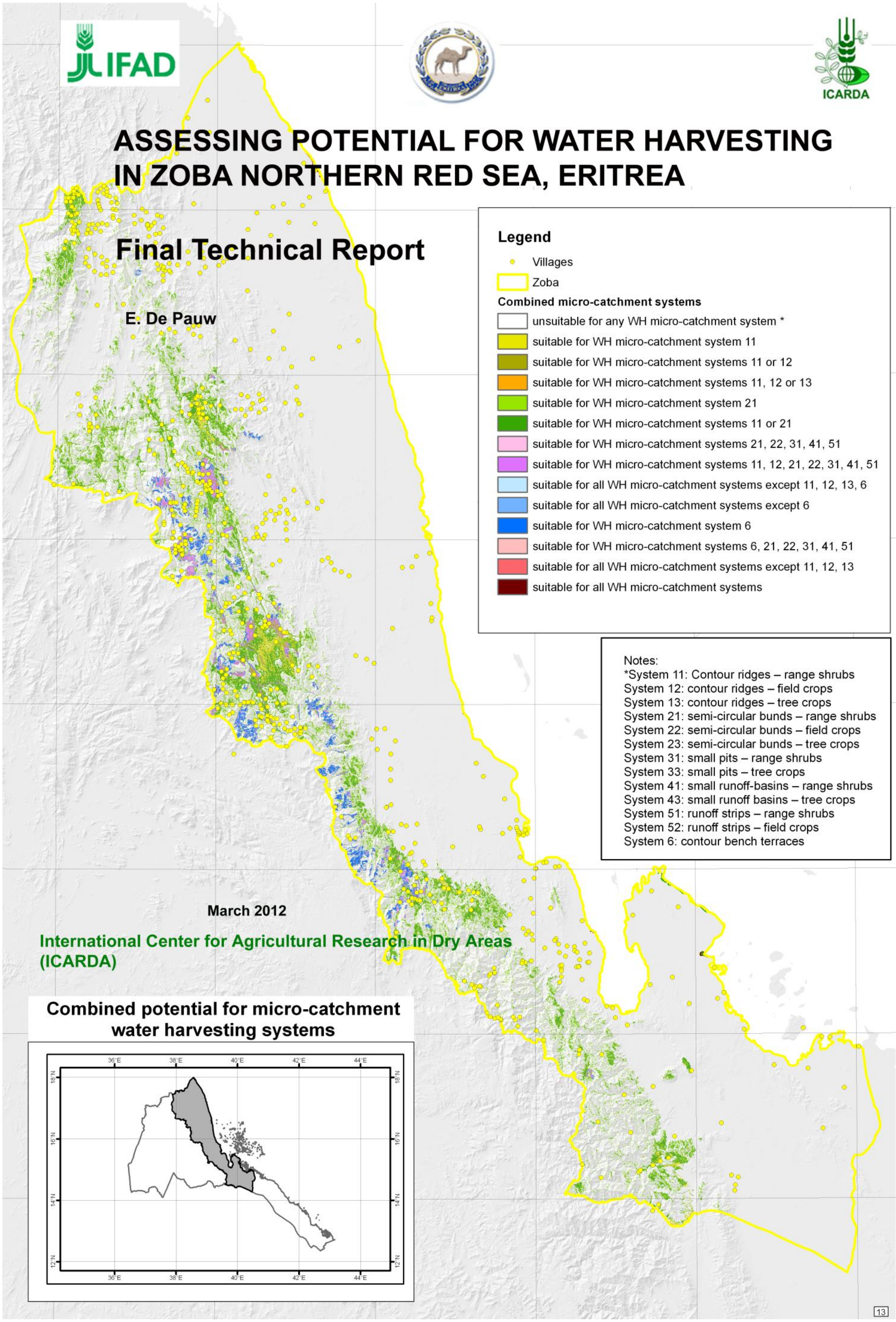
ASSESSING POTENTIAL FOR WATER HARVESTING IN ZOBA NORTHERN RED SEA, ERITREA

Final Technical Report

E. De Pauw



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EXECUTIVE SUMMARY

This study has been undertaken by ICARDA in response to a request by the International Fund for Agricultural Development (IFAD) and the Government of Eritrea to provide, within the framework of the National Agricultural Program (NAP), scientific support to a development project for agriculture in Zoba Northern Red Sea (Semenawi Keih Bahri).

The proposed NAP aims at enhancing food security, alleviating poverty and sustaining the natural resource base through agricultural development. The support requested from ICARDA was specifically to identify and map areas with potential for introducing specific methods of water harvesting through GIS analysis and supporting field studies, in follow-up to a similar study undertaken in Zoba Debub.

The current study is confined to a GIS-based desk study of Zoba Northern Red Sea (NRS) as no clearance was given by the Government of Eritrea to conduct field investigations and to collect new data in country.

GIS desk study

Given the scarcity of basic maps for Zoba Debub, a number of maps were prepared, first to gain better insights into the agricultural environment of the Zoba, and, in a second stage, to serve as input data for the suitability assessment for water harvesting.

A base map (Map 1) was prepared by extraction from the 2000 Geocover series of ortho-rectified Landsat 7 ETM+ Mosaics . The Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was the source of major topography-related data, such as watersheds and drainage lines (Map 2), elevation (Map 4), slopes (Map 5), and Compound Topographic Index (CTI).

Precipitation data, available from meteorological stations, were converted into continuous grids. Maps of mean annual precipitation (Map 7), reliable/effective precipitation for assessing water harvesting potential (Map 8) and annual potential evapo-transpiration (Map 9) were prepared using these grids.

These input data were then transformed into suitability maps for water harvesting (Maps 11-29), using an adaptation of a methodology developed for Syria, to take into consideration the datasets available in Eritrea and local conditions, particularly in relation to current land use/land cover (Map 10). Suitability was evaluated for both micro-and macro-catchment systems. Suitability was evaluated separately for the following systems:

- Micro-catchment systems
    a. System 11: contour ridges/ range shrubs
    b. System 12: contour ridges/ field crops
    c. System 13: contour ridges/ tree crops
    d. System 21: semi-circular bunds – range shrubs
    e. System 22: semi-circular bunds – field crops
    f. System 23: semi-circular bunds – tree crops
    g. System 31: small pits – range shrubs
    h. System 33: small pits – tree crops
    i. System 41: small runoff-basins – range shrubs
    j. System 43: small runoff basins – tree crops

k. System 51: runoff strips – range shrubs
l. System 52: runoff strips – field crops
m. System 6: contour bench terraces

- Macro-catchment systems: evaluated for suitability as
  a. water catchment area
  b. agricultural use: field crops and tree crops

The assessment of suitability for different water harvesting techniques was undertaken by matching in a GIS environment simple biophysical information, systematically available for the entire Zoba Northern Red Sea, to the broad requirements of the specified water harvesting systems using an expert-based empirical decision model.

The GIS analysis is communicated in the form of maps (Annex 2) and summary tables that contain all areas of the classes distinguished in the base maps and suitability maps. Areas were calculated in hectare and refer to both the entire Zoba and selected watersheds.

Very large differences exist in elevation in Zoba NRS. Although not directly affecting the potential for water harvesting, these differences in elevation and, consequently, temperature, have an effect on crop water requirements and may affect the physical suitability and comparative advantage for different crops. The Zoba has a wide range of slopes, ranging from very flat (0-2%) to very steep (>30%). The well balanced spread of slope classes indicates that both water-shedding and water-receiving areas exist in the Zoba pointing to a good potential for water harvesting from a topographical perspective.

The rainfall distribution in Zoba NRS is spatially very uneven, from less than 150 mm as annual mean in the lowland plains to more than 800 mm in the highlands. About two thirds (68%) of the Zoba receives a mean annual precipitation of less than 400 mm. In Zoba Debub this was only the case in 2% of the area. Whereas in about 80% of Zoba Debub the reliable annual precipitation is in the 250-300 mm range and the remainder in the 300-350 mm range, this is only the case in respectively about 7% of Zoba NRS and less than 2% for the 300-350 mm range.

In line with the large differences in elevation, annual potential evapo-transpiration (PET) rates, which determine crop water requirements, vary considerably in Zoba NRS. The range in the annual PET in 85% of the Zoba is 600 mm. Compared to Zoba Debub, higher PET levels occur in a larger proportion of the Zoba: whereas in Zoba Debub 85% of the area has an estimated annual PET of less than 1800 mm, in Zoba NRS this is only the case in 49% of the area.
It is therefore obvious that from the perspective of water resource availability, the overall potential for water harvesting in Zoba NRS is much lower as compared to Zoba Debub due to two main reasons: lower reliable precipitation and higher potential evapo-transpiration rates.

Despite these less favourable conditions, the potential for most water harvesting systems in Zoba Northern Red Sea is considerable, although much less than in Zoba Debub in both absolute and relative terms. Whereas in Zoba Debub about 70% (673,435 ha) was assessed as being suitable for at least one micro-catchment system, in Zoba NRS this is only the case in about 10% of the Zoba (335,742ha), despite the fact that Zoba NRS is about 3.5 times larger than Zoba Debub.

The potential for water harvesting is summarized in the following table, which estimates the total areas that are considered 'suitable' for different combinations of micro-catchment water harvesting systems.

Table i. Areas suitable for various combinations of micro-catchment systems in Zoba NRS

Class	% of Zoba	Hectare
Unsuitable for any system	90.09	3,053,182
Suitable for S11	0.75	25,265
Suitable for S11, S12	0.12	3,949
Suitable for S11, S12, S13	0.01	315
Suitable for S21	4.00	135,525
Suitable for S11, S21	3.27	110,855
Suitable for S21, S22, S31, S41, S51	0.18	5,984
Suitable for S11, S12, S21, S22, S31, S41, S51	0.48	16,391
Suitable for all except S11, S12, S13, S6	0.00	71
Suitable for all except S6	0.01	474
Suitable for S6	0.85	28,697
Suitable for S21, S22, S31, S41, S51, S6	0.20	6,945
Suitable for all except S11, S12, S13	0.00	59
Suitable for all micro-systems	0.04	1,213

Watersheds selection

Given the inability to undertake field activities in Zoba Northern Red Sea, it was not possible to adopt a similar approach to selection as implemented for Zoba Debub, which relies on on-site participatory expert evaluation of potential watersheds and meetings with farmers and government officials in order to identify plausible interventions. Therefore it is only possible at this stage to identify a number of watersheds which, on the basis of the simple modeling of potential undertaken in this desk study, appear to indicate a reasonable potential that deserves to be explored further by through the appropriate field activities and consultations with farmers, government officials and local experts.

For micro-catchment systems the following priority classes were distinguished for further assessments of potential and interventions:

- 1st priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system occupying more than 20% of the watershed (dark green colored in Fig. 14: watersheds 6, 15, 19, 21, 22, 24, 122)
- 2nd priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system but occupying less than 20% of the watershed (light green coloured in Fig. 14: watersheds 12, 20, 126, 140);
- 3rd priority: watersheds 8,000-10,000 ha of land suitable for one or another micro-catchment water harvesting system and occupying more than 20% of the watershed (yellow-colored in Fig. 14: watersheds 79, 87).

These priority watersheds are shown in the following map.

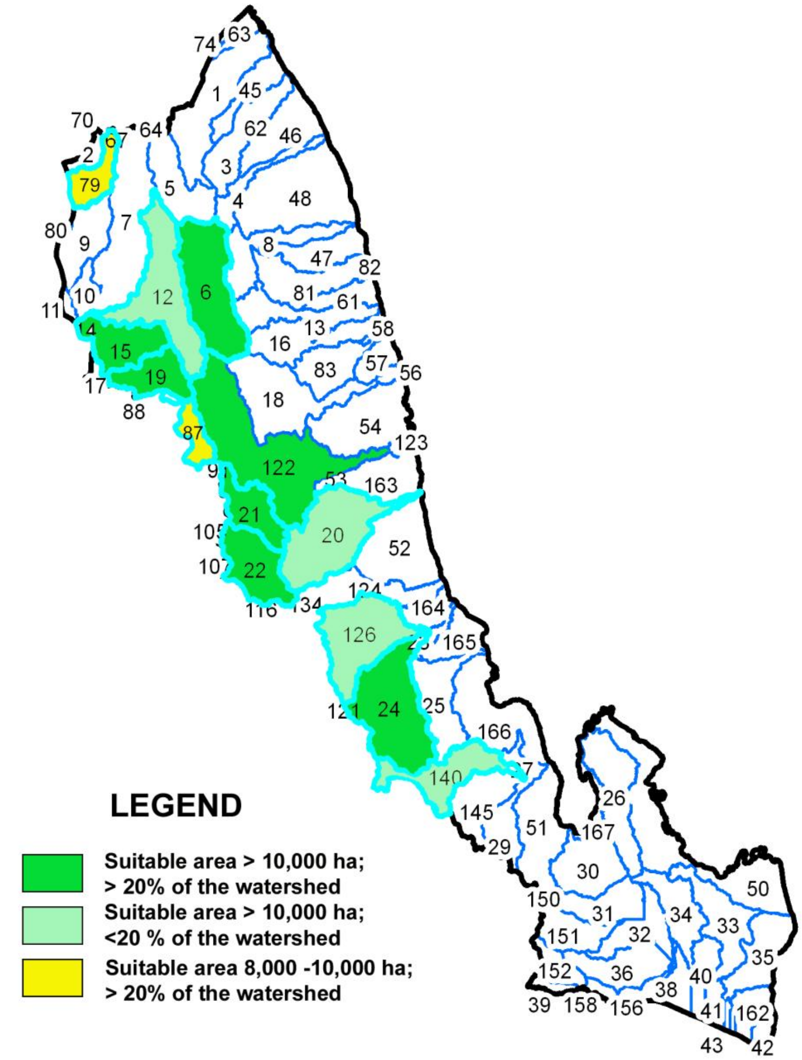

Figure i. Priority watersheds for micro-catchment water harvesting systems based on absolute and relative suitable area

The total suitable area covered by these watersheds (252,814 ha) is about 75% of the total suitable area for micro-catchment systems in Zoba NRS.

A breakdown of suitable and non-suitable areas for these priority watersheds is provided in Table ii. Land use/land cover and annual precipitation patterns in these priority watersheds are mapped at large scale in the report.

Table ii. Priority watersheds for micro-catchment systems: estimation of suitable and non-suitable areas

Watershed	Area	Area suitable	Area unsuitable	% suitable
6	98,550	25,164	73,387	26
12	102,872	14,909	87,964	14
15	51,460	12,745	38,715	25
19	40,745	10,461	30,284	26
20	103,412	14,692	88,720	14
21	42,260	25,285	16,974	60
22	57,144	26,580	30,564	47
24	111,856	31,909	79,947	29
79	29,652	9,895	19,757	33
87	23,298	8,452	14,845	36
122	176,329	47,737	128,591	27
126	87,774	14,822	72,952	17
140	57,159	10,163	46,995	18

With very few exceptions, these watersheds are also the ones where suitable conditions may exist for macro-catchment systems. However, the suitable areas are much smaller: about 6,400 ha for macro-catchments planted with tree crops, and nearly 12,000 ha for catchments planted with field crops. Moreover the areas suitable for these systems are more scattered than is the case for the micro-catchment systems. This is not surprising given the fact that three conditions have to be met: (i) that there is a suitable catchment generating enough runoff, (ii) that there is a suitable water-receiving area for the runoff, (iii) that the runoff-generating and runoff-receiving areas are sufficiently close together (< 1km). The locations of areas with potential for macro-catchment systems are shown in the report.

Conclusions and recommendations

Zoba Northern Red Sea has many locations where potential exists for one or several water harvesting methods. At the same time the potential for water harvesting in Zoba NRS is considerably lower than in Zoba Debub in both absolute and relative terms, due to a less favourable waterbalance in Zoba NRS, with less precipitation and higher potential evapo-transpiration rates than in Zoba Debub.

The priority watersheds identified through the GIS analysis are the locations where further assessments of potential and interventions could start. Whereas the current study offers a good basis for targeting research for development, this assessment of potential for water harvesting is entirely based on a GIS desk study and needs therefore to be treated as less than final. A follow-up stage of studies is therefore required to make a more definitive selection of watersheds for priority development. These studies would involve both review of documents and collection of in-country data as well as field studies.

Better datasets than the ones available for this desk study may be available in-country and need to be identified. The data requirements for this Zoba refer in particular to farming systems, meteorological and hydrological data, interpretation of very high resolution satellite imagery and establishing a high-resolution digital elevation model. Developing a GIS database for Zoba Northern Red Sea is an effective way to integrate heterogeneous data and analyze data gaps.

Field studies in the various parts of the Zoba and meetings with farmers, specialists and officials including the Governor and researchers are essential in order to provide ground truthing for the desk study, and allow a final identification and selection of a few top priority areas for water harvesting development. Once such areas are identified, a second stage of more localized studies will be required, pertaining in particular to local hydrology but in which also soil survey will have to play a major role, in order to identify at greater detail important properties such as soil depth, stoniness, texture, salinity.

Adaptive research and capacity building should go in parallel with the development of the identified watersheds, with particular focus on crop water requirements, irrigation scheduling, agronomy, and water harvesting techniques adapted to variable terrain and soil conditions.

1. INTRODUCTION

Drought is a recurrent phenomenon in Eritrea. Due to a variety of reasons, related to poor infrastructure, poor agricultural practices and governance issues, drought in Eritrea causes immediately food shortages. Inadequacies in the country's ability to respond to or mitigate the failure of rains may even lead to famine. Water harvesting/soil-water conservation are among the possible strategies for coping with drought, while also offering in the longer-term prospects for increasing land and water productivity for resource-poor farmers. Whether water harvesting is a feasible option depends on many factors, biophysical as well as socioeconomic. The fact remains that not everywhere there will be physical potential, but also that where there is some degree of potential; some techniques will be more suited than others to make use of that potential. A spatial analysis of suitability for various water harvesting techniques could therefore be useful for development agencies.

In the context of and as part of the preparation of the National Agriculture Program (NAP), particularly with reference to the component Agricultural Water Resources and Infrastructure Development (AWRID), IFAD had granted an institutional contract to ICARDA to conduct a pilot GIS/watershed development study, aiming at identifying potential for water harvesting, spate irrigation and soil-water conservation interventions in Zoba (Province) Debub. After completion of this study in 2010, it was proposed to conduct a similar study in Zoba Northern Red Sea, using the same methodology and leading to similar deliverables as for Zoba Debub.

The Zoba Debub study consisted of the following elements:

1) a general framework for designing potential agricultural development programs based on optimizing rainwater in rainfed systems, runoff water harvesting and irrigation.

2) a GIS study focusing on mapping suitability for potential water harvesting interventions, identification and characterization of potential watersheds, selection of watersheds to implement a pilot project and recommendations for appropriate soil and water interventions

To implement the Zoba Debub study, basic information for watershed characterization and mapping was collected by a GIS/land management consultant during a 4-week mission to Zoba Debub in May-June 2010. Field visits to watersheds with potential for water harvesting in the Zoba were undertaken by the consultant and two ICARDA staff members. The ground truth visits in Zoba Debub in combination with the GIS study made it possible to prioritize watersheds and to select two for immediate development as a pilot project.

IFAD's intent to extrapolate the methodology used in Zoba Debub and extend the deliverables to Zoba Northern Red Sea led to a new institutional contract between IFAD and ICARDA. The contract called for delivery of a GIS desk study leading to a similar identification of priority areas for development of water harvesting potential as was delivered for Zoba Debub. The contract also required fielding an experienced consultant in soil and water conservation in order to analyze watersheds based on integrated watershed development, to develop criteria for soil and water conservation intervention and irrigation, to identify sites for priority development in relation to the agreed criteria, and to provide in-country training.

Throughout the contract period, the Government of Eritrea did not give clearance to ICARDA to field its staff in order to undertake the field activities, required for getting acquainted with the new project area and for collecting in-country data on climate, soils, land use and water resources. As a six-month extension period did not change the situation vis-a-vis field activities, IFAD authorized ICARDA to deliver only the GIS desk study, on the basis of documents and data already available at ICARDA. The desk study, summarized in this report, contains suitability maps for different water harvesting techniques, as envisaged in the contract, and is able to identify watersheds where that potential is more concentrated than in others, but is unable to identify priority areas for development, as this requires field verification. For this reason the current report also outlines further steps to be taken in order to use this desk study as a basis for the development of water harvesting in Zoba Northern Red Sea.

2. METHODOLOGIES

2.1. BASE MAPS

Given the scarcity of basic maps for Zoba Northern Red Sea, a number of maps were prepared, first to gain better insights into the agricultural environment of the Zoba, and, in a second stage, to serve as input data for the suitability assessment for water harvesting.

An overall birds-eye view of the Zoba (Map 1) was extracted from the 2000 Geocover series of ortho-rectified Landsat 7 ETM+ Mosaics . This dataset is from the Landsat 7 Enhanced Thematic Mapper (ETM+) with the 15m band panchromatic band fused with the 30m multi-spectral bands 7-4-2. The pixel size is 14.25 meters and the absolute positional accuracy is 50 meters Root Mean Square Error. The projection is Universal Transverse Mercator (UTM)/World Geodetic System 1984 (WGS84). Apart from ortho-rectification these Landsat images have been tonally balanced, mosaiced, tiled and wavelet compressed, and are of the highest quality. The coverage date is scene-dependent, nominally 2000 +/- 2 years.

The Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM) was the source of major topography-related data, such as elevation (Map 4), slopes, watersheds and drainage lines. Slopes (Map 5) were calculated using the Slope function of the Spatial Analyst Tools in ESRI ArcGIS software.

Watersheds and drainage lines (Map 2) were delineated using the Arc Hydro Tools utility for ArcGIS. Using the SRTM DEM as input grid, the following steps were followed for creating watersheds and drainage lines:

- Fill Sinks : If a cell in DEM is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.
- Flow Direction: create flow direction grid from a DEM grid.
- Flow Accumulation: create flow accumulation grid from a flow direction grid.
- Stream Definition: create a new grid (stream grid) with cells from a flow accumulation grid that exceed user-defined threshold.
- Stream Segmentation: create a stream link grid from the stream grid (every link between two stream junction gets a unique identifier).
- Catchment Grid Delineation: create a catchment grid for a link grid. It identifies areas draining into each link.
- Catchment Polygon Processing: create catchment polygons out of the catchment grid.
- Drainage Line Processing: create streamlines out of the stream link grid.

Watersheds and drainage lines were created at 2 different levels, with 25,000 and 5,000 upstream pixels as thresholds. With 25,000 pixels threshold there are fewer but smaller watersheds, in which sub-watersheds are nested based on the 5,000 upstream pixels threshold.

The Compound Topographic Index (CTI), a.k.a. the Wetness Index, is a single value quantification of the position of a site in the local landscape, expressed as a measure of concavity of the land surface. It is a useful guide to water and sediment movement in particular landscapes. Smaller values indicate a tendence to shed water, i.e. to generate runoff, and higher values to receive runoff water.

The CTI (Map 6) is calculated as:

$$CTI = \ln (As / \tan B)$$

where *'As'* is the specific catchment area expressed as m^2 per unit width orthogonal to the flow direction and *'B'* is the slope angle.

Precipitation data, available from meteorological stations (Table 1), were converted into continuous grids, a.k.a. 'climate surfaces'. Maps of mean annual precipitation (Map 7) and reliable/effective precipitation for assessing water harvesting potential (Map 8) were prepared using these climate surfaces. The procedure followed is explained in more detail in section 2.2.2.1.
The surface of annual potential evapo-transpiration (Map 9) was extracted from the CWANA surface of annual potential evapo-transpiration at 30 arc-seconds (about 1 km, 0.00833 decimal degrees) spatial resolution using the Zoba NRS vector mask and resampled to a spatial resolution of 3 arc-seconds (about 90 m , 0.000833 decimal degrees).

2.2. MAPPING SUITABILITY FOR WATER HARVESTING

2.2.1. General principles

The methodology used for mapping suitability for water harvesting is an adaptation of the method used in Syria (De Pauw et al., 2008) by taking into consideration the datasets available in Eritrea and local conditions. The key elements of the methodology are the following:

1. The assessment of suitability for different water harvesting techniques was undertaken by matching in a GIS environment simple biophysical information, systematically available for the entire Zoba NRS, to the broad requirements of the specified water harvesting systems using an expert-based empirical decision model.

2. Suitability was evaluated for both micro-and macro-catchment systems. Suitability was evaluated separately for the following systems:

- Micro-catchment systems
    a. System 11: contour ridges/ range shrubs
    b. System 12: contour ridges/ field crops
    c. System 13: contour ridges/ tree crops
    d. System 21: semi-circular bunds – range shrubs
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    f. System 23: semi-circular bunds – tree crops
    g. System 31: small pits – range shrubs
    h. System 33: small pits – tree crops
    i. System 41: small runoff-basins – range shrubs
    j. System 43: small runoff basins – tree crops
    k. System 51: runoff strips – range shrubs
    l. System 52: runoff strips – field crops
    m. System 6: contour bench terraces
- Macro-catchment systems: evaluated for suitability as
    a. water catchment area
    b. agricultural use: field crops and tree crops

For details on each of these systems is referred to section 2.2.2.

3. Suitability was evaluated through a scoring system based on climate and land criteria, using threshold values that are considered relevant for the different systems evaluated. The scoring system itself was based on the expert judgment documented in the guidelines for selecting water-harvesting techniques in the drier environments (Oweis et al. , 2001), but modified in function of the current data availability and new research findings. The criteria used in the current suitability maps were the 80% minimum annual precipitation, the slope, the soil depth and the land use/land cover type. In the case of precipitation and slope, the scoring system is *continuous*, with values between 0 and 100. In the case of the soil depth and land use/land cover, the scores are based on classes, which can have only 2 values, 0 (suitable) or 100 (unsuitable).

4. The scores for precipitation, slope, soil type and land use/land cover type were combined using the 'minimum rule': the lowest factor score determines the final score.

5. For each micro-catchment system one evaluation was undertaken. For macro-catchment systems two separate evaluations were undertaken: one to assess suitability for use as water catchment area, the other to assess suitability for agricultural use. The two suitability maps were then overlaid to assess where areas with high suitability for catchment and for agricultural use are within a distance that can be overcome by technical means.

2.2.2. Description of evaluated water harvesting systems

These systems are briefly described in the following paragraphs, based on Oweis et al. (2001) and Oweis (2004).

2.2.2.1. Contour ridges

These are bunds or ridges constructed along the contour lines, usually spaced between 5 and 20 m apart (Fig. 1). The first 1–2 m upstream of the ridge is used for cultivation, whereas the rest is used as a catchment. The height of each ridge varies according to the slope's gradient and the expected depth of the runoff water retained behind it. Bunds may be reinforced by stones if necessary.

Contour ridges are one of the most important techniques for supporting the regeneration and new plantations of forages, grasses and hardy trees on gentle to steep slopes in the steppe. In the semi-arid tropics, they are used for arable crops such as sorghum, millet, cowpeas and beans.

Figure 1. Contour ridges at the IWLM Water Harvesting Site, ICARDA, Tel Hadya

2.2.2.2. Semi-circular and trapezoidal bunds

These are usually earthen bunds in the shape of a semi-circle, a crescent, or a trapezoid facing directly upslope. They are created at a spacing that allows sufficient catchment to provide the required runoff water, which accumulates in front of the bund, where plants are grown. Usually they are placed in staggered rows. The diameter or the distance between the two ends of each bund varies between 1 and 8 m and the bunds are 30–50 cm high.

Bunds are used mainly for the rehabilitation of rangeland or for fodder production, but may also be used for growing trees, shrubs and in some cases field crops and vegetables.

Figure 2. Overview of the semi-circular bunds area at the IWLMP Water Harvesting Site, ICARDA

Figure 3. Semi-circular bunds, reinforced with stones, at the IWLMP Water Harvesting Site, ICARDA

2.2.2.3. Small pits

Pitting is a very old technique used mainly in Western and Eastern Africa, but adopted in some WANA areas. It is used for rehabilitating degraded agricultural lands. The pits are 0.3–2 m in diameter. The most famous pitting system is the *zay* system used in Burkina Faso (Fig. 4). This consists of digging holes with a depth of 5–15 cm. Pits are applied in combination with bunds to conserve runoff, which is slowed down by the bunds. This system allows much degraded agricultural land to be put back into use. Pitting systems are used mainly for the cultivation of annual crops, such as cereals. If the pits are dug on flat instead of sloping ground, they may be regarded more as an *in situ* moisture-conservation technique than as water harvesting one.

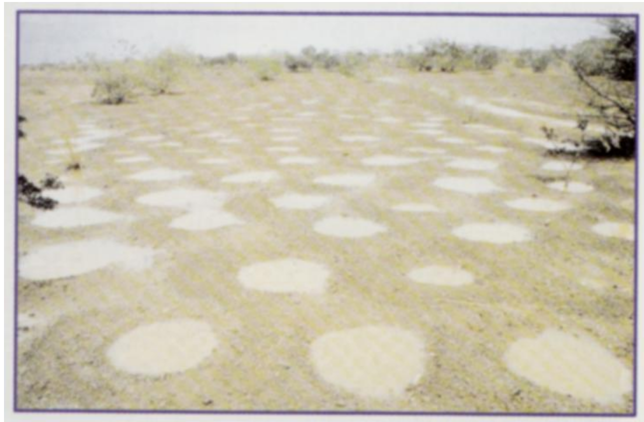


Figure 4. Example of small pits in Burkina Faso (photo from Oweis et al. 2001)

2.2.2.4. Small runoff basins

Sometimes called *negarim*, small runoff basins consist of small diamond- or rectangular-shaped structures surrounded by low earth bunds (Fig.5). They are oriented to have the maximum land slope parallel to the long diagonal of the diamond, so that runoff flows to the lowest corner, where the plant is placed. The usual dimensions are 5–10 m in width and 10–25 m in length. Small runoff basins can be constructed on almost any gradient, including plains with 1–2 % slopes. They are most suitable for trees. The soil should be deep enough to hold sufficient water for the whole dry season.

Figure 5. Small runoff basins at the IWLMP Water Harvesting Site, ICARDA

2.2.2.5. Runoff strips

In this technique the farm is divided into strips along the contour (Fig.6). An upstream strip is used as a catchment, while a downstream one is cultivated. The strip with crops should not be too wide (1–3 m), while the catchment width is determined in accordance with the amount of runoff water required. This technique is highly recommended for barley cultivation and other field crops in large steppe areas of WANA, where it can reduce risk and substantially improve production. The catchment area can be used for grazing after the crop has been harvested.

Figure 6. Runoff strips at the IWLMP Water Harvesting Site, ICARDA

2.2.2.6. Contour bench terraces

Contour-bench terraces are constructed on very steep slopes to combine soil and water conservation with water harvesting. Cropping terraces are built level with supporting stonewalls to slow down the flow of water and control erosion. They are supplied with additional runoff water from steeper, non-cropped areas between the terraces. The terraces are usually provided with drains to release excess water safely. They are frequently used to grow trees and bushes, but rarely used for field crops in the WANA region. The historic bench terraces in Yemen are a good example of this system (Fig. 7).

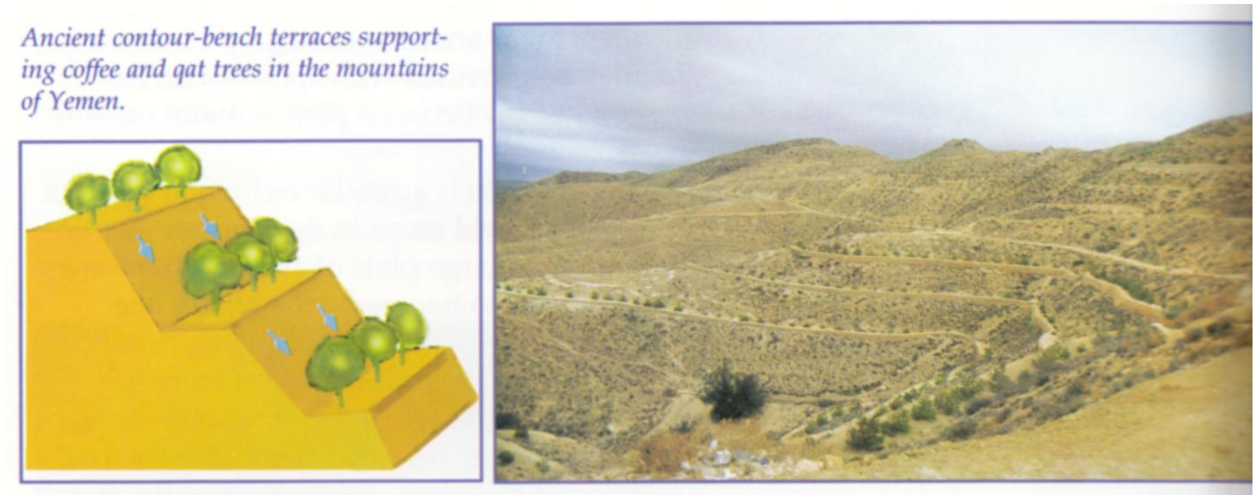


Figure 7. Example of contour bench terraces in Yemen (photo from Oweis et al. 2001)

2.2.3. Scoring suitability for micro-catchment systems

2.2.3.1. Factor scoring: precipitation

For precipitation, the scoring of suitability was NOT based on the mean annual precipitation, as in the Syria methodology, but on the 80% minimum annual precipitation, which is the annual precipitation that can be expected to be exceeded in at least 4 years out of 5 (based on frequency counts within a time series). This has two advantages:

(i) A safety factor was considered to account for high precipitation variability in Eritrea;
(ii) the area where water harvesting can be useful was more realistically approximated than by using average annual rainfall.

The location-specific 80% minimum probability annual precipitation was derived by the following procedure:

Step 1. A list of precipitation stations in Zoba Northern Red Sea and neighbouring areas (other Zobas and northern Ethiopia) was compiled. Data sources were meteorological records provided by the Ministry of Agriculture and the FAOCLIM2 database (FAO, 2001). In order to qualify, only stations with at least 15 years of complete monthly records were accepted. The stations finally selected for spatial interpolation are shown in Figure 8.

Step 2. For each station the average annual precipitation (PrecYr) for the years of record was calculated.

Step 3. The calculation of the 80% probability minimum annual precipitation assumes a standard reference period of 1978-2007. For the stations inside Zoba Debub no adjustment was required, as they already contain the most recent data. For those stations in Eritrea and Ethiopia with older data an adjustment was made by adding the trend precipitation per decade as follows:

$$PrecYr_{adj} = PrecYr * (1 + {DecChg\% * No_{Dec}}/{100})$$

With PrecYr_adj: annual precipitation for the reference period, adjusted for the trend
PrecYr: mean annual precipitation, based on the available record

Dec_Chg%: percentage change (+ or -) of the annual precipitation per decade (10 year period)
No_Dec: number of decades difference with the reference period (1978-2007)

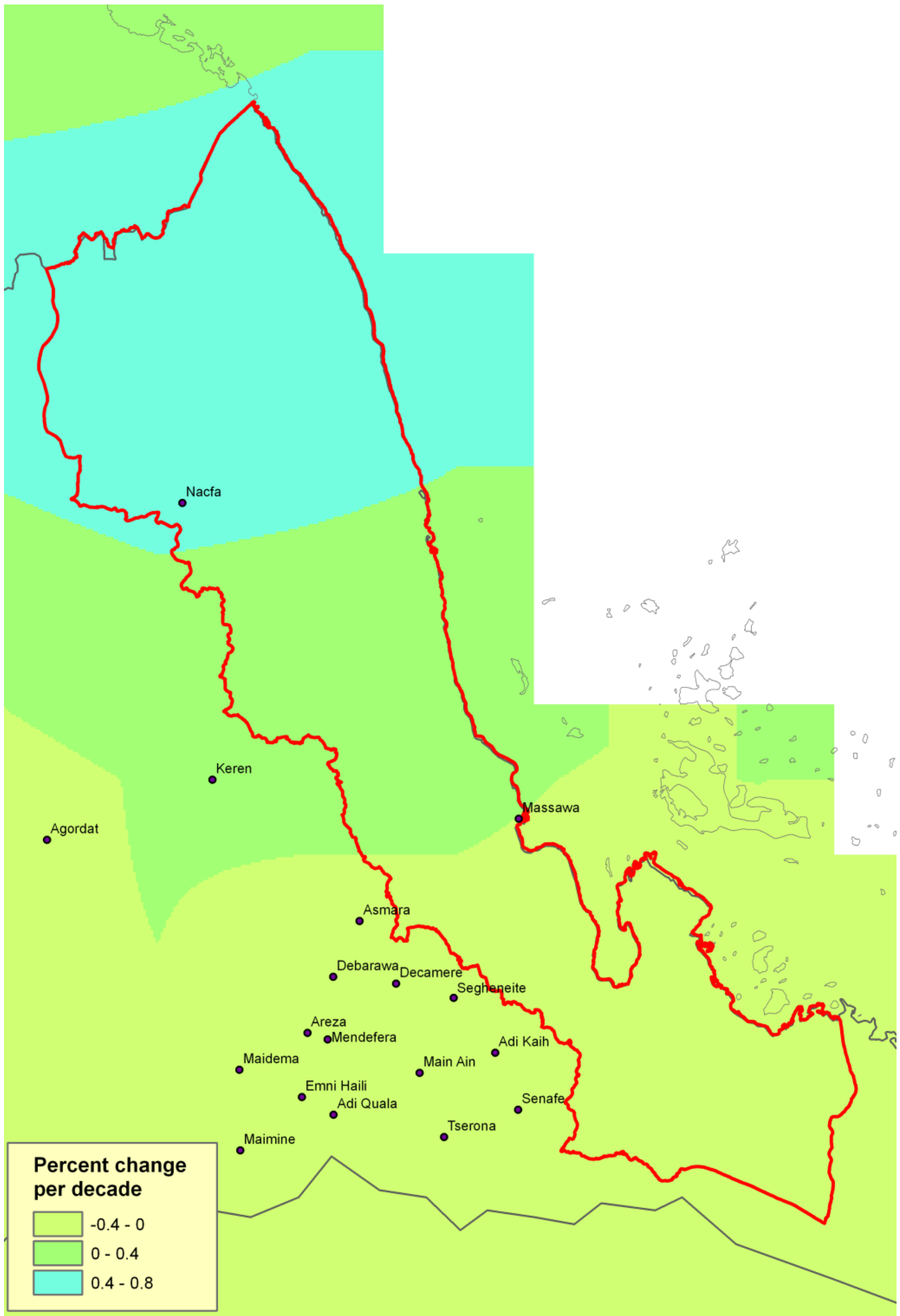


Figure 8. Trend in annual precipitation in the Horn of Africa 1901-2007

The trend precipitation per decade was obtained from a 1-km trend surface grid for the Horn of Africa (Fig. 8).

Step 4. The individual annual precipitation totals were sorted from low to high and given a rank number n.

For each ranked value $Prec_{nn}$ the frequency of exceedance $freqex_n$ was calculated as:

$$\frac{N-n}{N}$$

the precipitation to be exceeded in 4 years out of 5 was calculated as:

$$80\%P = Prec_{n,l} + \frac{0.8 - freqex\,,h}{freqex\,,l - freqex\,,h} * (Prec_{n,l} - Prec_{n,h})$$

with $Prec_{n,l}$: the ranked precipitation value immediately below the 0.8 frequency
$Prec_{n,h}$: the ranked precipitation value immediately above the 0.8 frequency
freqex,l: the frequency of exceedance immediately below the 0.8 frequency
freqex,h: the frequency of exceedance immediately above the 0.8 frequency

Step 5. A station-specific ratio Ratio_80%P2Av was calculated as $\frac{80\%P}{PrecYr}$. It was assumed that this ratio remains a constant throughout, in other words that no change in precipitation variability occurred, irrespective of the time period of actual measurements.

Step 6. The final value for the precipitation to be exceeded in 4 years out of 5 was then calculated as:

*Adj_80%P2Av = PrecYr_adj *Ratio_80%P2Av*

Step 7. For the purpose of giving a suitability score to precipitation (Step 9), it was necessary to account for differences in effectiveness of precipitation between Syria and Zoba Northern Red Sea. The precipitation scoring is calibrated for winter rainfall patterns in non-tropical areas, with relatively lower levels of potential evapo-transpiration (PET). In tropical areas with summer rainfall, the PET is higher and, as a result, the effectiveness of precipitation is lower. To adjust for differences in precipitation effectiveness between Syria and Zoba Northern Red Sea, the effective precipitation in the Zoba was calculated as:

*P_eff = Adj_80%P2Av * 0.9368*

The value 0.9368 is the ratio of the mean annual PET in Syria over the mean annual PET in Zoba NRS.

Step 8. After due correction to obtain values for a comparable time period, the station data were converted into gridded maps of mean annual precipitation, using the 'thin-plate smoothing spline' method of Hutchinson (1995), as implemented in the ANUSPLIN software (Hutchinson, 2000). The Hutchinson method is a smoothing interpolation technique in which the degree of smoothness of the fitted function is determined automatically from the data by minimizing a measure of the predictive error of the fitted surface, as given by the generalized cross-validation (Hutchinson, 2000). The method uses three independent spline variables: latitude, longitude and altitude. The latter was input to the model in the form of a digital elevation model (DEM) grid file. The DEM used to generate the climate surfaces was the SRTM DEM[1] with 3 arc-second (about 90 m) resolution. Parameter estimation was undertaken over a regular grid with the same dimensions and resolution as the user-provided DEM.

[1] URL: http://www2.jpl.nasa.gov/srtm/

<u>Step 9. Factor scoring:</u> scores for suitability can have a value between 0 (minimum) and 100 (maximum). Scores for the location-specific 80% minimum annual precipitation were obtained by linear interpolation between cardinal points as follows (Fig. 9):

A: 0 mm (score 0)
B: 150 mm (score 100)
C: 250 mm (score 100)
D: 500 mm (score 0)

For all WH micro-catchment systems the same scoring system for precipitation was applied.

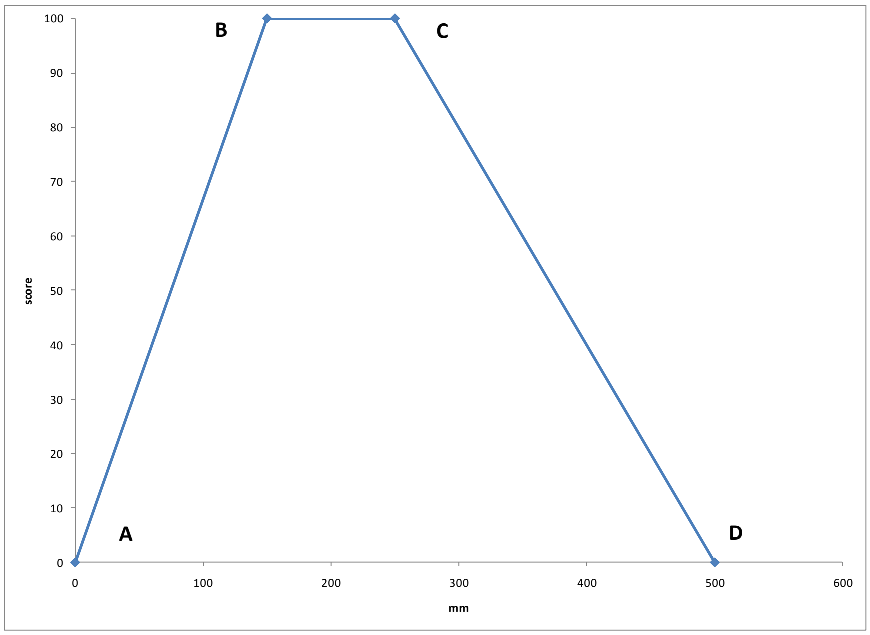


Figure 9. Scores for the effective 80% minimum annual precipitation (all systems)

Table 1. Stations used for the spatial interpolation of the mean and 80% probability minimum annual precipitation

Source	Country	Station name	Lati	Longi	Alti	No. Years	Begin	End	PrecYr	80%P	Ratio	DecChg %	No_Decades	PrecYr _adj	Adj_80% P2Av	P_eff
MoA	ERITREA	Adi Kaih	14.841	39.371	2407	15	1992	2006	407	296	0.7280	0.0000	0	407	**296**	278
MoA	ERITREA	Adi Quala	14.635	38.833	2046	16	1992	2007	652	477	0.7326	0.0000	0	652	**477**	447
MoA	ERITREA	Areza	14.9071	38.7468	2070	16	1992	2007	384	307	0.7992	0.0000	0	384	**307**	287
MoA	ERITREA	Debarawa	15.094	38.832	1932	16	1992	2007	491	339	0.6916	0.0000	0	491	**339**	318
MoA	ERITREA	Decamere	15.071	39.041	2036	16	1992	2007	459	361	0.7863	0.0000	0	459	**361**	338
MoA	ERITREA	Emni Haili	14.694	38.728	1975	11	1999	2009	447	278	0.6208	0.0000	0	447	**278**	260
MoA	ERITREA	Maidema	14.785	38.52	1770	14	1992	2005	345	178	0.5149	0.0000	0	345	**178**	166
MoA	ERITREA	Maimine	14.517	38.523	1614	15	1992	2006	514	357	0.6958	0.0000	0	514	**357**	335
MoA	ERITREA	Main Ain	14.774	39.12	1712	12	1996	2009	435	328	0.7551	0.0000	0	435	**328**	308
MoA	ERITREA	Mendefera	14.886	38.814	1976	16	1992	2009	619	449	0.7256	0.0000	0	619	**449**	421
MoA	ERITREA	Senafe	14.652	39.448	2637	17	1992	2008	519	302	0.5826	0.0000	0	519	**302**	283
MoA	ERITREA	Segheneite	15.024	39.233	2205	15	1993	2009	450	308	0.6844	0.0000	0	450	**308**	289
MoA	ERITREA	Tserona	14.561	39.201	1609	13	1994	2009	403	267	0.6624	0.0000	0	403	**267**	250
FAOCLIM	ERITREA	Agordat	15.55	37.88	626	30	1931	1960	278	111	0.3997	-0.5130	5.5	270	**108**	101
FAOCLIM	ERITREA	Asmara	15.28	38.92	2325	30	1961	1990	518	377	0.7272	-0.0048	2.5	518	**377**	353
FAOCLIM	ERITREA	Assab	13.07	42.72	14	27	1961	1990	42	1	0.0239	-0.2451	2.5	41	**1**	1
FAOCLIM	ERITREA	Keren	15.75	38.43	1460	28	1933	1963	367	299	0.8134	0.5100	5.5	377	**307**	288
FAOCLIM	ERITREA	Massawa	15.62	39.45	10	30	1931	1960	187	100	0.5337	0.0022	5.5	187	**100**	94
FAOCLIM	ERITREA	Nacfa	16.67	38.33	1676	21	1942	1967	168	50	0.2958	0.5219	5	173	**51**	48
FAOCLIM	ETHIOPIA	Mekelle	13.5	39.48	2212	30	1960	1989	626	443	0.7072	-0.0792	2.5	625	**442**	414
FAOCLIM	ETHIOPIA	Gondar	12.53	37.43	1966	30	1961	1990	1,066	853	0.8006	0.0210	2.5	1,066	**853**	800

column headers:

Source:source data (MoA: Ministry of Agriculture; FAOCLIM: FAO 2001)

Lati: latitude (in decimal degrees); Longi: longitude (in decimal degrees); Alti: station elevation (in m)

NoYears: number of years with recorded data

Begin: begin year for the record; End: end year for the record

PrecYr: mean annual precipitation, based on the available recordDec_Chg%: percentage change (+ or -) of the annual precipitation per decade (10 year period)

No_decades: number of decades difference with the reference period (1978-2007)

PrecYr_adj: annual precipitation for the reference period, adjusted for the trend

Ratio_80%P: ratio between the 80% minimum probability annual precipitation and the mean annual precipitation

P_80%: adjusted 80% minimum probability annual precipitation

P_eff: effective annual precipitation (the minimum to be expected in 4 years out of 5, adjusted for reference period and for potential evapo-transpiration)

2.2.3.2. Factor scoring: slopes

The main source for slope information was the Shuttle Radar Topographic Mission (SRTM) Digital Elevation Model (DEM)[2]. Slopes were calculated using respectively the Slope function of the Spatial Analyst Tools in ESRI ArcGIS software.
Slope scores are also obtained by linear interpolation between cardinal points. The cardinal points are different between the considered WH systems (Fig. 10), which can be divided into 3 'slope response groups':

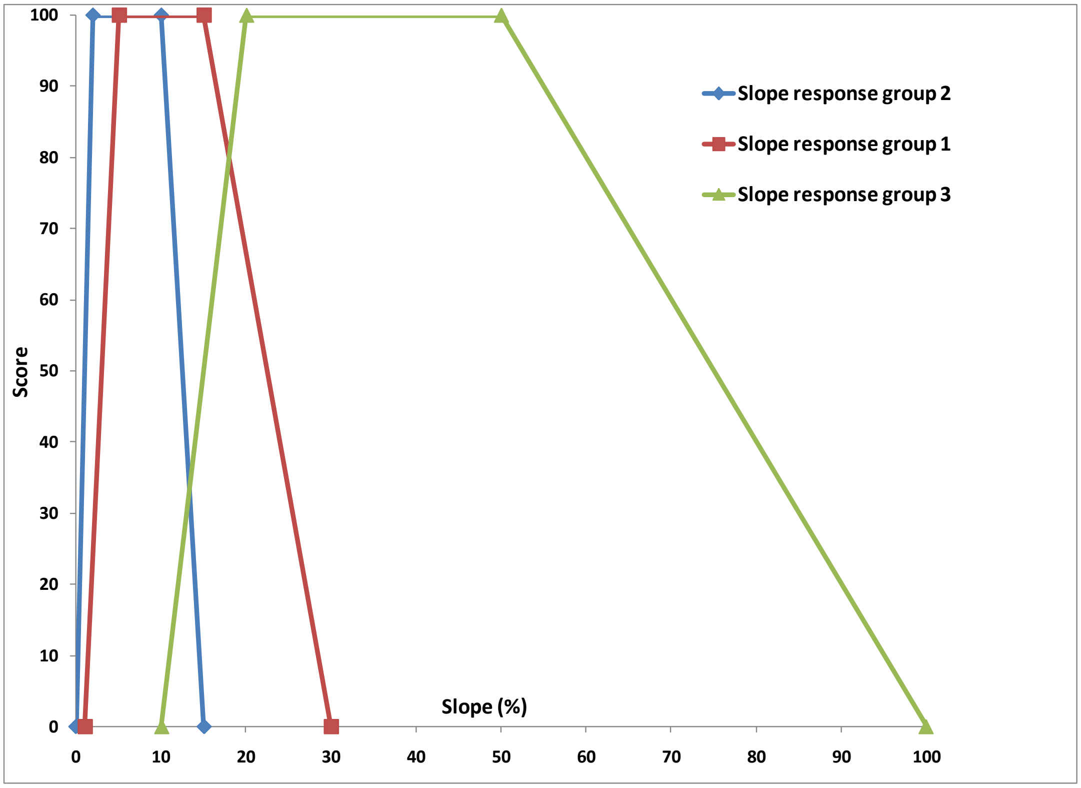


Figure 10. Slope scores for micro-catchment systems

Slope response group 1: contour ridges
A: 1% slope (score 0)
B: 5% slope (score 100)
C: 15% slope (score 100)
D: 30% slope (score 0)

Slope response group 2: small pits, runoff strips, small runoff basins, semi-circular bunds
A: 0% slope (score 0)
B: 2% slope (score 100)
C: 10% slope (score 100)
D: 15% slope (score 0)

[2] URL: http://www2.jpl.nasa.gov/srtm/

Slope response group 3: contour bench terraces
A: 10% slope (score 0)
B: 20% slope (score 100)
C: 50% slope (score 100)
D: 100% slope (score 0)

The scores are nearly identical to the slope scores used in Syria (De Pauw et al. 2008), with exceptions for response group 1, where point A, previously at 2% slope, has been repositioned to 1 % slope, and for response group 2, where point A, previously at 1% slope, has been repositioned to 0% slope, following new research findings in the Badia area in Jordan[3].

2.2.3.3. Factor scoring: land use/land cover

The source of land use/land cover information is the Eritrea Multi-purpose Land Cover Database (FAO/ Africover, 2002). Land use/land cover can be a constraint for the development of water harvesting in two ways: from a land use planning/zoning perspective, and from the physical nature of the land cover. The presence of urbanized areas is an example of the first type of constraint, forest areas an example of the second type of constraint. None of these constraints is important in Zoba NRS. For this reason land use/land cover has not been considered a limiting factor for water harvesting development at the scale of the Zoba.

2.2.3.4. Factor scoring: soils

There is a severe scarcity of good soil information in Eritrea in general, and for Zoba NRS in particular. The best source of soil data is the Soil Map of IGADD countries, including Eritrea. However, this map is still at an exploratory level (scale: 1:2,000,000) with mapping units that are associations of FAO soil classification groups: a limited number of broad soil types that occur in groups, which could not be further separated and characterized at the scale of the study. In some countries (e.g. Palestine, see De Pauw and Wu, 2010) it has been possible to improve the resolution of the soil map, with respect to critical soil properties for water harvesting (such as soil depth), by visual interpretation of high-resolution QuickBird[4] imagery in Google Earth Pro. Quickbird imagery was not available for Zoba NRS and in any case would not have been very useful in the absence of field verification.

As a general rule, all soils are acceptable for micro-catchment systems unless they are too shallow, too saline, too stony or have very severe limitations of soil texture (De Pauw et al., 2008). The most critical determinant of soil suitability for different water harvesting systems is soil depth. As the available soil map and satellite imagery did not provide a sound basis for estimating soil depth, this factor was inferred from the Eritrea Multi-purpose Land Cover Database using a land cover/depth conversion table (Table 2). Using expert judgment, each land use/land cover class was associated with a soil depth class.

[3] T. Oweis, personal communication.
[4] URL: http://www.digitalglobe.com/index.php/85/QuickBird

Table 2. Land cover and estimated soil depth and hydrological classes

Land cover	**Depth Class**	**Estimated_depth**	**DRG_1**	**DRG_2**	**DRG_3**	**DRG_4**	**Hydro-class**
Artificial Waterbodies	n.a.	n.a.	0	0	0	0	n.a.
Bare rocks and river banks	Bare	<25 cm	0	0	0	0	D
Bare soil	Bare	<25 cm	0	0	0	0	D
Closed Herbacous Vegetation (Seasonally Flooded)	Shallow	25-75 cm	100	50	0	0	C
Closed Shrubs	Shallow	25-75 cm	100	50	0	0	C
Closed to Open Herbaceous Vegetation	Shallow	25-75 cm	100	50	0	0	C
Closed Trees (Broadleaved Evergreen)	Shallow	25-75 cm	100	50	0	0	C
Closed Trees (Needle leaved Evergreen)	Shallow	25-75 cm	100	50	0	0	C
Closed Woody Vegetation Thickets	Shallow	25-75 cm	100	50	0	0	C
Irrigated Herbaceous Fields	Deep	>75 cm	100	100	100	100	B
Irrigated Herbaceous Fields (mixed unit with natural vegetation or other) (field area approx. 60% polygon area	Mixed1	60% deep; 40% shallow	100	80	60	80	B
Irrigated Shrub Crop - Banana	Deep	>75 cm	100	100	100	100	B
Irrigated Tree Crop - Citrus	Deep	>75 cm	100	100	100	100	B
Irrigated Tree Crop - Citrus (mixed unit with natural vegetation or other) (field area approx. 60% polygon area)	Mixed1	60% deep; 40% shallow	100	80	60	80	B
Isolated (in natural vegetation or other) Rainfed Small Herbaceous Fields (field frequency 10-20% polygon are	Mixed3	20% deep; 80% shallow	100	60	20	60	C
Open Shrubs	Shallow	25-75 cm	100	50	0	0	C
Open Trees	Shallow	25-75 cm	100	50	0	0	C
Rainfed Large to Medium Herbaceous Fields	Deep	>75 cm	100	100	100	100	B
Rainfed Small Herbaceous Fields	Mixed1	60% deep; 40% shallow	100	80	60	80	B
Rainfed Small Herbaceous Fields (mixed unit with natural vegetation or other) (field area approx. 60% polygor	Mixed1	60% deep; 40% shallow	100	80	60	80	B
Savannah (Shrub or Tree and Shrub)	Shallow	25-75 cm	100	50	0	0	C
Scattered (in natural vegetation or other) Irrigated Herbaceous Fields (field frequency 20-40% polygon area)	Mixed2	40% deep; 60% shallow	100	70	40	80	B
Scattered (in natural vegetation or other) Rainfed Small Herbaceous Fields (field frequency 20-40% polygon ar	Mixed2	40% deep; 60% shallow	100	70	40	80	B
Scattered (in natural vegetation or other) Tree Plantation - Eucalyptus (field frequency 20-40% polygon area)	Mixed2	40% deep; 60% shallow	100	70	40	80	B
Sparse Herbaceous Vegetation	Shallow	25-75 cm	100	50	0	0	C
Sparse Shrubs	Shallow	25-75 cm	100	50	0	0	C
Sparse Trees	Shallow	25-75 cm	100	50	0	0	C
Tree Plantation - Eucalyptus	Mixed2	40% deep; 60% shallow	100	70	40	80	B
Tree Plantation - Eucalyptus (mixed unit with natural vegetation or other) (field area approx. 60% polygon are	Mixed2	40% deep; 60% shallow	100	70	40	80	B
Urban and Associated Areas	Shallow	25-75 cm	100	50	0	0	D

Notes:

DRG_1,DRG_2, DRG_3, DRG_4: soil depth suitability scores for the 4 depth response groups (Table 3)

Hydro-Class: soil hydrological class

Using this simple classification, a map of estimated soil depth map was prepared. On this basis it was possible to subdivide the soils of the Zoba into a limited number of 'soil depth response classes' and provide suitability scores to the latter (Table 3).

Table 3. Scores of soil depth by WH system and soil depth response group

WH class	Depth response group	Deep	Shallow	Mixed1	Mixed2	Mixed3	Other
Micro	S11, S21	100	100	100	100	100	0
Micro	S12, S22, S31, S41, S51	100	50	80	70	60	0
Micro	S13, S23, S33, S43, S52	100	0	60	40	20	0
Micro	S6	0	0	80	80	60	0
Macro	Tree crops	100	33	73.2	59.8	46.4	0
Macro	Field crops	100	50	80	70	60	0

2.2.3.5. Combined suitability

Individual factor scores are integrated by the 'minimum' rule: the lowest factor score sets the overall suitability score.

$$\text{Combined score} = \text{minimum}(\text{Score}_{\text{precipitation}}, \text{Score}_{\text{slope}}, \text{Score}_{\text{soil depth}}, \text{Score}_{\text{land use/land cover}})$$

2.2.4. Scoring suitability for macro-catchment systems

The suitability criteria for the 'catchment' and 'use' areas are different: for the catchment area, strongly sloping land with soils that are shallow, rocky, or have poor infiltration capacity is preferable. On the other hand, for the use area, level or gently undulating land with deep soils and no other limitations to agricultural use is preferable. In addition, land suitable for use as a catchment, must be within a certain distance of land suitable for agricultural use that can be overcome by technical means.

Using these simple rules of thumb, the problem of identifying, in a GIS environment, land with these contrasting requirements is then reduced to a separate assessment of suitability for catchment and agricultural purposes, followed by an assessment of the constraint imposed by distance between these two different environments.

2.2.4.1. Suitability for catchment use

The following factors are considered: precipitation, slope and hydrological properties of soils.

Factor scoring: Precipitation

For macro-catchment systems precipitation suitability is different from micro-catchment systems. The basic principle is: other factors (soil, slope, land cover) being equal, the more rainfall the better the catchment is for capturing water.

As in the micro-catchment systems, suitability is approximated using the 80% minimum annual precipitation, with the precipitation score calculated by linear interpolation between only 2 inflection points A: 150 mm (0); B: 250 mm (100).

Factor scoring: Slope

Any surface can act as a catchment as long as it has some slope, very limited permeability for precipitation and no obstacles. As a first approximation, one could consider the slope as non-limiting, as long as it is not near zero. This condition can be simulated by a score function with two inflection points A: 0% (0); B: 5% (100) and intermediate values obtained by linear interpolation (Fig. 11).

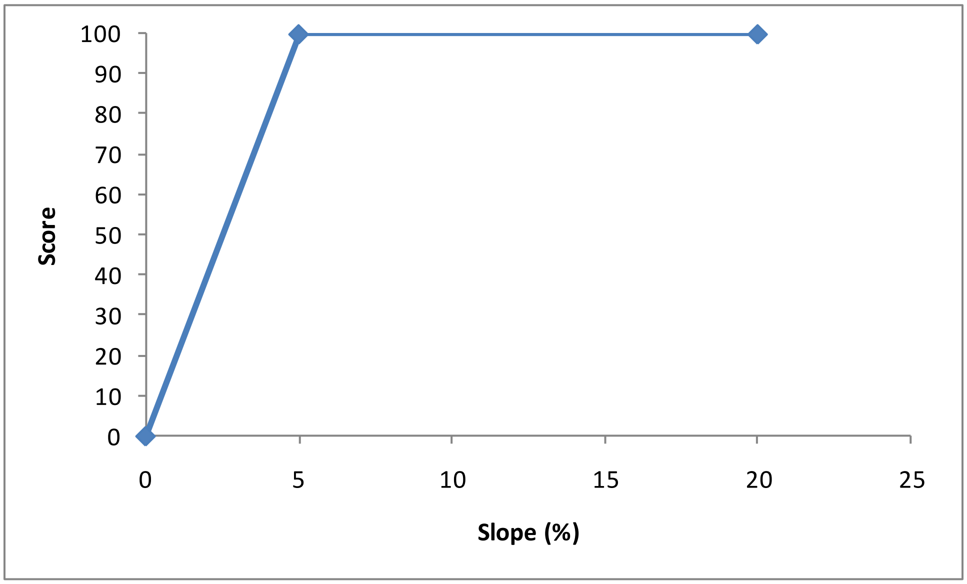


Figure 11. Catchment suitability scores for slope assuming very limited permeability

Taking into consideration soil hydrological properties
Soils have different hydrological properties and as such are a major factor in the run-off generating potential of catchments. The Soil Conservation Service of the US Department of Agriculture (1969) differentiates four major hydrological classes:

- Class A (low run-off potential): deep sandy soils;
- Class B: shallow sandy soils and medium-texture soils with above average infiltration rates;
- Class C: shallow soils of medium to heavy texture with below-average infiltration rates;
- Class D (high run-off potential): clay and shallow soils with hardpan, high groundwater table etc.

The hydrological properties of the soils were inferred from the combinations of soil depth class and land use/land cover class (Table 2).

Referring to the values [a] and [b] in Table 4, a reduction factor was applied for each soil hydrological class as follows:

if Slope ≥a then RF_i = 0

if Slope ≤b then RF_i = 100

if Slope between (a,b) then $RF_i = \frac{Slope - a_i}{b_i - a_i} * 100$

with RF= reduction factor for soil hydrological class i.

<u>**Table 4.** Reduction factors for slope in relation to hydrological classes</u>

Hydrological class	a	b
A	40	15
B	15	8
C	8	3
D	3	0

The relationship between the reduction factor and slope per soil hydrological class is shown in Figure 12.

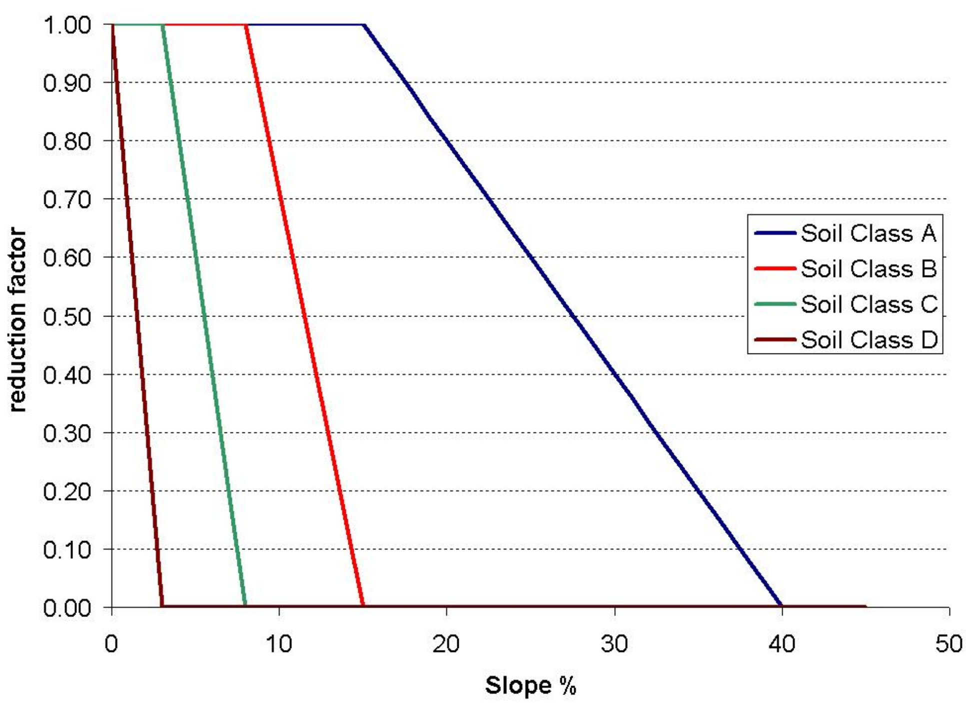


Figure 12. Reduction factors for soil hydrological classes

The interpretation of Figure 5 is that if, for example, the soil in a particular pixel belongs to hydrological class D, there will be no reduction in runoff if the slope is 3% or higher; if, on the other hand, the soil belongs to hydrological class C, a reduction factor of .5 will be applied as compared to the optimal slope range for this class (> 8%).

It is useful to use for Class D, with its very low permeability, the analogy of a plastic sheet. No water will run away from the sheet if the slope is zero. However, the slightest slope will be cause for runoff. At the other end one could visualize for Class A the same plastic sheet, but full of holes. Water poured over the sheet will drain through the holes. To generate runoff, the slope must be quite steep for the water to run off before it has the time to seep through the holes. Classes B and C have intermediate drainage properties.

The soil-corrected score for slope is then taken as the lowest value of either the slope score or the reduction factor as follows:

$$\mathbf{S_{slope,cor} = Min(\ S_{slope},\ 100\text{-}RF_i)}$$

Apart from its influence on the hydrological class (Table 2), no land use/cover category has a prohibitive effect on the suitability as a catchment. Thus, the final score for suitability as a catchment is then taken as the lowest of the precipitation score and the soil-corrected slope score:

$$\mathbf{S = Min\ (S_{slope,cor};\ S_{precip})}$$

2.2.4.2. Suitability for agricultural use

The same precipitation criterion and thresholds apply as in the micro-catchment systems.
In terms of slope suitability, 'flat to gentle' slopes are optimal for agricultural use. This condition is simulated by a score function with two inflection points A: 0% (100); B: 15% (0) and intermediate values obtained by linear interpolation (Fig. 13).

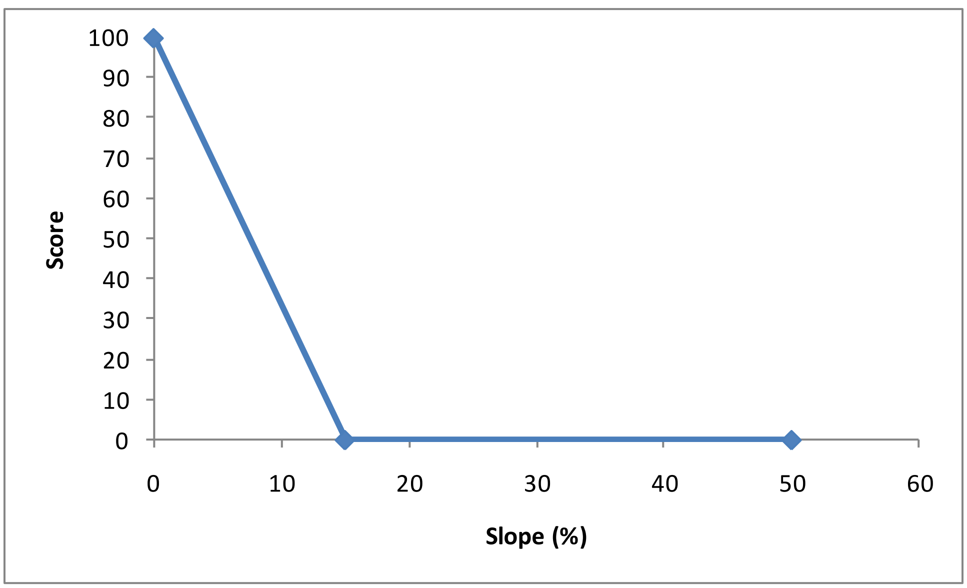


Figure 13. Slope suitability scores for agricultural use

Soil suitability is, as in the micro-catchment systems, evaluated using the soil depth classes (Table 3).

2.2.4.3. Combining suitability for catchment and agricultural uses

The combined suitability for catchment and agricultural purposes is assessed by identifying those areas where suitable catchments and agricultural areas are close together. The limiting distance between the two is taken as 1km.
This is implemented in a GIS environment through the following steps:

- Step 1: suitability scores for catchment use are reclassified into 5 groups (score: 0, >0 – 20, >20 – 40, >40 – 60, > 60)
- Step 2: to avoid over-fragmented patterns, a smoothing function is applied
- Step 3: the reclassified smoothened suitability score rasters are converted to vector layers.
- Steps 1-3 are repeated for the suitability scores for agricultural use
- Step 4: 1km buffer zones are created around the vector features that represent the highest score class (>60)
- Step 5: The geometric intersection is calculated of the buffer zones for both the high-score catchment and agricultural use classes, as well as with the watershed boundary.

The output of the intersection procedure is the area suitable for catchment and agricultural use within 1km proximity of each other.

3. RESULTS

3.1. GIS analysis

This analysis is based on the calculation of areas of the classes distinguished in the base maps and suitability maps. Areas were calculated in hectare, using an equal-area projection in the GIS software, and converted into percent of Zoba NRS.
All maps resulting from the GIS analysis are provided in Annex 2.

3.1.1. Base maps

Map 4 ('Elevation') and Table 5a indicate very large differences in elevation in Zoba NRS. Although not directly affecting the potential for water harvesting, these differences in elevation and, consequently, temperature, may affect the physical suitability and comparative advantage for different crops.

Table 5a. Areas in different elevation classes (meter)

Class (m)	Area (%)
<0	4.18
0-200	34.81
200-400	13.46
400-600	6.73
600-800	7.23
800-1000	7.20
1000-1200	6.68
1200-1400	5.84
1400-1600	4.89
1600-1800	3.61
1800-2000	2.29
2000-2200	1.33
2200-2400	1.06
2400-2600	0.65
2600-2820	0.04

Table 5b. Areas in different slope classes (%)

Class (%)	Area (%)
0-2	21.38
2-5	19.58
5-8	8.57
8-15	12.64
15-30	17.72
>30	20.11

Map 5 ('Slopes') and Table 5b show a wide range in slopes, ranging from very flat (0-2%) to very steep (>30%). The well balanced spread of slope classes indicates that both water-shedding and water-receiving areas exist in the Zoba.

Map 6 ('Compound Topographic Index') basically shows only two classes: areas of which the curvature is such as to promote shedding runoff water, and those that tend to promote concentration of runoff. The first CTI class (value 9-12) covers about 42% of the Zoba, the second CTI class (12-19) covers about 55% of the Zoba. A third CTI class (>19) covers less than 4% of the Zoba, and is associated with river beds and the beginning of the Danakil depression..

Map 7 ('Mean annual precipitation') and Table 6 indicate that the rainfall distribution in Zoba NRS is spatially very uneven, from less than 150 mm in the lowland plains to more than 800 mm in the highlands.

Table 6. Areas in different mean annual precipitation classes (mm)

Class (mm)	Area (%)
120-150	5.59
150-200	13.11
200-250	17.64
250-300	12.73
300-400	18.83
400-500	10.36
500-600	12.47
600-700	6.92
700-850	2.34

About two thirds (68%) of the Zoba receives a mean annual precipitation of less than 400 mm. In Zoba Debub this was only the case in 2% of the area. It is therefore obvious that from the perspective of the available water resources the potential for water harvesting is much less in Zoba NRS than in Zoba Debub. This lower potential for water harvesting in Zoba NRS is also indicated by Map 8 ('Reliable/Effective Annual Precipitation) and by Table 7.

Table 7. Areas in different reliable/effective annual precipitation classes (mm)

Class (mm)	Area (%)
0-50	47.84
50-100	23.11
100-150	14.20
150-200	3.43
200-250	2.50
250-300	7.19
300-350	1.74

Whereas in about 80% of Zoba Debub the reliable annual precipitation is in the 250-300 mm range and the remainder in the 300-350 mm range, this is only the case in respectively about 7% of Zoba NRS and less than 2% for the 300-350 mm range .

In line with the large differences in elevation (Table 5a), annual potential evapo-transpiration (PET) rates vary considerably in Zoba NRS (Map 9, 'Annual Potential Evapo-transpiration' and Table 8). The range in the annual PET in 85% of the Zoba is 600 mm. Compared to Zoba Debub, higher PET levels occur in a larger proportion of the Zoba: whereas in Zoba Debub 85% of the area has an estimated annual PET of less than 1800 mm, in Zoba NRS this is only the case in 49% of the area.

Table 8. Areas in different PET classes (mm)

Class (mm)	Area (%)
1400-1500	5.59
1500-1600	13.11
1600-1700	17.64
1700-1800	12.73
1800-1900	18.83
1900-2000	10.36
2000-2100	12.47
2100-2200	6.92
2200-2350	2.34

Thus from the perspective of water resource availability, the overall potential for water harvesting in Zoba NRS is much lower as compared to Zoba Debub due to two main reasons: lower reliable precipitation and higher potential evapo-transpiration rates.

3.1.2. Suitability for water harvesting in Zoba Northern Red Sea

Suitability by system in Zoba NRS is summarized in Table 9 (hectare) and Table 10 (% of the Zoba). Areas are provided for 10 suitability score classes, with increments of 10 points, as well as the totals for the suitability score classes from 60 to 100, with 60 considered the minimum value for 'suitable'.

The spatial distribution of suitability for all assessed micro-catchment systems is shown in Maps 11-23. Map 24 is a synthesis map showing suitable areas for different combinations of micro-catchment systems.

Table 9. Areas (hectare) in different suitability score classes by system in Zoba NRS

Suitability	Micro-catchment systems													Macro-catchment systems		
scores	S11	S12	S13	S21	S22	S23	S31	S33	S41	S43	S51	S52	S6	Tree	Field	Catch.
0-10	2,285,292	2,285,292	3,198,628	2,116,671	2,116,671	3,216,548	2,116,671	3,216,548	2,116,671	3,216,548	2,116,671	3,216,548	3,256,244	2,303,347	2,303,247	2,918,265
10-20	202,712	202,712	45,585	263,919	263,919	78,555	263,919	78,555	263,919	78,555	263,919	78,555	9,342	221,953	221,353	30,499
20-30	304,540	304,540	37,936	258,652	258,652	26,453	258,652	26,453	258,652	26,453	258,652	26,453	7,643	324,408	324,408	26,336
30-40	265,919	265,919	92,090	211,375	211,375	49,400	211,375	49,400	211,375	49,400	211,375	49,400	7,200	502,681	293,795	18,829
40-50	116,787	287,159	2,997	158,847	469,662	2,310	469,662	2,310	469,662	2,310	469,662	2,310	5,883	20,446	217,966	18,929
50-60	55,163	20,950	9,678	101,907	37,490	13,826	37,490	13,826	37,490	13,826	37,490	13,826	65,690	9,657	15,491	17,793
60-70	69,887	14,283	147	121,075	20,010	83	20,010	83	20,010	83	20,010	83	5,093	2,971	8,427	17,659
70-80	39,497	6,242	36	65,166	9,450	55	9,450	55	9,450	55	9,450	55	30,469	2,033	2,033	17,569
80-90	15,352	99	99	34,414	101	101	101	101	101	101	101	101	11	136	136	18,188
90-100	33,775	1,728	1,728	56,898	1,593	1,593	1,593	1,593	1,593	1,593	1,593	1,593	1,348	1,293	1,293	304,856
Score >60	158,511	22,352	2,011	277,553	31,154	1,831	31,154	1,831	31,154	1,831	31,154	1,831	36,922	6,432	11,889	358,272

Table 10. Areas (percent) in different suitability score classes by system in Zoba NRS

Suitability	Micro-catchment systems													Macro-catchment systems		
scores	S11	S12	S13	S21	S22	S23	S31	S33	S41	S43	S51	S52	S6	Tree	Field	Catch.
0-10	67.4%	67.4%	94.4%	62.5%	62.5%	94.9%	62.5%	94.9%	62.5%	94.9%	62.5%	94.9%	96.1%	68.0%	68.0%	86.1%
10-20	6.0%	6.0%	1.3%	7.8%	7.8%	2.3%	7.8%	2.3%	7.8%	2.3%	7.8%	2.3%	0.3%	6.5%	6.5%	0.9%
20-30	9.0%	9.0%	1.1%	7.6%	7.6%	0.8%	7.6%	0.8%	7.6%	0.8%	7.6%	0.8%	0.2%	9.6%	9.6%	0.8%
30-40	7.8%	7.8%	2.7%	6.2%	6.2%	1.5%	6.2%	1.5%	6.2%	1.5%	6.2%	1.5%	0.2%	14.8%	8.7%	0.6%
40-50	3.4%	8.5%	0.1%	4.7%	13.9%	0.1%	13.9%	0.1%	13.9%	0.1%	13.9%	0.1%	0.2%	0.6%	6.4%	0.6%
50-60	1.6%	0.6%	0.3%	3.0%	1.1%	0.4%	1.1%	0.4%	1.1%	0.4%	1.1%	0.4%	1.9%	0.3%	0.5%	0.5%
60-70	2.1%	0.4%	0.0%	3.6%	0.6%	0.0%	0.6%	0.0%	0.6%	0.0%	0.6%	0.0%	0.2%	0.1%	0.2%	0.5%
70-80	1.2%	0.2%	0.0%	1.9%	0.3%	0.0%	0.3%	0.0%	0.3%	0.0%	0.3%	0.0%	0.9%	0.1%	0.1%	0.5%
80-90	0.5%	0.0%	0.0%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%
90-100	1.0%	0.1%	0.1%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	9.0%
Score >60	4.7%	0.7%	0.1%	8.2%	0.9%	0.1%	0.9%	0.1%	0.9%	0.1%	0.9%	0.1%	1.1%	0.2%	0.4%	10.6%

Notes:

S11, S12, S13, S21, S22, S23, S31, S33, S41, S43, S51, S52, S6: symbols for micro-catchment systems explained in section 2.2.1. , step 2.

Catch.: suitability for catchment use; Tree: suitability for use as target area (tree crops); Field: suitability for use as target area (field crops)

In grey: areas with suitability score above 60.

These tables indicate that overall the potential for most water harvesting systems in Zoba Northern Red Sea is considerable. One exception are the micro-catchment systems with tree crops. For these systems (S13, S23, S33, S43, S52) the potential is considered low due to soil depth limitations. However, it has to be reiterated (see also section 2.3.2.4.) that knowledge of soil depth in Zoba NRS is currently inferred from land use/land cover, not from any direct soil observations or even remote sensing. The accurate positioning of water harvesting interventions therefore requires a second stage of studies in which soil survey will have to play a major role, in order to identify at greater detail important properties such as soil depth, stoniness, texture, salinity.

Map 24 ('Combined suitability for micro-catchment water harvesting systems'} and Table 11 show the location and areas that are considered 'suitable' (suitability score >60) for different combinations of micro-catchment water harvesting systems. The potential for micro-catchment water harvesting systems in Zoba NRS is considerably lower than in Zoba Debub in both absolute and relative terms. Whereas in Zoba Debub about 70% (673,435 ha) was assessed as being suitable for at least one micro-catchment system (De Pauw and Oweis, 2011), in Zoba NRS this is only the case in about 10% of the Zoba (335,742ha), despite the fact that Zoba NRS is about 3.5 times larger than Zoba Debub. As hinted at already in section XXX, the main reason is the difference in the overall waterbalance between the two Zobas: less precipitation and higher potential evapo-transpiration rates in Zoba NRS than in Zoba Debub.

Table 11. Areas suitable for various combinations of micro-catchment systems in Zoba NRS

Class	% of Zoba	Hectare
Unsuitable for any system	90.09	3,053,182
Suitable for S11	0.75	25,265
Suitable for S11, S12	0.12	3,949
Suitable for S11, S12, S13	0.01	315
Suitable for S21	4.00	135,525
Suitable for S11, S21	3.27	110,855
Suitable for S21, S22, S31, S41, S51	0.18	5,984
Suitable for S11, S12, S21, S22, S31, S41, S51	0.48	16,391
Suitable for all except S11, S12, S13, S6	0.00	71
Suitable for all except S6	0.01	474
Suitable for S6	0.85	28,697
Suitable for S21, S22, S31, S41, S51, S6	0.20	6,945
Suitable for all except S11, S12, S13	0.00	59
Suitable for all micro-systems	0.04	1,213

Table 14 in Annex 1 provides a breakdown for each watershed in Zoba NRS of areas suitable for the various combinations of micro-catchment systems.

3.2. Selection of watersheds

3.2.1. Overview

Given the inability to undertake field activities in Zoba Northern Red Sea, it was not possible to adopt a similar approach to selection as implemented for Zoba Debub, which relies on on-site participatory expert evaluation of potential watersheds and meetings with farmers and government officials in order to identify plausible interventions. Therefore it is only possible at this stage to identify a number of watersheds which, on the basis of the simple modeling of potential undertaken in this desk study, appear to indicate a reasonable potential that deserves to be explored further by through the appropriate field activities and consultations with farmers, government officials and local experts.

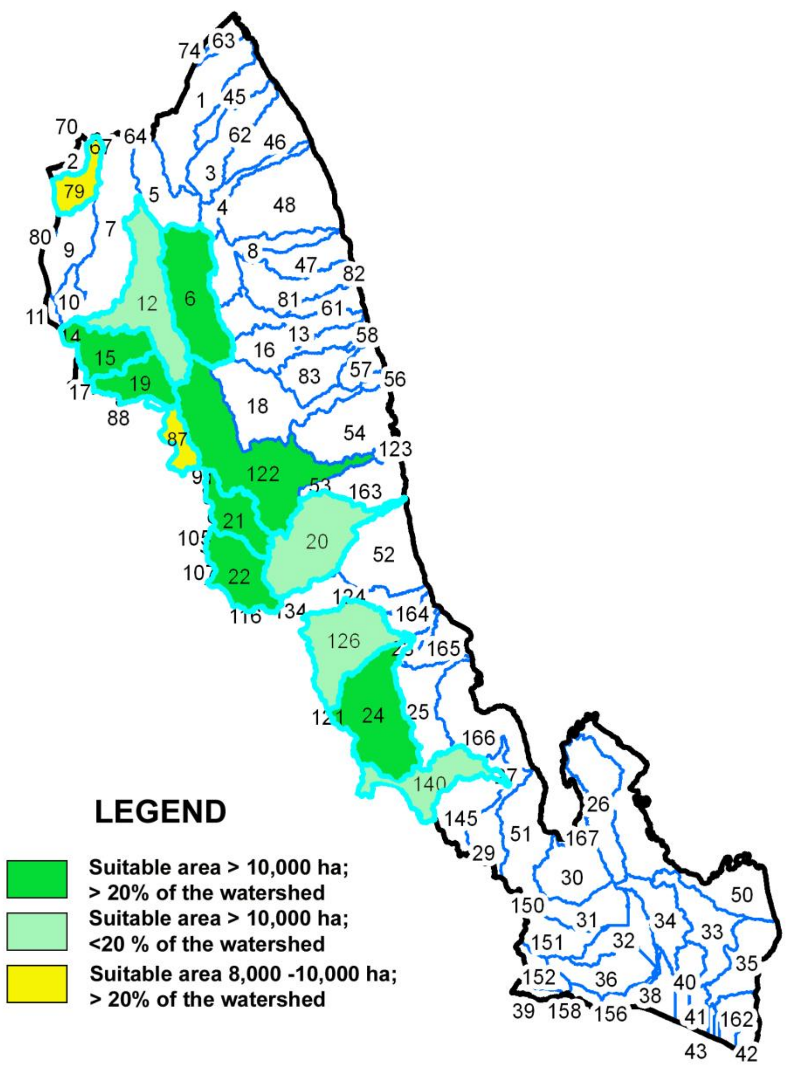


Figure 14. Priority watersheds for micro-catchment water harvesting systems based on absolute and relative suitable area

For micro-catchment systems the following priority classes were distinguished for further assessments of potential and interventions:

- 1st priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system occupying more than 20% of the watershed (dark green colored in Fig. 14: watersheds 6, 15, 19, 21, 22, 24, 122)
- 2nd priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system but occupying less than 20% of the watershed (light green coloured in Fig. 14: watersheds 12, 20, 126, 140);
- 3rd priority: watersheds 8,000-10,000 ha of land suitable for one or another micro-catchment water harvesting system and occupying more than 20% of the watershed (yellow-colored in Fig. 14: watersheds 79, 87).

The total suitable area covered by these watersheds (252,814 ha) is about 75% of the total suitable area for micro-catchment systems in Zoba NRS.
A breakdown of suitable and non-suitable areas for these priority watersheds is provided in Table 12.

Table 12. Priority watersheds for micro-catchment systems: estimation of suitable and non-suitable areas

Watershed	Area	Area suitable	Area unsuitable	% suitable
6	98,550	25,164	73,387	26
12	102,872	14,909	87,964	14
15	51,460	12,745	38,715	25
19	40,745	10,461	30,284	26
20	103,412	14,692	88,720	14
21	42,260	25,285	16,974	60
22	57,144	26,580	30,564	47
24	111,856	31,909	79,947	29
79	29,652	9,895	19,757	33
87	23,298	8,452	14,845	36
122	176,329	47,737	128,591	27
126	87,774	14,822	72,952	17
140	57,159	10,163	46,995	18

With very few exceptions, these watersheds are also the ones where suitable conditions may exist for macro-catchment systems. However, the suitable areas are much smaller: about 6,400 ha for macro-catchments planted with tree crops, and nearly 12,000 ha for catchments planted with field crops (Table 9). Moreover the areas suitable for these systems are more scattered than is the case for the micro-catchment systems. This is not surprising given the fact that three conditions have to be met: (i) that there is a suitable catchment generating enough runoff, (ii) that there is a suitable water-receiving area for the runoff, (iii) that the runoff-generating and runoff-receiving areas are sufficiently close together (< 1km). The locations of areas with potential for macro-catchment systems are shown in Figures 15-20.

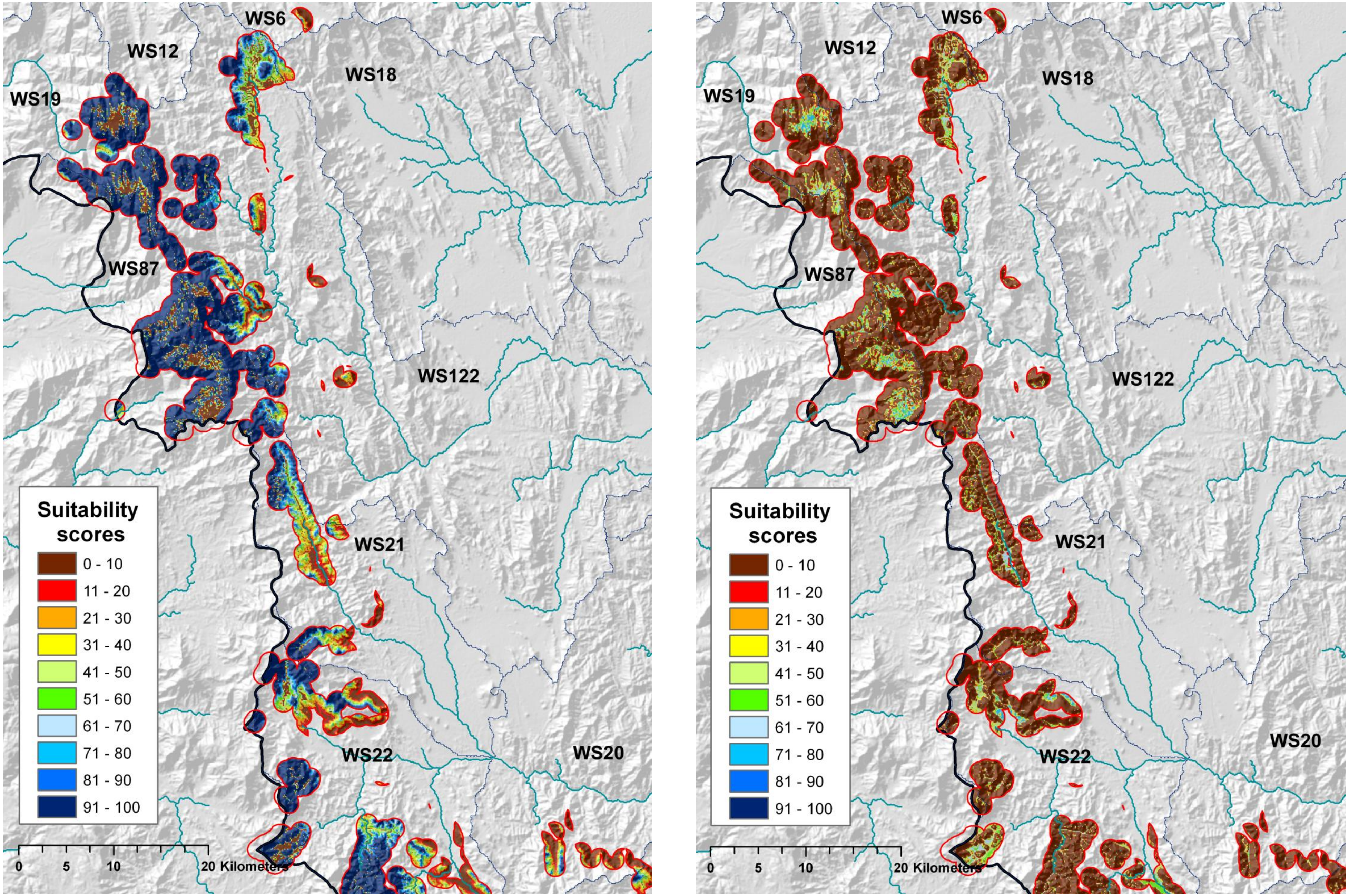


Figure 15. Northern areas with high suitability for macro-catchment water harvesting systems for field crops: suitability to serve as catchment (left) and for field crops (right)

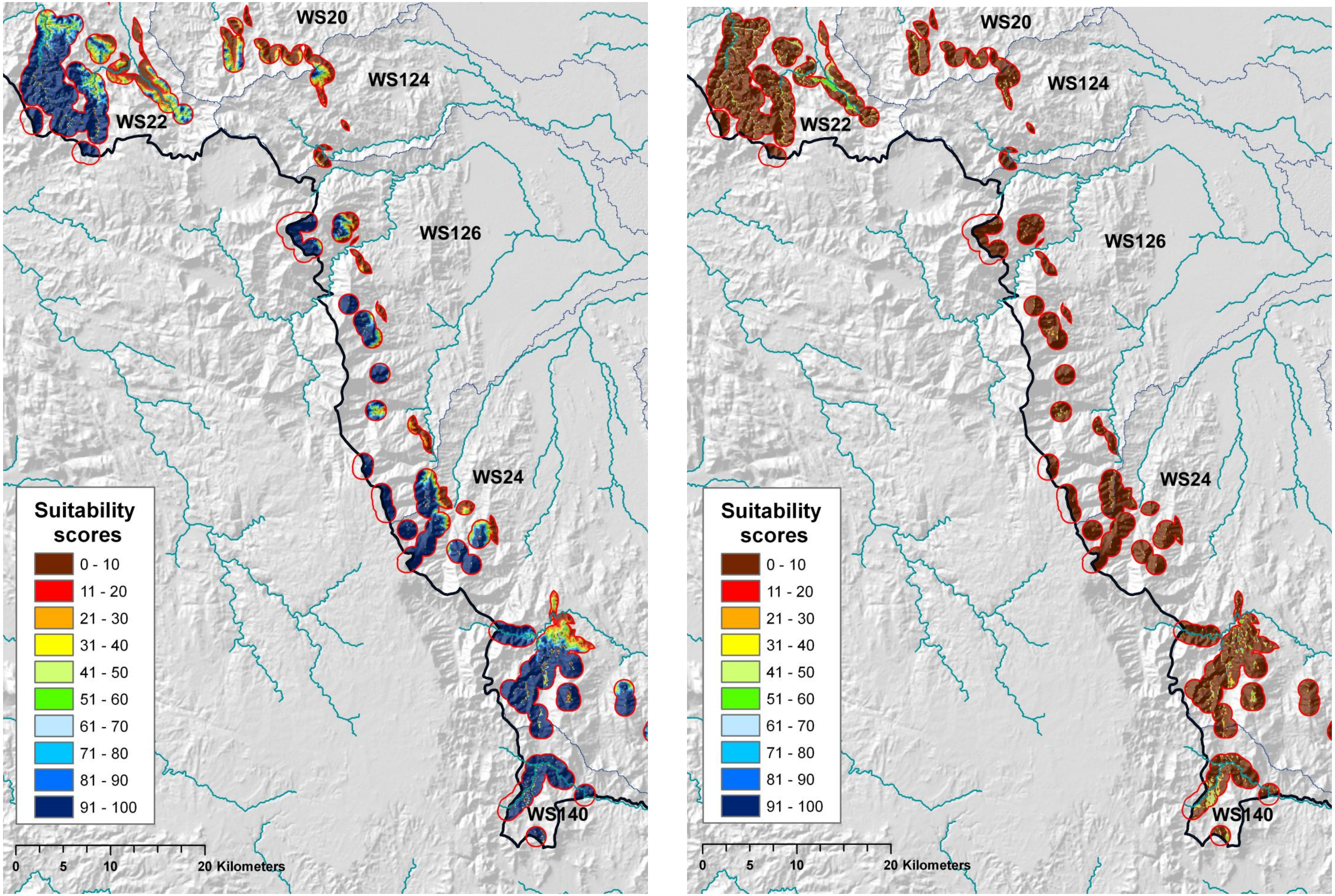


Figure 16. Central areas with high suitability for macro-catchment water harvesting systems for field crops: suitability to serve as catchment (left) and for field crops (right)

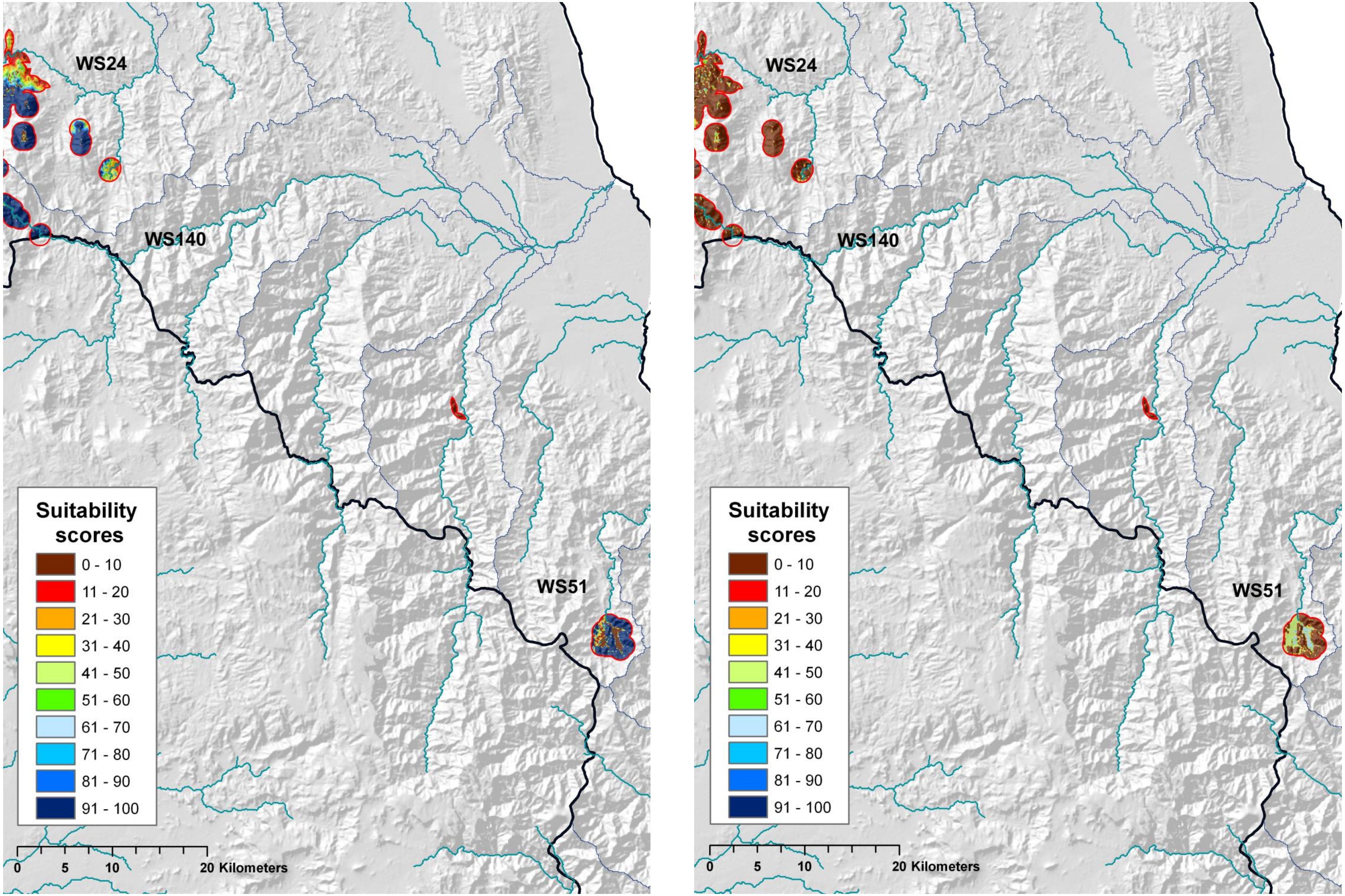


Figure 17. Southern areas with high suitability for macro-catchment water harvesting systems for field crops: suitability to serve as catchment (left) and for field crops (right)

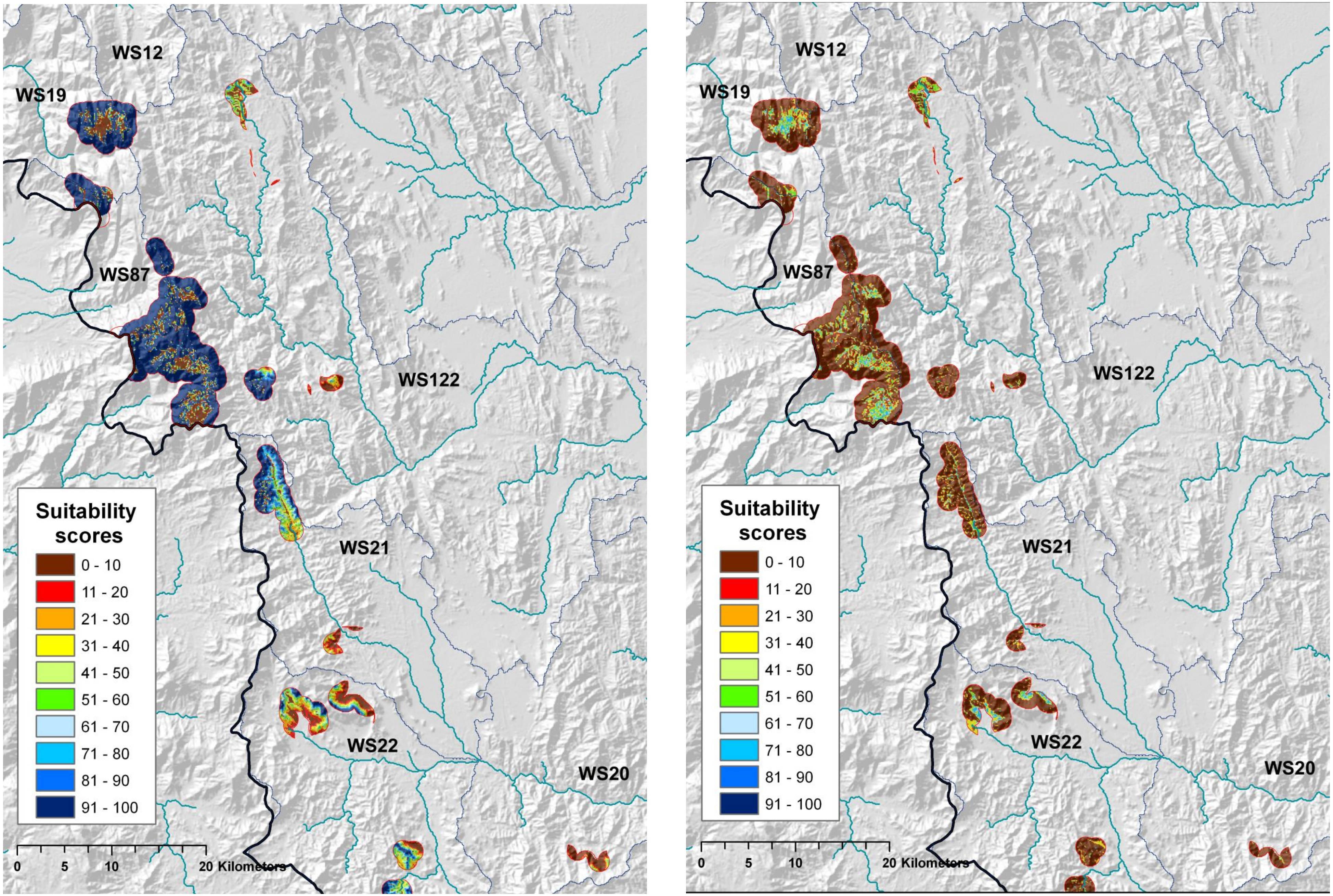


Figure 18. Northern areas with potential for macro-catchment water harvesting systems for tree crops: suitability to serve as catchment (left) and for tree crops (right)

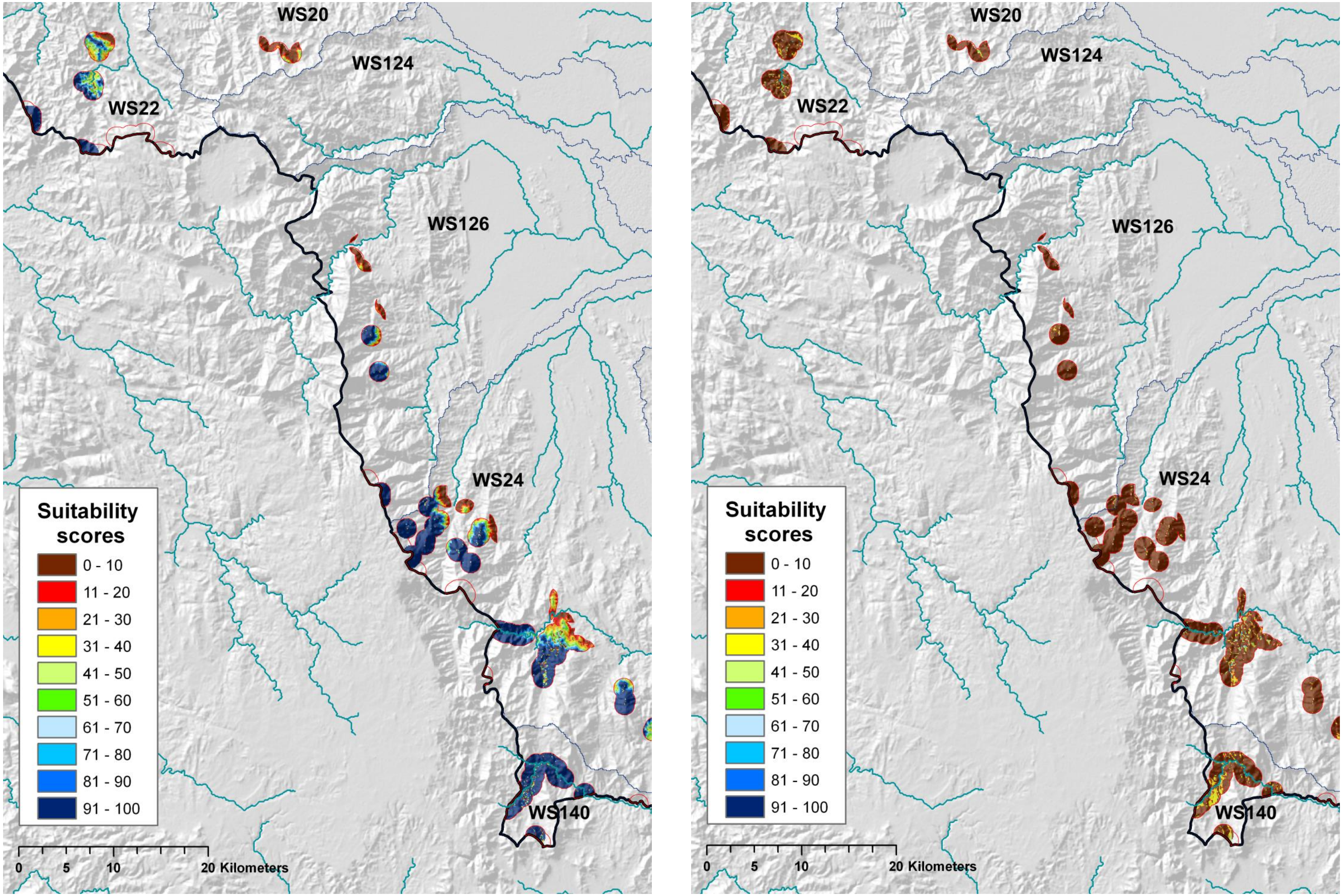
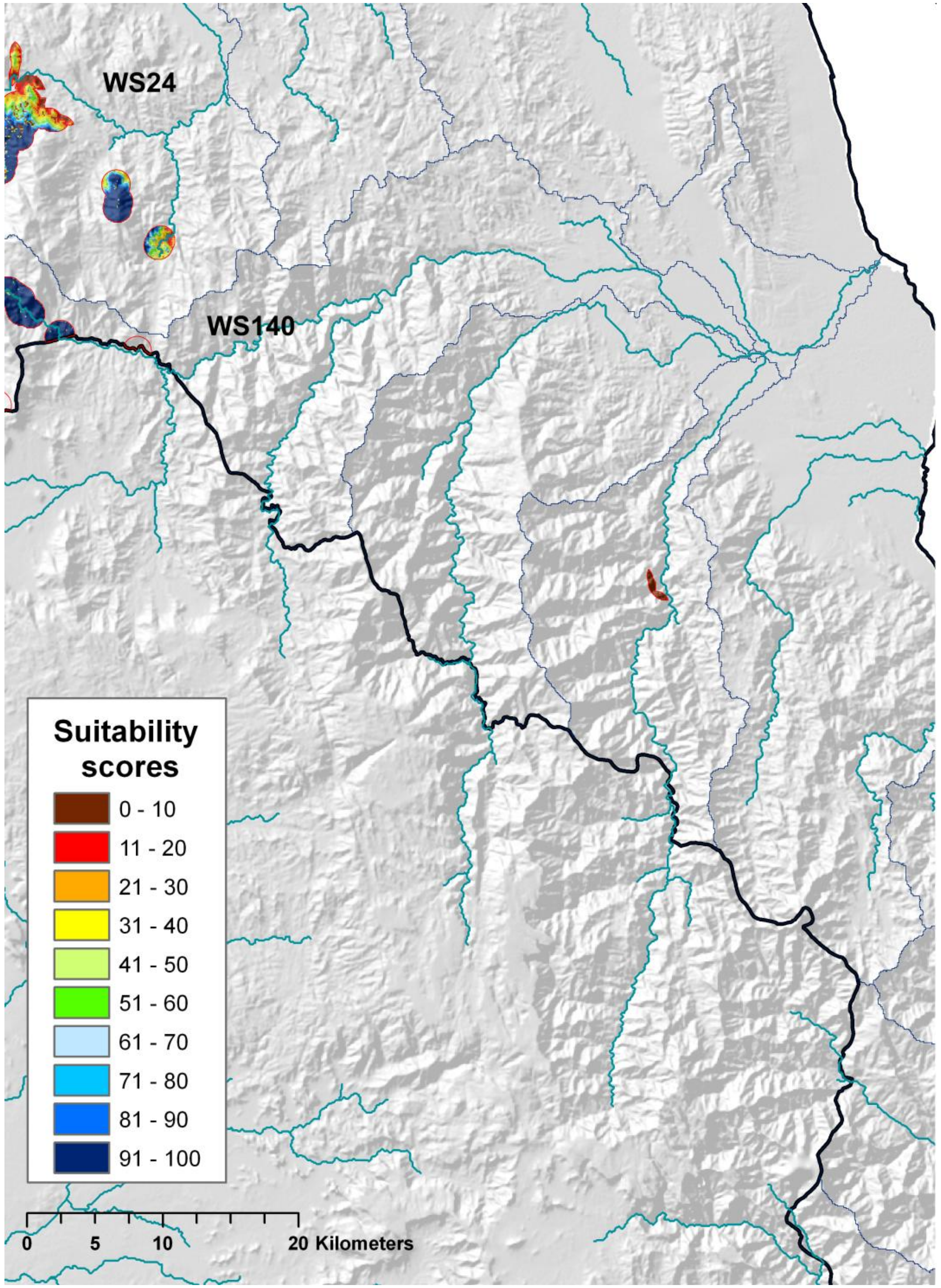


Figure 19. Central areas with potential for macro-catchment water harvesting systems for tree crops: suitability to serve as catchment (left) and for tree crops (right)



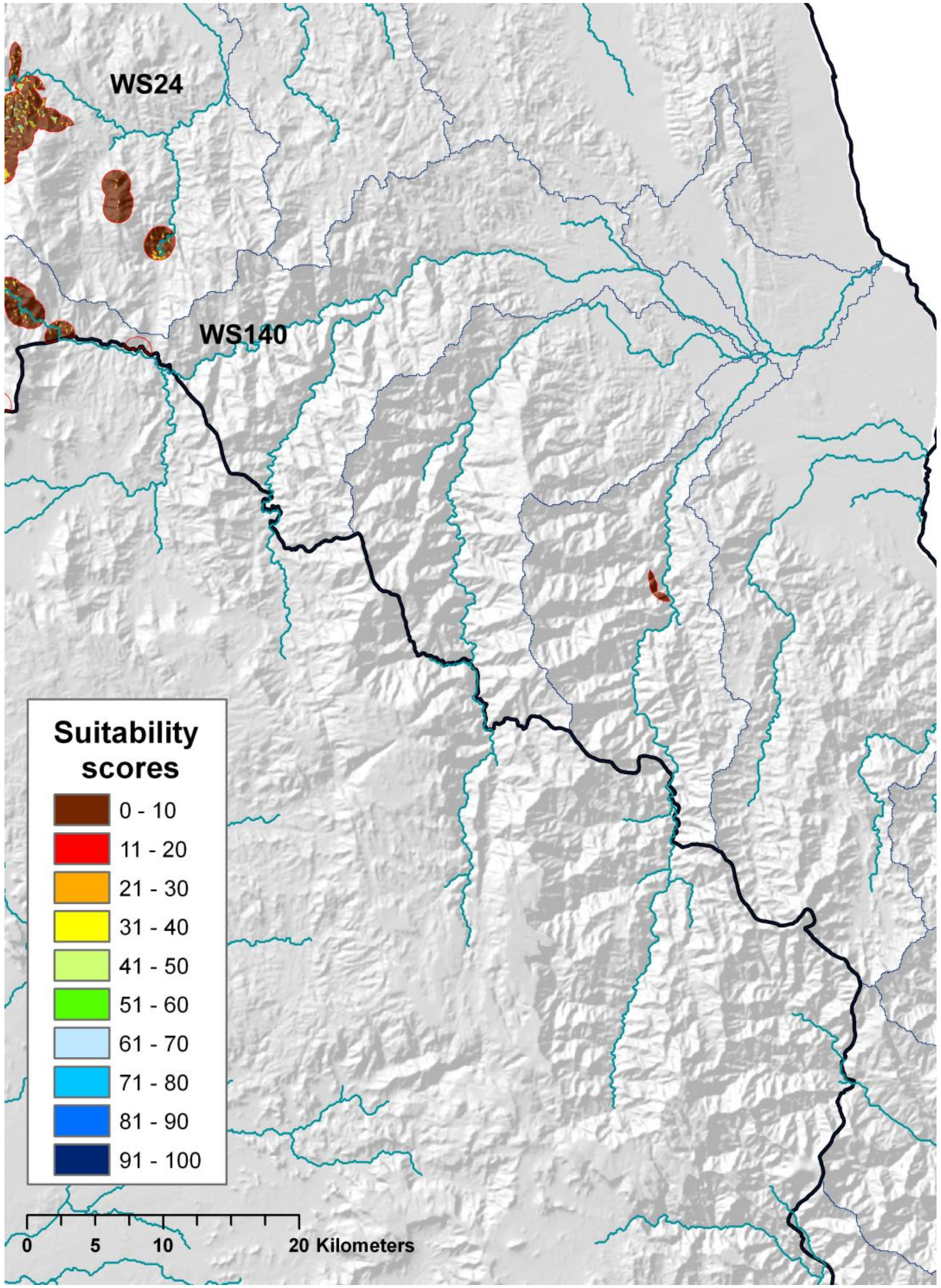


Figure 20. Southern areas with potential for macro-catchment water harvesting systems for tree crops: suitability to serve as catchment (left) and for tree crops (right)

Table 13. Land use/land cover and reliable/effective precipitation in potential watersheds in Zoba Northern Red Sea

LULC_class	Watershed No.												
	6	**12**	**15**	**19**	**20**	**21**	**22**	**24**	**79**	**87**	**122**	**126**	**140**
Sand	0	0	0	0	1	0	0	0	0	0	0	1	0
Sparse natural vegetation	50	66	63	35	61	32	38	24	58	22	29	36	54
Closed Herbacous Vegetation (Seasonally Flooded)	0	0	0	0	0	0	0	0	2	0	0	0	0
Open shrubs or trees	41	30	29	38	15	24	26	52	30	19	23	28	33
Bare soil	0	0	4	0	11	0	0	0	0	0	8	3	3
Bare rocks and river banks	1	0	0	0	0	1	0	0	1	1	0	1	1
Closed to Open Herbaceous Vegetation	4	0	0	0	0	0	0	0	0	0	0	0	0
Closed shrubs or trees	0	0	0	5	0	0	0	6	2	0	1	10	5
Scattered fields among natural vegetation	2	2	1	16	7	40	29	9	4	29	31	13	2
Closed woody vegetation thickets	2	1	3	1	0	0	2	2	2	8	2	0	0
Rainfed crops	0	0	0	4	0	4	5	5	0	20	4	2	0
Irrigated crops	0	0	0	0	3	0	0	1	0	0	1	5	2
Effective Precipitation class	**Watershed no.**												
	6	**12**	**15**	**19**	**20**	**21**	**22**	**24**	**79**	**87**	**122**	**126**	**140**
0 – 50 mm	6	0	0	0	36	0	0	4	2	0	16	19	0
50-100 mm	36	49	35	4	25	0	0	36	22	0	24	36	24
100-150 mm	49	34	58	49	29	54	22	27	17	10	29	22	19
150-200 mm	6	6	4	12	5	16	20	7	6	9	10	4	6
200-250 mm	2	4	1	7	2	14	18	5	11	11	6	3	6
250-300 mm	2	7	2	23	2	16	39	18	42	50	14	13	31
300-350 mm	0	0	0	5	0	0	1	4	0	20	2	3	14

Note: Magenta color indicates that a class occupies more than 15% of the watershed

3.2.2. Characteristics of priority watersheds for micro-catchment and macro-catchment water harvesting systems

The characterization of these priority watersheds is a very important step requiring field activities and participatory research. At this stage the desk study can only provide some useful indicators for the selection process, of which land use/land cover and effective precipitation are currently the most reliable characteristics. They are summarized in Table 13.

The land use/land cover map[5] indicates that all watersheds are dominated by sparse natural vegetation, at best by open bush or tree country, a fact indicative of the general aridity which prevails in most of the Zoba. Very little irrigated agriculture currently exists in any of the potential watersheds (maximum 5% in watershed 126). The presence of rainfed crops is substantial only in watershed 87 (20%), which also is the one with the highest reliable precipitation in the Zoba (70% in the range 250-350 mm). In other watersheds agriculture does occur, but only as scattered fields in between the natural vegetation (especially in watersheds 21, 22, 87, 122), probably in sites with favorable water-receiving characteristics.

In the following map set (Fig. 21-34) the distribution of these key variables is indicated for each potential watershed.

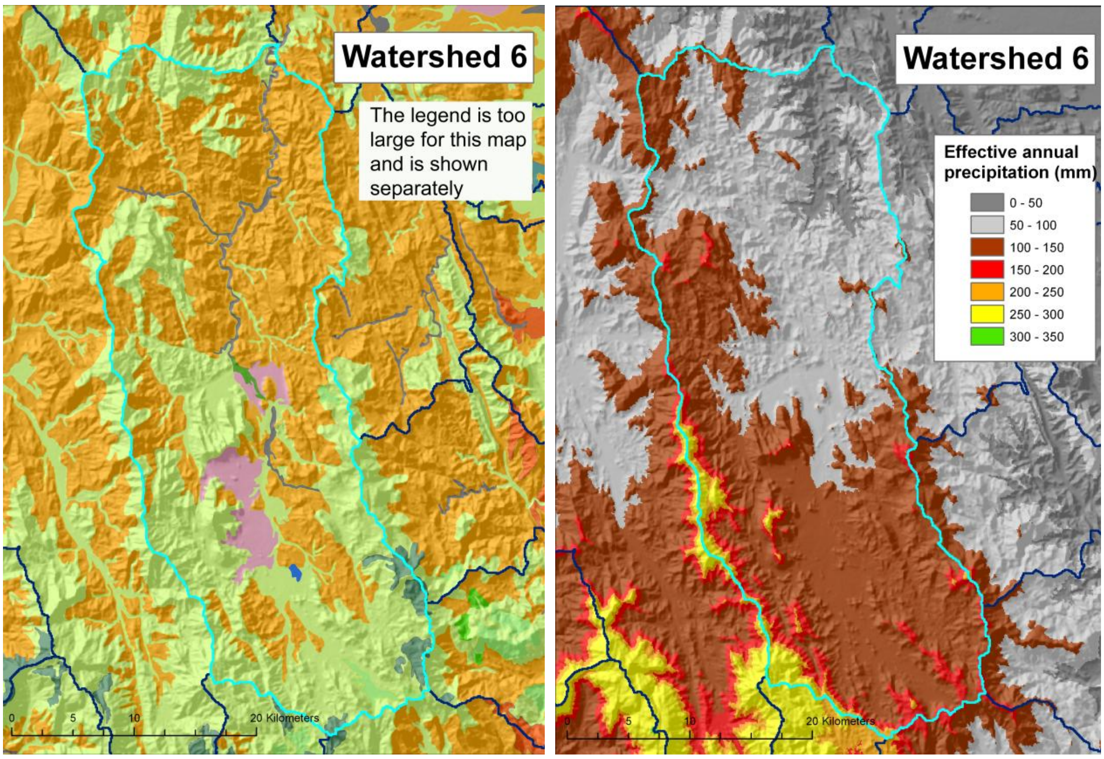


Figure 21. Land use/land cover (left) and reliable annual precipitation (right) in watershed 6

[5] Source: Eritrea Multi-purpose Land Cover Database (FAO/Africover, 2002)

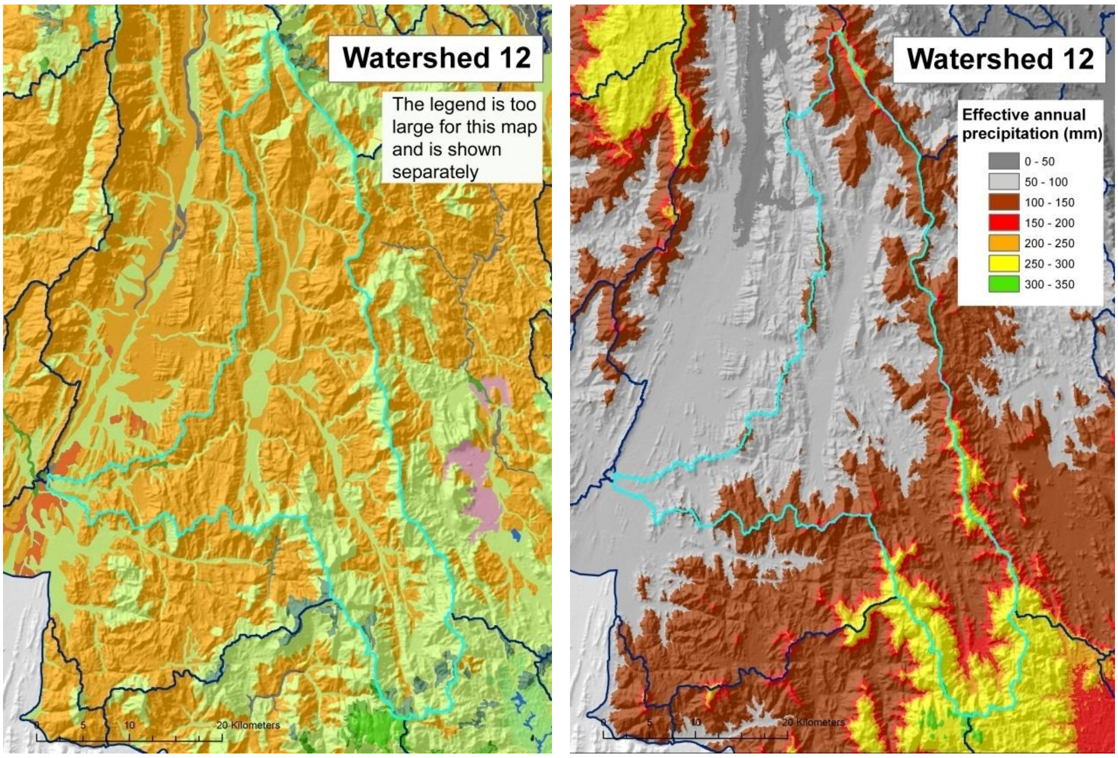


Figure 22. Land use/land cover (left) and reliable annual precipitation (right) in watershed 12

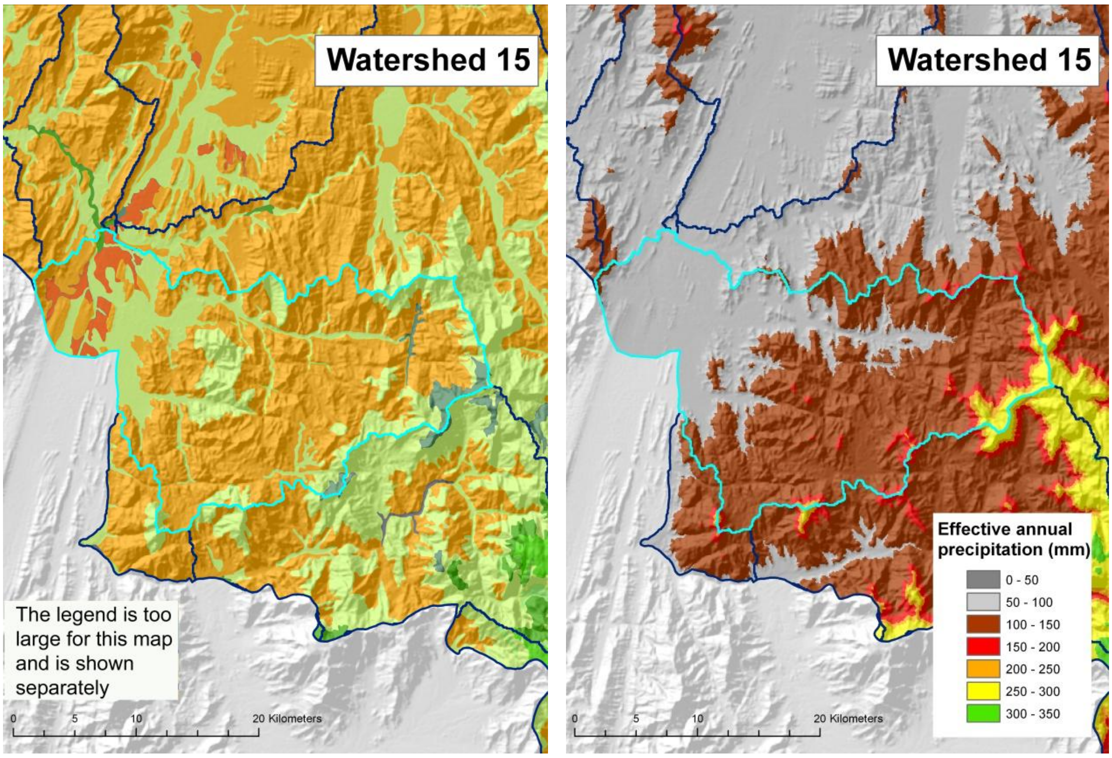


Figure 23. Land use/land cover (left) and reliable annual precipitation (right) in watershed 15

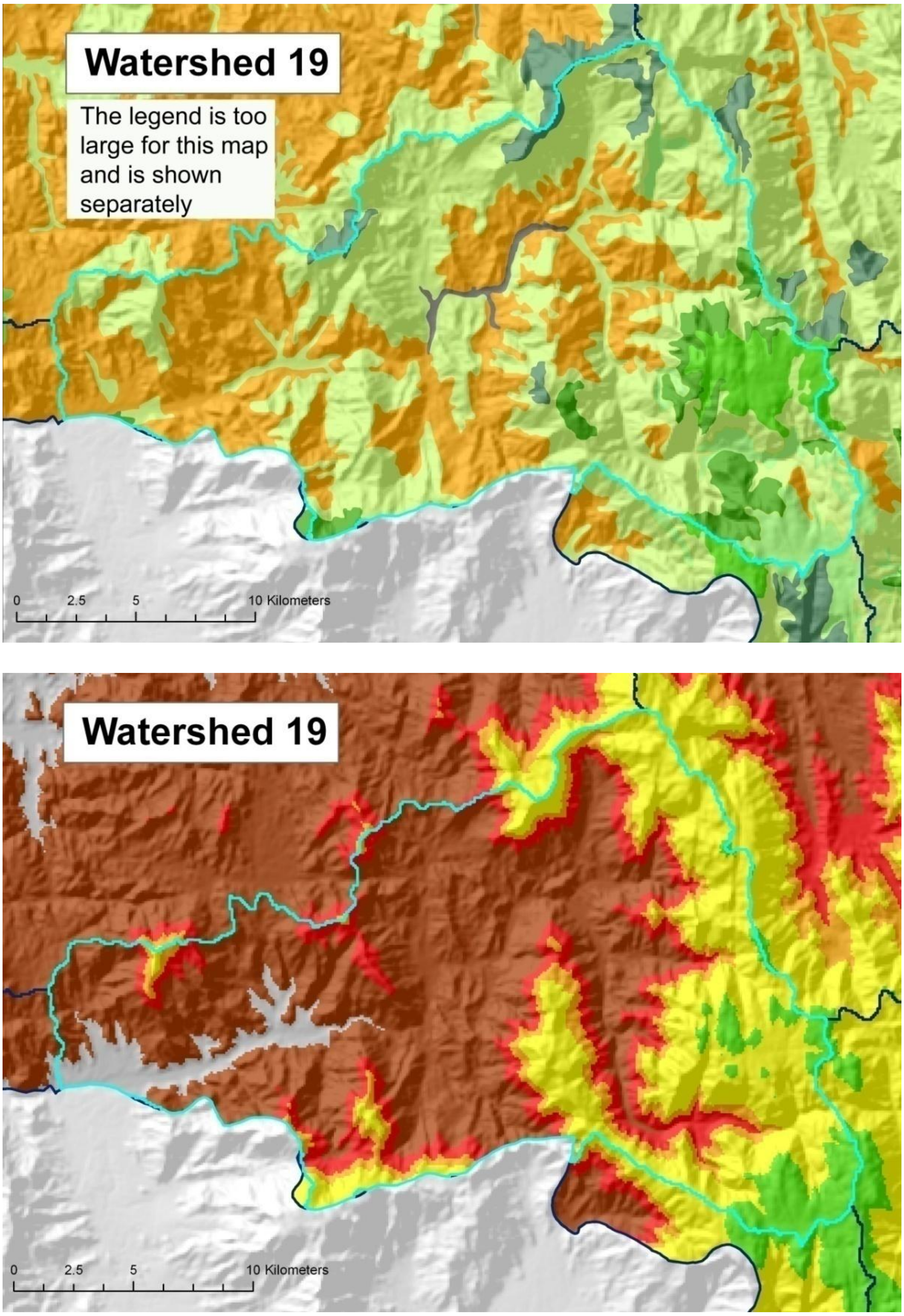
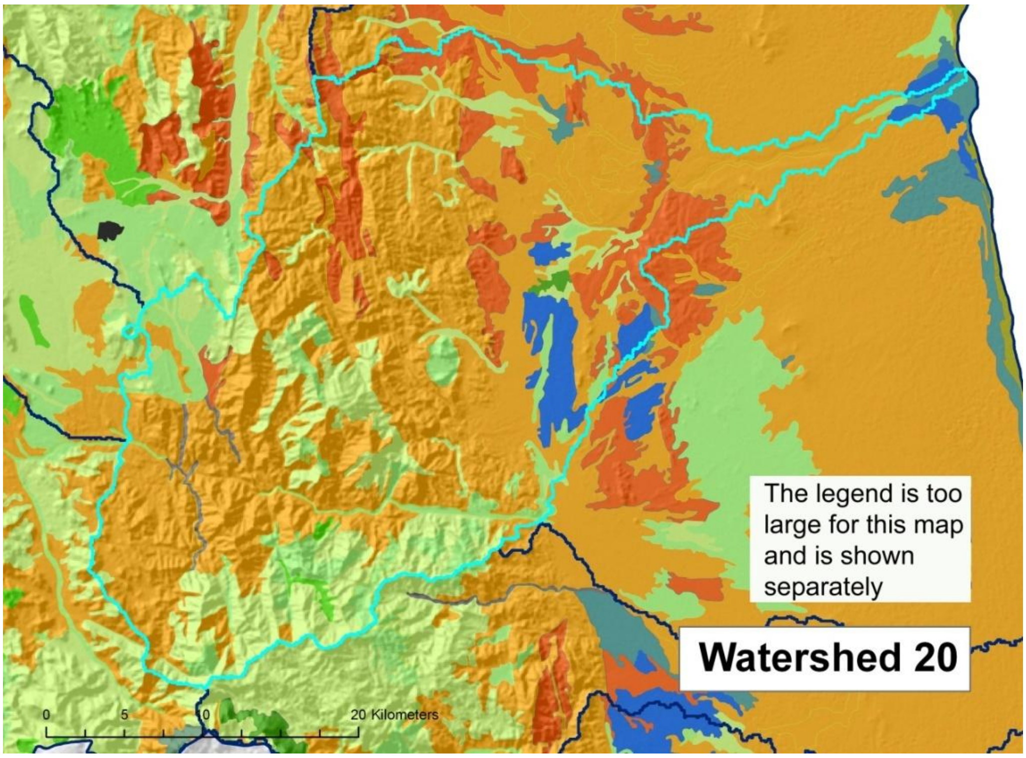


Figure 24. Land use/land cover (top) and reliable annual precipitation (bottom) in watershed 19



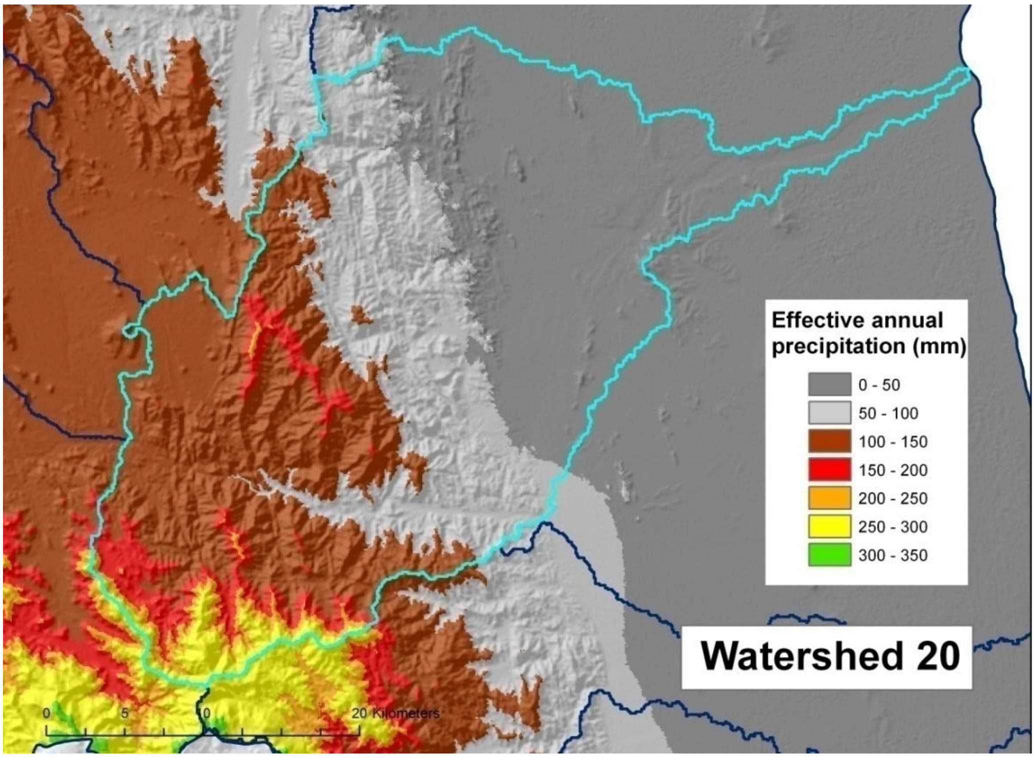
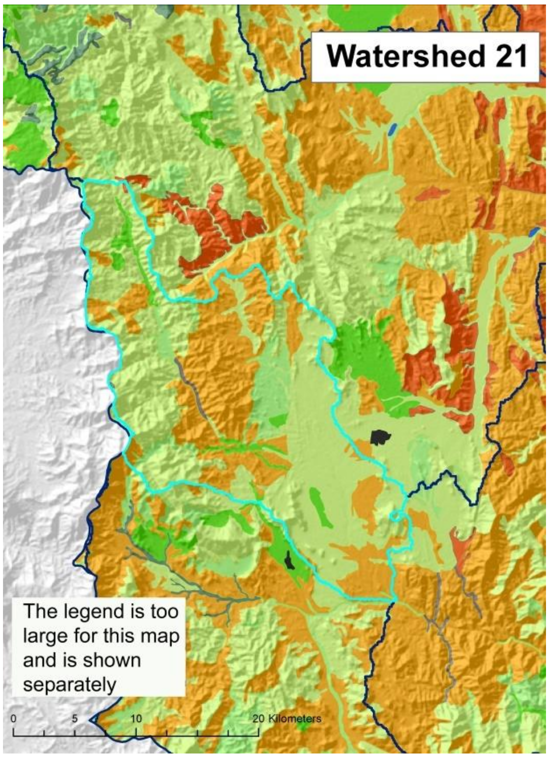


Figure 25. Land use/land cover (top) and reliable annual precipitation (bottom) in watershed 20



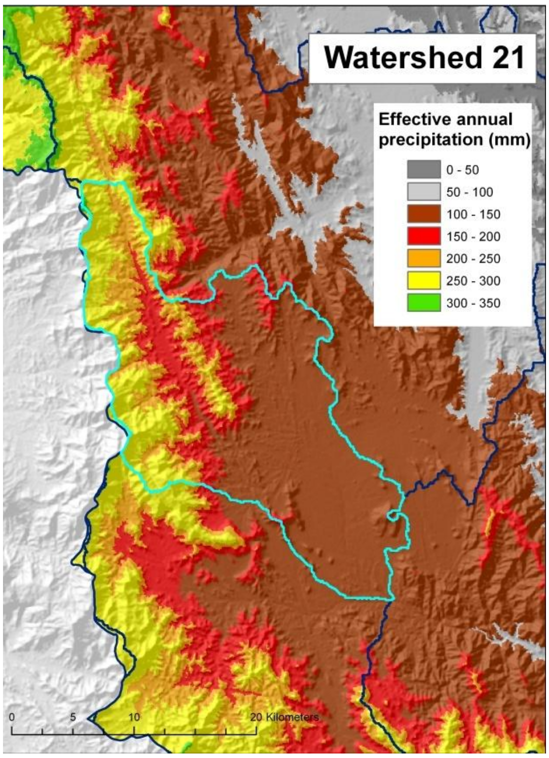
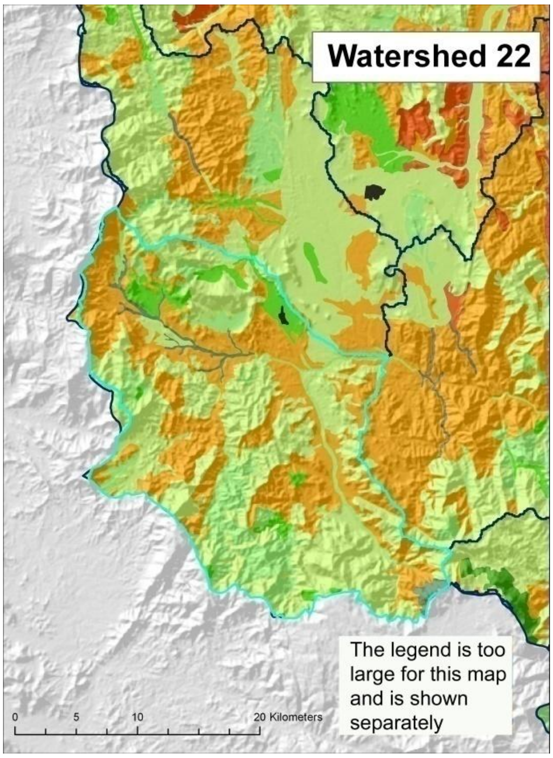


Figure 26. Land use/land cover (left) and reliable annual precipitation (right) in watershed 21



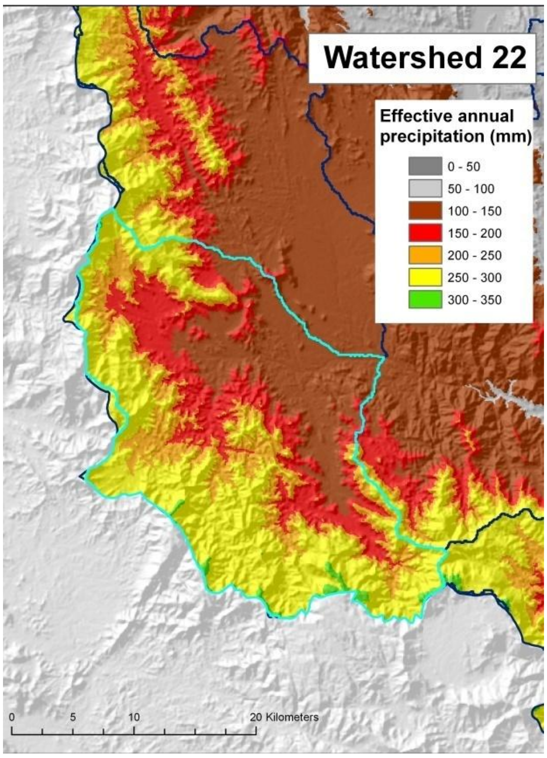


Figure 27. Land use/land cover (left) and reliable annual precipitation (right) in watershed 22

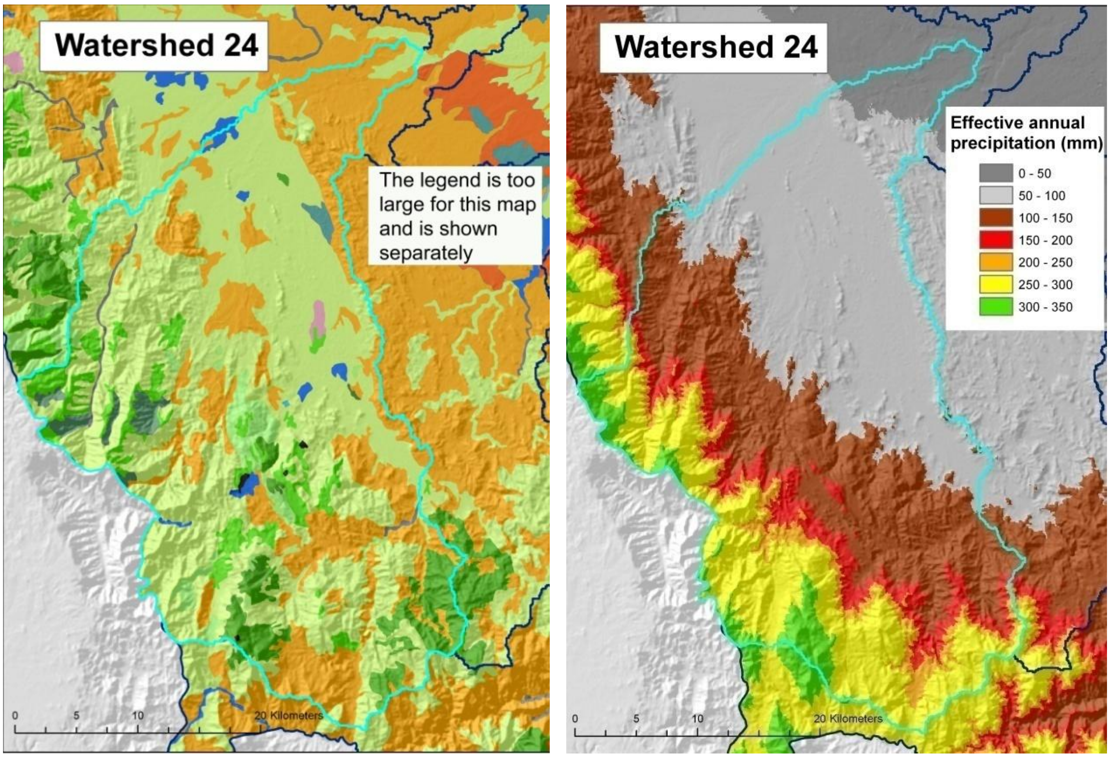


Figure 28. Land use/land cover (left) and reliable annual precipitation (right) in watershed 24

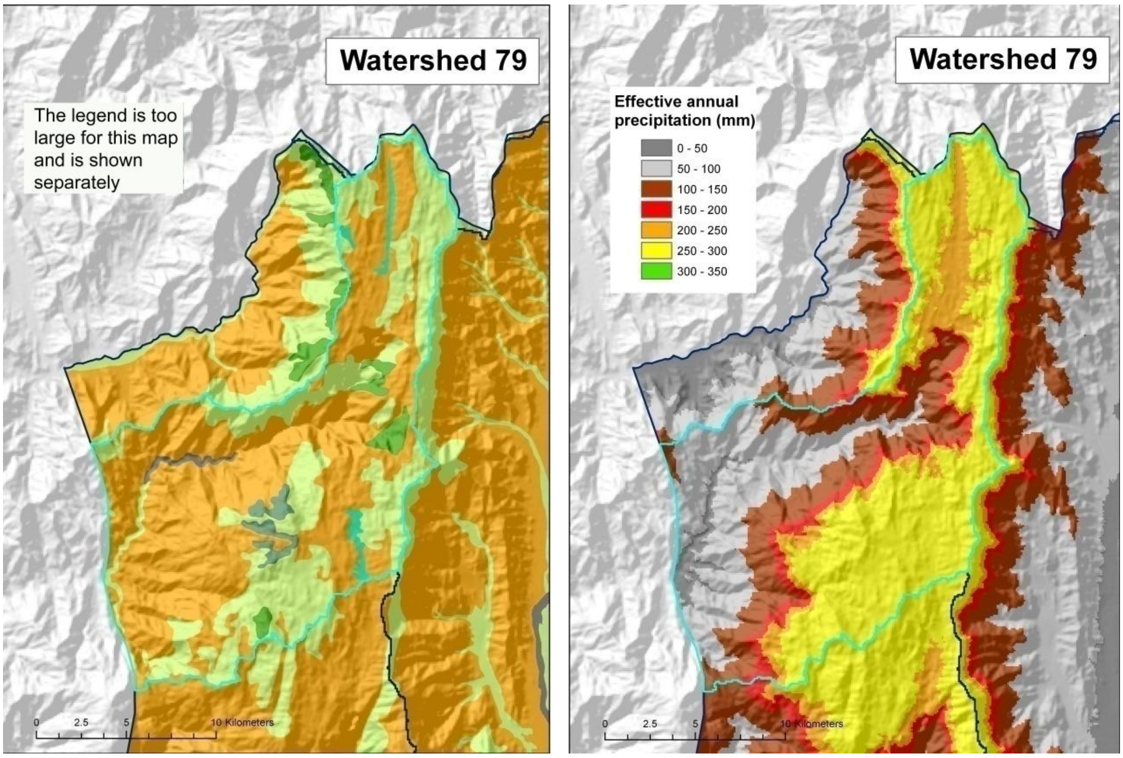


Figure 29. Land use/land cover (left) and reliable annual precipitation (right) in watershed 79

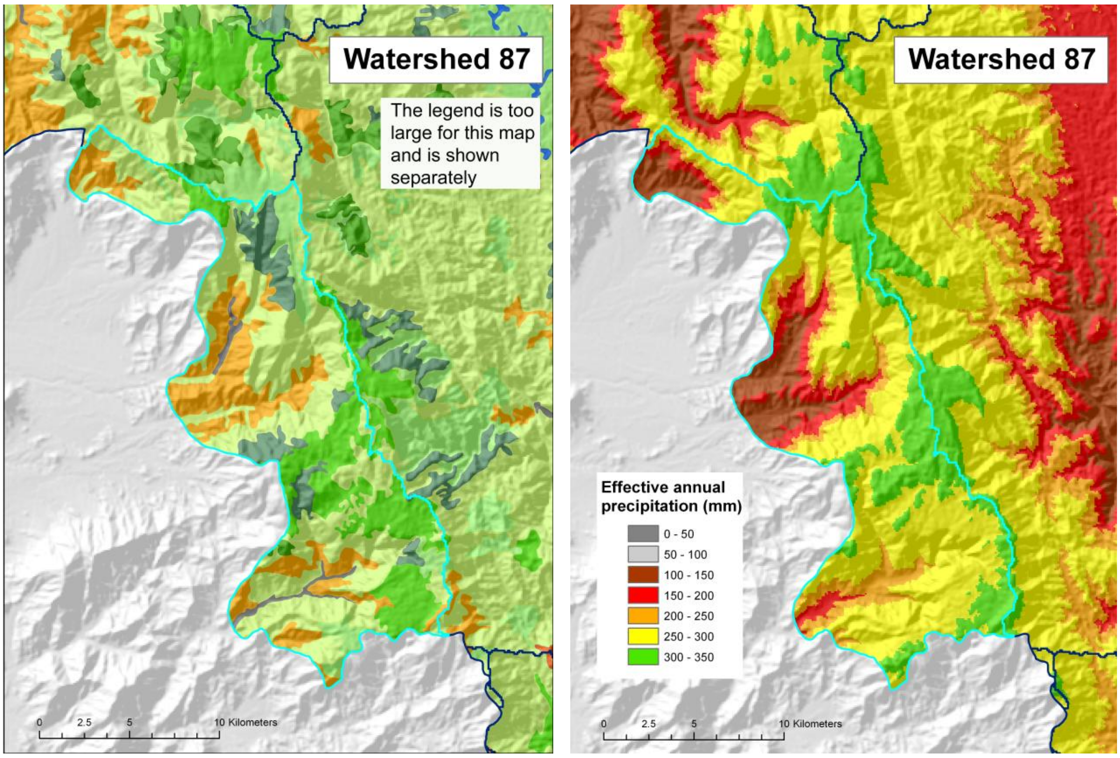
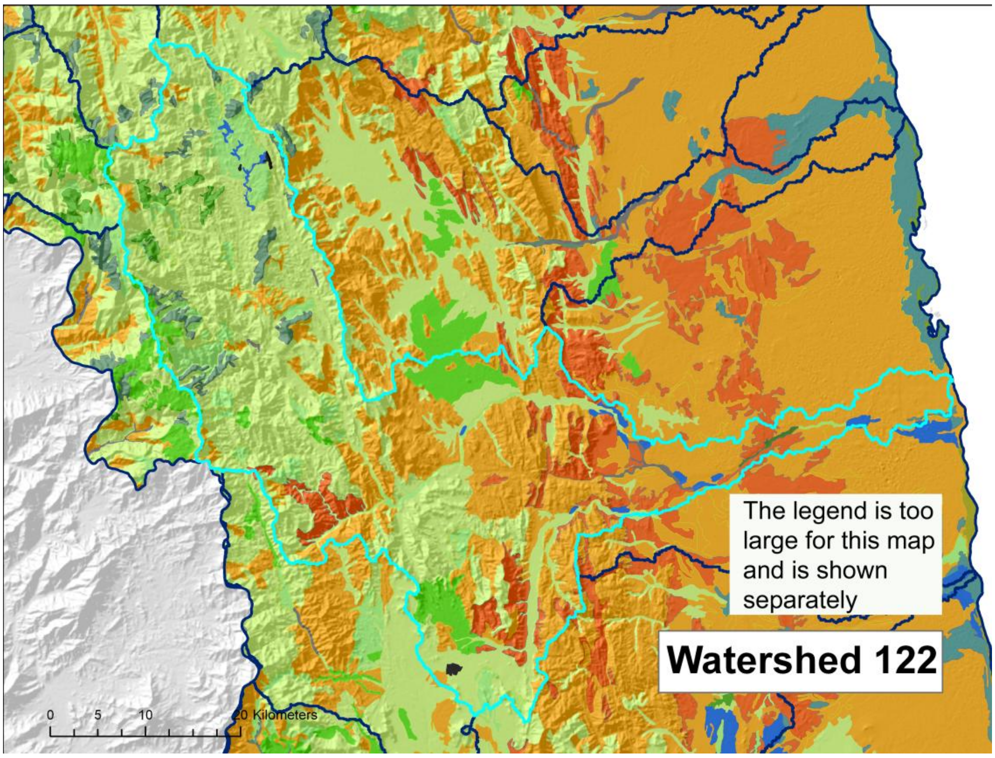


Figure 30. Land use/land cover (left) and reliable annual precipitation (right) in watershed 87

Figure 31. Legend land use/land cover map (reclassified from the Eritrea Multi-purpose Land Cover Database)



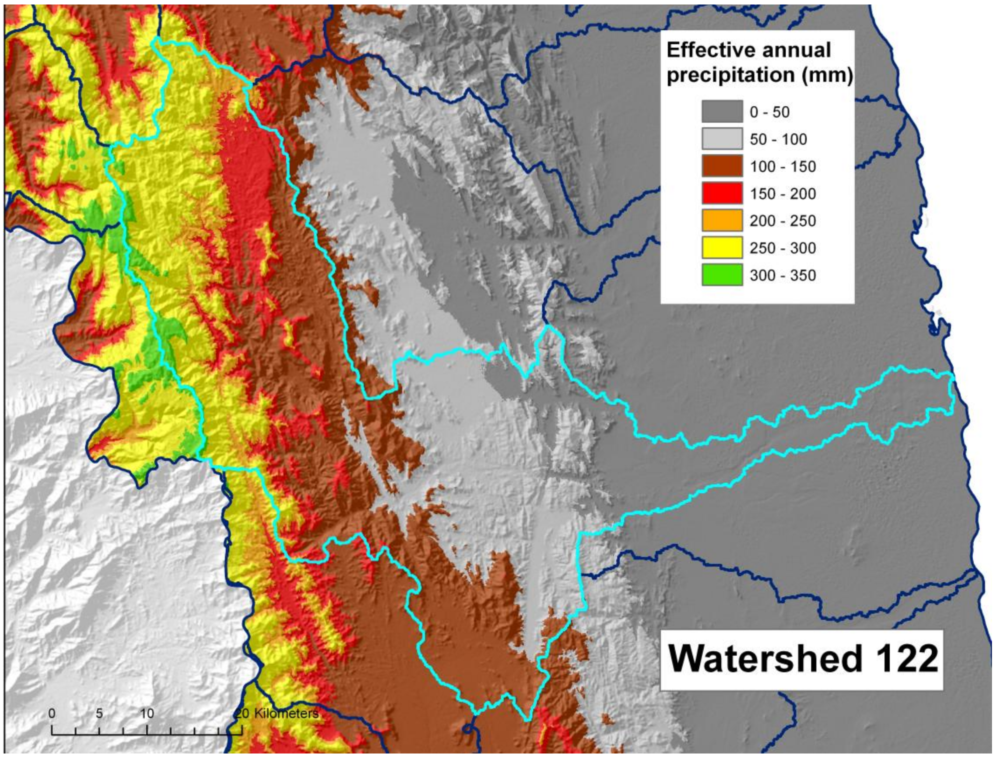


Figure 32. Land use/land cover (top) and reliable annual precipitation (bottom) in watershed 122

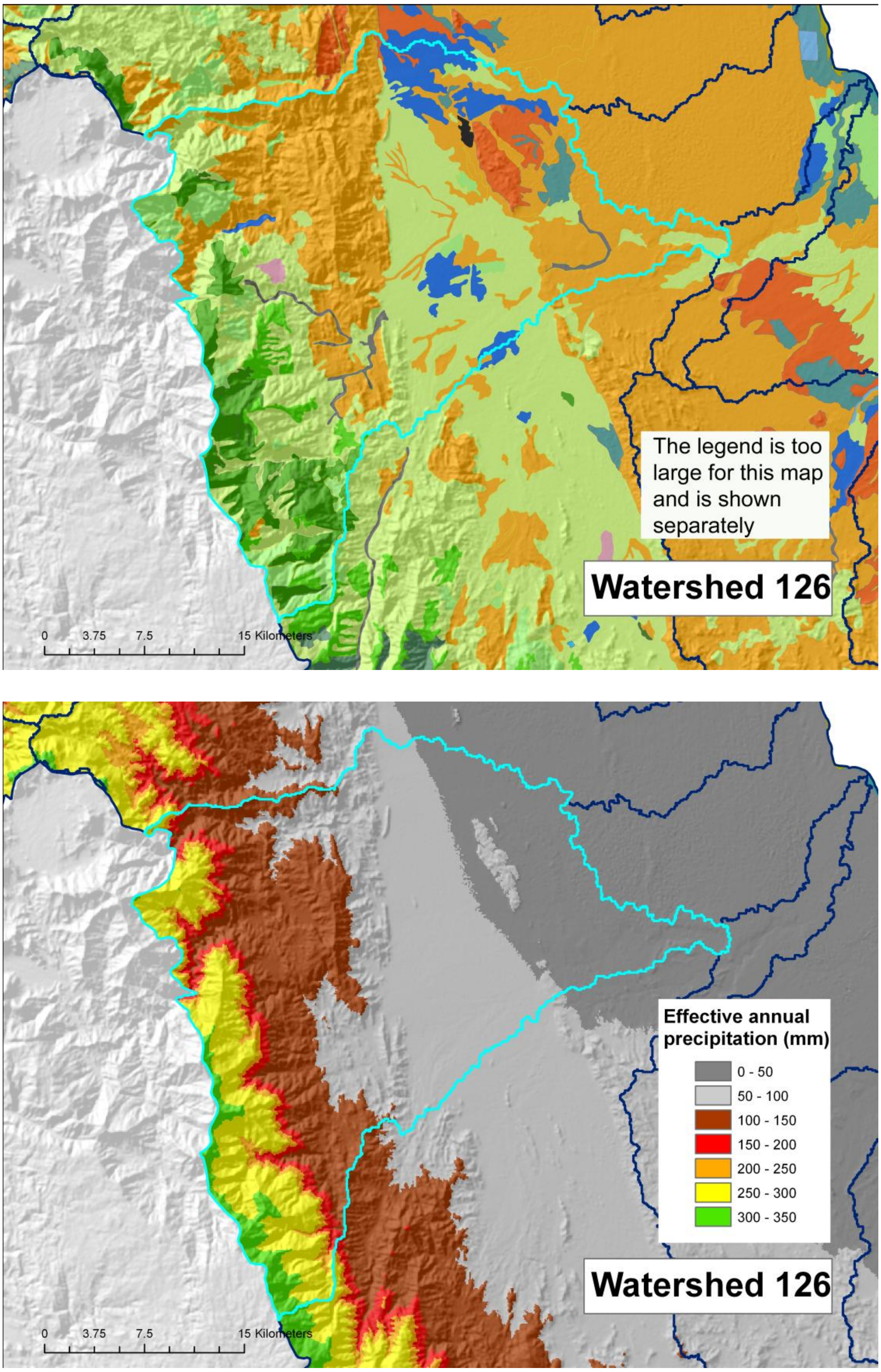


Figure 33. Land use/land cover (top) and reliable annual precipitation (bottom) in watershed 126

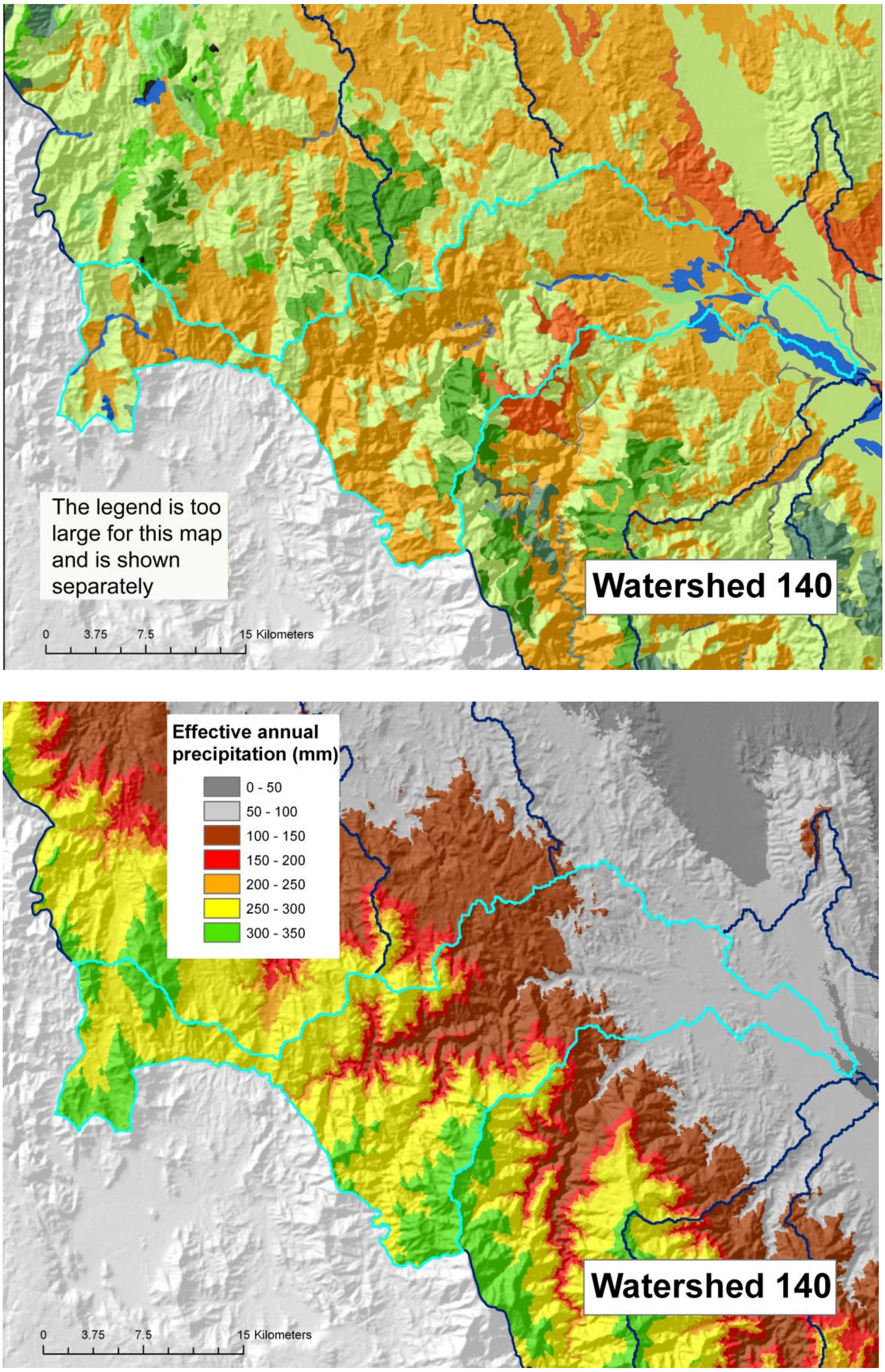


Figure 34. Land use/land cover (top) and reliable annual precipitation (bottom) in watershed 140

4. CONCLUSIONS AND RECOMMENDATIONS

Zoba Northern Red Sea has many locations where potential exists for one or several water harvesting methods. At the same time the potential for water harvesting in Zoba NRS is considerably lower than in Zoba Debub in both absolute and relative terms. Whereas in Zoba Debub about 70% (673,435 ha) was assessed as being suitable for at least one micro-catchment system, in Zoba NRS this is only the case in about 10% of the Zoba (335,742ha), despite the fact that Zoba NRS is about 3.5 times larger than Zoba Debub. The basic reason is a less favourable waterbalance in Zoba NRS, with less precipitation and higher potential evapo-transpiration rates than in Zoba Debub.

For micro-catchment systems three priority classes were distinguished for further assessments of potential and interventions:

- 1st priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system occupying more than 20% of the watershed;
- 2nd priority: watersheds with more than 10,000 ha of land suitable for one or another micro-catchment water harvesting system but occupying less than 20% of the watershed;
- 3rd priority: watersheds 8,000-10,000 ha of land suitable for one or another micro-catchment water harvesting system and occupying more than 20% of the watershed.

The total suitable area covered by these priority watersheds (252,814 ha) is about 75% of the total suitable area for micro-catchment systems in Zoba NRS.

These priority watersheds are also the ones where suitable conditions may exist for macro-catchment systems. However, the suitable areas are much smaller (about 6,400 ha for macro-catchments planted with tree crops, and nearly 12,000 ha for catchments planted with field crops and are more scattered.

Whereas the current study offers a good basis for targeting research for development, this assessment of potential for water harvesting is entirely based on a GIS desk study and needs therefore to be treated as less than final. A follow-up stage of studies is therefore required to make a more definitive selection of watersheds for priority development. These studies would involve both review of documents and collection of in-country data as well as field studies.

Better datasets than the ones available for this desk study may be available in-country and need to be identified. The data requirements for this Zoba refer in particular to farming systems, meteorological and hydrological data, interpretation of very high resolution satellite imagery and establishing a high-resolution digital elevation model. Developing a GIS database for Zoba Northern Red Sea is an effective way to integrate heterogeneous data and analyze data gaps.

Field studies in the various parts of the Zoba and meetings with farmers, specialists and officials including the Governor and researchers are essential in order to provide ground truthing for the desk study, and allow a final identification and selection of a few top priority areas for water harvesting development. Apart from biophysical potential based on climate and soils, additional criteria include (i) local and economic importance, (ii) political priority, (iii) size of agricultural communities, (iv) area, (v) accessibility, (vi) potential for agricultural development, (vii) cost of development, and (viii) availability of data (De Pauw and Oweis, 2011). This selection process and criteria were discussed and agreed upon

Once such areas are identified, a second stage of more localized studies will be required, pertaining in particular to local hydrology but in which also soil survey will have to play a major role, in order to identify at greater detail important properties such as soil depth, stoniness, texture, salinity.

Adaptive research should go in parallel to the development of the identified watersheds. Areas of research on water and land management recommended are:

- Crops water requirements, irrigation schedules, modern irrigation systems, water harvesting, supplemental irrigation, runoff-rainfall relations, watershed management;
- Agronomy/ soil: characterization, soil-water-plants relations, tillage, crop varieties testing, fertility, erosion, agronomic practices;
- On farm demonstrations of: supplemental irrigation, water harvesting, fertility impacts, new varieties, deficit irrigation, conservation agriculture.

Research may be focused in the research stations but also at the community level and with farmers.

In a broader context, the development of water harvesting potential in this Zoba requires strengthening community level institutions and extension services. All activities require capacity building of its members in key components of the development, such as training in water harvesting, supplemental irrigation, soil conservation, agronomic practices and institutional setups.

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ANNEX 1.
SUITABILITY FOR DIFFERENT WATER HARVESTING SYSTEMS IN THE WATERSHEDS OF ZOBA NORTHERN RED SEA

Table 14. Areas by water harvesting suitability class for the watersheds of Zoba Northern Red Sea

Watershed no.	Area (ha)	Area by water harvesting class (ha)														Total (ha)suit-able	Total (ha)un-suitable	Ratio (%)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14			
1	87,875	87,809	1	0	11	3	4	0	0	2	7	38	0	1	0	66	87,809	0
2	10,201	9,927	4	0	0	175	87	0	0	3	1	4	0	0	0	274	9,927	3
3	53,001	52,999	0	0	0	0	0	0	0	0	0	0	0	0	2	2	52,999	0
4	24,820	24,820	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24,820	0
5	53,234	51,930	14	0	0	871	266	2	2	0	0	148	2	0	0	1,305	51,930	2
6	98,550	73,387	3,724	205	52	9,983	10,729	57	292	0	3	63	55	0	0	25,164	73,387	26
7	108,477	105,895	48	1	0	1,711	707	11	21	0	1	67	14	2	0	2,582	105,895	2
8	48,364	47,790	15	0	0	303	256	0	0	0	0	0	0	0	0	574	47,790	1
9	46,445	41,347	110	0	0	3,306	1,682	0	0	0	0	0	0	0	0	5,098	41,347	11
10	16,022	15,627	6	0	0	305	85	0	0	0	0	0	0	0	0	395	15,627	2
11	5,235	5,075	8	0	0	105	48	0	0	0	0	0	0	0	0	160	5,075	3
12	102,872	87,964	624	0	0	8,411	5,712	10	8	0	0	122	21	0	0	14,909	87,964	14
13	48,922	48,343	12	0	0	396	155	0	0	0	0	14	1	0	0	579	48,343	1
14	123	123	0	0	0	0	0	0	0	0	0	0	0	0	0	0	123	0
15	51,460	38,715	926	0	0	6,730	5,089	0	0	0	0	0	0	0	0	12,745	38,715	25
16	51,434	50,586	4	2	0	228	73	30	38	0	0	418	52	0	1	848	50,586	2
17	5,670	4,067	191	8	0	745	635	2	12	0	0	8	3	0	0	1,604	4,067	28
18	94,085	91,815	34	5	0	1,316	659	24	58	0	0	143	31	0	0	2,271	91,815	2
19	40,745	30,284	356	83	0	4,365	2,974	383	1,042	0	0	930	329	0	0	10,461	30,284	26
20	103,412	88,720	1,588	188	0	5,598	4,589	233	434	0	0	1,766	296	0	0	14,692	88,720	14
21	42,260	16,974	5,772	694	0	5,301	9,849	373	1,985	0	0	931	380	0	0	25,285	16,974	60
22	57,144	30,564	1,510	719	0	6,747	8,587	668	2,650	0	0	4,777	920	0	0	26,580	30,564	47
23	8,300	8,299	0	0	0	0	0	0	0	0	0	0	0	0	1	1	8,299	0
24	111,856	79,947	1,208	160	35	12,225	8,667	1,083	1,708	9	143	5,267	1,392	12	0	31,909	79,947	29
25	57,288	48,287	569	20	0	4,385	3,970	1	20	0	0	32	4	0	0	9,000	48,287	16
26	65,058	64,706	8	0	0	78	265	0	0	0	0	0	0	0	0	352	64,706	1
27	12,374	12,207	2	0	0	124	41	0	0	0	0	0	0	0	0	167	12,207	1
28	59	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	59	0
29	31,324	28,089	65	0	2	2,158	988	0	0	1	7	12	0	2	0	3,236	28,089	10
30	53,222	49,323	140	0	0	2,266	1,493	0	0	0	0	0	0	0	0	3,898	49,323	7
31	42,898	39,603	123	0	0	2,052	1,120	0	0	0	0	0	0	0	0	3,295	39,603	8
32	38,696	34,665	610	0	0	1,504	1,917	0	0	0	0	0	0	0	0	4,031	34,665	10
33	58,555	58,555	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58,555	0
34	44,036	43,822	1	0	0	50	163	0	0	0	0	0	0	0	0	214	43,822	0
35	48,634	48,633	0	0	0	0	1	0	0	0	0	0	0	0	0	1	48,633	0

Table 14. (continued)

Watershed no.	Area (ha)	Area by water harvesting class (ha)														Total (ha)suit-able	Total (ha)un-suitable	Ratio (%)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14			
36	48,146	38,782	1,199	0	15	4,060	4,071	0	0	1	15	1	0	2	0	9,363	38,782	19
37	1,465	1,465	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,465	0
38	19,819	19,766	1	0	0	38	13	0	0	0	0	0	0	0	0	53	19,766	0
39	7,500	6,274	45	0	0	622	551	2	1	0	0	6	0	0	0	1,226	6,274	16
40	24,009	24,009	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24,009	0
41	12,477	12,477	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12,477	0
42	10,112	10,111	0	0	1	0	0	0	0	0	0	0	0	0	0	1	10,111	0
43	3,109	3,109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3,109	0
44	1,891	1,891	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1,891	0
45	32,560	32,415	0	0	0	0	0	0	0	0	0	0	0	0	146	146	32,415	0
46	52,465	52,113	0	0	2	0	60	0	0	0	0	0	0	0	289	352	52,113	1
47	39,587	39,526	0	0	0	0	61	0	0	0	0	0	0	0	0	61	39,526	0
48	117,760	117,495	1	0	2	0	131	0	0	0	0	0	0	0	132	265	117,495	0
50	128,368	126,901	43	0	36	0	1,259	0	0	0	13	0	0	0	117	1,467	126,901	1
51	70,416	60,562	320	33	2	5,499	3,603	25	202	0	0	72	19	0	82	9,855	60,562	14
52	82,324	82,311	0	0	0	1	0	0	0	0	0	0	0	0	12	13	82,311	0
53	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
54	82,477	82,452	1	0	4	0	4	0	0	0	2	0	0	0	13	25	82,452	0
56	8	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0
57	20,281	20,251	0	0	1	0	2	0	0	0	0	0	0	0	27	30	20,251	0
58	2,816	2,810	0	0	0	0	0	0	0	0	1	0	0	0	5	6	2,810	0
60	815	811	0	0	0	0	0	0	0	0	0	0	0	0	4	4	811	1
61	22,627	22,594	3	0	1	0	28	0	0	0	0	0	0	0	1	33	22,594	0
62	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
63	13,166	13,002	0	0	5	0	1	0	0	0	0	0	0	0	158	164	13,002	1
64	294	261	0	0	0	23	4	0	0	0	2	4	0	0	0	33	261	11
65	118	102	0	0	0	9	0	0	0	0	0	6	0	0	0	15	102	13
67	320	206	1	0	0	55	38	0	0	2	0	12	0	5	0	113	206	35
69	48	42	0	0	0	0	0	0	0	0	0	6	0	0	0	6	42	12
70	142	94	2	0	0	31	5	0	0	0	1	7	0	2	0	49	94	34
71	21	12	0	0	0	1	0	0	0	0	0	6	0	1	0	9	12	43
72	6	0	0	0	0	0	0	0	0	0	0	6	0	0	0	6	0	100
74	2,245	2,226	0	0	10	0	0	0	0	1	8	0	0	0	0	19	2,226	1
75	7	5	0	0	1	0	0	0	0	0	0	0	0	0	0	1	5	17
76	25	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	0
77	138	126	0	0	0	5	3	0	0	0	0	4	0	0	0	12	126	8

Table 14 (continued)

Watershed no.	Area (ha)	Area by water harvesting class (ha)														Total (ha)suit-able	Total (ha)un-suitable	Ratio (%)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14			
79	29,652	19,757	502	0	2	4,950	4,435	0	0	2	1	2	0	1	0	9,895	19,757	33
80	418	415	0	0	0	2	2	0	0	0	0	0	0	0	0	3	415	1
81	55,789	55,785	0	0	0	2	2	0	0	0	0	0	0	0	0	4	55,785	0
82	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
83	43,185	43,184	0	0	0	1	1	0	0	0	0	0	0	0	0	2	43,184	0
84	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
85	11	5	0	0	0	1	4	0	0	0	0	0	0	0	0	5	5	50
87	23,298	14,845	48	156	0	1,831	907	994	2,092	0	0	1,462	962	0	0	8,452	14,845	36
88	82	77	0	0	0	4	1	0	0	0	0	0	0	0	0	5	77	6
89	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	33
90	9	3	0	0	0	5	1	0	0	0	0	0	0	0	0	6	3	67
91	96	30	0	0	0	5	4	16	26	0	0	4	9	0	0	65	30	68
92	58	44	0	0	0	11	3	0	0	0	0	0	0	0	0	13	44	23
94	15	12	1	0	0	1	1	0	0	0	0	0	0	0	0	4	12	24
95	44	35	0	0	0	5	4	0	0	0	0	0	0	0	0	9	35	21
96	35	23	0	0	0	9	3	0	0	0	0	0	1	0	0	12	23	35
99	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
100	114	91	0	0	0	14	10	0	0	0	0	0	0	0	0	24	91	21
102	7	5	0	0	0	2	0	0	0	0	0	0	0	0	0	2	5	29
103	23	8	1	0	0	3	3	0	1	0	0	4	3	0	0	14	8	63
105	163	95	0	0	0	30	9	5	2	0	0	18	5	0	0	68	95	42
107	365	196	1	1	0	61	26	10	16	0	0	39	15	0	0	170	196	46
108	22	0	0	0	0	0	0	1	2	0	0	10	9	0	0	22	0	100
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
111	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
112	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116	8	0	0	0	0	0	1	0	1	0	0	4	1	0	0	8	0	100
117	3	0	0	0	0	0	0	1	2	0	0	0	1	0	0	3	0	100
122	176,329	128,591	3,559	1,498	87	15,005	12,176	1,601	5,000	48	250	6,784	1,706	23	0	47,737	128,591	27
123	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
124	48,923	42,978	106	38	0	2,911	1,460	108	144	0	0	1,013	166	0	0	5,945	42,978	12
125	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
126	87,774	72,952	359	62	0	5,178	3,587	302	501	0	0	4,328	507	0	0	14,822	72,952	17
127	11	6	0	0	0	4	1	0	0	0	0	0	0	0	0	5	6	47
130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 14 (continued)

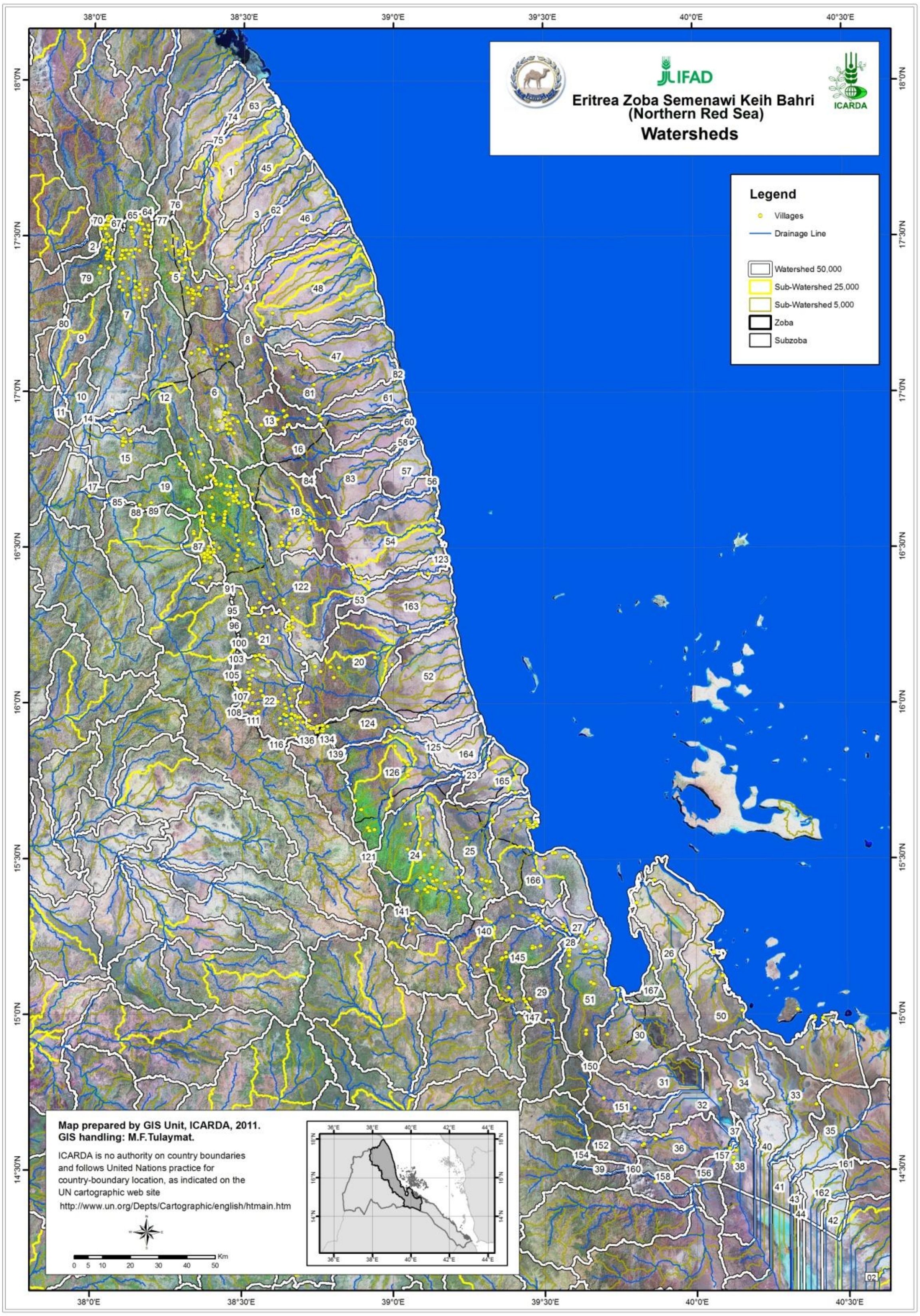
Watershed no.	Area (ha)	Area by water harvesting class (ha)														Total (ha)suit-able	Total (ha)un-suitable	Ratio (%)
		1	2	3	4	5	6	7	8	9	10	11	12	13	14			
134	47	8	2	0	0	17	20	0	0	0	0	0	0	0	0	39	8	82
135	2	1	0	0	0	2	0	0	0	0	0	0	0	0	0	2	1	67
136	3	1	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	60
137	2	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	67
138	26	21	0	0	0	4	1	0	0	0	0	0	0	0	0	5	21	20
140	57,159	46,995	248	19	0	6,127	3,374	46	134	3	5	156	45	6	0	10,163	46,995	18
141	15	14	0	0	0	0	1	0	0	0	0	0	0	0	0	1	14	8
145	45,572	41,559	58	1	0	2,782	1,111	5	6	0	0	44	7	0	0	4,013	41,559	9
147	3	1	0	0	0	0	2	0	0	0	0	0	0	0	0	2	1	67
151	36,704	33,152	69	0	0	2,437	1,046	0	0	0	0	0	0	0	0	3,552	33,152	10
152	19,299	17,912	18	0	0	1,052	318	0	0	0	0	0	0	0	0	1,388	17,912	7
154	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
156	13,036	12,113	356	0	2	210	355	0	0	0	1	0	0	0	0	923	12,113	7
157	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
158	11,007	8,709	613	58	23	733	862	0	7	0	0	0	0	0	0	2,297	8,709	21
159	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
160	4	3	0	0	0	0	1	0	0	0	0	0	0	0	0	1	3	20
162	23,179	23,179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23,179	0
163	50,801	50,793	1	0	0	6	1	0	0	0	0	0	0	0	0	7	50,793	0
164	18,586	18,566	0	0	0	0	0	0	0	0	0	0	0	0	20	20	18,566	0
165	29,581	29,494	0	0	0	0	25	0	0	0	0	0	0	0	62	87	29,494	0
166	82,272	81,266	29	0	0	390	455	0	0	0	0	0	0	0	132	1,007	81,266	1
167	17,507	17,339	17	0	23	34	67	0	0	0	14	0	0	2	11	168	17,339	1

Notes: Water harvesting suitability classes:

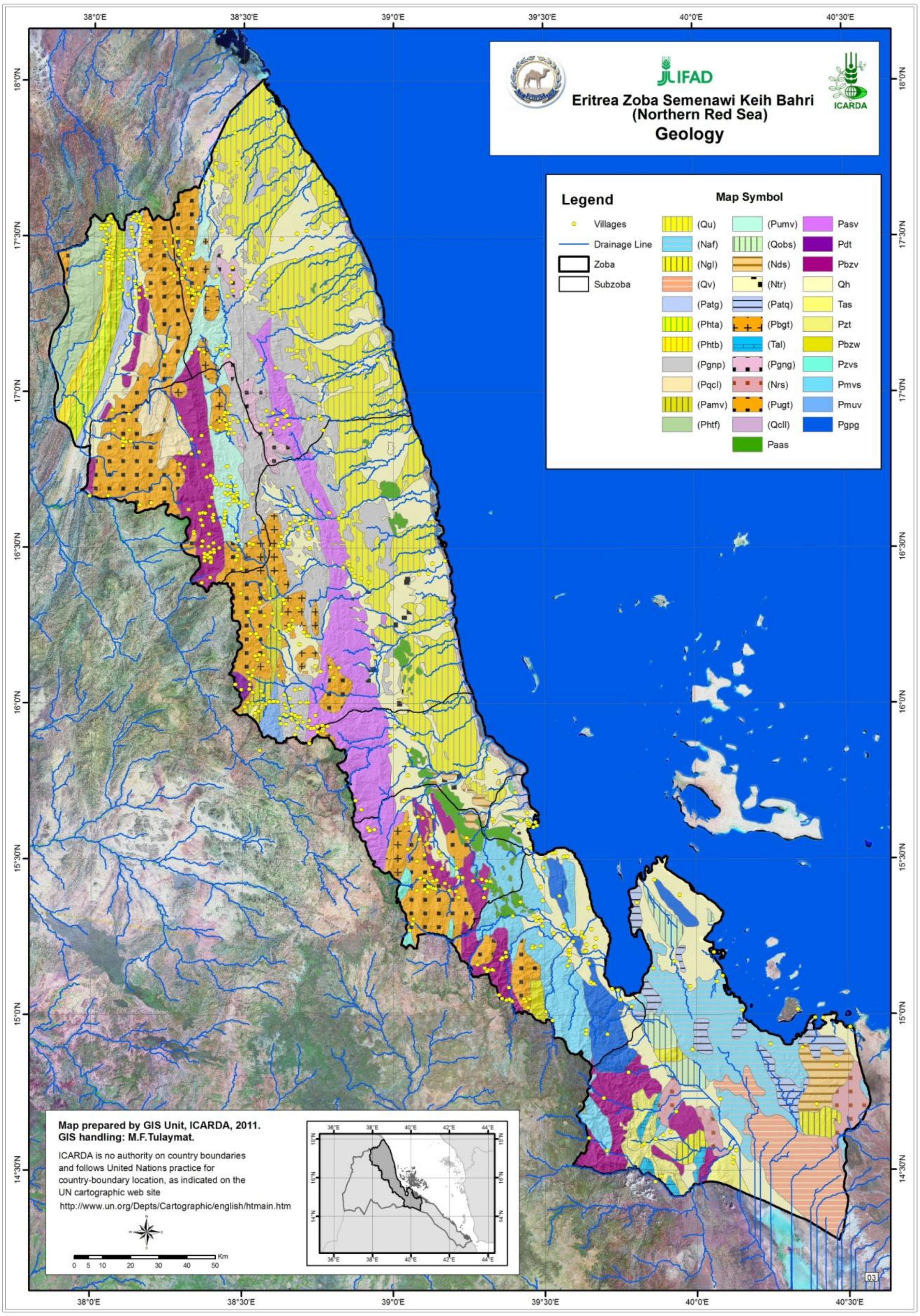
1 Unsuitable for any system
2 Suitable for S11
3 Suitable for S11, S12
4 Suitable for S11, S12, S13
5 Suitable for S21
6 Suitable for S11, S21
8 Suitable for S11, S12, S21, S22, S31, S41, S51
9 Suitable for all except S11, S12, S13, S6
10 Suitable for all except S6
11 Suitable for S6
12 Suitable for S21, S22, S31, S41, S51, S6
13 Suitable for all except S11, S12, S13

ANNEX 2. MAPS

Map 1. Base Map



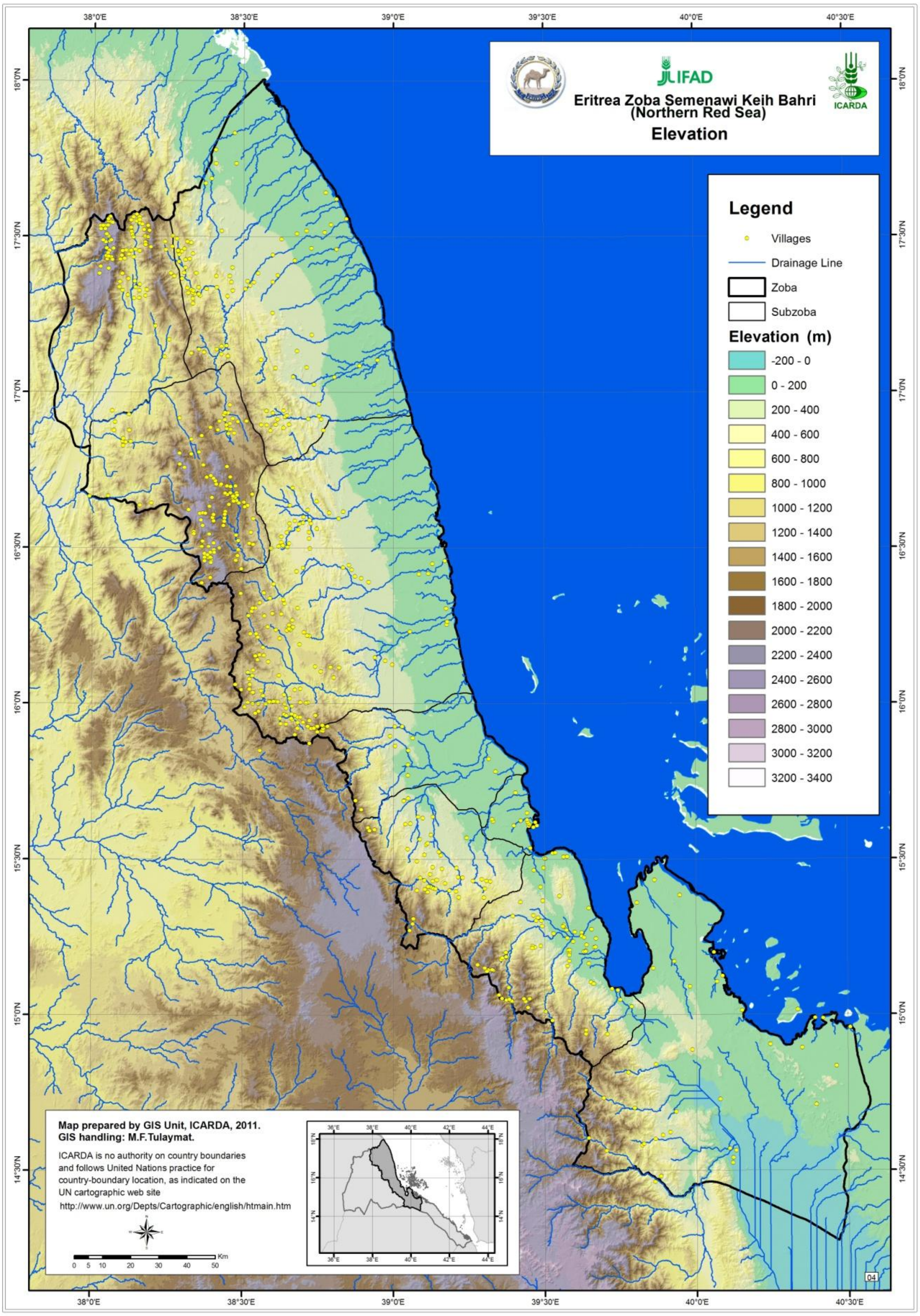
Map 2. Watersheds



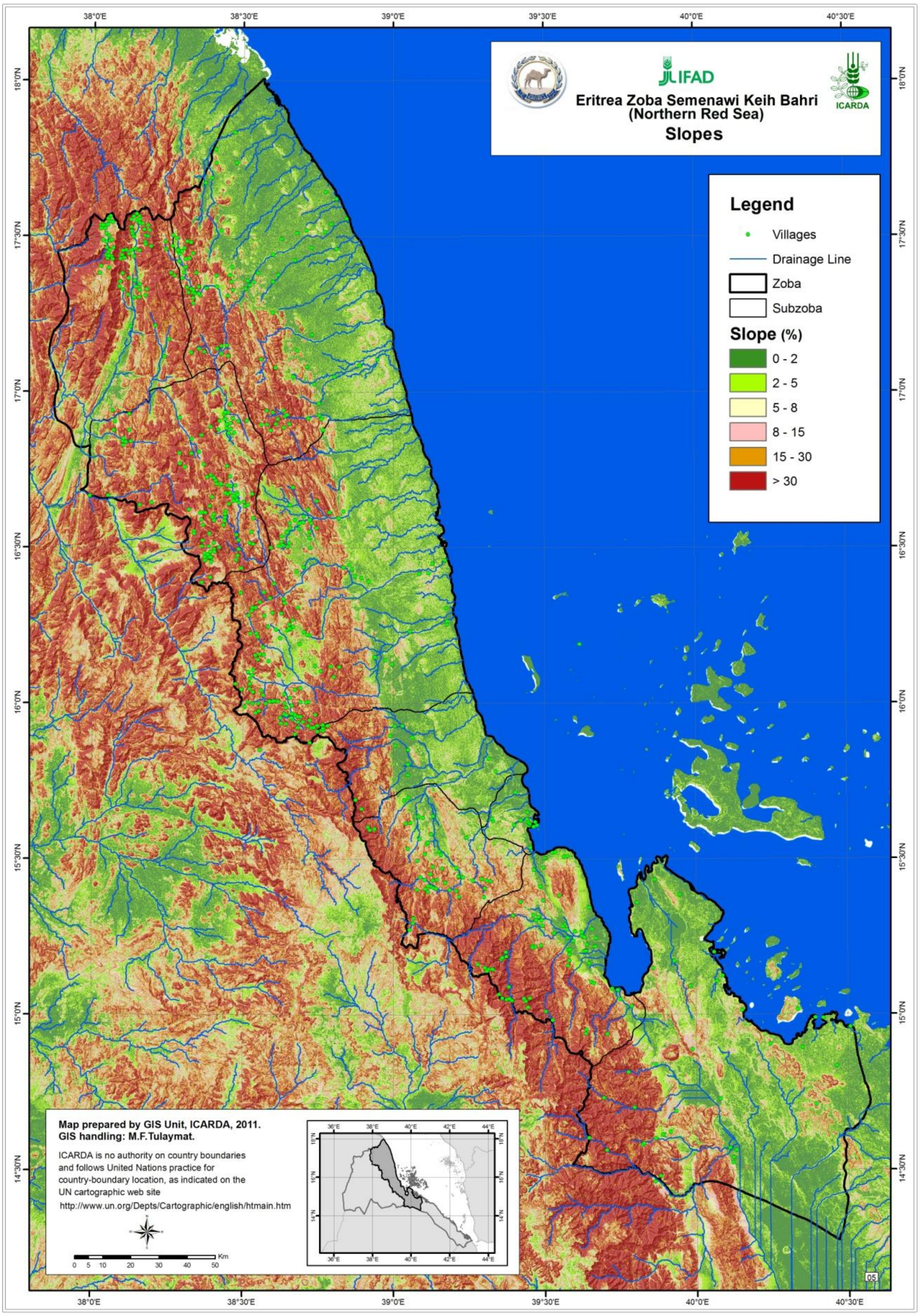
Map 3. Geology

Legend Geological Map

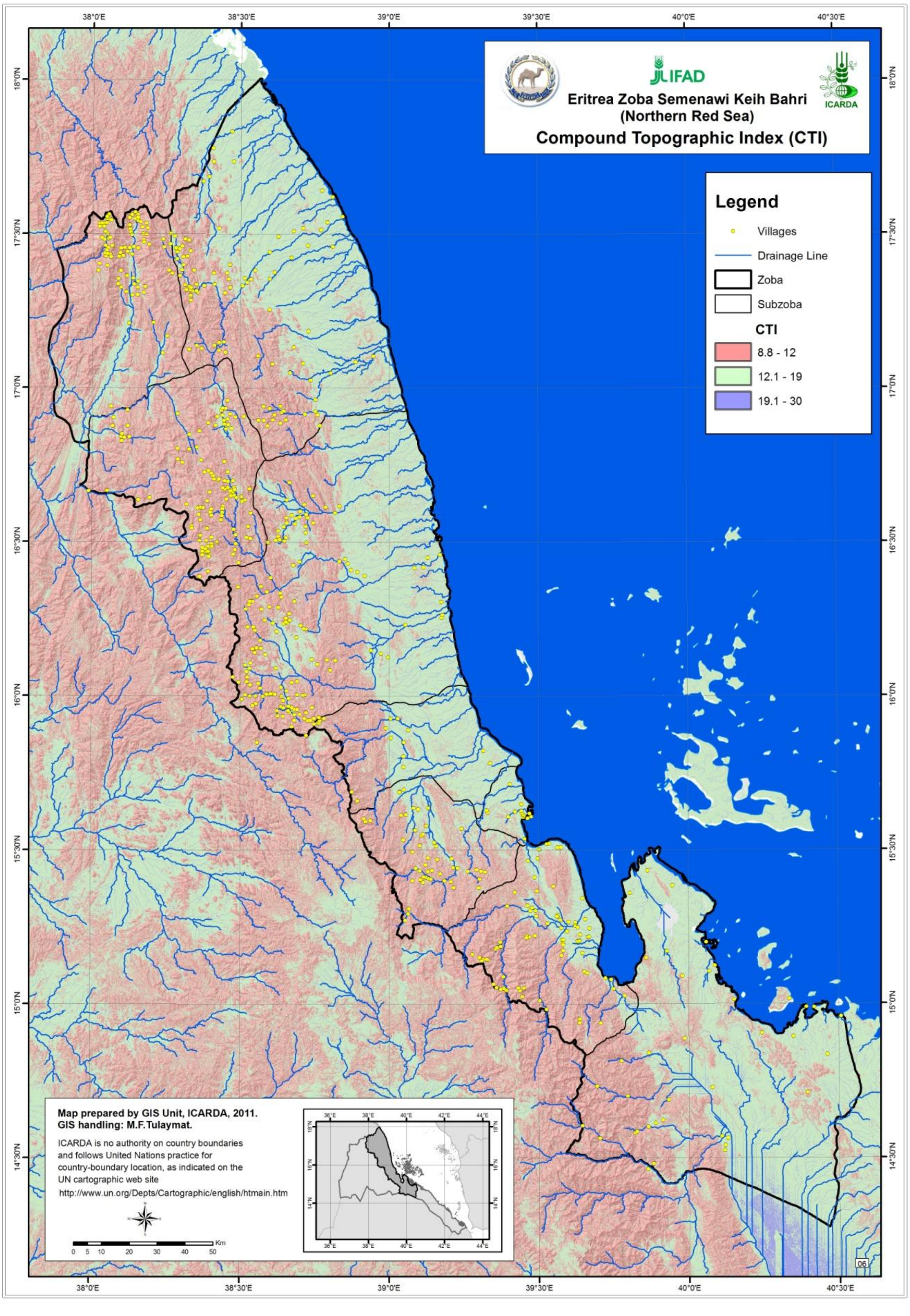
Map Symbol	
(Qu)	Elluvium and aolian sediment. undifferentiated
(Naf)	Fissural dominantly basaltic lavas, subordinate acid lavas, ignimbrites. Afar Group
(Ngl)	Siliceous centers and associated tuffs (rhyolites)
(Qv)	Evaporites, mainly halite with subordinate gypsum
(Patg)	Marbles, grey, impure intercalated with graphitic sericitic and phyllites and phyllites, pink stromatolitic marbles
(Phta)	Metabasaltic andesites, interbedded with turbidites, sulphidic cherts and thin Olistromicsediments, minor Dacites and rhyolites
(Phtb)	Chloritic, sericitic and Fe-Mn Phyllites with board basaltic metavolcanics (MORB)
(Pgnp)	Paragneisses, garnet-mica schists
(Pqcl)	Late basin Sediments, metagreywacks with interbeds of metasandstones and polymict metaconglomerates
(Pamv)	Intermediate to mafic flows, tuffs, agglomerates, minor felsic flows and tuffs
(Phtf)	Alternating chloritic schist and deformed silicic metavolcanic rocks with ferruginous phyllites, impure marble, thin metabasilts
(Pumv)	Undifferentiated meta-volcano-sedimentary rocks
(Qobs)	Alkaline olivine basalt, picritic basalt flows often connected to volcanic edifices
(Nds)	Dogalli series: sandstones, lacustrine clays and silts, interbedded basalt flows, gypsiferous marls and coral limestone
(Ntr)	Transitional and shallow marine deposits, sands silts, reefal limestone, evaporites
(Patq)	Quartzo-feldspathic arkoses, micaceous sandstone, conglomerates (Hurum Formation)
(Pbgt)	Late-to post-tectonic granite
(Tal)	Aantalo limstone, neritic fossiliferous limestones and marls
(Pgng)	Gniessose granite
(Nrs)	Red Series: red or varigated sandstones, sands or shales with minor volcanics
(Pugt)	Undifferentiated deformed granitoid rocks
(Qcll)	Coastal Sediments
(Paas)	Asmara Basalt includes undifferentiated flood basalts
(Pasv)	Lower Volcanics (Asmara group of Mafic flows, mafic to intermediate tuffs and felsic flows and associated tuffs)
(Pdt)	Meta-diorites
(Pbzv)	Intermediate and basic lavas, greywack, tuffaceous slate, phyllite, agglomerate rhyolite
(Qh)	Recent sediments undifferentiated: conglomerates, sands, silt clays, coral reef, ellvium and aolian sediments
(Tas)	Adi Grat(Lower varigated quartzose) sandstone of fluvitile and/or littoral origin
(Pzt)	Enticho sandstone and Edaga Arbi Glacials not divided. Sandstone, conglomerates shale, erratic boulders, tillite
(Pbzw)	Black slate, calcareous intercalations os slate
(Pzvs)	Undifferentiated metavolcanic rocks and metasediments
(Pmvs)	Meta-volcanic of intermediate composition associated with the above metasediments
(Pmuv)	Undifferentiated metavolcanic and or volcalic pyroclasti rocks
(Pgpg)	Pelitic (staurolite, kyanite and garnet-bearing) schists and gneisses



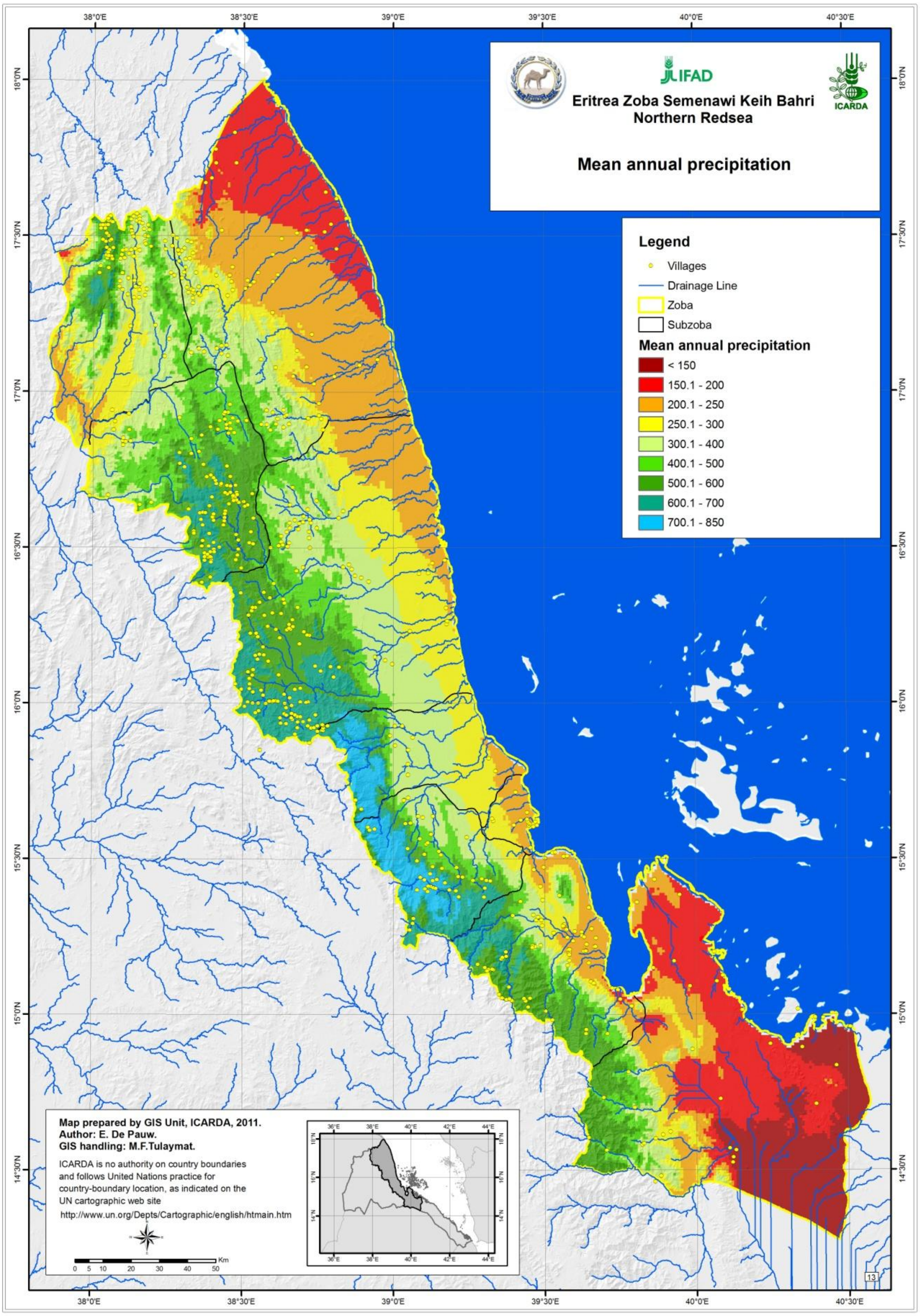
Map 4. Elevation


IFAD
Eritrea Zoba Semenawi Keih Bahri
(Northern Red Sea)
Slopes
ICARDA
Legend
Villages
Drainage Line
Zoba
Subzoba
Slope (%)
0 - 2
2 - 5
5 - 8
8 - 15
15 - 30
> 30
Map prepared by GIS Unit, ICARDA, 2011.
GIS handling: M.F.Tulaymat.
ICARDA is no authority on country boundaries and follows United Nations practice for country-boundary location, as indicated on the UN cartographic web site
http://www.un.org/Depts/Cartographic/english/htmain.htm
0 5 10 20 30 40 50 Km
38°0'E
38°30'E
39°0'E
39°30'E
40°0'E
40°30'E
18°0'N
17°30'N
17°0'N
16°30'N
16°0'N
15°30'N
15°0'N
14°30'N
05

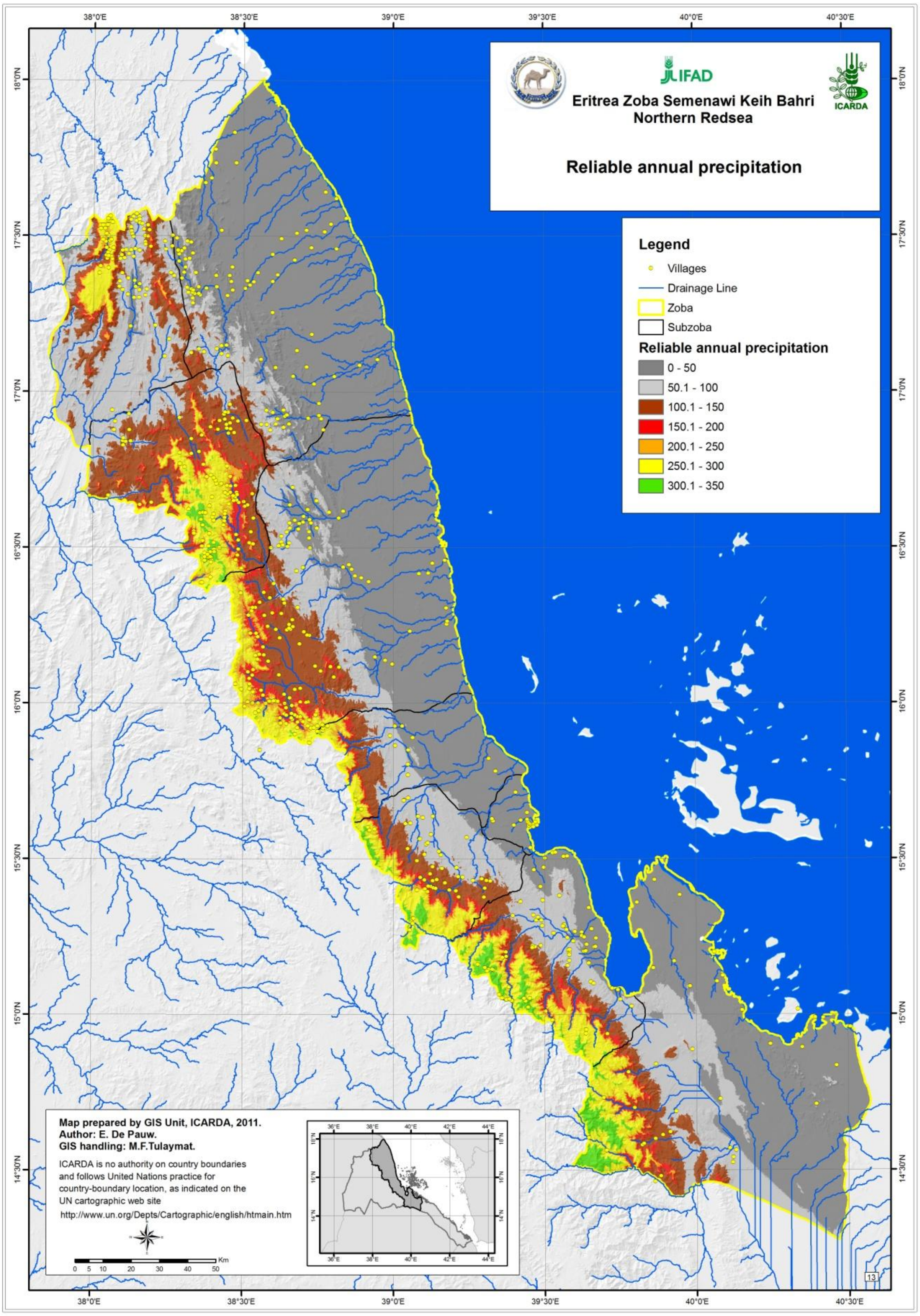
Map 5. Slopes



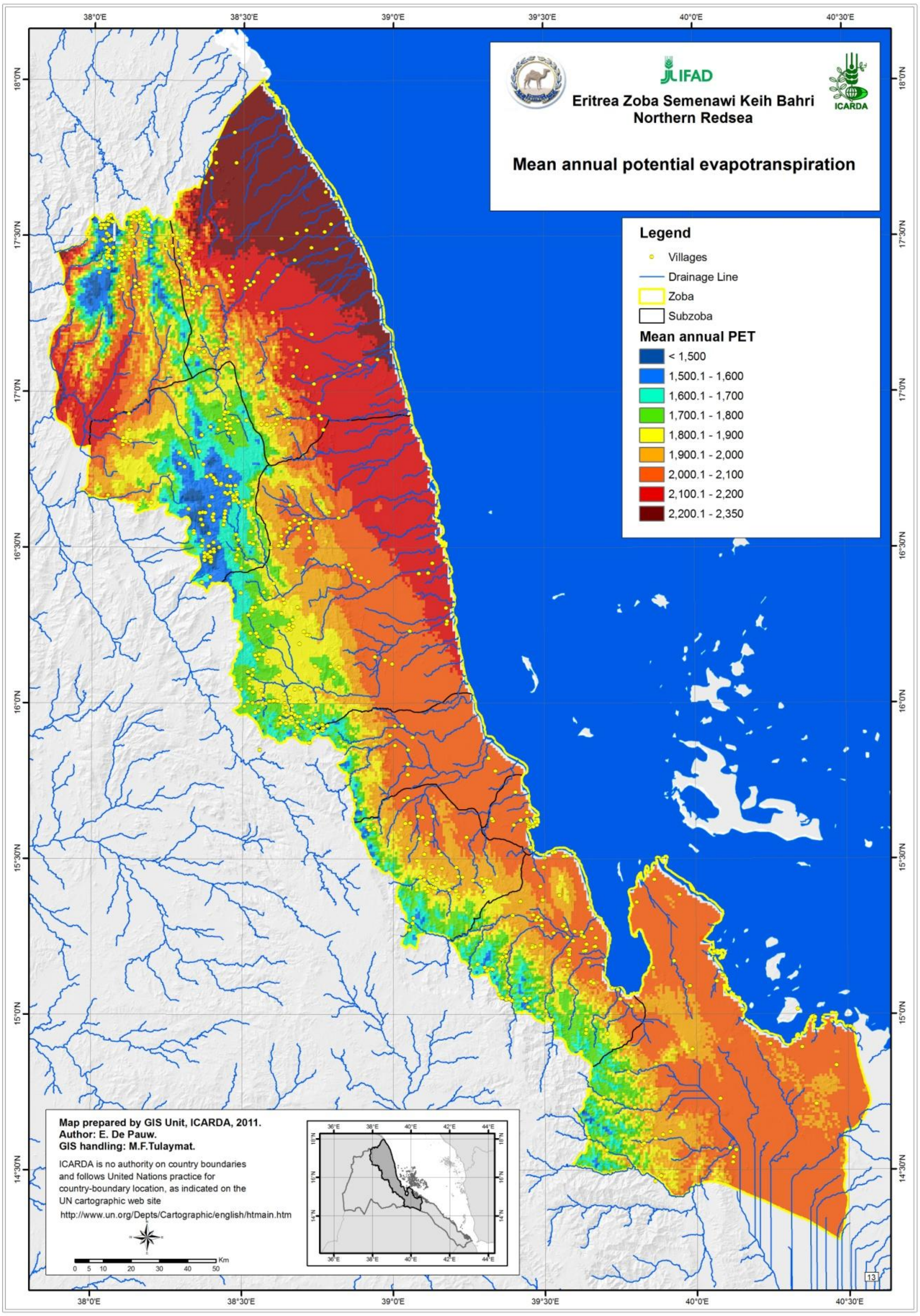
Map 6. Compound Topographic Index (CTI)



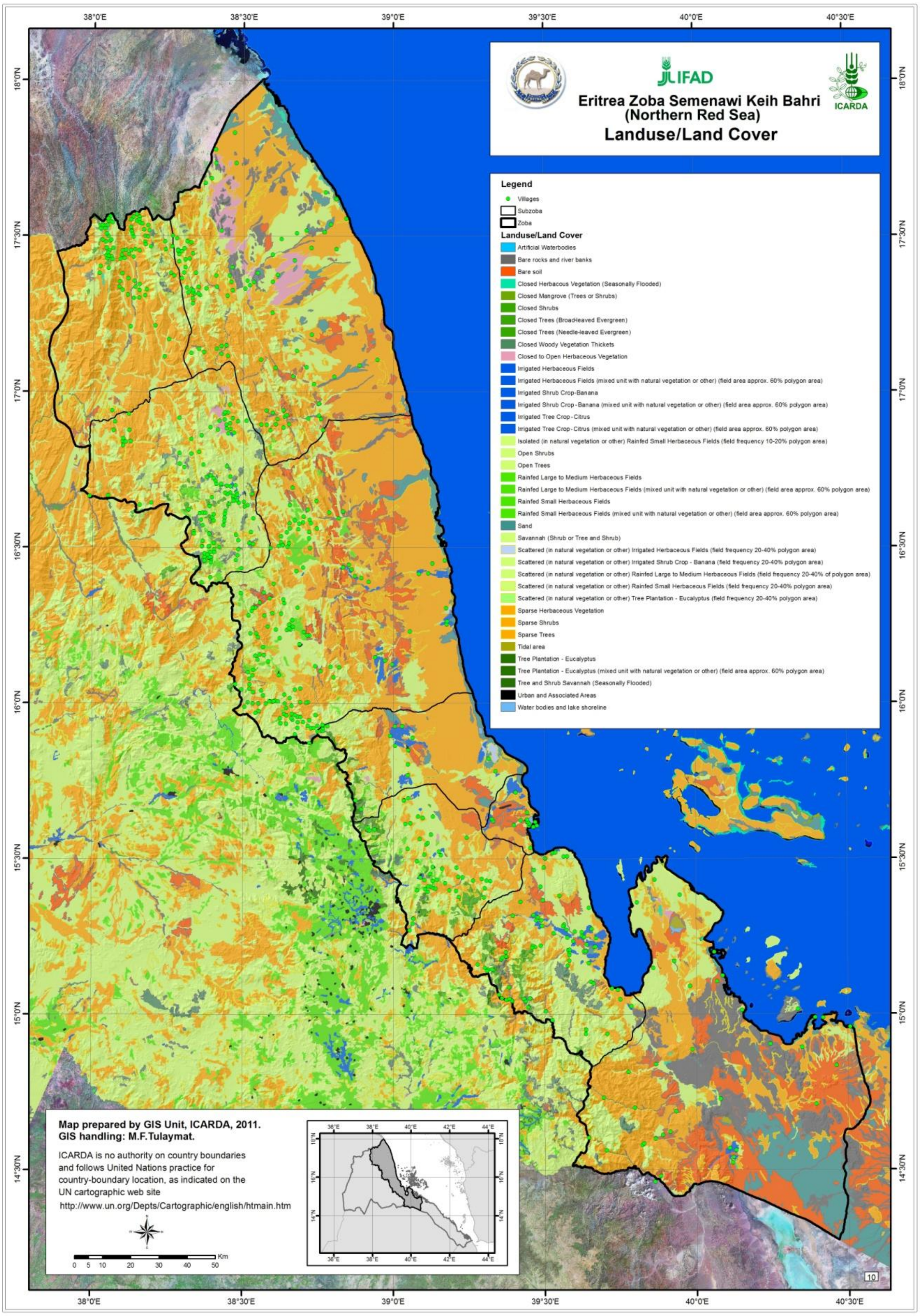
Map 7. Mean annual precipitation



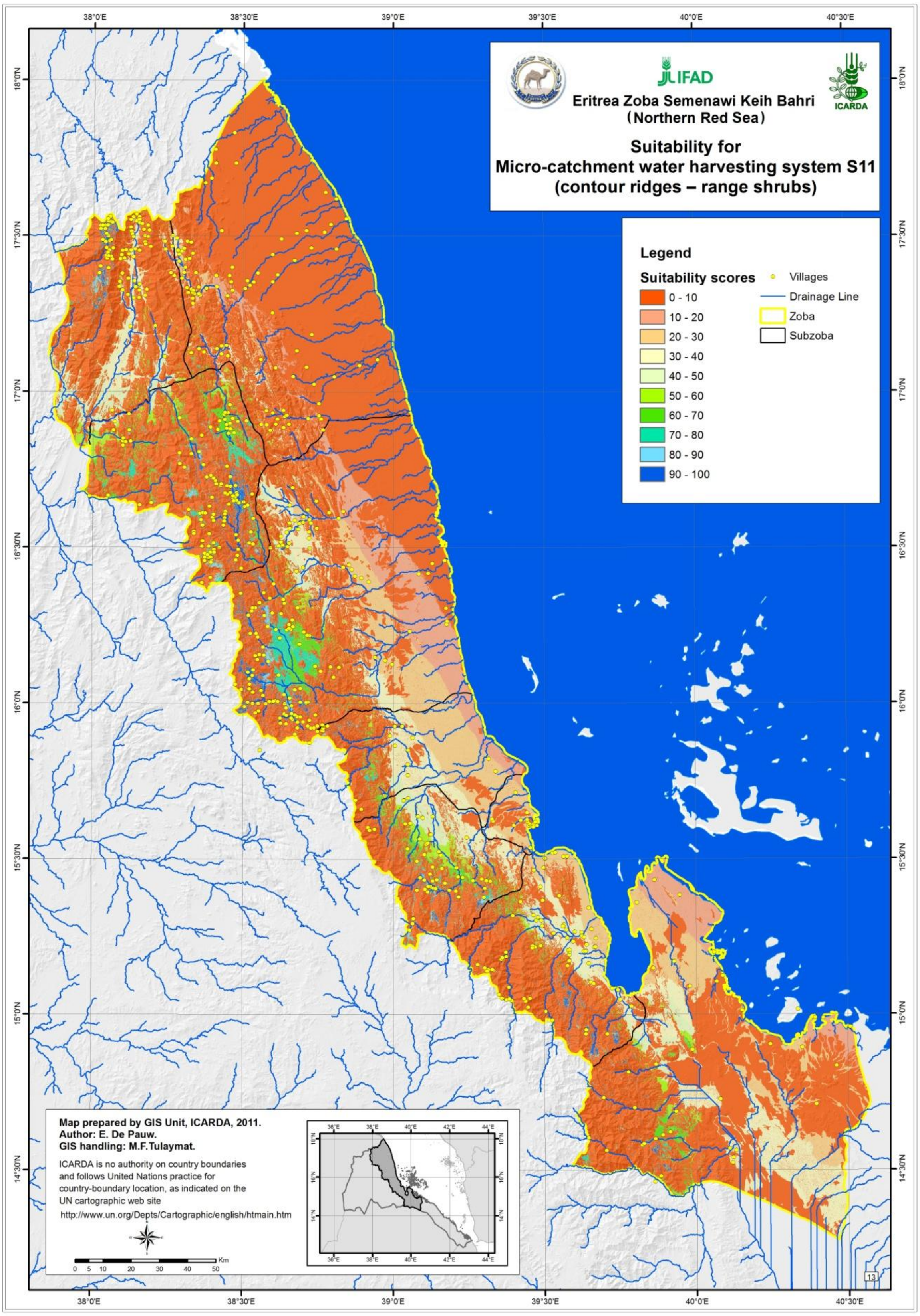
Map 8. Reliable annual precipitation



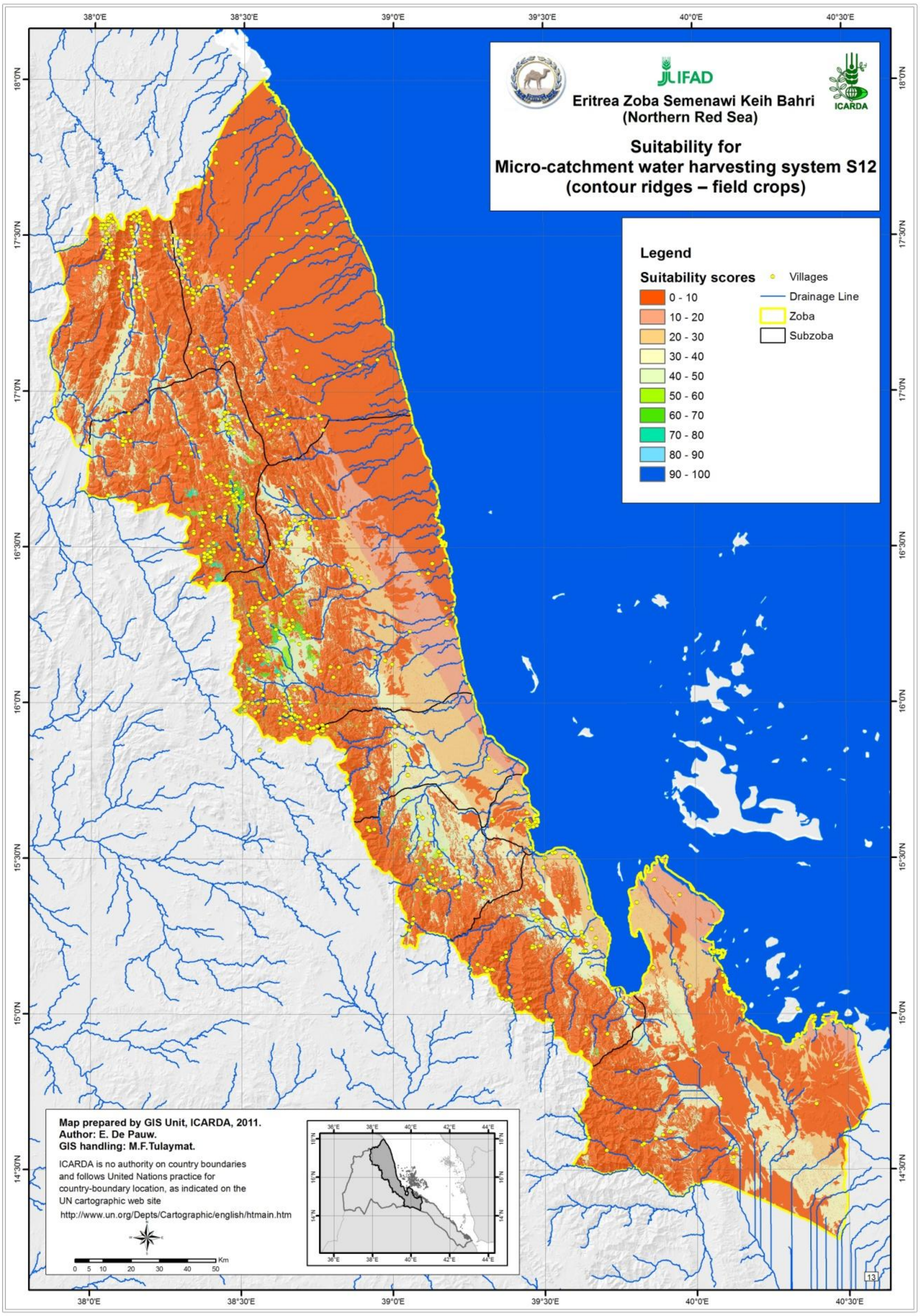
Map 9. Mean annual potential evapo-transpiration



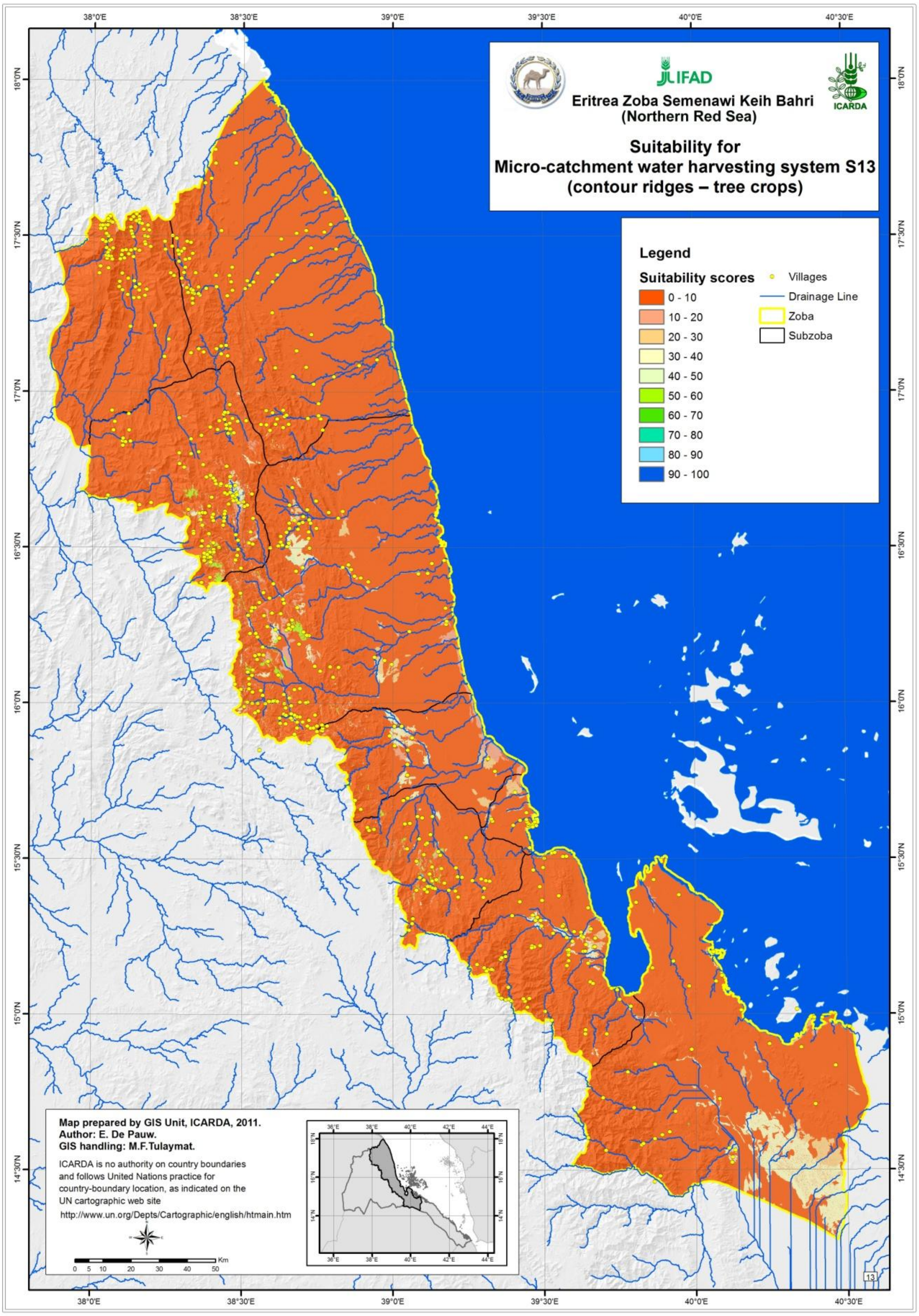
Map 10. Land use/land cover



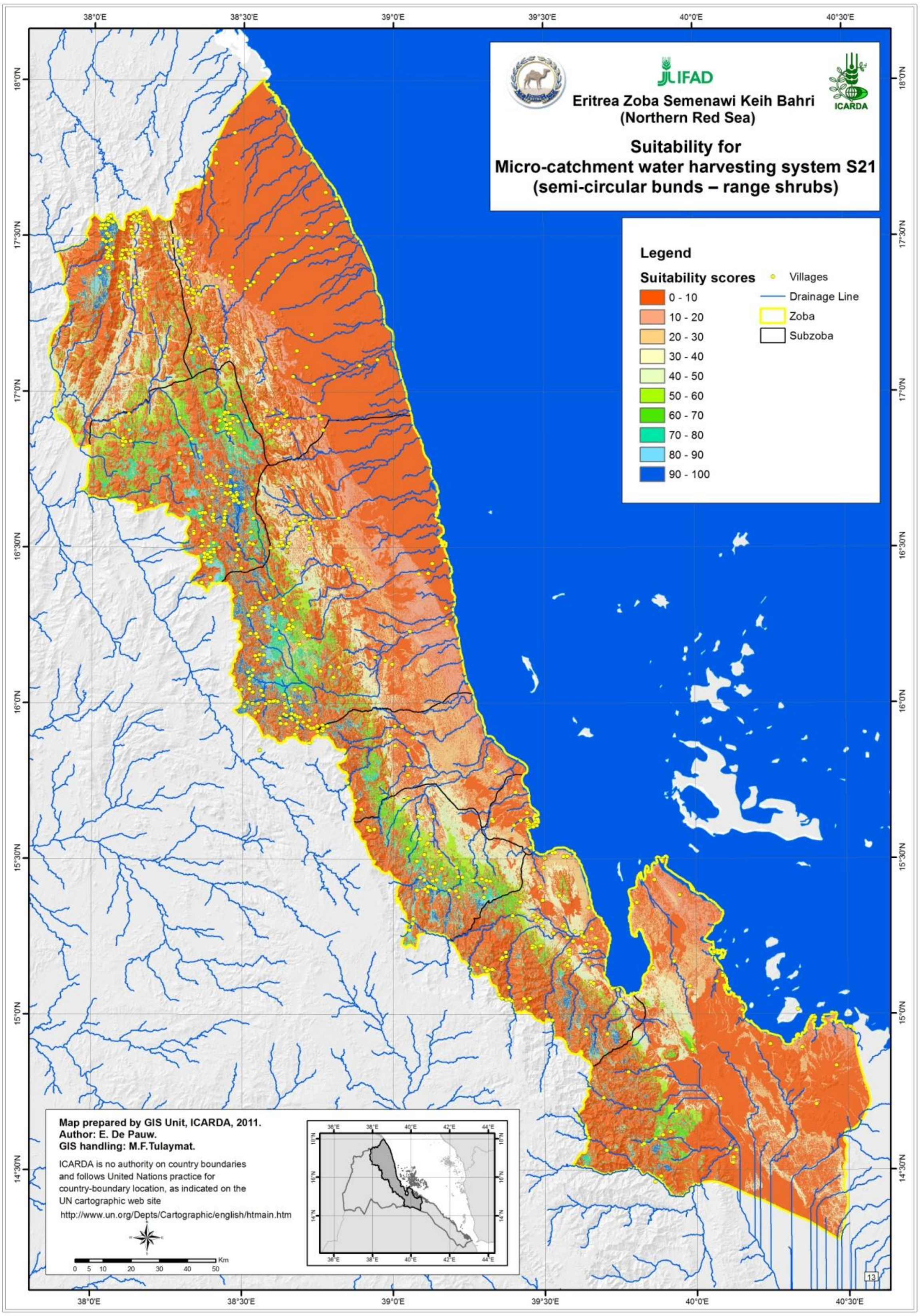
Map 11. Suitability for micro-catchment water harvesting system S11



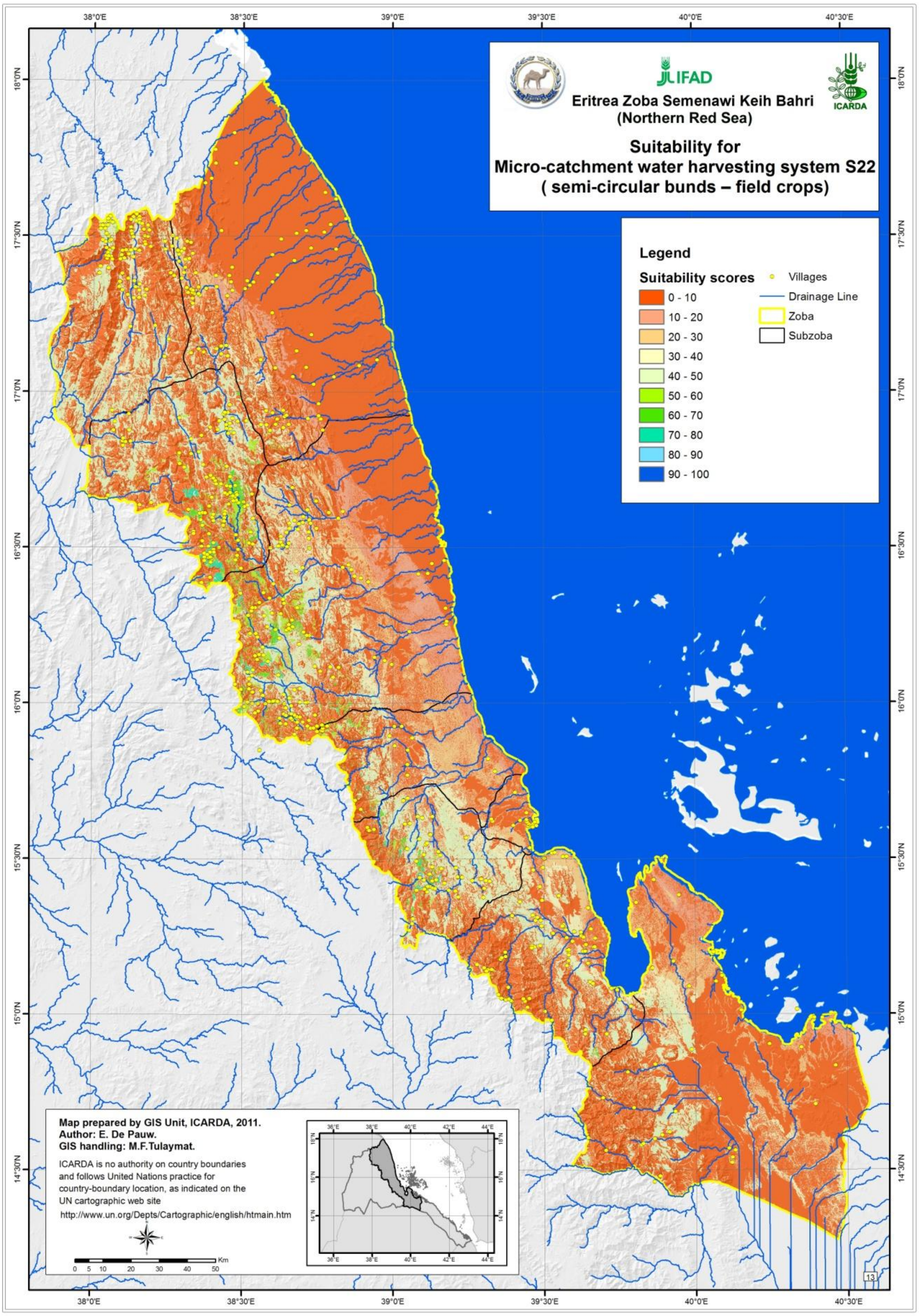
Map 12. Suitability for micro-catchment water harvesting system S12



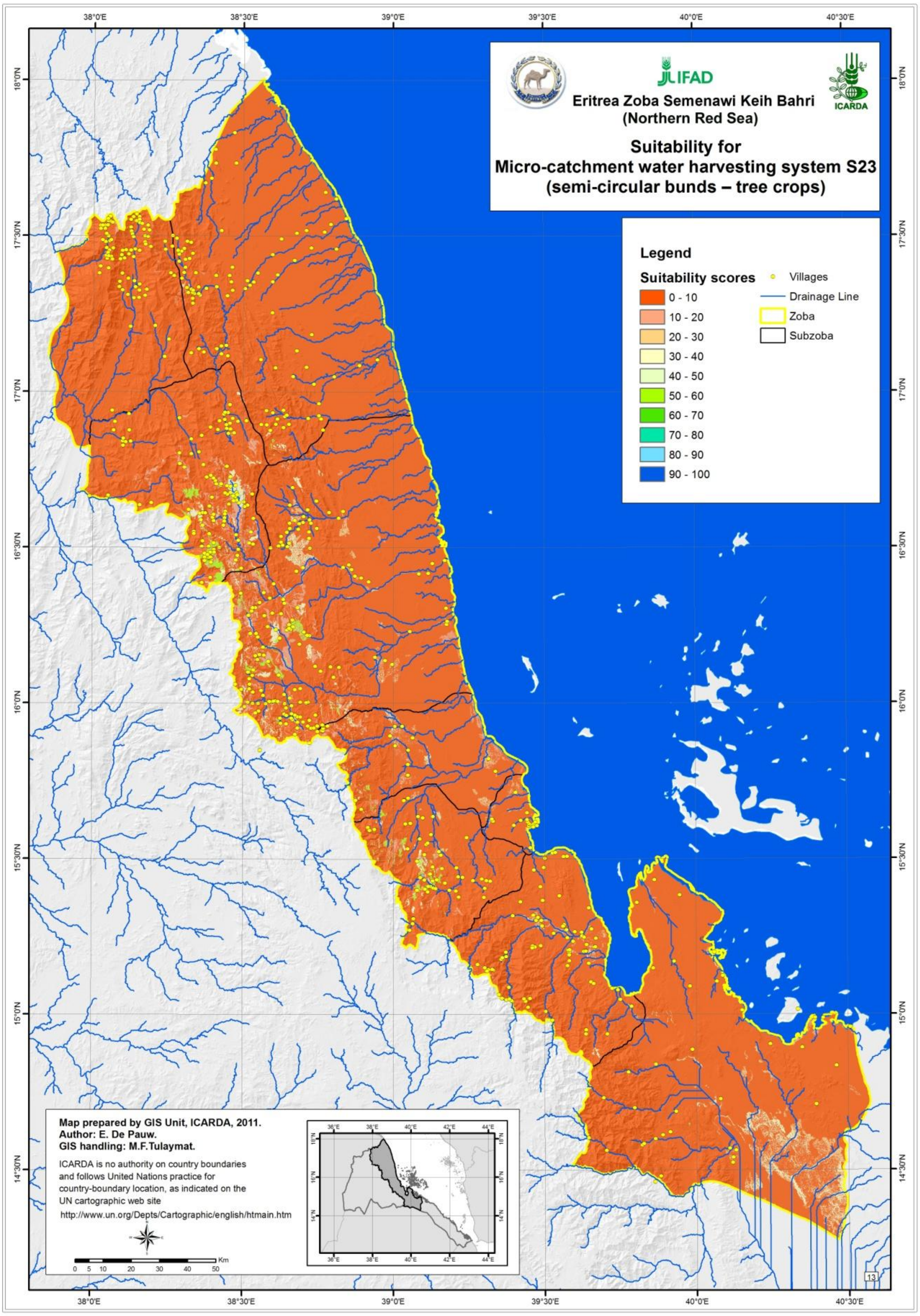
Map 13. Suitability for micro-catchment water harvesting system S12



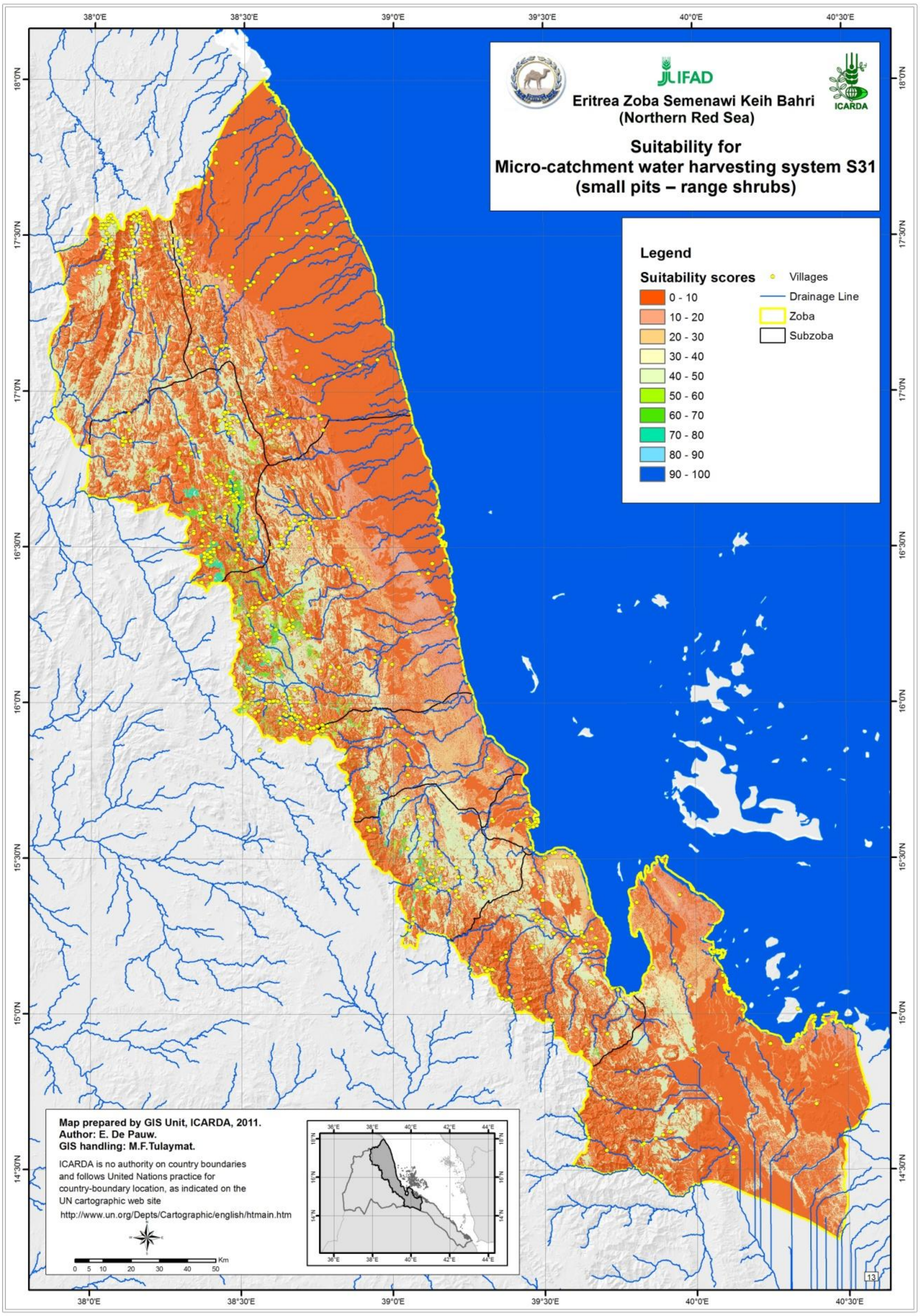
Map 14. Suitability for micro-catchment water harvesting system S21



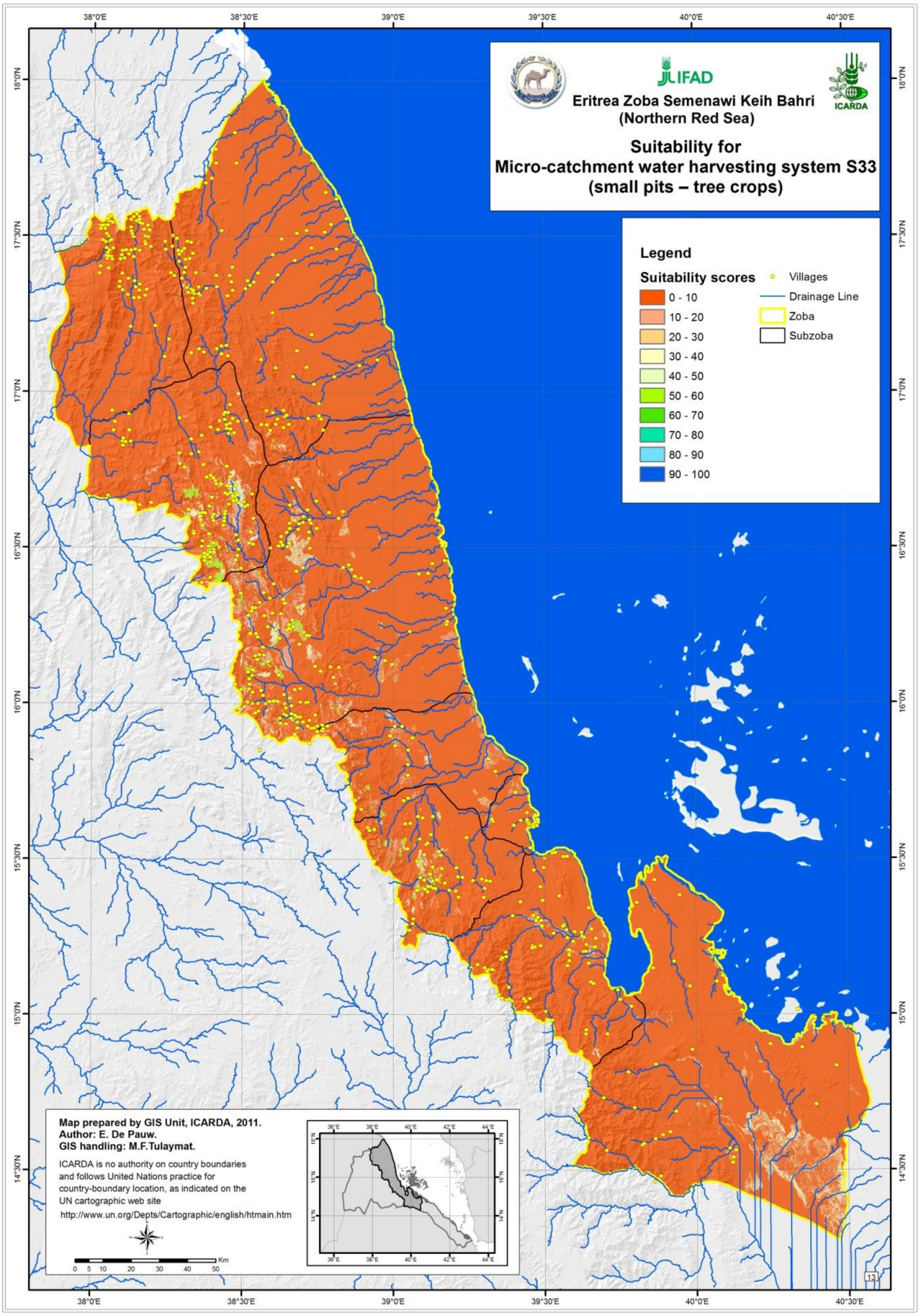
Map 15. Suitability for micro-catchment water harvesting system S22



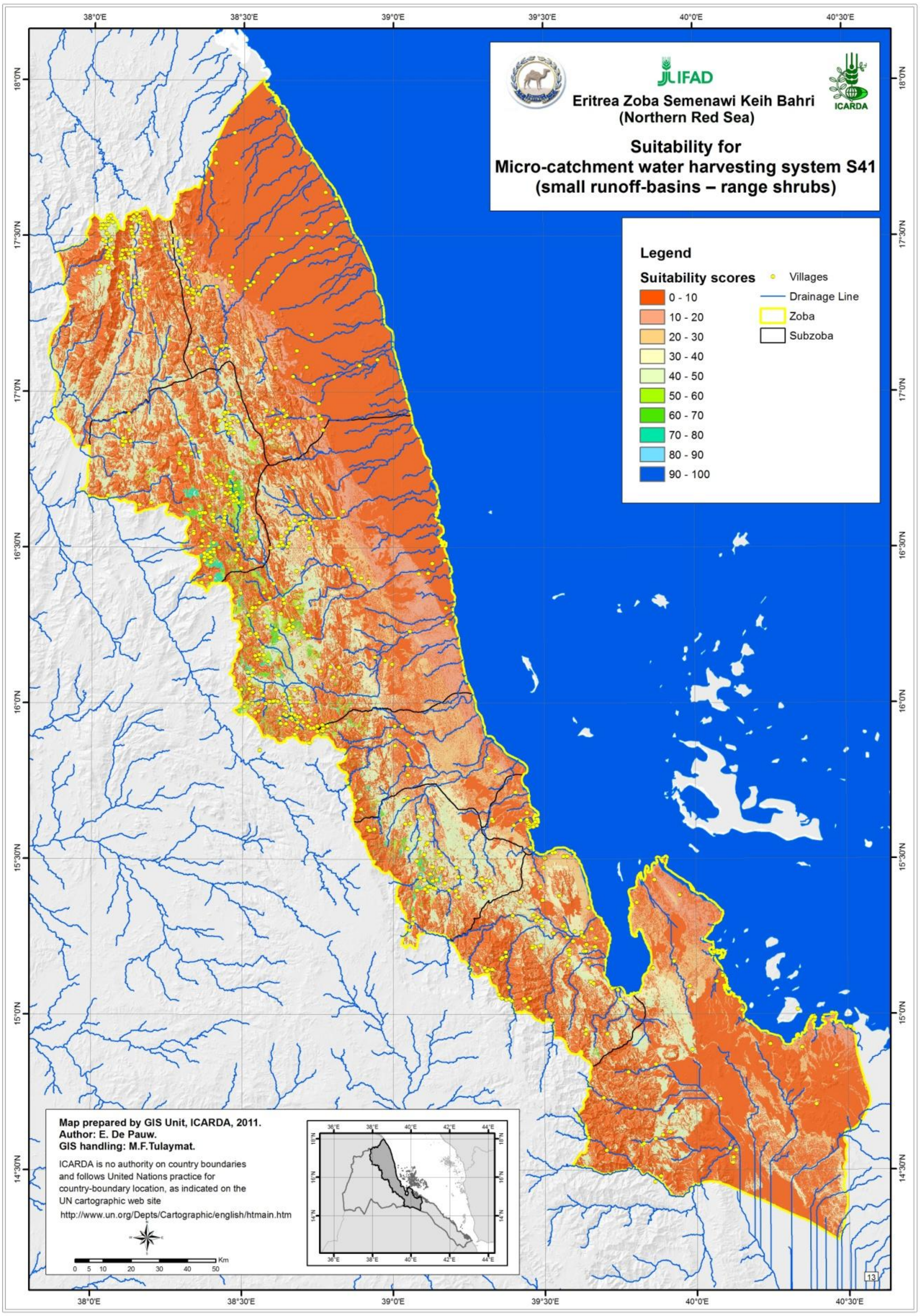
Map 16. Suitability for micro-catchment water harvesting system S23



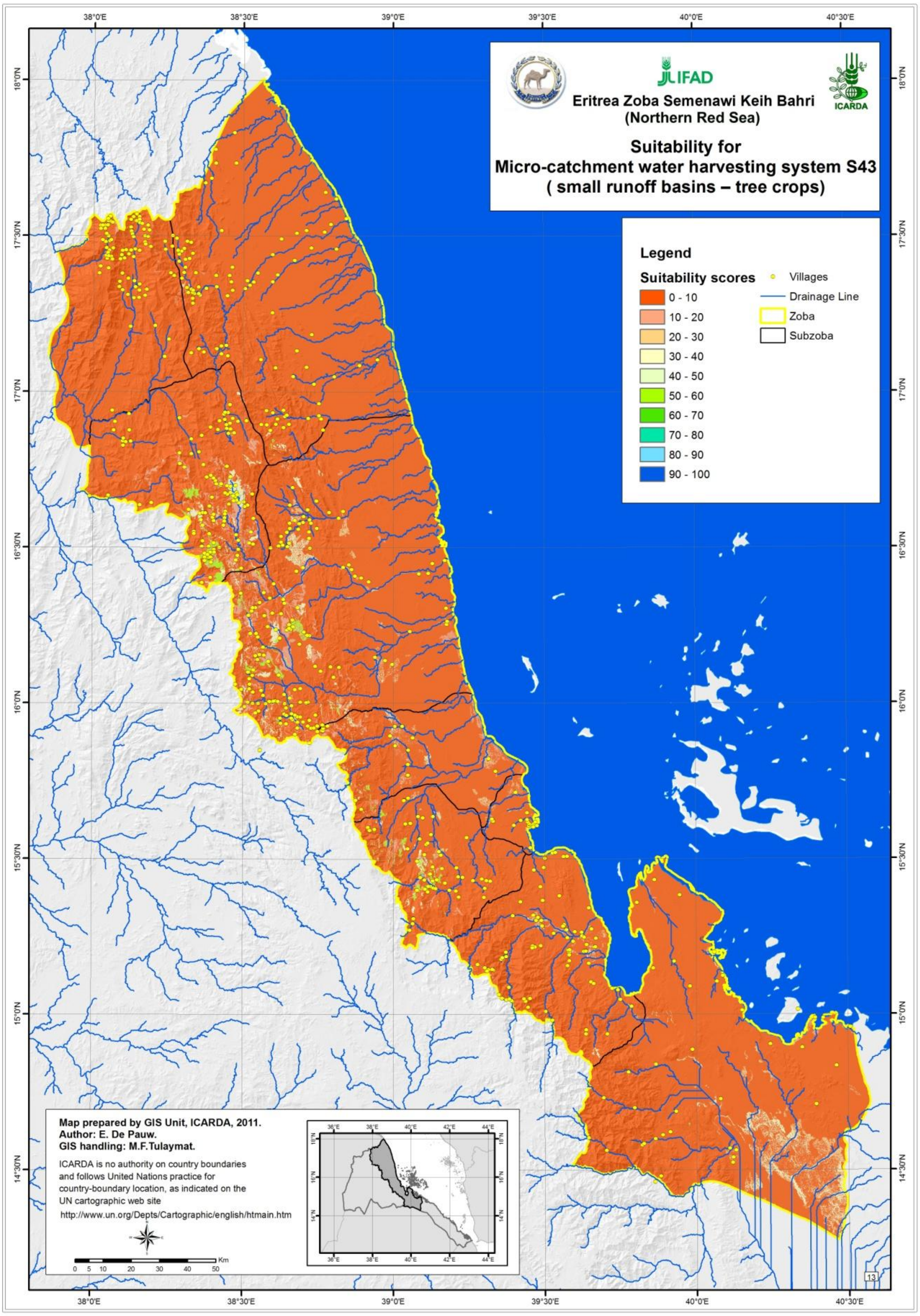
Map 17. Suitability for micro-catchment water harvesting system S31



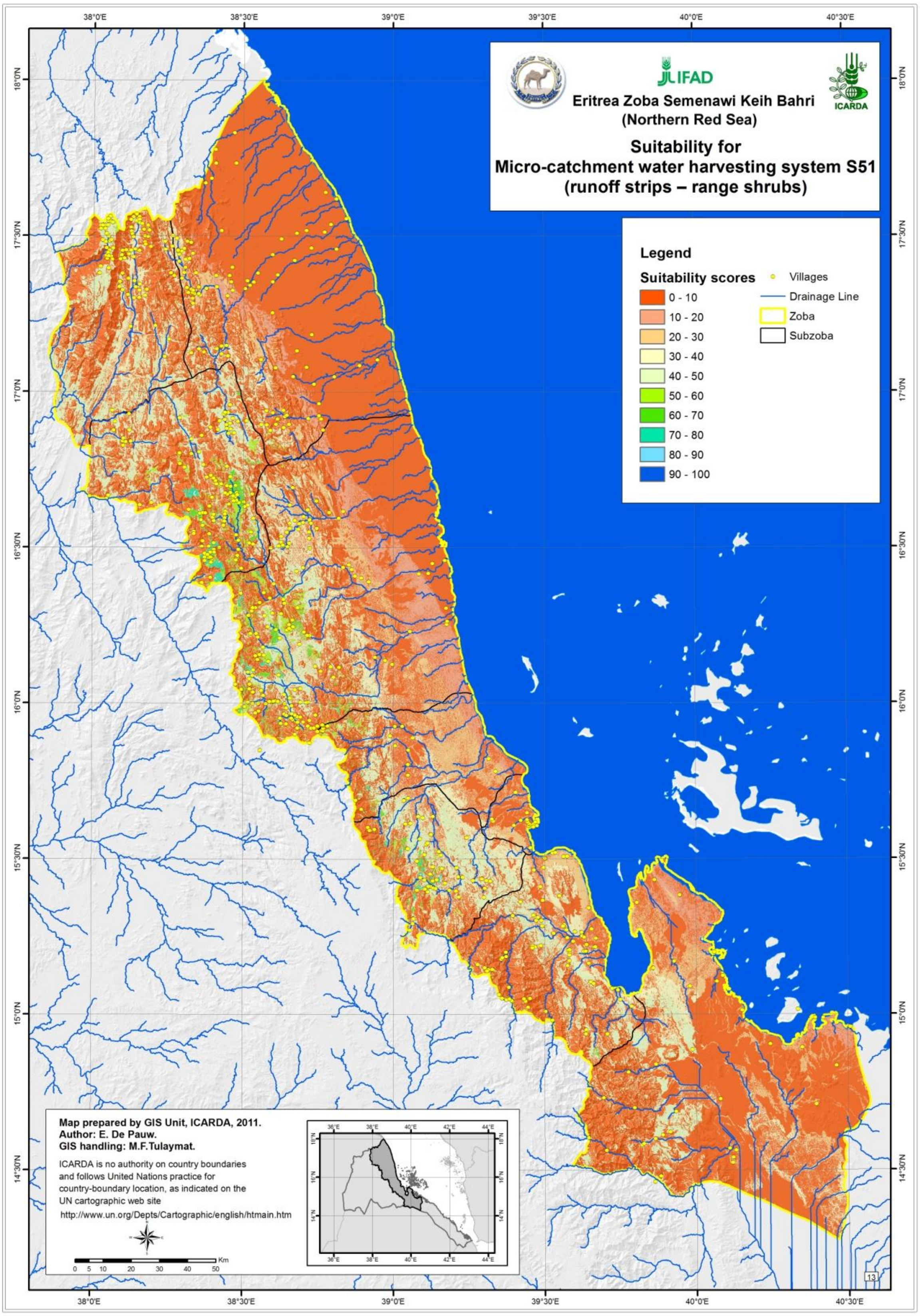
Map 18. Suitability for micro-catchment water harvesting system S33



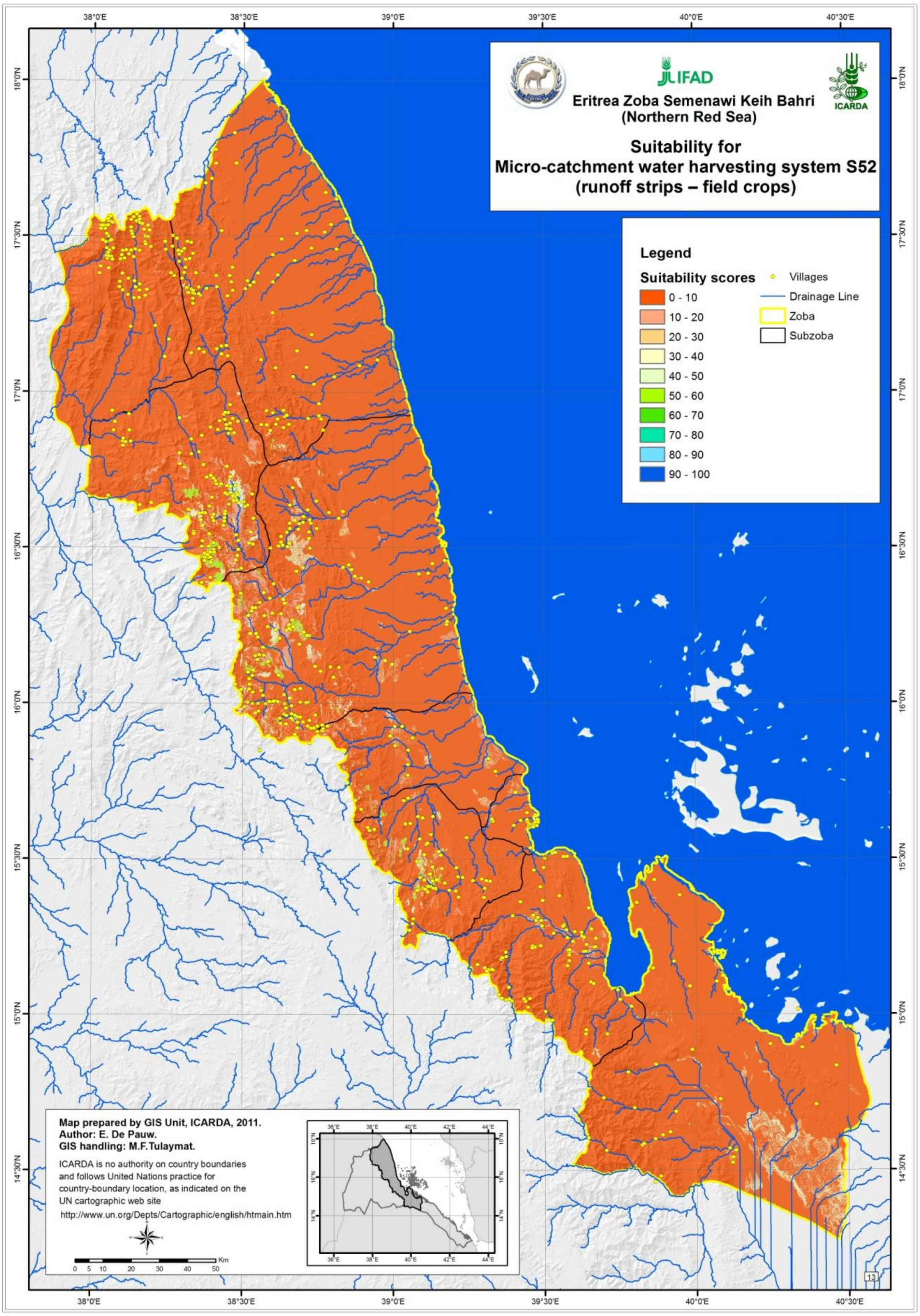
Map 19. Suitability for micro-catchment water harvesting system S41



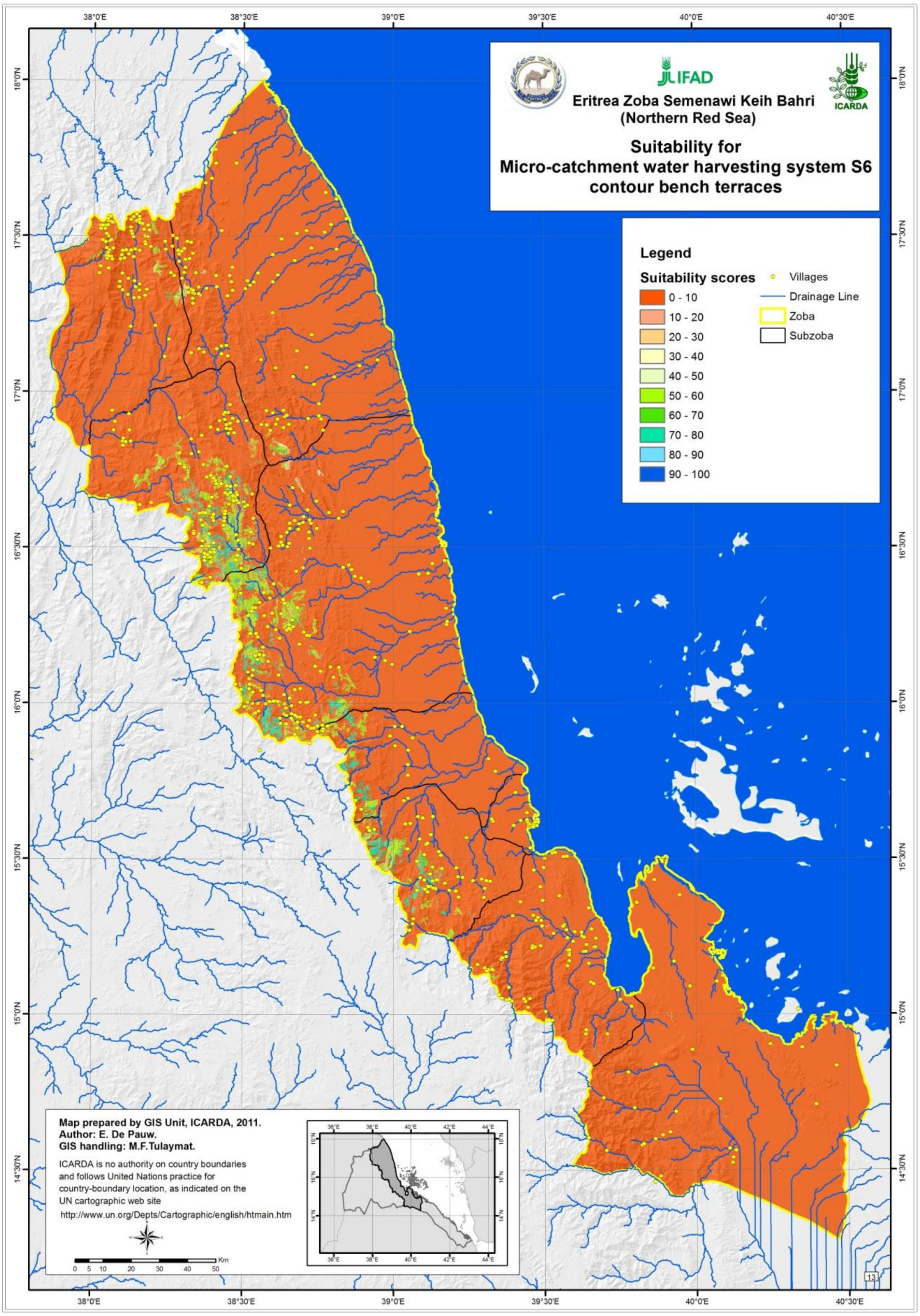
Map 20. Suitability for micro-catchment water harvesting system S43



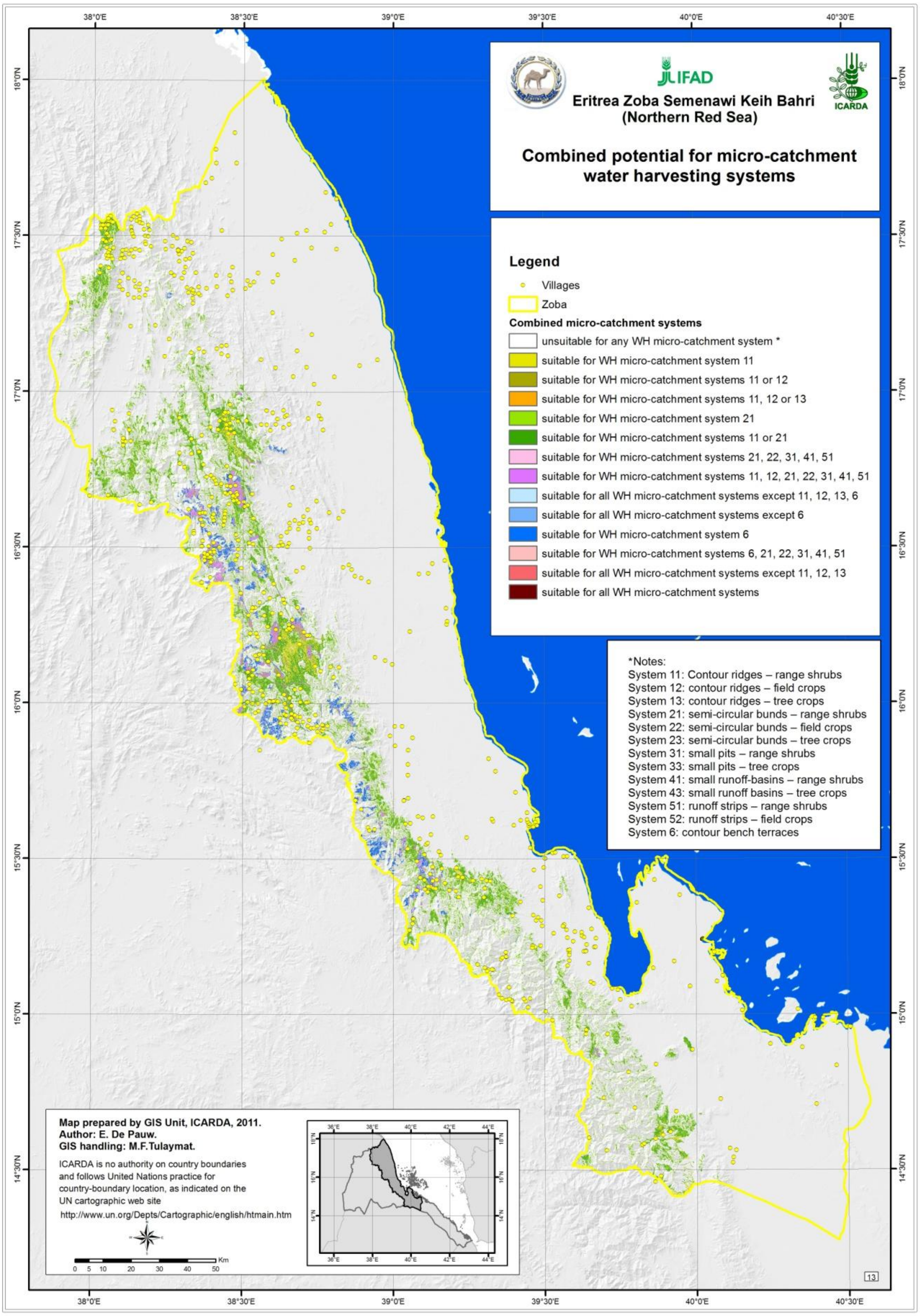
Map 21. Suitability for micro-catchment water harvesting system S51



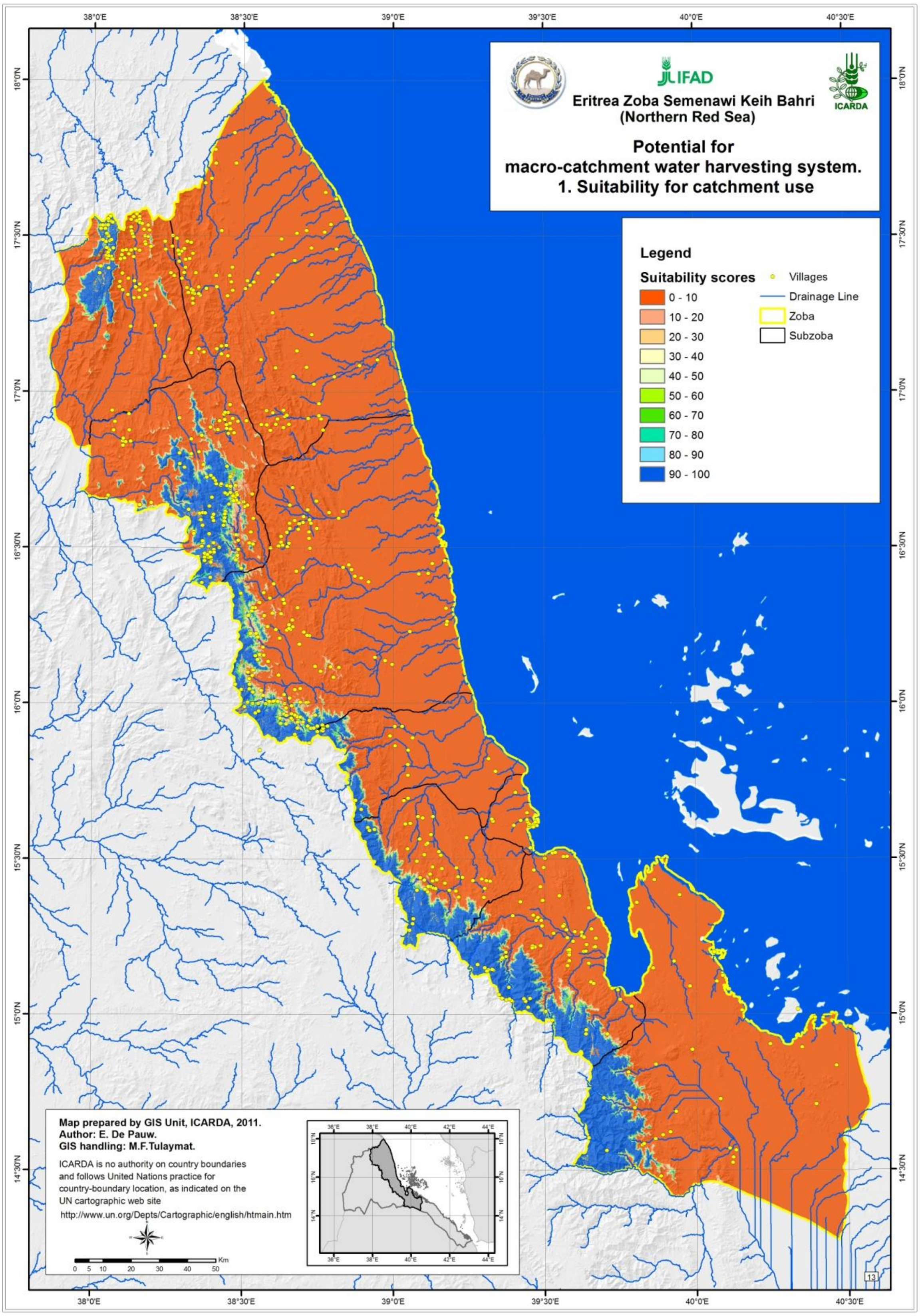
Map 22. Suitability for micro-catchment water harvesting system S52



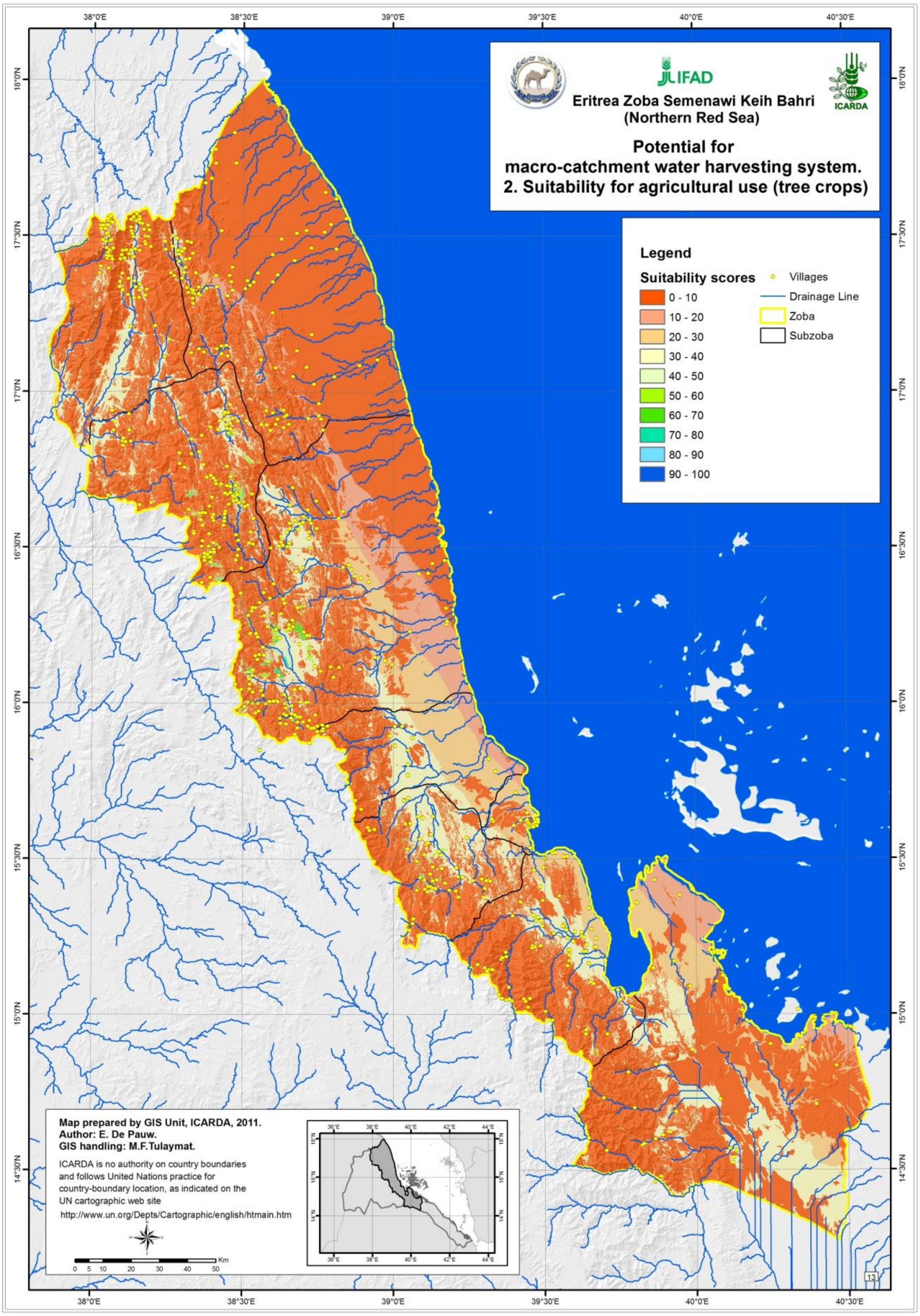
Map 23. Suitability for micro-catchment water harvesting system S6



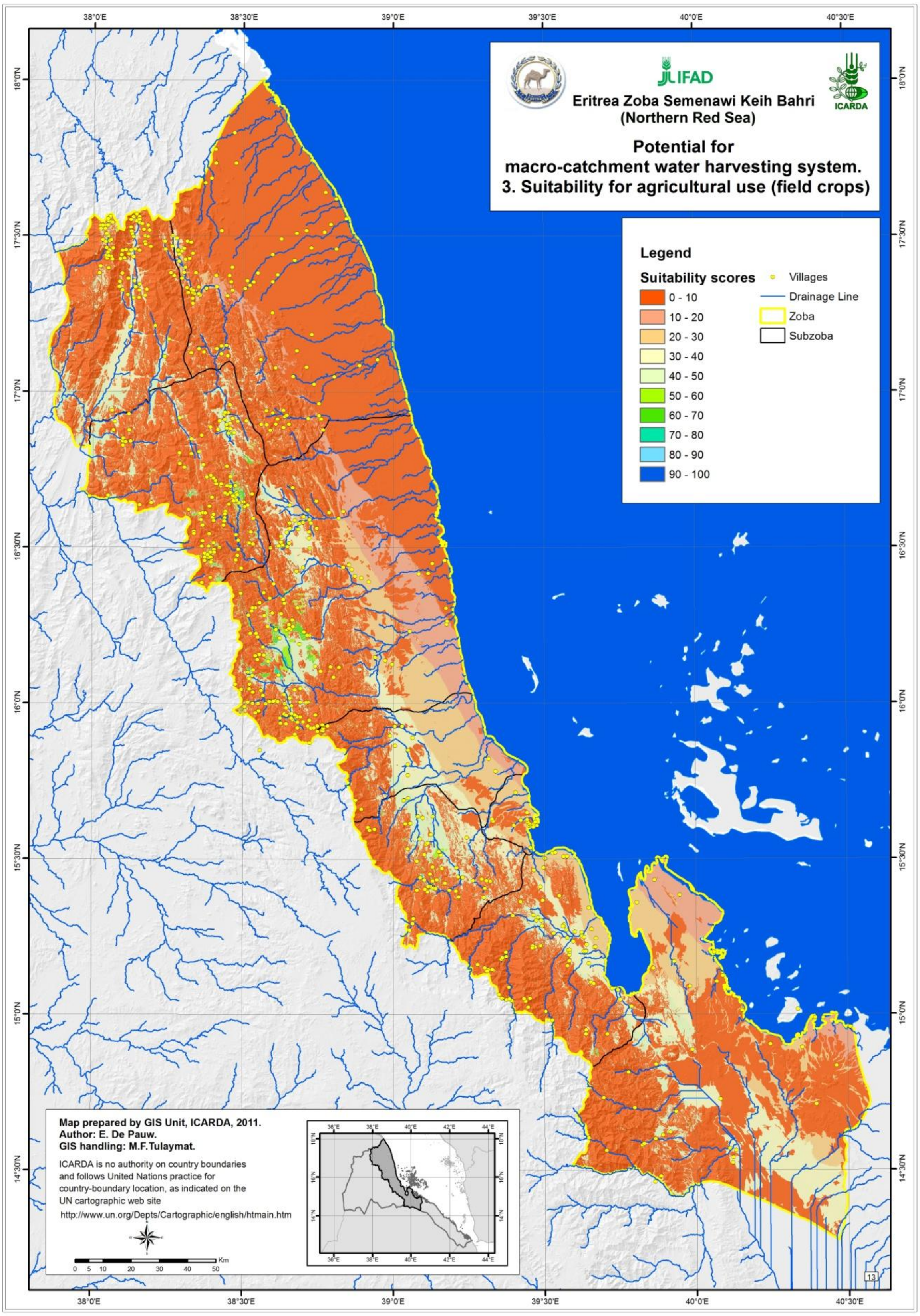
Map 24. Combined potential for micro-catchment water harvesting systems



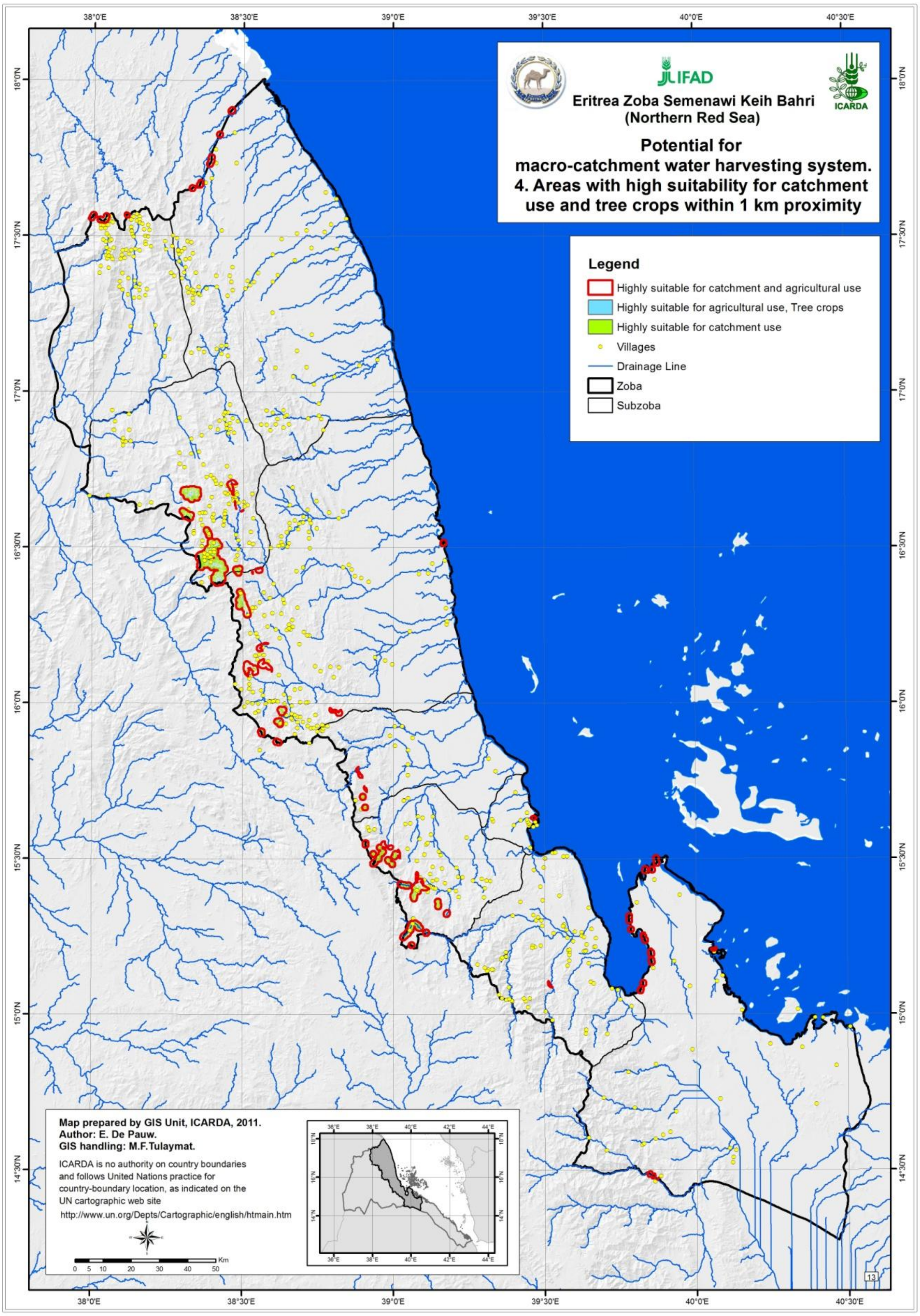
Map 25. Potential for macro-catchment water harvesting systems. 1. Suitability for catchment use



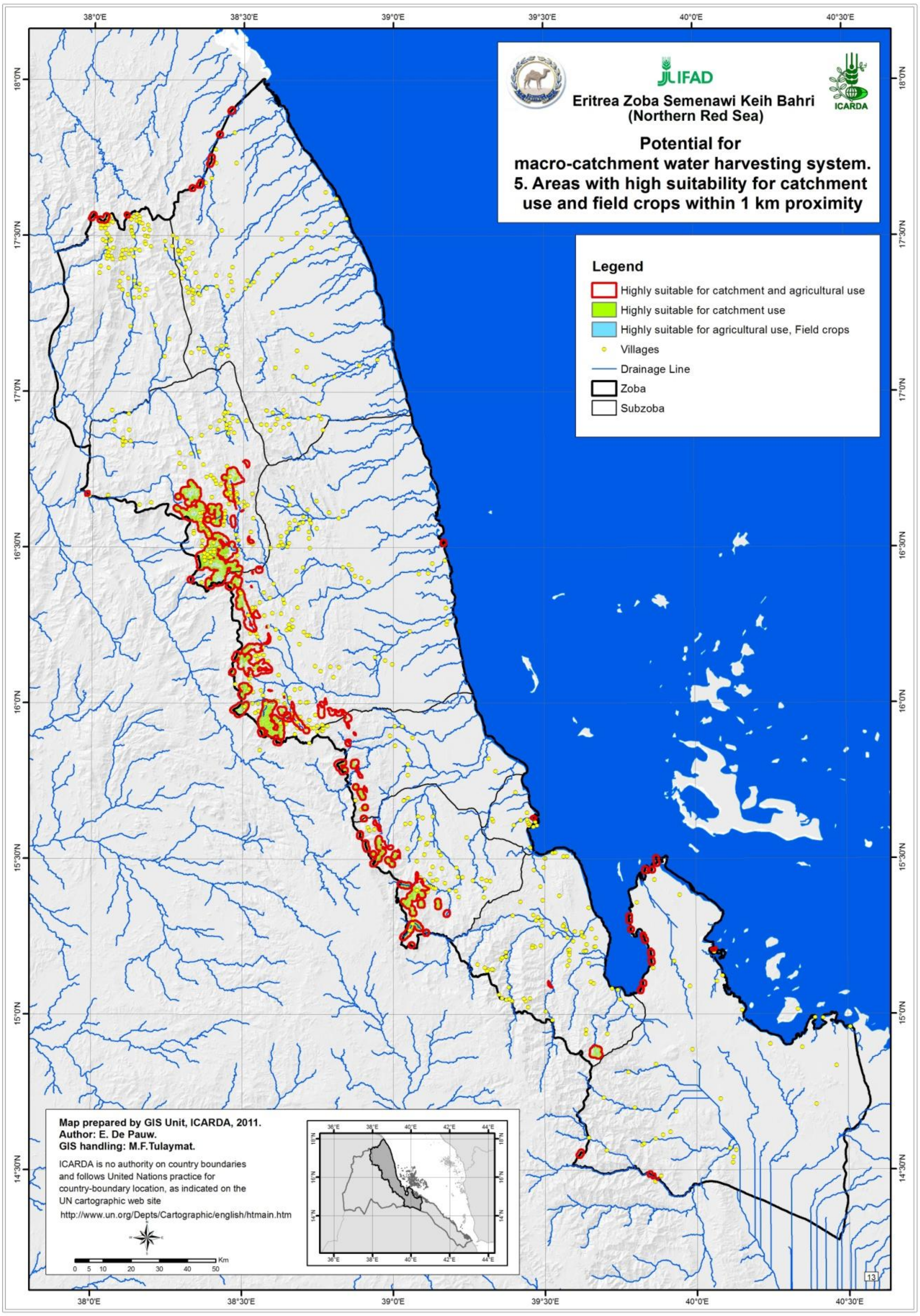
Map 26. Potential for macro-catchment water harvesting systems. 2. Suitability for agricultural use (tree crops)



Map 27. Potential for macro-catchment water harvesting systems. 3. Suitability for agricultural use (field crops)



Map 28. Potential for macro-catchment water harvesting systems. 4. Areas with high suitability for catchment use and tree crops within 1 km



Map 29. Potential for macro-catchment water harvesting systems. 5. Areas with high suitability for catchment use and field crops within 1 km