetic Aperture Radar (SAR) data to estimate discharge in braided river systems. Their study correlated water surface area (effective width) with discharges obtained from ground measurements. Smith et al. (1996) enhanced this methodology by determine river sinuosity derived from SAR images. Additionally fluvio-morphologic features like meander-wavelength, bankful width and width/depth ratio which are related to energy dissipation processes may comprise useful data for discharge estimation from space (Bjerklie et al. 2005).

Our own research proposes that optical satellite imagery may be used to derive discharge information in ungaged arid areas. Whilst the above described methods are based on running water we want to develop an approach to estimate discharges by comparing morphologic changes which were caused by flood events. In arid areas seldom precipitation events lead to flash floods which may significantly alter the geomorphology of a wadi river system. These morphologic changes can be observed and judged from space. There is a correlation between intensity of a flood and the resulting changes in riverbed structure. The approach of the research work is to compare satellite data from date A with data from date B. If a change in river morphology can be observed it was due to a flood event. Now multitemporal analysis (change detection) enables to observe the intensity of morphological changes. These structural changes are correlated to ground discharge measurements which were taken whilst the flood. Exemplarily test sites are located in Jordan and Oman.

To present our intended methodology we now (1) describe hydrology of the test sites and intention of preliminary fieldwork, (2) present suitable satellite sensors, (3) show workflow of satellite data analysis and discharge estimation, (4) introduce the new parameter MAI (Morphologic Activity Index) which contains information about general river patterns, river energy and the behaviour of the river system, and (5) discuss requirements for application of the intended methodology in ungaged arid river systems.

MATERIAL & METHODS

Study Sites

Within the scope of the project two test sites exist in repeatedly inundated arid environments. One is situated in the Azraq Basin in Jordan and one is located in the Sultanate of Oman in the Al-Batinah Plain. Both test sites exhibit gauge stations for discharge measurement which are run by national authorities. Additionally rainfall stations are located inside or near the test sites to provide further hydrologic data for the research project. In this paper only Wadi Hawasinah in the Sultanate of Oman will be introduced more profound.

Wadi Hawasinah lies in the northern part of the Sultanate of Oman (Figure 1). The wadi drains from the Jebal Akhdar region to the Gulf of Oman and comprises approx. 110 km². Average precipitation reaches between 300 and 50 mm per year in the Sultanate of Oman (Al-Ismaily & Probert, 1998) whereas single rainfall events in the mountain areas can reach several 10 mm within a few hours. The Geology is mainly dominated by rocks of the Oman Ophiolite (dunite, basalt, radiolarite), conglomerates, limestone and recent wadi deposits. In the Al-Batinah Plain fan shaped, strongly branched wadi channels can be found which are composed of gravel, sand and fine materials.

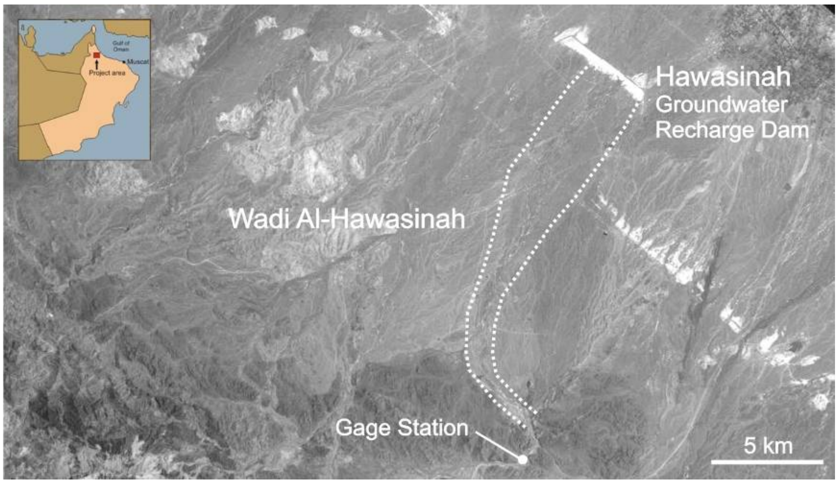

Figure 1: Landsat 7 ETM+ satellite image of the test site Wadi Hawasinah in the Sultanate of Oman. The Wadi Hawasinah groundwater recharge dam is visible due to fine sediments in the reservoir. The Water drains to the Gulf of Oman in the upper right corner of the image. Image source: www.landcover.org

Fieldwork

Within the frame of the research project comprehensive fieldwork was executed in Jordan and the Sultanate of Oman. The goal of these preparation stays was to observe and categorise specific fluviomorphologic structures in the field. Furthermore information about surface properties such as constitution and texture of soil were recorded which is important for the later interpretation of satellite images. Moreover the fieldworks dealt with the question which of the structures observed in the wadis can be recognised in satellite data. Recognisability mostly depends on the spatial resolution of the satellite image but can also be affected by surface roughness and formation of shades.

Spaceborne optical satellite images

Within the scope of the research project optical satellite data from 1972 until 2007 is used. Optical data means that information is recorded within the visible part of the electro magnetic spectrum (approx. 0,4 – 0,7 μm) and the infrared spectrum (approx. 0,7 μm – 0,5 mm). The spatial resolution of the existing images varies between 79 * 57 m per pixel (Landsat 1) and 0,6 * 0,6 m per pixel (Quickbird). Panchromatic data comprises one band in the electro magnetic spectrum which is displayed in levels of grey colour. In contrast multispectral data contains more than one band in the visible and infrared reach. Spectral resolution of existing satellite scenes varies between 3 bands (JERS) and 14 bands (ASTER). Following Table 1 shows the most commonly used satellite data.

Table 1: Satellite data used in the research project.

Satellite	Sensor	Resolution [m/pixel]		Bands	Launch
		multispectral	panchromatic		
Landsat 1	MSS	57 x 79	-	4	1972
Landsat 5	TM	30 x 30	-	7	1984
Landsat 7	ETM+	30 x 30	15 x 15	7	1999
JERS	OPS	18 x 18	-	3	1992
Terra	ASTER	15 x 15	-	14	1999
SPOT 3	HRV	20 x 20	10 x 10	4	1993
IKONOS	-	3,28 x 3,28	0,82 x 0,82	4	1999
Quickbird	-	2,44 x 2,44	0,61 x 0,61	4	2001

Satellite data analysis and discharge analysis

Satellite data analysis consists of three main parts: A) Image processing B) Image analysis and C) Discharge estimation. The work flow is illustrated in Figure 2 below.

Image processing. Mainly unregistered raw data is used which has to be processed with special image processing software. This work was carried out at the German Remote Sensing Data Center (DFD) in Oberpfaffenhofen, Bavaria, which is part of the German Aerospace Center. First the satellite data had to be georeferenced. To “georeference” means that coordinates in the image are projected onto map coordinates of an existing reference system. This rectification was done with the computer software ERDAS Imagine from Laica Geosystems. The chosen map system is UTM / WGS 84. With the ERDAS tool “auto sync” and a reference image the automatic detection of GCPs (Ground Control Points) for the unregistered satellite scene was performed. After eliminating GCPs with a high RMS (Root Mean Square Error) the co-registration to the reference image was done. The average accuracy of co-registration (RMS error) reaches between 0,6 pixel for Landsat data and 0,3 pixel for JERS data. As reference images Landsat 7 ETM+ data was used which was already orthorectified by USGS (Jordan: Path 173, Row 038, 2000-11-06; Oman: Path 159, Row 43, 2000-07-31). This data is available free of charge in the internet from Earth Science Data Interface of the Global Land Cover Facility (http://glcf.umiacs.umd.edu/index.shtml). After rectification the satellite images were cut into uniform subsets of both test sites to reduce the computational efforts. Also colour adjustment was executed to raise the contrast of the images to emphasize the fluviomorphologic features of the wadis systems.

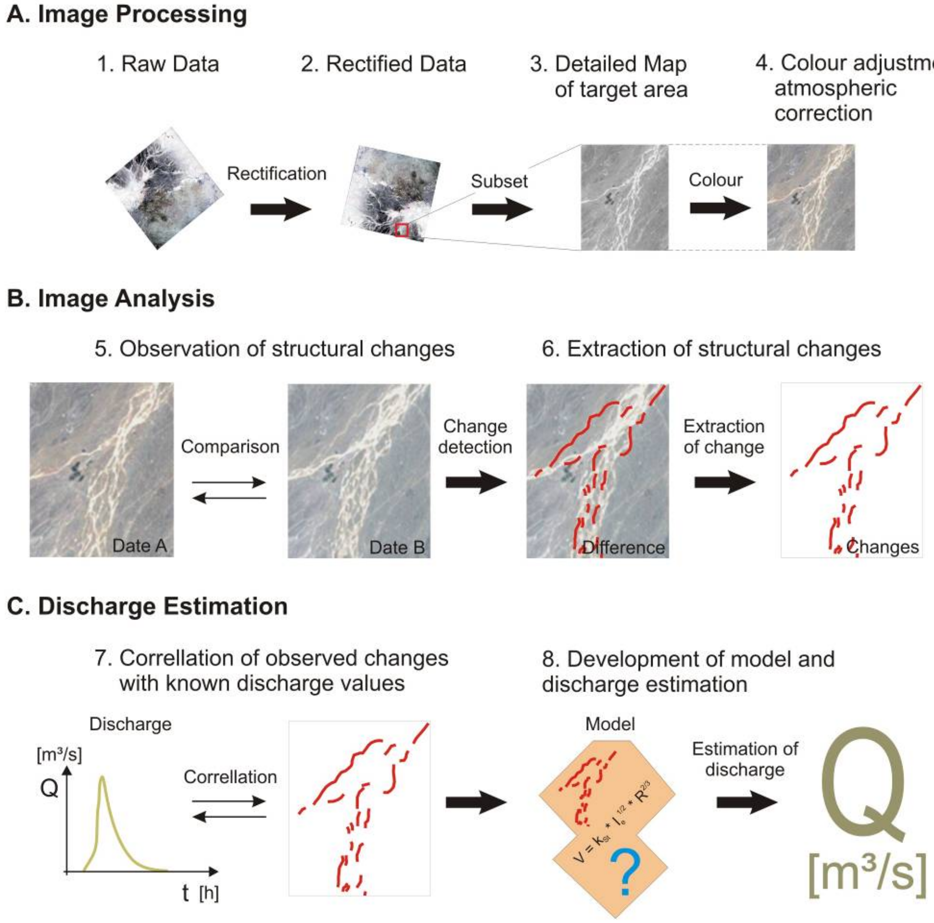

Figure 2: Schematic flow chart of the main steps within the research project.

Image analysis. In the first step image analysis is done visually. Two satellite scenes from different moments are laid on top of each other in the software ERDAS Imaging. Via "flicker" mode morphologic changes can be observed easily. Areas which exhibit strong morphologic changes are extracted from the images to be compared visual. With the extracted river details a catalogue of different fluvial patterns will be compiled. The goal is to identify fluviomorphologic structures or pattern assemblies which are specific and unique for one discharge amount. For this the above mentioned experiences from field work are substantially. The most relevant river features which deliver insights in stream behaviour are listed below and illustrated in Figure 3.

River dimensions: Observed river width is displayed by sedimentation of fine sediments during the maximum stage of the flood event. Also the total area of wadi streams and length gives evidence about the flow behaviour of the river system.

River sinuosity: Sinuosity is defined as the length of the river divided by the length of the floodplain. River sinuosity is already used by Smith et al. (1996) to estimate discharges in flowing braided rivers in alpine regions and offers promising potential for this research application in arid areas without water.

River patterns: Erosion and deposition processes can be observed by studying sand bars and gravel bars. Deep channels occur in river reaches of high fluid energy, whereas deposition of fine material displays low stream energy.

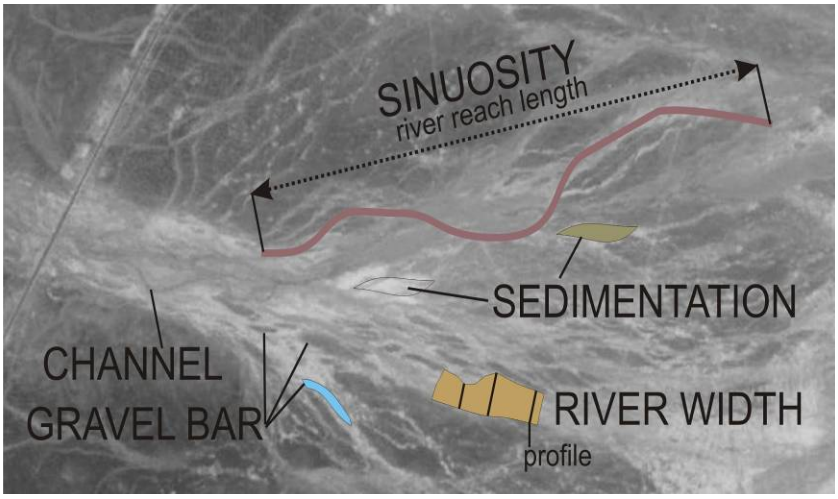

Figure 3: Illustration of different fluviomorphologic features which are essential for the research project.

Multispectral data contain information about spectral signatures of surface materials. Spectral signatures are specific for a material and therefore can be used to classify and categorize areas of equal materials. Spectral classification was done with the software ERDAS Imagine®. The satellite scenes were computed in 100 or 200 different classes which means that maximum 200 different surface types can be discriminated. On the basis of spectral classification wadi sediments were determined (Figure 4b) and extracted from the satellite images (Figure 4c).

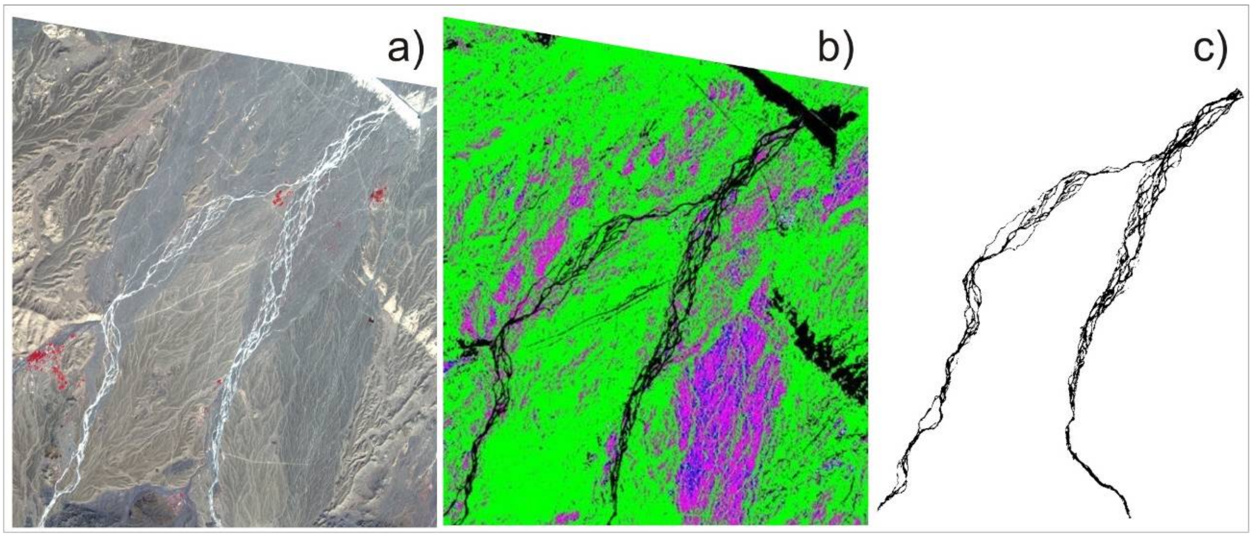

Figure 4: Exemplary classification of surface materials regarding their spectral signature in Wadi Hawasinah, Oman. A) Original satellite image. B) Classified Sattelite image. Green colour represents young gravel deposits, pink represents old gravel deposits. Fluvial sediments are displayed with black colour. C) extracted fluvial patterns.

Discharge estimation – first conception. The development of a methodology to derive discharge information from satellite data in arid areas is the core module of the research project. Since there are no comparable approaches so far, at this stage of the project the final and definite methodology can not be presented yet. Instead the planned technique will be introduced briefly and the most important working steps will be pointed out. The schematic flowchart of discharge analysis is shown in Figure 5 below.

Energy estimation: Geomorphologic changes depend on river energy. For energy estimation basic information about river patterns, slope conditions and approximated water levels can be derived from satellite data. With the observation of erosion and deposition processes a valuation of bed load transport (= river energy) is possible. In this context works of Hunzinger (1998) about the relation between river extension, river slope and water depths deliver valuable approaches for the project.

Fractal analysis: Fractal analysis exhibits great potential to describe structural patterns. Fractal geometry is based on the self similarity of patterns and allows to (1) characterize structures quantitatively, (2) gather information about anisotropy of pattern and (3) to derive information about pattern forming processes (Kruhl et al., 2004). The preferred technique for fractal analysis within the research project is the “box counting method”.

Creation of “MAI”: With the “Morphologic Activity Index” it is planned to combine the above acquired information to one specific parameter for the examined test site. MAI contains information about general river patterns, river energy and the behaviour of the river system. MAI will be necessary for calibrating the river discharge data.

Calibration works: Primarily MAI and discharge data from the test sites are needed to execute the calibration. The approach is to correlate specific river patterns and the kind of morphologic change respectively (both incorporated in MAI) to certain discharges. In this scope the hydraulic approach of Marti (2006) to determine discharge data from 2 D information seems suitable for the project.

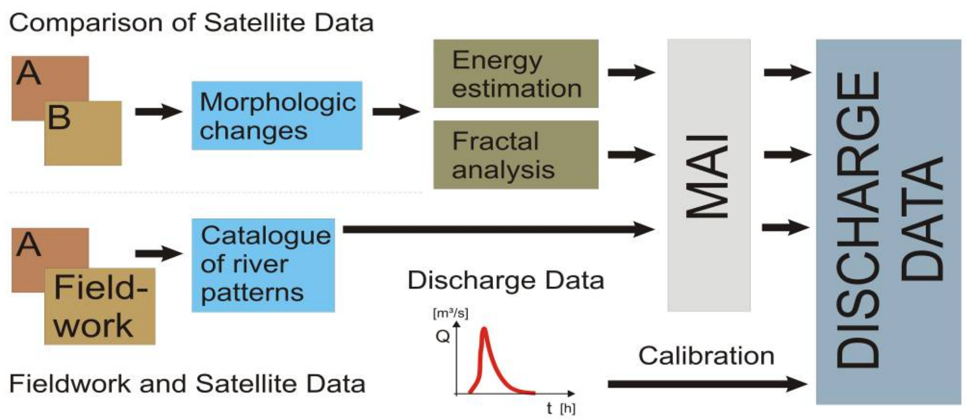

Figure 5: Schematic flowchart of the first conception of discharge estimation.

RESULTS AND DISCUSSION

In the initial phase of this research work approx. 30 different satellite images were orthorectified and roughly compared regarding morphologic changes. One promising example from the test site Wadi Hawasinah in Oman is presented exemplarily below. In April 2004 one severe discharge event was recorded by the Ministry of Regional Development, Environment and Water Resources (Muscat, Oman). Within 5 days a thunderstorm caused enormous discharge in Wadi Hawasinah with the maximum of 3.222.720 m³ per day at April 15th. Flood events in arid areas occur very fast. This is caused by locally restricted strong precipitation and bare soils which can hardly store the rain water. Typically discharge increases very fast in the beginning and slows down with the end of precipitation. Unfortunately gage recordings of April 16th are missing but the assumed trend of the hydrograph is completed in Figure 6a below.

The flood event of 15th April 2004 caused severe changes in the geomorphology of Wadi Hawasinah. This can be observed in two Landsat scenes which were taken shortly before and after the flood (Figure 6b, c). Mainly river characteristics like width and total length of river branches changed due to the flood. These features are displayed by fine sediments which were disposed during the maximum flow. Also new wadi branches occurred and changed the overall character of the wadi. Especially in the middle part of the wadi old river reaches were reactivated which drastically raises the sinuosity of the whole wadi system. (Note: In this context measurements of sinuosity are not finished yet and therefore can not be presented in this paper). Furthermore within the whole wadi area sand- and gravel bars were modified or newly created. Also areas of sediment deposition can be distinguished and areas prone to erosion can be delineated in satellite images of different spatial and spectral resolution.

Via spectral analysis the river patterns after the flood event were classified and extracted from a multispectral Landsat 7 ETM+ image (Figure 6d). The extracted river patterns are the basis for the first fractal analysis which is currently performed.

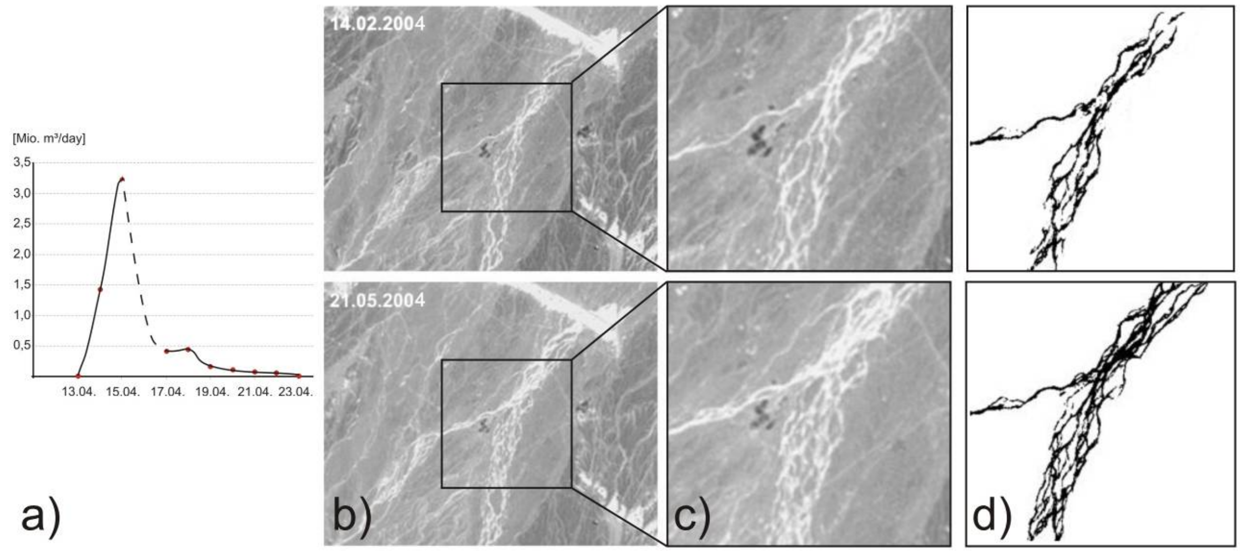

Figure 6: Comparison of fluvio-morphologic structures before and after the flood event of mid-April 2004. A) shows the hydrograph of the flood event. Because of one missing value on April 16th the assumed graph is dashed. B) and C) point out the structural changes after the flood. D) shows the extracted pattern from spectral classification which will be the basis for later fractal analysis.

At the current state of research work the presented methodology was not fully applied to the described test sites. We are aware that the proposed workflow is still of theoretical quality and may be changed or modified whilst the research period. But literature research strongly proves that our approach may be suitable to gain information about discharges in ungaged arid river basins where ground measures of discharge are absent. Here the proposed methodology can deliver information about relative changes in discharge. Determination of absolute discharges will be more difficult. Similar works of Smith et al. (1996) allowed an estimation of absolute discharges within factor 2. Errors could be substantially reduced by using time series of satellite images of several decades. Sample frequency and image quality are proved to be sufficient for large arid areas from the early 1970ies until now. Also resolution of the most satellite sensors is sufficient to recognize and extract fluvial patterns for the purpose of the project.

CONCLUSIONS

Satellite technology enables an enormous potential to obtain hydrological information also from remote areas in a distributed way and allows creating such information from flood events in the past. The main intention of the research work is to develop an innovative and low cost methodology to derive discharge information in arid areas from remotely sensed data which were recorded in discrete time intervals (e.g. one year).

As secondary goals the research project also intents to improve the knowledge about the context between flood events and fluvio-morphologic changes in arid areas. Furthermore it is proposed gather information how to optimise satellite sensors for future hydrological applications and to provide information about availability and usability of different remote sensing systems in the spectrum of hydrological applications.

First findings on a flood event in Oman show the potential of the method. Fluviomorphologic changes can be identified clearly by comparing the data. Also river structures can be extracted from the images via spectral classification and can be analysed with fractal analysis regarding the change of river structures.

REFERENCES

Al-Ismaily H. and Probert D. (1998). Water-resource facilities and management strategy for Oman. In: *Applied Energy* 61, pp. 125 - 146.

Alsdorf D. E., Melack J. M., Dunne T., Mertes L., Hess L. and Smith L. (2000). Interferometric radar measurements of water level changes on the Amazon flood plain. In: *Nature* 404(6774), pp. 174-177.

Baumgartner A. and Reichel E. (1975). Die Weltwasserbilanz. R. Oldenbourg Verlag München Wien.

Belz S. (2000). Nutzung von Landsat Thematic Mapper Daten zur Ermittlung hydrologischer Parameter. Universität Karlsruhe, Dissertation.

Birkett C. M. (2000). Synergistic Remote Sensing of Lake Chad - Variability of Basin Inundation. In: *Remote Sensing of Environment* 72, pp. 218-236.

Bjerklie D., Moller D., Smith L. and Dingman L. (2005). Estimating discharge in rivers using remotely sensed hydraulic information. In: *Journal of Hydrology*, 309(1-4), pp. 191-209.

Bouwer H. (2002). Artificial recharge of groundwater: hydrogeology and engineering. In: *Hydrogeology Journal* 10(1), pp. 121-142.

Bryant R. and Gilvear D. (1999). Quantifying geomorphic and riparian land cover changes either side of a large flood event using airborne remote sensing: River Tay, Scotland. In: *Geomorphology* 29, pp. 307 - 321.

Fakete B. and Vörösmarty C. (2007). The current status of global river discharge monitoring and potential new technologies complementing traditional discharge measurements. In: *Predictions in Ungauged Basins: PUB Kick-off IAHS Publ.* 309, pp. 129 - 136.

Hunzinger L. M. (1998). Flussaufweitungen – Morphologie, Geschiebehaushalt und Grundsätze zur Bemessung. In: *Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH-Zürich*, 159.

Kruhl J. H., Andries, F., Peternell, M. and Volland S. (2004). Fractal geometry analyses of rock fabric anisotropies and inhomogeneities. In: *Fractals in Geotechnical Engineering. Advances in Geotechnical Engineering and Tunnelling* 9. Kolymbas, D. (ed.), Logos, Berlin, pp. 115 - 135.

Lane S., Westaway R. and Hicks M. (2003). Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. In: *Earth Surface Processes and Landforms* 28, pp. 249 - 271.

Legleiter C. J. and Roberts A. D. (2005). Effects of channel morphology and sensor spatial resolution on image-derived depth estimates. In: *Remote Sensing of Environment* 95, pp. 231 - 247.

Marti C. (2006). Morphologie von verzweigten Gerinnen – Ansätze zur Abfluss-, Geschiebetransport- und Kolktiefenberechnung. In: *Mitteilung der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH-Zürich,* 199.

Meinel G., Schumacher U. and Gössel J. (2003). Analyse der Hochwasserkatastrophe vom Sommer 2002 für die Stadtfläche Dresdens auf Basis von GIS und Fernerkundung. In: *CORP 2003 - Computergestützte Raumplanung*, pp. 109 - 116.

Sharma K. (1998). The hydrological indicators of desertification. In: *Journal of Arid Environments* 39, pp. 121 - 132.

Simonis E. (2001). Wasser als Konfliktursache - Plädoyer für eine internationale Wasserstrategie. Berlin, Wissenschaftszentrum Berlin für Sozialforschung GmbH (WZB).

Smith L. C., Isacks B. L., Forster R., Bloom A. and Preuss I. (1995). Estimation of discharge from braided glacial rivers using ERS 1 synthetic aperture radar: First results. In: *Water Resources Research* 31(5), pp. 1325 - 1329.

Smith L. C., Isacks B. L. and Bloom A. (1996). Estimation of discharge from three braided rivers using synthetic aperture radar satellite imagery: Potential application to ungaged basins. In: *Water Resources Research* 32(7), pp. 2021 - 2034.

United Nations (2001). Demographic Yearbook 2001. Department of Economic and Social Affairs, Population Devision, New York.

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