Satellite Imagery follow-up study

Groundwater and Soil Conservation Project (GSCP) | Ministry of Agriculture and Irrigation | Ministry of Water and Environment | National Water Resources Authority (NWRA) | WorldBank

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Final Report

Satellite Imagery follow-up study
(RFP No. GSCP/SATELLITE IMAGERY/CQS/1/2010)
By

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Executive Summary

The Groundwater and Soil Conservation Project (GSCP) was set up to implement field measures and conserve groundwater in the agricultural sector of Yemen since 2006. The GSCP program will come to a close in 2012. After several years of implementation, the impact of GSCP interventions needs to be assessed. It was decided to use satellite measurements based on the Pixel Intelligence Mapping system for making an objective assessment feasible. The spatial data set and the changes thereof that can be derived from PI Mapping are (i) green vegetation cover, (ii) agricultural land use, (iii) crop evapotranspiration (ET), (iv) incremental evapotranspiration due to irrigation water supply and (v) gross groundwater abstraction. The aim of this study is to determine the changes of these 5 parameters that occurred between 2006 and 2010. A similar study was executed with 2006 satellite data using the same interpretation technologies. The analysis focussed on three different spatial scales: catchments (n=14), regions (n=4) and individual GSCP points (n=487). Especially the difference between GSCP points and their surrounding area in the region are relevant for assessing the impact of the multiple year GSCP program. The data from the regional scale and catchment provide a good insight in the irrigation developments of Yemen.

The regions comprise approximately 360 000 ha each: Siham, Dhamar, Rada and Abyan. Dhamar and Rada are located in the mountains while Siham and Abyan are located in the coastal belts of the Red Sea and Arabian Sea respectively.
In general terms, the green vegetation cover expanded and agricultural land use became more intensive. The area under irrigation expanded by 5 702.ha or 6%. Conserved land practices occurred in 61% of the cases near GSCP intervention schemes. A total of 29% of irrigated land moved to more irrigation intensive agricultural land use systems, i.e. vertical expansion: Water savings were achieved on 10% of irrigated land.

A direct comparison of GSCP point data environments with the same data set of the region surrounding these points, will exclude manifold perturbing factors such as climate and socio-economic development. The conserved land practices at the regional scale remains for 84% constant, and this number is higher than the 61% for the GSCP points. Apparently, farmers living near GSCP points have decided to intensify their practices. There must be some good reasons for that. Likely they receive more irrigation water per unit of land at the farm gate, and the inclusion of localized irrigation practices requires less water to be applied. If pumping is not diminished, farmers can expand horizontally, which is witnessed for the study areas Siham, Rada and Abyan.

Due to (i) less rainfall (14.5%), (ii) more irrigated land (6%) and (iii) more intensive use of the existing land area (7%), the total consumptive use has increased from 864 to 917 mcm/yr for the four regions investigated. This is an increase of consumed water of 6%. The crop water use of irrigated crops per unit of land increased with 2% relatively less (from 843 mm/yr in 2006 to 857 mm/yr in 2010). This slight increase can be explained by a similar level of increase caused by an increase in ETref of the coastal study areas, while ETref decreased in the mountainous study areas. Hence the horizontal expansion of water use is more developed than the vertical expansion.

The gross groundwater abstraction in 2010 was 465 mcm/yr and the vast majority of this water originates from the coastal aquifers (Siham: 105 mcm/yr; Dhamar 204 mcm/yr; Rada: 21 mcm/yr; Abyan: 135 mcm/yr). If one integrates this number with a total

irrigated area of 108 224 ha, it implies that Yemen abstracts on average a layer of 511 mm per ha from underlying aquifers for all types of irrigated land. The gross groundwater abstraction in 2006 in the four regions investigated was similar (324 mcm/yr). The overall groundwater situation thus deteriorated further at a rate of 9% during a period of 4 years. It is recommended in future studies to include more attention to recharge processes.

An analysis of the 14 major catchments over a period of 13 years revealed a rather constant rainfall with no apparent trends. A slight increase in ET was found from surface energy balance models confirmed by an independent observation of an increase in green vegetation cover during the same time frame. Neither rainfall, nor ET can be validated. Future investment in advanced instrumentation to measure rainfall and ET under actual field conditions is recommended.

It is not feasible to measure and administer the abstracted groundwater volumes for all fields in Yemen. Satellite measurements of crop water evapotranspiration can measure every individual field and assess the real consumptive use. The in situ and satellite-based measurements are thus complementary. A comparison of interventions at different scales showed that results in the direct vicinity of GSCP points were not generally better than at the regional scale of the study area. The Field Units of GSCP reported a saving of 56 mcm due to reduced conveyance losses and lower application rates with localized irrigation systems. This saving is related to savings in applied water volumes. This saving of water by GI and PVC pipes creates the unfortunate situation that more water arrives at the farm gate, and that vertical and horizontal expansion occurs.

The net result of efficiency improvements, however, is that a larger portion of the gross groundwater abstracted will be converted into crop evapotranspiration. While this is an excellent achievement for irrigation engineering, it is not favourable from a water resources management point of view. An increase in overall ET from plants and wet soil will aggravate the over-exploitation at catchment scale. The only solution at catchment scale is to impose a limit on overall ET, so that a larger portion of rainfall will be stored in aquifers and be available for stream flow (instead of being vaporized) from irrigated land. It is recommended to review some international endeavours to the formulation of ET caps to irrigated river basins.

Overall it can be concluded that the differences between 2006 and 2010 are more accurate than the absolute values. Not all data components have the same accuracy. Considering that the level of accuracy in change detection is more or less similar to the changes, the results presented in this report are neither soft nor hard. The limitation of this study is that the changes detected can also be related to socio-economic factors that affected classical farming practices. Another limitation is that gross groundwater abstractions are treated uniformly for specific irrigation types, and that the efficiencies are forced to be similar between 2006 and 2010, while all interventions are based upon efficiency improvements.

The deteriorating of the water resource situation in Yemen and unsustainable agriculture practices need to be checked urgently, and an operational monitoring system of the water resources has to be set up and implemented at the national scale. The sparse field data sets and difficulty in accessing data from in situ measurements make satellite-based monitoring of water resources and agricultural development in Yemen a necessity. The Pixel Intelligence Mapping methodology is paramount to making this feasible and doable.

This study commenced in 2011 and was put on a hold due to the Arab Spring. Due to the start of this project in early 2011, the field work could not coincide with the satellite image acquisitions of 2010, leading to a certain degree of inaccuracy in the overall analysis. The incremental ET is computed with more evidence than groundwater abstraction due to the uncertainty being associated with (i) source of water and (ii) prefixed irrigation efficiencies.

It is of paramount importance to differentiate the water path ways into total crop evapotranspiration, gross groundwater abstraction, conveyance of irrigation water to the farm gate, the on-farm efficiency and incremental evapotranspiration, and define the strategies on water savings in relation to these flows.

1. Introduction

This Satellite Imagery follow-up study is executed under contract number GSCP/SATELLITE IMAGERY/CQS/1/2010. The main contractor of the project is WaterWatch, a scientific advisory bureau based in Wageningen, the Netherlands. WaterWatch specialises in remote sensing surveys for agricultural water management. The eLEAF Competence Centre is executing the WaterWatch activities since 2012. The sub-contractor to this project is Hydro-Yemen, an advisory firm specialised in GIS, hydrological analysis and water management, based in Sana'a, Yemen. This study is a follow up of the 2006 project *Satellite Imagery for Cropping Pattern and Irrigated Area Monitoring*. The final report of the 2006 study became available in 2009 (WaterWatch, 2009).

The contract for the current project was granted to WaterWatch and Hydro-Yemen in December 2010, which unfortunately was only at the end of the year (2010) designated by the Groundwater and Soil Conservation Project (GSCP) administration for the evaluation of the GSCP project achievements. It was thus not possible to synchronize image acquisitions with field work and field inspections for 2010. The field work was done by Hydro-Yemen during 10 February to 12 March 2011. Due to the security situation in the South, Abyan could be not be visited. The political instability and security issues interrupted the project execution during 2011. The project was resumed in February 2012.

The GSCP is designed to address the critical groundwater problems of Yemen. Overexploitation of groundwater for rapidly growing irrigation demands, combined with dwindling rates of recharge make groundwater resources unsustainable. A budget of 55 million US$ has been made available to establish GSCP interventions and solutions in the field.

Awareness campaigns were raised to promote the reduction of irrigation areas and for saving water. Extension agents promoted the use of crops which are less water demanding as a means to compensate for the reduction of areas under irrigation. The GSCP has its own Field Units throughout the country to aid with the implementation of these interventions. The reported water savings by GSCP are based on the observations of their own Field Units of GSCP.

GSCP is a country wide program with the project coordination unit based in Sana'a. The scope of the project includes the fifteen governorates of Sana'a, Amran, Mahweet, Saada, Dhamar, Al-Baidaa, Hodeidah, Taiz, Ibb, Lahj, Abyan, Shabwa, Hajja, Dali and Hadramaut. The objectives of the GSCP are to conserve water (especially groundwater) in farming areas; to improve recharge; and to protect catchments by: (i) improving water use efficiency and increasing farmer returns on groundwater use in order to bring aquifers to sustainable levels; (ii) increasing surface and groundwater availability through catchment management and groundwater recharge by supporting the rehabilitation of small to medium spate irrigation schemes, bank protection works, water harvesting structures, and the rehabilitation of terraces and other soil and water conservation investments; and (iii) supporting a groundwater management framework and institutions that will have the incentive and capacity to manage local water resources in a sustainable manner.

The locations of the irrigated areas of Yemen are displayed in Figure 1. Irrigation takes place on hills up to an altitude of 1 800 m AMSL. Above this range, the green vegetation exists of pastures and bush land. The total irrigated area is estimated to vary between 400 000 and 500 000 ha.

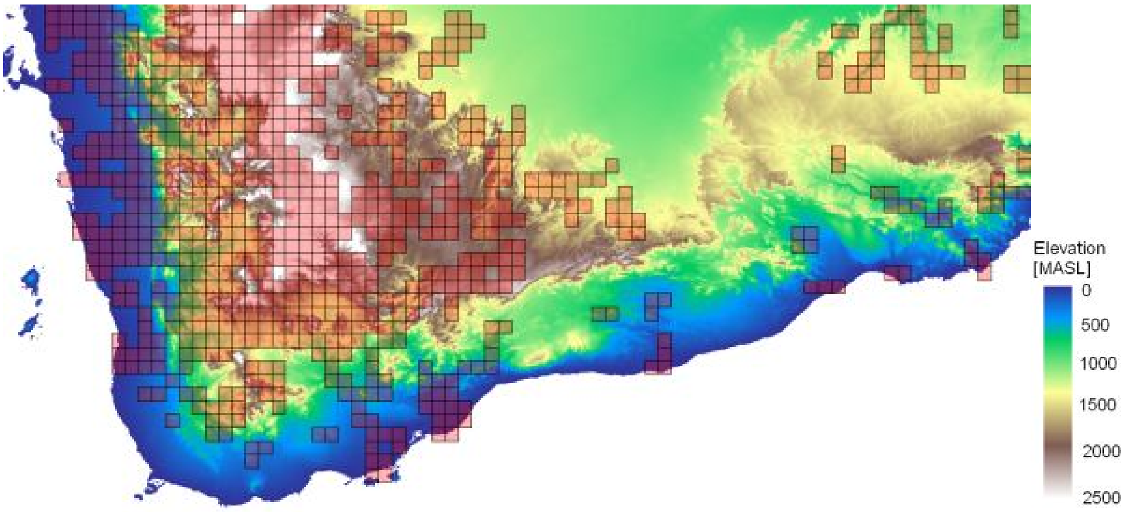


Figure 1: Location of the irrigated areas in Yemen (source: FAO & University of Kassel) being superimposed on the elevation map. The irrigation intensity varies for every cell.

The GSCP also encourages the supply and installation of buried PVC and above ground PE pipes and galvanized (GI) pipes to replace low efficiency unlined earth channels and so reduce losses of irrigation water conveyed from irrigation wells to farms. The GSCP is also involved with installation of localized on-farm irrigation systems such as drip, bubbler and micro-sprinklers to reduce within farm water losses and increase the uniformity in water applications; thus improving distribution and irrigation efficiencies.

Target areas to be covered by these systems over 5 years have been identified by GSCP. The installation of piped systems in 48 200 ha and localized irrigation systems in 2 266 ha is projected to save 81 MCM of water per annum.
It was estimated through field surveys that approximately 56 MCM water has been saved by the installation of 34 035 ha under piped conveyance system. An area of 1 365 ha became under localized irrigation systems up to April 2010. More background information can be found in http://www.gscp.gov.ye/iaseng.php?op=listarticles&topaid=7 and at http://www.gscp.gov.ye/index1.php.
Earth observation techniques can help to see if irrigation beneficiaries comply with legal requirements such as (i) reduction in irrigated cropped areas after subsidised improvements of irrigation schemes, (ii) restrictions on qat production on farms provided with these improved technologies under the project and (iii) reductions of crop water use. The original study established a baseline for 2006 in four regions or study areas. Those regions were selected after discussions with members of the GSCP: the National Water Resources Authority and the Central Water Management Unit of the Ministry of Agriculture and Irrigation:

- Siham
- Dhamar
- Rada
- Abyan

The exact position of the 4 regions to be covered by satellite images was determined by the spatial coverage of the Spot images used in the 2006 study. For the sake of compatibility and ability to draw conclusions on changes, the 2010 study boundaries were kept identical (see Figure 2). All study areas are located in the western part of Yemen. Siham is located at the Red Sea coast in the Tihama plain. Dhamar and Rada are located in the mountains of the Wadi Adhana catchment. Abyan is located at the coast of the Gulf of Aden.

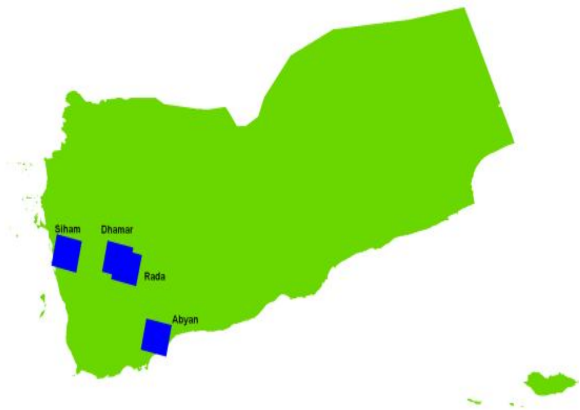


Figure 2: Areas being investigated as part of this remote sensing study. The areas are based on the coverage of the SPOT images in 2006.

This follow-up study aims to identify changes in green vegetation cover, agricultural land use and crop water use (ET, incremental ET and gross groundwater abstraction) between 2006 and 2010. It basically aims at verifying the 56 MCM of claimed water savings, and at detecting other possible changes being relevant for conserved irrigation practices. During the 2006 study, it appeared that the variable cropping calendar of Yemen requires almost weekly images for an appropriate coverage of all crops and their phenology stages. It was at that time agreed by the GSCP administration in 2006 to identify agricultural land use classes, rather than individual crop types. The same definition will be applied in the current study.

This final report presents the findings of the year 2010 as well as the changes between 2006 and 2010.

2. Materials

2.1 Satellite-based analysis

Because of the difficulty to access field data in Yemen, the main data source used in the current study is satellite imagery. It should be noted that satellite measurements are increasingly used as an alternative source of in situ data in various water resources studies worldwide. The number of satellites and the Data Active Archive Centers (DAACs) from where fresh image data can be downloaded is rapidly growing and is nowadays highly professional. As a consequence, the number of diagnostic studies using satellite measurements for land and water management analysis is growing.

This chapter provides an overview of the different types of satellite images used. The acquisition dates are proven as well. Figure 3 shows the data stream between the various types of satellites. A distinction needs to be made between high resolution images for field scale analysis (Aster, Landsat, Alos) and low resolution images (Modis, AMSR-E, MSG, TRMM) for catchment scale analysis and for time integration between consecutive high resolution images.

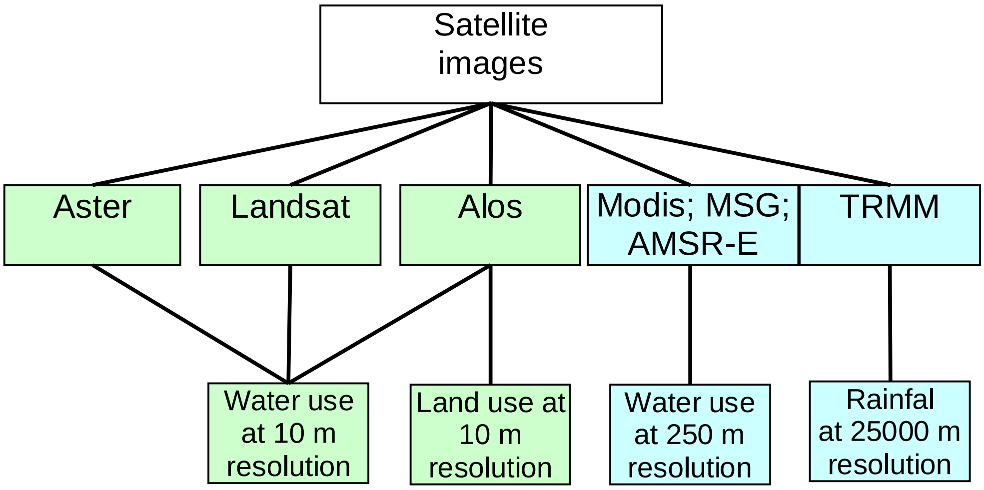


Figure 3: Different types of satellite images used in this study. Green boxes indicate high resolution and blue boxes indicate that the resolution is coarser.

As explained earlier, only archived images could be explored in a retrospective analysis mode. Hence, it was not possible to program acquisition of new images during particular periods of interest. This imposes a technical limitation in the selection procedure of the type of satellite images that could be processed. The images used in this study are thus a result of the availability in the database, and has not been the preferred choice and moment of acquisition of the consultant. The images from Alos, Aster, Landsat, Modis, AMSR-E, MSG and TRMM are elaborated on in the next sections.

2.2 Alos images

The Alos satellite provides images with an attractive spatial resolution of 10 m. Fortunately Alos images happened to be present in the archive for Yemen and could be retrieved from the Japanese Aerospace Exploration Agency (JAXA). The Alos satellite was launched by JAXA in 2006 and functioned until 2011; it is no longer available. The spectral data from the AVNIR-2 sensor (Advanced Visible and Near Infrared Radiometer type 2) has been used. The characteristics of Alos-AVNIR are summarised in Table 1.

Table 1: Characteristics of the Alos satellite.

Sensor	Electromagnetic Spectrum	Pixel size	Spectral bands
AVNIR-2	B1: blue	10 m	0.42 – 0.50 μm
	B2: green	10 m	0.52 – 0.60 μm
	B3: red	10 m	0.61 – 0.69 μm
	B4: near infrared	10 m	0.76 – 0.89 μm

The high spatial and spectral resolution of Alos images makes them very suitable for agricultural land use classifications as well as for downscaling of the energy balance calculations that will be elaborated on in Chapter 3. The Alos images selected are listed in Table 2.

Table 2: Acquisition dates of the Alos satellite during the 2010 period.

Area	Date	Path/row	Conditions	Comments
Abyan	2010 / March / 25	234/3330	Clear	Northern part
Abyan	2010 / March / 25	234/3340	Clear	Southern part
Abyan	2010 / June / 25	234/3340	Clear	Shifted
Dhamar	2009 / October / 26	236/3300	Clear	Northern part
Dhamar	2009 / October / 26	236/3310	Clear	Southern part
Dhamar	2010 / June / 13	236/3300	Clouded	Northern part
Dhamar	2010 / June / 13	236/3310	Clouded	Southern part
Dhamar	2010 / December / 14	236/3310	Clear	Shifted
Rada	2010 / April / 11	235/3310	Clear	
Rada	2010 / May / 27	235/3310	Clear	
Rada	2010 / July / 12	235/3310	Clear	
Siham	2010 / January / 06	238/3300	Clear	North-East
Siham	2010 / January / 06	238/3310	Clear	South-East
Siham	2010 / January / 14	238/3310	Clear	South-East
Siham	2010 / January / 31	239/3300	Clear	West
Siham	2010 / February / 12	238/3310	Clear	South-East
Siham	2010 / March / 18	239/3300	Clear	West
Siham	2010 / April / 16	238/3300	Few clouds	North-East
Siham	2010 / April / 16	238/3310	Few clouds	South-East
Siham	2010 / June / 18	239/3300	Few clouds	West
Siham	2010 / October / 17	238/3310	Few clouds	South-East
Siham	2010 / November / 03	239/3300	Clear	West
Siham	2010 / December / 19	239/3300	Clear	West

From this table it can be seen that for instance the Siham area is encompassed by three different Alos frames (238/3300 North-East; 238/3310 South-East and 239/3300 West).

One frame represents only a part of the study area, as is demonstrated in the quick look overviews in Figure 17 of Chapter 4.

2.3 Aster images

Another satellite sensor that provides images with a good spatial resolution is the Advanced Space borne Thermal Emission and Reflection radiometer (ASTER). ASTER originates also from Japan, and is mounted aboard the NASA satellite Terra. Its resolution is 15 meters for the visible radiation range, and the shortwave infrared radiation range holds a pixel size of 30 m. The 90 m pixels of the thermal infrared part of the electromagnetic spectrum have not been explored during this study. The characteristics of the Aster sensor are listed in Table 3.

Table 3: Characteristics of the Aster satellite.

Electromagnetic Spectrum	Pixel size	Spectral bands
B1: green/yellow	15 m	0.52 – 0.60 µm
B2: red	15 m	0.63 – 0.69 µm
B3: near infrared nadir	15 m	0.76 – 0.86 µm
B4: near infrared backward	15 m	0.76 – 0.86 µm
B5: short-wave infrared	30 m	1.60 – 1.70 µm
B6: short-wave infrared	30 m	2.145 – 2.185 µm
B7: short-wave infrared	30 m	2.185 – 2.225 µm
B8: short-wave infrared	30 m	2.235 – 2.285 µm
B9: short-wave infrared	30 m	2.295 – 2.365 µm
B10: short-wave infrared	30 m	2.360 – 2.430 µm
B11: thermal infrared	90 m	8.125 – 8.475 µm
B12: thermal infrared	90 m	8.475 – 8.825 µm
B13: thermal infrared	90 m	8.925 – 9.275 µm
B14: thermal infrared	90 m	10.25 – 10.95 µm
B15: thermal infrared	90 m	10.95 – 11.65 µm

Only four images from the 2010 Aster archive covered the study areas in Yemen (see Table 4). Aster images are used as an addendum to the Alos images.

Table 4: Acquisition dates of the Aster satellite during the 2010 period.

Area	Date	Conditions	Comments
Dhamar and Rada	2010 / June / 26	Clear	
Rada	2009 / October / 22	Clear	
Siham	2010 / February / 18	Few Clouds	North
Siham	2010 / December / 03	Clear	South

2.4 Landsat images

Another satellite programme from which images were used in this project is the Landsat Program. Landsat 5 was launched in 1984 and,it carries the Thematic Mapper that takes multi-spectral images. In 1999 Landsat 7 was launched. It is the latest satellite of the Landsat Program to date: The sensor aboard Landsat 7 is the Enhanced Thematic Mapper (ETM), with a panchromatic band added to the original Thematic Mapper and an improved resolution on the thermal band. Since May 31, 2003 the Landsat 7 ETM sensor does not function properly. The scan line corrector failed and has not been repaired since. The result of this failure is that some areas are imaged twice and some not at all. The effect is visible in the images as a set of missing lines increasing in width from the middle of the image to the border of the images. To solve this problem the images are gap-filled with data from other satellites for the same time and with older data from the Landsat satellites. Table 5 provides an overview of the main characteristics of the Landsat sensors. Bands 2, 3 and 4 have large similarities to Alos bands 1, 2, and 3 and to Aster bands 1, 2 and 3.

Table 5: Some characteristics of the Landsat 5 and 7 satellites.

Sensor	Electromagnetic Spectrum	Pixel size	Spectral bands
Landsat 5: TM	B1: blue	30 m	0.45 – 0.52 µm
	B2: green	30 m	0.52 – 0.60 µm
	B3: red	30 m	0.63 – 0.69 µm
	B4: near infrared	30 m	0.76 – 0.90 µm
	B5: shortwave infrared	30 m	1.55 – 1.75 µm
	B6: thermal infrared	120 m	10.4 – 12.5 µm
	B7: shortwave infrared	30 m	2.08 – 2.35 µm
Landsat 7: ETM	Panchromatic	15 m	0.50 – 0.90 µm
	B1: blue	30 m	0.45 – 0.52 µm
	B2: green	30 m	0.52 – 0.60 µm
	B3: red	30 m	0.63 – 0.69 µm
	B4: near infrared	30 m	0.75 – 0.90 µm
	B5: shortwave infrared	30 m	1.55 – 1.75 µm
	B6: thermal infrared	60 m	10.4 – 12.5 µm
	B7: shortwave infrared	30 m	2.08 – 2.35 µm

Table 6 provides an overview of the Landsat data used in this study. Despite that the resolution of 30 m data is not as sharp as for Alos and Aster, the large amount of Landsat images has been of great help to describe the dynamic changes of local scale agricultural and irrigation processes.

Table 6: Dates on which Landsat 5 and 7 acquisitions have taken place.

Area	Date	Path/row	Conditions	Comments
Abyan	2009 / October / 22	165/51	Clouded	Landsat 7
Abyan	2009 / December / 17	165/51	Clouded	Landsat 5
Abyan	2010 / January / 18	165/51	Clouded	Landsat 5
Abyan	2010 / March / 15	165/51	Clear	Landsat 7
Abyan	2010 / October / 09	165/51	Clear	Landsat 7
Abyan	2010 / October / 25	165/51	Clouded	Landsat 7
Dhamar	2009 / November / 22	166/50	Clear	Landsat 5
Dhamar	2009 / December / 08	166/50	Clear	Landsat 5
Dhamar	2010 / February / 10	166/50	Clear	Landsat 5
Dhamar	2010 / April / 07	166/50	Clear	Landsat 7
Dhamar	2010 / April / 23	166/50	Clear	Landsat 7
Dhamar	2010 / September / 14	166/50	Few clouds	Landsat 7
Dhamar	2010 / September / 30	166/50	Clear	Landsat 7
Dhamar	2010 / October / 16	166/50	Clear	Landsat 7
Rada	2010 / January / 18	165/50	Clear	Landsat 5
Rada	2010 / January / 26	165/50	Clear	Landsat 7
Rada	2010 / March / 15	165/50	Clear	Landsat 7
Rada	2010 / September / 23	165/50	Clear	Landsat 7
Rada	2010 / October / 09	165/50	Clear	Landsat 7
Rada	2010 / October / 25	165/50	Clear	Landsat 7
Siham	2009 / November / 22	166/50	Few clouds	Landsat 5
Siham	2009 / December / 08	166/50	Few clouds	Landsat 5
Siham	2010 / February / 10	166/50	Clouded	Landsat 5
Siham	2010 / April / 07	166/50	Clear	Landsat 7
Siham	2010 / April / 23	166/50	Few clouds	Landsat 7
Siham	2010 / September / 14	166/50	Clouded	Landsat 7
Siham	2010 / September / 30	166/50	Clouded	Landsat 7
Siham	2010 / October / 16	166/50	Clear	Landsat 7

2.5 Modis images

The MODerate-resolution Imaging Spectroradiometer (Modis) is located aboard the Terra and Aqua satellites in 1999 and 2002 respectively. Both satellites were launched by NASA. They cover the entire world in one day. It is therefore possible to have two Modis images for every day covering the entire Yemen. The difference between Terra and Aqua is the overpass time. Terra has an overpass time slot during the mid-morning, whereas Aqua has an overpass time in the early afternoon.

The Modis sensor provides the possibility to measure the Normalized Difference Vegetation Index (NDVI) at a resolution of 250 meters. The Modis sensor also has five bands in the visible and near infrared region of the electromagnetic spectrum. These bands have a resolution of 500 meters. The Modis sensor further has a large number of bands in the thermal infrared spectrum. Two of those, at 11 and 12 micrometers, can be used to calculate the surface temperature. These data have a resolution of 1000 meters. The characteristics of the Modis sensor are summarised in Table 7.

Table 7: Spectral characteristics of the Modis satellite.

Electromagnetic Spectrum	Pixel size	Spectral bands
B1: red	250 m	0.62 – 0.67 µm
B2: near infrared	250 m	0.84 – 0.87 µm
B3: blue	500 m	0.46 – 0.48 µm
B4: green	500 m	0.54 – 0.56 µm
B5: shortwave infrared	500 m	1.23 – 1.25 µm
B6: shortwave infrared	500 m	1.62 – 1.65 µm
B7: shortwave infrared	500 m	2.10 – 2.15 µm
B31: thermal infrared	1000 m	10.78 – 11.28 µm
B32: thermal infrared	1000 m	11.77 – 12.27 µm

The Modis data is employed to calculate (i) the vegetation index (NDVI) and (ii) the surface energy balance for the entire Yemen. A list of the Modis data used in the calculations is given in Table 8. For calculations at the regional scale, composite images are used instead of single images. These composite images are created by NASA from satellite images over a period of 16 days. The images are combined to minimise cloud cover in the resulting composite. By this reduction of cloud obstacles, Modis data products are available for every period of the year and with regular time intervals that ensure a sufficiently good coverage across the year.

Table 8: Time intervals of the composite Modis dataset.

Period	Starting date	End date
1	2009 / December / 27	2010 / January / 08
2	2010 / January / 09	2010 / January / 24
3	2010 / January / 25	2010 / February / 09
4	2010 / February / 10	2010 / February / 25
5	2010 / February / 26	2010 / March / 13
6	2010 / March / 14	2010 / March / 29
7	2010 / March / 30	2010 / April / 14
8	2010 / April / 15	2010 / April / 30
9	2010 / May / 01	2010 / May / 16
10	2010 / May / 17	2010 / June / 01
11	2010 / June / 02	2010 / June / 17
12	2010 / June / 18	2010 / July / 03
13	2010 / July / 04	2010 / July / 19
14	2010 / July / 20	2010 / August / 04
15	2010 / August / 05	2010 / August / 20
16	2010 / August / 21	2010 / September / 05
17	2010 / September / 06	2010 / September / 21
18	2010 / September / 22	2010 / October / 07
19	2010 / October / 08	2010 / October / 23
20	2010 / October / 24	2010 / November / 08
21	2010 / November / 09	2010 / November / 24
22	2010 / November / 25	2010 / December / 10
23	2010 / December / 11	2010 / December / 26
24	2010 / December / 27	2011 / January / 08

2.6 Other satellite images

The before mentioned satellite images form the core data set for this study, and are for this reason reported upon separately. In addition to that, information has been gathered from other satellites and sensors. For instance, the Advanced Microwave Scanning Radiometer for Earth observation (AMSR-E) sensor aboard of the Aqua satellite, measures radiation in the microwave region of the electromagnetic spectrum. The specific characteristic of AMSR-E makes it feasible to determine soil moisture conditions with daily time steps. The wavelength in the microwave region is sufficiently long not to be affected by atmospheric water particles. The implication is that AMSR-E can do measurements under all weather conditions. This is a powerful advantage for the cloudy highlands of Yemen. It is customary to express wavelength in the microwave region by means of frequencies. Frequency and wavelength are inversely proportional. The C band thus has the lowest frequency and the largest wavelength (Table 9) in the order of a few centimeters.

Table 9: AMSR-E characteristics.

Letter designation	Pixel size	Spectral band	Frequency
W band	6 x 4 km	0.0034 m	89.0 GHz
Q band	14 x 8 km	0.0082 m	36.5 GHz
K band	32 x 18 km	0.013 m	23.8 GHz
K band	27 x 16 km	0.016 m	18.7 GHz
X band	51 x 29 km	0.028 m	10.65 GHz
C band	75 x 43 km	0.043 m	6.925 GHz

Another source of spatial information is the Meteosat Second Generation (MSG) satellite. MSG is a geostationary satellite that measures cloud cover with time steps of 30 minutes. Cloud cover information has been used to quantify the transmissivity of the atmosphere for shortwave solar radiation. Due to atmospheric interferences (reflection, absorption, scattering), not all solar radiation at the top of the atmosphere is transmitted through the atmosphere towards the land surface; only a certain fraction of solar radiation will reach the evaporating surface of the land, and will subsequently be used for crop consumptive water use calculations. Under clear sky conditions, typically 75% of all solar radiation reaches the land surface, and this number will reduce to 25% when heavy clouds prevail. The characteristics of the SEVIRI sensor on MSG are provided in Table 10.

Table 10: Characteristics of the SEVIRI sensor on MSG.

Electromagnetic Spectrum	Pixel size	Spectral bands
Visible band – red	3 km	0.56 - 0.71 μm
Visible band - near infrared	3 km	0.75 - 0.88 μm
Near infrared – shortwave	3 km	1.50 - 1.78 μm
Infrared	3 km	3.48 - 4.36 μm
Water vapour	3 km	5.35 - 7.15 μm
Water vapour	3 km	6.85 - 7.85 μm
Infrared - thermal	3 km	8.30 - 9.10 μm
Ozone	3 km	9.38 - 9.94 μm
Infrared - thermal	3 km	9.80 - 11.80 μm
Infrared - thermal	3 km	11.00 - 13.00 μm
Carbon dioxide	3 km	12.40 - 14.40 μm
Broadband high resolution visible	1 km	11.77 – 12.27 μm

Rainfall has a distinct spatial variability across Yemen. The density of traditional rain gauges is small, and the data is not available online. Rainfall can also be measured by the Tropical Rainfall Monitoring Mission (TRMM) that hosts the data online a few hours after satellite overpass. The TRMM satellite has the first spaceborne C-band radar system that in combination with a microwave imager measures the distribution of atmospheric water droplets. Rainfall rates are determined from the microwave propagation and backscatter coefficients. Some characteristics of the TMI sensor aboard the TRMM satellite are given in Table 11. TMI measures passive microwave radiation. Similar to AMSR-E, the wavelength is usually expressed as a frequency. While TRMM has several data products that can be downloaded, the 3B43 product is a monthly rainfall product that is pre-calibrated by NASA (http://trmm.gsfc.nasa.gov/). It is however generally known, that a post-calibration procedure is needed (e.g. Cheema and Bastiaanssen, 2011). The TRMM 3B43 product is consistent with the 2006 rainfall data set, so that differences in rainfall can be described.

Table 11: Characteristics of the TMI sensor aboard the TRMM satellite.

Letter designation	Pixel size	Spectral band	Frequency
W band	5 x 7 km	0.0035 m	85.5 GHz
Q band	16 x 9 km	0.0081 m	37.0 GHz
K band	23 x 18 km	0.014 m	21.3 GHz
K band	30 x 18 km	0.015 m	19.35 GHz
X band	63 x 37 km	0.028 m	10.65 GHz

3. Methodology

The spatial data sets from various satellites were combined with meteorological measurements at routine weather stations for the computation of agricultural water use at the GSCP points, the regional scale and for catchments. To identify the agricultural land use and the water consumption of the four study areas in Yemen, the raw images needed to be processed by image interpretation and data integration techniques. The in-house technology of eLEAF is referred to as the Pixel Intelligence Mapping. The basic features of these methodologies are explained in this chapter.

3.1 Agricultural Land Use Classification

Agricultural land use can in general terms be identified based upon the differences of the spectral signatures of vegetation and bare soil. Every pixel uniquely reflects and absorbs spectral solar radiation by the different bands described for every sensor in chapter 2. The near-infrared part of the spectrum contributes most significantly to variability in crop types, crop ages, vegetation cover and crop management aspects, simply because absorption is low and the reflected signal is strong. The signal is 3 to 5 times stronger than in the visible part of the spectrum. The satellites selected therefore all possess a near-infrared spectral channel (i.e. Alos band 3, Aster band 3, Landsat band 4).

The satellite images used for the agricultural land use classification are described in Chapter 2. The exact overpass day and spatial coverage for each of the four study areas is also described in the subsequent Chapters 4, 5, 6 and 7.

The procedure for identification of crops was similar to the 2006 study. A full multi-spectral crop identification procedure is cumbersome for Yemen with its manifold different cropping calendars. Corn of 4 months and corn with an age of 4 weeks old can be grown side-by-side. Their spectral signature will be entirely different, yet in both cases the classifier should recognize the pixel to be a corn field. To avoid this confusion induced by various crop phenological phases that occur simultaneously, the classification is based on green vegetation cover features that distinguish agricultural land use classes, rather than individual crop types.

Humans can only see the visible part of the electromagnetic spectrum, typically between 0.4 and 0.75 micrometer (μm). It can be seen from the profiles below that vegetation reflects little radiation in the visible part of the spectrum, making it appear relatively dark compared to for example (dry) bare soil. The reflectance in the green part of the electromagnetic spectrum exceeds the reflectance of blue and red, and this is the reason that leaves are green.

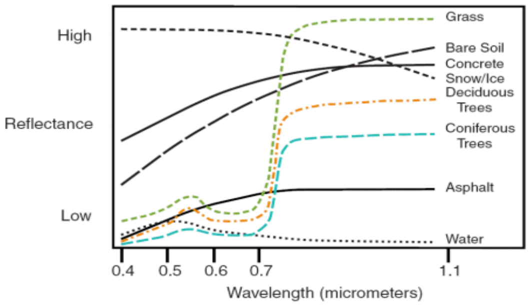


Figure 4: The spectral reflectance for some typical land use classes (source: NASA).

Vegetation has a low reflection in the red part (± 0.65 µm), but high in the near-infrared part of the spectrum (± 0.86 µm). It is beneficial for plants to absorb all radiation that can be used for biomass production in the visible part of the spectrum. The near-infrared (NIR) component does not contribute to photosynthesis, and has therefore a significantly higher reflectance value. These higher values are important to measure by satellite-borne sensors; they provide strong signals that can be interpreted into meaningful biophysical parameters. The difference between the near-infrared and red reflectance can be used to detect green leaves. Even without any field knowledge, such type of reflectance data can be used to identify the presence of crops, and the duration of their life cycle. This difference in the red and infrared reflectances is often expressed as the Normalized Difference Vegetation Index (NDVI):

NDVI = (NIR – Red) / (NIR + Red)

Figure 5 is a schematic example of the NDVI for lush and for dry vegetation. While the equation of the NDVI has a theoretical range of -1.0 to +1.0, values for vegetation range between 0.12 and a maximum value of 0.85. Maps of NDVI are used for detecting the agricultural land use classes mentioned above.

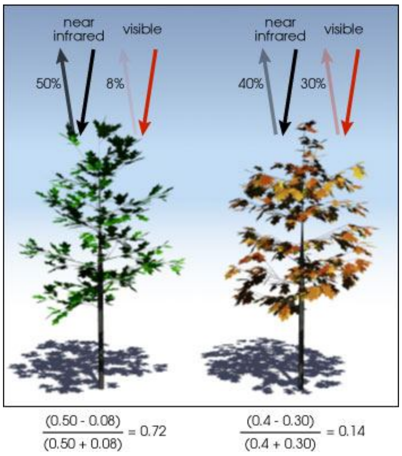


Figure 5: Schematic example of the NDVI for lush and dry vegetation (Source: NASA).

The presence of green leaves was determined for every pixel of an Alos image, using the principles of the NDVI. Depending on the time of the year and the duration of green vegetation, pixels were classified as being a single season crop (green leaves for a restricted period only; fallow during the remainder of the year), a double season crop (two green cycles separated by a fallow period), perennial crop (green leaves throughout the year) and non-cropped (never a green leaf). The further breakdown of perennial crops into qat and banana has been established by region. All perennial crops in Rada are identified as qat. The perennial crops in Abyan are assumed to be banana, if these pixels were also labelled as banana in 2006.

In addition, every pixel designated as single season crop had to be described as either being rainfed or irrigated land. Pixels with an ET rate exceeding the net rainfall across the season must have been irrigated. Net rainfall is approximately 80% of the gross rainfall at field scale, due to losses that do not infiltrate into the soil profile. It may not have received a full irrigation water supply, and may have had supplementary irrigation. However, every irrigation activity – intensive or extensive – was labelled as irrigation. Pixels with the net rainfall exceeding ET are defined as rainfed.

The final land use classification was a combination of crop types and rainfed/irrigation systems. The double season and perennial crops (i.e. banana and qat) are assumed to be irrigated, while non-cropped land is not irrigated. This decision tree leads to six agricultural land use classes to be distinguished:

- Single-season, rainfed
- Single-season, irrigated
- Double-season, irrigated
- Perennial, irrigated
- Banana, irrigated
- Qat, irrigated

This level of classification can be established accurately, and provides a better basis for comparing changes between 2006 and 2010 than considering individual crop types. Fieldwork is in any case required to validate the satellite based land use classification. Although (as will be seen later) exceptions to this rule also exist. The fieldwork was carried out by Hydro-Yemen in the study areas Siham, Dhamar and Rada. The Abyan area was insecure and could not be inspected without taking unacceptable risks. Equipped with a GPS-transponder, fields were visited across the study areas to describe crop and irrigation type. Figure 6 provides an overview of locations where field information was collected.

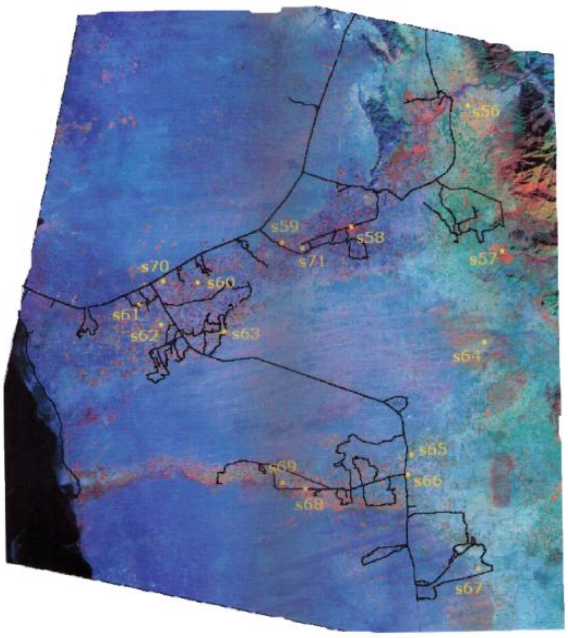


Figure 6: Overview of fieldwork locations in the Siham study area. The field site locations are indicated in yellow. The black line shows the GPS-track.

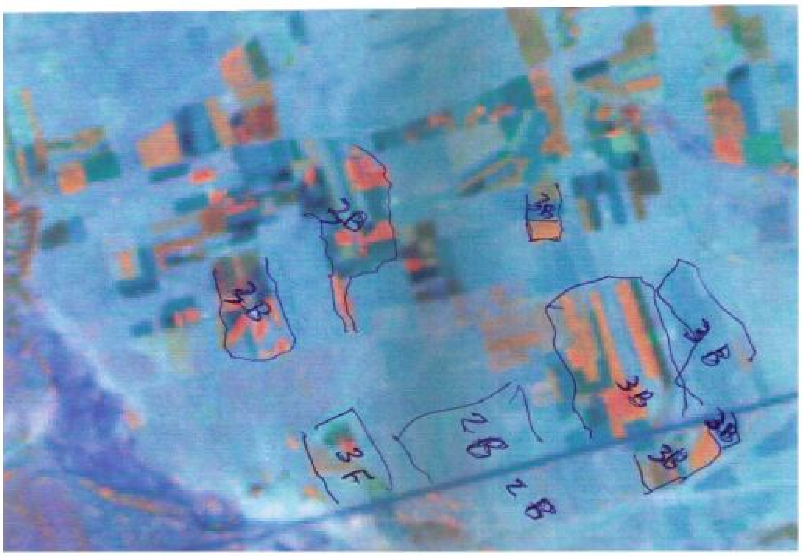


Figure 7: Detailed example of field notes from location s67, located in the Southern part of Siham. 2 = Single-season irrigated crop; B = Border irrigated; 3 = Double-season irrigated crop; F = Furrow irrigated.

Figure 7 shows an example of the digitization of the fieldwork. This site is located in the Siham study area, and is irrigated by a classical border system. The main crop type is single-season irrigated crop (see Figure 8). The near infrared-red reflectance is shown in red. Red pixels thus have a strong signal in the near-infrared and indicate vigorous crops. The marked field most left in Figure 8 is a good example of that. Other fields have a higher red value in April, for example the 3rd marked field from the right. Other fields always show a low red value or – on the contrary - possess a high red value throughout all periods. The purple (perennial) and red (double-season) fields in the upper right panel are lush green in all of the three images shown here, so to distinguish between those, more images were used. From this figure it can be seen that no specific common growing season and crop phenological phase existed.

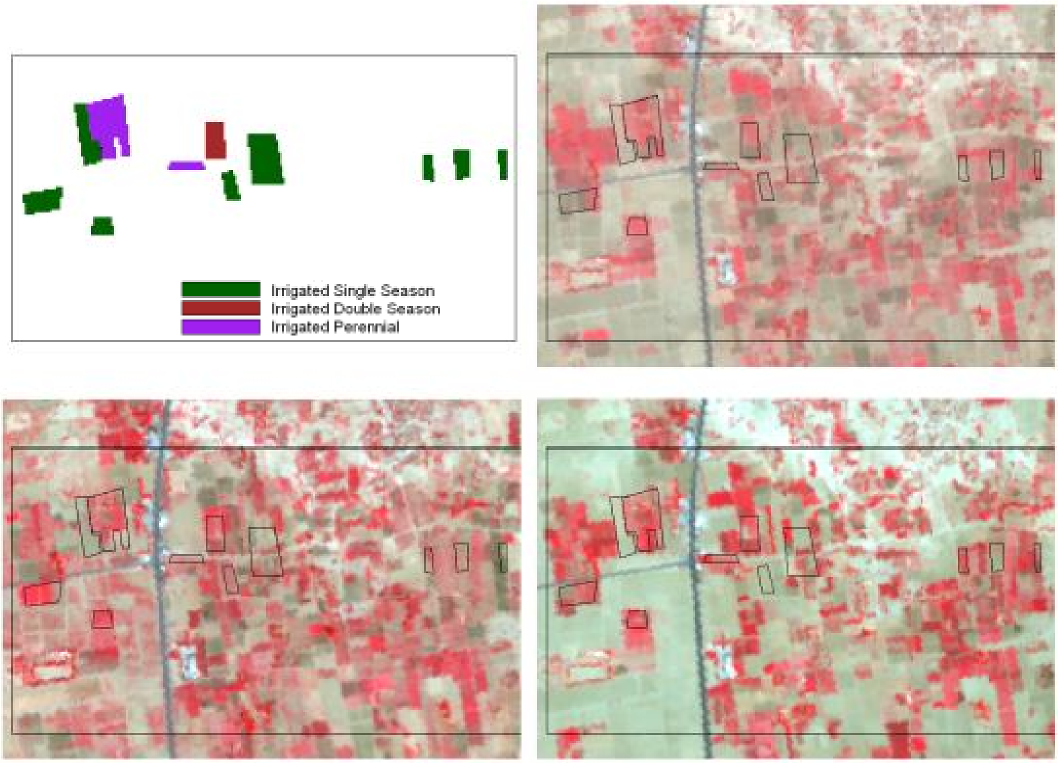


Figure 8: Digitization of the field work, site s66 in the Siham study area. Upper left corner: crop class. The other panels are Alos satellite images with the shape of the fields overlain. A higher intensity of red is associated with a higher NDVI value. The acquisition dates of the Alos images are: Upper right corner: 14 January 2010; Lower left corner: 12 February 2010 and Lower right corner: 16 April 2010.

3.2 Water consumption

Rainfall and irrigation are the two major sources of water available to crops. Part of this total water supply is consumed, and the other part is non-consumed (Perry, 2007). Consumed water is withdrawn from the local water cycle, and is no longer available for allocation to for instance (i) irrigated crops, (ii) wetlands, (iii) industries and (iv) domestic sectors downstream. Evapotranspiration (ET) is the term for the physical process of water consumed from vegetated surfaces. By controlling consumed water or ET, more water will remain in the land hydrological system. Water saving programs should thus be focussing on ET reduction, and not only on the reduction of abstractions.

The non-consumed water remains physically present in the soil-land continuum. Non-consumed water is dissipated into deep percolation, drainage, and surface runoff. The majority of non-consumed water is recaptured in aquifers, streams, rivers, lakes and reservoirs.

In this study ET was mapped by using a surface energy balance model that calculates the dissipation of solar radiation energy into the various land surface bio-physical processes. Radiation is absorbed, reflected and emitted at the land surface. The net amount of radiation is a source of energy for warming up soil, warming up air and the evaporation of water from plants, soil and water bodies. Evaporation takes up energy and 28 W/m^2 will evaporate 1 mm/d. Hence, by computing the radiation and energy used by the evaporation process, water consumed by crops can be derived. The surface energy balance is thus a good vehicle to compute water consumption without the involvement of complex hydrological models, soil information systems and advanced field measurements.

The potential evapotranspiration (ET_{pot}) is the amount of water that could evaporate from the soil and be transpired from the plant if the area is well-watered under the actual meteorological conditions and prevailing vegetation and crop development properties. A crop cannot consume more water than ET_{pot}; there is a physical limit for this process that is related to the flow path of water through the roots, stem and stomatal cavities of the crop as well as the state conditions of the atmosphere to remove water vapour away from the land surface. Well-watered and healthy plants that are properly fertilised can grow optimally and they have the maximum crop water consumption. When, however, there is not enough water available in the soil for uptake by plant roots, they gradually reduce transpiration to save water by partial closure of the stomata. When stomata close, both exhalation of H_2O and inhalation of CO_2 will reduce, and this will result in a lower actual evapotranspiration (ET_{act}). Due to this influence of soil moisture, computation of ET_{act} is more complex than ET_{pot}. The surface temperature and soil moisture measurement from satellites make it feasible to compute ET_{act} under real environmental conditions and that is the greater advance of this study.

The Alos, Aster, Landsat, Modis and AMSR-E images were used to measure the actual environmental conditions for every pixel. The measurements in the visible, near-infrared, thermal infrared and microwave part of the electromagnetic spectrum were converted to surface albedo, leaf area index, vegetation index, surface temperature, soil moisture and cloud cover. These bio-physical data together with weather data were used to compute ET_{act} and ET_{pot}.

The estimation of ET for the entire study area – and for Yemen (see Chapter 9) – cannot be accomplished by using the climatic conditions observed at a few weather stations. The spatial variability of the weather data needs to be known prior to running energy balance models. The gridding of the meteorological data was done with the MeteoTool developed by WaterWatch. MeteoTool computes the near-surface atmospheric conditions on the basis of the physical state of the underlying land surface. Temperatures will be lower, and humidity will be higher over wet land. The temperature will be lower if cloud cover prevails etc.. This type of interpretation is preferred over a standard geo-statistical scheme such as Thiessen Polygons. One example of output data is demonstrated in Figure 9.

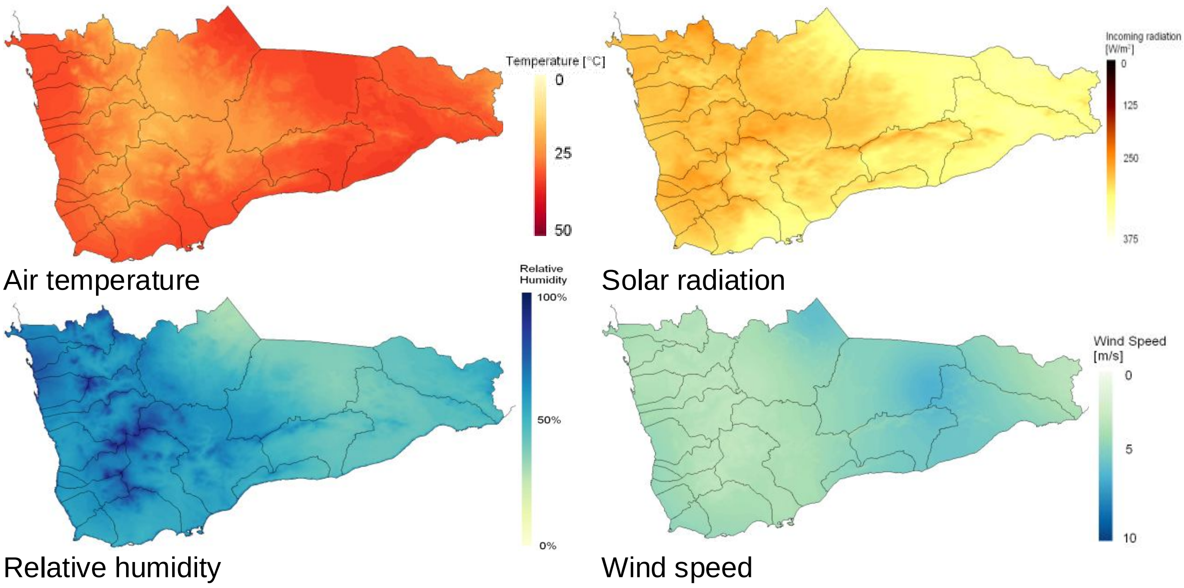


Figure 9: Spatial distribution of the standard meteorological parameters necessary for ET computations representative for the period 8 to 15 July 2010.

The FAO developed a framework of crop reference evapotranspiration for assessing the impact of weather data on ET. The biophysical parameters of the reference crop are fixed for the entire world, and will neither change with climate, nor across time. The reference crop is 12 cm tall well-watered grass, with a surface albedo of 23%, a canopy resistance of 70 s/m, and a surface roughness of 0.017 m. This hypothetical grass surface does neither experience any stress due to moisture in soil or atmosphere, nor from air temperature and solar radiation. The impact of climatological differences between different years on ET fluxes – and thus consumptive use – can be expressed by means of the reference ET.

Digital Elevation Models and land use maps are used to determine the surface roughness, which affects the land surface and atmosphere interactions. The SRTM Digital Elevation Model was used to compute the slopes and azimuths for the mountains in Yemen.

WaterWatch/eLEAF has developed a series of energy balance models which do not require much input data. The Surface Energy Balance Algorithm for Land (SEBAL) is applied in more than 30 countries, and was used also during these GSCP evaluation studies in 2006 and 2010. A more elaborate and technical description of SEBAL is given in Appendix 1. The accuracy of SEBAL has been widely published in the international literature. A paper reviewing 15 years of accuracy testing of SEBAL in irrigated crops was presented during the national irrigation congress in Australia during 2010 (Evans et al., 2009). In summary, it can be claimed to reach a 95% accuracy for ET_{act} accumulated across growing seasons.

The 2006 ET results were verified by field scale soil water balance studies. The Agricultural Research & Extension Authority (AREA) in Dhamar executed an interesting field investigation on the soil water balance of qat during 2000/2001. Two locations were selected: the northern part of Sana'a basin (Amran) and the south-western part of the central Highlands between 2 350 to 2 400 m AMSL in Sanaban, Henz and Dhi Mankar. The following information, Table 12, was derived from field measurements:

Table 12: Results of field measurements by AREA in 2000/2001. For Total water evaporated, it is assumed that 10% of the water percolates.

	Northern Uplands	Central Highlands
Before irrigation	7.0 cm (0.058 cm^3/cm^3)	18.9 cm (0.157 cm^3/cm^3)
After irrigation	14.6 cm (0.121 cm^3/cm^3)	28.3 cm (0.236 cm^3/cm^3)
Water depleted	7.0 cm	9.5 cm
Number of irrigations	6 to 8	8 to 9
Total water depleted	420 to 560 mm	760 to 855 mm
Total water evaporated (90%)	378 to 504 mm	684 to 770 mm
Conveyance efficiency	91%	75%
Field application efficiency	79%	75%
Water applied at farm gate	478 to 638 mm	912 to 1027 mm
Water pumped	525 to 701 mm	1 216 to 1 369 mm

Hence, the ET of qat in the Northern Uplands is 441 mm during the irrigation season (average value of 378 and 504 mm). The ET value outside the irrigation season has not been determined. The annual ET is likely to be in the range between 500 to 600 mm. ET of qat in Central Highlands is 727 mm (average value of 684 and 770 mm). The average ET value for the two locations is 584 mm. The 2006 study report an average ET of all pixels being 587 mm/yr. These two values resemble each other, and confirm a consistent result with the findings in this report.

Hence, the determination of the land surface energy balance from satellite images provides pixel based information on crop water consumption without further knowledge of crop age, cultivation, rooting depth, soil type, management practices etc. Determining ET through soil water balancing requires significantly more efforts, and results apply to one specific field only. The combination of energy balance and satellite measurements provides a new opportunity to survey the full spatial variability of ET in dispersed and different irrigated crops. Monitoring and controlling of crop ET is an essential first step in the conservation of groundwater in Yemen.
The differences in crop ET between 2006 and 2010 form an attractive source of information to detect changes in agricultural water use due to GSCP interventions. Hence, agricultural water use can be defined in alternative ways, and crop ET is preferred by the consultant because it is expressed as consumed water and can be computed for every 10 m x 10 m.

3.3 Irrigation supply

The combination of spatial information on land use, water use (i.e. ET) and rainfall can be used to appraise the irrigation water supply. The incremental evapotranspiration needs to be calculated first. The basic assumption is that the water source for ET of irrigated crops consists of rainfall and irrigation. ET from rainfall can be estimated from rainfed crops in close proximity that have not received irrigation water. A field is regarded as rainfed if P_{net}>ET. The incremental ET is the part of the applied water that is consumed by the crop. This must be equal to the difference in total ET of the irrigated crop and the rainfed crop:

Incremental ET = ETact$_{irrigated\ crop}$ - ETact$_{rainfed\ crop}$ [mm/yr]

Incremental ET (due to irrigation) is also referred to as the net irrigation supply. Gross irrigation supply can be computed from incremental ET and the on-farm efficiency. Gross irrigation supply comprises, besides incremental ET, runoff losses, drainage losses, and percolation to groundwater. Because the latter hydrological processes are difficult to quantify, an irrigation engineering approach is to lump these losses together into one single efficiency factor:

Efficiency = incremental ET / gross irrigation supply

Tables for typical efficiencies are available in the international literature and the values change mainly with the type of irrigation system, besides the type of crop and the type of water resource. The main focus of GSCP is on groundwater abstraction. Gross irrigation supply thus has to be broken down into surface water and groundwater resources. Since this is currently not feasible to do by means of satellite images, a look-up table was used (see Table 13). This look-up table has been agreed upon during the 2006 study after consultation with the irrigation experts from Yemen and the GSCP team of supervisors. Estimates were made of the proportion of irrigation water that originates from surface water sources and from groundwater abstraction for every study area. For the sake of compliance with the 2006 data, the same look-up table was applied to the 2010 ET data.

Table 13: Values enforced for on-farm irrigation efficiencies and the contribution of surface and groundwater resources.

	Groundwater partitioning				Surface water partitioning			
	Siham	Dhamar	Rada	Abyan	Siham	Dhamar	Rada	Abyan
Single Season	5 %	90 %	90 %	95 %	95 %	10 %	10 %	5 %
Double Season	60 %	90 %	95 %	60 %	40 %	10 %	5 %	40 %
Perennial / Qat	75 %	95 %	100 %	75 %	25 %	5 %	0 %	25 %
Banana				100 %				0 %

	Groundwater efficiency	Surface water efficiency
Single Season	55 %	40 %
Double Season	55 %	40 %
Perennial / Qat	70 %	40 %
Banana	75 %	40 %

The steps discussed above yield a combined data flow scheme that is schematised in Figure 10. Numbers are added for the sake of clarification and understanding of the technical steps.

Figure 10: Calculation scheme of incremental ET and gross irrigation supply: with in red an example for perennial crops in the Siham study area.

When dealing with water savings, it is of paramount importance to define the savings properly by relating it to a particular flow path. Irrigation water flows in a withdrawal – consumption – return cycle. What matters is the consumptive use of water, or better, the extra consumptive use of water due to withdrawals. This extra consumptive use transfers water resources into the atmosphere, and this water is no longer physically present in the land water cycle. By having ET measurements – and especially the incremental ET measurements - measurements of inflows and return flows are no longer necessary because the depletion can be obtained directly. The symbol for incremental ET is ET_Q (see Figure 11).

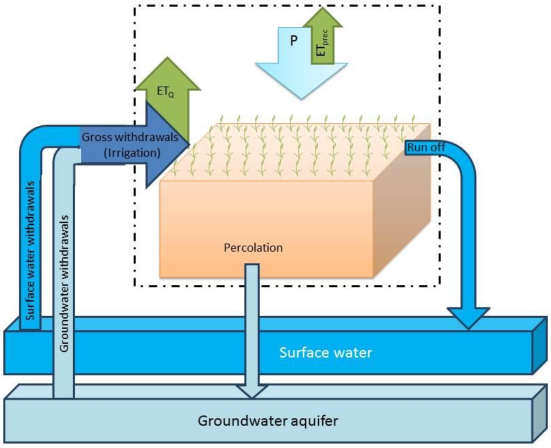


Figure 11: Schematic diagram of the water flow path in irrigation systems. Water savings must be explicitly addressed to a water flow path.

The incremental ET is the depletion related to withdrawals only; without water applications to the fields, this incremental ET would not occur. The gross withdrawals always exceed the incremental ET because not all water applied is evaporated. A reduction in gross withdrawals due to for instance PVC conveyance pipes can (i) affect the incremental ET and (ii) affect the return flow. As long as the gross withdrawal is more than the incremental ET, the major effect will be a reduced return flow. The incremental ET will not reduce if the conveyance efficiency is improved. Reductions in gross withdrawals thus do not necessarily equate to savings in consumption. By improving the conveyance efficiency, the gross groundwater abstraction can be reduced, while the same amount of water will arrive at the farm gate. If pumping hours are – for certain reasons - not cut back, higher conveyance losses will automatically provide more water at the farm gate. Hence, it is very well possible that the farmer receives more irrigation water at his field.

Localised irrigation systems represent a set of techniques to better distribute the water across the field and convert applied water into crop ET. Sprinkler and drip irrigation systems reduce the on-farm water losses, and often increase the crop yield. This is a positive contribution to irrigation management. It is not certain, that these irrigation systems reduce crop ET. It is very well possible that the ET increases by the higher efficiency between water applied and water consumed. The schematics of irrigation water flow are summarized in Figure 12. The impact of conveyance efficiency and on-farm efficiency is displayed.

At the one hand, water savings of the conveyance system can be estimated from field visits and in situ measurements, while at the other hand it is very difficult to estimate crop evapotranspiration, incremental ET and the changes thereof. Longer term field measurements and advanced equipment is necessary to measure ET. Hence, it is a straightforward situation that GSCP officers reports on conveyance savings and yield improvements. From remote sensing however, conveyance losses are difficult to quantify while it's possible to estimate crop evapotranspiration. Both types of water savings form a complementary and rich source of information for GSCP.

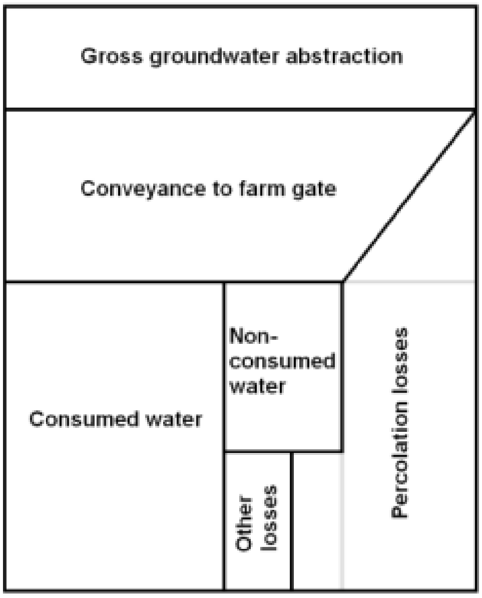


Figure 12: Simplified scheme of water flows in groundwater irrigated systems

For an agricultural system to be sustainable it should abstract small volumes of groundwater while trying to keep production as high as possible. Deficit irrigation is a method that is often suggested for saving applied water (Costa *et al*, 2007). Deficit irrigation is based on the principle that a crop is able to optimize between carbon fluxes and water fluxes. By regulating mechanisms, a crop exposed to a certain (limited) level of water stress is able to maintain photosynthesis and produce biomass and harvestable products. Without any detailed analysis, the level of acceptable crop water stress was fixed at 80% of ETpot. Hence deficit irrigation is encouraged when ET exceeds 0.8 ETpot.

3.4 Comparison Methodology

The conventional method of expressing progress in irrigation management is by means of field surveys. Field Unit teams have collected data on water savings, labour savings, fuel savings, reduction in pumping hours, and higher agricultural productivity. While most – if not all – World Bank projects used field surveys for their impact assessment studies, they represent only a very small fraction of the area where changes in groundwater management are introduced. Moreover, it is simply impossible to measure various relevant flows under field conditions. This remote sensing study quantifies land and water data for millions of pixels, as well as the changes between 2006 and 2010. This complementary information provides a data rich basis for understanding the changes in irrigation management. This indicates that ET is likely increased as well because crop yield and ET are usually positively correlated (FAO, 1973). Reduced application rates by 33% in conjunction with higher ET values (~ 10%) imply that irrigation efficiencies have improved by approximately 30 to 35% (e.g. from 50 % to 65%). The changes in crop ET from satellite measurements only will shine an independent light on this matter.

Table 14 provides an overview of the achievements in all the demo farms. The locations of these demo farms are spread throughout the 15 governorates mentioned in Chapter 1. Piped conveyance system (29 demo farmers) saved 12% of gross irrigation supply. A 12% reduction of 1 482 m^3/ha implies a gross abstraction of 12 350 m^3/ha which can only hold true for double season crops and perennial crops. Localized irrigation systems (60 demo farmers) saved 33% of water applied, which at a saving of 3 892 m^3/ha implies that 11 794 m^3 irrigation water is applied to each hectare. These are very large volumes of water per hectare, and are not representative for single season crops.

The field data reveal that despite water saving measures being introduced, crop yields have increased by 9 to 13%. This indicates that ET is likely increased as well because crop yield and ET are usually positively correlated (FAO, 1973). Reduced application rates by 33% in conjunction with higher ET values (~ 10%) imply that irrigation efficiencies have improved by approximately 30 to 35% (e.g. from 50 % to 65%). The changes in crop ET from satellite measurements only will shine an independent light on this matter.

Table 14: Summary of field observations on savings achieved by Demo Farms (source: GSCP).

System	Water saving		Labour saving		Fuel saving		Saving in pumping hrs		Increase in crop yield	
	m^3/ha	%	md/hr	%	l/hr	%	hr/ha	%	kg/ha	%
Piped conveyance system	1 482	12	7	12	121	12	37	13	1 061	9
Localized system	3 892	33	21	33	548	30	172	33	2 222	13

The total irrigated area in Yemen varies between approximately 400 000 and 500 000 ha. According to the GSCP Field Units, the water savings achieved from the installation of 34 035 ha under piped conveyance system and 1 365 ha under localized irrigation system amounted to about 56 MCM over the period September 2009 to April 2010. While not compatible it is very interesting to compare the results of Table 13 with the ET results in subsequent chapters.

The GSCP office has a database with the coordinates of tube wells where GSCP interventions have been implemented, as well as the area served by every tube well and the irrigation type. Within the boundaries applied in the current remote sensing study, Siham had 53 points, Dhamar had 234 points and Abyan contained 200 points respectively. There are many more GSCP points located outside the current study area which were not considered for this analysis. The total number of GSCP observation points that are included in this analysis is 487.

The GSCP dataset with GPS points pertain to 2011, and there is no field data available for 2006, partially because the interventions were introduced afterwards. The GPS points are measured by the receiver at the well, and not in the centre of irrigation plots. To overcome these problems of (i) missing data in 2006 and (ii) unclear coupling between wells and location of the fields served by this well, the images have been used to analyse the changes within a certain radius from the GSCP points. This procedure is not entirely correct as some fields can be located inside the radius that are not served by the well, but the error is identical for 2006 and 2010, which allows to study the changes. The well has been taken as the central point in this analysis. This radius or footprint has been kept identical for the 2006 and 2010 images, and it provided a vehicle for systematic quantification of the changes retrospectively. An area of approximately 4 to 7 ha was taken into consideration around each GSCP point, which is equal to a radius of 100 to 150 m. This concept is shown in Figure 13.

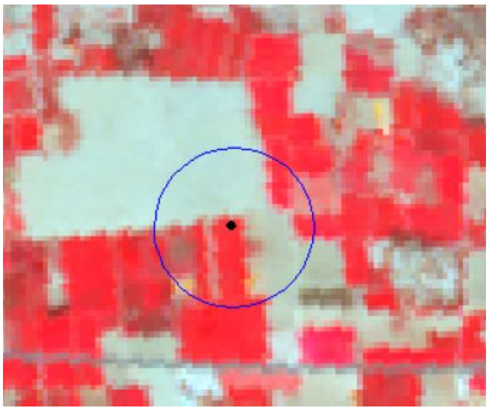


Figure 13: A GSCP point with a blue circle indicating the influence area assumed for that point. The area served for 2006 and 2010 is kept identical.

It is not certain that all these fields are supplied by water from that particular well, but at least a group of particular pixels that are likely to be exposed to GSCP interventions can be evaluated separately from all the other remaining pixels in the same region. The hypothesis is that the changes in the GSCP points are more favourable than at regional scale. By directly comparing GSCP point changes and regional changes, all other external effects such as climate variability and socio-economic factors can be excluded. Differences are expressed by means of the following parameter data set:

- Green vegetation cover (NDVI);
- Agricultural land use class area (m^2);
- ET (mm & m^3);
- Incremental ET (mm);
- Gross groundwater abstraction (m^3).

The changes will be expressed as the 2006 results minus the 2010 results. Negative numbers imply that the 2010 values are larger, hence more acreages, depths and volumes.
To prevent an overabundance of data, changes in land use are presented as trends (-1, 0, +1). A trend is considered favourable (+1) if the agricultural land use becomes less water use intense. Changing from an irrigated single season crop to a rainfed single season crop is for instance favourable (+1). Changing from perennial to double season irrigated crop could be a step in the right direction (+1). Positive changes in land use intensity are presented in blue. Negative changes in land use occur when rainfed single season crops are converted into double season crops (-1). Negative changes are expressed as red. Green is selected if there is no change in land use (0).

The changes described in this report are presented at three different spatial aggregation levels, shown in Figure 14:

- Changes in the direct vicinity from a number of GSCP points (each 4 to 7 ha);
- Changes in the 4 selected regional scale study areas (each 360 000 ha);
- Changes in the 14 selected major catchments.

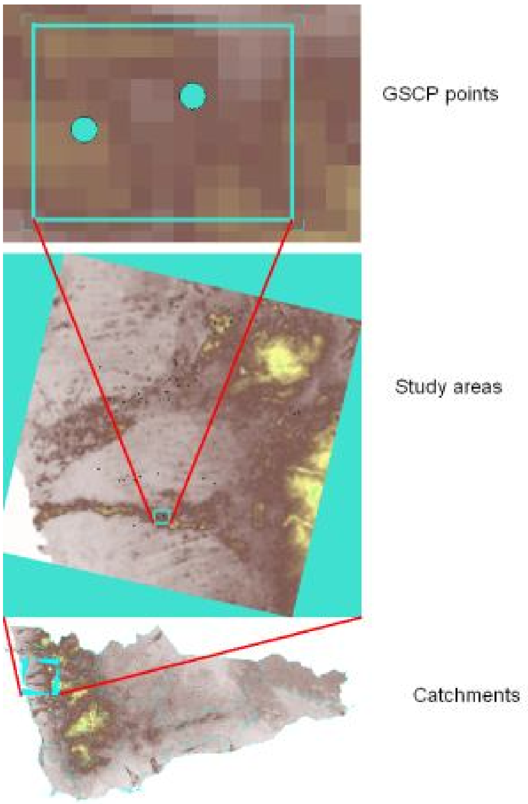


Figure 14: The different spatial scales considered in this study for change detection.

Due to the fact that parameters have been calculated and determined at different spatial resolutions, not all changes are presented at all spatial aggregation levels. Rainfall, for example, has been measured with 25 km pixels and small areas of GSCP points will not be exposed to rainfall variability. Another example is that land use type has been determined at 10m resolution, only for the study areas. Land use changes, therefore, cannot be given at catchment scale.
Regarding the timescale, most parameters are compared at annual averages or sums for 2006 and 2010. An exception is NDVI, a vegetation index that is also compared for February 2006 and February 2010. This has been included because February is a very suitable month to detect irrigation practices.

4. Siham

4.1 General

Siham consists of two parallel wadis and a plain area in between: Wadi Siham in the north and Wadi Jahbah in the south. Wadis Siham and Jahbah both cover part of the Tihama plain.

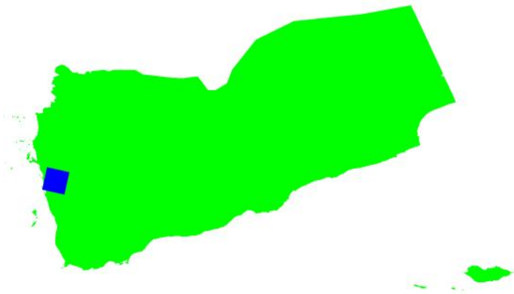


Figure 15: The area of interest of Wadi Siham in the Tihama plain.

Alos images were available for 10 different dates. Aster images were acquired during 2 dates and Landsat could be acquired 8 times. The 20 images are reasonably well spread throughout the year, except for the period May – August for which there was only one image available. The satellite images are shown in Figure 17. The blue boundaries of the study area (i.e. “blue bounding box”) were defined during the 2006 study. Since the 2010 images were recorded by other satellites, the area they covered does not exactly match the area defined in 2006 on the basis of SPOT images. The purpose of Figure 17 is to demonstrate that the total area is covered several times if all 22 images are being superimposed because each image will cover one particular portion. The area of interest is 343 509 ha.

There are 53 GSCP points present in Siham. The location of these points is demonstrated in Figure 16. It is obvious that not all points are located in the wadi area; several of them are installed in the areas stretched between Wadi Siham and Wadi Jahbah. The background colours used are true colours; hence the Red represents the reflectivity of the red band, Green the green reflectance and Blue the blue reflectance.

After that, the images in Figure 17 are displayed as False Colour composites. The spectral bands green, red and near-infrared are displayed as colours Blue, Green and Red respectively. Red thus shows near-infrared reflectance, that otherwise cannot be discerned by the human eye, and for this reason it is referred to as false colours; these colours are not true.

Strong near-infrared reflectance signals are shown as bright red. These bright red areas have a high vegetation index (NDVI) and these pixels must contain vigorous and photosynthetic active vegetation. If the vegetation is cropland, it can be certain that these crops have had access to soil moisture. If surveyed during the dry season, such pixels must represent irrigated land.

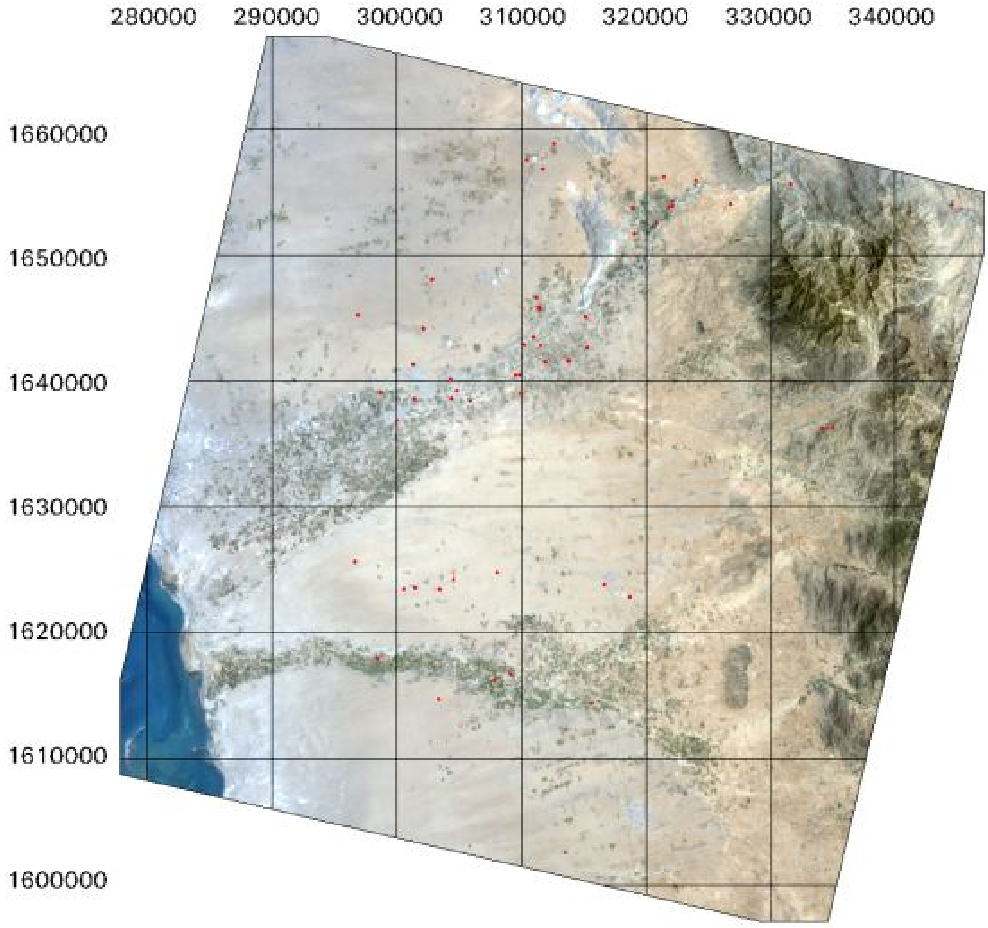
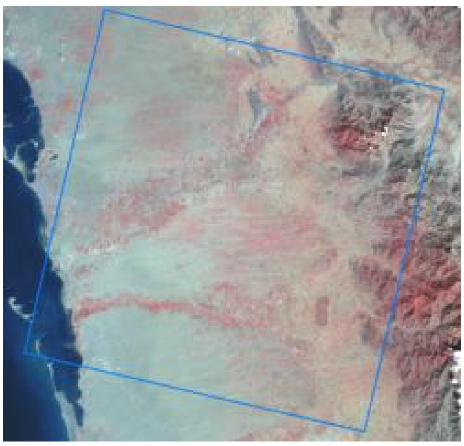
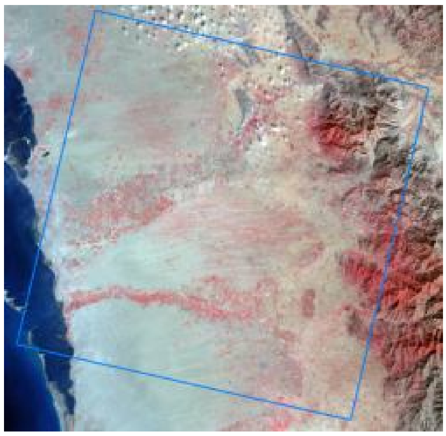


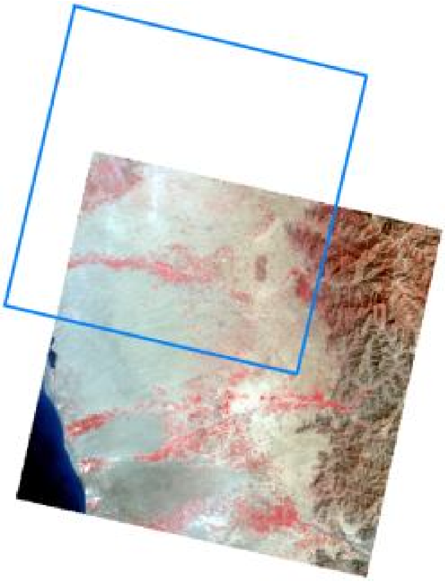
Figure 16: Distribution of the GSCP points across the Siham study area. The points are indicated by red dots.



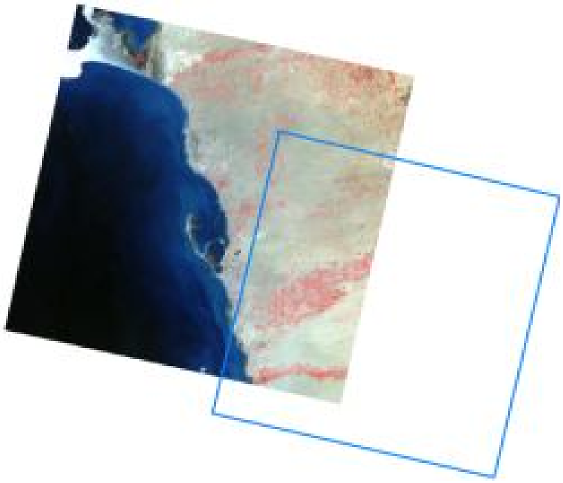
a) Landsat 7 - 22 November 2009



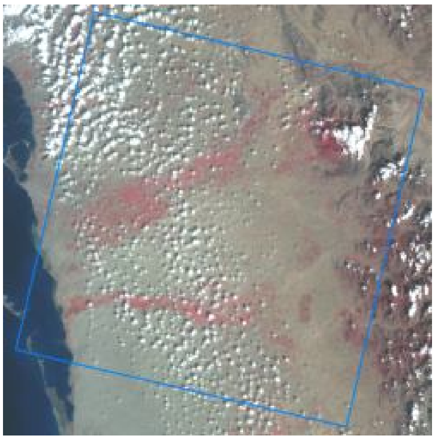
b) Landsat 5 - 8 December 2009



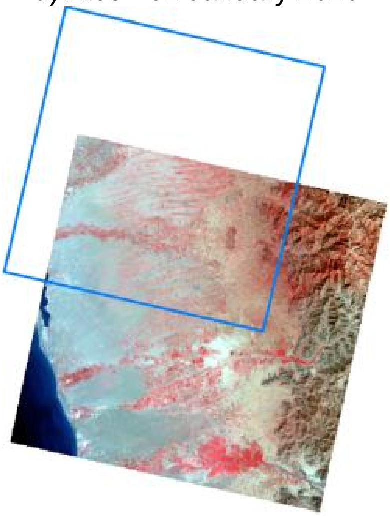
c) Alos - 14 January 2010



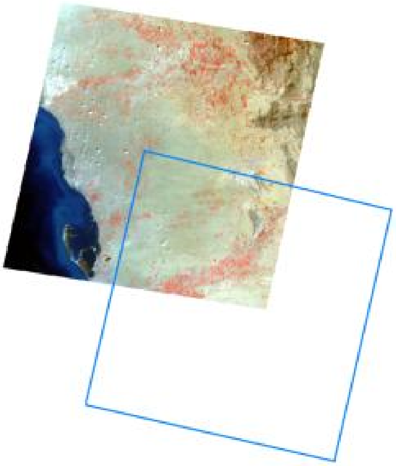
d) Alos - 31 January 2010



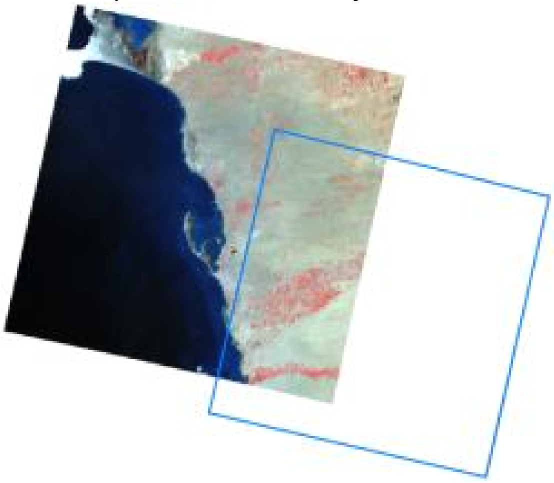
e) Landsat 5 - 10 February 2010



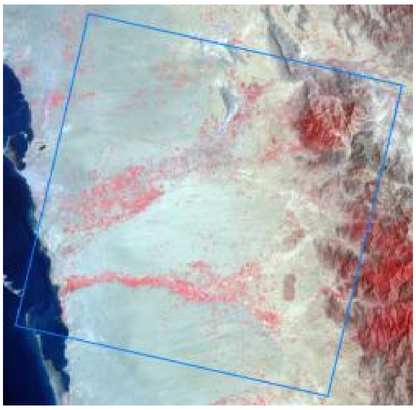
f) Alos - 12 February 2010



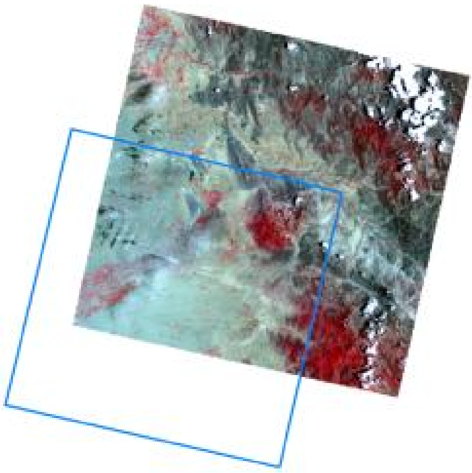
g) Aster - 18 February 2010



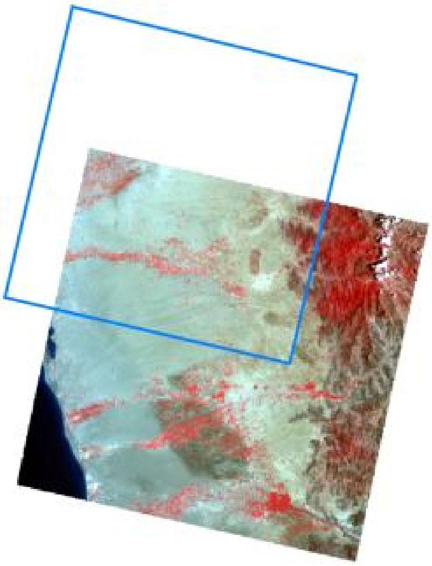
h) Alos - 18 March 2010



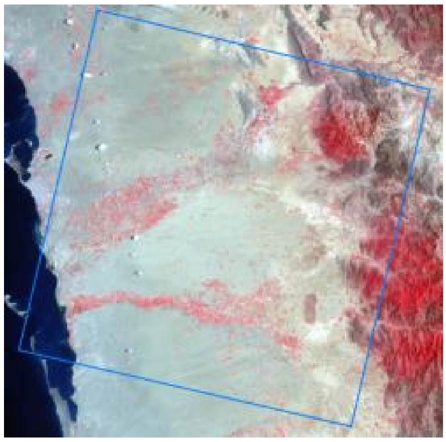
i) Landsat 7 - 7 April 2010



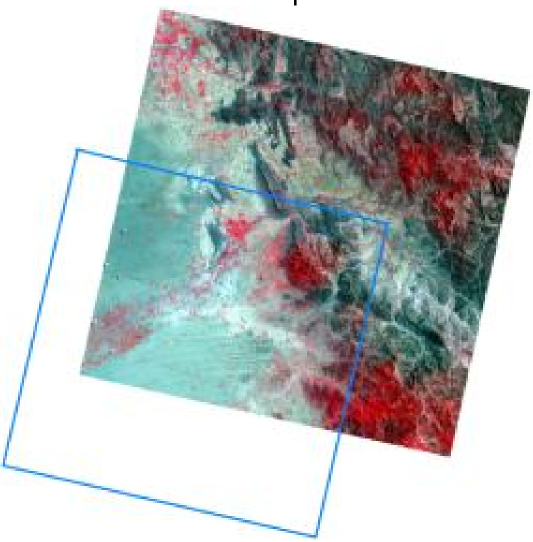
j) Alos - 16 April 2010



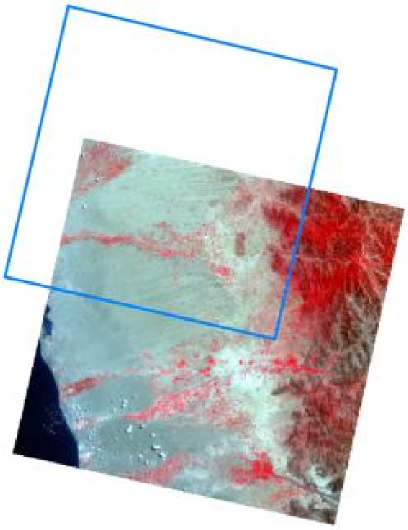
k Alos - 16 April 2010



l) Landsat 7 - 23 April 2010

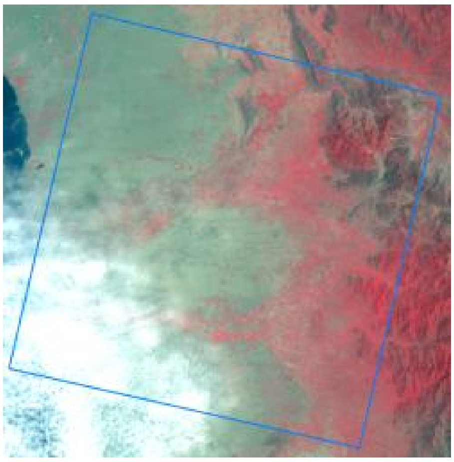


m) Alos - 1 June 2010

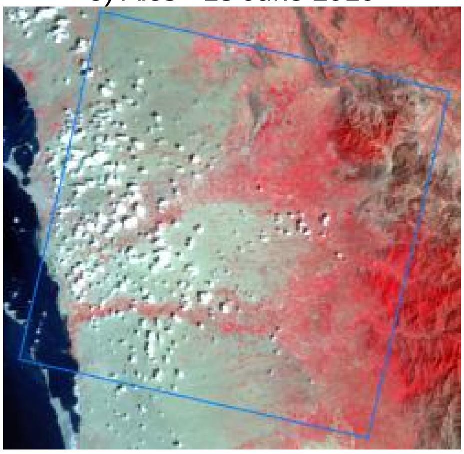


n) Alos - 1 June 2010

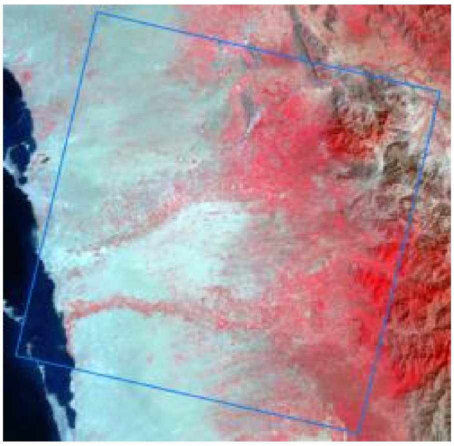
o) Alos - 18 June 2010



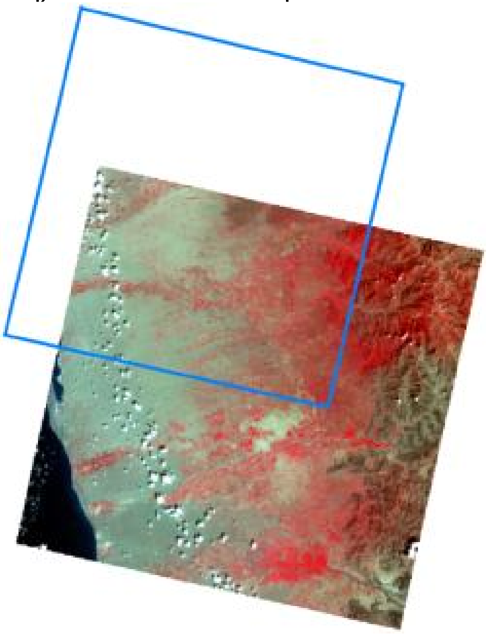
p) Landsat 7 - 14 September 2010



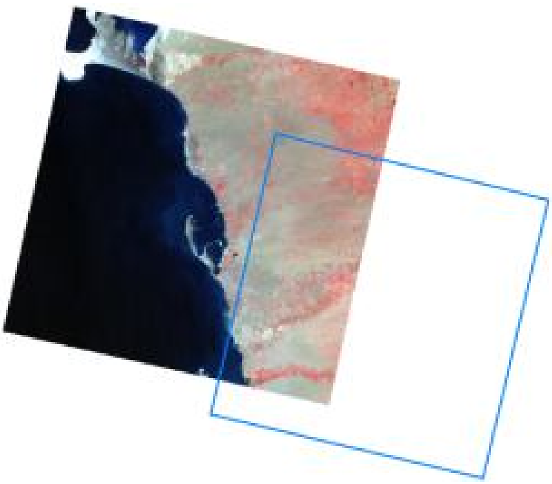
q) Landsat 7 - 30 September 2010



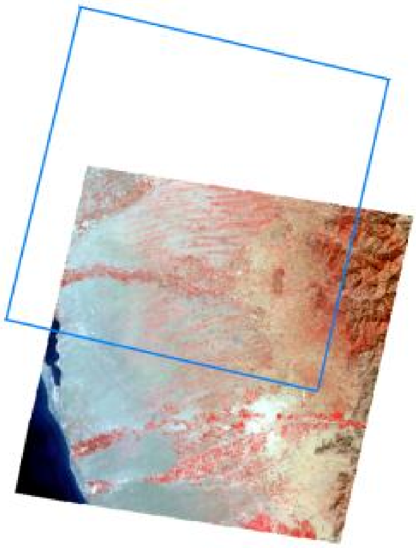
r) Landsat 7 - 16 October 2010



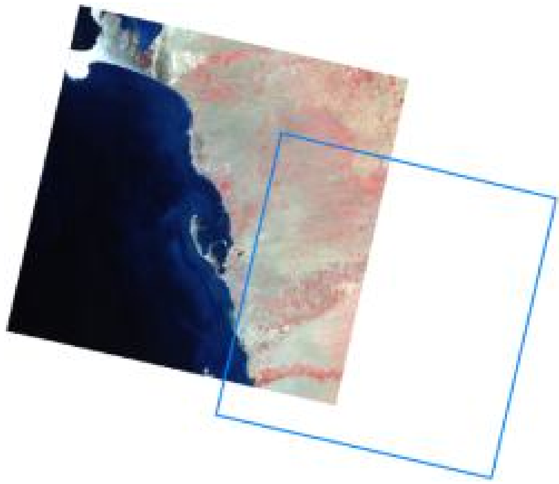
s) Alos - 17 October 2010



t) Alos - 3 November 2010



u) Aster - 3 December 2010



v) Alos - 19 December 2010

Figure 17: Satellite images of the Siham study area, with in blue the extent of the study area.

Only very shallow water tables can provide sufficient moisture to have the same effect on water use and crop development as irrigation, but a high water table is a rare phenomenon in Siham. It can also be seen from these images that the mountainous area, in the south-east of the blue framework, has vegetation that grows most vigorously during October. This is most obvious when the results of 17 October 2010 are compared with 1 June 2010. October is the end of the rainy season, when all soils are moist and rainfed cropping is practiced everywhere.

4.2 Climate

Figure 18 shows the mean monthly rainfall distribution and its range among individual TRMM pixels for Siham during 2010. The TRMM rainfall data set was used for this time series. The higher located terrain in the eastern edge of the study area receives more rainfall than the coastal part of the study area. This is demonstrated in the country-wide rainfall maps displayed in Figure 75. The average annual rainfall in Siham for 2010 was estimated to be 486 mm. The average rainfall in Siham for 2006 was estimated as being 455 mm. This small difference between both years can be ascribed to differences in peak rainfall in June, July and August.

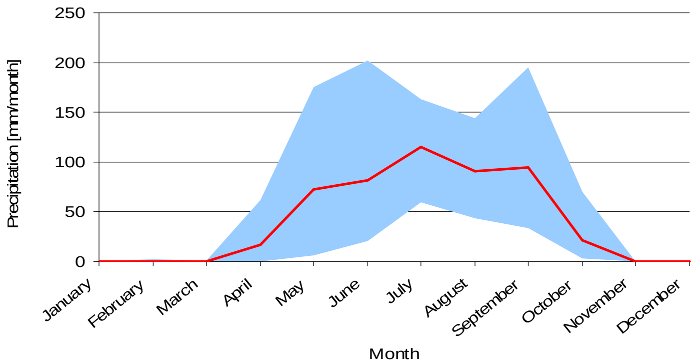


Figure 18: Monthly rainfall for the Siham area. The red solid line shows the average rainfall for the total area. The blue area shows the range of local rainfall within the study area.

Figure 20 shows the location of the meteorological station Al Hodeidah. The air temperature measurements at this location are shown in Figure 19. There is a clear annual pattern, with temperatures in summer being approximately 10°C higher than during the winter. The climate is favourable for cropping throughout the entire year, and water resources availability is the clear bottleneck to agricultural production in this part of Yemen. The lack of rain makes irrigation essential for crop cultivation during November to April.

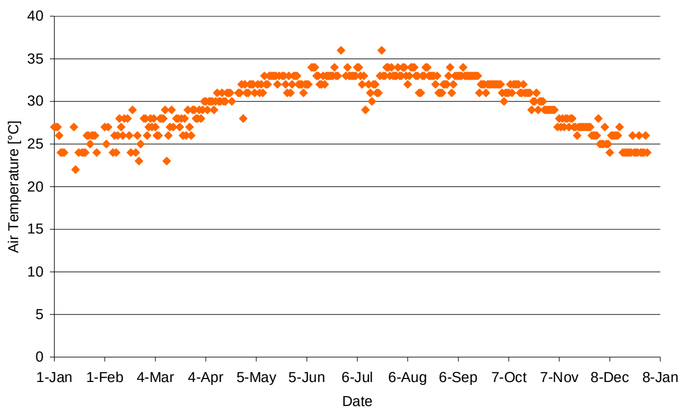
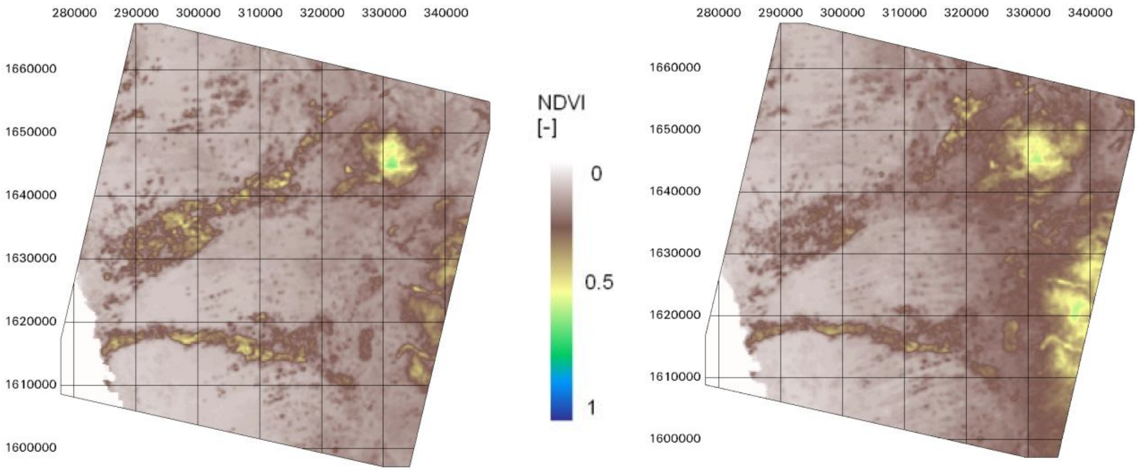


Figure 19: Temporal variability of the daily air temperature values [°C] for the year 2010, Al Hodeidah meteorological station [Latitude 14.8° N; Longitude 43.0° E; Altitude 115 m].

Figure 20: Location of meteorological station Al Hodeidah within study area Siham.

4.3 Green vegetation cover

The MODIS satellite measures NDVI in time intervals of 16 days, which is useful for siting of crops and their phenological phases, even though the spatial resolution is 250 m. Figure 21 demonstrates the spatial patterns of NDVI during the dry season in February. It is obvious that there are irrigated crops in the wadis during the dry season as well as irrigation practices on certain areas in the mountains. This will be confirmed later by the land use map. All yellow (NDVI~0.4) and green (NDVI ~0.7) pixels reveal irrigated land or groundwater dependent ecosystems. The latter represent ecosystems with deep rooting vegetation that directly tap water from the underlying aquifers. The annually average NDVI shows patterns being similar to the irrigated crops and the groundwater dependent ecosystems in February, but with additional green areas due to rainfed pasture land and rainfed single season crops.



February Annual mean

Figure 21: Spatial distribution of the NDVI during February 2010 and the annual mean NDVI.

4.4 Land Use

Most of the plain area is non-cropped, as well as the higher elevated parts with steep mountainous slopes and rocky areas. The non-cropped area accounts for almost 2/3 of the study area (63%).

Approximately half of the agricultural land is irrigated in Siham. This can be seen from the land use map that is presented in Figure 22 and from the statistics in Table 15. The total irrigated area is 65 525 ha, being approximately 15% of the total irrigated area of Yemen. Agriculture in the foothills is mainly rainfed (48.5% of cropped area). This coincides with the areas of higher rainfall (see Figure 75). Pixels with a high annually average NDVI value contain green vegetation during and after the rainy season.

Croplands in the wadis are often irrigated, enabling the cultivation of not only single season crops (39.5% of cropped area), but also double season crops (6.3% of cropped areas) and even perennial crops (5.8% of cropped areas). Spate irrigation during flood events is a common method to capture sufficient water from seasonal streams. Spate irrigation occurs during the wet season. Only farmers with access to groundwater can irrigate during the off-flood season. The annual cropping intensity for Siham is 123%.

The annual cropping intensity is defined as the total irrigated area from the two seasons (i.e. sum) over the irrigated area during the wet season.

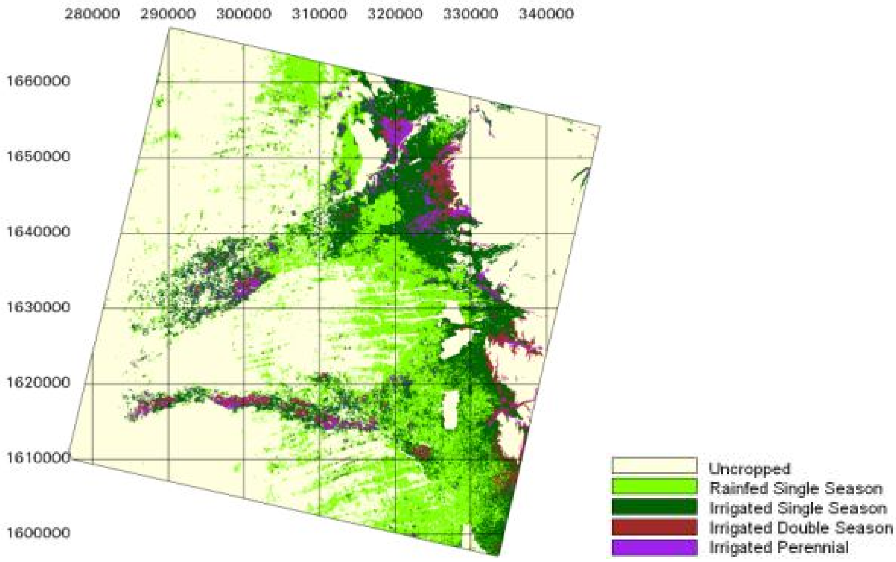


Figure 22: Results of the agricultural land use classification. A larger size map is given in Appendix 2 .

Table 15: Agricultural land use in the Siham study area. The irrigated area is 65 525 ha.

				Area [ha]	**% of total**	**% of cropped**
Classification	Rainfed			61 630	17.9%	48.5%
	Irrigated	Single Season		50 226	14.6%	39.5%
		Double Season		7 978	2.3%	6.3%
		Perennial		7 321	2.1%	5.8%
	Non-cropped			216 353	63.0%	
	Total			343 509	100.0%	

Figure 23 provides more detail on the methodology and the automatic classification procedure being applied. Uncultivated land shows up as a bright colour. Crops will be mature at the end of the rainy season during October. Single season crops in Siham can be both rainfed (61 630 ha) and irrigated (50 226 ha). Note that irrigation can be a one time per season event only. Siham is an area of smallholder farming. The differences between two consecutive months - January and February - are striking in Figure 25, and pinpoint the dynamics of complex cropping patterns induced by these small holders. While one would expect gradual changes during the dry season, abrupt changes are clearly visible when comparing January to February. This is related to the short crop cycles, and the warm weather that fosters crop production. Vegetables and fruit are grown in very small field plots and within less than 100 days.

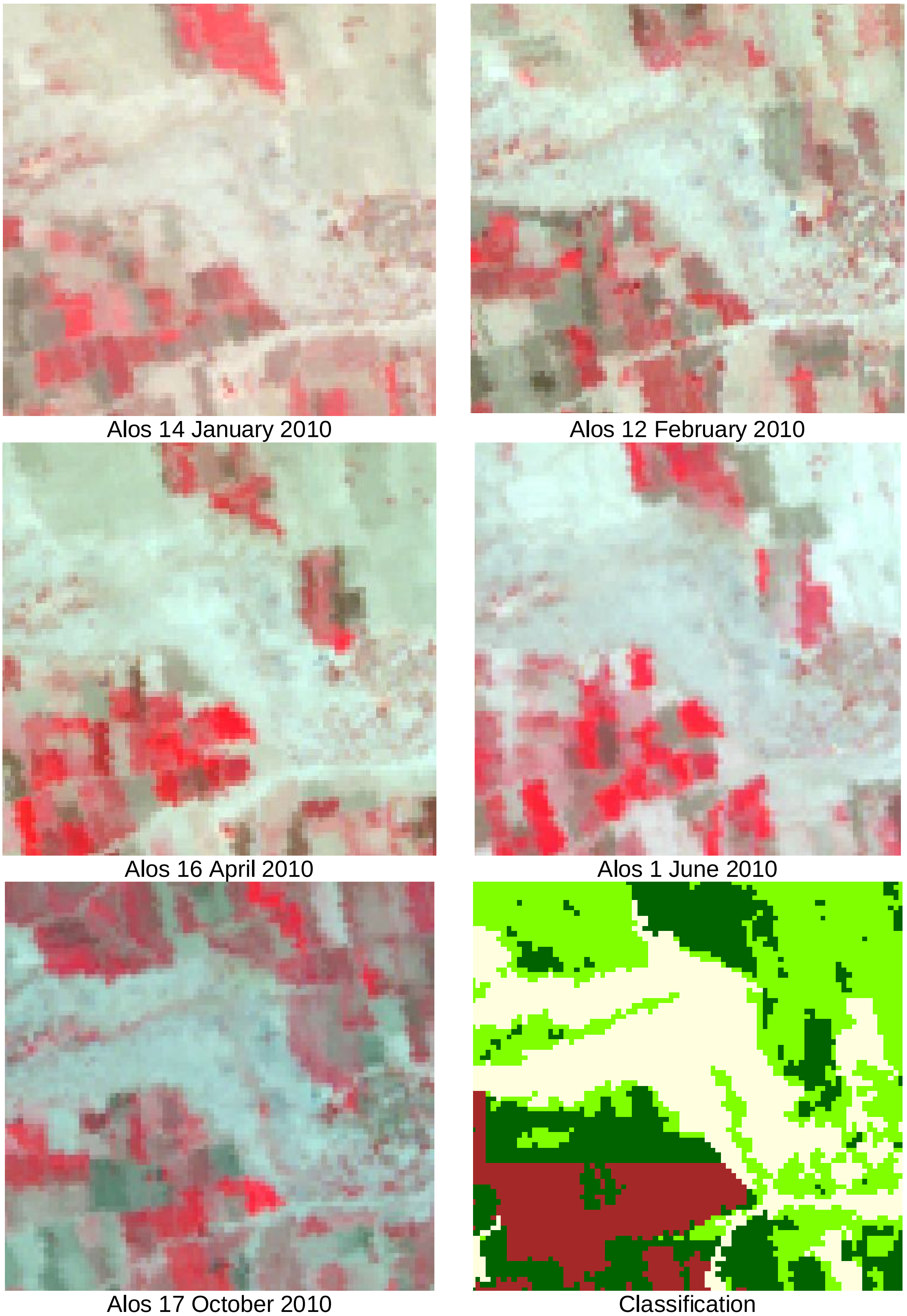


Figure 23: Example of the raw satellite images and the classification results for Siham.

The effectiveness of a classification can be verified by a contingency table. It displays the statistics of the classification results and assigns to it a reliability and accuracy. Every pixel that was identified during the field visit was checked in the satellite-based classification and all results are presented in Table 16. Out of all pixels that were identified as perennial in the field (639 + 27 + 94 + 1 393 + 316 = 2 469 pixels), 1 393 pixels were also automatically classified as perennial on the basis of the satellite classification. This is an accuracy of 56%.
A different way to evaluate the classification is to check how many of the classified pixels (0 + 382 + 722 + 1 393 = 2 497 pixels) appear indeed to be perennial crops in the field survey. This had a reliability of 56%.

Table 16: Contingency table for the agricultural land use classification of Siham. The numbers express the number of pixels; one pixel represents 100 m^2.

			Fieldwork				
			Rainfed	Single Season	Double Season	Perennial	**Reliability**
Classification	Rainfed		3 309	6 003	4 880	639	22%
Classification	Irrigated	Single Season	22 334	2 657	1 464	27	10%
Classification	Irrigated	Double Season	73	1 363	535	94	26%
Classification	Irrigated	Perennial	0	382	722	1 393	56%
Classification	Non-cropped		172	601	524	316	
Accuracy			13%	24%	7%	56%	17%

The accuracy and reliability results shown in the contingency table are not encouraging. The overall accuracy is 17% only! This poor result could in part be ascribed to limited availability of high resolution satellite images for most of the rainy season for the Siham area (June until October). Absence of images during the rainy season will impact the classification accuracy of the single season crops (accuracy 18%; reliability 16%). The few satellite images of that period that are available appeared to be clouded.

The field data also has its own sources of error. The fieldwork was executed during March 2011, a year after certain satellite images were taken. The mismatch between images and field data is believed to be the major source of the low overall accuracy. Figure 23 demonstrated that cropping patterns change rapidly, and that field visits simultaneously with image acquisitions are crucial for accurate classification.

Even if both field and satellite measurement are done properly they sometimes don't match. An example is shown in Figure 24. In the four upper panels Alos images throughout the year are shown while in the lower panels the field identification and the satellite-based classification are displayed. The red-outlined field in the left upper corner of all panels was identified as double season crop during the field visit. However, in none of the satellite images it appears to be vegetated: hence it is not likely that these fields were cropped during 2010, while in 2011 it might have had two cropping systems. Also the three fields located to the right hand side of the panels were identified as double season crops, while it is clear that they were vegetated in January and April only. The October images show irrefutably that the field was not cropped in the rainy season.

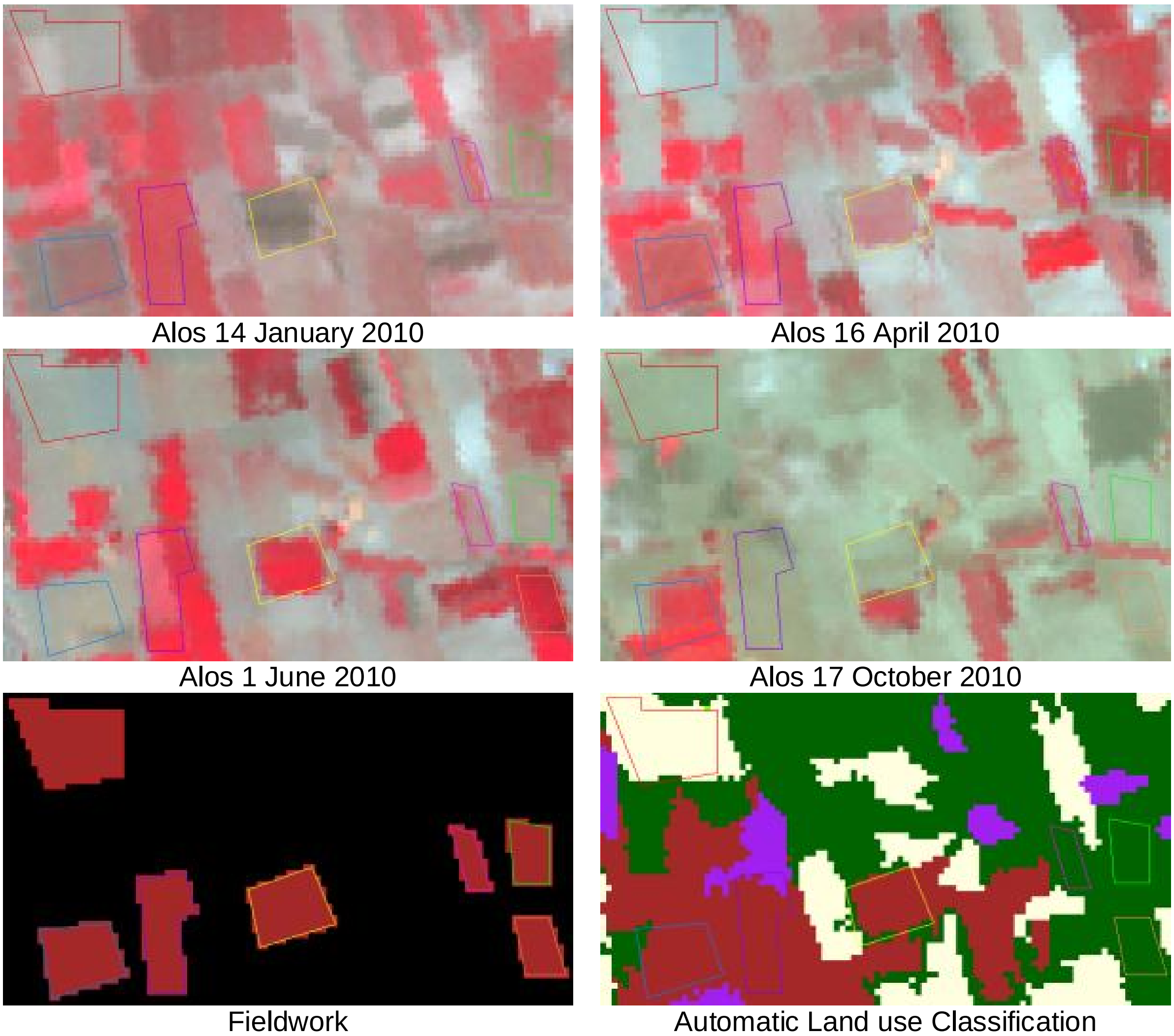


Figure 24: Comparison of satellite images, fieldwork and land use classification for Siham, field site s62. Coloured outlines indicate fields that were identified in the field. All fields were identified as double season crops during the field visit, while the satellite-based classification identified some fields as single season crop and one field even as non-cropped.

A manual classification has been applied to demonstrate that fieldwork is not a good criterion to validate the overall classification accuracy if field surveys and image acquisition are not coinciding. All high resolution satellite images were displayed as False Colour Composites and they were visually inspected to see if there was a crop present in a field or not. Some fields were partially covered with crops in some images, with the result that they were classified in two or even three land use classes. The results are shown in Table 17.

From that table it is clear that in 74% of the cases, the manual and automatic classifications were identical, which differs significantly from the 17% achieved earlier. The main conclusion from this exercise is that the field identification of 2011 cannot be used for the optimization process in the land use classification. Minimizing the difference between images and field notes would results in erroneous land use mapping results.

The field work was therefore not used in further analyses and the contingency table should be disregarded. The overall accuracy of land use mapping for Siham area in 2006 was 88.1%, and this is closer to the 74% agreement between the manual and automatic classification. Hence, an overall accuracy of 81% (i.e. average of 74 and 88 %) is typically the level of confidence that one can achieve from small holder cropping practices in Wadi Siham.

Site	#	Field identification	Automated classification	Manual classification
s62	1	Double	Non-cropped	Non-cropped
	2	Double	Double	Double
	3	Double	Double	Double
	4	Double	Double	Irrigated single
	5	Double	Irrigated single	Irrigated single
	6	Double	Irrigated single	Irrigated single
	7	Double	Irrigated single	Irrigated single
s66	1	Irrigated single	Irrigated single	Irrigated single
	4	Irrigated single	Perennial	Perennial
	5	Perennial	Irrigated single	Perennial
	7	Irrigated single	Irrigated single	Irrigated single
	9	Irrigated single	Double	Double
	10	Irrigated single	Rainfed	Non-cropped
s58	1	Irrigated single	Non-cropped	Non-cropped
	3	Irrigated single	Rainfed	Rainfed
	4	Irrigated single	Irrigated single	Double
	5	Irrigated single	Irrigated single	Irrigated single
	6	Irrigated single	Rainfed	Rainfed
s68	1	Irrigated single	Double	Double
	2	Irrigated single	Double	Double
	3	Irrigated single	Perennial	Perennial
	4	Irrigated single	Double	Double
	5	Irrigated single	Double	Double
	6	Irrigated single	Non-cropped	Non-cropped
	7	Irrigated single	Double	Double
	8	Irrigated single	Perennial	Double
	9	Irrigated single	Double	Irrigated single
	10	Irrigated single	Double	Irrigated single
	11	Irrigated single	Irrigated single	Irrigated single
	12	Irrigated single	Irrigated single	Double
	14	Irrigated single	Double	Double
	15	Perennial	Irrigated single	Irrigated single
	17	Irrigated single	Irrigated single	Irrigated single
	18	Irrigated single	Irrigated single	Double

Table 17: Comparison of field identification, satellite based classification and manual classification. Colours are the same as in the land use map.

The Alos images are of good quality, but the new generation earth observation satellites have even better spatial resolutions. Siham has been measured by GeoEye on 24 February 2010 with an unsurpassed pixel size of 0.41 m, and multispectral images with a pixel dimension of 1.65 m. These images are freely accessible on Google Earth, and were used to verify the presence of crops. All the dark areas displayed in Figure 25 are irrigated during February 2010. The unprecedented spatial accuracy allows even to recognize perennials crops from single season crops. Orchards have a clearly blocked structure with paths between lanes. Individual houses can even be spotted. This type of imagery will be recommended for future validation studies.

Figure 25: Google Earth excerpt for the Siham area. The area is identical to the classification example demonstrated before.

4.5 Water Use

ET results of the energy balance computations are reported on in this section. The basic calculations were done with Modis images that covered the entire area in intervals of 16 days. The Alos images were used to scale the ET results down from 250 m to 10 m pixels. The resulting ET map in Figure 26 shows some linear features in the plain area between the wadis. These artefacts can be disregarded, and are merely a consequence of the combining of Alos images that partially encompass the study area.

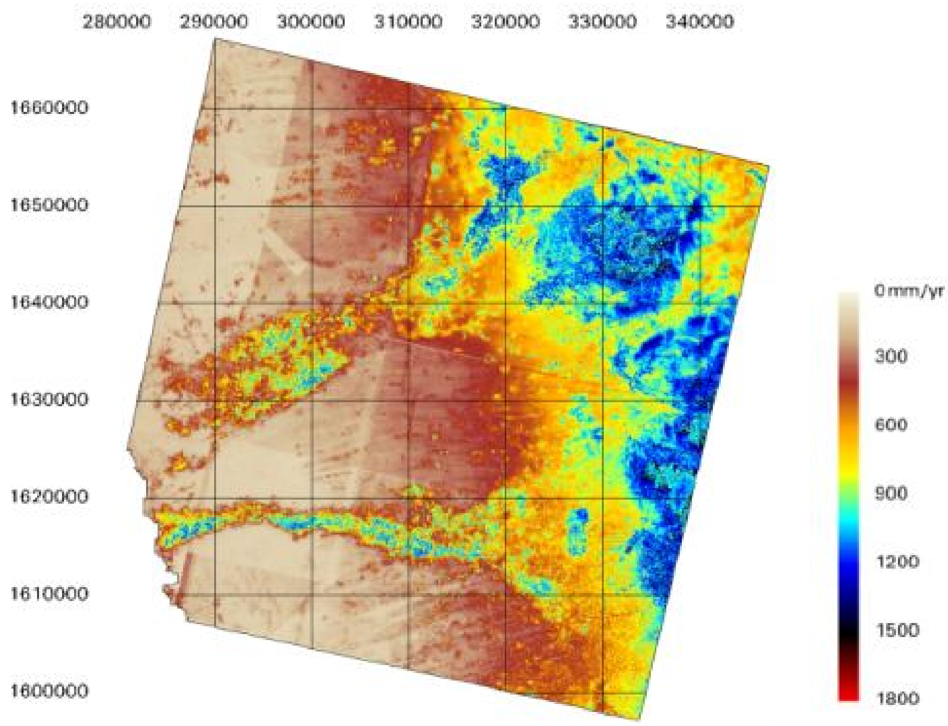
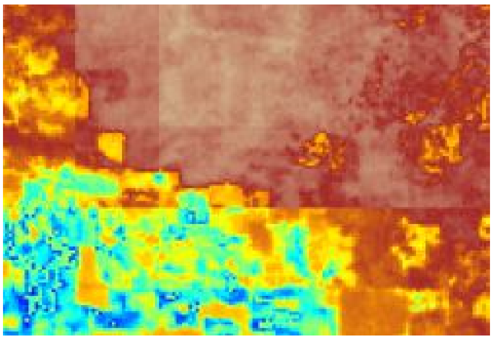
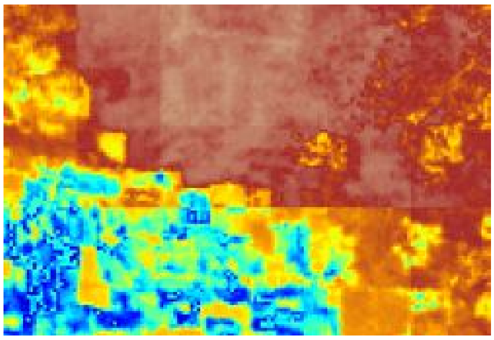


Figure 26: Map of actual evapotranspiration in Siham during 2010. A larger size map is given in Appendix 4.

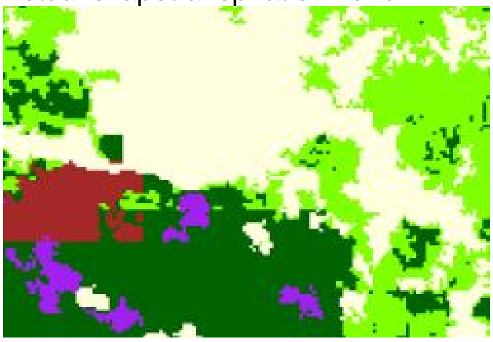
The mountains exhibit the highest ET rates due to relatively high rainfall in the areas. ET values exceed 1 000 mm while rainfall is around 700 to 800 mm, which suggests that crops are fed with other water resources than rainfall only, i.e. irrigation. The ET reduces into the direction of the Red Sea coast, with an exception for the wadis that have high ET rates as a result of spate irrigation as well as complementary irrigation from groundwater. The ET of agricultural fields with a cropping intensity of 200% can be as high as 1000 to 1400 mm/yr (i.e. 10 000 to 14 000 m^3/ha/yr).

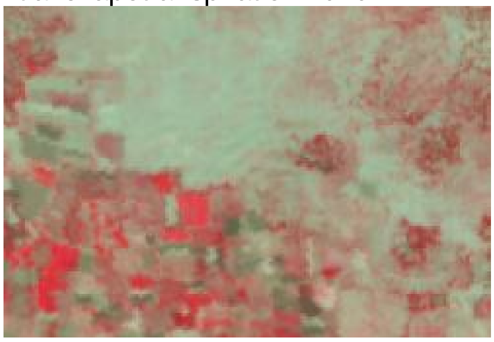
The comparison between ETact and ETpot is shown in Figure 27. The difference is the largest for pixels with high ET rates. These pixels contain intensive water using crops (e.g. perennial crops). Irrigating these high water demanding crops to fullfil water use demand can be approximated by deducting ETact from ETpot. Differences between ETact and ETpot are visible, and imply that the full irrigation water requirements have not been supplied; otherwise ETact and ETpot would be similar. The explanatory factors are the presence of scarce water resources in conjunction with the local irrigation culture.





Actual evapotranspiration 2010 Potential evapotranspiration 2010





Land use map 2010 Alos image 17 October 2010

Figure 27: Example of actual and potential evapotranspiration of agricultural land use.

The impact of agricultural land use on evapotranspiration is presented graphically in Figure 28. The average rainfall is 486 mm. Non-cropped and rainfed single season crops both have ET rates lower than the rainfall. These land use classes consume water that originates from rainfall only. Due to the low rainfall, their ET is constraint by a lack of soil moisture. Land use classes with an irrigation label have higher ET rates. Figure 28 shows the overlap in ET between rainfed and irrigated crops, but also the distinct differences of their mean values.

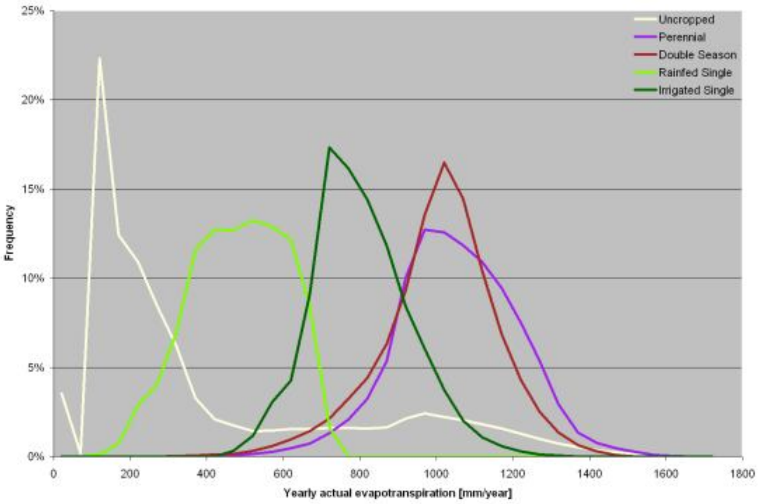


Figure 28: Frequency distribution of total actual evapotranspiration for the year 2010 for different agricultural land use classes in the Siham area. Frequencies are calculated on 50 millimetre intervals.

The statistics of the frequency distributions of Figure 28 are summarised in Table 18. The average and standard deviations are presented. ETref is 2 042 mm during 2010. Peak ET values of 1 600 to 1 700 mm were observed as can be seen at the tail end of the ET histogram (Figure 17). Peak values of ETpot are expected to be higher, and will approximate the reference ET.

Table 18: Actual, potential and reference evapotranspiration for various agricultural land use classes in Siham. The annual values for 2010 are presented. Annual rainfall is 486 mm.

	ET_{act}		ET_{pot}		ET_{ref}	
	Average	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
	[mm/yr]	**[mm/yr]**	**[mm/yr]**	**[mm/yr]**	**[mm/yr]**	**[mm/yr]**
Non-cropped	416	366	448	387	2 014	309
Rainfed	487	125	528	129	2 126	35
Irrigated						
Single Season	808	129	861	135	2 090	44
Double Season	1 011	153	1077	160	2 042	55
Perennial	1 058	159	1141	170	2 057	53

While spatial data on ET at a resolution of 10 m is highly exceptional, and useful, GSCP objectives are more focussed on reducing groundwater abstractions and increasing efficiencies. Surface water irrigation is a reasonably sustainable irrigation method: withdrawals from rivers can never exceed the discharge that flows at that moment through the river bed. If the river flow is low, irrigation must be adjusted accordingly. This fundamental principle does not hold true for groundwater irrigation processes, thus being the root cause of the general decline in water resources in Yemen.

All fields with a second cropping season (or perennial crops) require groundwater for irrigation. To determine the amount of water that is abstracted for irrigation, incremental ET has been calculated first. It is assumed that the ET of irrigated crops consists of a rainfed part, equal to the ET of rainfed crops, and one component of ET that can be ascribed to irrigation (i.e. the incremental ET), see Chapter 3.

The results shows incremental ET to vary between 321 to 571 mm/yr (i.e. 3 210 to 5 710 m^3/ha/yr). The abstraction of 451 mcm/yr from streams for spate irrigation is a factor 4.3 more than for aquifer abstractions. It is estimated that a total groundwater volume of 105 mcm/yr was abstracted from the aquifers in Siham. The gross abstracted volumes for double season and perennial crops are similar (45 and 46 mcm/yr).

Table 19: Synopsis of the annual irrigation supply to the various land use classes of Siham during 2010.

	Area	ET_{act}	**Incremental ET**	**Gross irrigation supply** [mcm/yr]		
	[ha]	[mm/yr]	[mm/yr]	Surface	Ground	Total
Total study area	343 508	513	27	451	105	556
Non-cropped	216 353	416				
Rainfed	61 630	487				
Irrigated						
Single Season	50 226	808	321	383	15	398
Double Season	7 978	1 011	524	42	46	87
Perennial	7 321	1 058	571	26	45	71

For every cropped pixel, potential water savings were defined as the difference between ETact and 0.8 x ETpot. The results per irrigated land use class are provided in Table 20. The conclusion is that deficit irrigation is already commonly applied in Siham. Only a total amount of 7 mcm/yr gross groundwater abstractions could further be reduced to reach 0.8 x ETpot. Since the total abstraction was 105 mcm/yr, this is a reduction of 7%. If sustainable abstraction levels of 105 - 7 = 98 mcm/yr are not in line with the annual recharge, the cropping intensity of 123% should be reduced.

Table 20: Possible water savings for irrigated crops in the Siham study area without effect on production and extent of the irrigated area. Net savings describe the allowable application volume that can be reduced with minimum effects on crop yield

	Area	**Net savings**		**Gross savings** [mcm/yr]		
	[ha]	[mm/yr]	[mcm/yr]	Total	Surface	Ground
Irrigated area	65 525	23	15	33	26	7
Single Season	50 226	18	9	22	22	1
Double Season	7 978	30	2	5	2	3
Perennial	7 321	48	4	6	2	4

4.6 Changes with respect to 2006

In this paragraph changes with respect to 2006 are presented. One should keep in mind that the climatic conditions (i.e. rainfall and reference ET) were not identical for these two years, and that changes in crop water use and groundwater abstraction can also be ascribed to this climatic variability.

The average rainfall for Siham was 455 mm and 486 mm in 2006 and 2010 respectively; 2010 was thus a bit wetter. The reference ET in Siham was 1 982 and 2 042 mm for 2006 and 2010 respectively. The water demand in 2010 is thus slightly higher, and the ET can be expected to be approximately 2 042 – 1 982 is 58 mm higher due to climatic influences, which is not related to differences in irrigation behaviour.

The changes in land use are expressed by three different criteria: the change in green vegetation cover, which is a first indication of different biophysical plant processes; the change of annual cropping intensity; and the change in ranking of water use intensity. Agriculture water use increases in the following order: non-cropped - rainfed single - irrigated single - irrigated double - irrigated perennial. This sequence was defined and discussed in Chapter 3.

The green vegetation cover or NDVI was measured by Modis. The mean 2010 value for NDVI was 0.232. The NDVI was 0.228 in 2006; hence Siham became a little greener (2%).

The annual irrigation intensity has remained rather similar (from 122% to 123%). The change in agricultural land use intensity is demonstrated in Figure 29 and Table 21. It appears that a larger area was irrigated in 2010 (65 525 ha) as compared to 2006 (58 210 ha). This is equal to an expansion in area of 13%. While the overall accuracy of agricultural land use classes is estimated to be 81%, the mapping of changes is expected to be higher, as the bias in crop classification results will persist in both years. Considering that irrigation practices can be estimated at more than 90% accuracy, the 13% change in horizontal expansion can be considered as being true.

Table 21: Changes in land use in the Siham area. Absolute areas for 2010 and 2006 are given as well as the difference between the years (2006-2010).

			2006	2010	Difference [ha]	Difference [%]
Classification	Rainfed		59 751	61 630	-1 879	-3%
	Irrigated	Single Season	45 653	50 226	-4 573	-10%
		Double Season	5 591	7 978	-2 387	-43%
		Perennial	6 966	7 321	-355	-5%
	Non-cropped		216 187	216 353	-167	0%
	Total		334 148	343 509	-9 361	-3%

In Figure 29 the red colours occur in the main agricultural areas, and these are all areas that shifted in land use intensity practices (20%). This is a non-desirable trend that needs to be reversed. The major area (74%) remained unchanged.

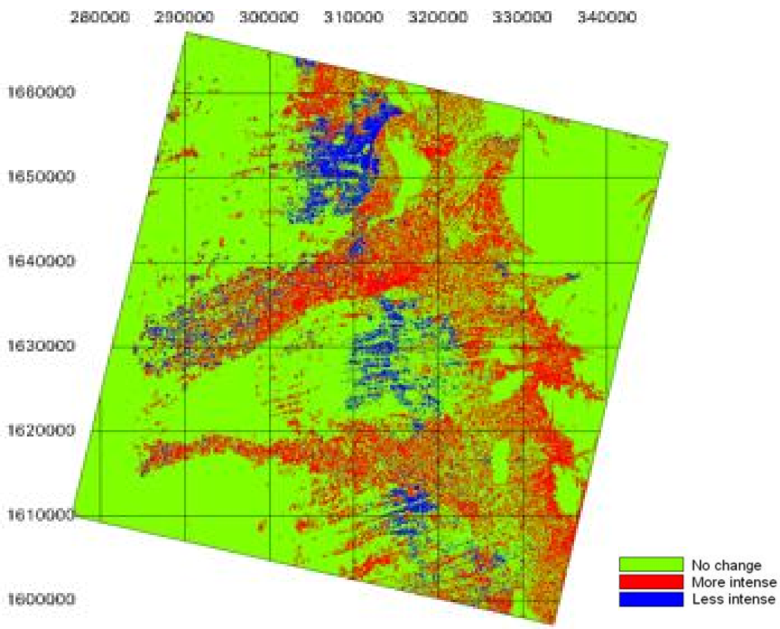


Figure 29: Map of changes in land use in the Siham study area. 5% of the pixels had less intense water use in 2010 than in 2006; 20% was more intense land use and 74% had the same land use as in 2006.

The ET rates have changed slightly. The largest improvement is achieved in the class perennial crops (from 1207 to 1058 mm), being a good signal considering that reference ET increased by 60 mm. The total gross groundwater supply went up from 103 to 105 mcm/yr. The results of Table 21 are consistent with this earlier observation of more intensified agricultural land use. The class “double season irrigated” reveals that groundwater abstractions have increased from 35 to 46 mcm/yr. Groundwater abstraction for perennial crops reduced from 55 to 45 mcm/yr.

Table 22: Changes of actual evapotranspiration and gross groundwater abstraction between 2006 and 2010 for the agricultural land use classes in Siham.

	2006		2010		Difference	
	ET_{act}	Gross groundwater abstraction	ET_{act}	Gross groundwater abstraction	ET_{act}	Gross groundwater abstraction
	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]
Non-cropped	382		416		-34	
Rainfed	470		487		-17	
Irrigated						
Single Season	791	13	808	15	-17	-2
Double Season	1 037	35	1 011	46	26	-11
Perennial	1 207	55	1 058	45	149	10
Total study area	482	103	513	105	-31	-2

The changes in possible water savings between 2006 and 2010 are significant. It seems that the crops experienced higher crop water deficit in 2010 than in 2006. From Table 23 it appears that the potential savings decreased by 85 to 23 mm/yr, a difference of 10 mcm/yr. This shows that deficit irrigation is practices and implemented in Siham. This will be discussed again further down in this report.

It is not clear whether the savings are due to GSCP, a better irrigation water scheduling system, falling groundwater tables or simply a lack of sufficient good quality groundwater. It seems that deficit irrigation – intended or by chance – is a success in Siham.

Table 23: Changes in possible water savings between 2006 and 2010 in study area Siham.

	Area [ha]			Net savings [mm/yr]			Gross groundwater savings [mcm/yr]		
	2006	2010	Dif	2006	2010	Dif	2006	2010	Dif
Irrigated area	58 210	65 525	-7 315	85	23	62	17	7	10
Single Season	45 653	50 226	-4 573	81	18	63	3	1	2
Double Season	5 591	7 978	-2 387	93	30	63	6	3	3
Perennial	6 966	7 321	-355	102	48	54	8	4	4

Main conclusions Siham:

- Rainfall in 2010 was 7% more than in 2006; reference ET was 7% more; Actual crop ET increased for single season crops accordingly.
- The irrigated area has expanded by 13%. More agricultural land use intensive cropping systems have been introduced (20%) and this has resulted into a greener vegetation cover;
- Deficit irrigation is practiced at a large scale. This is one reason that total groundwater abstraction increased only marginally from 103 to 105 mcm/yr, despite the horizontal expansion experienced;
- An amount of 105 mcm/yr was abstracted from aquifers. It is possible to reduce another 7 mcm/yr while keeping up with the same crop production.

5. Dhamar

5.1 General

Dhamar is a typical Yemen highland area, located approximately 50 km south of Sana'a and to the west of Rada (see chapter 6). In contrast to the coastal areas where spate irrigation can be practiced, irrigation water in the highlands originates mainly from groundwater resources and some local stream flow. The GSCP points for intervention are displayed in Figure 31.

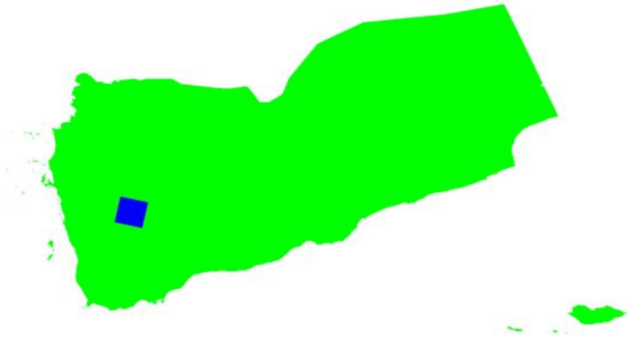


Figure 30: The Area of Interest of the Dhamar study area.

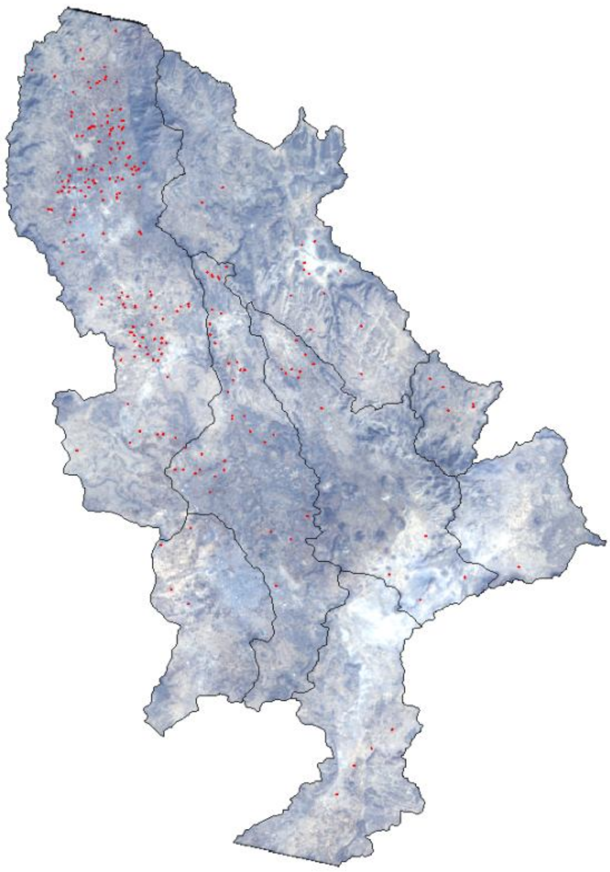
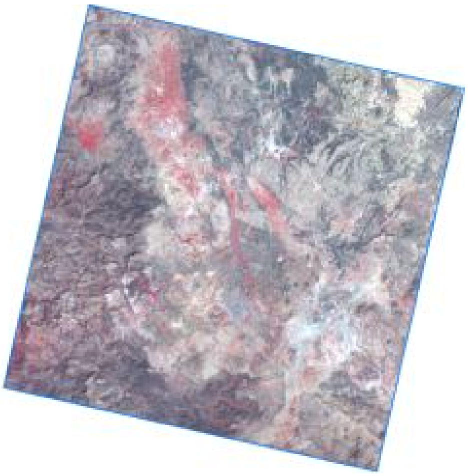
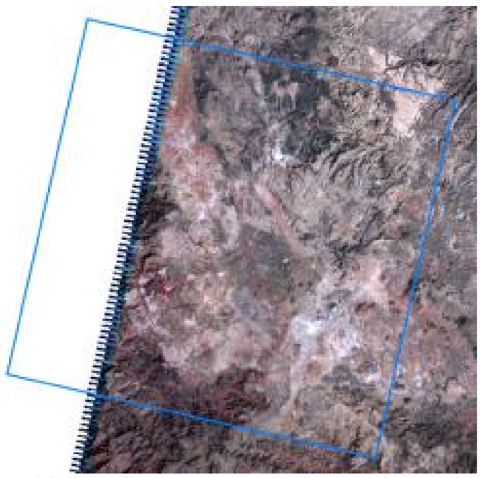


Figure 31: Location of the GSCP intervention schemes in Dhamar.

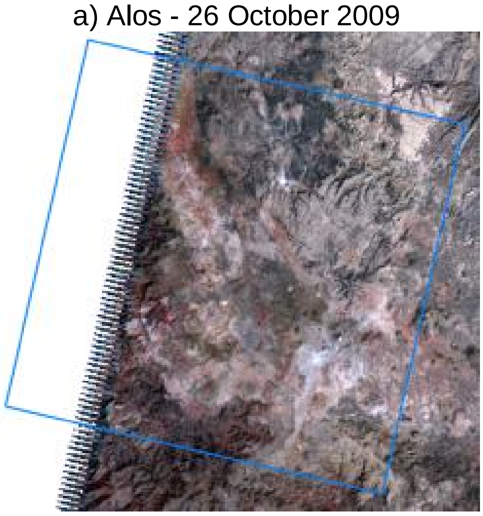
Satellite images made on 12 different days encompass the Dhamar area: 3 images from Alos, 1 from Aster and 8 from Landsat. These 12 image acquisition days are well spread over the year which facilitates the accuracy of the crop classification and determination of water use. The images are shown in Figure 32.



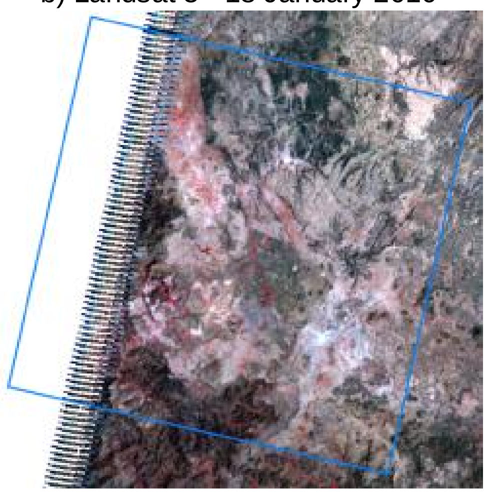
a) Alos - 26 October 2009



b) Landsat 5 - 18 January 2010



c) Landsat 7 - 26 January 2010



d) Landsat 7 - 15 March 2010

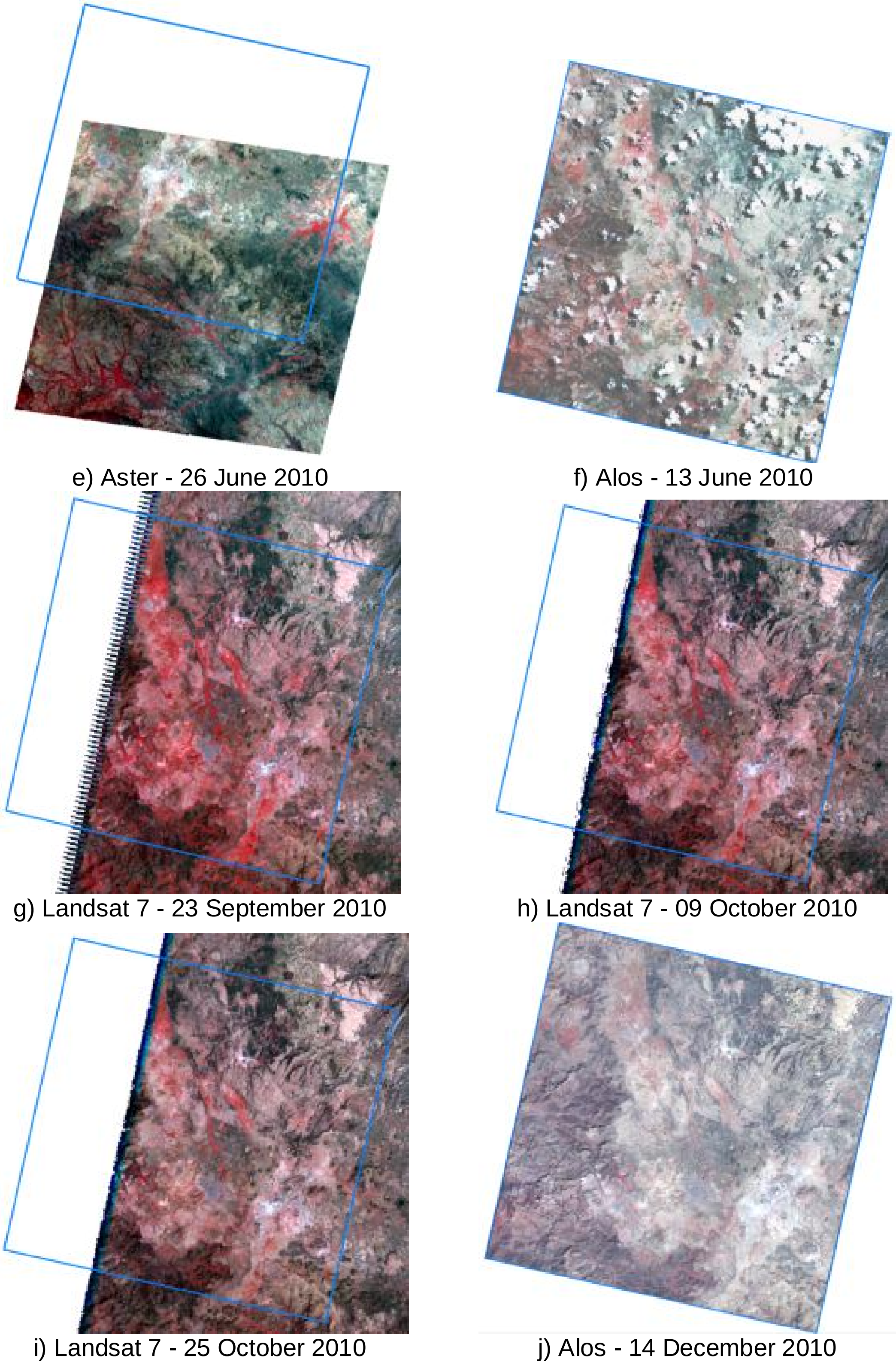


Figure 32: Satellite images of the Dhamar study area. The blue boundary box displays the boundaries of the study area.

5.2 Climate

Figure 33 shows the total monthly rainfall for the Dhamar area in 2010, based on TRMM rainfall data. The south-west of the study area is closer connect to the central highlands of Yemen and receives slightly more rainfall than the north-eastern part of the study area. The average annual rainfall for 2010 is 395 mm for Dhamar. The rainfall variability is bi-modal. June is a dry month in between two consecutive periods of rain. In 2006 the amount of rain is estimated to be 448 mm. The difference between both years is quite large (12%). The first rainfall period (March, April, May) yields more rainfall in 2010 than in 2006, but the second rainfall period (July, August, September) as well as the end of the year are drier in 2010 than in 2006.

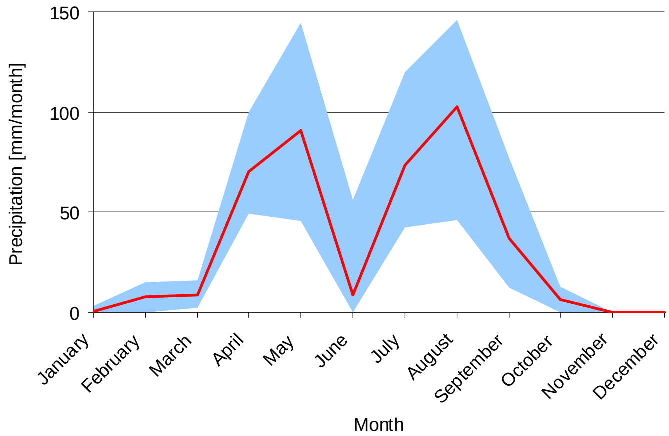


Figure 33: Monthly rainfall for the Dhamar area. The red solid line shows the average rainfall for the total area. The blue area shows the range of rainfall for the total area.

Figure 35 shows the Dhamar study area, with an indication for the location of the meteorological stations of Dhamar [Latitude 14.6° N; Longitude 44.4° E; Altitude 2425 m] and Sana'a shown [Latitude 15.5° N; Longitude 44.2° E; Altitude 2199 m]. The elevations are 2 425 and 2 199 m AMSL for Dhamar and Sana'a respectively. Since the Dhamar meteorological station doesn't have records for most of February and March 2010, the meteorological station of Sana'a is inserted in the graph as well. The temperatures in Sana'a are consistently higher than at Dhamar, but they follow the same pattern of temporal variability. The measurements of these stations from 2010 can be seen in Figure 34.

The meteorological station Dhamar, together with the station in Sana'a, is one of the cooler locations with temperatures below 25°C, due to their higher altitude of 2425 meters. There is an annual pattern in these measurements with temperatures in summer being approximately 10°C higher for Sana'a. The summer temperature is 15°C warmer than the winter situation. Compared to the coastal study areas, the temperature in the highlands is more variable, especially in the first four months of 2010. The reference ET in 2010 is 1 720 mm/yr.

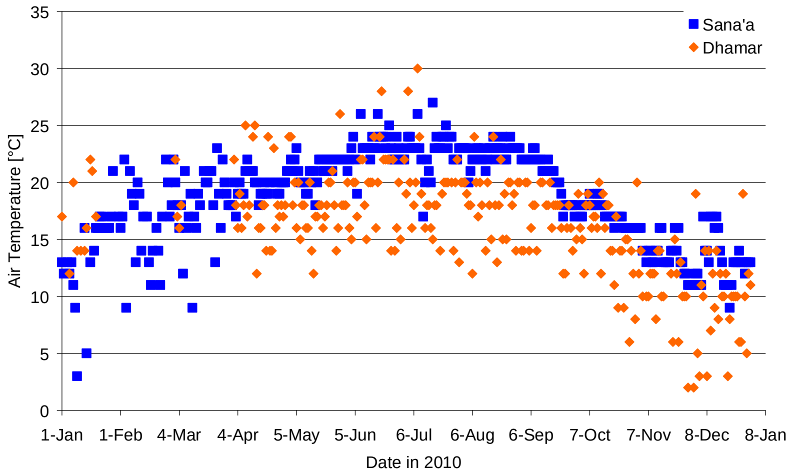


Figure 34: Daily air temperature values [°C] for the year 2010.

Figure 35: The location of the meteorological stations Sana'a (upper blue dot) and Dhamar (blue dot within frame).

5.3 Green vegetation cover

The MODIS satellite measures the NDVI with time intervals of 16 days. This is a good data set to understand the presence of crops and its phenological phases, despite that the spatial resolution is 250 m only. Figure 36 demonstrates the spatial patterns of NDVI during the dry season (February). No clear hot spots of concentrated irrigated land can be found, although areas with the highest NDVI (~0.3) are irrigated areas that grow potatoes, vegetables, wheat and barley at the end of the winter season. The same graph also displays the annual average NDVI values. Some centres with irrigation appear in yellow (NDVI~0.4). From these images it becomes clear that large areas in Dhamar are non-cropped and that the NDVI values are very low throughout the study area. In Dhamar, vegetation is sparse indeed.

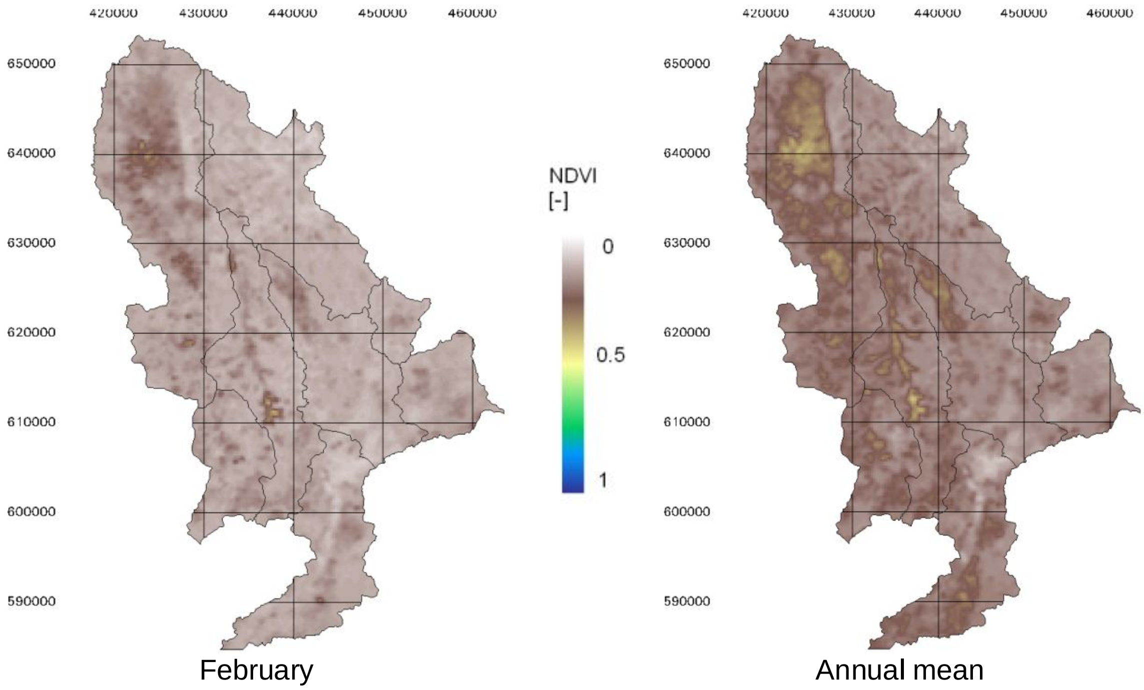


Figure 36: Spatial distribution of the NDVI during February 2010 and the annual mean NDVI.

5.4 Land Use

A large proportion (80%) of the land is non-cropped In the Dhamar study area. Of the land under agriculture approximately 2/3 is used to grow irrigated single season crops. Cropping of rainfed crops is not very popular in Dhamar because the annual rainfall of 395 mm is hardly sufficient for crop cultivation. Irrigation during the summer to compensate for low rainfall is a common practice in June. Double and perennial cropping is uncommon, and they form small pockets of land where this occurs. Dhamar typically hosts single season irrigated crops (18 694 ha). The spatial distribution is shown in Figure 37 and the relative areas are specified in Table 24.

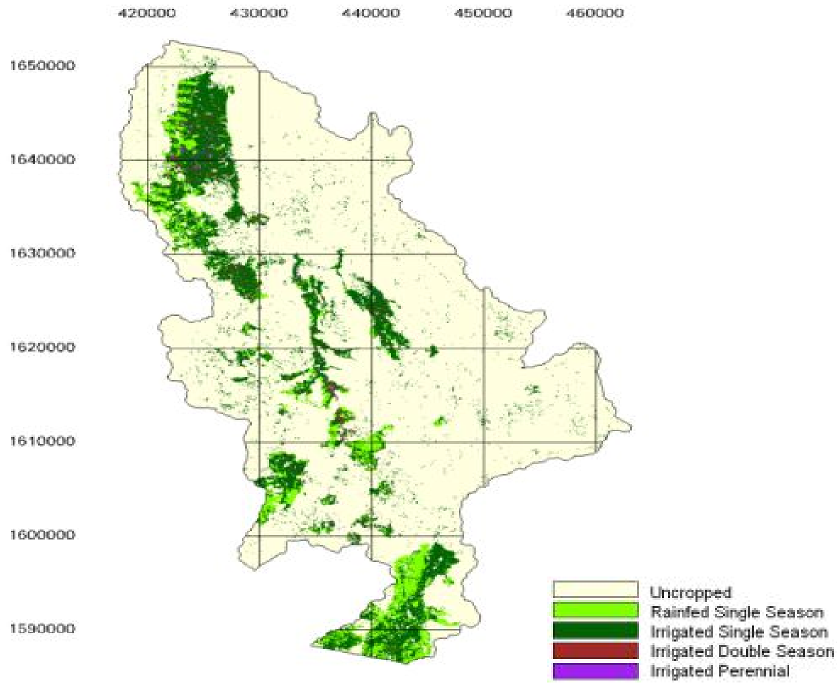


Figure 37: Land use map, Dhamar. A larger size map is given in Appendix 10.

Table 24: Agricultural land use in the Dhamar study area.

				Area [hectare]	% of total	% of cropped
Classification	Rainfed			7 573	5.3%	27.3%
	Irrigated	Single Season		18 694	13.0%	67.5%
		Double Season		923	0.6%	3.3%
		Perennial		518	0.4%	1.9%
	Non-cropped			116 102	80.7%	

In Figure 38 an example is presented of the high resolution satellite images and the resulting classification. Since the Alos images don't cover the main growing season very well, also two Landsat images are shown.

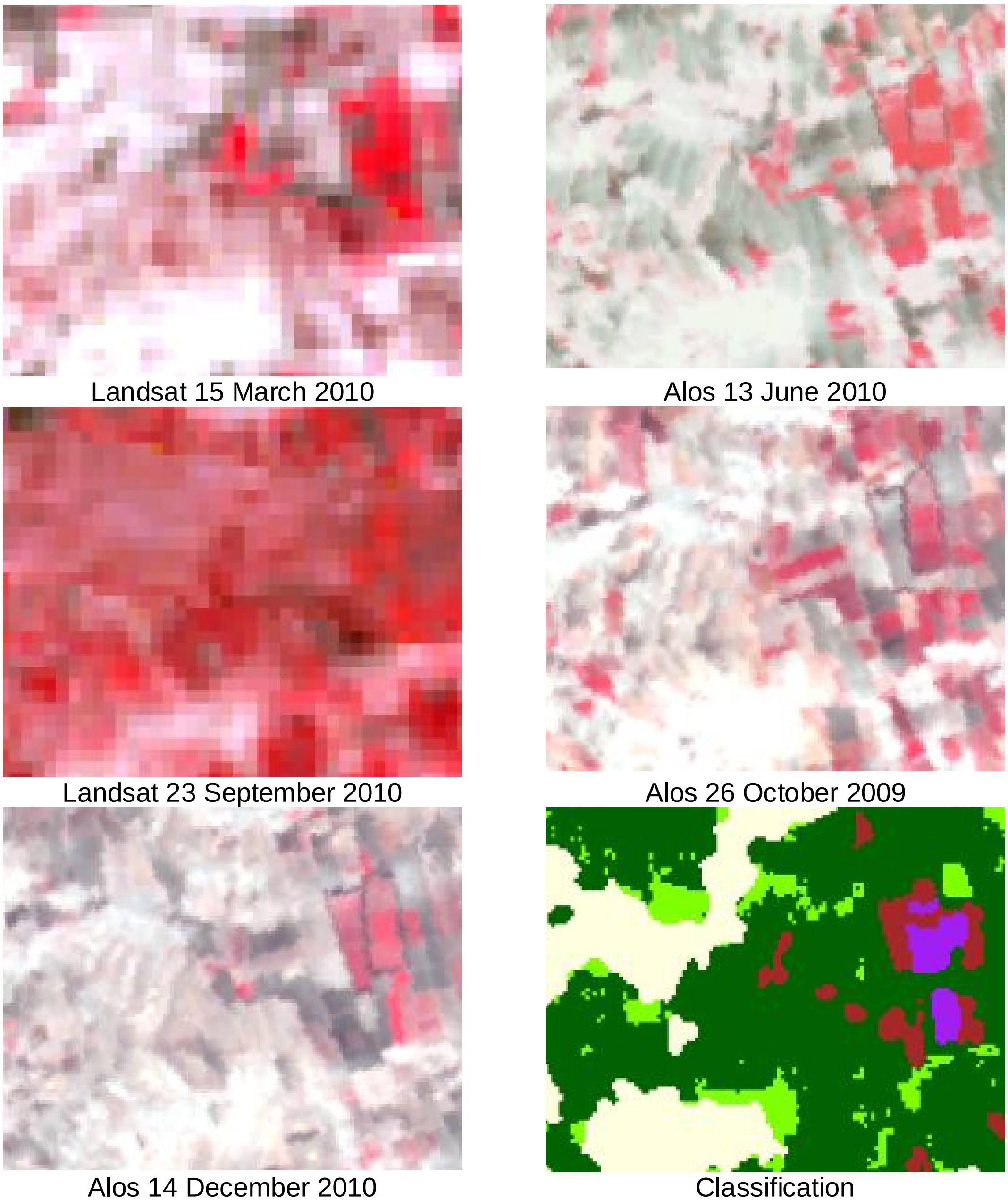


Figure 38: Example of satellite images and classification in Dhamar.

The fieldwork was carried out in March 2011, the year after the satellite images were recorded. The example of Figure 39 shows that in some cases the field identification doesn't match the satellite images acquired during 2010. An example is the blue-outlined field in the lower left corner. Like all outlined fields in this figure, it has been identified as double season crop. In the Alos images it appears bare, with whitish and greenish colours. Similarly the yellow-outlined field in the centre of the figures appears to be bare land on 26 October 2009, 15 March 2010, and 14 December; therefore it has been classified as single season crop.

From Figure 39 it appears that in the field the number of fields with double season crops has been overestimated. 70% of the area visited in the field has been identified as double season. That is at sharp contrast with the 3.3% of the cropped area that was classified as double season from the satellite imagery. At the same time only 3% of the visited area was identified as irrigated single season versus 67.5% from satellite imagery.

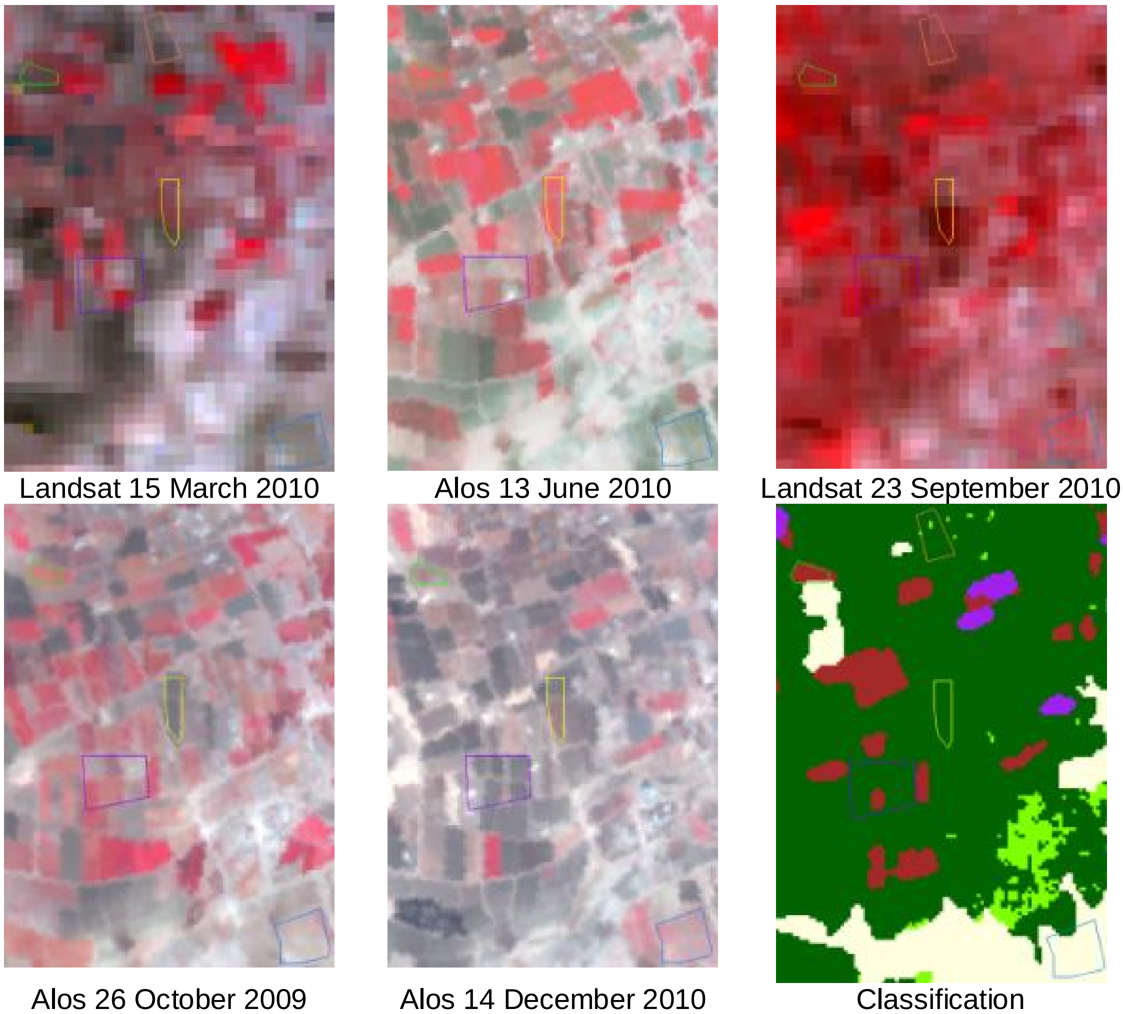


Figure 39: Comparison of satellite images and land use classification for Dhamar, field site d7. Coloured outlines indicate fields that are identified in the field. All fields at this site are identified as double season crops, while the satellite-based classification results in single season crops and for one field even non-cropped.

For the fields shown in Figure 39 and for three other sites of fieldwork a manual classification is done to compare fieldwork, satellite based classification and expert judgement. For the manual classification all high resolution satellite images were displayed in false colour and it was visually determined if there was a crop present in a particular field or not. Some fields were partially covered with crops in some images, so that some fields received two or even three land use classes. The results are shown in Table 25.

From Table 24 it is clear that in most cases both classifications based on satellite images are comparable. The manual classification utilizes more images than the automatic classification procedure, and this is one reason that the image-based results differ. Ten manual classifications – which are assumed to be good – deviate from the automatic classification. A total of 27 cases were considered so this is an accuracy of 63%. The overall accuracy in the 2006 classification for Dhamar was also 63%. Hence, crop identification in Dhamar is not straightforward, and has an accuracy that is lower than being observed for Siham and Rada (see later). The big issue in Dhamar is whether the fields have a crop, or are barren. The crops, even when irrigated, have a very sparse canopy and the background soil reflectance interferes with the canopy reflectance.

The Google Earth image based on GeoEye (in Figure 40) is again bringing extra insight information. It shows that many fields were bare on 20 April 2011, being the date of the Geo Eye satellite overpass. For site d10 it is apparent that the satellite based classification missed the growing season that was captured in the manual classification. These factors have resulted in poor results in the contingency table (see Table 26).

Table 25: Comparison of field identification, satellite based classification and manual classification. Split cells indicate that there were different land uses within a field. Colours are the same as in the land use map.

Site	#	Field identification	Automated classification	Manual classification
d7	1	Double		
	2		Irrigated single	
	3			
	4			
	5		Non-cropped	
d5	3			
	4			
	5			
	6			
	9	Perennial		
	10		Rainfed	
	11			
d9	1			
	2			
	3			
	5			
d10	1			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	12			
	13			

Figure 40: Google Earth excerpt for the Dhamar area, April 2011. The area encompasses the same area demonstrated in Figure 39.

Table 26: Contingency table for the agricultural land use classification of Dhamar. The numbers express the number of pixels; one pixel represents 100 m2.

			Fieldwork				
			Rainfed	Single Season	Double Season	Perennial	**Reliability**
Classification	Rainfed		1224	0	7278	258	14%
	Irrigated	Single Season	0	0	673	0	0%
		Double Season	231	0	566	30	68%
		Perennial	0	0	700	114	14%
	Non-cropped		1816	558	1972	554	
	Accuracy		37%	0%	5%	12%	12%

5.5 Water Use

Figure 41 shows the actual evapotranspiration for the Dhamar study area. The results for the eight administrative areas of Dhamar, called qa's, are described in more detail in Appendix 18. It can be seen that the upper and lower boundaries are cut off, because a small part of those qa's falls outside the study area originally defined. Furthermore it can be seen that areas with high evapotranspiration coincide with the irrigated agricultural areas while the non-cropped areas have lower evapotranspiration. This is also clearly visible in Figure 42.

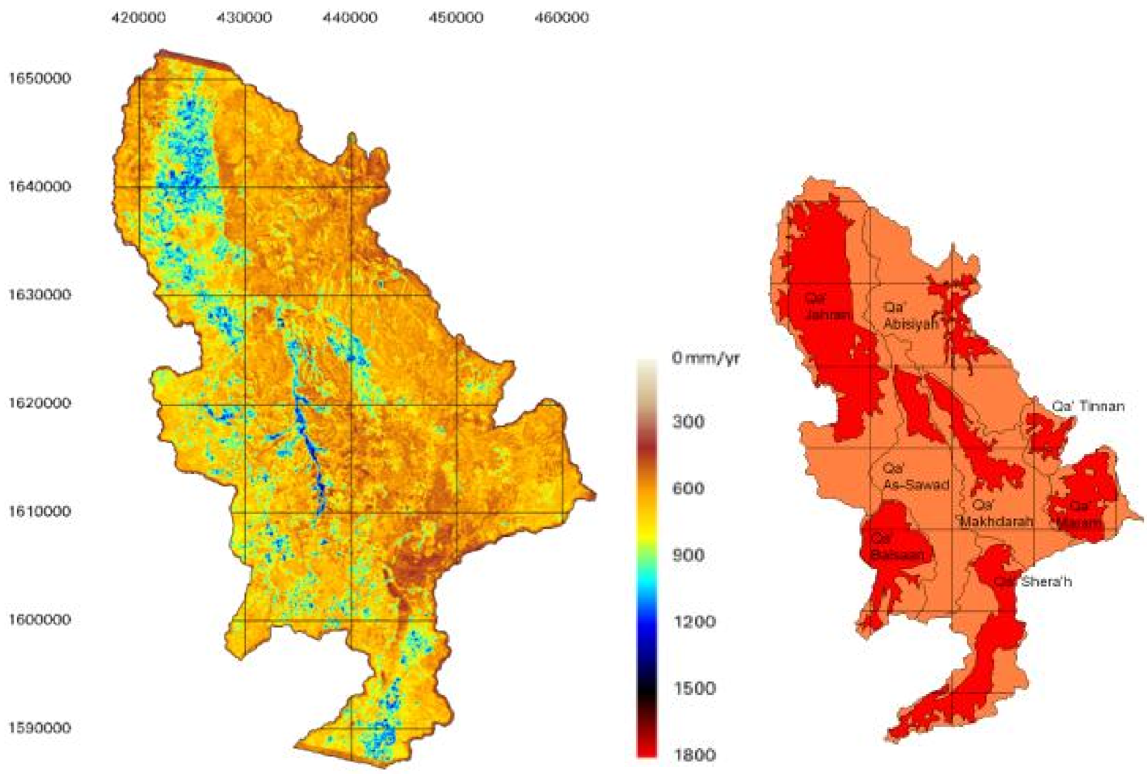
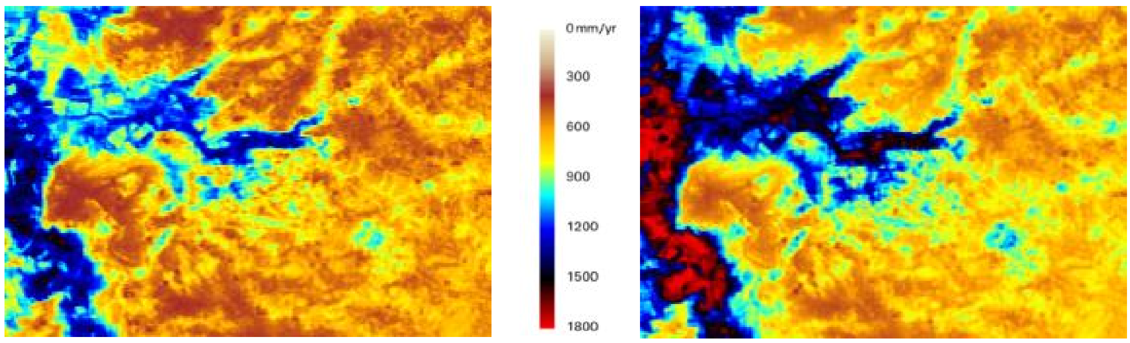
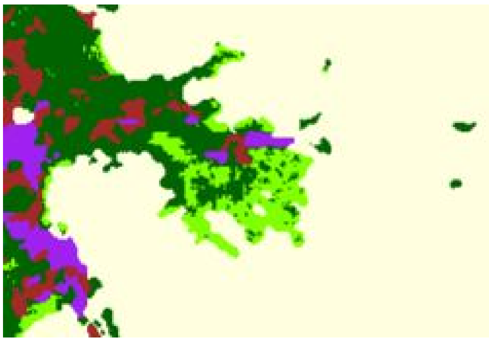


Figure 41: Map of actual evapotranspiration in 2010 for Dhamar. A larger size map is given in Appendix 12; a larger size map of potential evapotranspiration is given in Appendix 14.

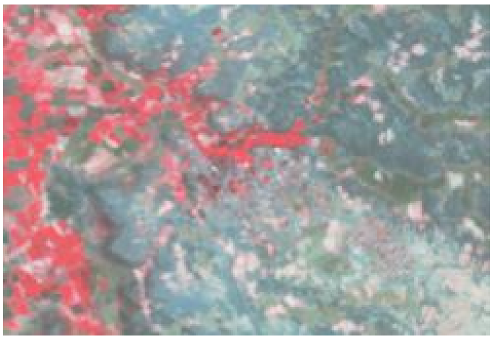
Non-cropped dryland is located at the right hand side of Figure 42. The non-cropped area is visible as dark green-grey in the Alos image of 13 June 2010. The spatial geometry of natural vegetation visible in the Alos image, is also visible in the maps of evapotranspiration. On the left side of the area displayed, there is irrigated agriculture. The evapotranspiration is very high and the highest evapotranspiration coincide with the double season crops and perennial crops.



Actual evapotranspiration Potential evapotranspiration



Land use map 2010



Alos 13 June 2010

Figure 42: Example of actual and potential evapotranspiration.

The main statistics of actual and potential evapotranspiration by land use class are provided in Table 27. From that table it is clear that irrigated crops have a higher water use than rainfed crops and non-cropped areas. The ET of rainfed crops (703 mm), however, exceeds the annual rainfall of 395 mm unrealistically. This demonstrates that either rainfall is too low or shows strong local variability or that ET is too high. The latter explanation is more likely. The difference between single season (922 mm) and double season crop (1 079 mm) is rather low. The over-irrigation during the irrigation season will fill the soil matrix, and residual moisture after the harvest must be in the soil that is evaporated during the fallow period.

Table 27: Actual, potential and reference evapotranspiration for the land use classes of Dhamar. The annual rainfall is 405 mm

	Actual Evapotranspiration		Potential Evapotranspiration		Reference Evapotranspiration	
	Average	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
Non-cropped	630	132	699	154	1 712	43
Rainfed	703	140	812	167	1 672	39
Irrigated						
Single Season	922	173	1079	206	1 685	39
Double Season	1 079	170	1288	210	1 689	28
Perennial	1 174	166	1391	208	1 685	28

The frequency distribution of actual evapotranspiration is given graphically in Figure 43.

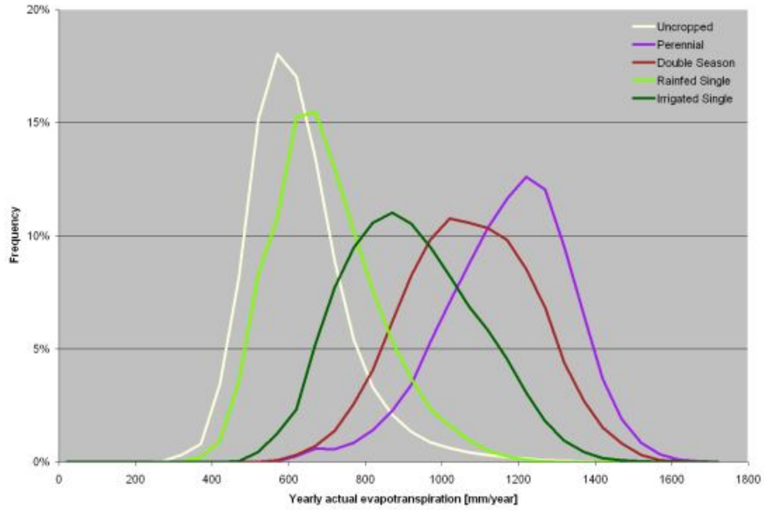


Figure 43: Frequency distribution of total actual evapotranspiration for the year 2010 for different agricultural land use classes in the Dhamar area. Frequencies are calculated on the basis of 50 millimetre intervals.

After estimating the evapotranspiration, the next step is to estimate the gross irrigation supply. The gross irrigation supply is then a result of combining Table 27 and Table 24; the gross irrigation supply is computed per land use class and partitioned between surface water irrigation and groundwater irrigation (see Table 28). The ET of rainfed crop has been forced to be 80% of the rainfall, i.e. 316 mm. The total groundwater abstraction is 204 mcm/yr, out of which an amount of 185 mcm is withdrawn for single season crops. The abstraction from streams and rivers is with 30 mcm/yr rather small.

Table 28: Total irrigation supply to the land use classes in Dhamar.

	Area	Actual Evapo-transpiration	Incremental ET	Gross irrigation supply [mcm/yr]		
	[hectare]	[mm/year]	[mm/year]	Surface	Ground	Total
Total study area	143 810			30	204	233
Non-cropped	116102	630				
Rainfed	7 573	316				
Irrigated						
Single Season	18 694	922	606	28	185	214
Double Season	923	1 079	763	1	12	13
Perennial	518	1 174	858	1	6	7

The opportunities for saving water have been explored. The net savings to reach 0.8 ETpot are marginal and lay in the range between 61 to 71 mm/yr only because ETact/ETpot for single season crops is currently 85%. This translates into a net water saving of 22 mcm/yr without significant detriment to crop production.

Table 29: Possible water savings for irrigated land use classes in Dhamar.

	Area	**Net savings**		**Gross savings** [mcm/year]		
	[hectare]	[mm/year]	[mcm/year]	Total	Surface	Ground
Irrigated area	20 135	66	13	25	3	22
Single Season	18 694	66	12	23	3	20
Double Season	923	61	1	1	0	1
Perennial	518	71	0	1	0	0

5.6 Changes with respect to 2006

The essence of this research is to evaluate the differences between 2006 and 2010. The average rainfall for Dhamar was 448 mm and 395 mm in 2006 and 2010 respectively. The climate in 2006 was thus moister.

The NDVI reveals that the green vegetation cover has increased from 2006 to 2010. The average NDVI in 2006 was 0.180 and it increased to 0.191. Also the February value of NDVI increased from 0.133 to 0.141. Since there is not more rain water available for growth of vegetation, an increase in NDVI indicates an increase in irrigation.

The changes in land use are displayed in Figure 44 and Table 30. The area of single season crops (irrigated) has decreased from 23 042 ha in 2006 to 18 694 ha in 2010; a difference of 19%. In Figure 44 the red colours prevail over blue in the main agricultural areas. This means that agricultural land use there became more intense (8% growth vs. 5% shrinkage). The explanation is that double seasons and perennial crops have gone through a process of horizontal expansion. While the size is controlled by a few hundred ha only, it is an undesirable and unexpected trend that needs to be arrested.

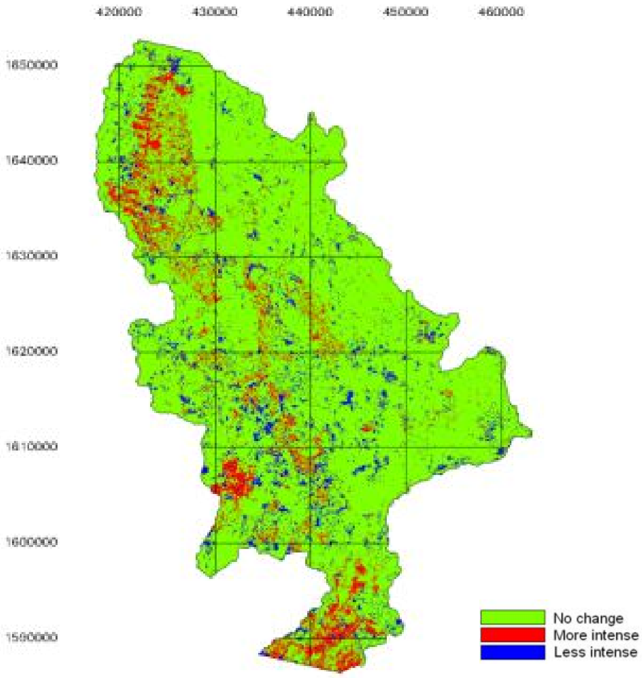


Figure 44: Map of changes in land use of the Dhamar study area. 5% of the pixels has less intense agricultural land use in 2010 than in 2006; 8% is more intense and 87% has the same land use as in 2006.

Table 30: Changes in land use in the Dhamar area. Absolute areas of 2010 and 2006 are given as well as the difference between the years.

			2006	**2010**	**Difference** [ha]	**Difference** [%]
Classification	Rainfed		9 329	7 573	1 756	19%
	Irrigated	Single Season	23 042	18 694	4 348	19%
		Double Season	637	923	-286	-45%
		Perennial	430	518	-88	-20%
	Non-cropped		105 475	116 102	-10 627	-10%
	Total		138 913	143 810	-4 897	-4%

From Table 31 it appears that evapotranspiration per unit of land has increased from 2006 to 2010 even though there was less rain in 2010. This difference might be caused by the increase in green vegetation cover and perhaps by an increase in irrigation supplied to single season crops. Due to the higher ET of single season crops (from 817 to 922 mm); the gross groundwater abstraction has increased from 156 to 204 mcm/yr.

Table 31: Changes between 2006 and 2010 in actual evapotranspiration and gross groundwater abstraction to the land use classes in Dhamar.

	2006		2010		Difference	
	ETact	Gross groundwater abstraction	ETact	Gross groundwater abstraction	ETact	Gross groundwater abstraction
	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]
Non-cropped	372		630		-258	
Rainfed	440		316		124	
Irrigated						
Single Season	817	142	922	185	-105	-43
Double Season	1 212	9	1 079	13	133	-4
Perennial	1 305	5	1 174	6	131	-1
Total study area	457	156	677	204	-220	-48

It seems like the irrigated area in Dhamar has decreased, although the decrease mainly comes from a decrease in single season irrigated crops. With the shrinkage of horizontal expansion, and a vertical expansion of ET, the potential water savings seem to have decreased from 376 mm to 66 mm/yr. The crops in Dhamar are thus more water stressed than before (see Table 32).

Table 32: Changes in possible water savings between 2006 and 2010 in Dhamar.

	Area [ha]			Net savings [mm/yr]			Gross groundwater savings [mcm/yr]		
	2006	2010	Dif	2006	2010	Dif	2006	2010	Dif
Irrigated area	24 109	20 135	3 974	396	66	330	12	22	-10
Single Season	23 042	18 694	4 348	376	66	310	11	20	-9
Double Season	637	923	-286	772	61	711	0	1	-1
Perennial	430	518	-88	865	71	794	0	0	0

Main conclusions Dhamar:

- The irrigated area has decreased by 16%, while the agricultural land use increased slightly with 8% at certain places and reduced by 5% in other places;
- The shrinkage in horizontal area occurred mainly in the class single season irrigated crops;
- The ET of single season crops increased from 817 mm to 922 mm, an increment of 105 mm or 1 050 m^3/ha/yr;
- Deficit irrigation is practiced in Dhamar, most likely due to a lower rainfall in 2006 (405 mm) than in 2006 (508 mm);
- An amount of 204 mcm/yr was abstracted from aquifers, and it is feasible to reduce it by another 22 mcm/yr.

6. Rada

6.1 General

Of the four study areas, Rada is the second highland area. It is located east of Dhamar and has been included for the presence of pockets with high concentration of qat cultivation. The study area covers a part of Wadi Adhanah, which drains towards the desert area in the eastern direction. From the other side of the water divide, Rada feeds the Wadi Bana that drains towards the Gulf of Aden in the western direction.

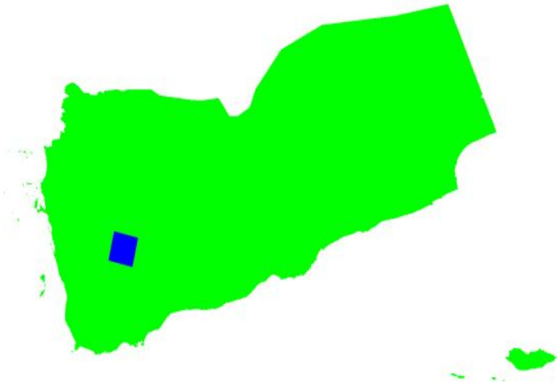
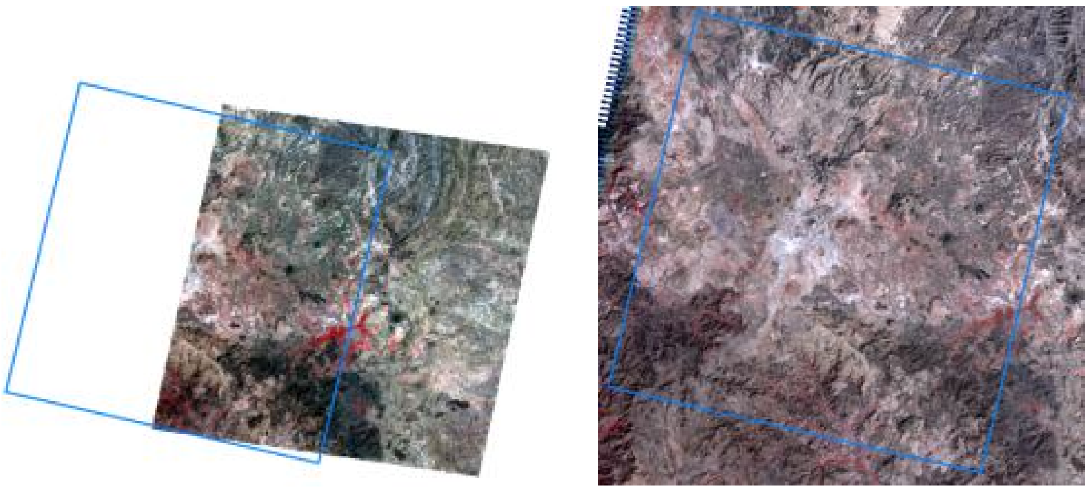
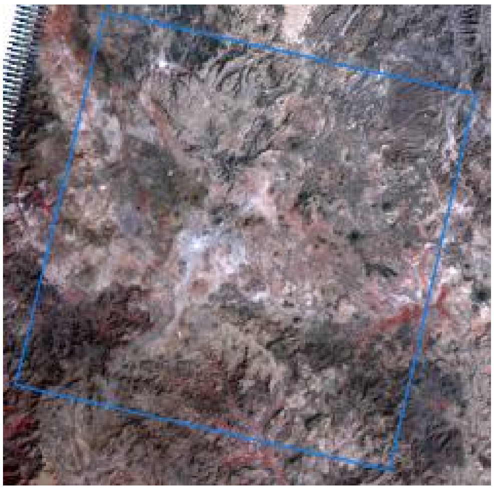


Figure 45: The Area of Interest of the Rada study area.

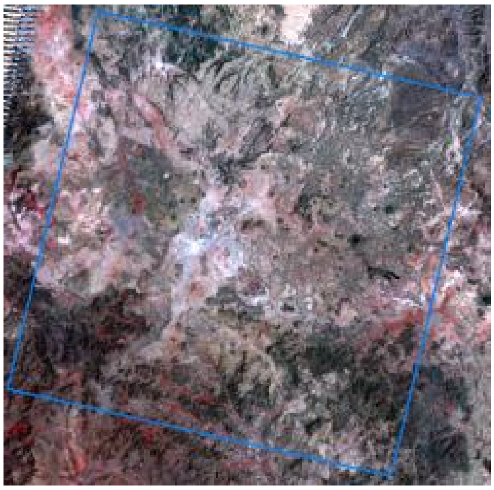
Eleven satellite images are available for Rada: 3 images from Alos; 2 from Aster and 6 from Landsat. These 11 dates are well spread over the year. The images are shown below. The image of 27 May 2010 contains some clouds; they present themselves as white spots with black spots to the left of them. Clouds reflect solar radiation while casting a shadow on the land surface below. Shadowed land surfaces decrease the reflectance from land and can contaminate the classification process.



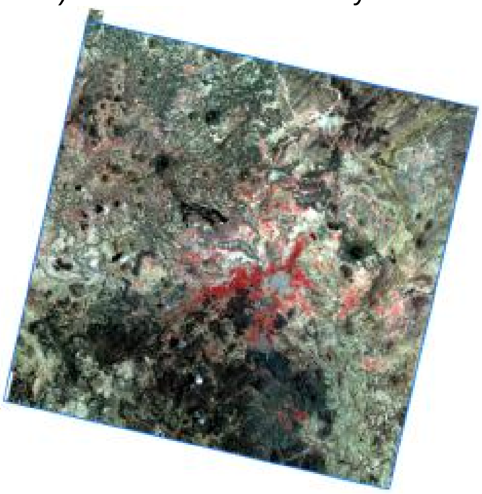
a) Aster - 22 October 2009 b) Landsat 5 - 18 January 2010



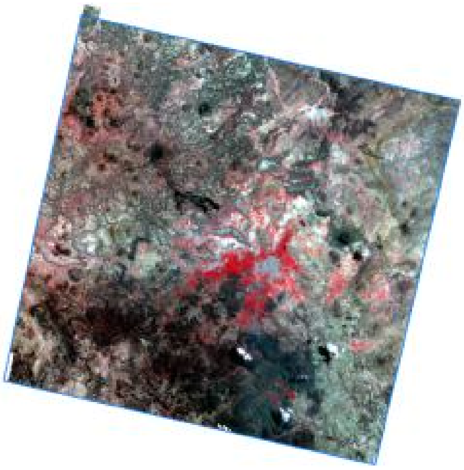
c) Landsat 7 - 26 January 2010



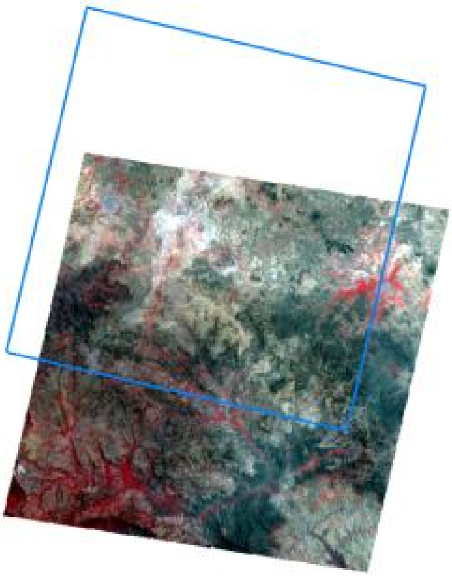
d) Landsat 7 - 15 March 2010



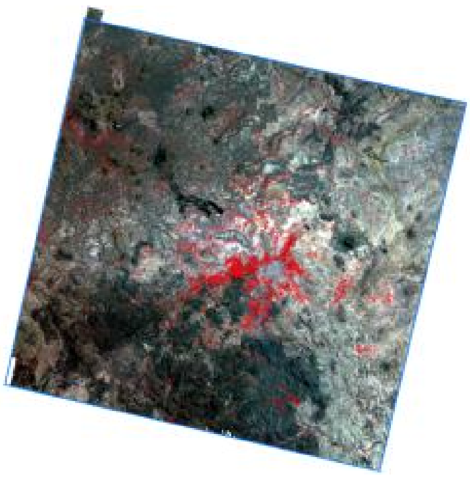
e) Alos - 11 April 2010



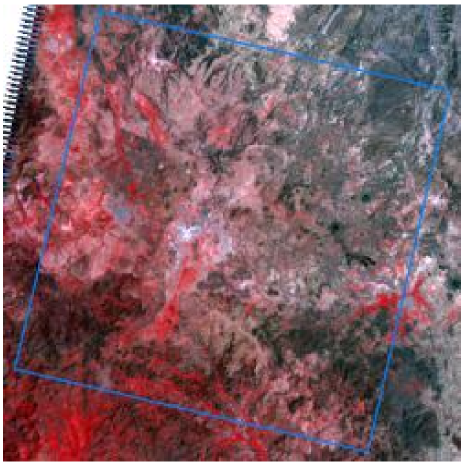
f) Alos - 27 May 2010



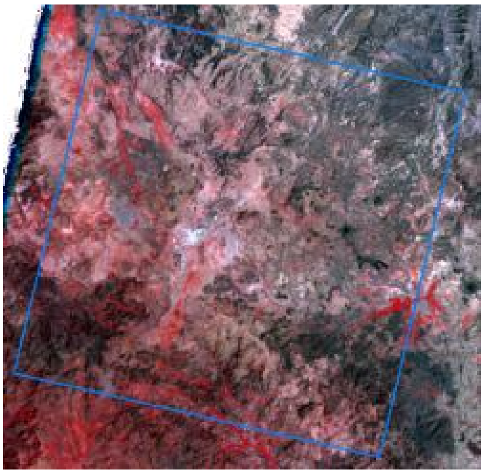
g) Aster - 26 June 2010



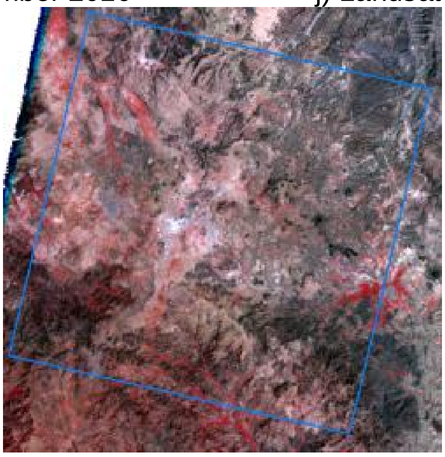
h) Alos - 12 July 2010



i) Landsat 7 - 23 September 2010



j) Landsat 7 - 09 October 2010



k) Landsat 7 - 25 October 2010

Figure 46: Satellite images for the study area Rada. The blue bounding box describes the extent of the study area.

6.2 Climate

Figure 47 shows the total monthly rainfall for the Rada area in 2010, based on TRMM rainfall data. The data from TRMM provides an universal data set on rainfall for every region. The rainfall pattern is very similar to that of Dhamar, caused by the overlap in area. The south-west of the study area receives slightly more rainfall than the north-eastern part of the study area. The average annual rainfall for Rada during 2010 is estimated to be 334 mm/yr. For 2006 the amount of rain was estimated to be 404 mm. The difference between both years is that in 2006 there was a weak rainfall season in February, March, April, May, while in 2010 this first rainfall season yielded more rain. However, the second rainfall period in July, August, September gave less rain, causing a lower total sum over the year. Hence, the low summer rain of 2010 reduces the annual value.

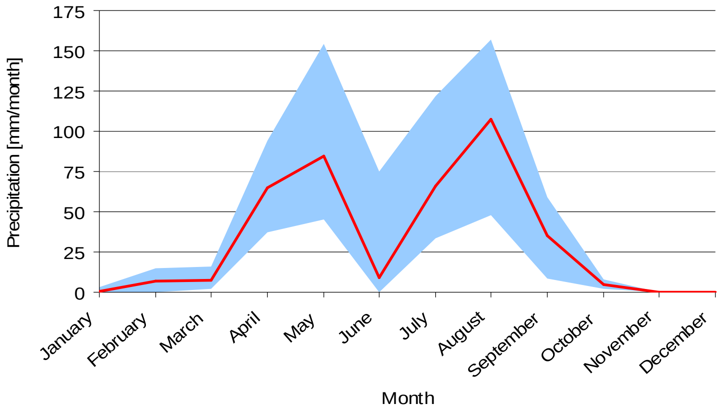


Figure 47: Monthly rainfall for the Rada area. The red solid line shows the average rainfall for the total area. The blue area shows the range of rainfall for the total area.

Since there are no measurements from meteorological stations in the Rada study area available, the same temperature measurements as for the Dhamar study area have been used to describe the climate in Rada. The location of these meteorological stations is shown in Figure 49.

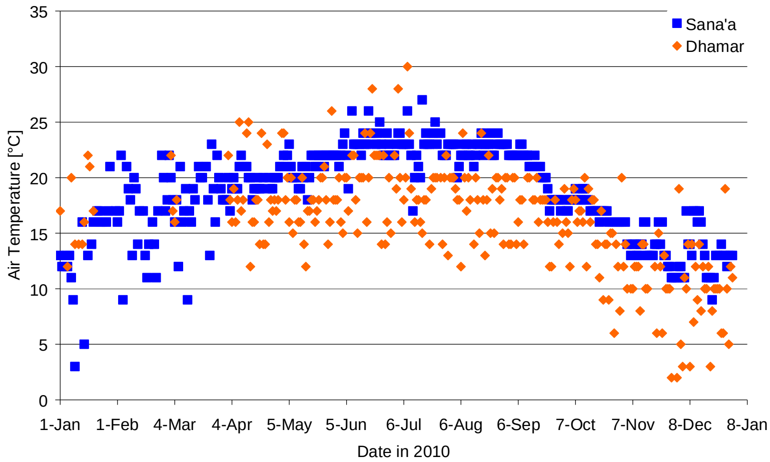


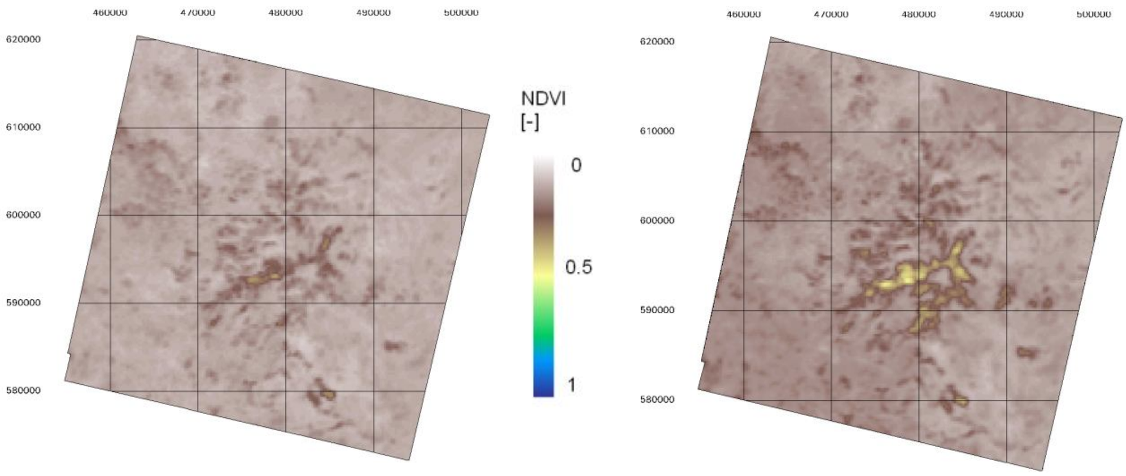
Figure 48: Daily air temperature values [°C] for the year 2010 as being measured at the, Sana'a and Dhamar meteorological stations.

Figure 49: Location of meteorological stations Sana'a (upper blue dot) and Dhamar (lower blue dot) and study area Rada (blue frame).

The reference ET is with a range between 1 740 to 1 835 mm/yr rather high. However, the temperatures measured at Dhamar during the winter season might be too cold for agriculture. November and December have days with night frost.

6.3 Green vegetation cover

Figure 50 demonstrates the spatial patterns of NDVI during the dry season when irrigation is expected to occur. NDVI values hardly exceed 0.3, which means that crop vigour is low due to the prevailing colder temperature regime (10 to 15 C). The same graph also displays the annual mean NDVI for all 24 Modis composites defined in paragraph 2.5. An area with higher NDVI values is present around the town of Rada.



February Average

Figure 50: Spatial distribution of the NDVI in February 2010 and the average NDVI of 2010.

6.4 Land Use

The Rada region hosts 11 203 ha of rainfed crops. Irrigation crops occupy 7 724 ha and the vast majority of the irrigated fields is grown with qat (6 544 ha or 85%) The areal patterns of land use match the NDVI patterns of February remarkably well. The green leaf area index for qat is low in February; otherwise the NDVI values would have been higher. The low NDVI values of irrigated land are nevertheless higher than the surrounding fields, and it portrays a consistent picture with the land use map.

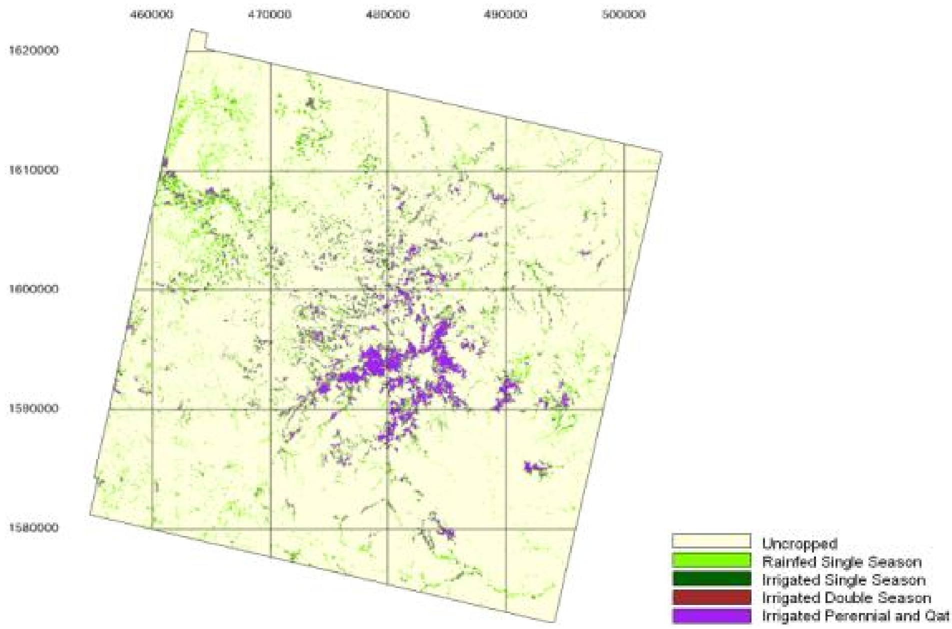
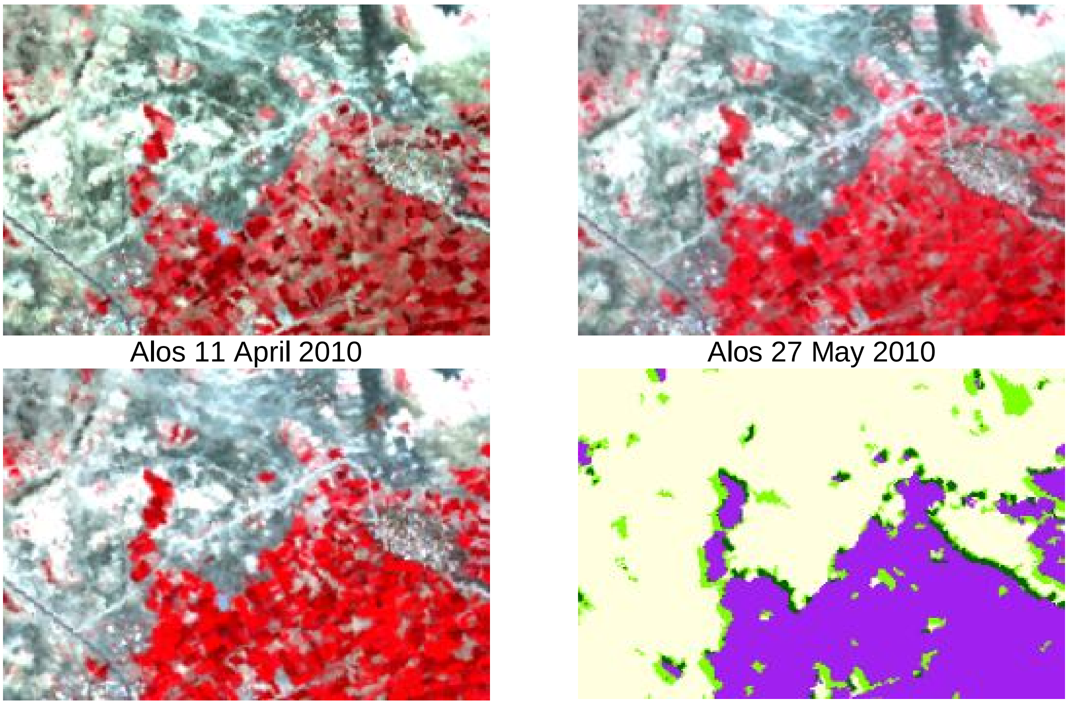


Figure 51: Land use map, Rada. A larger size map is given in Appendix 19.

Table 33: Agricultural land use in the Rada study area.

				Area [hectare]	% of total	% of cropped
Classification	Rainfed			11 203	6.8%	59.2%
	Irrigated	Single Season		1 172	0.7%	6.2%
		Double Season		8	0.0%	0.0%
		Perennial / Qat		6 544	4.0%	34.6%
	Non-cropped			146 301	88.5%	

Figure 52 is an example of the land use classification and the satellite images it is based on. The right lower corner is red in all three Alos images, indicating perennial crops, certainly being qat. The edges of the qat fields are classified as single season crops. That is caused by a small shift in the satellite images and mixed pixels at the edges.



Alos 11 April 2010 | Alos 27 May 2010

Alos 12 July 2010 | Classification

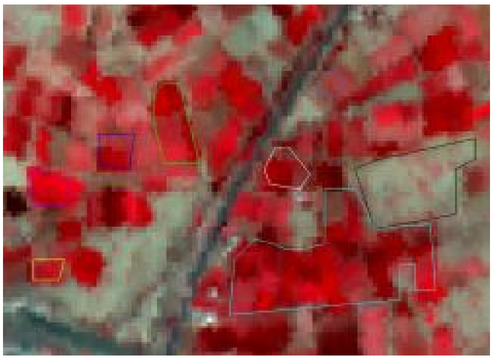
Figure 52: Example of raw satellite images and classification results from the qat areas in Rada.

The agricultural landscape in Rada is rather conserved and will not change rapidly between consecutive years. The variability between the images in 2010 and the fieldwork in 2011 is therefore expected to be minor, and a contingency table can be prepared. Every pixel that was identified during the field visit is checked in the satellite-based classification and the results of the comparisons are given (Table 34). Out of the pixels that were identified as rainfed in the field, 101 pixels were also classified as rainfed by the satellite-based classification. These 101 pixels can then be said to be successfully classified. The 334 + 0 + 550 + 223 pixels that are also identified as rainfed in the field, but which were classified as something else are inaccurate. The 0 + 26 + 411 pixels that are classified as rainfed but which are identified in the field as something else are unreliable.

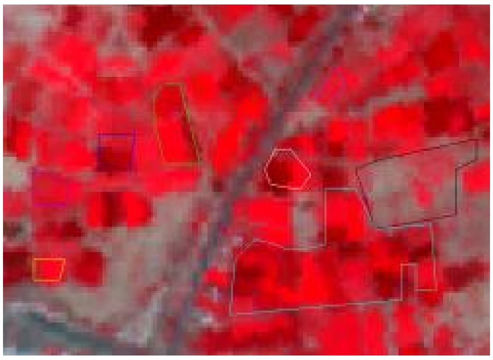
Table 34: Contingency table for the agricultural land use classification of Rada. The numbers are given for pixels; one pixel represents 100 m^2.

Classification			Fieldwork: Rainfed	Fieldwork: Single Season	Fieldwork: Double Season	Fieldwork: Perennial / Qat	Reliability
Classification	Rainfed		101	0	26	411	19%
	Irrigated	Single Season	334	1	114	512	0%
		Double Season	0	0	0	0	
		Perennial / Qat	550	11	496	18576	95%
	Non-cropped		226	150	189	359	
Accuracy			8%	1%	0%	94%	85%

The contingency table shows that the land use classification for Rada is successful. Especially for qat, the reliability and accuracy are high. A possible explanation for this result is that qat is easy to identify in the field; that between 2010 and March 2011, when the fieldwork was carried out, not much changed in the qat fields; and that qat is easily distinguished by satellite imagery. The classification of the other land use classes is less successful due to the rotational crop schedule as expected.

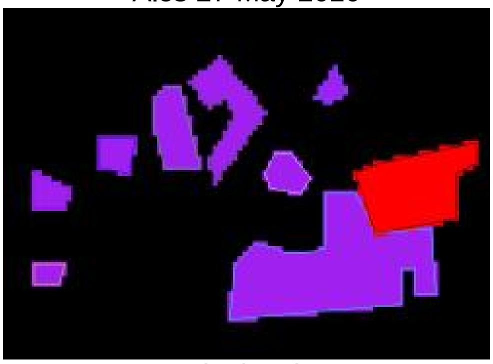


Alos 11 April 2010

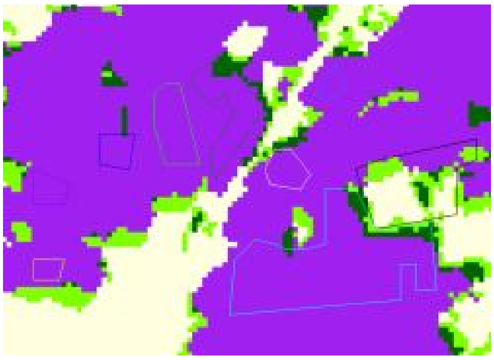


Alos 27 May 2010

Alos 12 July 2010



Fieldwork



Classification

Figure 53: Comparison of satellite images, field identification and land use classification for Rada, field site r18. Coloured outlines indicate fields that have been visited in the field.

For the fields shown in Figure 53 and for two other sites of fieldwork a manual classification is done to compare fieldwork, satellite based classification and common sense. For the manual classification all high resolution satellite images were consulted.

The main conclusion from this comparison seems to be that the field identification and the automated satellite based classification agree quite reasonable in Rada.
A screenshot was taken from Google Earth to add extra information (see Figure 54). Unlike the Google Earth imagery available for Siham and Dhamar, the image of Rada is not recently updated. Instead the situation of May 2004 is shown. All dark green areas on Google Earth are qat fields. The fallow land parcels in 2004 are covered by qat in 2010. This indicates that agriculture in Rada has intensified.

Figure 54: Google Earth excerpt for the Rada area, May 2004. The area is identical to the classification example demonstrated in Figure 53.

Table 35: Comparison of field identification, satellite based classification and manual classification. Split cells indicate that there were different land uses within a field. Colours are the same as in the land use map.

Site	ID	Field identification	Automated classification	Manual classification
r18	1	Qat		Irrigated single
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	11			
	12			
	13			
	15			
	16	Rainfed	Non-cropped	
r15	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			
	12			
	13			
	14			
	15			
r16	1			
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9			
	10			
	11			

6.5 Water Use

The evapotranspiration map of Rada is presented in Figure 55. A larger version of that map is given in Appendix 21; the potential transpiration is given in Appendix 23. The ET of non-cropped land is 224 mm. The rainfall was 334 mm, and the ET is only a fraction of that (~65%). The background ET is low and all irrigated crops have an ET that is approximately two times the value related to dry land vegetation. This can also be seen in Figure 56 and

Table 36, with an evapotranspiration rate of 224 mm/yr for non-cropped pixels and more than 542 mm/yr for pixels with qat. The evapotranspiration of qat is expected to be higher, as it is often associated as being a large water user. Qat does, however, not evaporate potentially (84% of ETpot) and the leaves of the shrubs do not fully cover the ground. Whereas the water use for one shrub can be high, the field-averaged values are moderate. Note that the green vegetation cover in February is relatively low (Figure 50).

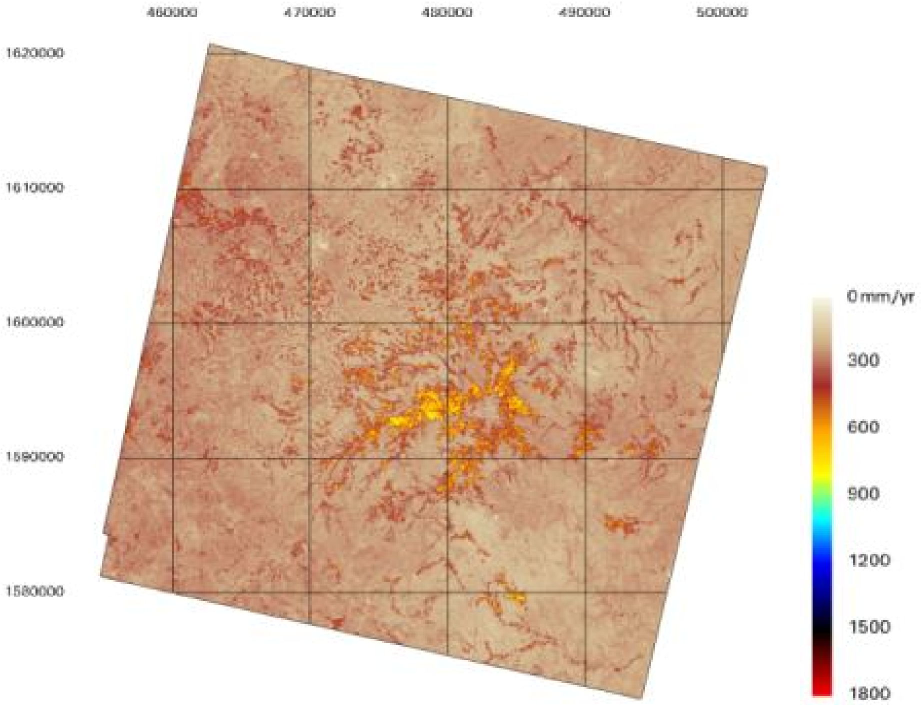


Figure 55: Map of actual evapotranspiration in 2010 for Rada.

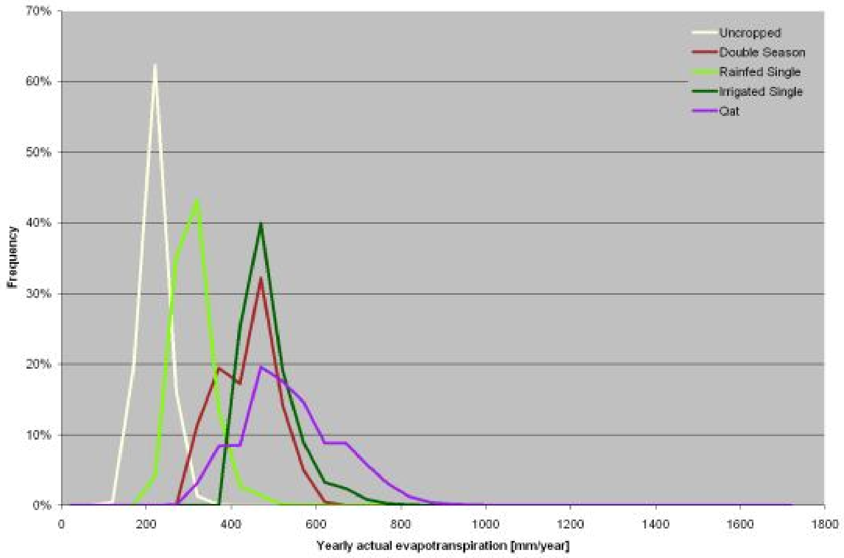


Figure 56: Frequency distribution of total actual evapotranspiration for the year 2010 for different agricultural land use classes in the Rada area. Frequencies are calculated on the basis of 50 millimetre intervals.

Atroosh and Moayad (2012) estimated after soil water balance field experiments on 6 different farms that crop ET of irrigated qat shrubs to vary between 603 to 787 mm/yr. Rainfed qat turned out to have a lower ET of 413 to 506 mm/yr. These authors report an average ET of 554 mm/yr, being 2% different from the 542 mm estimated in this study.

Table 36: Actual, potential and reference ET for the land use classes of Rada in mm/yr.

	Actual ET		Potential ET		Reference ET	
	Average	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
Non-cropped	224	31	297	34	1 835	134
Rainfed	315	44	398	49	1 807	119
Irrigated						
Single Season	495	62	595	69	1 855	83
Double Season	444	69	539	75	1 740	103
Perennial and Qat	542	116	649	129	1 830	80

In Figure 57 an example is given of how the ET is related to land use classes. The dark area in the lower half of the Alos images is non-cropped natural area; the whitish areas on the right and left are non-cropped urban areas. The ET in those areas is low. The areas that appear red in the satellite images are irrigated qat areas. The field boundaries cause sharp boundaries on the water use maps. Pockets with higher values can be found: this spatial geometry is typical for groundwater irrigation systems: they have isolated fields that receive water from a well, while neighbouring fields are dry land.

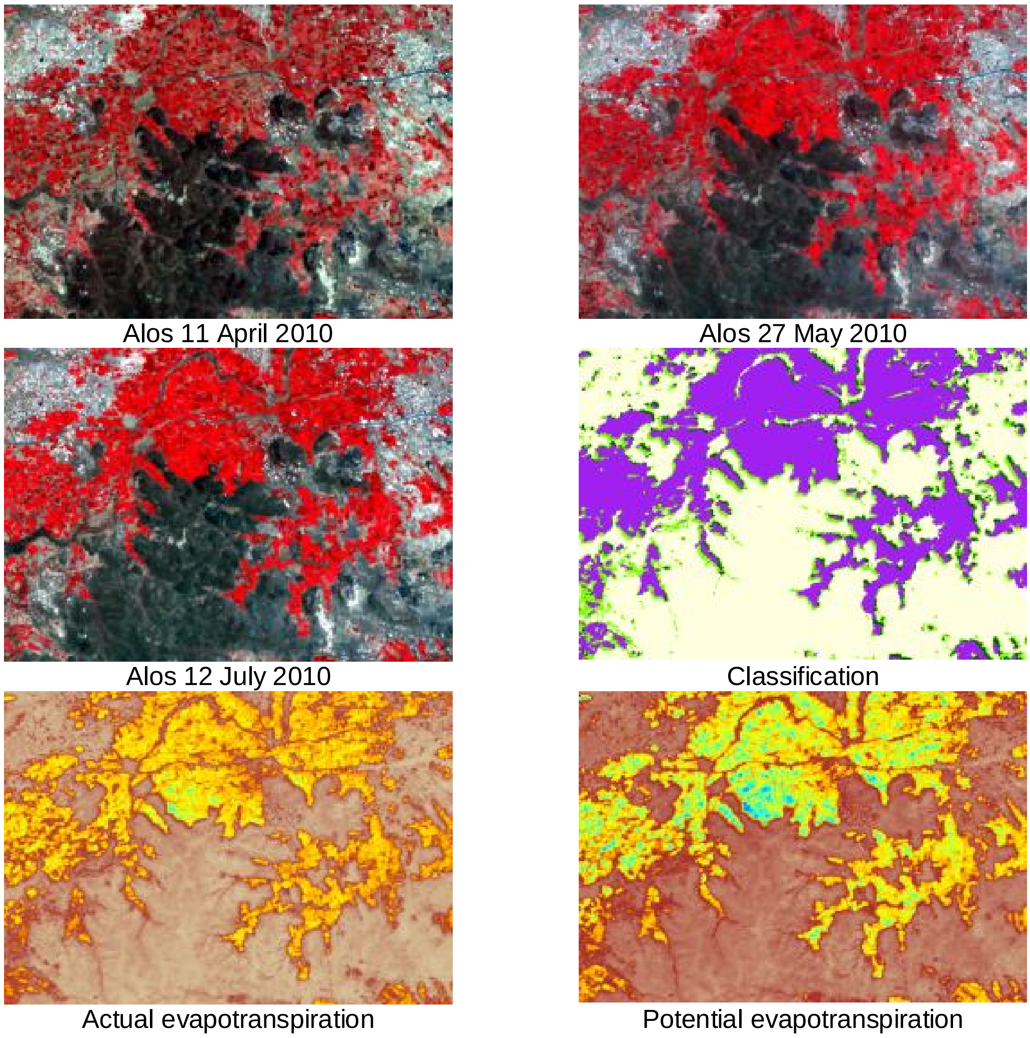


Figure 57: Example of actual and potential evapotranspiration.

The next step is to estimate the amount of groundwater being supplied to the qat fields. The results are shown in Table 37. The incremental ET for qat is 228 mm. At 70% efficiency and 100% groundwater resources, this is an amount of 325 mm or 3 257 m^3/ha. Atroosh and Moayead (2012) mention irrigation applications to vary between 1 700 and 5 200 m^3/ha during 2 to 7 irrigation turns. This large variability can be ascribed to the rainfall situation. The average value of 3 257 m^3/ha is thus plausible. All together, Dhamar extracts an amount of 21 mcm/yr from its underlying aquifers.

Table 37: Total irrigation supply to the land use classes in Rada.

	Area	Actual Evapo-transpiration	Incremental ET	Gross irrigation supply [mcm/yr]		
	[ha]	[mm/y]	[mm/yr]	Surface	Ground	Total
Total study area	165 228	245	-70	1	21	22
Non-cropped	146 301	224				
Rainfed	11 203	315				
Irrigated						
Single Season	1 172	495	180	1	3	4
Double Season	8	444	129	0	0	0
Perennial and Qat	6 544	542	228	0	18	18

The opportunity to save water resources has been computed. The results are given in Table 38. It is clear that deficit irrigation will not result in much extra groundwater savings (2 mcm/yr only).

Table 38: Possible water savings for irrigated land use classes in Rada.

	Area	Net savings		Gross savings [mcm/year]		
	[ha]	[mm/yr]	[mcm/yr]	Total	Surface	Ground
Irrigated area	7 724	22	2	3	1	2
Single Season	1 172	18	0	1	1	0
Double Season	8	12	0	0	0	0
Perennial and Qat	6 544	23	1	3	1	2

6.6 Changes with respect to 2006

The rainfall during 2006 was 404 mm, and this has reduced to an amount of 334 mm during 2010. The ETref during 2010 was 1 723 mm/yr, which is lower than the 2 018 mm of reference ET in 2006. These characteristics show the arid climate of Rada.

The NDVI reveals that the green vegetation cover has increased especially in February (from 0.124 in 2006 to 0.131 in 2010). The annual mean only increased from 0.164 to 0.165. This indicates that more irrigation is applied in 2010 to accommodate plant growth in February, a dry month. At the same time the vegetation cover of natural vegetation and rainfed crops decreased due to the lower amount of rainfall, thereby compensating in the annual mean NDVI.

The agricultural land use systems remained for 85% intact as compared to 2006. Transformation of crop land always occurs, and 7% cultures were less intense, and 8% is more intense. Hence, the net effect is insignificant. The extent of the irrigated area has been kept rather conserved.

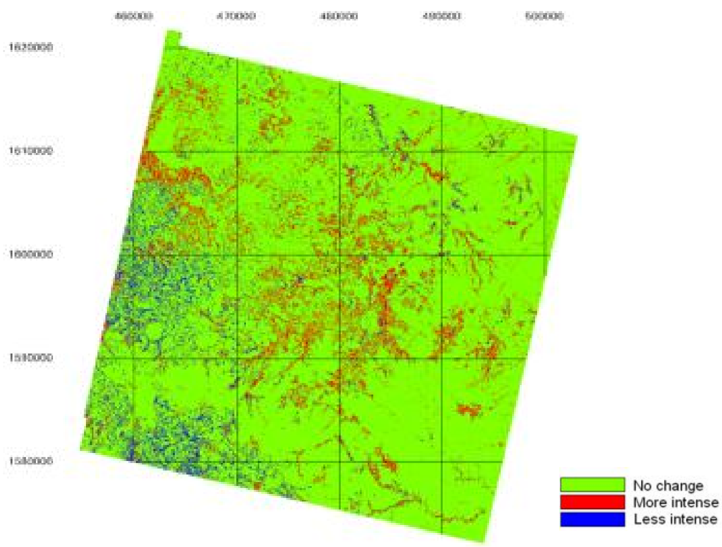


Figure 58: Map of changes in land use of the Rada study area. 7% of the pixels has less intense land use in 2010 than in 2006; 8% is more intense and 85% has the same land use.

From Figure 58 and Table 39 it appears like not much has changed. That impression mainly comes from the consistency in non-cropped area.

Table 39: Changes in land use in the Rada area. Absolute areas of 2010 and 2006 are given as well as the difference between the years.

			2006	2010	Difference [ha]	Difference [%]
Classification	Rainfed		10 495	11 203	-708	-7%
	Irrigated	Single Season	926	1 172	-246	-27%
		Double Season	9	8	1	11%
		Perennial / Qat	6 294	6 544	-250	-4%
	Non-cropped		145 248	146 301	-1 053	-1%
	Total		162 972	165 228	-2 256	-1%

Although the land use did not change much, the estimated irrigation supply did change. This can be understood from Table 40. From that table it becomes clear that the rate of evapotranspiration of the rainfed pixels decreased a lot. Indeed, the rainfall in 2010 was 17% lower as compared to 2006. A rainfall of 334 mm and ET of 315 mm is plausible.

The gross irrigation supply has increased from 11 mcm/yr in 2006 to 18 mcm/yr in 2010. This finding reveals that rainfall variability has large impact on groundwater abstraction. It would be better to include multiple years of data.

Table 40: Changes between 2006 and 2010 in actual evapotranspiration and gross groundwater abstraction for the land use classes of Rada.

	2006		2010		Difference	
	ETact	Gross groundwater abstraction	ETact	Gross groundwater abstraction	ETact	Gross groundwater abstraction
	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]
Total study area	252	13	245	21	7	-8
Non-cropped	222		224		-2	
Rainfed	434		315		119	
Irrigated						
Single Season	548	2	495	3	53	-2
Double Season	705	0	444	0	261	0
Perennial / Qat	587	11	542	18	45	-6

While the potential savings in 2006 were 13 mcm/yr, this has aggravated to a level of 18 mcm/yr in 2010. The latter 14% of the absolute abstraction rates. Hence, it is feasible to pump 14% less without noticeable effects on crop production.

Table 41: Changes in possible water savings between 2006 and 2010 in Rada.

	Area [ha]			Net savings [mm/yr]			Gross groundwater savings [mcm/yr]		
	2006	2010	Dif	2006	2010	Dif	2006	2010	Dif
Irrigated area	7 229	7 724	-495	16	22	-6	1	2	0
Single Season	926	1 172	-258	19	18	1	0	0	0
Double Season	9	8	-1	7	12	-5	0	0	0
Perennial	6 294	6 544	-250	14	23	-9	1	2	-1

Main conclusions Rada:

- Rainfall in 2010 was 17% less than in 2006;
- The horizontal expansion or shrinkage in Rada is neglegible; Rada represents a typical conserved agricultural landscape
- The vegetation cover has become greener in February, presumably due to increased irrigation; this is compensated annually by the less vigorous vegetation of non-cropped and rainfed crops, which is due to the lower rainfall;
- Independent field work has provided new insights in the water balance of qat. The average ET of qat is 554 mm/yr and the remote sensing estimates differ only 2% from the field measurements;
- Deficit irrigation is practiced at a large scale (ETact = 0.84 x ETpot)
- An amount of 21 mcm/yr was abstracted from aquifers. It is possible to reduce another 3 mcm/yr without changes in irrigated area and crop production;

7. Abyan

7.1 General

Abyan is a delta at the coast of the Gulf of Aden. Like the Siham study area, Abyan is a flat study area with parallel streams that carry water excess from the mountains towards the Arabian Sea. The three major wadis in the study area – from West to East - are called Wadi Suhaybiyah, Wadi Bana and Wadi Hassan.

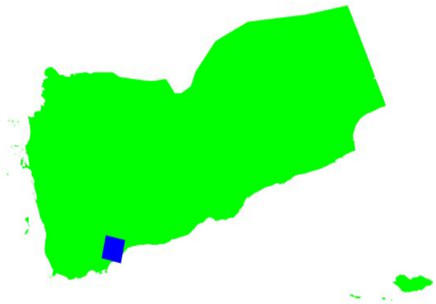


Figure 59: The Area of Interest in Abyan.

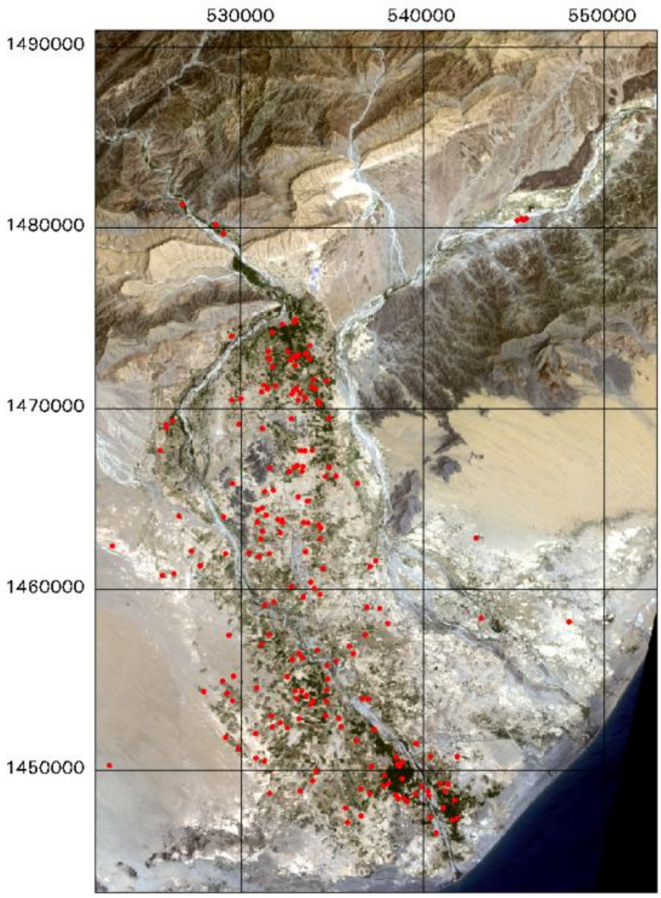
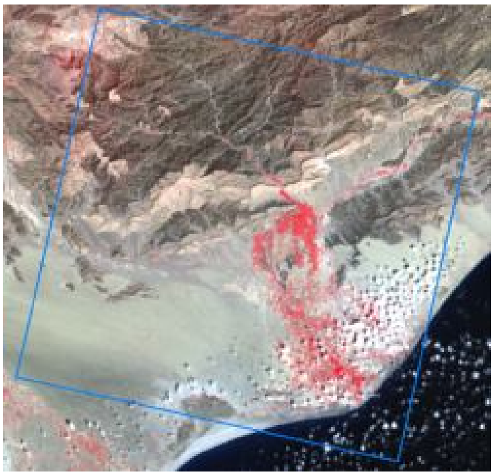


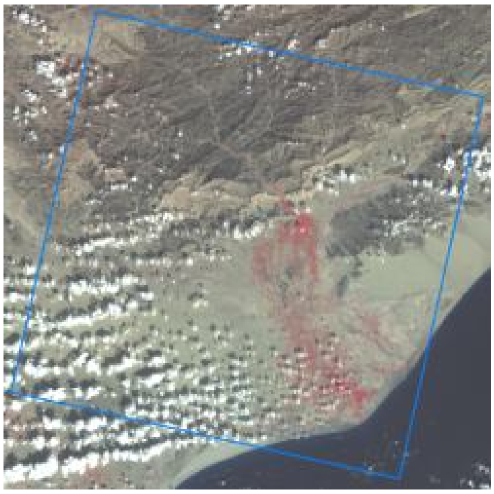
Figure 60: Location of the GSCP interventions points in the Abyan area.

Abyan is a spate irrigation system by origin, with most spates coming from runoff in Wadi Bana and a smaller fraction from Wadi Hassan. The irrigation water is distributed by a system of canals. Groundwater is used as an additional source of irrigation water to amend the shortage of surface water resources, especially for the fruit plantations in both the upper and the lower end of the wadi.

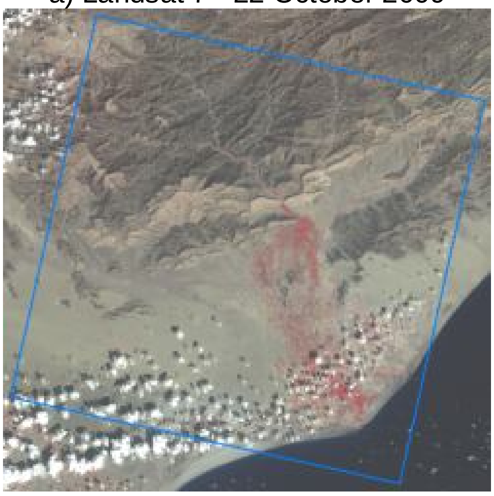
For Abyan less satellite images are available: 2 images from Alos; none from Aster and 6 from Landsat. Those images are shown below. The images are displayed in so-called False Colour composite. High near-infrared reflectances are shown as bright red in the images; these red areas contain vigorous crops and plants that have access to water, also during the dry season. The black area in the lower left corner is the water of the Gulf of Aden. The first 3 and also the last Landsat images have white spots with shading effects: those are clouds. Furthermore the mountains in the upper half of the images show up in dark colours while the non-cropped parts of the plain have light colours.



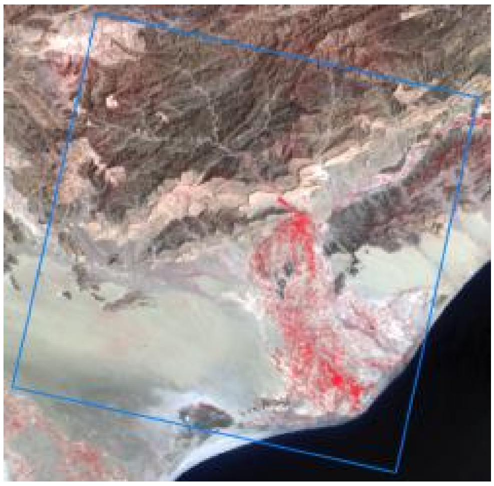
a) Landsat 7 - 22 October 2009



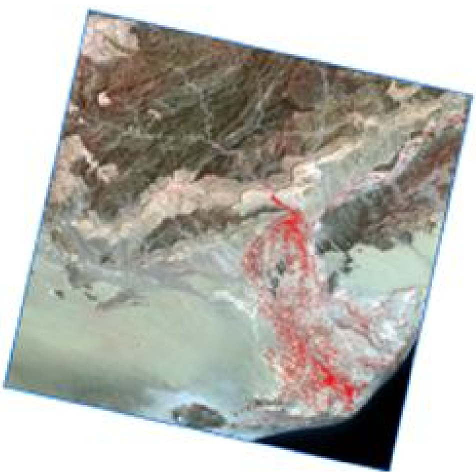
b) Landsat 5 - 17 December 2009



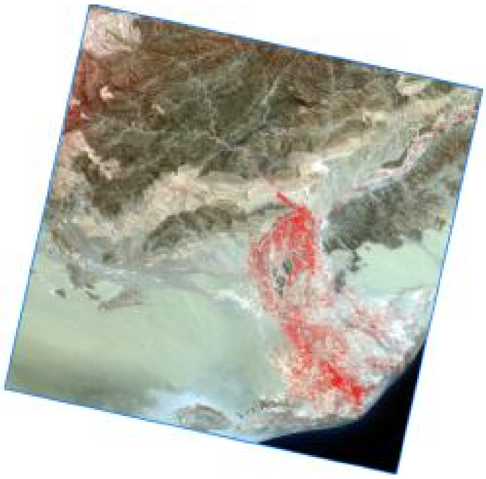
c) Landsat 5 - 18 January 2010



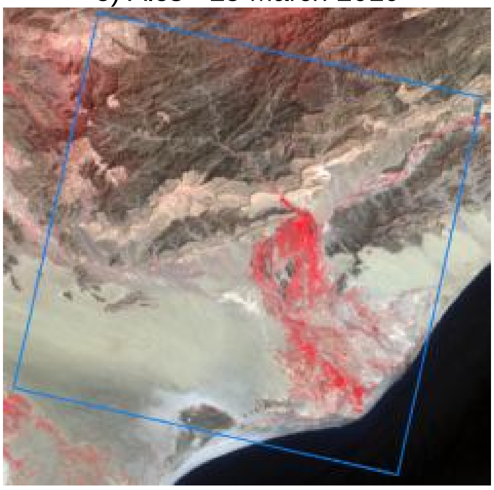
d) Landsat 7 15 March 2010



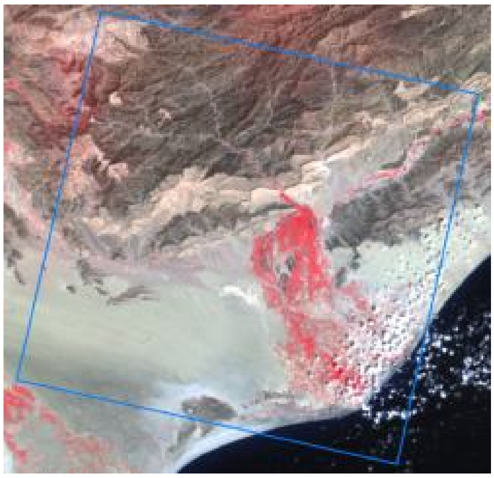
e) Alos - 25 March 2010



f) Alos - 25 June 2010



g) Landsat 7 - 09 October 2010



h) Landsat 7 - 25 October 2010

Figure 61: Satellite images of the Abyan study area, with in blue the extent of the study area.

7.2 Climate

Figure 62 shows the total monthly rainfall for the Abyan area in 2010, based on TRMM rainfall data. The coastal area in the south of the study area receives almost no rainfall. The average annual rainfall for 2010 is estimated to be 113 mm for Abyan, making Abyan the driest study area. For 2006 the amount of rain was estimated to be 199 mm, hence 2006 was slightly wetter. The lower amount of rain in 2010 is mainly due to less rainfall in July and August, which is only partly compensated by more rainfall in April and May.

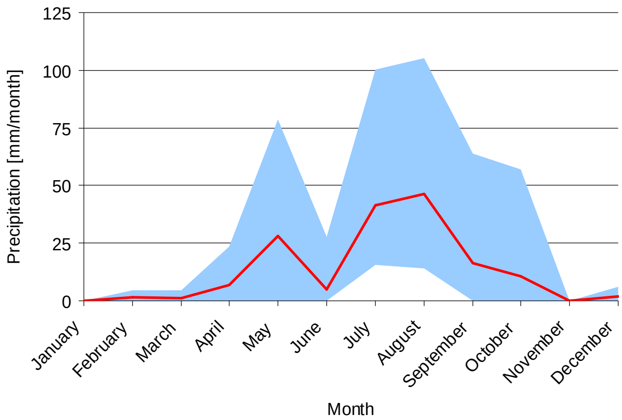


Figure 62: Monthly rainfall for the Abyan area. The red solid line shows the average rainfall for the total area. The blue area shows the range of rainfall values of individual TRMM pixels.

Temperature was measured at the meteorological station in Aden ([Latitude 12.8° N; Longitude 45.0° E; Altitude 3 m). The location of that station compared to the study area is shown in Figure 64 and the station typically presents the climatic conditions of the coast. The same station was used during the 2006 study. The meteorological station of Aden is located at an altitude of only 3 meters. Because of these high temperatures, crops will need more water. The higher winter temperatures can also accommodate a second cropping season, under the condition that there is sufficient water available.

Figure 63 shows the air temperature as measured at the meteorological station at Aden in 2010. There is an annual pattern in these measurements with temperatures in summer being approximately 10°C higher than in winter and with only small deviations from that pattern. It appears, however, that there is a small dip in temperatures in summer. A daily averaged temperature of 25°C in winter shows favourable growing conditions for crop production, and a high water use. Due to this warm winter climate, the annual reference ET varies between 2 371 mm at the coast to 2 431 mm and more inland.

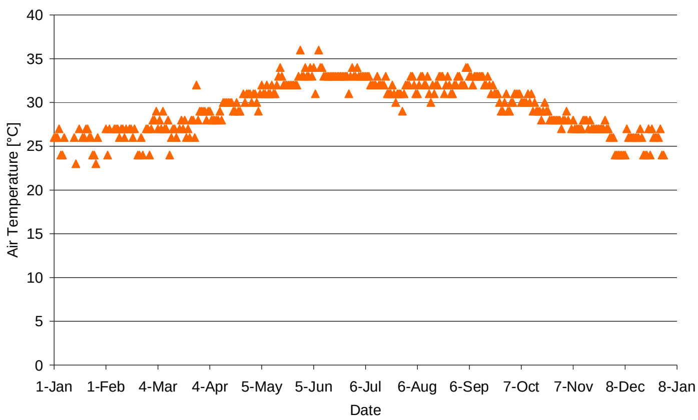


Figure 63: Daily air temperature values [°C] for the year 2010, Aden meteorological station.

Figure 64: Location of Aden meteorological station close to the Abyan study area (blue frame).

7.3 Green vegetation cover

The MODIS satellite measures the NDVI with time intervals of 16 days. This is a good data set to understand the presence of crops and its phenological phases; even though the spatial resolution is 250 m. Figure 65 demonstrates the spatial patterns of NDVI during the dry season (February). The same graph also displays the average NDVI for the entire year.

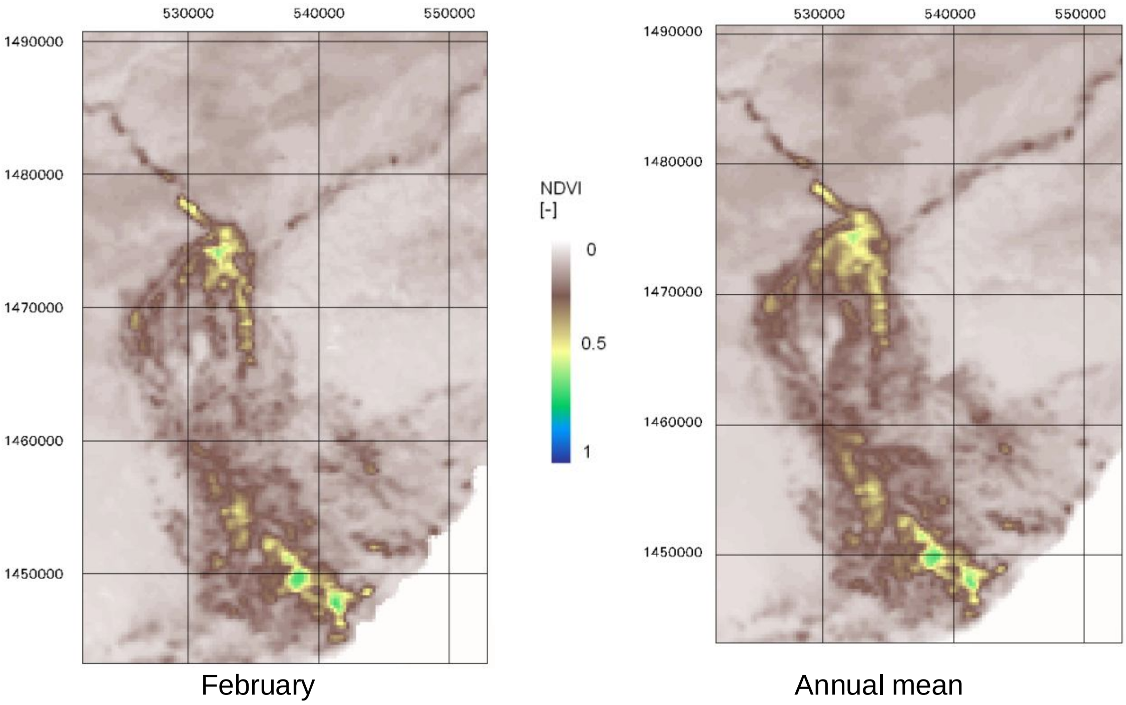


Figure 65: Spatial distribution of the NDVI during February 2010 and the annually average NDVI.

From these images it is clear that most, if not all, cropped areas are irrigated. The spatial patterns on the February image look very similar to the annual average counterpart of NDVI. This result suggests that many crops are cultivated in February. That indicates that at least the areas with high NDVI are perennial crops.

7.4 Land Use

The results of agricultural land use classification in the Abyan study area show predominantly irrigated single season crops. Due to very low rainfall, all agricultural fields are irrigated. Due to limited surface water resources and a falling groundwater table, only 10% of the area is in use for agriculture (hence 90% of Abyan is non-cropped).

The spatial distribution of land use classes can be seen in Figure 66. The statistical data is given in Table 42. The total irrigated land occupies 14 840 ha. The class of single season crops occupy 73% of the irrigated land. Perennial crops and bananas are clumped and occur in a few locations only. For security reasons, fieldwork could not be implemented. The contingency table could therefore not be compiled. The 2006 study showed an overall accuracy of 69%.

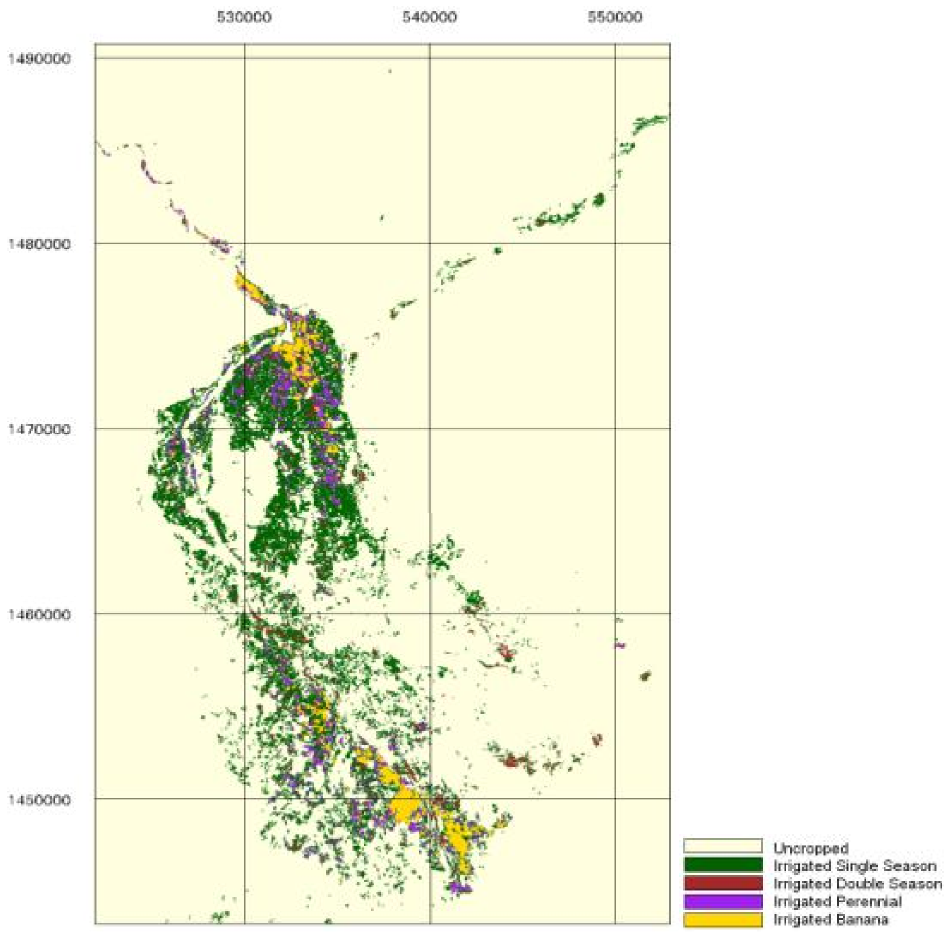


Figure 66: Land use map, Abyan. A larger size map is given in Appendix 27.

Table 42: Agricultural land use in the Abyan study area.

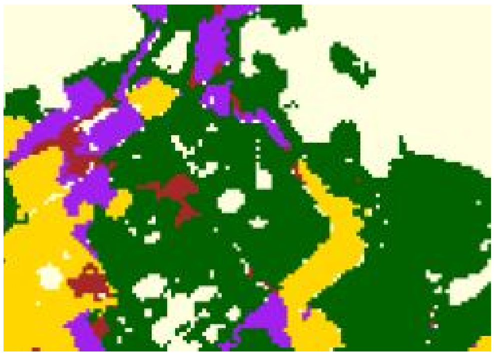
				Area [hectare]	% of total	% of cropped
Classification	Rainfed			0	0.0%	0.0%
	Irrigated	Single Season		10 808	7.3%	72.8%
		Double Season		1 305	0.9%	8.8%
		Perennial		1 483	1.0%	10.0%
		Banana		1 244	0.8%	8.4%
	Non-cropped			132 253	89.9%	

An example of the land use classification process is given in Figure 67. All land use classes of Abyan are present in this example. The whitish areas in the upper right corner of the satellite images are non-cropped areas. They grey-greenish fields are single season crops; most of those fields have a crop in the October image. In the centre of the images a bright red hook-shaped field is present and in the left side also some bright red fields are present. These bright red fields are used to grow bananas.

Alos 25 March 2010

Alos 25 June 2010

Landsat 9 October 2010



Classification

Figure 67: Example of satellite images and classification in Abyan.

On the next page, in Figure 68, an example is given of what Abyan looks like in Google Earth. The satellite image has been taken recently: in September 2011. For comparisons the same area in the upper reaches of the wadi is shown as an excerpt of the land use map (Figure 69).
The fields that appear dark green in the Google Earth image are vegetated while the brownish fields are bare in September 2011. These patterns match very well with the land use classification of 2010, with most of the areas vegetated in September being classified as banana. The bare agricultural fields in the main part of the image are not likely to be bare during the whole year, so the classification as single season seems logical. In the right upper corner of this excerpt are no agricultural fields visible; there don't seem to be field boundaries or crops. So the classification as non-cropped makes sense.

Figure 68: Google Earth excerpt for the Abyan area, September 2011. The area is identical to the classification example below.

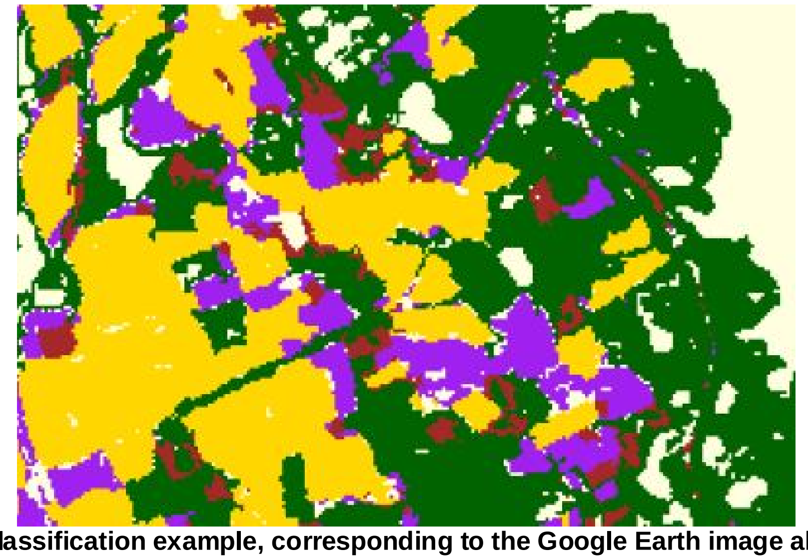


Figure 69: Classification example, corresponding to the Google Earth image above.

7.5 Water Use

The results of the determination of actual crop evapotranspiration are presented in Figure 68. The desert surfaces have a very low evaporation rate. All fields located closely to rivers and streams depict a higher ET rate. Especially the transition at the end of the valley and start of the coastal plain zone exhibits intensive irrigation practices. Not surprisingly, perennial and banana crops have ET rates that can be as large as 1 000 to 1 400 mm/yr. Higher ET rates near streams and rivers can also be related to higher groundwater abstraction volumes; Groundwater systems below rivers are often shallower and the water quality can be better than located further away from streams. Groundwater irrigation in Abyan was estimated by the team of GSCP experts to be 60, 75, 95 and 100% for double season crops, perennial/qat, single season crops and banana respectively. The high amount of groundwater abstraction for single season crops is confirmed from the high NDVI values during February. Streams don’t flow at this time of the year, so groundwater is the major source of water.

The calculations are achieved by measuring the amount of vegetation present and its temperatures. If vegetated pixels have a certain canopy temperature, the evapotranspiration is at the potential level. Usually water supply is below optimal and evapotranspiration is limited: that limited amount is the actual evapotranspiration; it’s shown in Figure 70. Larger maps of actual evapotranspiration and potential evapotranspiration are given in Appendix 29 and 31 respectively.

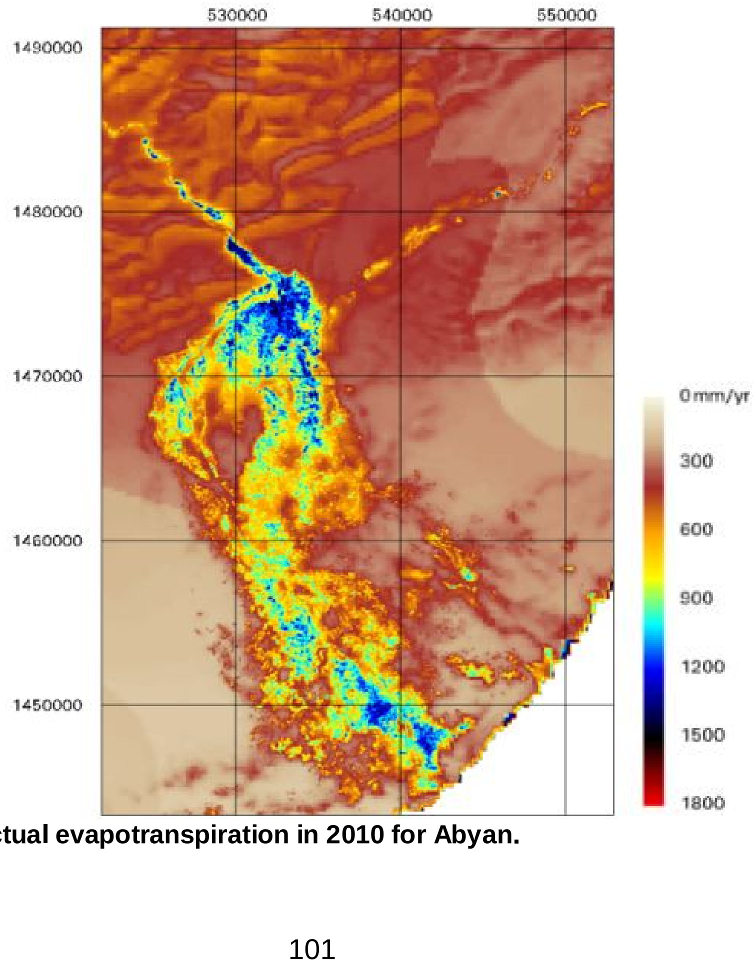


Figure 70: Map of actual evapotranspiration in 2010 for Abyan.

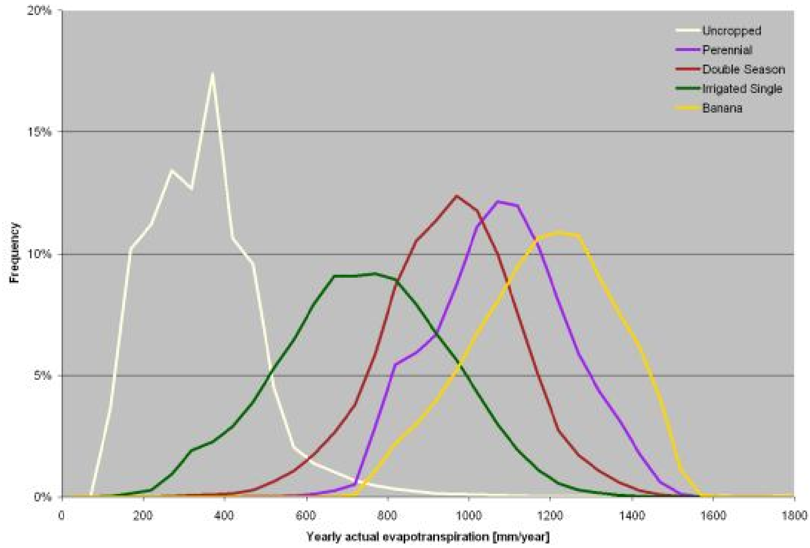


Figure 71: Frequency distribution of total actual evapotranspiration for the year 2010 for different agricultural land use classes in the Abyan area. Frequencies are calculated on the basis of 50 millimetre intervals.

Table 43 summarises the distribution of average values of accumulated actual ET of each land use class. The values for ETpot are systematically higher than for ETact. Single season crops occupy 10 808 ha and ETact/ETpot is 97%, which shows that full irrigation amounts are supplied. Bananas reach with 1187/1384 a value of 86%, which reveal more water stress than for single season crops, and a more careful planning of water applications.

Table 43: Average and standard deviation of actual, potential and reference evapotranspiration for the land use classes of Abyan, in mm/yr.

	Actual Evapotranspiration		Potential Evapotranspiration		Reference Evapotranspiration	
	Average	**Std Dev**	**Average**	**Std Dev**	**Average**	**Std Dev**
Non-cropped	333	163	333	165	2 402	356
Irrigated						
Single Season	747	208	769	233	2 431	63
Double Season	957	168	1 042	201	2 430	78
Perennial	1 082	163	1 223	201	2 389	62
Banana	1 187	171	1 384	210	2 371	57

The incremental ET relates actual evapotranspiration from irrigated crops to rainfed crops. By absence of the latter, a value of 235 mm has been considered. The irrigation water is taken from two main sources: surface water and groundwater. The efficiency of irrigation depends on the source of the water and the application method. In Abyan all banana fields are irrigated by groundwater, but with a high efficiency. The surface water irrigation is less efficient due to the irregular timing and availability of water.

The gross irrigation supply for surface water, groundwater and the total of both sources is presented in Table 44. The total amount of gross groundwater abstraction is 135 mcm/yr. For an irrigated area of 14 840 ha, this is equivalent to a layer of 909 mm/yr.

Table 44: Total irrigation supply to the land use classes of Abyan.

	Area	Actual Evapo-transpiration	Incremental ET	Gross irrigation supply [mcm/yr]		
	[ha]	[mm/yr]	[mm/yr]	Surface	Ground	Total
Total study area	147 093	329	329	24	135	159
Non-cropped	132 253	333				
Irrigated						
Single Season	10 808	747	512	7	96	103
Double Season	1 305	957	722	9	10	20
Perennial	1 483	1 082	847	8	13	21
Banana	1 244	1 187	952	0	16	16

The difference between actual and potential ET represents the potential water savings. Assuming that ETact can decline to a level of 0.8 x ETpot, the reduction in abstraction can be computed. The results of this estimation are given in Table 45.

Table 45: Water savings for irrigated land use classes in the Abyan study area.

	Area	Net savings		Gross savings [mcm/yr]		
	[ha]	[mm/yr]	[mcm/yr]	Total	Surface	Ground
Irrigated area	13 596	127	17	41	36	5
Single Season	10 808	131	14	35	34	1
Double Season	1 305	123	2	3	2	2
Perennial	1 483	103	2	3	1	2
Banana	1 244	79	1	1	0	1

7.6 Changes with respect to 2006

The average rainfall for Abyan was 199 and 113 mm for 2006 and 2010 respectively. The rainfall in the area is genuinely low, and insufficient for rainfed cropping systems. The reference ET during 2010 was 2 308 mm on average (and 2 075 mm in 2006). With such low amounts of rainfall and high levels of reference evapotranspiration it is clear that Abyan is a quite arid part of Yemen.

The change in land use from 2006 to 2010 is provided in Figure 72 and

Table 46. An amount of 90% of the cropped area remains the same. The single season crop has, however, expanded by 2 298 ha (27%) and this induced a further intensification of agricultural land use. This process occurred at several locations in Abyan, and there seems to be no control to arrest this growth of horizontal expansion.

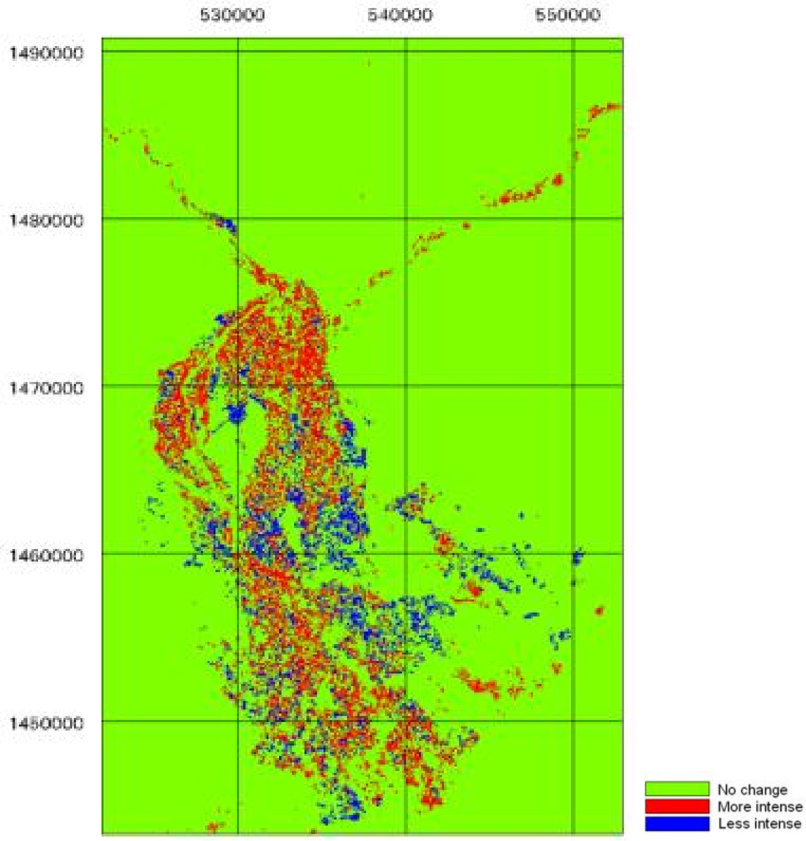


Figure 72: Map of changes in land use of the Abyan study area. 3% of the pixels has less intense land use in 2010 than in 2006; 6% is more intense and 90% has the same land use as in 2006.

In line with the somewhat more intense land use that is shown in Figure 72 and

Table 46, is also the change in green vegetation cover. The NDVI in February has slightly increased from 0.126 in 2006 to 0.127 in 2010. The annual mean has decreased from 0.148 to 0.131. That decrease is probably caused by the 43% decrease in rainfall, making the non-cropped areas even less suitable for vegetation to grow.

Table 46: Changes of land use in Abyan. Absolute areas in hectares of 2010 and 2006 are given as well as the difference between the years.

			2006	**2010**	**Difference** [ha]	**Difference** [%]
Classification	Rainfed		0	0	0	0%
	Irrigated	Single Season	8 510	10 808	-2 298	-27%
		Double Season	1 551	1 305	246	16%
		Perennial	1 344	1 483	-139	-10%
		Banana	1 568	1 244	324	21%
	Non-cropped		126 127	132 253	-6 126	-5%
	Total		139 100	147 093	-7 993	-6%

The most notable change in land use from the table is that double season crops and banana seem to have been modified into single season crops (and a few perennial fields). Not only does the land use in Abyan seem to have increased in intensity, also irrigation supply seems to have increased from 53 to 135 mcm/yr. The lower rainfall increases the irrigation water requirements, and this causes a vertical expansion of the irrigation processes. Hence, there is a growing trend of gross irrigation water supply that needs to be reverted.

Table 47: Changes between 2006 and 2010 in actual evapotranspiration and gross groundwater abstraction to the land use classes in Abyan.

	2006		**2010**		**Difference**	
	ETact	**Gross groundwater abstraction**	**ETact**	**Gross groundwater abstraction**	**ETact**	**Gross groundwater abstraction**
	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]	[mm/yr]	[mcm/yr]
Total study area	315	158	329	135	-14	33
Non-cropped	254		333		-79	
Irrigated						
Single Season	782	110	747	96	35	14
Double Season	937	12	957	10	-20	2
Perennial	1 154	13	1 082	13	72	0
Banana	1 343	23	1 187	16	156	7

The change in potential water savings is provided in Table 48. The results in that table show that 40 mcm/yr can be saved.

Table 48: Changes in possible water savings between 2006 and 2010 in Abyan.

	Area [hectare]			**Net savings** [mm/year]			**Gross groundwater savings** [mcm/year]		
	2006	2010	Dif	2006	2010	Dif	2006	2010	Dif
Irrigated area	12 973	13 596	-623		22		0	5	-5
Single Season	8 510	10 808	-2 298	5	131	-126	0	1	-1
Double Season	1 551	1 305	246	1	123	-122	0	2	-2
Perennial	1 344	1 483	-139	1	103	-102	0	2	-2
Banana	1 568	1 244	324	1	79	-78	0	1	-1

Main conclusions Abyan:

- Rainfall in 2010 was 20.9% less than in 2006; this has together with the reference ET great impact on the gross groundwater withdrawals;
- Irrigation with groundwater was 5.6 times more common than irrigation with surface water resources;
- The irrigated area has expanded by 1 867 ha, mainly due to the growth of single season crops;
- The area of bananas and double season crops shrunk;
- The volumetric ET of single season crops has increased from 53 to 135 mcm/yr;
- An amount of 135 mcm/yr was abstracted from aquifers. It is possible to reduce another 5 mcm/yr of groundwater without changing cropped area and production.

8. Synthesis of regional scale results in relation to the GSCP interventions

As described in section 3.4 Comparison Methodology, not all changes can be described at all spatial aggregation levels. In this chapter changes at the level of the study areas are summarised and, where possible, compared to the changes around GSCP points for understanding the impact of GSCP interventions. The data for GSCP points is presented in green in the tables.

8.1 Green vegetation cover

The green vegetation cover is an excellent expression for the horizontal distribution and the access to water of the plant community without the inclusion of any in situ data and field inspections. Increase in green cover does not occur suddenly, but is a result of changing land surface conditions and processes. These processes can be a change in climatic conditions, a change in land use practices or different groundwater management processes. Rainfall is known to have a positive impact on the rise of green vegetation in landscapes a certain time lag after the rainfall event occurs. Green vegetation cover development after a rainfall event is a natural process. Increase in green vegetation cover without a corresponding increase in rainfall suggests that irrigation intensity is expanding by human activities; either vertically (e.g. more applied water, more cropping intensity) or horizontally (e.g. more area). This section summarizes the changes in green vegetation cover (see Table 49). Note that detailed GPS coordinates for Rada GSCP points were not available with sufficient accuracy to the consultancy team, and consequently they had to be left out from the analysis.

Table 49: Average NDVI for the locations of the GSCP points as well as the total study areas, based on Modis composites at 250m resolution.

	2006		February 2006		2010		February 2010	
	Study area	GSCP points	Study area	GSCP points	Study area	GSCP points	Study area	GSCP points
Siham	0.228	0.212	0.182	0.21	0.232	0.216	0.191	0.208
Dhamar	0.18	0.241	0.133	0.176	0.191	0.257	0.141	0.180
Rada	0.164		0.124		0.165		0.131	
Abyan	0.148	0.252	0.126	0.24	0.131	0.257	0.127	0.249

The study areas Siham and Dhamar became greener at the regional scale while Rada remained at a similar level due to the conserved qat cultivation. Both annual NDVI data, as well as the February data set show this trend. Abyan shows a reduction in green vegetation cover when moving from 2006 to 2010 (0.148 to 0.131). However, this reduction did not occur in the vicinity of the GSCP points; instead NDVI increased from 0.252 to 0.257, suggesting more green crops in the direct vicinity of GSCP points in Abyan. This can also be witnessed for February (from 0.240 to 0.249). Because NDVI is a measurement – and it is measured by the same Modis instrument across the time span investigated - it is safe to conclude that at an annual time scale, the agricultural landscape near GSCP points became greener. This same holds true for the dry season in February: the regions Dhamar (0.133 to 0.141), Rada (0.124 to 0.131) and Siham (0.182 to 0.191) while Abyan remained similar (0.126 to 0.127). Hence, the conclusion is drawn that the plant community in 2010 is more vigorous than in 2006, and that the situation in the vicinity of GSCP points shows the trend in plant community greening. GSCP interventions in these 3 areas have not reduced irrigation intensity. The same appears from Figure 73. In 2010 the yellow areas of higher NDVI values are larger in the annual images. In the February NDVI maps it appears that in February 2010 there is more vigorous vegetation in the mountains than in 2006.

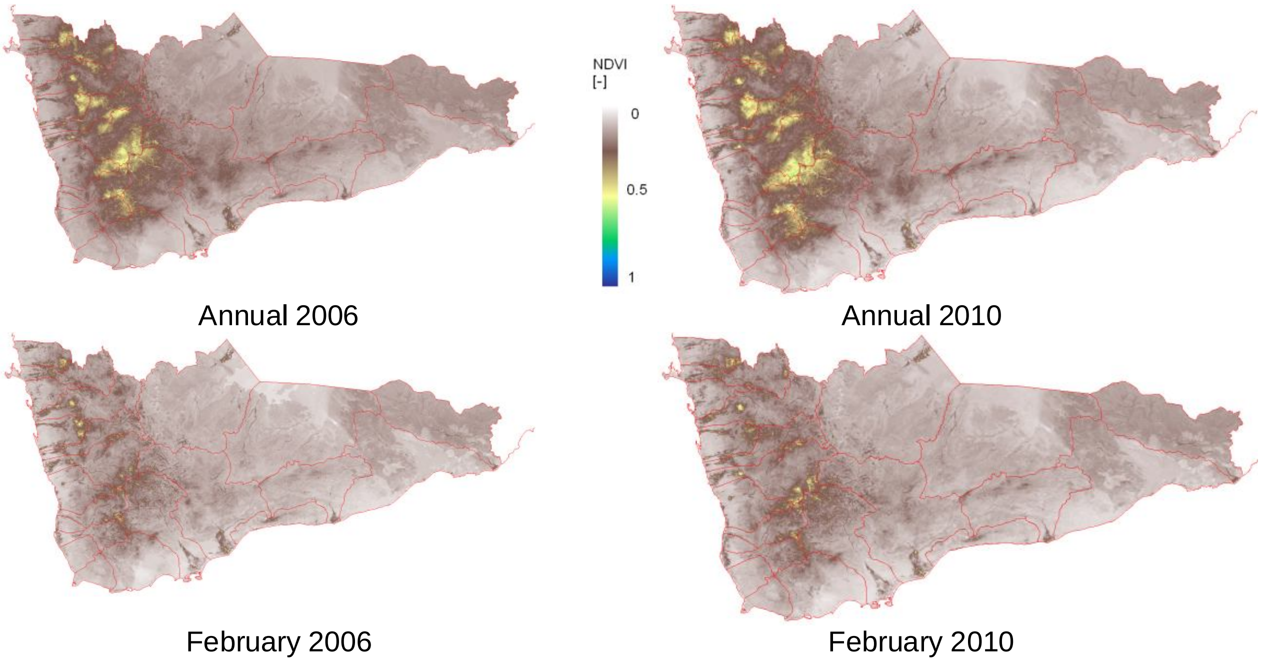


Figure 73: NDVI in Yemen for 2006 and 2010, annual averages and February situation.

Conclusions for GSCP:

- Land close to places with GSCP interventions show a greener landscape than their surrounding land at the regional scale;
- Crops have expanded either horizontally (more acreage) or vertically (other crops, larger plant density, higher leaf area index);
- Beneficiaries of GSCP interventions have not always complied to non-expansion of cropped area.

8.2 Land Use

Rainfed crops cover approximately 40% of the agricultural area, and irrigated agriculture occupies 60%. Irrigation is thus of great essence for the national food security in Yemen. In Abyan for instance, all crops are irrigated (see Table 50). A land use map was compiled for the four study areas based on classification of high resolution satellite Alos, Aster and Landsat images. The maps of agricultural land use in 2010 and of the differences between 2006 and 2010 are given in the appendices.

Table 50: Agricultural land use statistics in hectares based on the land use classification of 2010.

	Siham	Dhamar	Rada	Abyan	Total
Rainfed	61 630	7 573	11 203	0	80 406
Irrigated	65 525	20 135	7 724	14 841	108 225
Single Season	50 226	18 694	1 172	10 808	80 900
Double Season	7 978	923	8	1 305	10 214
Perennial / Qat	7 321	518	6 544	1 483	15 866
Banana				1 244	1 244
Cropped	127 155	27 708	18 927	14 841	188 631

The changes in agricultural land use are portrayed in Table 52. Monitoring and analysis of changes in cropping pattern and irrigated areas resulting from introduction of irrigation improvement investment indicated that there are increasing trend in areas of vegetables and fruit trees at the expense of cereals, cash and fodder crops in both the low and high land zones. The farmer' income depends on risk-minimizing production strategies by adopting higher productive and diversified crops in their cropping mix. While this can be profitable in the short term, this shift in farming illustrates an adverse impacts on irrigation water savings and groundwater sustainability. For the longer term situation, it is not recommended to diversify to higher productive crops.

The annual irrigation intensities have not changed much. The irrigation intensity in Siham changed from 122% to 123%. The irrigation intensity in Dhamar increased from 104% to 107%. Rada experienced a small decline from 187% to 185%, while Abyan also reduced from 134% to 127%. These magnitudes of changes are all marginally small. The mean irrigation intensity from the 4 study areas based on satellite images slightly increased from 124% to 125%. Hence, irrigation intensity in Yemen is rather constant, despite that horizontal expansion occurred.

Table 51: Summary of irrigated area statistics for the four study areas; all numbers in hectares.

	Siham		Dhamar		Rada		Abyan	
	2006	**2010**	**2006**	**2010**	**2006**	**2010**	**2006**	**2010**
Single season	45 653	50 226	23 042	18 694	926	1 172	8 510	10 808
Double season	5 591	7 978	637	923	9	8	1 551	1 305
Perennial/ Qat	6 966	7 321	430	518	6 294	6 544	1 344	1 483
Banana							1 568	1 244
Total	58 210	65 525	24 110	20 135	7 229	7 724	12 973	14 840
Irrigation intensity	122%	123%	104%	107%	187%	185%	134%	127%

According to the Field Unit data collection programs, the irrigation intensity in the large-scale farms ranges between 111 -172% with 142% as an overall average. It is in a good agreement with results obtained for the previous assessment periods, where irrigation intensity ranged between 115 – 140% with 138% as an overall average. The 142% mean intensity indicates that 42% of the farmers irrigate their land during two seasons.

The difference between the GSCP points (142%) and the image analysis (125%) reveals that double and perennial crops are more common within the radius of the GSCP points.

While the rainfed areas remained similar (only 832 ha change), the irrigated areas expanded by 5 702 ha. Siham expanded the irrigated area by 7 315 ha. Dhamar decreased the area by 3 975 ha, mainly by abandoning of single season crops. Rada remained with a net change of 475 ha rather conserved. Abyan has increased with 1 868 ha. Hence the total irrigated area increased by 5 702 ha, which at the 2006 reference of 102 522 ha implies a horizontal expansion of 5.6% in a period of 4 years, or a pace of 1.4% per year.

Table 52: Change in agricultural land use statistics based on the crop classification. Differences of 2006 - 2010 are presented.

	Siham	Dhamar	Rada	Abyan	Total	
	[ha]	[ha]	[ha]	[ha]	[ha]	[%]
Rainfed	-1 879	1 756	-708		-832	-1
Irrigated	-7 315	3 975	-495	-1 868	-5 702	-6
Single Season	-4 573	4 348	-246	-2 298	-2 769	-4
Double Season	-2 387	-286	1	246	-2 425	-31
Perennial / Qat	-355	-88	-250	-139	-832	-6
Banana				324	324	21
Cropped	-9 195	5 731	-1 203	-1 868	-6 534	-3%

The land use at the regional scale has remained the same for 82% of the cases, which for a time span of 4 years seems rather acceptable. The problem is that the increase of more intensive land use by 13% of the cases occurs more frequently than the reduction by 5% of the cases. This result from Alos, Aster and Landsat images and a complex classification system matches with the more simplified NDVI analysis of Modis described in the previous section. The results are thus consistent.

Table 53: Change in agricultural land use acreage.

	Siham	Dhamar	Rada	Abyan	Total	
	[ha]	[ha]	[ha]	[ha]	[ha]	[%]
Less intense	18 541	7 994	10 027	5 135	41 696	5
No change	254 550	144 534	121 938	132 600	653 621	82
More intense	69 995	12 700	11 817	9 358	103 870	13
Total	343 085	165 228	143 782	147 093	799 187	100

The GSCP points represent only a very small fraction of the total study area, but they are exposed to modern irrigation technologies, and it is very interesting to investigate the farmers response by means of satellite imagery. The data in Table 54 show that 61% of the land use is conserved, while this value is 84% for the regional scale situation. The situation at the regional scale is thus more conservative than around GSCP improvement schemes. More intensive irrigation (29%) is dominant over less intensive irrigation (10%), so GSCP has resulted into a situation where farmers grow more intensive crops. The intensification is most evident in Abyan with 56 % of the GSCP points having unchanged land use classes (and the regional sale 90 % !). The more intensive land use could be related to the fact that 56 mcm has been saved from earthen canals and fields, and this extra water delivers larger volumes at the farm gate.

Table 54: Changes of agricultural land use around GSCP points. The differences between 2006 and 2010 are presented in percentages.

	Study areas			GSCP points		
	More intensive	Same	Less intensive	More intensive	Same	Less intensive
Siham	20	74	5	34	56	10
Dhamar	8	87	5	22	72	6
Rada	8	85	7			
Abyan	6	90	3	31	56	14
Average	11	84	4	29	61	10

Field surveys by GSCP on cropping patterns indicated that on average the irrigated cropped area has been expanded and stabilized around 3% (horizontal expansion). The remote sensing data suggests a change of 19% in GSCP areas and 7% at the regional scale, and this is more than being identified by the FU teams. These are, however, bulk results, and the situation can differ for each specific location. For field units where horizontal expansion is more than 3%, it is basically confined to those field units with potential for spate flow (e.g. Siham).

Table 55 shows that the irrigated area near GSCP points in Siham (from 43 to 42%) and Dhamar (from 61 to 59%) have slightly decreased, but at the same time the irrigation intensity increased. In Abyan the opposite happened: the irrigated area increased (from 17 to 57%) but the irrigation intensity decreased (from 1460 to 140%). This trend can be seen both around the GSCP points as well as for the entire study area. It seems like changes in irrigated area (i.e. horizontal expansion) are compensated by changes in irrigation intensity (i.e. vertical expansion). Thus, beneficiaries in Siham and Dhamar generally complied with the condition of non-expansion of irrigated areas that is in the Tripartite Agreement. Since all changes in Rada are all marginal, the same conclusion is very likely to apply to Rada also. Abyan is a more problematic region for improving the irrigation management practices.

Table 55: Land use changes with a focus on GSCP points

Siham	Study area		GSCP points	
Land use	**2006**	**2010**	**2006**	**2010**
Non-cropped	59%	57%	45%	45%
Rainfed	20%	19%	12%	14%
Irrigated	21%	24%	43%	42%
Single Season	16%	18%	29%	26%
Double Season	2%	3%	7%	4%
Perennial	3%	3%	7%	11%
Irrigation intensity	122%	123%	133%	137%

Dhamar	Study area		GSCP points	
Land use	**2006**	**2010**	**2006**	**2010**
Non-cropped	78%	82%	33%	34%
Rainfed	6%	5%	5%	6%
Irrigated	16%	13%	61%	59%
Single Season	16%	12%	56%	52%
Double Season	0%	1%	4%	4%
Perennial	0%	0%	2%	3%
Irrigation intensity	104%	107%	110%	112%

Abyan	Study area		GSCP points	
Land use	**2006**	**2010**	**2006**	**2010**
Non-cropped	87%	85%	49%	43%
Irrigated	13%	15%	51%	57%
Single Season	9%	11%	27%	34%
Double Season	2%	1%	6%	5%
Perennial	1%	1%	6%	8%
Banana	2%	1%	12%	10%
Irrigation intensity	134%	127%	146%	140%

Conclusions for GSCP:

- A relative area of 61% of agricultural land use is conserved around GSCP wells, while this value is 84% for the regional scale situation. Hence, GSCP interventions create changes;
- More intensive irrigation (29%) is dominant over less intensive irrigation (10%) for GSCP points, and these values are higher than for the remainder of the study areas (more intensive 11%; less intensive 4%);
- GSCP farmers either expand their land or expand the annual irrigation intensity. The annual irrigation intensity near GSCP wells is with 134% higher than applicable at the regional scale (125%);
- Intensification of agricultural land use is most dominant in Abyan.

8.3 Rainfall

The un-calibrated annual rainfall for the four study areas varies with time. The deviation between TRMM estimates and rain gauge readings in the complex terrain of the Yemeni highlands is believed to be systematic, and the changes of rainfall from TRMM are therefore more accurate than the absolute values. The year 2006 was a relatively wet year, and the rainfall of 2010 is closer to the average rainfall and forms a better representation. Dhamar (12%), Rada (17%) and Abyan (43%) were all drier during 2010. Only Siham received 7% more rainfall. Table 56 shows that the South-West of Yemen received on average 8% less rainfall in 2010 as compared to 2006. Rainfall variability of 50 to 90 mm/yr at the regional scale needs consideration when discussing changes in groundwater abstraction and potential water savings. This demonstrates that is wiser to develop time series of data, rather than focussing on two years only.

Table 56: Summary of the TRMM rainfall statistics. "South-West Yemen" refers to the area covered by the 14 catchments described in Chapter 9.

	2006 [mm/yr]	**2010** [mm/yr]	**Difference** [mm/yr]	**Difference** [%]
Siham	455	486	-31	-7%
Dhamar	448	395	53	12%
Rada	404	334	70	17%
Abyan	199	113	86	43%
South-West Yemen	220	202	18	8%

8.4 Crop consumptive use

While studying changes of ET across time, the first pre-requisite is to analyse the reference ET, and the changes thereof. As introduced before, reference ET expresses the impact of climatology on crop consumptive use. Table 57 shows that changes of reference ET can be up to 15%. The mountains in Dhamar and Rada received less sunshine and lower temperatures in 2010 as compared to 2006. Consequently, their reference ET is about 13% lower. The climate in the coastal belts shows the opposite trend, and an increased reference ET occurs (7%). The negative value for Abyan can likely be explained by the lower rainfall in 2010 and lower cloud cover often related to that.

Table 57: Changes of reference ET in the 4 study areas.

Area	2006 [mm/yr]	2010 [mm/yr]	Difference [mm/yr]	Difference [%]
Siham	1 982	2 042	-60	-3.0
Dhamar	1 976	1 720	256	12.9
Rada	2 018	1 723	295	14.6
Abyan	2 075	2 308	-233	-11.2

Table 58 demonstrates the average values of crop consumptive use for 2010. The values are significantly lower than the reference ET due to non-pristine growing conditions. Not only soil moisture is often a limitation, also the warm and dry climate will introduce a permanent stress on the stomatal aperture of these crops. Furthermore, annual values are presented. The ratio of ETact/ETref during the growing season is significantly higher than when it is expressed on an annual time basis. The bananas in

Abyan (1 187 mm/yr) and the perennial crops in Dhamar appear to have the highest crop consumptive use (1 174 mm/yr).

Table 58: Agricultural water consumption for 2010 in millimetre/year.

	Siham	Dhamar	Rada	Abyan
Rainfed	487	316	315	
Irrigated				
Single Season	808	922	495	747
Double Season	1 011	1 079	444	957
Perennial / Qat	1 058	1 174	542	1 082
Banana				1 187

The ETact changes between 2006 and 2010 are displayed in Table 59. The sources of consumptive use are (i) rainfall, (ii) changes in surface water storage and (iii) changes of groundwater storage. The rates vary with the reference ET that is displayed in Table 57. Negative values suggest that the rate (mm/yr) has increased. This occurred for single season crops in Siham and Dhamar and also for the double season crops in Abyan. All other combinations of land use classes and locations show a declining rate. For Dhamar and Rada this can be attributed to the changing reference ET. The lower ET for Abyan can be explained by the lower rainfall. The difference is marginally small for the double season crops in Siham (26 mm/yr). The lower ET rate of perennial crops in Siham is related to deficit irrigation practices (more evidence on this issue is demonstrated later).

Table 59: Change in crop consumptive use. The 2006 - 2010 values are shown in mm/yr.

	Siham	Dhamar	Rada	Abyan
Rainfed	-17	124	119	
Irrigated				
Single Season	-17	-105	53	35
Double Season	26	133	261	-20
Perennial / Qat	149	131	45	72
Banana				156

The impact of the GSCP points on crop consumptive use has also been analysed (see Table 60). While there are some local differences, it can be concluded that the GSCP points exhibit a slightly higher crop ET (approximately 2%) in almost all cases than found for the regional scale. This finding supports earlier conclusions that the land use around the GSCP points is becoming more irrigation intensive. The higher crop consumptive use proofs that farmers receive more water at the farm gate and convert a higher fraction of this amount of applied water into crop consumptive use. Hence, the total efficiency has improved and the higher ET value will likely lead to more production per unit of land (kg/ha).

Table 60: Crop consumptive use for 2010 for GSCP points and the regional scale.

Area	Land use	Study area	GSCP points	Difference
		[mm/yr]	[mm/yr]	[%]
Siham	Single season	808	805	0
	Double season	1 011	1 028	-2
	Perennial	1 058	1 076	-2
	All irrigated crops	860		
Dhamar	Single season	922	981	-6
	Double season	1 079	1 092	-1
	Perennial	1 174	1 183	-1
	All crops	936		
Rada	Single season	495		
	Double season	444		
	Perennial	542		
	All crops	535		
Abyan	Single season	747		
	Double season	957	997	-4
	Perennial	1 082	1 131	-5
	Banana	1 187	1 202	-1
	All irrigated crops	912		

Reduction of crop consumptive use can be established by cultivating less water use intensive crops and by reducing the annual cropping intensity, besides shrinkage of irrigated acreage. Alternatively, crop water stress can be imposed as an intended process by means of deficit irrigation. This is referred to in this study as the possible water savings. The possible water savings have decreased in Siham and Dhamar while it increased in Rada and Abyan (Table 61). The unavoidable conclusion is therefore that Siham and Dhamar have implemented deficit irrigation practices in the period 2006 to 2010, and that Abyan should follow that same path way in the near future.

Table 61: Change in possible water savings between 2006 and 2010.

		Study area			
	Land use	**Siham**	**Dhamar**	**Rada**	**Abyan**
Change in net savings [mm/year]	Total irrigated	62	330	-6	
	Single	63	310	1	-126
	Double	63	711	-5	-122
	Perennial / Qat	54	794	-9	-102
	Banana				-78
Change in gross groundwater savings [mcm/year]	Total irrigated	10	-10	0	-5
	Single	2	-9	0	-1
	Double	3	-1	0	-2
	Perennial / Qat	4	0	-1	-2
	Banana				-1

Conclusions for GSCP:

- The crop consumptive use of GSCP points is slightly higher than for non-GSCP points and this observation holds true for 8 of the 9 cases;
- It is likely that GSCP farmers have increased their efficiency.

8.5 Groundwater abstractions

Clearly, irrigation is essential for a country with reference ET being approximately 2 000 to 2 500 mm/yr and a rainfall in the range of 200 to 500 mm/yr. Pixels with an ET rate that exceeds the rainfall across the season must be irrigated. It is perhaps not a full irrigation water supply, and the land located on a particular pixel could have a supplementary irrigation management. However, every irrigation activity – intensive or extensive – will be labelled as irrigation. Pixels with the rainfall > ET must be rainfed.

When combining values of incremental ET with the partitioning coefficients from Table 13 of how much irrigation water is withdrawn from the groundwater system, gross irrigation by groundwater and surface water resources can be calculated. The result is given in Table 62. The gross total abstraction is 337 mcm/yr and the vast majority of this water originates from the coastal aquifers in Siham and Abyan. Not all this water evaporates, and the non-consumed water feeds the return flow into the groundwater system. It is not clear where the return flow goes to. It can go to shallow layers from where exploitation is not straightforward. It can however also travel to the deep underground and recharge the deeper aquifers. More geo-hydrological analyses are needed to have more sensible thoughts on these aspects.

Table 62: Gross groundwater and surface water irrigation supply during 2010 in mcm/yr.

	Siham		Dhamar		Rada		Abyan	
	Ground	**Surface**	**Ground**	**Surface**	**Ground**	**Surface**	**Ground**	**Surface**
Single Season	15	383	185	28	3	1	96	7
Double Season	46	42	12	1	0	0	10	9
Perennial / Qat	45	26	6	1	18	0	13	8
Banana							16	0
Total	105		204		21		135	

The risk of groundwater irrigation, is that more water is abstracted then being replenished by recharge from excessive rainfall storms. This imbalance of water resources leads to receding groundwater tables and a decrease of water reserves.

The historic changes in gross irrigation supply between 2006 and 2010 are worked out in Table 63. It seems that three study areas have increased the groundwater abstractions while Abyan decreased the groundwater abstractions. The total abstraction in 2010 was estimated as being 465 mcm/yr, the abstraction in 2006 was 196 mcm/yr. Siham pumped 2 mcm/yr more groundwater irrigation, especially in double season crops. Dhamar pumped more water for single season crops and the total value for this region increased by 48 mcm/yr. Rada also pumped more groundwater: 8 mcm/yr more. Dhamar and Rada should thus be better controlled in terms of groundwater abstractions.

Table 63: Change in gross groundwater abstraction between 2006 and 2010. Numbers are given in million cubic metres per year [mcm/yr].

Change in irrigation supply groundwater	**Siham**	**Dhamar**	**Rada**	**Abyan**
Single Season	-2	-43	-2	14
Double Season	-11	-4	0	2
Perennial	10	-1	-6	0
Banana				7
Total study area	-2	-48	-8	23

To save water, deficit irrigation could be practised. An estimate of the amount of water that could possibly be saved is given in Table 64.

Table 64: Possible savings of gross groundwater abstraction during 2010 in mcm/yr.

	Siham	Dhamar	Rada	Abyan
Single Season	1	20	0	1
Double Season	3	1	0	2
Perennial / Qat	4	0	2	2
Banana				1

9. Catchment scale water balance analysis

Rainfall is the source of water and the most important hydrological process on catchment scale. Whereas rainfall is the input of water to a catchment ET is a major output of water and these two large water flow paths should balance each other. If ET is larger than Rainfall (P) there is a rainfall deficit. If P>ET there is excess water that flows to rivers, aquifers and lakes. If at catchment scale ET>P prevails, over-exploitation of water is occurring. In the latter case water is taken out of storage, which results in dropping groundwater levels, reduced surface water reservoirs and dwindling river flows.

The average annual rainfall, ET and rainfall deficit were calculated for 14 major catchments for the sake of demonstrating catchments scale water management practices. The locations and boundaries of the major catchments were provided by the Yemeni Agencies. The names and locations of these catchments – often referred to as wadis - are demonstrated in Figure 74.

Figure 74: Location and name of the catchments used in this study.

9.1 TRMM Rainfall

The volumetric gross rainfall for each catchment was estimated by means of the monthly TRMM 3B43 rainfall product. Due to a lack of complete and reliable rain gauge measurements, the TRMM data could not be calibrated. It provides nevertheless a good estimate and describes the spatial variation well (Almazroui, 2010). While there can be issues related to the absolute values of rainfall, the relative changes are most probably accurate.

The accumulated rainfall for 2010 is presented in Figure 75. The mountains of Wadi Tuban, Wadi Rasyan and Wadi Mawza show the highest amounts of rainfall. The highest mountain in southern Yemen receives 520 to 760 mm of rain per year. Some areas of the western highlands, most notably Ibb and Ta'izz, receive more than 1 000 mm/yr. The desert surface in the eastern part of Yemen (Wadi Maifaah) has an annual rainfall of 50 mm only. This area is clearly located in the rain shadow of the mountains.

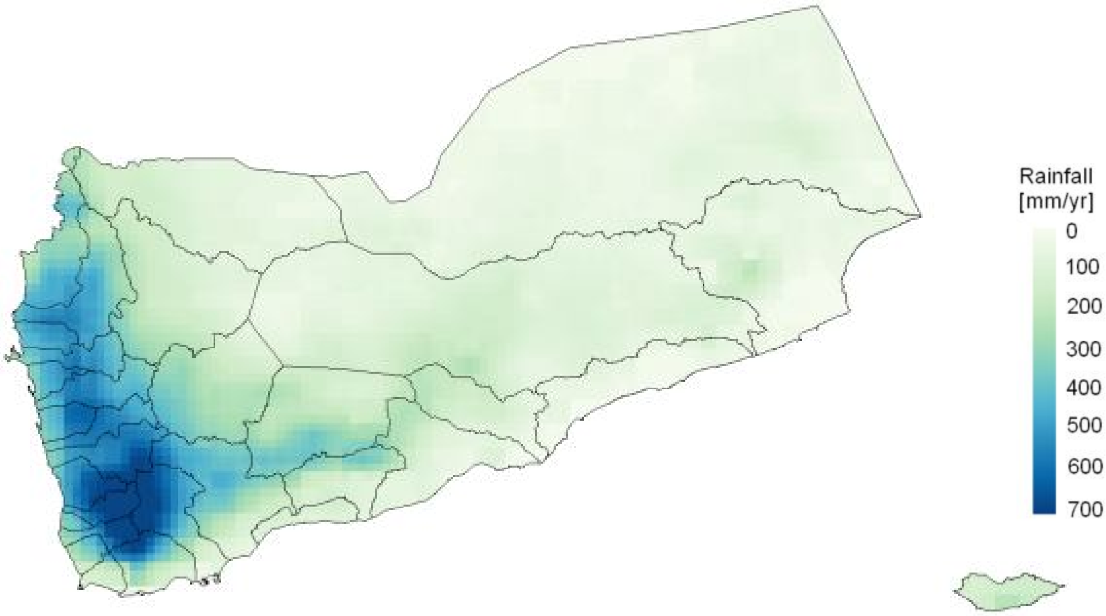


Figure 75: Spatial distribution of gross rainfall across Yemen based on the TRMM 3B43 product which was not calibrated against local rain gauges. The pixel size is 25 km.

The average rainfall per catchment is presented in Figure 76. The weighted average rainfall for a total catchment area of 110 861 km^2 is 202 mm/yr. The longer term average annual rainfall reported by the national line agencies is 127 mm/yr, and this applies to the total area of Yemen being 527 970 km^2. Hence, the driest catchments are not included in the analysis. Note that differences between coastal plains and highland areas - within a certain catchment - are now averaged out. For example, the average rainfall for Wadi Bana, in which Abyan is located, is estimated to vary between 300 and 400 mm/year. The Abyan study area is located on the coastal plain and received 113 mm of rain during 2010. Wadi Rasyan receives with an average value of 700 to 800 mm the highest rainfall rate.

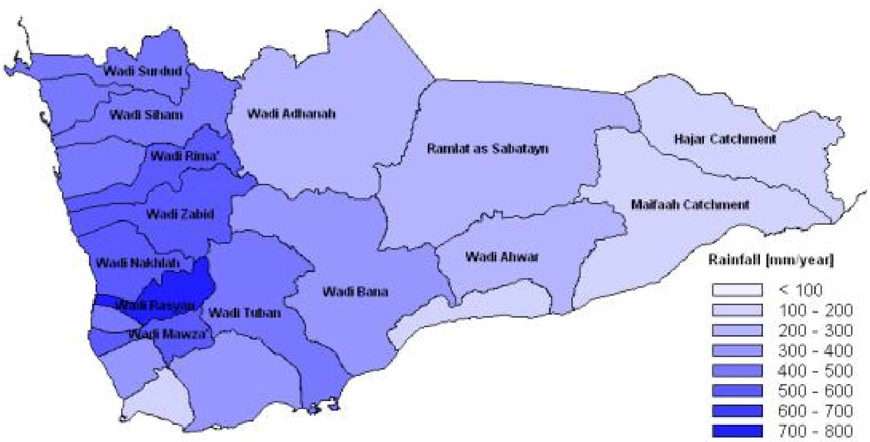


Figure 76: The annually total rainfall averaged per catchment during 2010.

The annual rainfall statistics for these 14 catchments for the period 1998 to 2010 are shown in Table 65. The column “Trend” represents the slope of the trend line for these 13 years. The slope indicates the longer term rainfall trend. The combination of both absolute and relative trends reflects the changes of rainfall. For example: although the absolute negative trend of 14.1 mm/yr in Wadi Zabid seems strong, it is only a small relative change (-2%). On the other hand: while the absolute positive trend in Maifaah Catchment is much smaller (+4.8 mm/yr) compared to the total amount of rain, it's an annual increase of 6%. It is apparent that 6 out of the 14 wadis show a negative trend in annual rainfall. For this period of 13 years, the trend for all fourteen catchments combined is -1.2 mm/yr only. This is negligibly small. It can therefore be concluded that there was no change in the short term rainfall over Yemen. The intra-annual variability is within normally accepted ranges.

Table 65: Rainfall trends in fourteen wadis in Yemen from 1998 to 2010.

Catchment	Average [mm/yr]	Minimum [mm/yr]	Maximum [mm/yr]	Trend [mm/yr]	Relative trend [%]
Wadi Adhanah	200	67	304	-6.8	-3%
Wadi Surdud	313	225	492	7.1	2%
Wadi Siham	392	235	560	-3.8	-1%
Hajar Catchment	135	37	282	8.6	6%
Ramlat as Sabatayn	144	37	223	-1.6	-1%
Wadi Rima'	431	237	563	-5.8	-1%
Maifaah Catchment	84	27	166	4.8	6%
Wadi Zabid	656	327	839	-14.1	-2%
Wadi Bana	291	112	494	-0.3	0%
Wadi Ahwar	145	45	233	3.0	2%
Wadi Nakhlah	486	336	894	-7.2	-1%
Wadi Tuban	416	229	611	-1.1	0%
Wadi Rasyan	809	507	974	-3.5	0%
Wadi Mawza'	536	435	692	4.1	1%

The periodic behaviour of annual rainfall is plotted in Figure 77 and Figure 78. For the sake of presentation, the catchments were split up in a group of seven catchments at the Gulf of Aden or inland (see Figure 74) and a group of seven wadis at the coast of the Red Sea (see Figure 74). From these graphs it is clear that 2009 was a dry year for all catchments. The total amount of rainfall in 2010 is closer to the average values for most of the catchments. The year 2010 is thus a representative rainfall year.

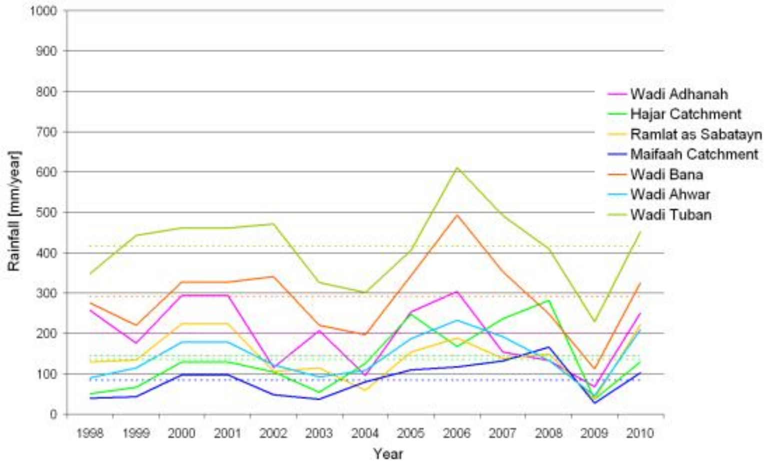


Figure 77: Rainfall trends from 1998 to 2010 for the catchments at the Gulf of Aden and inland. Dotted horizontal lines represent the average rainfall of this period.

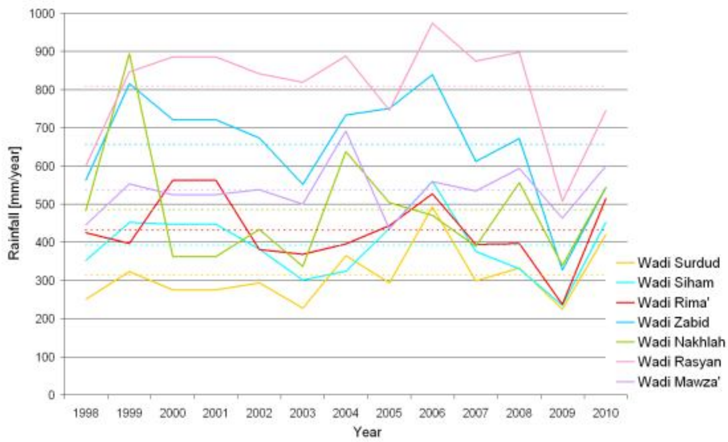


Figure 78: Rainfall trends from 1998 to 2010 for the wadis at the Red Sea coast. Dotted horizontal lines represent the average rainfall of this period.

9.2 Actual Evapotranspiration

ET rates were computed from the surface energy balance and the results are presented in Figure 80. Evaporation from deserts and water bodies can also be computed in a reliable manner by including temperature, albedo, etc. in the computations. The vast majority of evaporating surfaces in Yemen are considered to be natural pasture (75%). Grazing is greatly influenced by erratic annual precipitation. It is estimated that rangeland contributes to 53% of the total feed supply of sheep and goats. According to the Agricultural Statistics Yearbook, Yemen has about 600 000 ha of cereals (sorghum, maize, millet, wheat, barley) and 100 000 ha of fodder (pasture, sorghum, luzerne).

The ET is highest in the west and reduces sharply in a north-east and east direction. The spatial patterns of ET follow to a large extent the MODIS vegetation index, AMSR-E soil moisture, rainfall, and irrigation practices. ET is low when rain is low and irrigation is absent. ET is high when soils are moist – after a rainfall event or irrigation – and the land is covered with green vegetation. The green vegetation cover (expressed as NDVI) for the 14 catchments is presented.

The Normalized Difference Vegetation Index (NDVI) is calculated on the basis of the red and near infrared reflectances (see Figure 79). Yemen is a country with large contrasts in vegetation conditions. High NDVI values indicate actively growing vegetation. The green mountains in the vicinity of Abb and Al Mawit reflect moist land conditions, with abundant lush green vegetation. Bare soil, urban areas, natural vegetation and open water have low NDVI values. The coastal deserts adjacent to the Arabian Sea around the town of Am Juhar do not show any sign of vegetation.

Figure 79: NDVI index averaged over 2010. Green and yellow areas indicate the presence of lush green vegetation while grey areas barely have vegetation.

There is a good agreement between NDVI and ETact as expected according to environmental physics (see Figure 80).

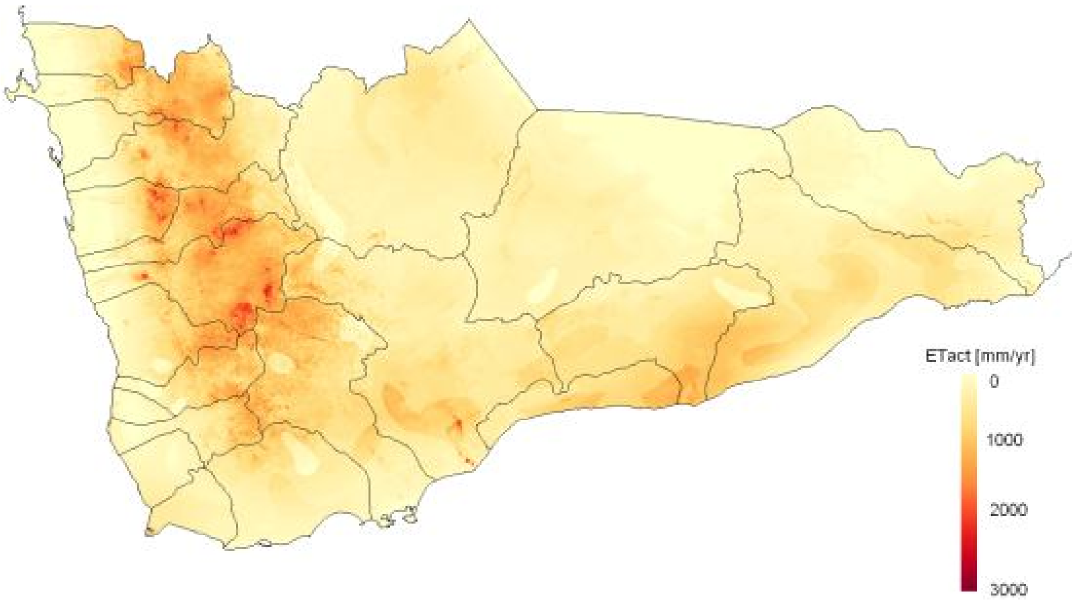


Figure 80: Spatial distribution of actual evapotranspiration across Yemen based on the energy balance. The results are not calibrated against local field instruments. The pixel size is 250 m.

The annual ET rates were averaged for each catchment (see Figure 81). The catchments with the highest ET values are Wadi Zabid and Wadi Rima. They contain areas with permanent green vegetation. This vegetation represents mixed landscapes with pastures, bushland, and forests.

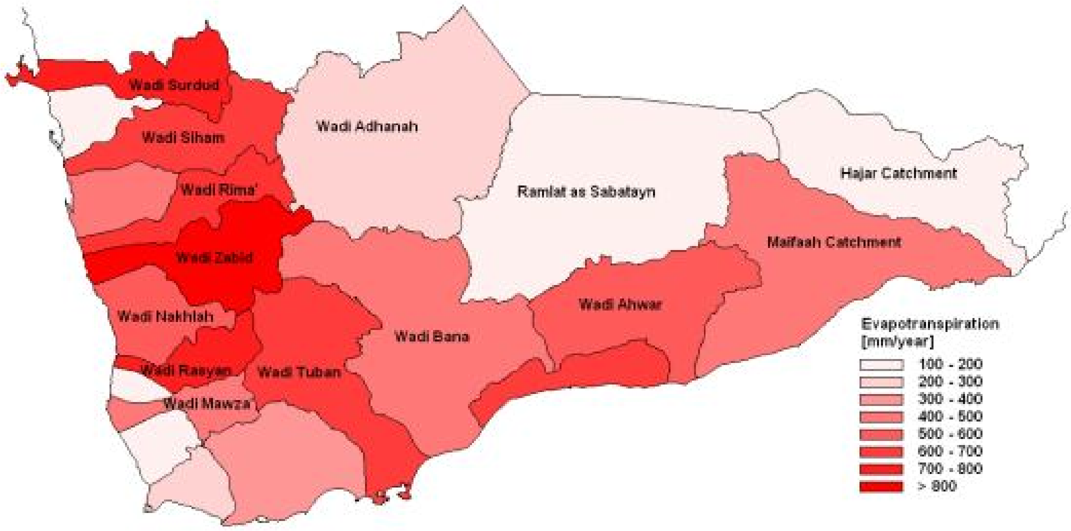


Figure 81: Total actual evapotranspiration per annum for 14 catchments during 2010.

The inclusion of MODIS images, or other low resolution images with a daily return period, makes remote sensing technology attractive for continuous monitoring of the evaporative depletion process throughout the entire Yemen. Together with the daily values of TRMM, it is feasible to produce daily reports on the water resources of Yemen; a breakthrough that has not been possible before. This could be beneficial for all water policy making processes in the country.

9.3 Rainfall Deficit

Rainfall deficit is the difference between ET and P (precipitation or rainfall). A negative rainfall deficit indicates the extent of the annually renewable water resources that recharges groundwater systems and causes rivers to flow. Out of the 14 catchments analysed, only 4 catchments have a “healthy” rainfall deficit (P>ET). See Figure 60 and Table 55. The catchments with good overall water resources situations are Hajar Catchment, Ramlat as Sabatayn, Wadi Nakhlah and Wadi Mawza. Both Wadi Nakhlah and Wadi Mawza are located at the Red Sea Coast. Their favourable geography induces windward rains at the western slopes of the hills with peaks exceeding 2 000 m. Hajar Catchment and Ramlat as Sabatayn probably have a healthy rainfall deficit because of an absence of groundwater abstractions for irrigation.

The 10 remaining catchments are in a desperate situation where annual ET exceeds annual rainfall (see Figure 82 and Table 66). The threat has been the rapid expansion of groundwater-based irrigation causing aquifer depletion and deterioration of water quality. The situation of declining recharge and water table depths is exacerbated when protection of watersheds as a primary source of aquifer replenishment and soil conservation is not receiving proper attention. The role of groundwater dependent ecosystems has not been investigated, but is known to be a source of direct groundwater withdrawals in countries such as Australia and Mexico that have similar climates and land use classes. In the wadi's, it is not only irrigation that causes this problem of declining water tables.

Of the over-exploited wadis, Wadi Adhanah is least over-exploited (ET - P = 31 mm) and Wadi Zabid is most over-exploited (ET - P = 400 mm). Due to the catchment size, the volumetric over-exploitation of Wadi Zabid is 2 148 mcm/yr, and is lower than for Wadi Maifaah. Wadi Maifaah has a water deficit layer of 309 mm, which for an area of 1 291 million ha adds up to a volumetric shortage of 3 986 mcm/yr.
The total over-exploitation for these 14 catchments in 2010 is estimated at 13 billion cubic metre per year (bcm/yr; is 13 159 mcm/yr). Note that both P and ET have not been validated and that this is an estimation only. This number far exceeds the general country estimate of groundwater abstraction of approximately 4 bcm/yr (Yehya and Al-Asbahi, 2005). Hellegers et al. (2009) estimated the total abstractions for Yemen to be 3.5 bcm/yr and the recharge to be 2.5 bcm/yr. Hence, these authors believe that there is a net withdrawal of 1 bcm/yr only. Without calibration, it is not feasible to compare four spatial data results with the classical surveys and estimates on bulk numbers made by local experts. With some minor supporting field work, it is however feasible to calibrate the P, ET and ET-P data components. Especially the bare soil evaporation needs to be reduced. This is a rather straightforward process to undertake after have calibrated the rainfall rates and the outflow for these wadi's.

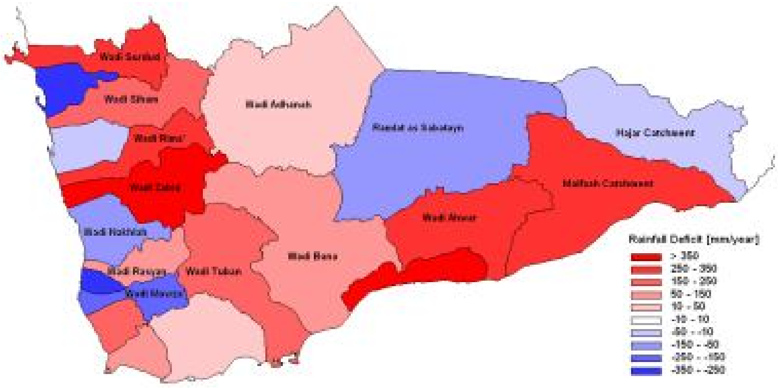


Figure 82: Annual rainfall deficit (ET – P) for 14 catchments in Yemen during 2010.

Table 66: Overview of rainfall (P), actual evapotranspiration (ET) and rainfall deficit (ET – P) for the 14 catchments investigated in Yemen during 2010. The dataset is uncalibrated

Wadi	**Area** [ha x 10^6]	**Rainfall** [mm/yr]	**Evapo-transpiration** [mm/yr]	**Rainfall Deficit** [mm/yr]	**Rainfall Deficit** [mcm/yr]
Wadi Surdud	0.3721	420	715	272	1 011
Wadi Siham	0.4997	453	642	184	918
Hajar Catchment	0.9438	129	139	-12	-116
Ramlat as Sabatayn	1.8390	222	171	-57	-1 046
Wadi Rima'	0.3171	515	813	297	940
Wadi Maifaah	1.2921	102	419	309	3 986
Wadi Zabid	0.5374	543	987	400	2 148
Wadi Bana	1.3470	325	475	142	1 913
Wadi Ahwar	0.7653	209	524	259	1 980
Wadi Nakhlah	0.3252	544	517	-97	-317
Wadi Tuban	0.7794	452	638	183	1 425
Wadi Rasyan	0.2253	744	730	54	122
Wadi Mawza'	0.2047	599	483	-154	-316
Wadi Adhanah	1.6380	249	273	31	507
Total	11.0861			119	13 159

9.4 Changes with respect to 2006

First the changes in green vegetation will be discussed as this is a good indicator of the health of the vegetation in general, and of the intensity of agriculture in particular. Figure 83 shows the change in annually averaged NDVI. For both 2006 and 2010, the measurements were based on the same Modis sensor, which made it possible to study changes in vegetation intensity at a resolution of 250m. The comparison shows that NDVI has increased mainly in the rainfed and irrigated areas (i.e. the red areas are cropped areas). Without any further analysis, this suggests that agriculture became more intensive, which is not in line with the overall policy to reduce water use in agriculture. We came to the same conclusion for the 4 study areas investigated. Intensification and greening of agricultural land is not desirable from a consumptive use point of view, and this process in the red areas needs to be arrested urgently.

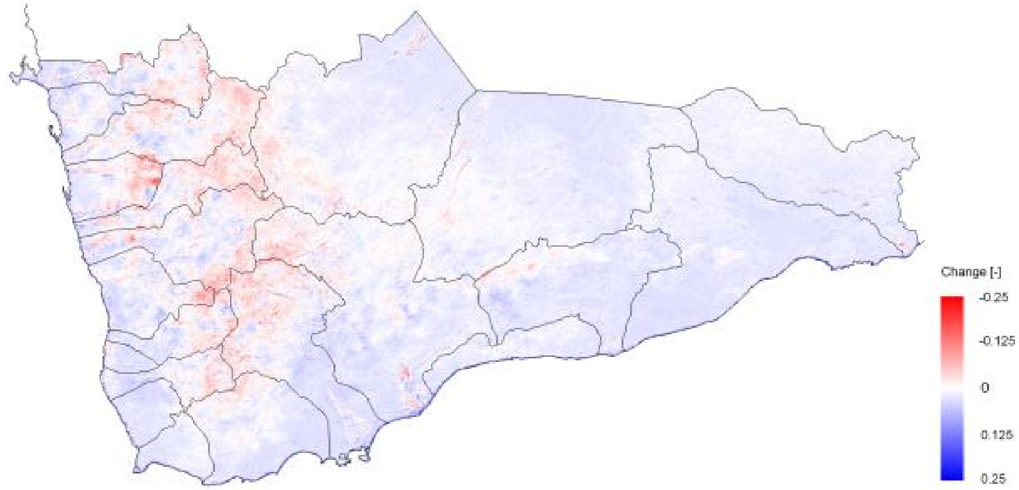


Figure 83: Difference in vegetation index between 2006 and 2010. Blue colours indicate less vegetation, red indicates more vegetation in 2010.

The overall objectives of the Yemeni Government and the World Bank in future studies should be to reduce the rainfall deficit across Yemen, by reducing the longer term ET to a level slightly lower than the longer term rainfall (ET~0.9 P). Since rainfall is a natural atmospheric process which cannot be managed, the only solution is to manage the reduction of ET. Fortunately, the ET did reduce in 2010 as compared to 2006 in 7 catchments. ET reduction was significantly in Hajar catchment (-254 mm/yr) and Wadi Surdud catchments (-180 mm/yr). This can be seen in
Table 67 and Figure 84. The reasons behind this phenomenon are not fully understood. It could be ascribed to reductions in groundwater pumping, but perhaps deforestation took place or the reference ET became lower (which will also lower ETact). The change in rainfall deficit is shown in Figure 84.

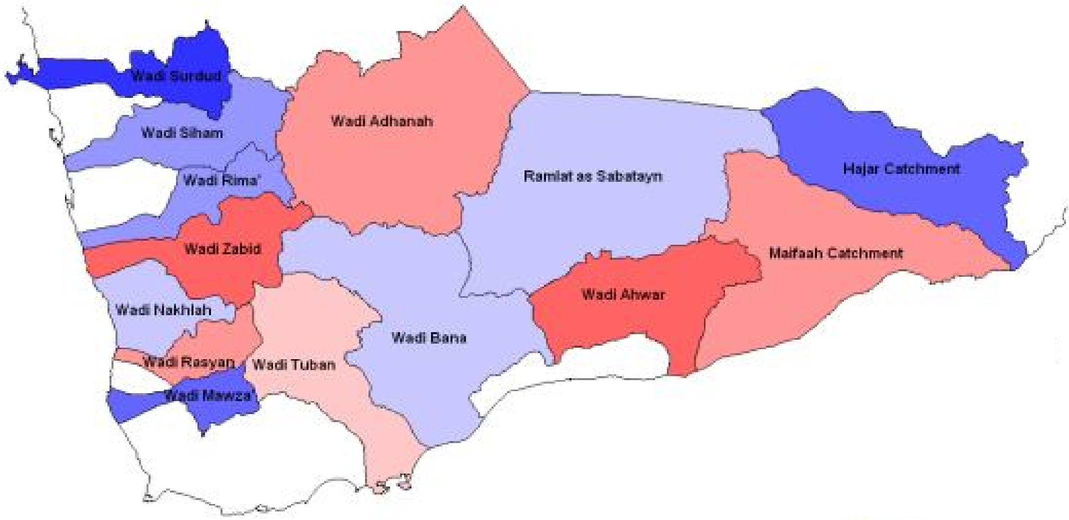


Figure 84: Changes in rainfall deficit as compared to 2006. Red colours indicate that the rainfall deficit increased since 2006 (i.e. undesirable). Blue colours indicate that the rainfall deficit decreased since 2006, indicating a healthier water balance (desirable).

The overall picture for the 14 catchments is an increase in ET of 21 mm. If the total consumptive use is similar, while vegetation intensity increases with time, then it is likely that the vegetation is exposed to more water stress. This was also observed in some study areas. The average rainfall deficit decreased by 7 mm/yr when averaged over all 14 catchments.

The primary solution is to restrict groundwater irrigation in cropland. A secondary solution is to implement catchment restoration in order to temper upstream water use and have more water available for downstream use. This needs to be introduced into Yemen, the sooner the better. This section has demonstrated that 250 m pixels values of annual rainfall deficit are extremely useful for implementation of a permanent monitoring system.

Table 67: Changes in the rainfall deficit with respect to 2006 expressed in mm/yr. Blue numbers indicate a positive effect on the water balance while red numbers indicate a negative effect.

Wadi	**Area** [10^6 ha]	**Rain** [mm/yr]		**Evapotranspiration** [mm/yr]		**Rainfall Deficit** [mm/yr]	
Wadi Surdud	0.3721	108	35%	-180	-20%	-289	-49%
Wadi Siham	0.4997	52	13%	-65	-9%	-117	-38%
Hajar Catchment	0.9438	-16	-11%	-254	-65%	-239	-96%
Ramlat as Sabatayn	1.8390	75	51%	31	22%	-44	624%
Wadi Rima'	0.3171	74	17%	-55	-6%	-128	-30%
Wadi Maifaah	1.2921	14	16%	136	48%	121	62%
Wadi Zabid	0.5374	-153	-22%	66	7%	219	97%
Wadi Bana	1.3470	21	7%	-9	-2%	-29	-16%
Wadi Ahwar	0.7653	61	41%	220	72%	159	102%
Wadi Nakhlah	0.3252	50	10%	24	5%	-26	∞
Wadi Tuban	0.7794	22	5%	42	7%	20	12%
Wadi Rasyan	0.2253	-98	-12%	-13	-2%	85	-86%
Wadi Mawza'	0.2047	63	12%	-125	-20%	-188	-261%
Wadi Adhanah	1.6380	42	20%	92	51%	51	-189%
Total	11.0861	29	11%	21	5%	7	5%

11. Limitations and recommendations

11.1 Limitations

In a study of this magnitude, there are always a number of assumptions, unsubstantiated deductions and interpretations that need to be reported. This chapter deals with the limitations of the current study and provides cautions regarding the interpretation of certain results.

The most important limitation is the scarcity of local measurements and which in a country like Yemen are difficult to get access to, especially in the light of the special situation of 2011. Without the ability to check against local field conditions and undertake measurements in particular areas, the definition of the overall accuracy is jeopardized. Validation of the surface energy balance has been achieved for other Middle East countries such as Egypt, Sudan, Saudi Arabia, Turkey and Iran before. It has been concluded and published that the accuracies for pixel values of crop consumptive use are 95% or more (Turkey: Bastiaanssen, 2000; Sudan: Mohamed et al., 2004; Egypt: Zwart and Bastiaanssen, 2007; Iran: Vazifedoust et al., 2007; Akbari et al., 2007). The new source from Atroosh and Moayad (2012) shows an accuracy of 98% and confirms the quality of the data components.

In general terms it can be mentioned that relative changes of data components computed by the same mathematical model are more accurate than their absolute levels. This is relevant in a study like this where ground verifications have been minimal and changes between 2006 and 2009 as well as between GSCP and neighbouring areas are paramount. The gross rainfall observed by the TRMM 4B43 product for instance has its own biases. So do the energy balance modelling and the land use classification results; the differences they display between 2006 and 2010 are however thought to be 95% accurate, which is more or less similar to the changes detected. The results presented are thus neither soft nor hard.

By selecting a restricted number of evaluation fields, the overall interpretation by the Field Unit may lead – unintentional - to different insights, and hence conclusions about the success of the interventions. There were 487 GSCP points located in the three study areas investigated. The field surveys in these locations focus on improving the conveyance and on-farm irrigation efficiencies, as well as the crop yields. The remote sensing data provides an unbiased and extra source of information.

Although the same methods were used for 2006 and 2010 analyses, the data sources were not the same. Spot images can be acquired upon request only. The collection of satellite images took place after the designated study period. This study was thus a retrospective study and all images had to be collected from archives at the Japanese and US space agencies. Future programming was not feasible, and for this reason, the study was merely based on Alos, Aster and Landsat images. To compensate for the differences in data sources, additional analyses have been undertaken with NDVI data sets of Modis. The same sensor has been used for 2006 and 2010.

The largest uncertainty in the irrigation water resources assessment is the assignment of irrigation efficiencies and the partitioning among surface water and groundwater resources. Flood irrigation was given a 40% efficiency, being a value typically used by spate irrigation. Groundwater irrigation was assumed to have a 55% efficiency, except for qat which is irrigated with tankers and had an efficiency of 85%. The current conveyance and on-farm water use efficiencies are very low, and GSCP interventions are aimed at increasing these efficiencies. The limitation of this study is that one single efficiency factor has been used for various combinations of land use classes and regions. Locally improved efficiencies at the GSCP points (34 000 ha) could not be inserted in the raster based calculations because it was simply not known which pixel had undergone efficiency improvements, and what the improved value is. Gross groundwater abstractions thus were computed from the efficiencies previously defined; which have led to a bias in the gross abstraction values. This is a problem, and a motivation to give extra attention to crop ET as an indicator of water savings. Crop ET can be computed by means of PI Mapping (Pixel Intelligence) procedures, and is not exposed to any assumption related to efficiency.

11.2 Recommendations

The first prerequisite in any water saving program is to define the pathways that exist to save water flows. Diminished groundwater abstractions can be achieved in a more general sense by accomplishing the following interventions:

- Reduce annual cropping intensity
- Cultivate less irrigation intensive crops
- Increase irrigation efficiency between point of abstraction to root water uptake by crops
- Apply deficit irrigation and induce crop water stress
- Reduce non-beneficial soil evaporation
- Shrink the acreage of irrigated land by early retirement programs

GSCP has focussed on reducing losses due to conveyance of water through earthen canals as well as losses through percolation from fields. The aim of GSCP is also to increase on-farm efficiency by the introduction of localized irrigation and plastic pipes. The efficiencies have been successfully implemented on 34 000 ha. In addition, GSCP has given ample attention to non-expansion of irrigated cropped areas and no qat production in the farms that receive technical assistance.

Satellites have the special capacity to monitor the beneficiaries' compliances with the covenants relating to non-expansion of irrigated cropped areas after installation of improved irrigation technologies. The GeoEye examples extracted from Google Earth seemed to be very useful to visually verify these changes. The digital shape boundaries of beneficiary fields should have been made available to the consultant for drawing conclusions. This was not done and a circle around every point has been used instead. The GeoEye images can also be explored for assessing the type of agricultural land use and the type of crop. This can save costs, and can be a good yardstick for improving the overall accuracy of agricultural land use classifications. While very high resolution images such as GeoEye, WorldView, Quickbird and Ikonos are expensive, they can be very helpful in understanding changes that occur at beneficiary farms.

All attention in groundwater management in Yemen is focussed on reducing of abstractions, and more attention is needed for reducing ET. In addition to that, the recharge from rainfall, groundwater return flows and losses from surface water irrigation should receive more attention as well. Because the climatology (rainfall and reference

ET) exhibit intra-annual variability, it is recommended to create multiple time series, and not just pick two years (2006 & 2010). By enhancing recharge and recapturing non-consumed water in the groundwater system for reuse, the entire situation can be become more resilient than it is today.

To solve the problem of validation of rainfall and ET data components, the network of weather stations should be extended and especially to remote locations where extreme weather conditions apply. It is recommended that a few more automatic weather stations are installed and that publicly accessibility to the data is guaranteed. It is of essence to have extra rain gauges on locations with very high rainfall. An open data distribution of these data sets is as important as the installation of new stations.

A second recommendation is to prepare sites for flux measurements. EuroFlux and AsiaFlux networks are gradually expanding for the measurement of vapour and carbon fluxes. There are no such stations present on the Arabian Peninsula. Access to sensible heat and evapotranspiration measurements is essential for the validation of SEBAL. Advanced instrumentation such as scintillometers and eddy covariance systems should be introduced in Yemen.

The unsustainable exploitation of groundwater cries out for a national monitoring system. Any basic hydrology data set starts with spatial layers of rainfall and ET. With the availability of daily Modis images and microwave soil moisture information, it is feasible to monitor daily and weekly ET rates for the entire Yemen with a spatial resolution of 250 m. In conjunction with TRMM rainfall – and the downscaled rainfall to 1 km – it will be possible to get an understanding of trends during the growing season. Real-time monitoring of the water accounts of all wadis in a standard manner is essential for modifying the daily operations. Yemen is a country that lends itself for water accounting by satellites.

12. Conclusions

The aim of the Groundwater and Soil Conservation Project (GSCP) is to stop the depletion of groundwater in Yemen, and to enhance soil conservation and recharge to groundwater. This report contributes to GSCP processes by evaluating and assessing impacts of GSCP interventions. We investigated specific techniques for monitoring of irrigated area; actual crop water use; and irrigation water supply. The final summary for 2010 is as follows:

Table 68: Summary of the most important parameters, comparison between study areas and the GSCP points within those areas.

Parameter	Study area			GSCP		
	Siham	Dhamar	Abyan	Siham	Dhamar	Abyan
Irrigated area	20%	12%	13%	29%	37%	36%
NDVI	0.232	0.191	0.131	0.216	0.257	0.257
Land use -- Less	5%	5%	3%	10%	6%	14%
More intense	20%	8%	6%	34%	22%	31%
Irrigation intensity	124%	107%	126%	137%	112%	140%
ET [mm/yr]	609	625	422	627	852	752

The results show that land use at the regional scale has remained the same for 84% of the cases, which is acceptable for a time span of 4 years. The increase in more irrigation intensive land use was 11% as compared to 4% cases where reduction occurred. This implies a net increase of 7% with fields with more intensive cropping patterns.

The trend in irrigation intensification is supported by the NDVI analysis of the Modis satellite. The green vegetation cover has increased in general, and even at a higher rate in the vicinity of GSCP schemes. The 487 GSCP points show a greener landscape (0.244 vs 0.185) and a higher irrigated land use (34% vs 15%) than further away from these beneficiary farms. The annual irrigation intensity was also higher: 129% vs 119%. The conclusion is that the majority of the farmers acted according to the sanctions agreed, and a minority did not, for whom GSCP interventions were an incentive for vertical (more density) and horizontal expansion (more area).

Indeed, the total irrigated area increased by 5 682 ha which, compared to the 2006 reference of 102 522 ha, implies a horizontal expansion of 6%. The annual irrigation intensity did not change much. The situation differs with area and crop type. A diversified and local solution seems to work the best.

Field units with a horizontal expansion of more than 3% were confined to areas with potential for spate flow irrigation (e.g. Siham 51 454 ha more net intense or 15.0%). Increased irrigation intensity in groundwater zones are moderate (e.g. Rada 1 790 ha more net intense or 1.2%), but unacceptable for arresting overdrafts.

While much attention goes to qat cultivation in the highlands of Yemen, this study shows that the single season crops on the coastal belts, especially in Abyan, consume a much larger volume of water, and that their groundwater abstractions are accordingly higher. The gross groundwater abstractions for perennials and qat in Dhamar and Rada are 24 mcm/yr while 111 mcm/yr is abstracted to irrigate the single season crops in Siham and Abyan.

Larger water volumes at the farm gate are thought to be the explanatory reason for more intensive cropping, a higher ET rate and more yield per unit of land. Farmers exploit this extra resource for sound economic reasons and vertically / horizontally intensify their land resources. This is confirmed by a consistent difference in results between GSCP points and regions.

The total water savings are insufficient to arrest groundwater over-exploitation in Yemen. Over-exploitation of groundwater in the 105 522 ha investigated suggests a gross aquifer withdrawal of 465 mcm/yr. This is equivalent to a water layer of 319 mm/yr.

The GSCP program has been very effective in communicating the over-exploitation issues to a large agricultural public in Yemen. The 56 mcm savings achieved are encouraging, but the effect is a more intense irrigation cropping system and more groundwater from deeper aquifers to be evaporated into the atmosphere. This does not contribute to the overall control of water resources, and it is recommended that more attention be given to the reduction of ET in future donor programs.

It seems that three study areas have increased the groundwater abstractions, Abyan being the exception. While the total abstraction in 2010 was estimated as being 465 mcm/yr, the same value for 2006 was 196 mcm/yr. Siham pumped 2 mcm/yr more groundwater irrigation, especially in double season crops. Dhamar pumped more water for single season crops and the total value for this region increased by 48 mcm/yr. Rada also pumped more groundwater: 8 mcm/yr more. Dhamar and Rada should thus be better controlled in terms of groundwater abstractions. The overall finding is that groundwater abstraction increases with 9 % per year. This needs to be stopped using the latest advances in technologies.

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Appendix 1: SEBAL description

Algorithm overview

The Surface Energy Balance Algorithm for Land (SEBAL) is an image-processing tool comprised of 25 computational steps that calculates the actual (ET_{act}) and potential evapotranspiration rates (ET_{pot}) as well as other energy exchanges between land and atmosphere. The key input data for SEBAL consists of spectral radiance in the visible, near-infrared and thermal infrared part of the spectrum (see Figure 85). SEBAL computes a complete radiation and energy balance along with the resistances for momentum, heat and water vapour transport for every individual pixel. The resistances are a function of state conditions such as soil water potential (and thus soil moisture), wind speed and air temperature and change from day-to-day.
Satellite radiances will be converted first into land surface characteristics such as surface albedo, leaf area index, vegetation index and surface temperature. Additional input used in deriving the land surface characteristics consists of a digital elevation model (DEM) and a land use map. The land used map should discriminate between water, vegetated areas, bare soil and built-up area. The land surface characteristics can be derived from different types of satellites.

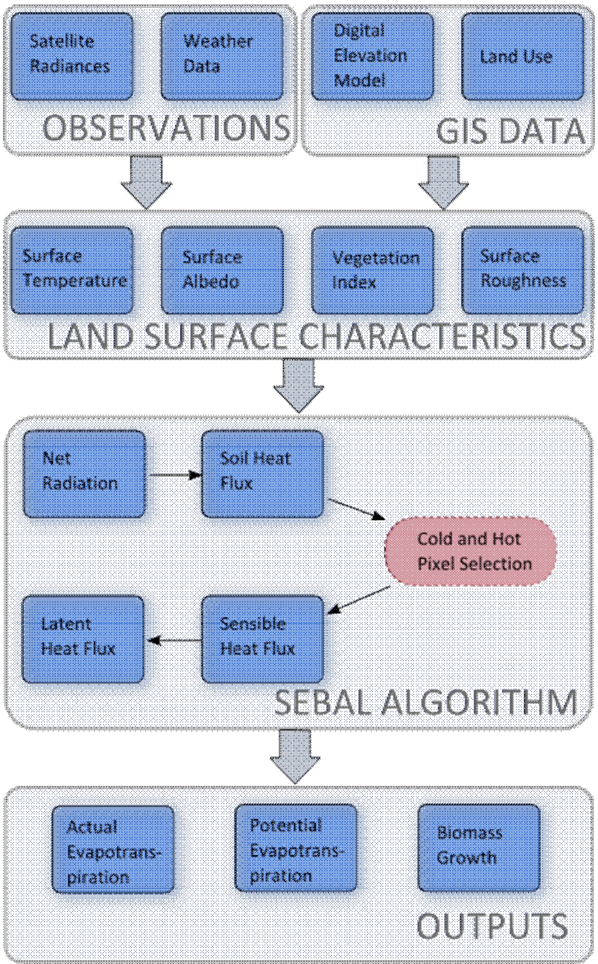


Figure 85: Schematic view of the SEBAL algorithm.

Data requirements

In addition to satellite images, the SEBAL tool requires the following routine weather data parameters:

- Wind speed
- Humidity
- Solar radiation
- Air Temperature

There is limited data on land use needed, and no data on soil type or hydrological conditions is required to apply SEBAL.

SEBAL Evapotranspiration

The primary basis for the SEBAL tool is the surface energy balance. The instantaneous ET_{act} flux is calculated for each cell of the remote sensing image as a 'residual' of the surface energy budget equation:

$$ET = R_n - G - H \qquad [W/m^2] \qquad (1)$$

Where; ET is the latent heat flux [W/m^2], R_n is the net radiation flux at the surface [W/m^2], G is the soil heat flux [W/m^2], and H is the sensible heat flux to the air [W/m^2], see Figure 86. The terms of the surface energy balance are different for different type of surfaces. For vegetation the ET value is larger than the H flux. For bare soil the situation is vice versa. SEBAL uses these differences in energy balance behaviour for the different surfaces to get a first estimate on the surface energy balance for all pixels.

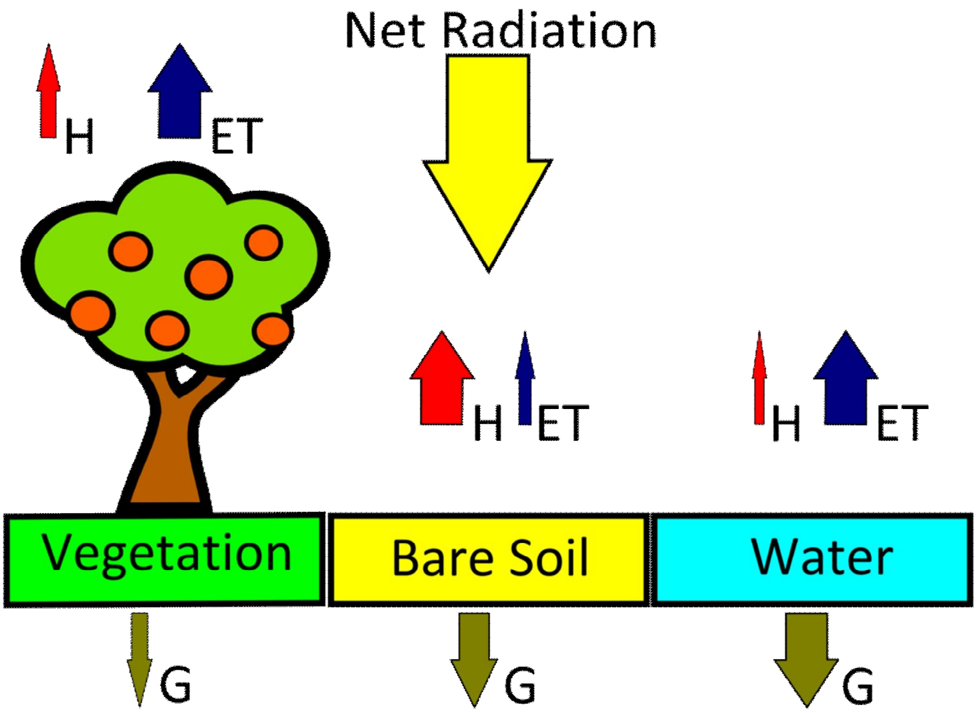


Figure 86: Surface Energy Balance for different types of surfaces.

R_n represents the actual radiant energy available at the surface. It is computed by subtracting all outgoing radiant fluxes from all incoming radiant fluxes. This is further specified in the surface radiation balance equation:

$$R_n = R_{S\downarrow} - \alpha R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\varepsilon_0)R_{L\downarrow} \quad [W/m^2] \qquad (2)$$

where $R_S\downarrow$ is the incoming short-wave radiation [W/m^2], α is the surface albedo (dimensionless), $R_L\downarrow$ is the incoming long wave radiation [W/m^2], $R_L\uparrow$ is the outgoing long wave radiation [W/m^2], and ε_o is the surface thermal emissivity (dimensionless).

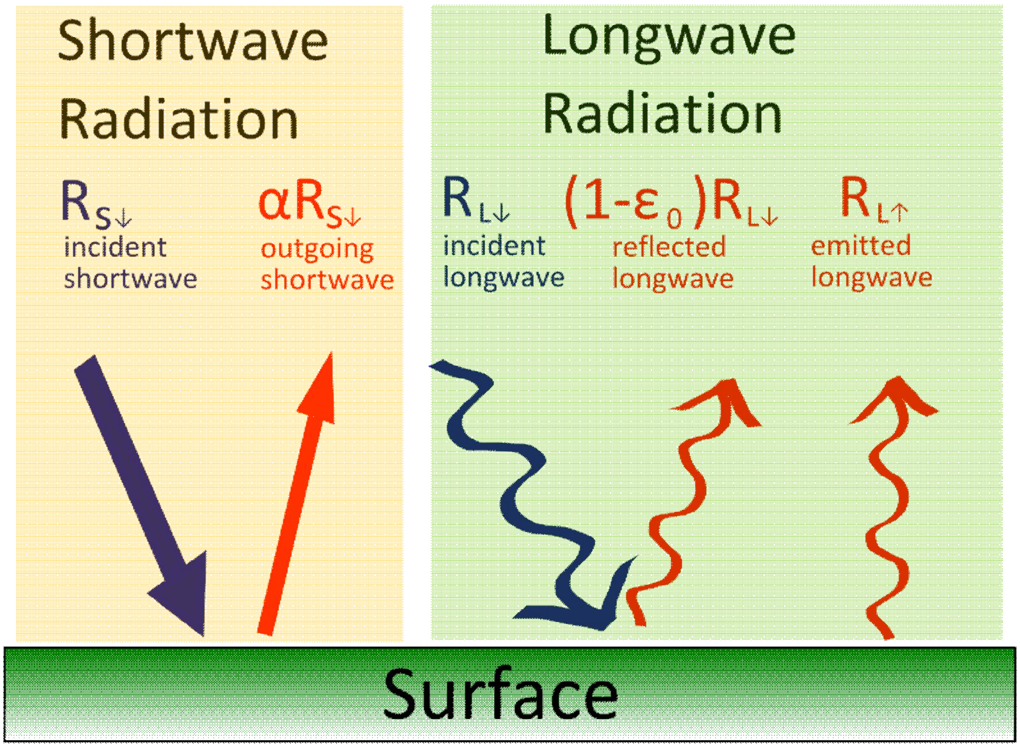


Figure 87: Surface Radiation Balance.

In Equation (2), the amount of net short-wave radiation ($R_S\downarrow$ - $\alpha R_S\downarrow$) that remains available at the surface, is a function of the surface albedo (α). The broad band surface albedo α is derived from the narrow band spectral reflectance's α(λ) measured by each satellite band. The incoming short-wave radiation ($R_S\downarrow$) is computed using the solar constant, the solar incidence angle, a relative earth-sun distance, and a computed broad band atmospheric transmissivity. This latter transmissivity can be estimated from sunshine duration or inferred from pyranometer measurements (if available). The incoming long wave radiation ($R_L\downarrow$) is computed using a modified Stefan-Boltzmann equation with an apparent emissivity that is coupled to the shortwave atmospheric transmissivity and a measured air temperature. Outgoing long wave radiation ($R_L\uparrow$) is computed using the Stefan-Boltzmann equation with a calculated surface emissivity and surface temperature. Surface temperatures are computed from the satellite measurements of thermal radiances.

In Equation (1), the soil heat flux (G) and sensible heat flux (H) are subtracted from the net radiation flux at the surface (R_n) to compute the "residual" energy available for evapotranspiration (λE). Soil heat flux is empirically calculated as a G/R_n fraction using vegetation indices, surface temperature, and surface albedo. Sensible heat flux is computed using wind speed observations, estimated surface roughness, and surface to air temperature differences that are obtained through a sophisticated self-calibration between dry (λE≈0) and wet (H≈0) pixels. SEBAL uses an iterative process to correct for atmospheric instability caused by buoyancy effects of surface heating.
The λE time integration in SEBAL is split into two steps. The first step is to convert the instantaneous latent heat flux (λE) into daily λE24 values by holding the evaporative fraction constant. The evaporative fraction EF is:

$$EF = \lambda E / (R_n - G) \qquad [-] \qquad (3)$$

Field measurements under various environmental circumstances have indicated that EF behaves temporally stable during the diurnal cycle. Since EF ~ EF24, i.e. the 24 hour latent heat flux can be determined as:

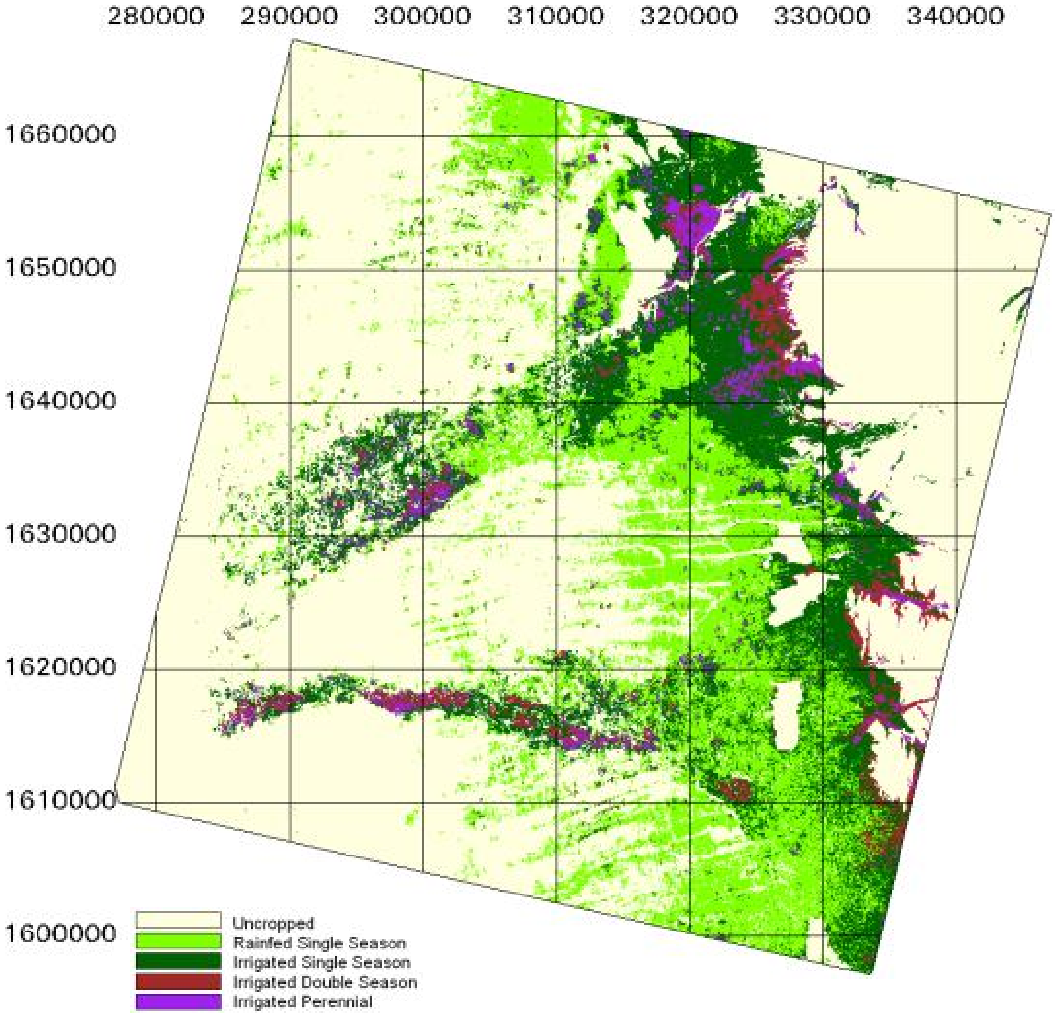
$$\lambda E24 = EF\ R_{n,24} \qquad [W/m^2] \qquad (4)$$

For simplicity, the 24 hour value of G is ignored in Equation (4). The second step is the conversion from a daily latent heat flux into monthly values, which has been achieved by application of the Penman-Monteith equation:

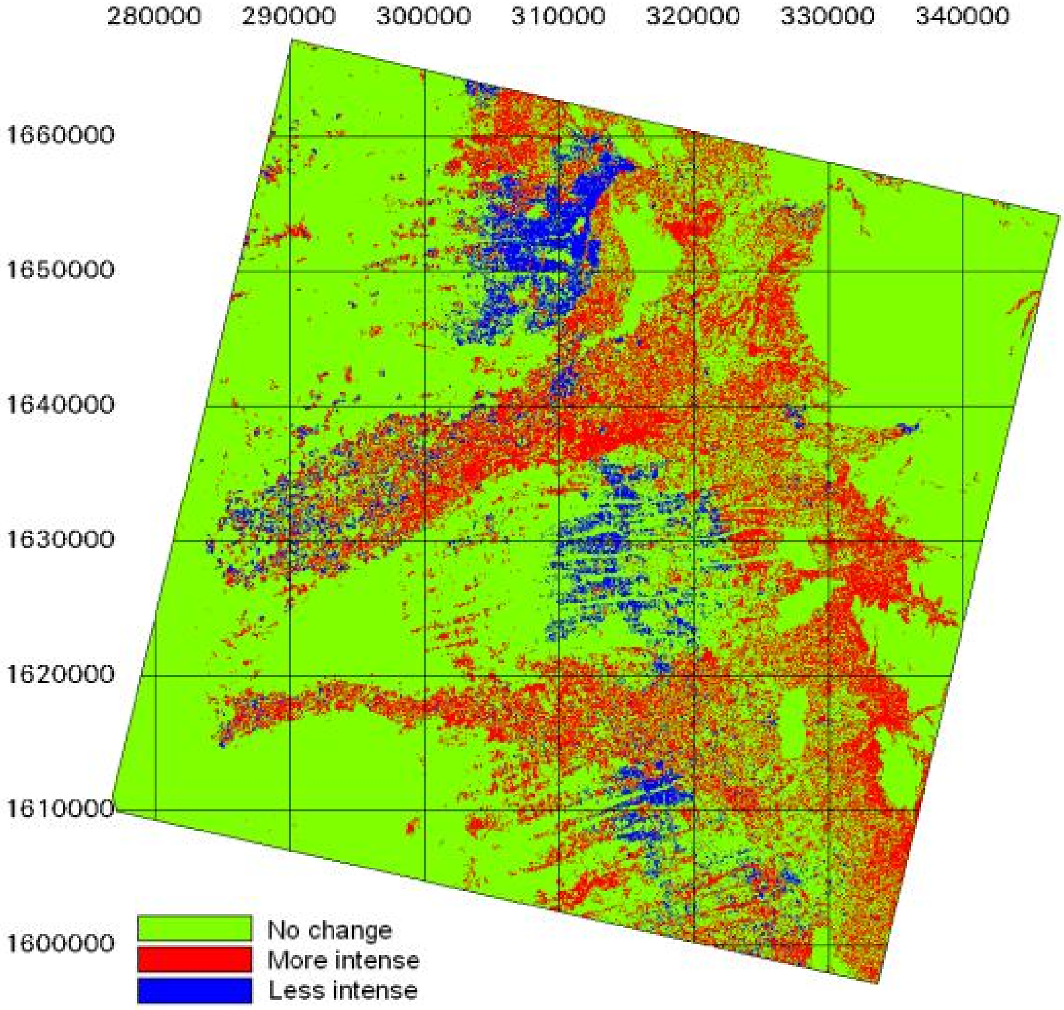
$$\lambda E_{PM} = (sa\ R_{n,24} + \rho_a c_p\ \Delta e/ra) / (s_a + \gamma\ (1 + r_s/r_a)) \qquad [W/m^2]\ (5)$$

where s_a (mbar/K) is the slope of the saturated vapor pressure curve, $\rho_a c_p$ (J/m3 K) is the air heat capacity, Δe (mbar) is the vapor pressure deficit, γ (mbar/K) is the psychrometric constant and ra (s/m) is the aerodynamic resistance. The parameters s_a, Δe and r_a are controlled by meteorological conditions, and R_n and r_s by the hydrological conditions.
The SEBAL computations can only be executed for cloudless days. The result of λE24 from Eq. (4) has been explored to convert the Penman-Monteith equation (Eq. 5) and to quantity r_s inversely using $\lambda E_{24} = \lambda E_{PM}$. The spatial distribution of r_s so achieved, will consequently be used to compute λE_{24} by means of Equation (5) for all days without satellite image available (Bastiaanssen and Bandara, 2001). The total ET_{act} for a given period can be derived from the longer term average λE flux by correcting for the latent heat of vaporization and the density of water.

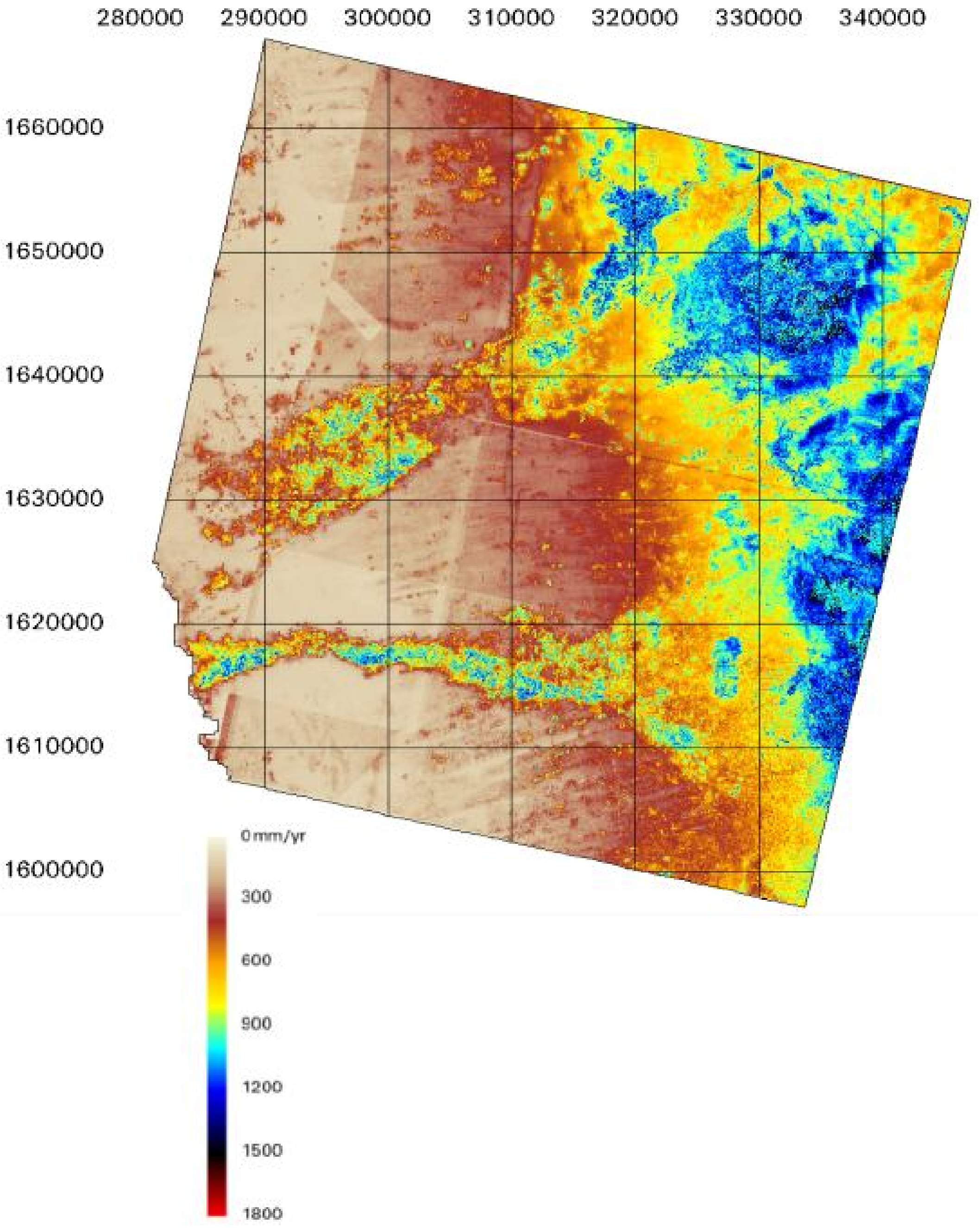
Appendix 2: Land Use Map, 2010 Siham



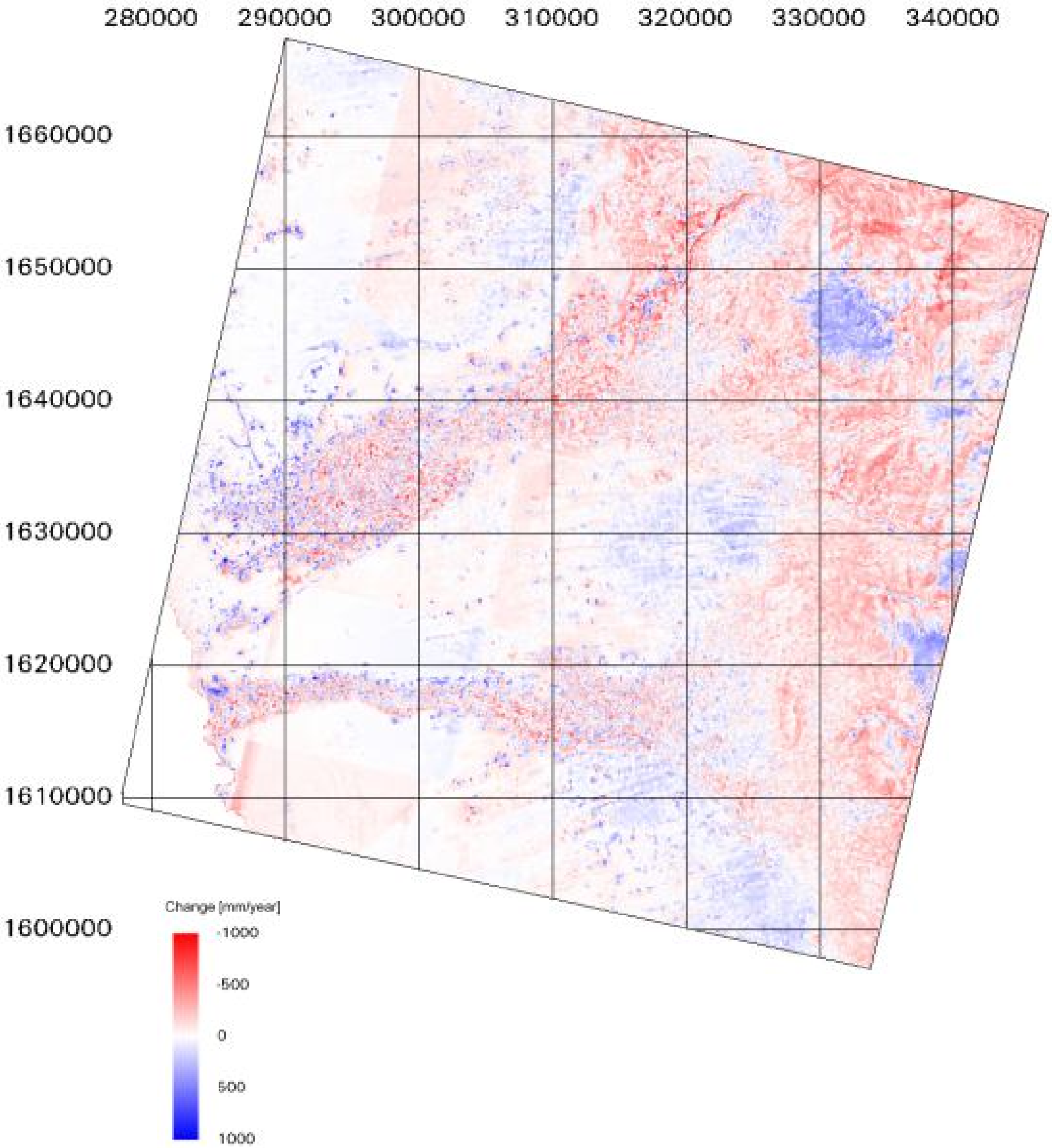
Appendix 3: Changes in Land Use between 2006 and 2010 Siham



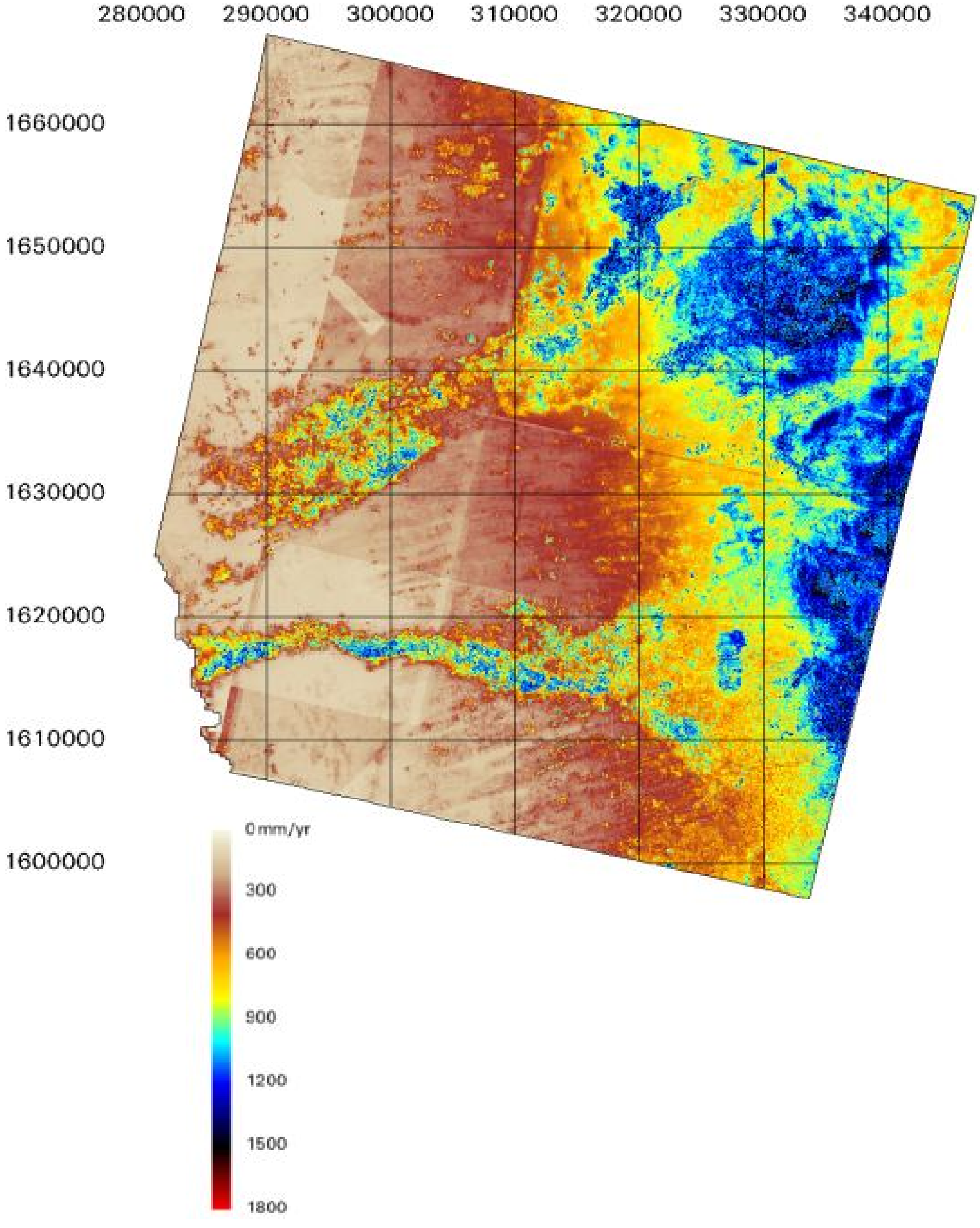
Appendix 4: Actual Evapotranspiration Map, 2010 Siham



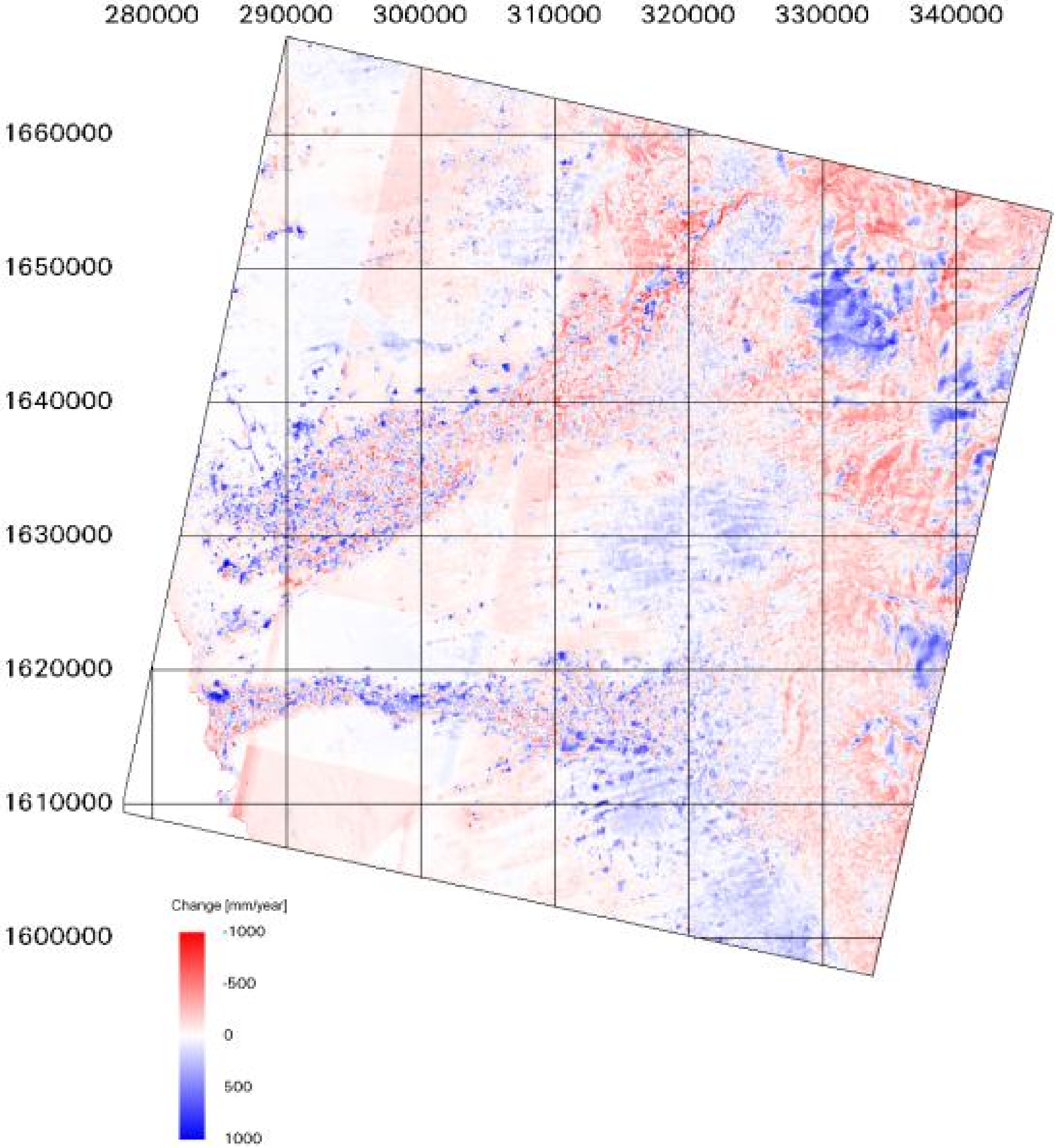
Appendix 5: Changes in Actual Evapotranspiration between 2006 and 2010 Siham



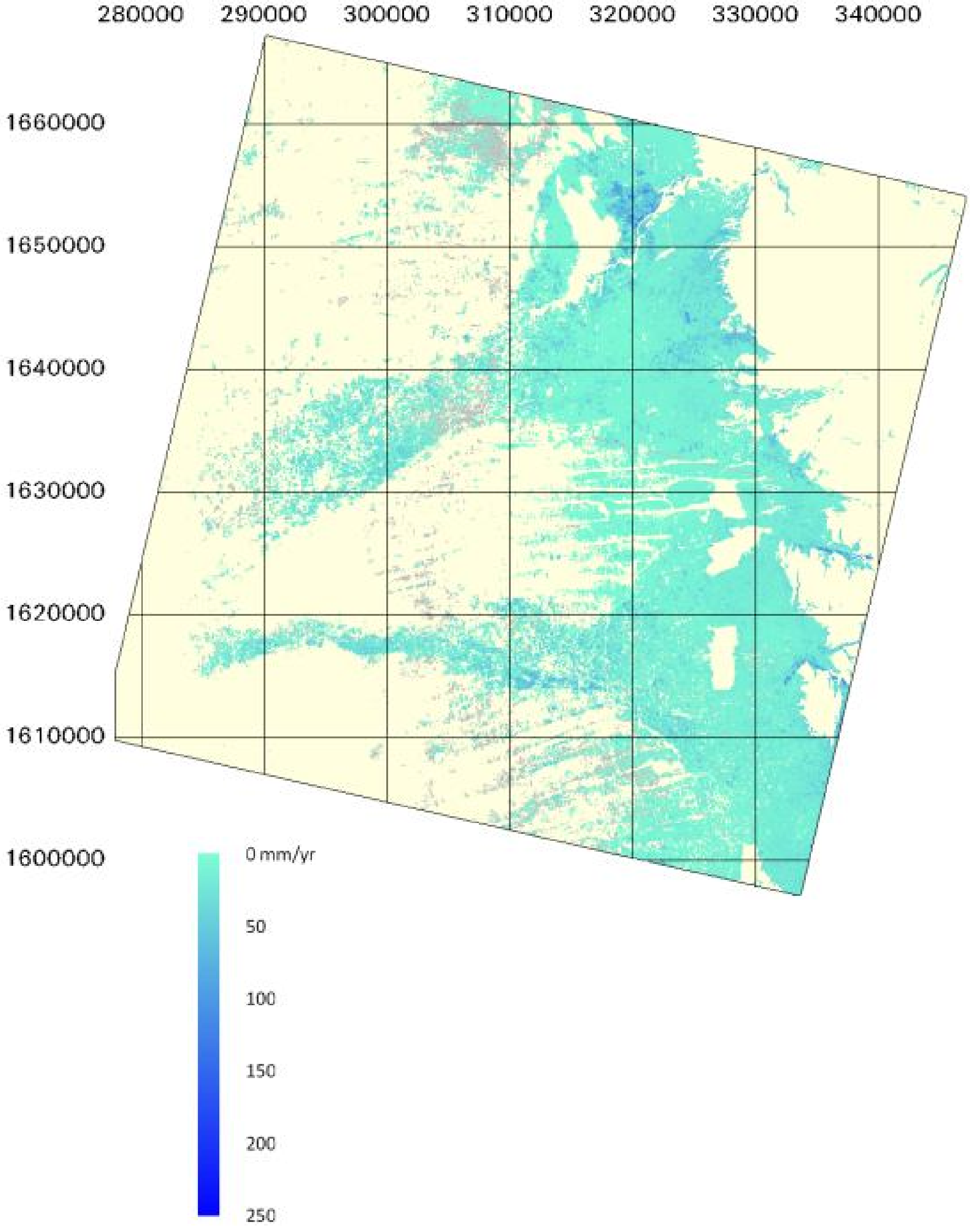
Appendix 6: Potential Evapotranspiration Map, 2010 Siham



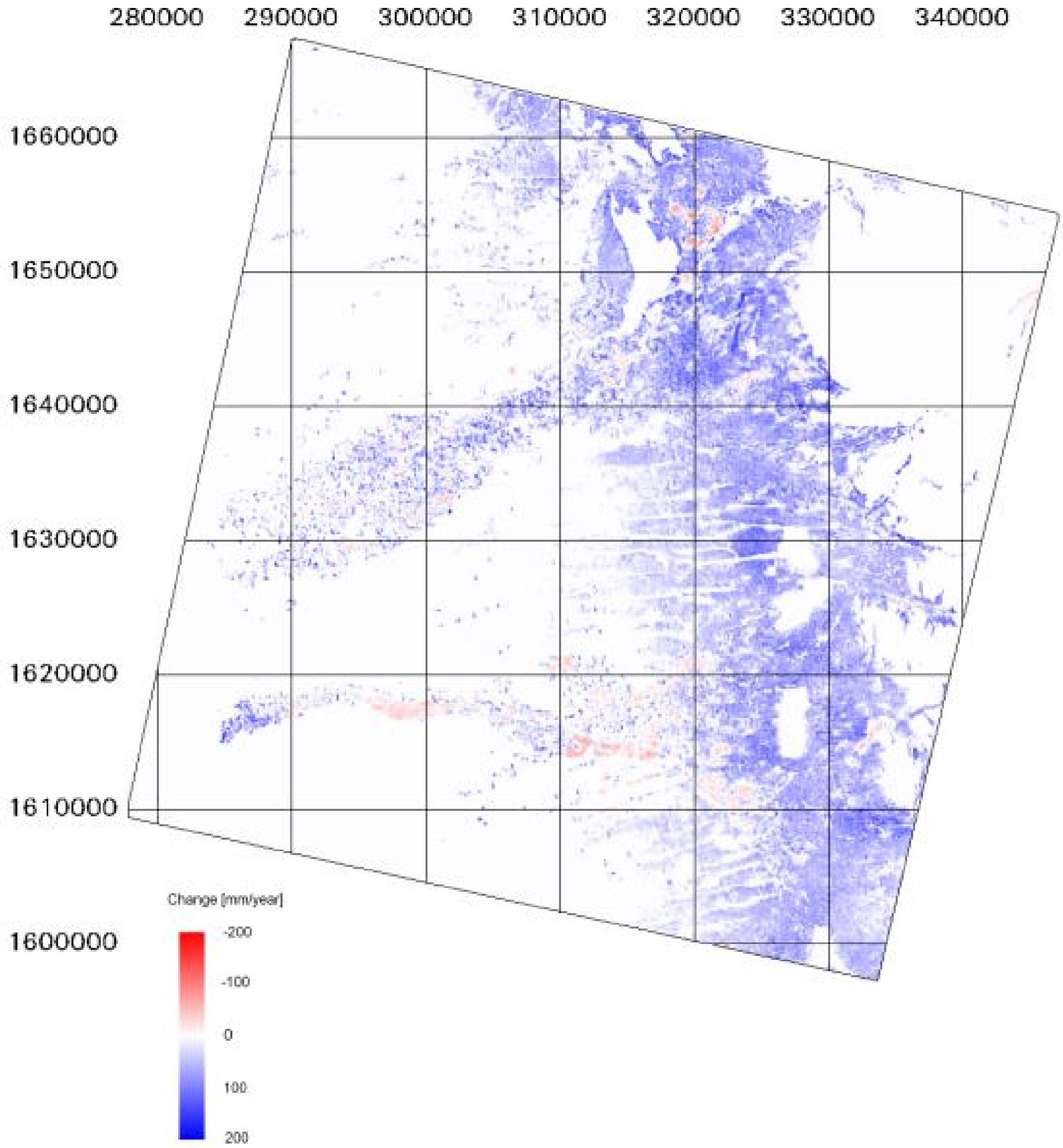
Appendix 7: Changes in Potential Evapotranspiration between 2006 and 2010 Siham



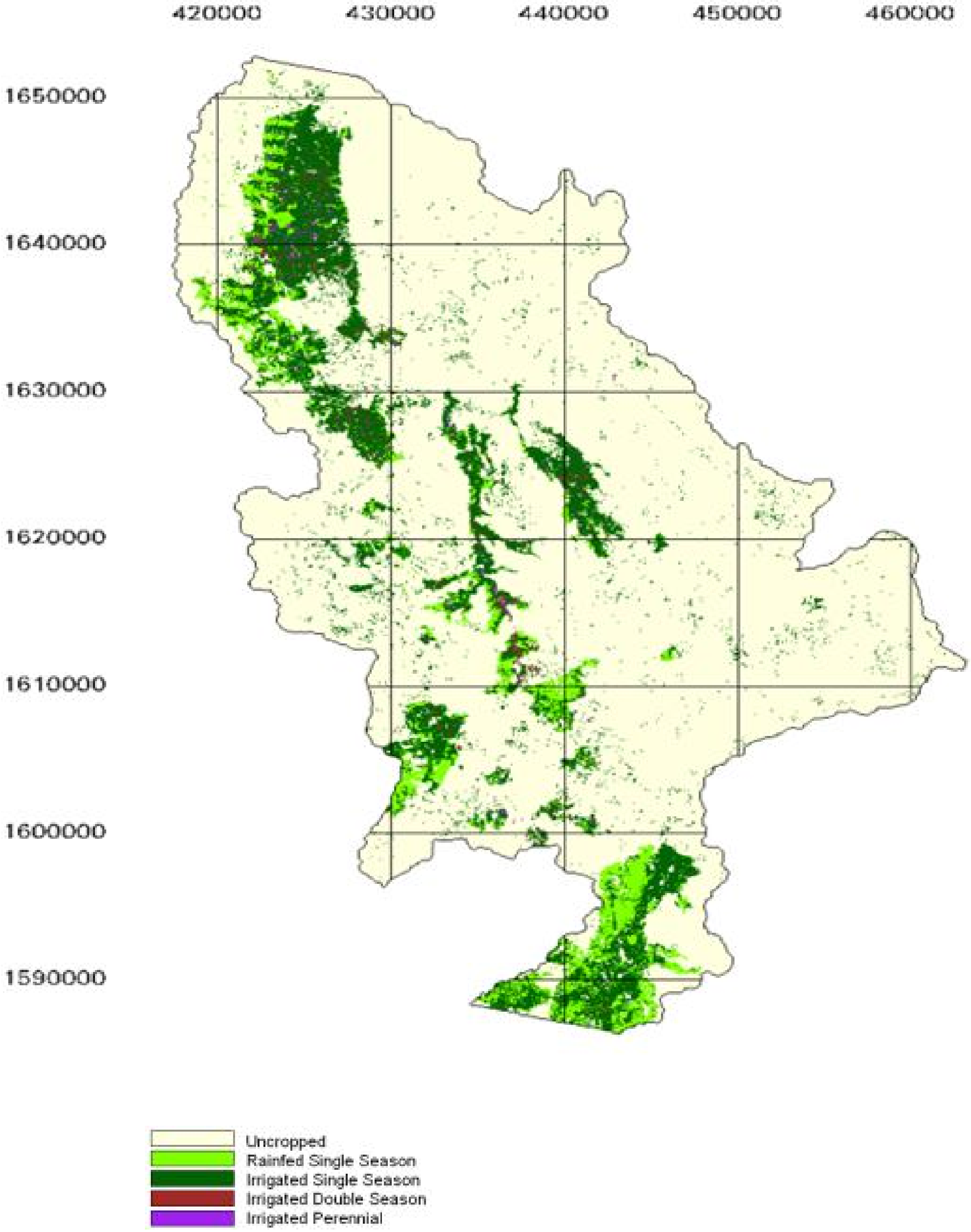
Appendix 8: Water Savings Map, 2010 Siham



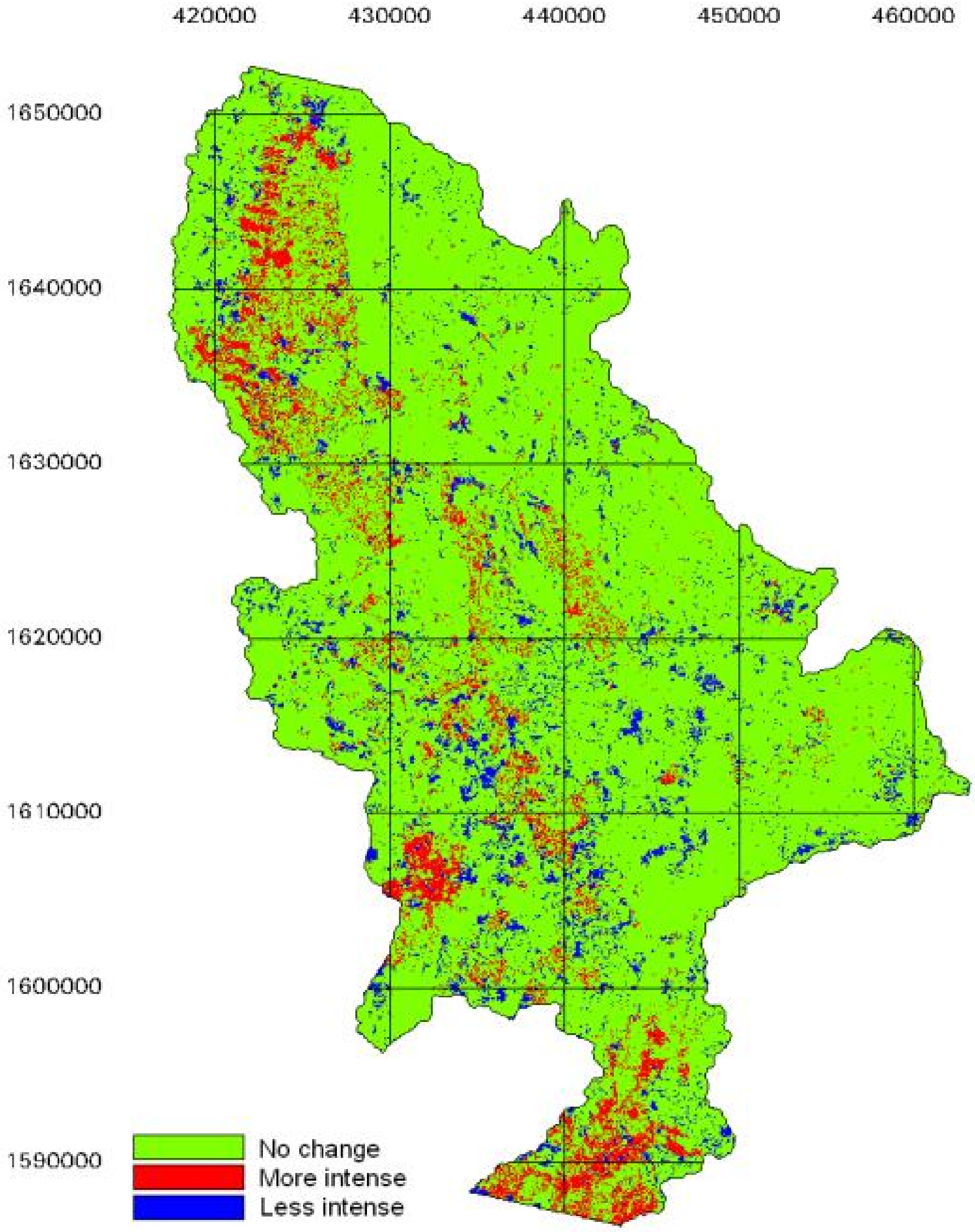
Appendix 9: Changes in Water Savings between 2006 and 2010 Siham



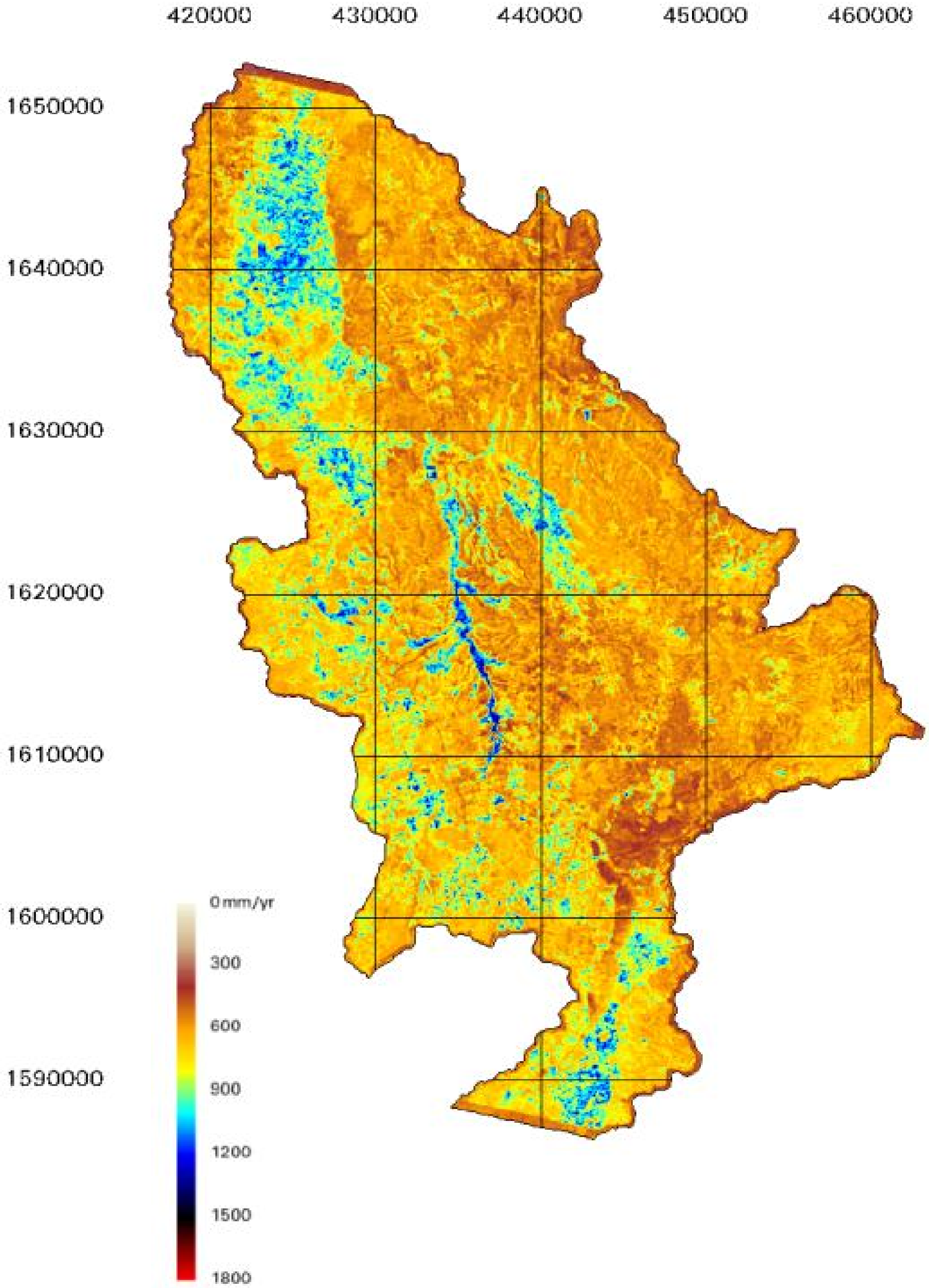
Appendix 10: Land Use Map, 2010 Dhamar



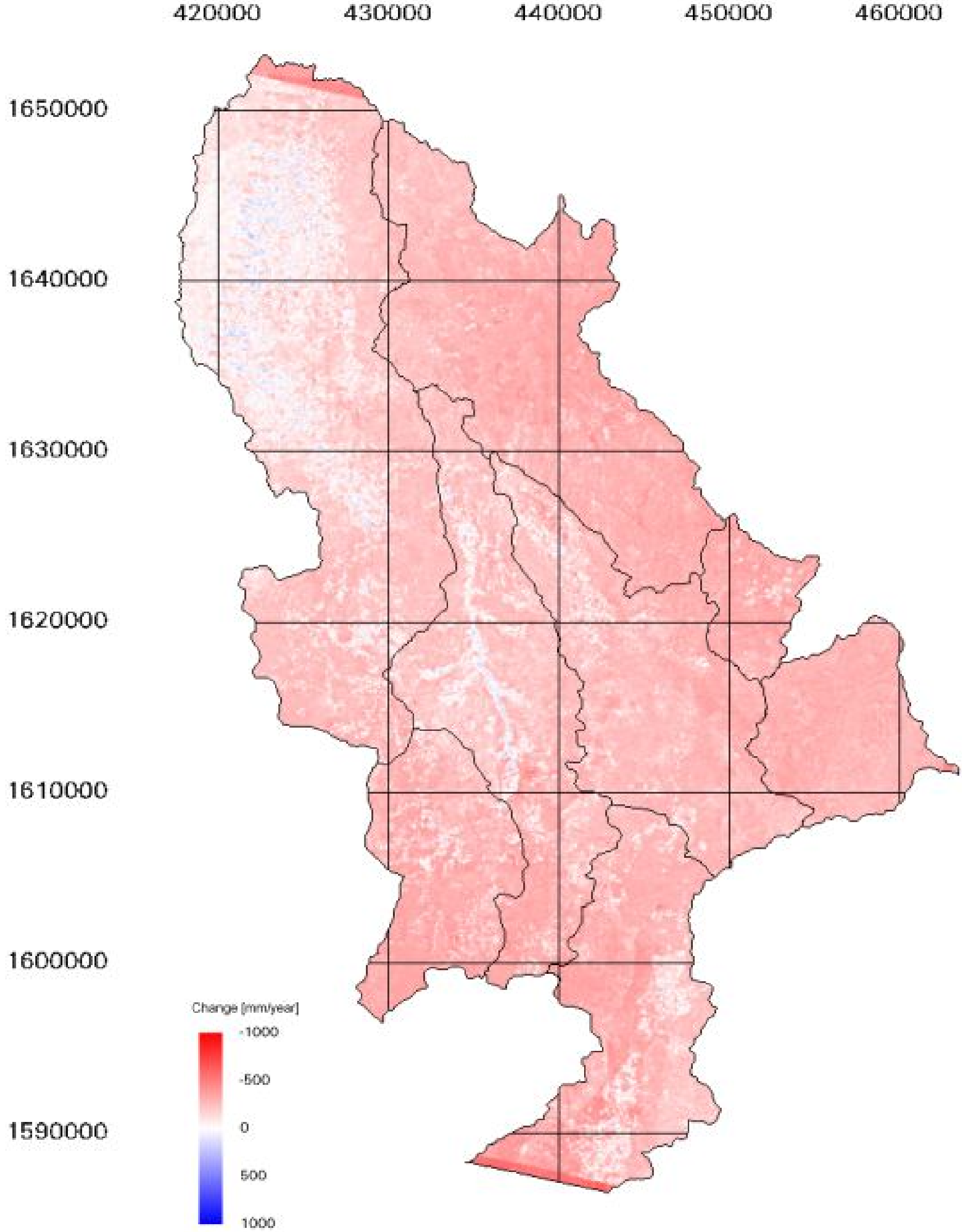
Appendix 11: Changes in Land Use between 2006 and 2010 Dhamar



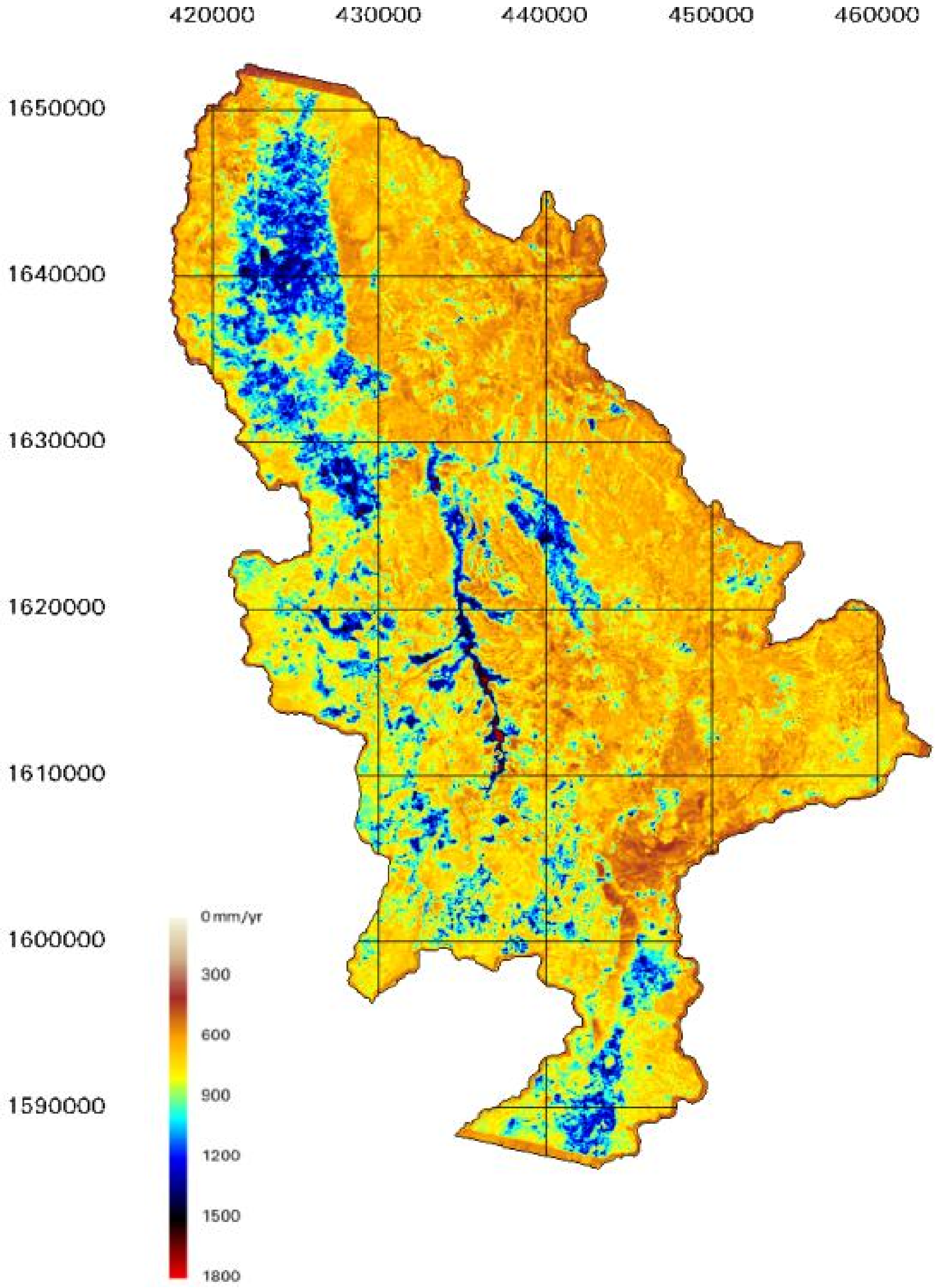
Appendix 12: Actual Evapotranspiration Map, 2010 Dhamar



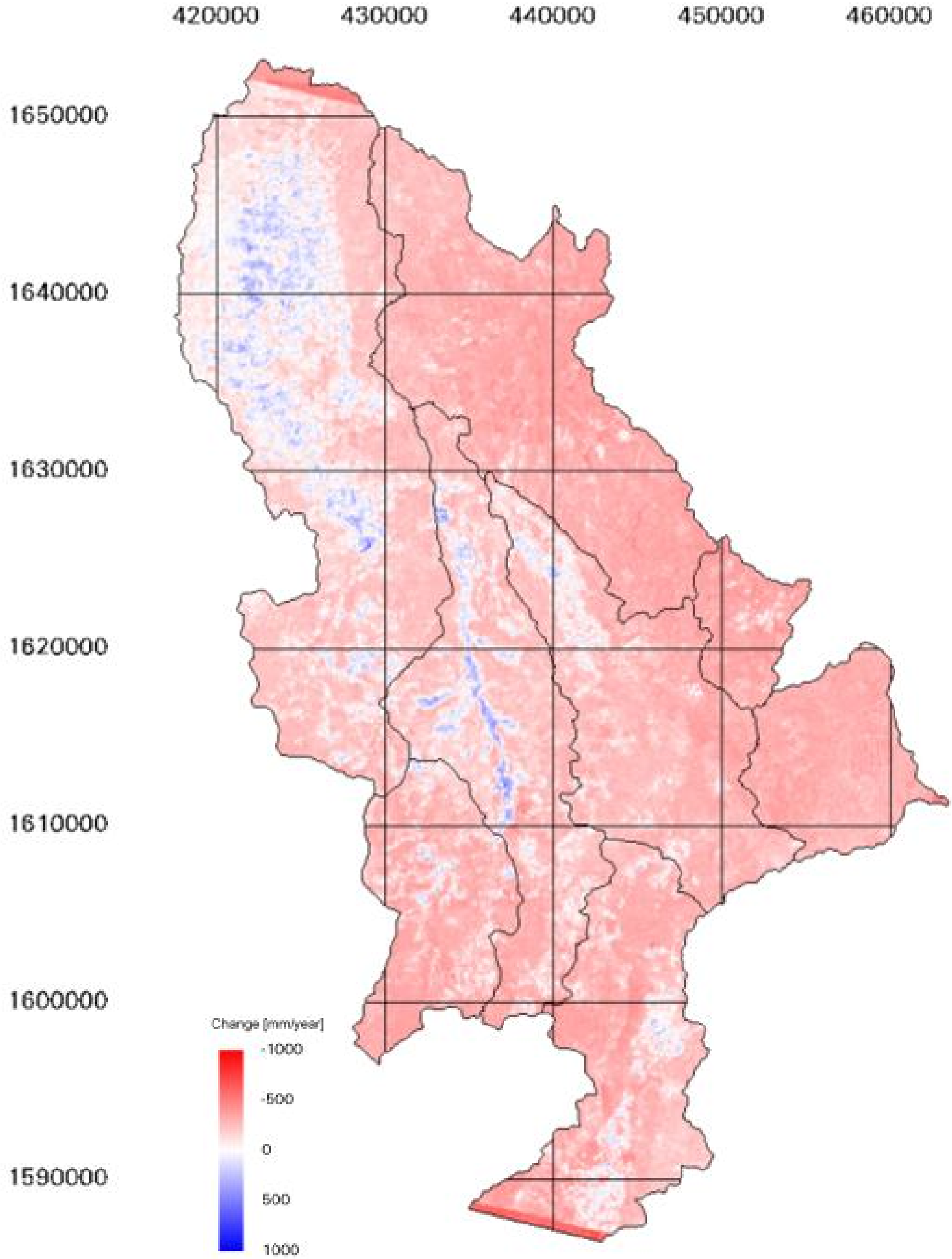
Appendix 13: Changes in Actual Evapotranspiration between 2006 and 2010 Dhamar



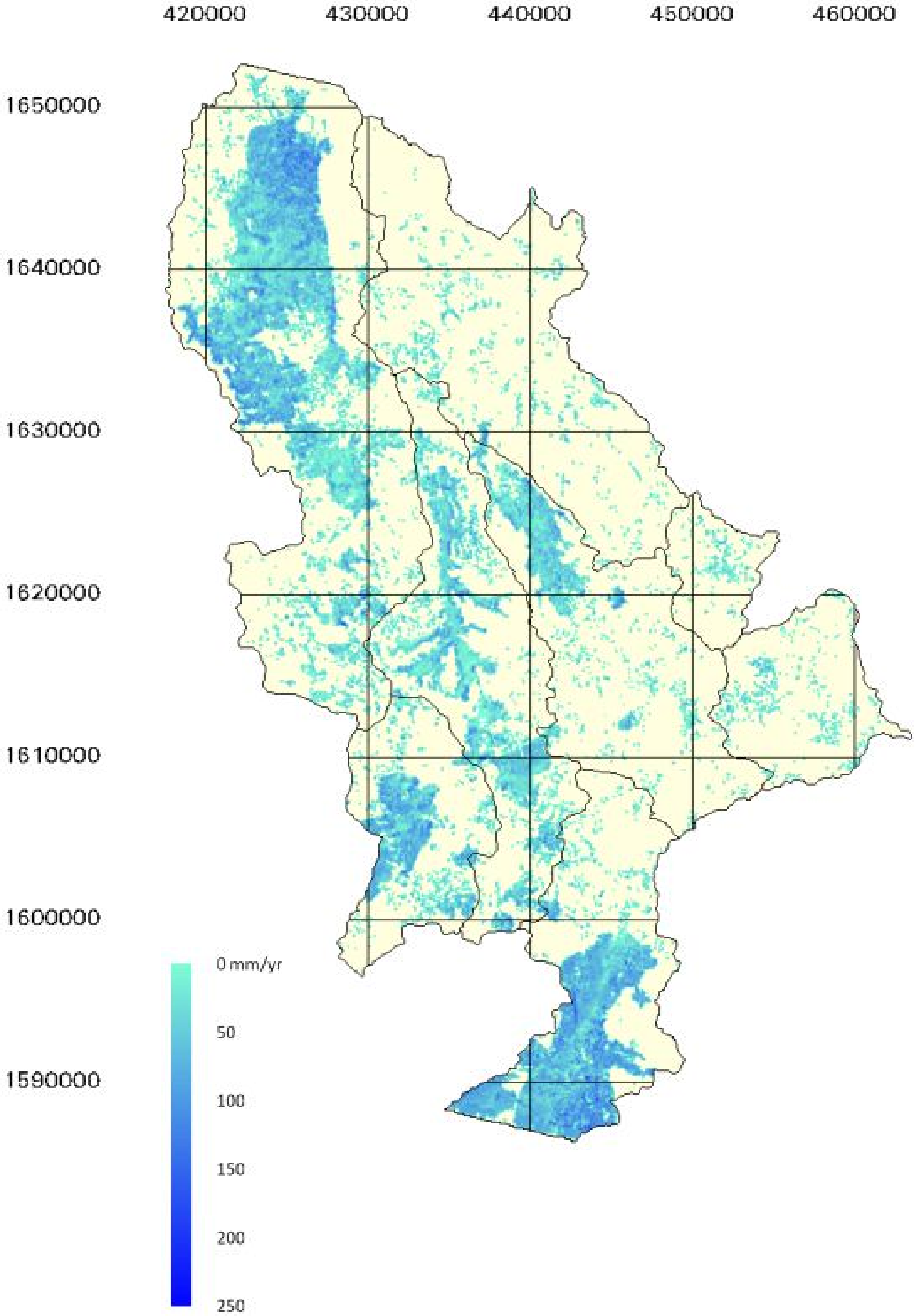
Appendix 14: Potential Evapotranspiration Map, 2010 Dhamar



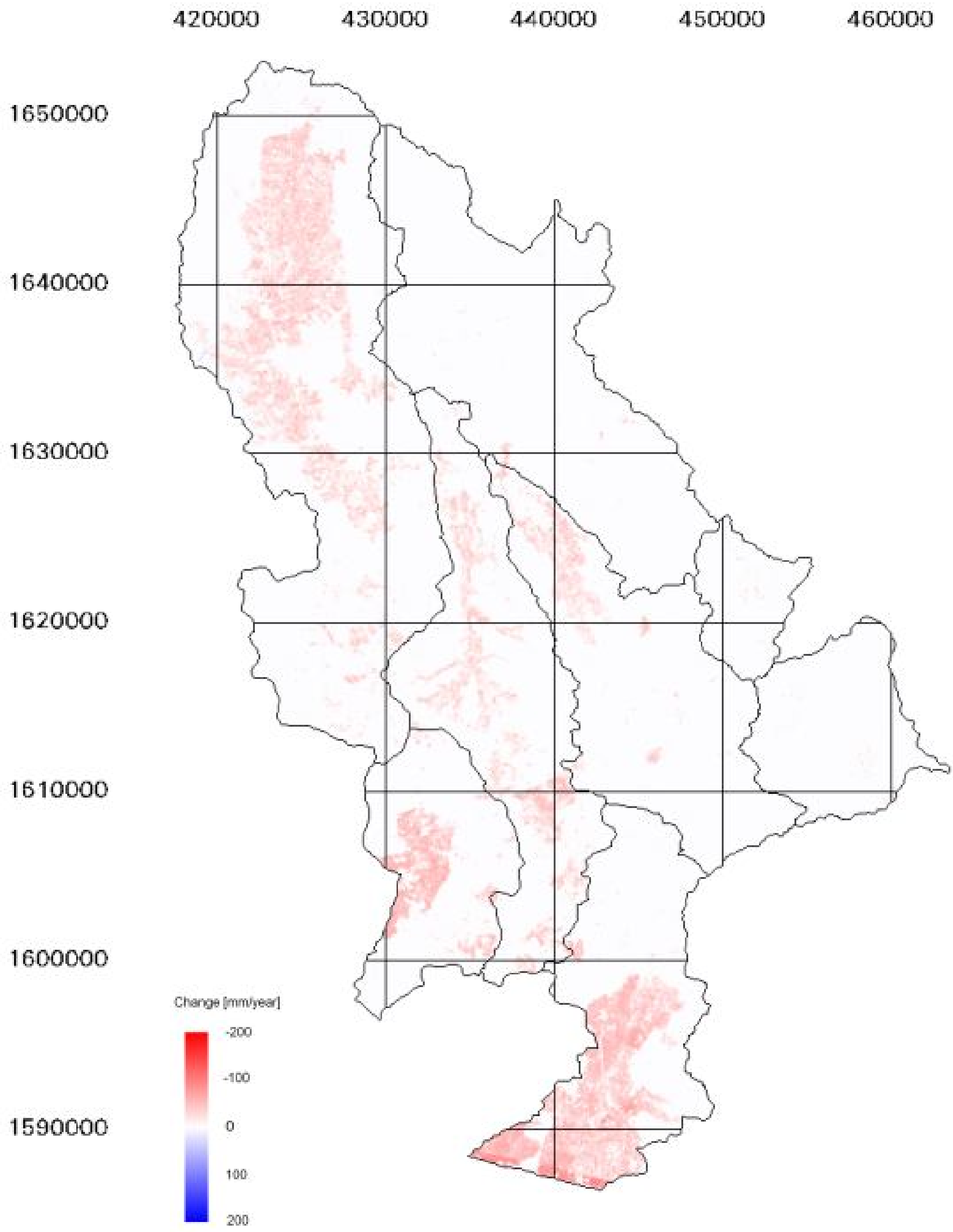
Appendix 15: Changes in Potential Evapotranspiration between 2006 and 2010 Dhamar



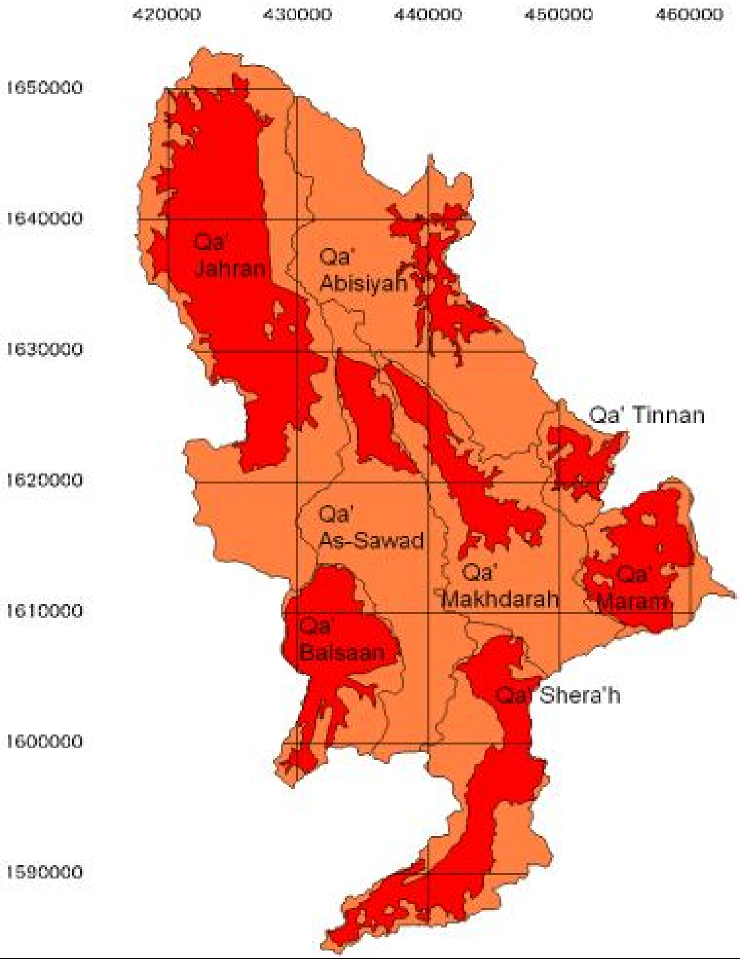
Appendix 16: Water Savings Map, 2010 Dhamar



Appendix 17: Changes in Water Savings between 2006 and 2010 Dhamar

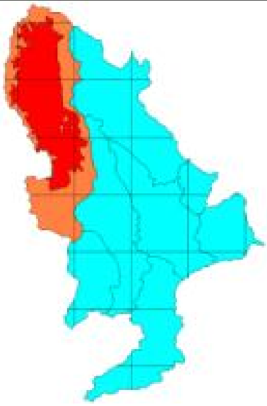


Appendix 18: Detailed results for the Qa's in Dhamar



Total Qa's Land Use	**Area** ha	**ETact** mm/year	**ETpot** mm/year	**Incremental ET** mm/year	**Gross irrigation** mcm/year
Total basin	98 712	738	850	31	552 049
Non-cropped	112 432	636	707		
Rainfed Single	7 420	707	818		
Irrigated Single	18 567	924	1 082	217	736 272
Double Season	920	1 080	1 290	373	62 658
Perennial	513	1 179	1 398	473	44 224
Irrigated Total	20 000	938	1 100	231	843 154
Total plain	52 175	1 783	761	1 060	10 094 252
Non-cropped	32 084	662	745		
Rainfed Single	4 446	723	840		
Irrigated Single	13 939	926	1 088	203	517 477
Double Season	682	1 065	1 264	342	42 586
Perennial	351	1 161	1 380	438	28 028
Irrigated Total	14 972	938	1 103	215	588 090

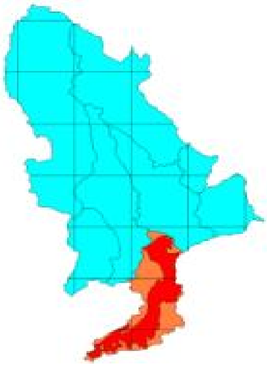
Qa' Jahran **Land Use**	**Area** ha	**ETact** mm/year	**ETpot** mm/year	**Incremental ET** mm/year	**Gross irrigation** mcm/year
Total basin	39 300	750	888	-28	-204 031
Non-cropped	27 464	669	750		
Rainfed Single	2 436	778	914		
Irrigated Single	8 412	955	1 125	176	270 352
Double Season	518	1 065	1 262	287	27 082
Perennial	289	1 167	1 384	389	20 521
Irrigated Total	9 219	967	1 141	189	317 956
Total plain	19 583	690	800	-90	-321 607
Non-cropped	9 171	702	806		
Rainfed Single	2 205	780	920		
Irrigated Single	7 488	954	1 127	174	237 470
Double Season	499	1 065	1 264	285	25 947
Perennial	284	1 167	1 384	387	20 041
Irrigated Total	8 271	968	1 144	188	283 458



← Qa' Jahran & Qa' Balsaan →

Qa' Balsaan **Land Use**	**Area** ha	**ETact** mm/year	**ETpot** mm/year	**Incremental ET** mm/year	**Gross irrigation** mcm/year
Total basin	1 963	740	861	76	27 342
Non-cropped	8 262	707	795		
Rainfed Single	698	664	757		
Irrigated Single	1 475	879	1 011	215	57 999
Double Season	50	1 090	1 269	427	3 871
Perennial	34	1 199	1 374	536	3 294
Irrigated Total	1 559	893	1 027	229	65 164
Total plain	6 755	609	659	-47	-57 536
Non-cropped	4 967	712	799		
Rainfed Single	564	656	744		
Irrigated Single	1 198	866	998	211	46 026
Double Season	48	1 092	1 274	437	3 803
Perennial	10	1 135	1 342	479	903
Irrigated Total	1 256	877	1 011	221	50 732

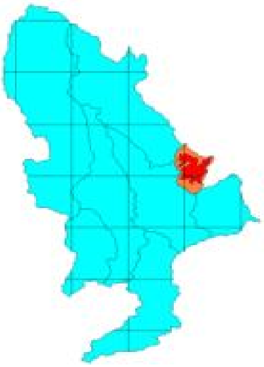
Qa' Shera'h Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	5 442	715	811	30	30 169
Non-cropped	9 780	636	711		
Rainfed Single	2 616	685	769		
Irrigated Single	3 457	886	1 013	202	127 178
Double Season	38	1 064	1 208	379	2 655
Perennial	11	1 167	1 314	482	946
Irrigated Total	3 506	889	1 016	204	130 779
Total plain	9 172	6 996	774	6 328	10 592 415
Non-cropped	3 927	619	701		
Rainfed Single	1 476	668	759		
Irrigated Single	2 823	887	1 021	220	113 104
Double Season	31	1 048	1 193	380	2 148
Perennial	3	1 160	1 314	492	286
Irrigated Total	2 857	889	1 023	222	115 538



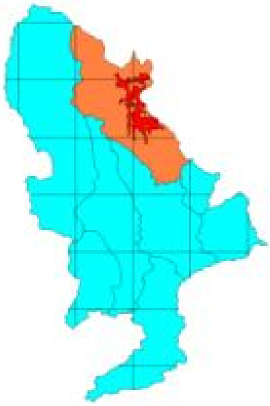
← Qa' Shera'h & Qa' As-Sawad →

Qa' As-Sawad Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	17 055	823	961	170	527 770
Non-cropped	14 307	633	723		
Rainfed Single	1 404	653	779		
Irrigated Single	2 788	937	1 124	283	144 129
Double Season	242	1 121	1 373	468	20 675
Perennial	135	1 224	1 470	571	14 027
Irrigated Total	3 165	963	1 158	310	178 831
Total plain	2 452	745	851	79	35 430
Non-cropped	1 520	650	757		
Rainfed Single	123	666	806		
Irrigated Single	766	937	1 126	271	37 857
Double Season	42	1 064	1 288	398	3 051
Perennial	17	1 181	1 493	515	1 552
Irrigated Total	825	948	1 142	282	42 460

Qa' Tinnan Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	3 997	604	661	37	27 313
Non-cropped	3 903	619	669		
Rainfed Single	1	567	613		
Irrigated Single	93	843	932	277	4 692
Double Season	0	0	0	-567	0
Perennial	1	930	1 008	364	34
Irrigated Total	93	844	932	277	4 726
Total plain	1 670	635	714	71	21 489
Non-cropped	1 611	662	723		
Rainfed Single	1	565	612		
Irrigated Single	76	845	941	281	3 900
Double Season	0				0
Perennial	1	930	1 008	366	34
Irrigated Total	77	846	941	282	3 934

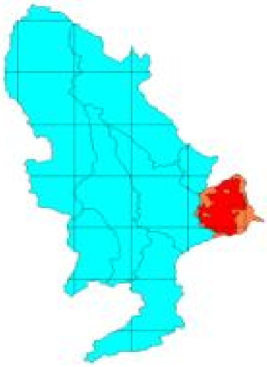


← Qa' Tinnan & Qa' Abisiyah →



Qa' Abisiyah Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	12 066	738	834	84	184 129
Non-cropped	24 099	605	654		
Rainfed Single	9	654	717		
Irrigated Single	395	833	915	178	12 860
Double Season	7	1 077	1 209	423	527
Perennial	5	1 116	1 268	461	410
Irrigated Total	407	840	924	186	13 797
Total plain	2 895	624	685	-15	-7 763
Non-cropped	2 845	594	650		
Rainfed Single	1	639	710		
Irrigated Single	90	873	968	234	3 866
Double Season	4	1 158	1 326	520	384
Perennial	3	1 279	1 496	640	300
Irrigated Total	97	896	997	257	4 551

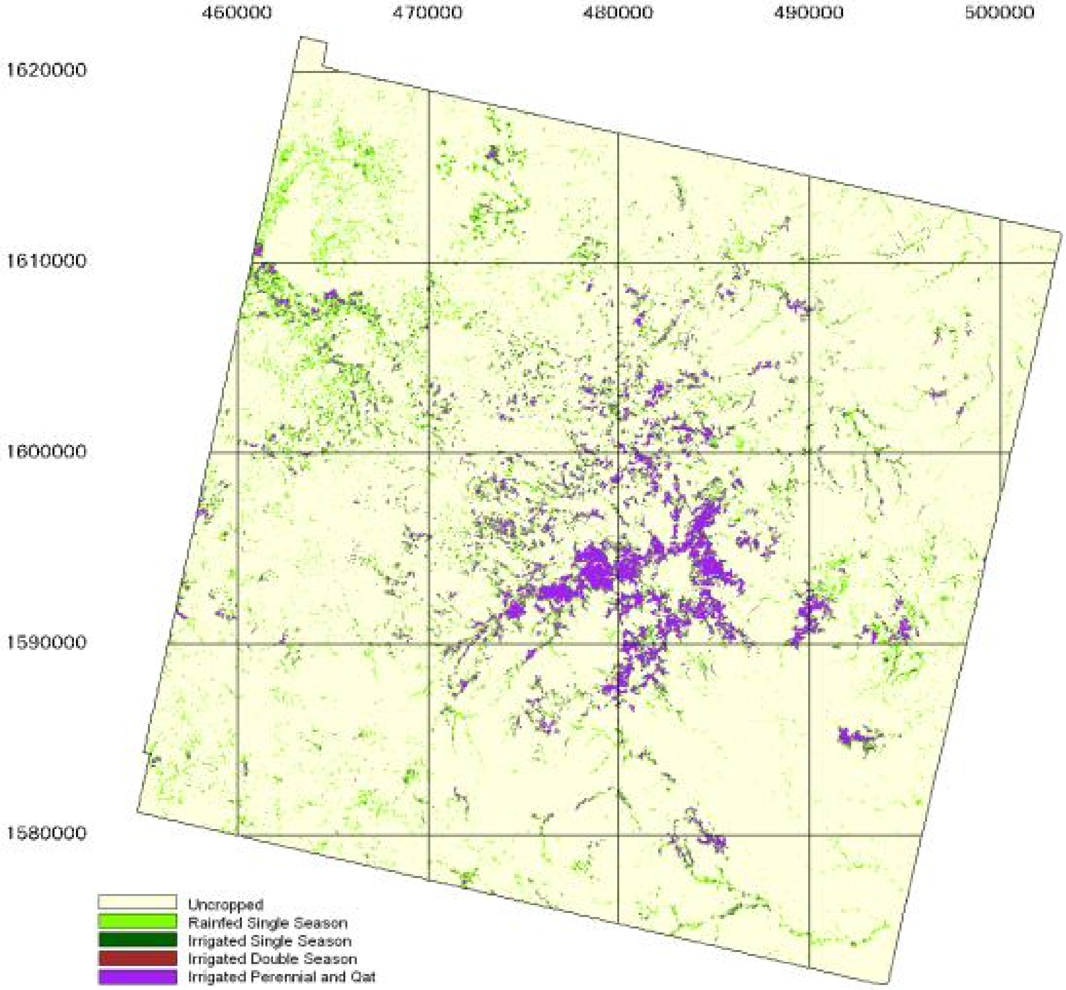
Qa' Maram Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	690	635	689	-13	-1 590
Non-cropped	8 482	629	681		
Rainfed Single	1	648	709		
Irrigated Single	205	846	921	199	7 442
Double Season	0	1 064	1 169	417	33
Perennial	1	1 323	1 442	676	141
Irrigated Total	207	849	924	202	7 616
Total plain	5 389	634	686	-29	-28 176
Non-cropped	5 271	630	683		
Rainfed Single	1	663	716		
Irrigated Single	144	835	909	172	4 529
Double Season	0	1 090	1 191	427	28
Perennial	0	1 327	1 413	664	34
Irrigated Total	145	837	910	174	4 591



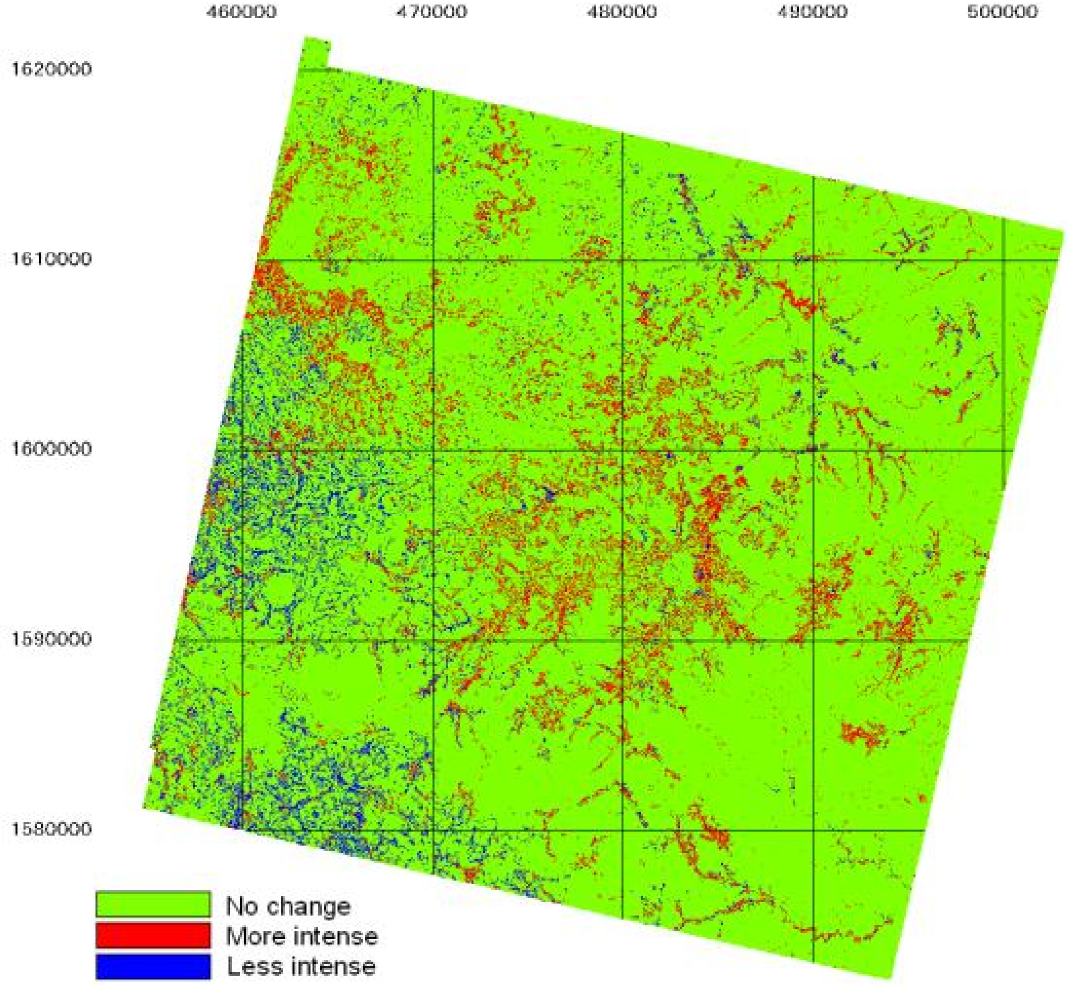
← Qa' Maram & Qa' Makhdarah →

Qa' Makhdarah Land Use	Area ha	ETact mm/year	ETpot mm/year	Incremental ET mm/year	Gross irrigation mcm/year
Total basin	18 199	670	733	3	9 279
Non-cropped	16 135	603	670		
Rainfed Single	256	667	776		
Irrigated Single	1 741	905	1 074	238	75 711
Double Season	64	1 052	1 272	385	4 499
Perennial	38	1 107	1 308	439	3 048
Irrigated Total	1 843	915	1 086	247	83 258
Total plain	4 259	732	827	11	8 619
Non-cropped	2 770	642	728		
Rainfed Single	77	721	862		
Irrigated Single	1 354	919	1 106	198	49 022
Double Season	57	1 048	1 275	327	3 423
Perennial	33	1 100	1 309	379	2 310
Irrigated Total	1 445	929	1 117	208	54 755

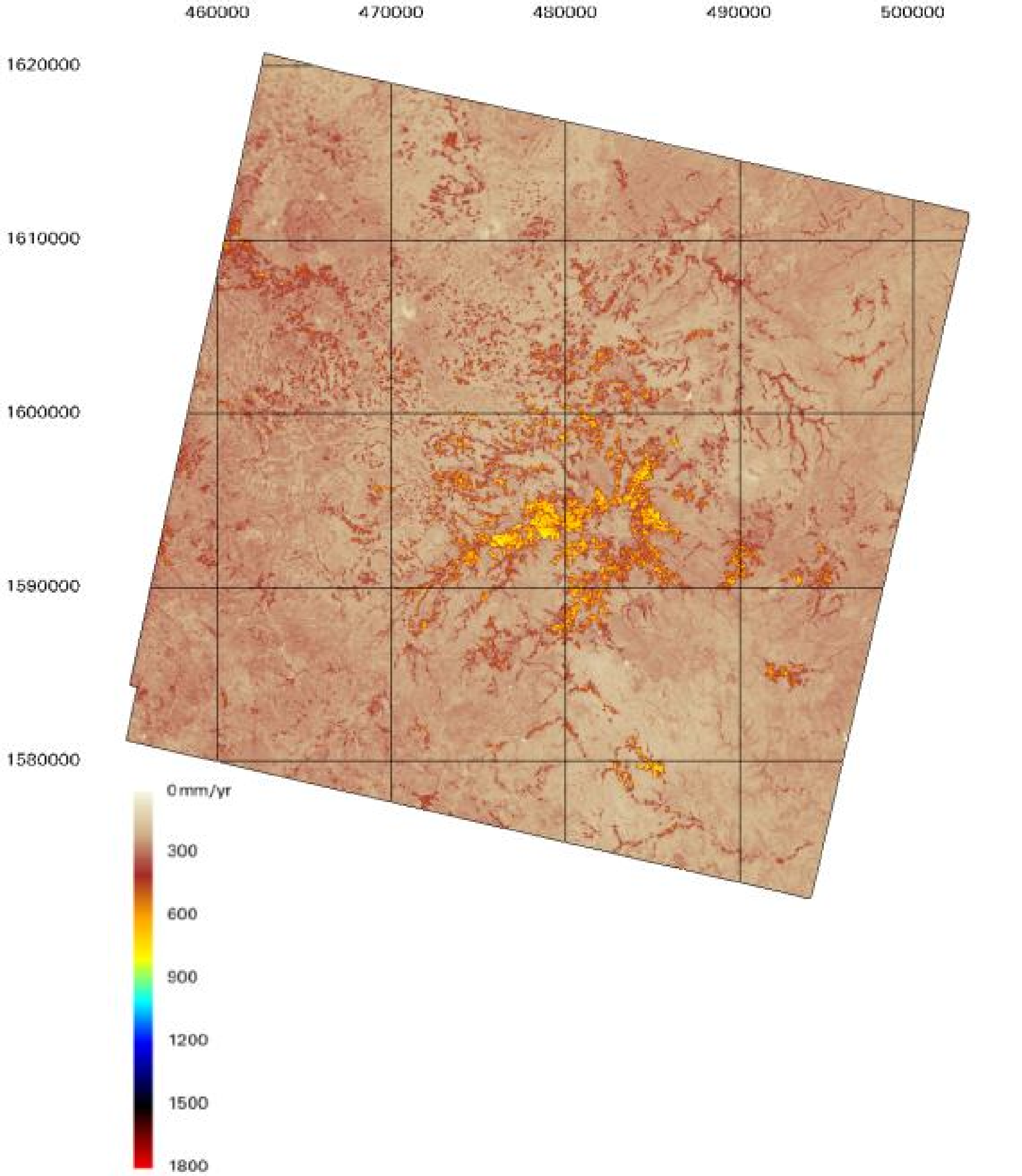
Appendix 19: Land Use Map, 2010 Rada



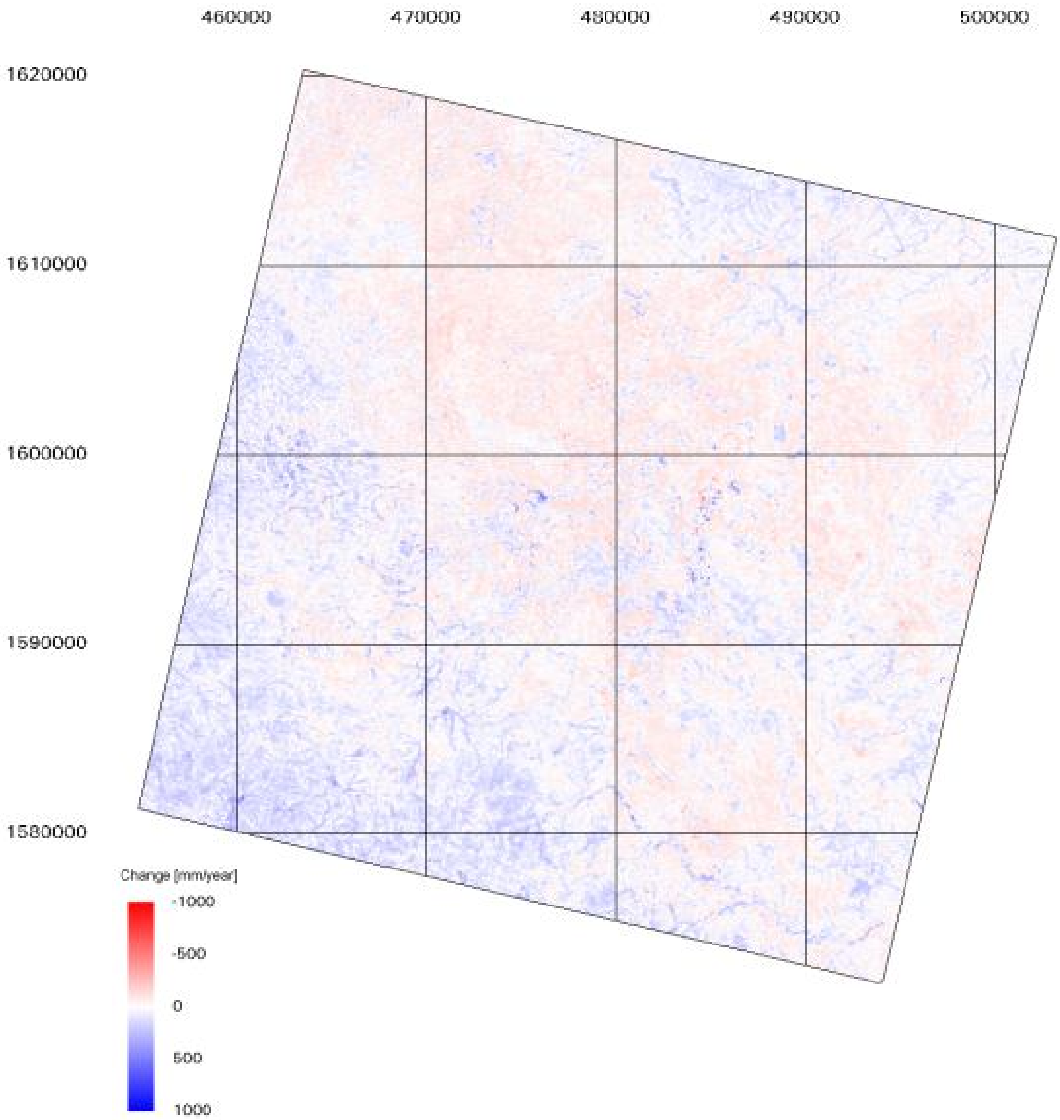
Appendix 20: Changes in Land Use between 2006 and 2010 Rada



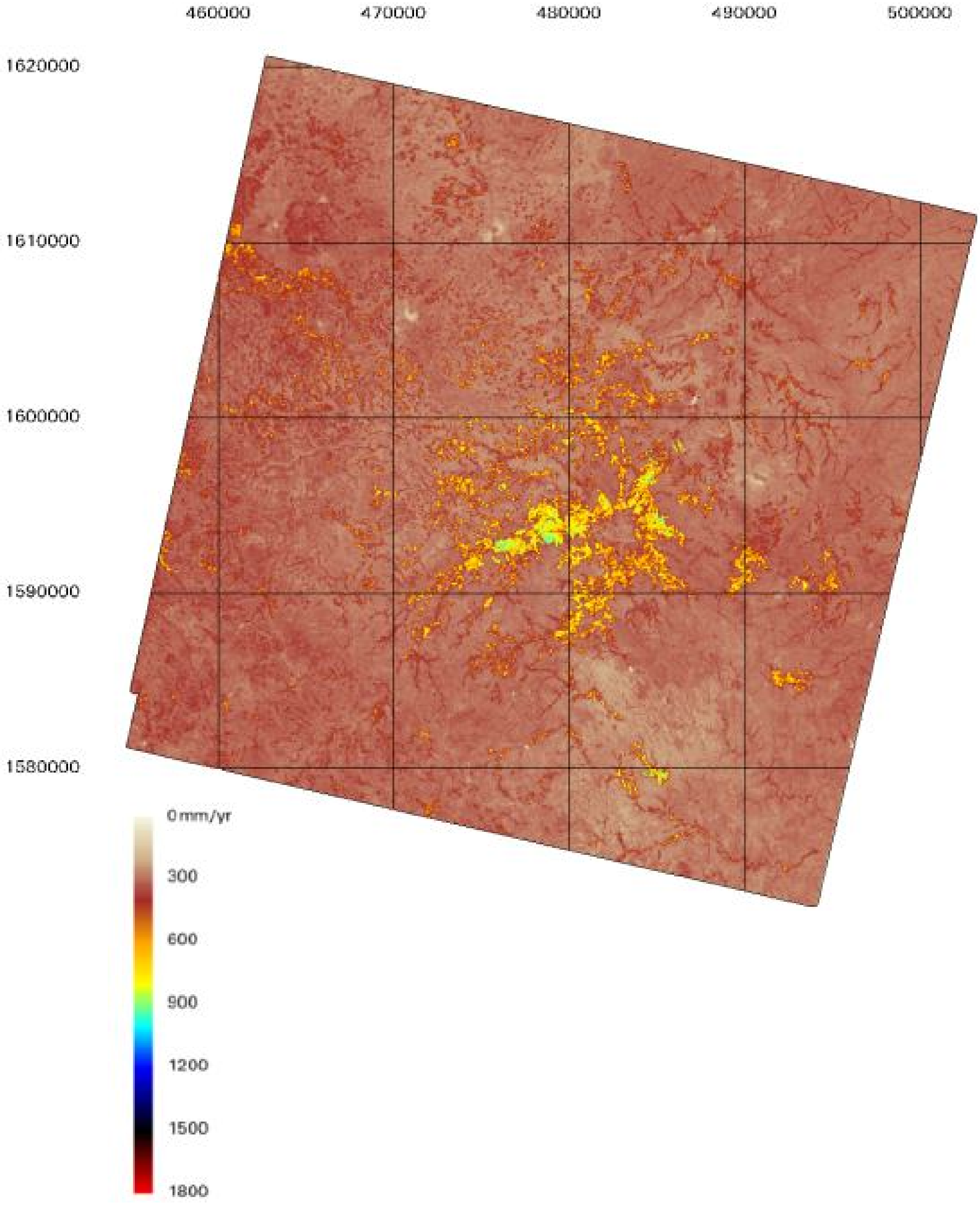
Appendix 21: Actual Evapotranspiration Map, 2010 Rada



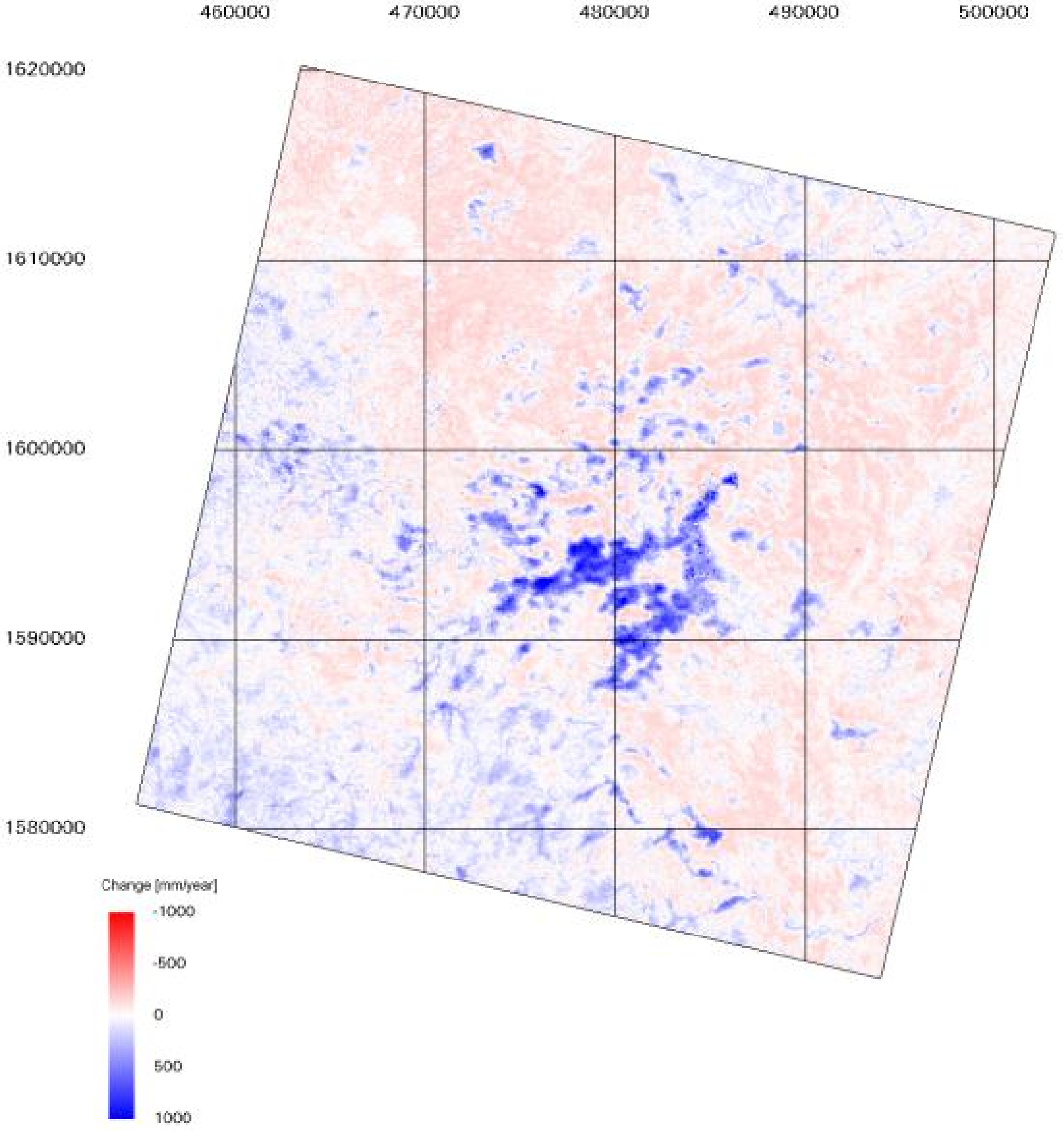
Appendix 22: Changes in Actual Evapotranspiration between 2006 and 2010 Rada



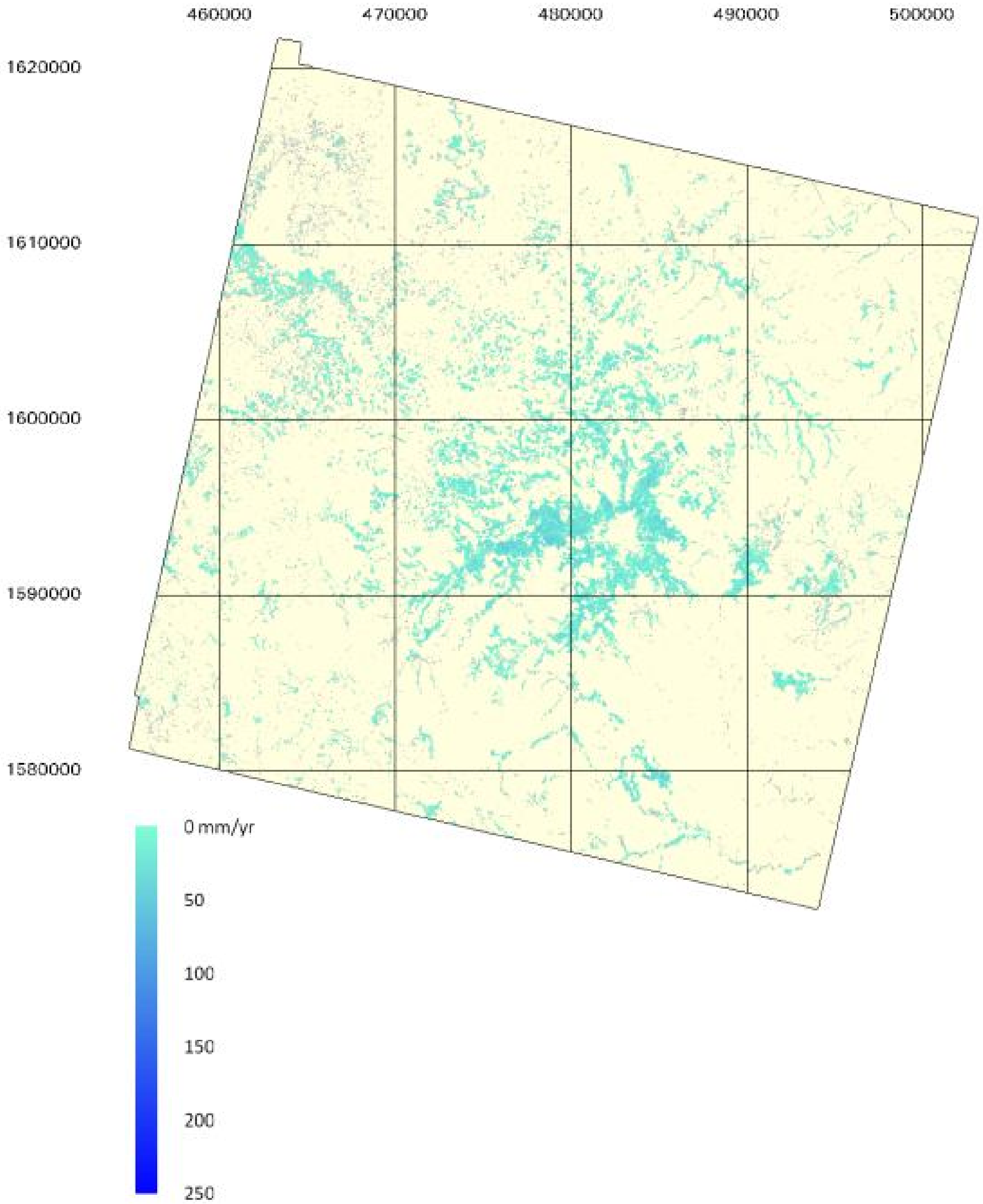
Appendix 23: Potential Evapotranspiration Map, 2010 Rada



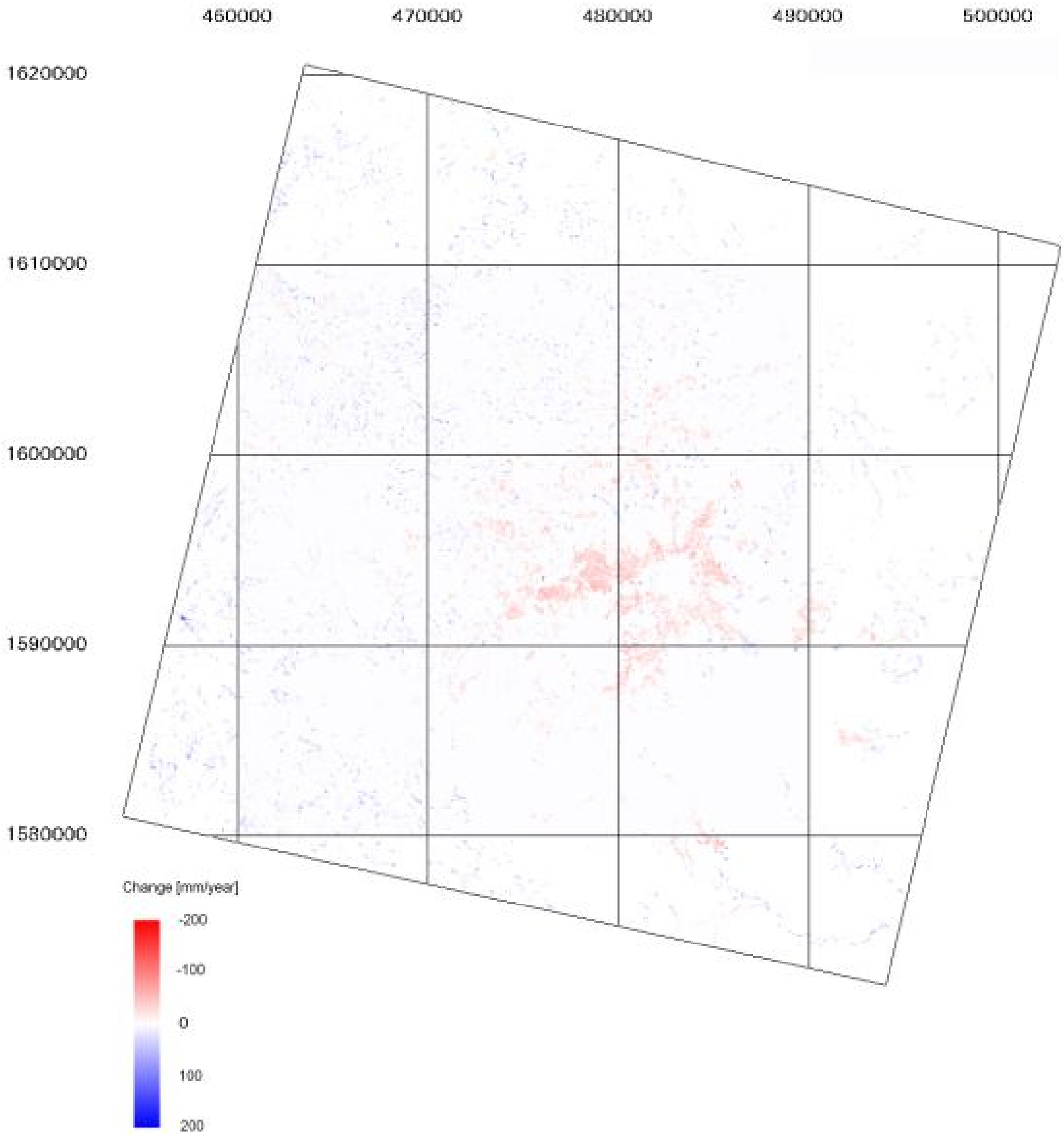
Appendix 24: Changes in Potential Evapotranspiration between 2006 and 2010 Rada



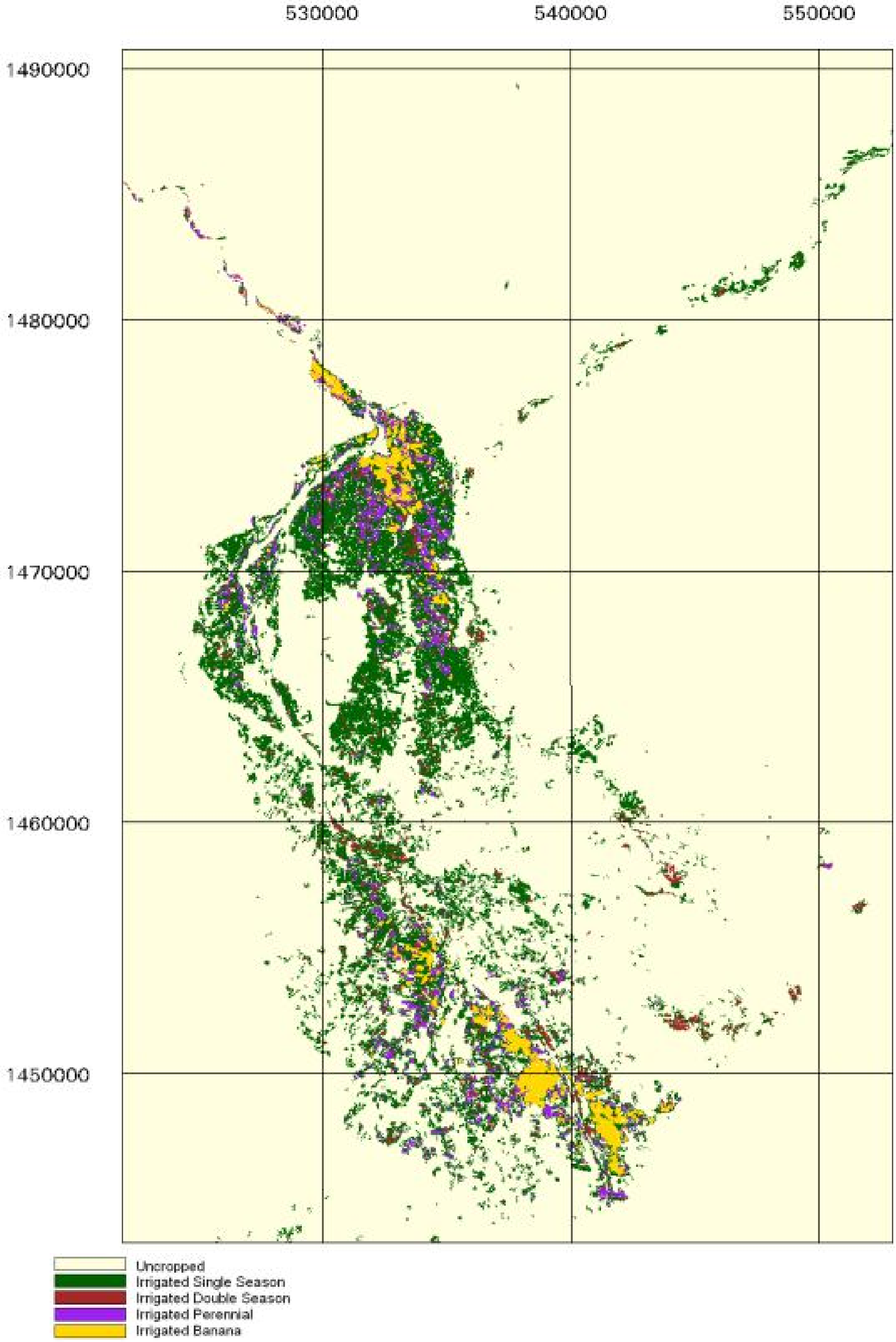
Appendix 25: Water Savings Map, 2010 Rada



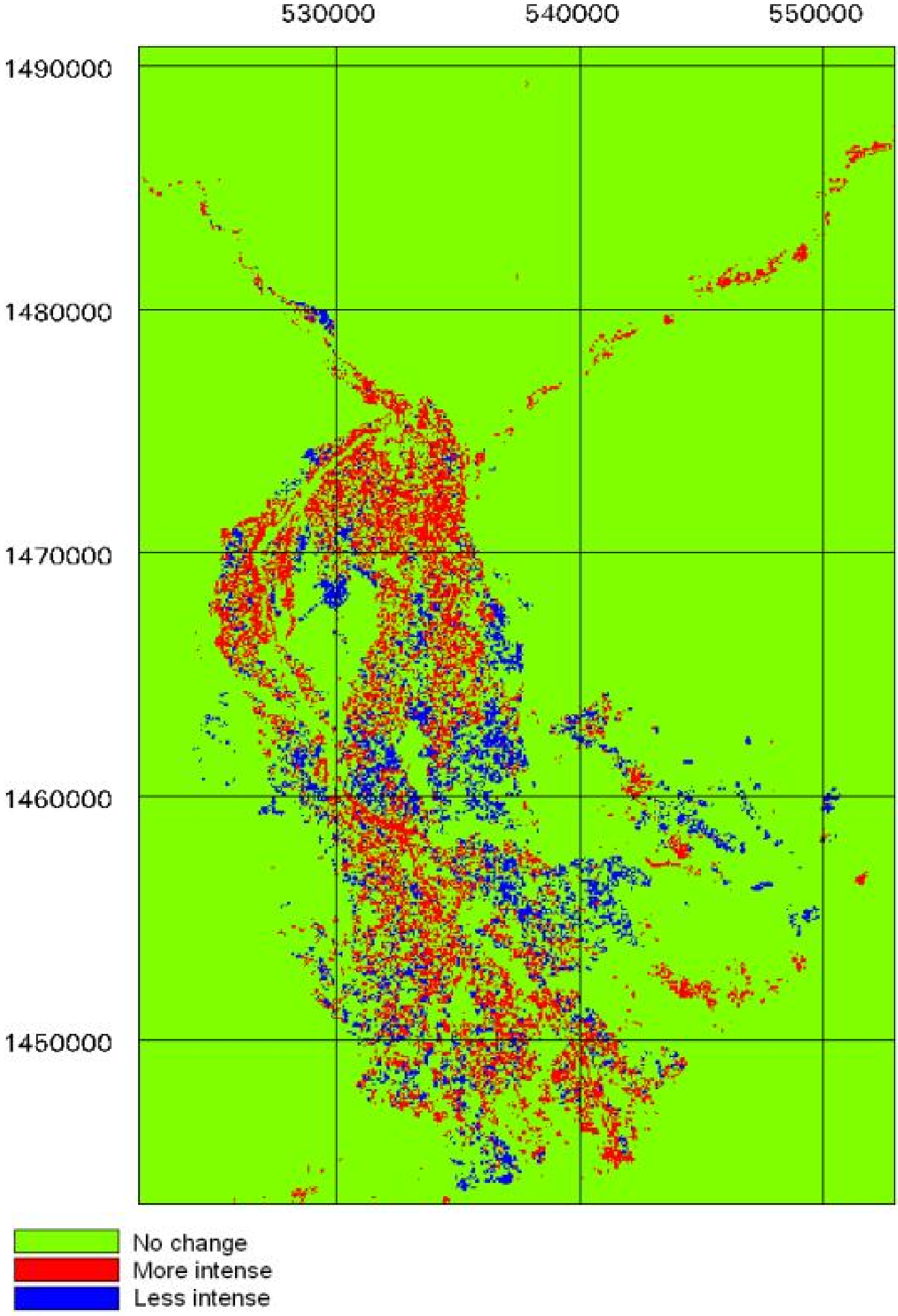
Appendix 26: Changes in Water Savings between 2006 and 2010 Rada



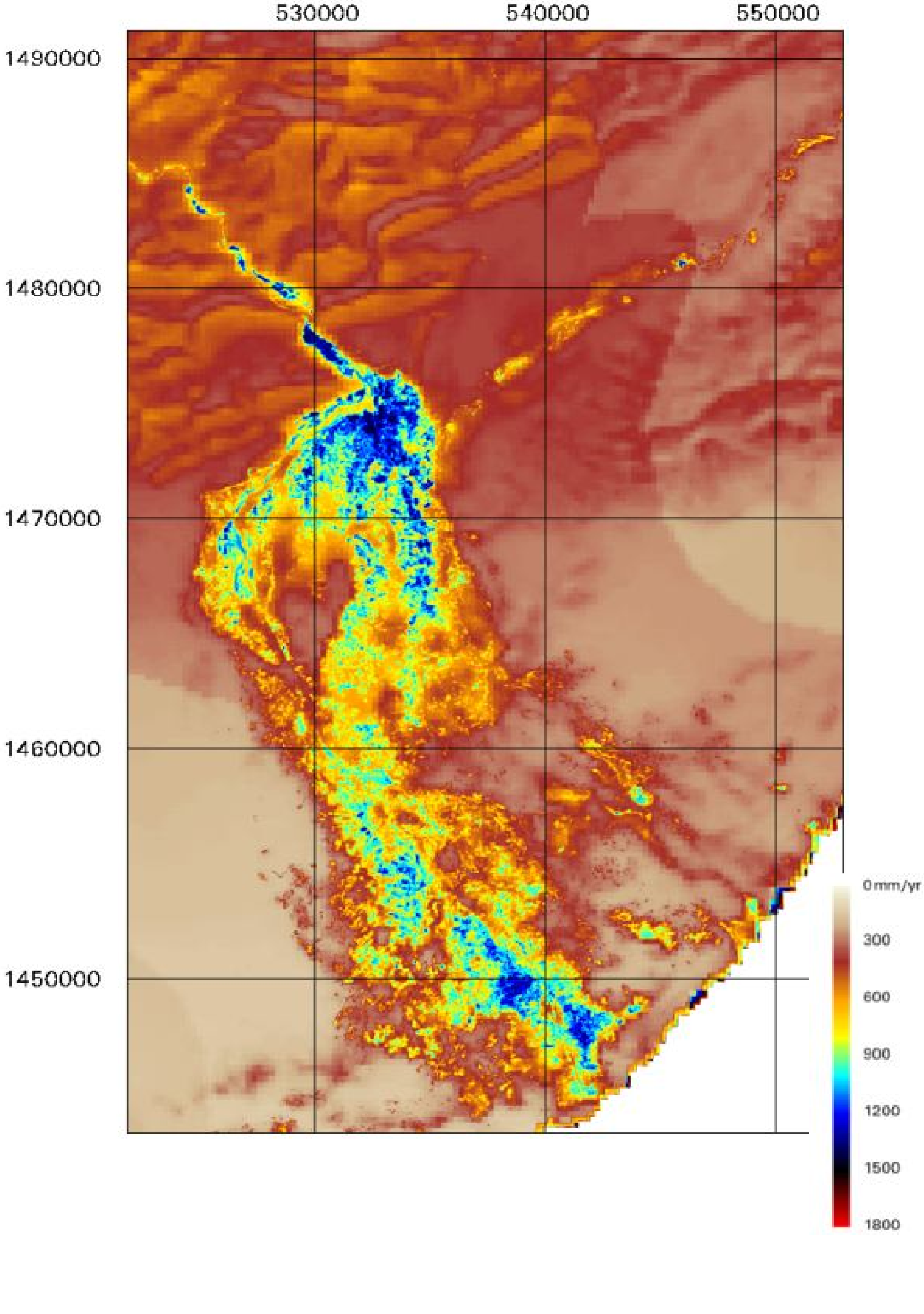
Appendix 27: Land Use Map, 2010 Abyan



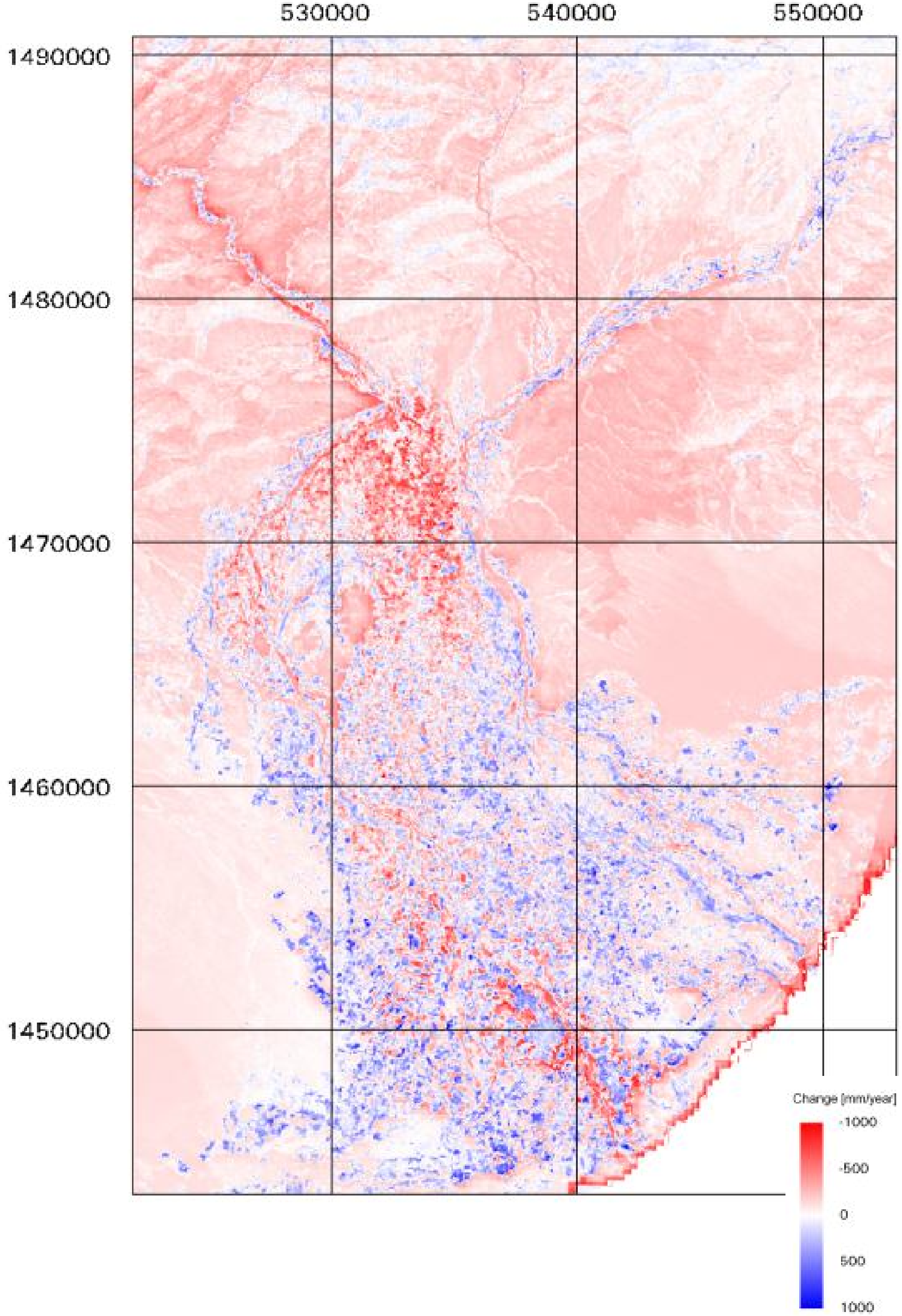
Appendix 28: Changes in Land Use between 2006 and 2010 Abyan



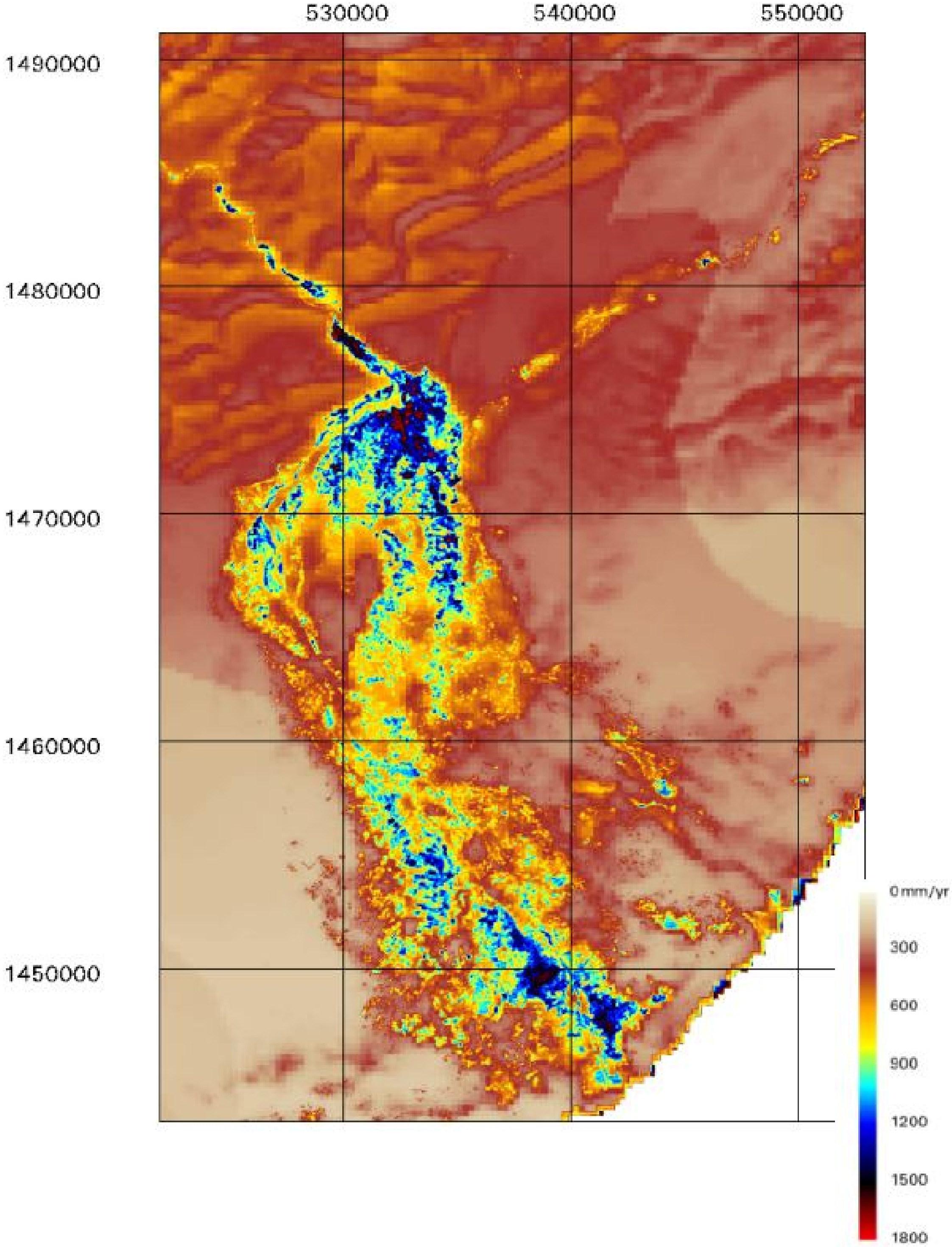
Appendix 29: Actual Evapotranspiration Map, 2010 Abyan



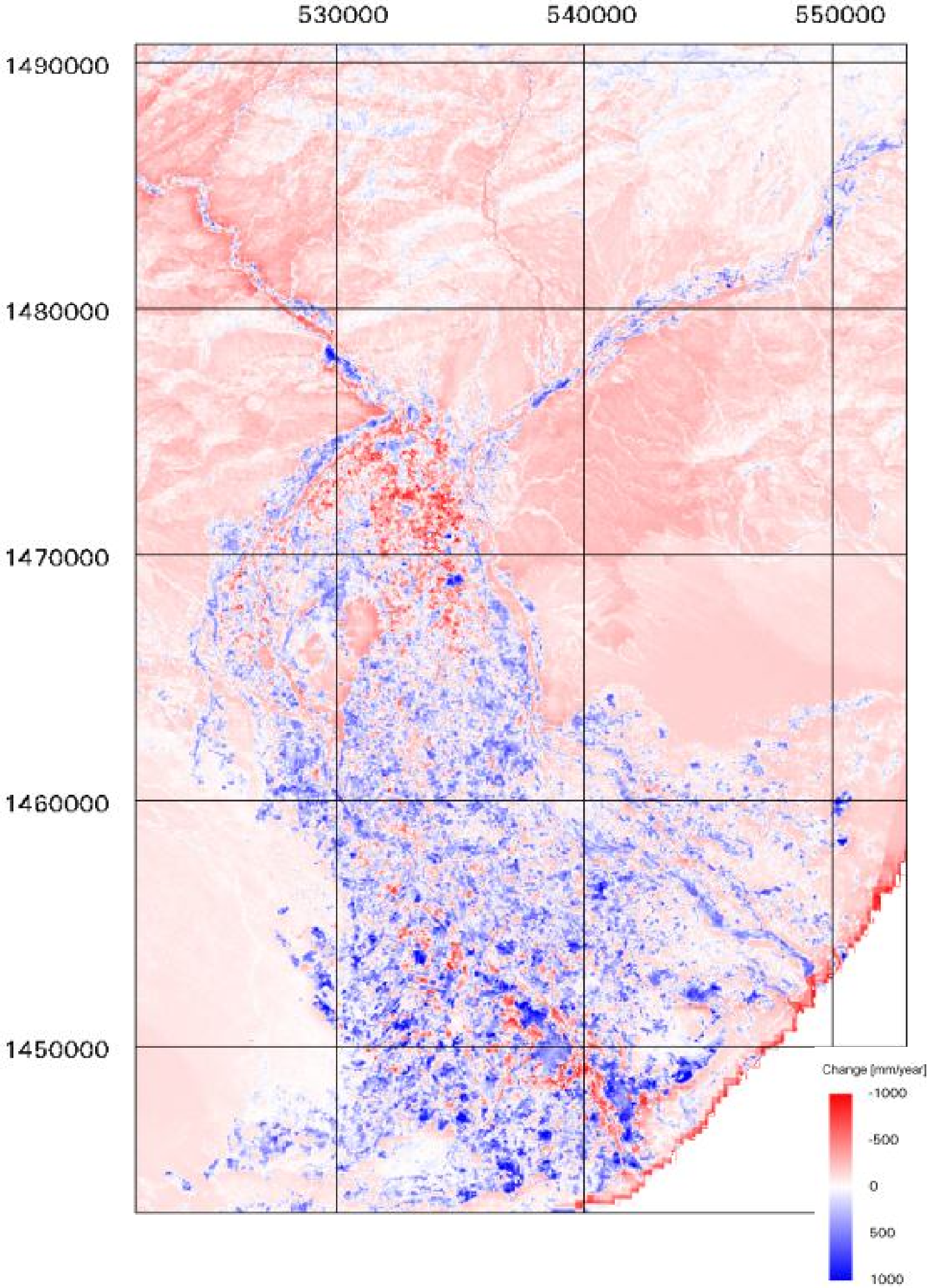
Appendix 30: Changes in Actual Evapotranspiration between 2006 and 2010 Abyan



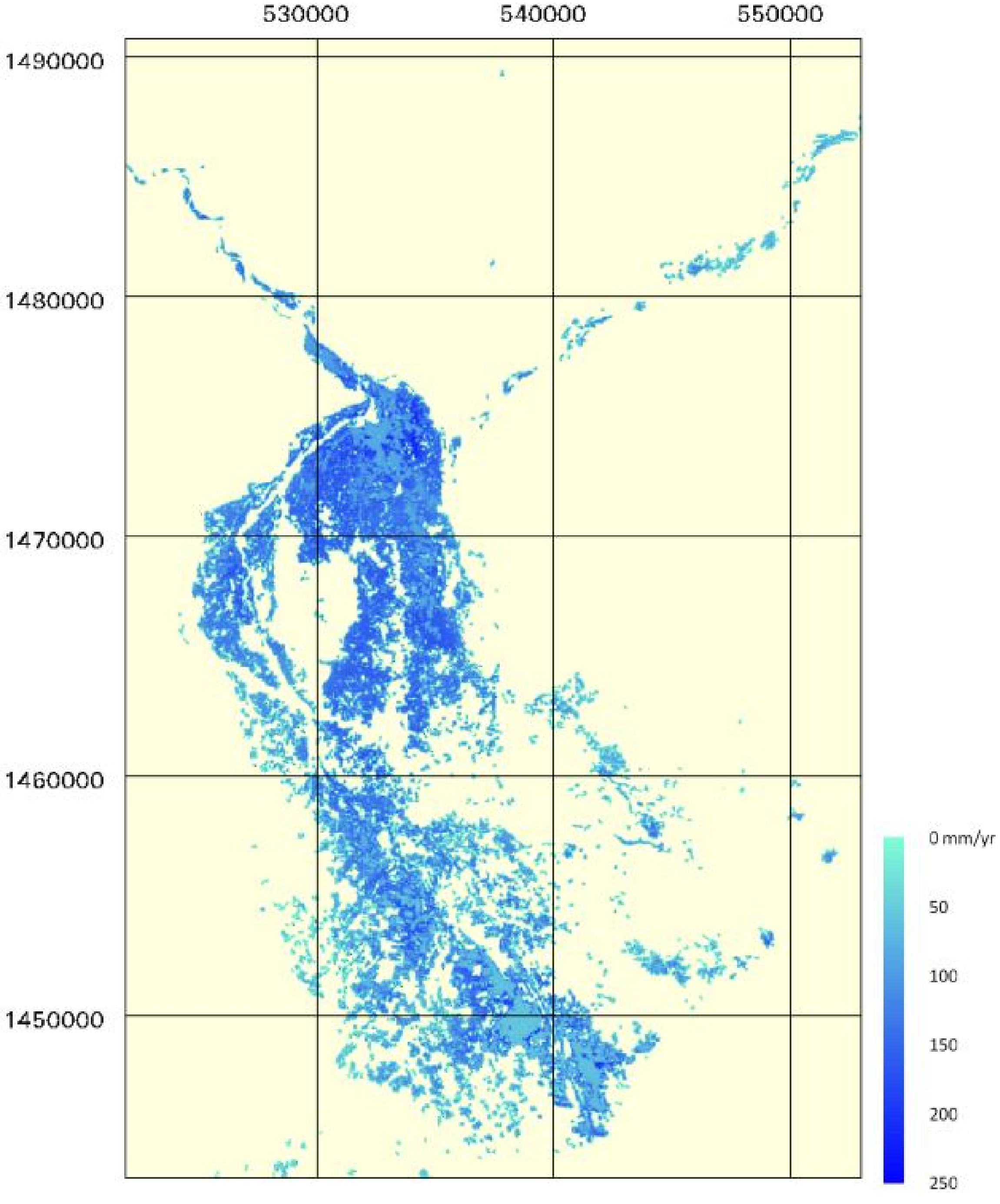
Appendix 31: Potential Evapotranspiration Map, 2010 Abyan



Appendix 32: Changes in Potential Evapotranspiration between 2006 and 2010 Abyan



Appendix 33: Water Savings Map, 2010 Abyan



Appendix 34: Changes in Water Savings between 2006 and 2010 Abyan