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Mapping Road Infrastructure in Developing Countries

Applying Remote Sensing and GIS – The Case of the Taita Hills, Kenya

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Tiivistelmä – Referat ◦ Abstract

Road transport and –infrastructure has a fundamental meaning for the developing world. Poor quality and inadequate coverage of roads, lack of maintenance operations and outdated road maps continue to hinder economic and social development in the developing countries. This thesis focuses on studying the present state of road infrastructure and its mapping in the Taita Hills, south-east Kenya. The study is included as a part of the TAITA-project by the Department of Geography, University of Helsinki.

The road infrastructure of the study area is studied by remote sensing and GIS based methodology. As the principal dataset, true colour airborne digital camera data from 2004, was used to generate an aerial image mosaic of the study area. Auxiliary data includes SPOT satellite imagery from 2003, field spectrometry data of road surfaces and relevant literature.

Road infrastructure characteristics are interpreted from three test sites using pixel-based supervised classification, object-oriented supervised classifications and visual interpretation. Road infrastructure of the test sites is interpreted visually from a SPOT image. Road centrelines are then extracted from the object-oriented classification results with an automatic vectorisation process. The road infrastructure of the entire image mosaic is mapped by applying the most appropriate assessed data and techniques. The spectral characteristics and reflectance of various road surfaces are considered with the acquired field spectra and relevant literature. The results are compared with the experimented road mapping methods.

This study concludes that classification and extraction of roads remains a difficult task, and that the accuracy of the results is inadequate regardless of the high spatial resolution of the image mosaic used in this thesis. Visual interpretation, out of all the experimented methods in this thesis is the most straightforward, accurate and valid technique for road mapping. Certain road surfaces have similar spectral characteristics and reflectance values with other land cover and land use. This has a great influence for digital analysis techniques in particular. Road mapping is made even more complicated by rich vegetation and tree canopy, clouds, shadows, low contrast between roads and surroundings and the width of narrow roads in relation to the spatial resolution of the imagery used.

The results of this thesis may be applied to road infrastructure mapping in developing countries on a more general context, although with certain limits. In particular, unclassified rural roads require updated road mapping schemas to intensify road transport possibilities and to assist in the development of the developing world.

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Kenya, Taita Hills, remote sensing, GIS, aerial photography, road transport, infrastructure, developing countries, spectrometry

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Tiivistelmä – Referat ◦ Abstract

Tieliikenteellä ja -infrastruktuurilla on keskeinen merkitys kehitysmaissa. Tiestön kattavuudessa, kunnossa, tienpidossa ja kartoituksessa on puutteita, jotka rajoittavat taloudellista ja sosiaalista kehitystä. Tämä tutkimus keskittyy tieinfrastruktuurin nykytilan tutkimiseen ja kartoitukseen Taita Hillsin alueella Kaakkois-Keniassa, sekä tiekartoituksen mahdollisuuksien arviointiin yleisesti kehitysmaissa. Tutkimus on osa Helsingin yliopiston maantieteen laitoksen TAITA-projektia.

Tutkimusalueen tieinfrastruktuuria tutkitaan kaukokartoitus- ja paikkatietomenetelmien avulla. Tutkimuksen pääaineistona ovat vuoden 2004 digitaaliset oikeaväri-ilmakuvat, joista muodostetaan ilmakuvamosaiikki. Lisäaineistona ovat SPOT–väärävärisatelliittikuva vuodelta 2003, tiepintojen spektrometrimittaukset, olemassa olevat kartta-aineistot sekä aihetta käsittelevä kirjallisuus.

Tiestö tulkitaan ilmakuvamosaiikin kolmelta testialueelta pikselipohjaisella ohjatulla luokituksella, objekti-orientoiduilla ohjatuilla luokituksilla sekä visuaalisella tulkinnalla. SPOT–kuvalta testialueiden tiestö tulkitaan visuaalisesti. Toisen objekti-orientoidun luokituksen tuloksesta tiestön keskilinjat ”irrotetaan” automaattisella vektoroinnilla. Lopuksi tieverkko kartoitetaan koko ilmakuvamosaiikin alueelta parhaiksi havaituilla menetelmillä ja aineistolla. Spektrometrimittauksien ja kirjallisuuden avulla tarkastellaan eri tiepintojen heijastusarvoja ja teiden spektraalisia ominaisuuksia ja tuloksia verrataan testattujen tulkintamenetelmien tuloksiin.

Yhteenvetona voidaan sanoa, että tieverkon luokittelu ja ”irrottaminen” on digitaalisilla menetelmillä vaikeaa ja tulokset epätarkkoja ilmakuva-aineiston korkeasta spatiaalisesta resoluutiosta huolimatta. Visuaalinen tulkinta ja digitointi on toistaiseksi yksinkertaisin, tarkin ja validein tutkituista menetelmistä. Tietyillä tiepinnoilla on koostumuksen ja rakennusmateriaalien takia samankaltaiset heijastusominaisuudet muun maanpeitteen- ja maankäytön kanssa, mikä vaikuttaa etenkin digitaalisten tulkintamenetelmien tuloksiin. Teiden kartoitusta vaikeuttaa myös runsas kasvillisuus, puiden latvuskerros, pilvet, varjot, heikko kontrasti ympäristöön ja teiden kapeus suhteessa käytetyn aineiston spatiaaliseen resoluutioon.

Tämän tutkimuksen tuloksia ja menetelmiä voidaan soveltaa tietyin rajoituksin myös laajempaan, kehitysmaiden tiekartoituksen kontekstiin. Erityisesti maaseutujen luokittelemattomat tiet ovat ajantasaisen tiekartoituksen tarpeessa tieliikenteen tehostamiseksi ja kehityksen edesauttamiseksi kehitysmaissa.

Avainsanat – Nyckelord ◦ Keywords
Kenia, Taita Hills, kaukokartoitus, paikkatiedot, ilmakuvaus, tieliikenne, infrastruktuurit, kehitysmaat, segmentointi, spektrometria

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ABBREVIATIONS

ASAL	Arid and Semi-Arid Lands
BBA	Bundle Block Adjustment
BRDF	Bidirectional Reflectance Distribution Function
CCD	charge-coupled devices
COMESA	Common Market for Eastern and Southern Africa
DCW	The Digital Chart of the World
DN	Digital number
DRC	District Road Committee
DEM	Digital Elevation Model
DTM	Digital Terrain Model
FWHM	Full-Width Half-Maximum
GCP	Ground Control Point
GDP	Gross Domestic Product
GIS	Geographical Information Systems
GPS	Global Positioning System
HELM	Historical Empirical Line Method
ILO	International Labour Organization
ITCZ	Intertropical Convergence Zone
KRB	Kenya Roads Board
KWS	Kenya Wildlife Service
MIR	Mid infrared (spectral region)
ML	Maximum Likelihood
MRP	Minor Roads Programme
MRPW	Ministry of Roads and Public Works
NN	Nearest Neigbourhood
NIR	Near Infrared (spectral region)
RARP	Rural Access Roads Programme
RMI	Africa Road Maintenance Initiative
RMLF	Road Maintenance Levy Fund
RMSE	Root Mean Square Error
RS	Remote Sensing
SSA	Sub-Saharan Africa
SSATP	The Sub-Saharan Africa Transport Policy Program
UNECA	United Nations Economic Commission for Africa
VIS	Visible (spectral region)

1 INTRODUCTION

1.1 TAITA PROJECT

This thesis is a part of the TAITA project, which is carried out by the Department of Geography at the University of Helsinki and funded by the Council of Development Studies of the Academy of Finland. The project leader and the coordinator is Professor Petri Pellikka. The general objective of the TAITA project is “development of land use change detection methodology in the East African highlands applying geographic information systems” (Pellikka 2004; Pellikka et al. 2004). The project focuses on various land use change issues in Taita Hills applying remote sensing (RS) data and geographical information systems (GIS). The main objectives of the project are to develop a cost-effective and practical land use change detection methodology and to create a geographic database for the land use and its changes in the area (The Taita Project 2006). This thesis focuses on land use issues in terms of the road infrastructure and state of road network in the Taita Hills. In addition, remote sensing and GIS methodologies and data issues are taken into deep consideration in the context of this study.

In 2006, the TAITA project moved on to a second phase, TAITATOO (2006-2009), which “focuses on the application of the compiled geographic database of land use and land cover for conservation and biodiversity studies” (The Taita Project 2006). The groundwork – the base land cover data and the research results – achieved in the first phase of the Taita project will be applied to the TAITATOO project.

1.2 AIMS OF THE STUDY

This thesis has five principal aims:

1) To describe the present state of the road transport and the road infrastructure in Kenya and in the Taita Hills.
2) To define the meaning of the functional road transport and road infrastructure in developing countries.
3) To study the possibilities of a GIS and remote sensing based methodology in the road mapping of the Taita Hills.
4) To map and update the road infrastructure of the Taita Hills.
5) To analyse the strengths and weaknesses of the applied GIS and remote sensing based methods in the more general context of road mapping in developing countries.

The first objective is achieved with background information on Kenya and the Taita Hills: their special features, transport history, road administration and road management. The road infrastructure of the Taita Hills is considered in terms of its present extent and condition, to understand the meaning of the functional road transport for the general development in the region.

The second aim is closely related to the first objective. By means of studying the road transport and the road infrastructure of Kenya and Taita Hills, the wider purpose is to describe generally the meaning of road infrastructure and the status of functional road transport as an indicator of development in the developing world.

The third aim is implemented with the experiment and comparison of different methods and data at different scales. Various digital and visual techniques are tested to find the best options available for the road mapping of the Taita Hills.

The fourth objective is implemented as a consequence of the third objective. The methods found to be best for this purpose, and within the limits of the available data, will be applied to update the existing road infrastructure data layer of the Taita Hills and to acquire information about the theme of the first objective.

The fifth aim is closely related to the third and fourth objective. The results of the Taita Hills road mapping are used to discuss generally the possibilities of these methodologies in the road mapping of the developing countries. The main questions related the last three objectives are:

The objectives from three to five are strongly methodology-orientated - that is to say, one principal aim of this study is to set various remote sensing data and techniques for trial in context of the road mapping, to analyse the results with each other and in a wider context.

1.3 THE STRUCTURE OF THE THESIS

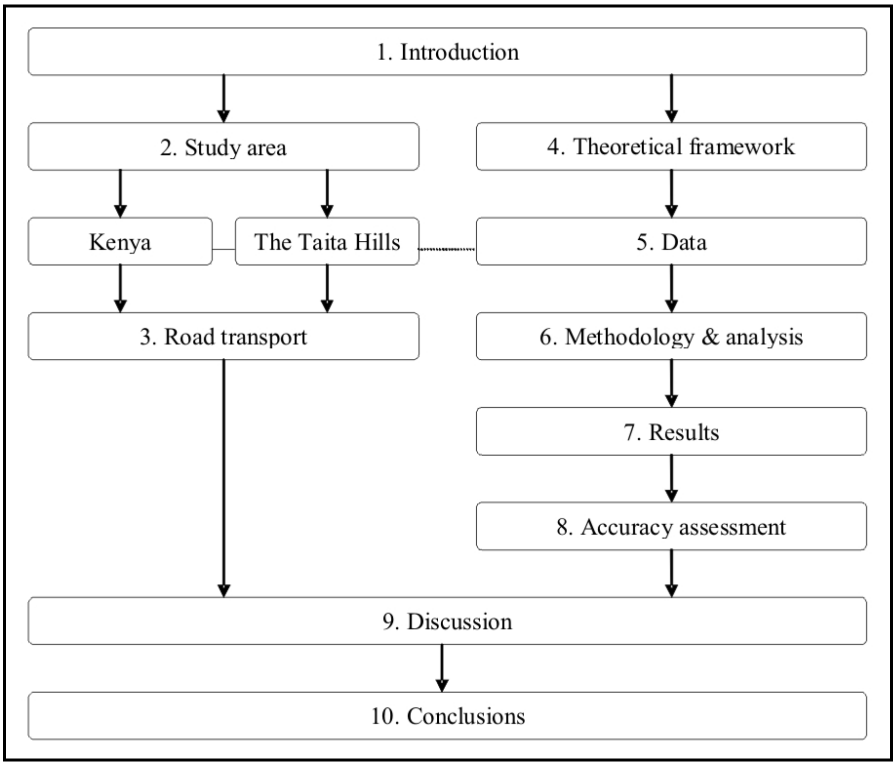

Figure 1. The structure of the thesis.

The thesis is formed around the two major subject matters: the concept of road transport and the theoretical framework of RS & GIS methodology. The study is structured into ten main chapters (Figure 1). The major subject matters are considered to some extent separately but, however, both concepts have common introduction, discussion and conclusions chapters.

The first chapter gives an introduction to the main concepts with the aims of the study and with the outline of transport and road transport in the developing world. In addition, the potential of the methodology applied to the thesis is discussed generally. Second and third chapters form the first part of the thesis. At the beginning, the geographical facts of Kenya and the actual study area Taita Hills are presented in the second chapter from the perspective of road transport and infrastructure. Road transport of Kenya and the Taita Hills are then considered with more detail in chapter three where background information of history, development and present state of road transport is given with the personal experiences of the author.

Chapters from four to eight constitute the second, methodology-oriented part of the thesis. Chapter four presents the theoretical framework of a GIS and RS based methodology in the context of road mapping. Chapter five introduces the characteristics of the data applied to the research, and chapter six outlines different methods and analysis techniques that are considered step by step from pre-processing and visual interpretation to more sophisticated, semi-automated techniques of road extraction. Chapter seven presents briefly the results of the pre-processing and analysis on each main step of the procedure, and the accuracy of the results is assessed in chapter eight.

Finally, both the main topics of the thesis are discussed in chapter nine. Results of the different methods and analyses are considered with experiences in the field, previous studies and other relevant literature. In addition, the results are reviewed in the wider context of the theoretical framework and road transport in the developing world. The last chapter ten concludes the study.

1.4 TERMINOLOGY AND CENTRAL CONCEPTS

1.4.1 INFRASTRUCTURE

Infrastructure is generally defined a set of interconnected structural elements, utilities and services – such sectors of economy and society as transport, water and sanitation, power and electricity, telecommunications, irrigation, health care, education and other basic services – that provide the framework for supporting people's daily life operations. Furthermore, infrastructure is divided as *economic* infrastructure, also referred as public utilities, and *physical* infrastructure that is the actual set of interconnected, structural elements that provide the framework for supporting the entire structure of basic services and public utilities essential to the commodity-producing sectors of an economy. Physical infrastructure includes the transport networks that are used, as well as the nodes or terminals.

Here, the concept of infrastructure is discussed since road transport, road infrastructure and roads are a crucial part of the transport and infrastructure sectors in the developing world, as well as in the developed world. Infrastructure, transport and development have complex linkages to each other, and this central concept of the thesis is reviewed in chapter 1.4.4.

1.4.2 TRANSPORT

"Even in the most remote and least developed parts of inhabited regions, transport in some form is a fundamental part of the daily rhythm of life" (Hoyle 1973: 9). Transport – also referred as transportation - is a basic human activity and it includes the movement of people, goods and information from one place to another. In a wider sense, transport is a context of complex interrelationships that exist between physical environment, patterns of social and political activity, and levels of economic development. The purpose of transport is to provide accessibility or the ability to make a journey for a specific purpose (Nutley 1998). Transport is not consumed for its own sake, but the demand of transport is usually derived, and the main motivation in the demand for transport is economic (White & Senior 1983:1). Transport is a central dimension of the local, regional and global economies that are reshaping the world. It is the major factor interlinked with the environment and with the spatial distribution and development of all other forms of economic and social activity (Hoyle & Knowles 1998: 1).

There are two dimensions of transport, space and time (Hawkins 1962). Transport is not only a basic human activity but movement in space as well (White & Senior (1983: 1). In terms of the space dimension, good transport means cheap movement of goods through space from the point of production to the point of consumption, thus having the effect of widening markets and economic growth. In the time dimension, markets can be served on a larger scale in big economies because capital in the forms of stocks, work in progress and finished goods can be turned over more quickly (Hawkins 1962). New modes of transport have dramatically changed the time and space dimensions of travelling, providing notably faster connections between distant regions, even across national and continental boundaries, than often exist between places within the same country or even sub-national region which are far closer together in terms of physical distance (Simon 1996: 29). These new trends have led to changing geographies of production, distribution and consumption, different delineations of the world with differing degrees of integration with, or marginality to, such technologies and processes.

1.4.3 ROAD TRANSPORT, ROAD INFRASTRUCTURE, ROADS

More than any other mode of transport, road transport has improved the mobility and accessibility of the majority of the world’s population (Hoyle & Smith 1998: 32). The field of road transport can loosely be divided into *infrastructure, vehicles,* and *operations*, and this triad of the elements applies to other modes of transport as well. The vehicles generally ride on the networks while the operations deal with the control of the system.

The essential features of infrastructure are *nodes*, *linkages* and *hierarchies* (Dickenson et al. 1996: 234). Road infrastructure is a set of roads (*linkages*) which are organised as a network connecting all areas inhabited and exploited by human beings. The denser the area is inhabited and the more intensively used, the denser the road network is. A road is a strip of land, smoothed, paved, or otherwise prepared to allow easy travel, connecting two or more destinations (*nodes*). Roads are arranged in a *hierarchy* of different categories with different attributes based on the importance and the function of a road. Furthermore, according to the different categories, roads differ with respect to width, construction and paving material, minimum curvature radius and maximum allowed slope. There is a wide variety of road hierarchies and categories due to the different functions and characteristics of roads. In general, roads are classified into three levels:

1) Highways, national, main or primary roads that connect strategic points (e.g. capital and cities).
2) Departmental, provincial, regional or secondary roads that connect regions with the country and are feeder routes that provide the main links between highways, national, main or primary roads.
3) Municipal, local and tertiary roads including urban and rural roads that connect towns within one province or provide basic access of rural areas.

On occasion, there is a fourth level of classification, if the “international roads” class is included in the categorisation as well. Furthermore, international, national and primary roads are sometimes grouped as “trunk roads”, while local and tertiary roads are referred to “minor roads”. In addition, there is a wide variety of *unclassified* roads that include urban and rural roads, tracks, paths etc. Term “unclassified” refers to the administration of these roads: the roads are not typically managed by the major road sector parties - that deal with the classified road network - but lower level or other road administration parties. These roads are often most essential at a local level and in daily life to enable people’s and goods’ mobility and to provide access to basic services.

The main reason for building a new road is to create or improve road transport between two or more nodes and to attain benefits related to certain level of economic and social development that generally occurs with the road construction. Roads are built to make accessible new settlement areas, services or other functions and to connect such areas to the existing road network but also to relieve existing roads from too much traffic. On the other hand, the construction of a new road does not inevitably guarantee that development will follow; there is no necessary or direct causal relationship between infrastructural improvements and development (Simon 1996). On the contrary, previously remote, self-reliant areas and communities may suffer if they are integrated into wider systems in which they have marginal status in many ways (ibid.). In addition, if there are not sufficient resources or demand for transport or there are other constraints or undeclared motives behind infrastructural expansion, the road construction may result in negative impacts.

In this thesis, road transport is mainly reviewed in terms of road infrastructure: the extent, condition and meaning of the functional infrastructure for road transport. The term road network is used more or less as a synonym for road infrastructure. In addition, vehicles are studied to some degree while controlling operations are excluded in the consideration. The term road traffic, which refers to the movement of motorised or unmotorised vehicles and pedestrians on roads, is used as a synonym for road transport.

1.4.4 THE INTERRELATIONSHIP BETWEEN INFRASTRUCTURE, TRANSPORT AND DEVELOPMENT

Development, in its economic and social meaning, is a complex, multi-phases series of events influenced greatly by infrastructure and transport services. Infrastructure can deliver major benefits in economic development and poverty reduction and environmental sustainability (World Bank 1994). Furthermore, infrastructure contributes to economic growth and to raising the quality of life through reduced costs of production, employment creation and improved transport facilities (Kessides 1993). The existence of infrastructure increases the productivity of capital and labour, thereby described as an “unpaid factor of production” that leads to more efficient economies and to higher returns (ibid: 2). Poverty is reduced through the availability of infrastructure facilities, and respectively, individuals are poor when they are lacking access to services of the necessary quality. There exists a causality between economic development and infrastructure: higher incomes enables people to acquire better infrastructure facilities and, respectively, improved infrastructure leads to higher incomes (Kessides 1993: 18).

In recent decades, the transport field has been dominated by the perspective of the modernisation theory which sees transport and technological innovation as important and beneficial to the process of economic development (Simon 1996: 57). It is also generally proved that infrastructure promotes economic development most effectively in situations where there is already a high level of economic activity. The state of transport facilities is much poorer in the developing world than in the developed world, where transport infrastructure is more extensive, of higher quality and better maintained due to the better economic conditions. The developing world has most population of the world, but only a slight proportion of advanced transport facilities (e.g. motor vehicles and paved highways) are placed in these countries. Figure 2 shows the unequal distribution of roads between the different territories of the world. Territory size shows the proportion of all the roads in the world that are located there. Least roads are located in Central Africa, Southeastern Africa and Northern Africa. Figure 3 presents the uneven distribution of passenger cars in the world. Territory size shows the proportion of all cars in the world that are found there. There are 590 million cars in the world, that is to say one for every ten people. Fewest cars are in Central Africa, Southeastern Africa and in Northern Africa where there are under one passenger car per hundred people

Furthermore, appropriate location with good access through the physical infrastructure is a key factor for success of economic activities. The core areas of economy, industry, production and services are generally more beneficial than the more remote hinterlands. Therefore, developed countries have generally an advantage over the developing world and respectively, urban areas over the rural regions in the developing countries.

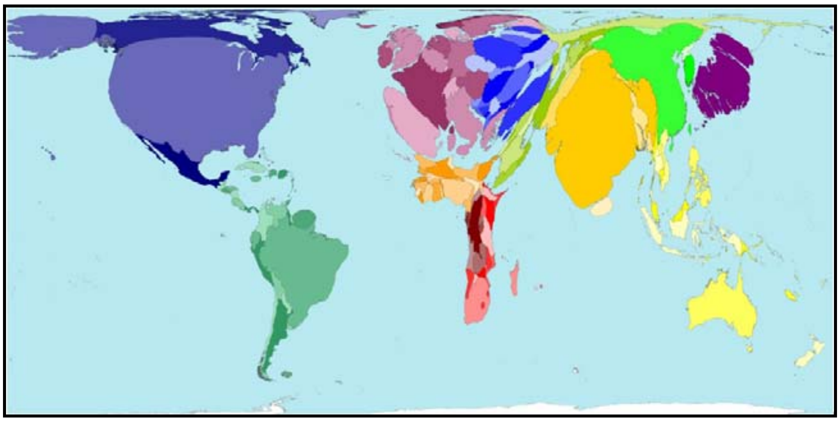

Figure 2. The unequal distribution of roads (total 29 million kilometres) in the world (in 2002) (Worldmapper 2007).

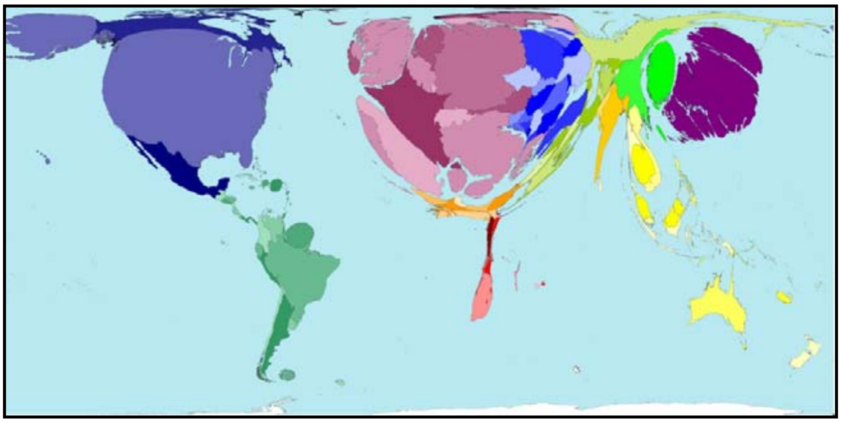

Figure 3. The unequal distribution of passenger cars in the world (Worldmapper 2007).

There is a huge mobility gap between the developed and the developing world closely related to economic progress, and this can be seen in the comparison between gross national product (GNP) per capita and transport facilities and traffic (Owen 1987: 7-12; Simon 1996: 2-6). Because the transport technological innovations were initially evolved in the developed world and exported rapidly to the different social, economic, political and environmental conditions of the developing world, the adoption of these technologies and the impacts of these innovations have been very dissimilar from the countries they were developed for (Simon 1996: 13).

The interrelationships between transport and development within the developing countries have been described in a well-known model by Taaffe, Morrill & Gould (Taaffe et al. 1963). It is based on the assumption that transport networks are rooted, both physically and historically, in seaports. The model has been adapted successfully to the East African transport complex (Hoyle 1973; Hoyle 1983). The original model and the adaptation to East Africa are shown in Figure 4. The original model represents the parallel evolution of political, economic and transport systems within a developing area of the world. An adaptation to East Africa shows that the transport networks have gradually evolved from a pre-colonial situation of underdevelopment, through a period of external political intervention to the period of political independence

The development of the less-developed parts of the world is substantially dependent upon transport, in terms of intercontinental transport between the industrial and the developing world and regional and local transport within the less-developed regions. The limited development of interaction is both a cause and an effect of low levels of economic activity and technology (Dickenson et al. 1996: 235). In all developing countries, expansion and intensification of the existing transport networks has been a central feature of development efforts at different scales. Social and economic development is more probable when facilities are of good quality and respectively, the progress of economic development often creates the resources for better transport systems. Development, construction and maintenance of road infrastructure are prerequisites for rapid economic growth and poverty reduction, since they affect production costs, employment creation, access to markets, and investments (Wasike 2001). Furthermore, infrastructure have an influence on a wide range of consumption, labour productivity and wealth issues. In particular, rural roads have a major influence in improving marketing opportunities and reducing transaction costs in the developing countries (Kessides

1993: 14). Adequate road infrastructure increases improves personal mobility and access to services and affects the time allocations and household's welfare through the time spent for such daily operations as firewood and drinking water collection.

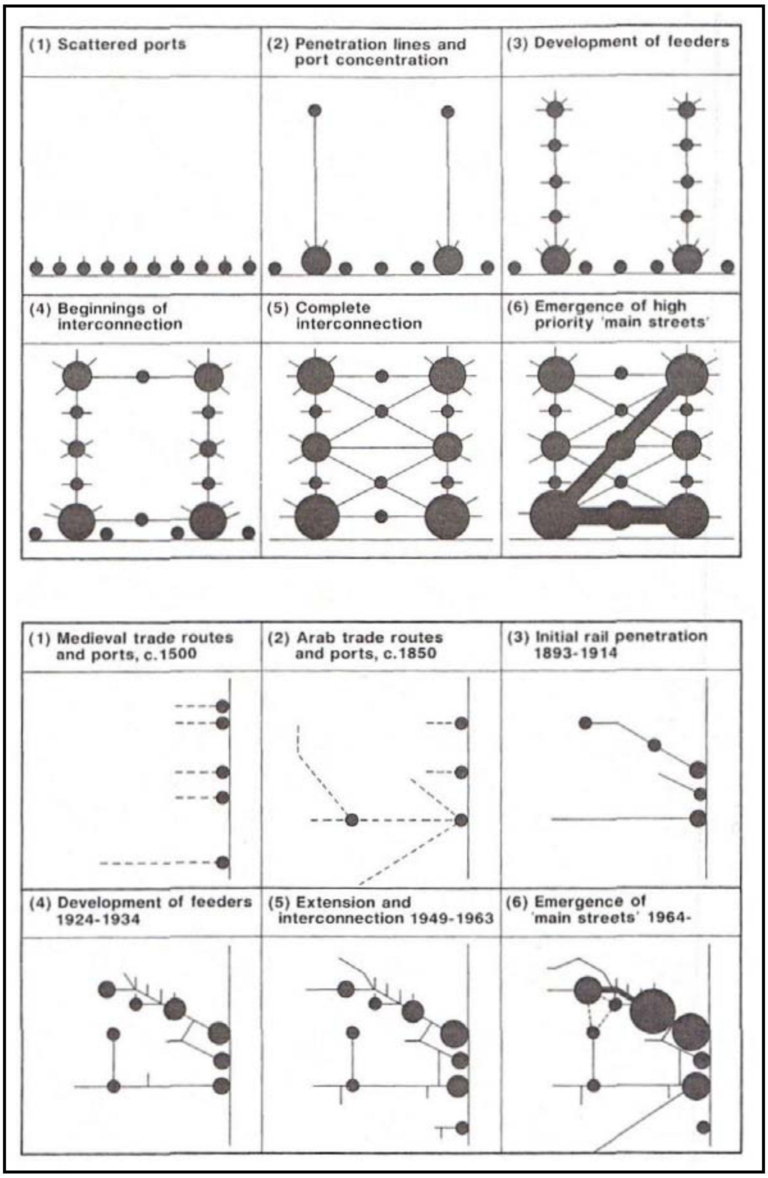

Figure 4. The original version of the Taaffe, Morrill and Gould model (top) and an adaptation to East Africa (bottom) (Taaffe et al. 1963; Hoyle 1973).

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1.5 ROAD TRANSPORT IN AFRICA AND SUB-SAHARAN AFRICA

Before the introduction of railways, roads had been little developed in Africa. Road construction was firstly carried out from colonial purposes and roads performed useful functions as feeders to the railways. At the same time, however, governments regarded roads as a threat to the success of railways (Morgan 1992). The main emphasis remained in the railway sector until the 1960s, ever since then road transport has been one of the dominant sectors in African transport in terms of demand and investments (Akinyemi 2003). Nowadays, road transport is the most widely used means of transport in Africa.

Sub-Saharan Africa (SSA) is the term used to describe those 42 mainland countries and 6 island nations of the African continent that are not considered as a political part of North Africa and are geographically located at least partially south of the Sahara desert (Wikidedia 2007). However, many countries belong to both regions as shown in Figure 5. In many SSA countries, the era since the 1960s has been characterised by the considerable alternations of the road networks. The road networks expanded substantially in the 1960s and 1970s when new roads were built to open up land for development, and the transition from colonial, primary road networks to more sophisticated infrastructure has been remarkable during the last few decades in the SSA. Nowadays, road transport is the dominant form of transport in all SSA countries where it accounts for close to 90 % of all transport services, and provides generally the only access for communities of rural areas, where over 70 % of Africans live (Heggie 1995; SSATP 2006a).

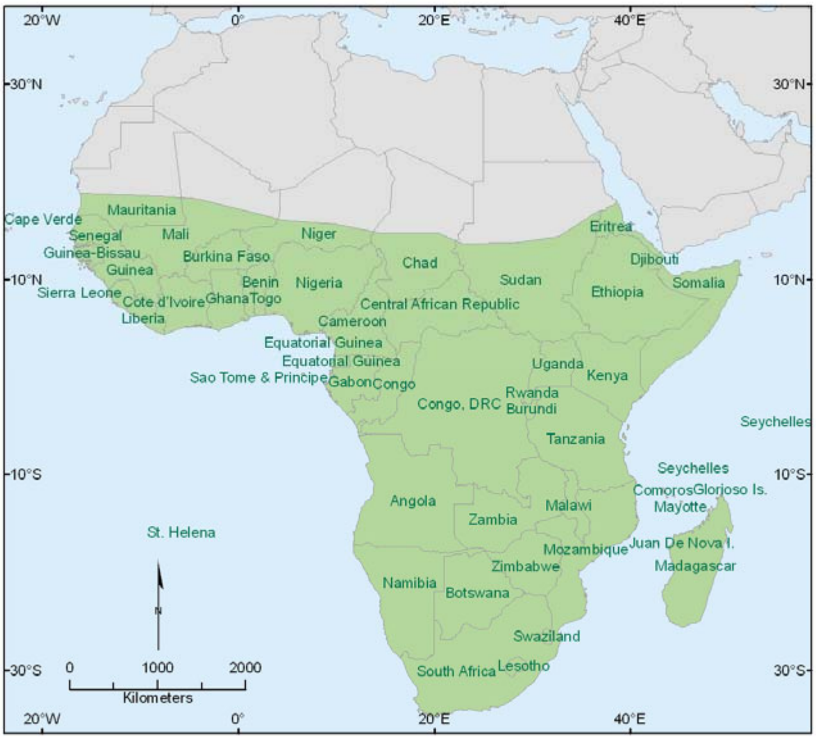


Figure 5. Sub-Saharan Africa countries and the demarcation line of the southern edge of the Sahara desert.

Many of the poorest countries have experienced the highest relative increases of paved road networks that also reflects the low base from which they started and the poor quality of existing roads, accounting for a high proportion of the growth for the upgrading of existing gravel roads (Simon 1996: 19). Traditionally in most African countries road construction has been given a higher priority than road maintenance that is often been neglected by the ineffective coordination of the road sector. Lack of maintenance has left over 50 % of the paved roads in Africa in poor condition and more than 80 % of the unpaved main roads are considered just fair (Wasike 2001: 1-2). The status of rural roads is even worse: up to 85 % of them are in poor condition with accessibility limited to dry seasons (ibid.).

Paved roads account for less than 17 % (in 1996) in the SSA where also road density per km² is generally much lower than those of North Africa, Asia and Latin America (Wasike 2001: 1). The majority of road infrastructure in the SSA countries has been poorly managed and badly maintained with the result that nearly a third of the $170 billion investment has been lost through the lack of maintenance (Heggie 1995). The insufficiency and the degradation of the road infrastructure have a great influence on the economies of the SSA countries.

Lack of road access in the developing countries has been a primary factor in underdevelopment (Owen 1987). In Africa, road links tend to be built with former colonial powers rather than with other African countries, and transport networks are limited with relatively few cross-border connections. Moreover, in many cases road transport between neighbouring African countries is restricted due to political difficulties which may close borders altogether or at least seriously inhibit the movement of goods. In East Africa, however, the inter-state trade flows have ranged at a rather high level, from 8 to 12 % (Hodder & Gleave 1992).

Lack of resources for providing even basic level of access and infrastructure, has caused serious problems particularly in the rural areas of Africa. Rural roads connect villages and farming areas with each other and with market centres. The purpose of rural transport is primarily to service agricultural demands and local markets, the everyday needs of people for basic levels of mobility and access to services within their own localities (Nutley 1998; Booth et al. 2000: 35-48). However, the emphasis has often been placed on the construction and maintenance of national, primary and secondary roads and hence, there exists a major gap in the rural transport of many African countries. Rural population would benefit more if there were an extensive network of rural roads in good condition. In essence, the basic problem of many rural areas is the lack of all-weather roads, non-availability of motorised vehicles, consequent isolation and poverty. Large populations are impeded from entering markets and basic services in the absence of adequate roads, and this is a major obstacle for the economic development of those rural areas.

On the other hand, the investments of the road transport sector by both national governments and international institutions have increased in recent years. Major infrastructural projects (e.g. rehabilitation or construction of new trunk roads) are often funded by means of foreign aid loans, grants and technical assistance from the developed countries. Not only are there major new highway projects, but the emphasis has shifted from the trunk roads towards the expansion of secondary and other minor road connections, particularly in the rural areas (Hoyle & Smith 1998: 32-33). More funds have been allocated for the construction and the maintenance of rural access roads (Irandu 1996). Hence, a bigger percentage of the population in developing countries can benefit from the projects, since not all the investments are channelled to a few new highway projects but more comprehensively in terms of the whole road infrastructure. In addition, the issues of maintaining the existing network and providing wider access to motorised transport have become more essential. However, there is still a lack of maintenance component in many projects, so that newly completed infrastructural development is in danger of deteriorating, thus undermining the value of the initial projects (Simon 1996: 159-160).

In recent years, there have been a number of efforts for improving the management of the road sector in SSA countries (Heggie 1995; Heggie & Vickers 1998; Nyangaga 2001). To date, there exists a broad partnership program, The Sub-Saharan Africa Transport Policy Program (SSATP), between the member countries of SSA and the regional international organisations such as the Common Market for Eastern and Southern Africa (COMECA), the World Bank and the United Nations Economic Commission for Africa (UNECA) (SSATP 2006a). In practise, the collaboration between the members has been implemented in various ways such as by introducing the Africa Road Maintenance Initiative (RMI) with its central concept of *commercialisation* (Heggie 1994; Heggie & Vickers 1998), establishing road funds in forms of levies on automotive fuel, restructuring road sector governance including the private sector to the management of roads and involving of road users in road management and financing through the establishment of roads boards (Sylte 1999).

The transition from the formerly strictly and inflexible led, government-controlled road transport management and financing to the more flexible, road transport business has begun but there are still a number of challenges in the road transport sector of SSA countries, particularly in terms of the execution of different programs, initiatives and financing schemes. Existing road networks will require tremendous extension and improvement in quality. Above all, there are a number of cross-cutting issues related to rural road networks. The rural roads of the SSA countries constitute 80 % of the total road network length, carry 20 % of the total road transport and provide the basic access to the majority of population in SSA countries (SSATP 2006b). Quite commonly, the basic definition and the classification of these roads are unclear, and the maintenance, management and financing of these roads are mishandled or undervalued. In addition, paved road infrastructure has been overmuch neglected in recent time. Paved roads have deteriorated when affected by poor drainage and systematic axle overloading of trucks with serious consequences on safety and road deaths (Goldstein & Kauffmann 2006).

1.6 REMOTE SENSING AND GIS FOR ROAD MAPPING IN THE DEVELOPING WORLD

The current status of available mapping data varies significantly according to different scale ranges and between the continents and countries of the world. In Africa, the status of mapping is the worst. At the scale range of 1:25 000 only 2.9 %, at 1:50 000 41.4 %, at 1:100 000 21.7 % and at 1:200 000 89.1 % of the land area is covered by topographic maps (UN Secretariat 1993, cit. Konecny 2003: 12). If there exist maps, they are usually outdated, inaccurate and in analogue form. Therefore, novel, cost-effective methods of mapping are needed for rapid, cost-effective and accurate mapping and digital cartographic database building to produce new maps, update existing ones and store various geospatial data in digital format.

Many African countries have undergone enormous transformations from former colonies to independent, rapidly changing nations. Existing maps are often extremely outdated and of poor quality because of the heavy growth of population and urbanisation that have led to dramatic changes of land use, natural environment, settlements patterns and transport intensities. Land use planning has not always followed general land use policies and planning has been fragmented, unsustainable and hindered by bureaucracy and complex land ownership issues (Hermunen 2004). In addition, environmental damages and disasters such as flooding, drought, bush fires, desertification and the consequence stream of refugees and migration have had a great influence on the living conditions of many African countries.

Remote sensing and GIS have great potential in the land use and land cover mapping of the developing countries. Remotely sensed data can be used effectively for planning and decision-making at local, regional, national and international levels. In particular, high resolution satellite imagery such as SPOT or Landsat imagery offer a cost-effective source of information with synoptic and extensive spatial coverage and spectral information, and with a high repetitive cycle to detect temporal changes of land use and land cover, urban development and to revise topographic maps (Ottichilo & Khamala 2002). Furthermore, aerial photographs – that have conventionally been used for national mapping in Africa – provide a platform for accurate, up-to-date surveying, but aerial photography is usually more expensive to conduct and it needs more resources for wide area mapping. However, airborne digital imagery and more sophisticated techniques for data processing have advanced airborne imagery based mapping in the recent years. In addition, very high resolution remote sensing data, such as IKONOS imagery, can be used for the production of different kinds of maps and to extract vector information, such as roads. In particular, in countries where experience in mapping, aerial photography, data acquisition and handling is not developed and the road infrastructure is in need of updating, these data sources provide a rapid and high-quality data source for map production (Gianinetto et al. 2004). However, these data sources are currently too expensive to be utilised other than in developed countries.

Remote sensing-based GIS offers an effective approach in Africa to handle, store and utilise different kinds of spatial data for such purposes as land administration and environmental planning, managing natural resources and protection areas and surveying of the most remote areas. As a consequence of the rapid growth and dispersion of population, one of the most important functions of GIS in developing countries is the mapping and management of infrastructure, especially road infrastructure. Many countries have experienced rapid expansion and upgrading of road networks, and the existing map data are out-of-date. Roads and road transport have fundamental, supportive functions in many sectors of the economy and hence, updated and reliable road data are needed at different levels and for different purposes. Reliable road information is needed for transport planning and the effective management of the road transport sector itself, since the state of the road infrastructure in Africa has deteriorated substantially in recent times with consequences on road safety, economic integration and poverty reduction (Goldstein & Kauffmann 2006). In addition, road information is essential for land use planning of settlements, services and industry, trade, nature conservation, tourism services, etc.

Digitalisation of existing and new road data is of the essence to better manage road information in its various purposes. Many African countries are lacking permanent, regularly updated and locally managed road databases and that is why in practise large-scale, systematic monitoring can only exceptionally be directly based on a pre-existing road databases (Fernique 2000). Monitoring and databases of road information are needed at all levels of administration and for diverse regional, national and continental purposes. In addition, uniform methodologies and data formats, free availability and data sharing are needed to better benefit from the potential of GIS. Therefore, Open Source GIS applications and map servers would increase the usage of GIS and remotely sensed data - especially in the developing countries where resources of mapping are still insufficient and limited in many ways. Currently, at least national road data of Africa (at 1:1000000 scale) is available for free on the Internet in The Digital Chart of the World Data Server (DCW 1997) (see also Figure 14). However, these data are insufficient for more detailed purposes of use. Moreover, the server data is very outdated, since the data set was created in 1997 and it is based on the sources from several years before the database compilation date.

On the other hand, the implementation of GIS and remote sensing in road mapping has several challenges in Africa. First of all, local circumstances and have to be considered carefully when planning and building a GIS and remote sensing-based road mapping in an African context. Above all, there is an urgent need for surveying basic road network data, since the road information on many topographic maps are extremely outdated and road infrastructure of changing economies has altered substantially. Unsustainable management of land, land ownership issues, informal settlements, urbanisation and migration have resulted in unorganised planning and construction of roads and thus, road infrastructure need to mapped and updated systematically and regularly. Most of the road infrastructure in Africa is built with natural construction materials (e.g. gravel and red laterite soil), and unclassified roads, tracks and paths – that form the majority of the road networks in Africa – have not been mapped comprehensively yet. In places, roads are covered by dense vegetation (e.g. rainforests) or they are poorly distinguished from their surrounding due to their similar construction materials. Consequently, high spatial and spectral resolution remote sensing data are needed to conduct road mapping at the sufficient level of examination.

Exhaustive remote sensing-based mapping implemented with aerial photography or high resolution satellite imagery and ground inventory requires often great and diverse resources of skills, hardware, software – that are often insufficient in the developing countries and especially in Africa. High or very high resolution remote sensing data are too expensive for many purposes as well. In addition, the management and distribution of data can be problematic and hindered by ineffective computational capacity and the relatively sparse distribution of internet services and web-based mapping operations in African countries. As a result, practical and straightforward methods with cost-effective data sources and simple means of data management are prerequisites for the effective exploitation of remote sensing and GIS in the road mapping of Africa. Local perspectives and education in GIS and remote sensing based techniques are needed as well to maintain continuous, repetitive work in the field of road mapping.

2. STUDY AREA

2.1 BASIC FEATURES OF KENYA

2.1.1 PHYSICAL GEOGRAPHY

Kenya is located in East Africa between the latitudes 5°S-5°N and the longitudes 34°-42°E, bordering on five countries, Lake Victoria and Lake Turkana and the Indian Ocean (Figure 6). The total area of Kenya is approximately 582 650 km² (CIA 2006) which covers territories from coastal plains and low plateaus to Lake Victoria borderlands, and central highlands bisected by the Great Rift Valley. From the marginal coastal strip the elevation increases from close to sea level to around 1200 m a.s.l. and up to 3000 meters in the highlands of south-west Kenya. The highest point of Kenya and also the second highest peak of the Africa continent is Mount Kenya (5199 m a.s.l.) sited north of Nairobi near the equator. The largest physical regions of Kenya are low plateaus at around 600 m a.s.l. covering 72 % of the total area of Kenya (Soja 1968: 6).

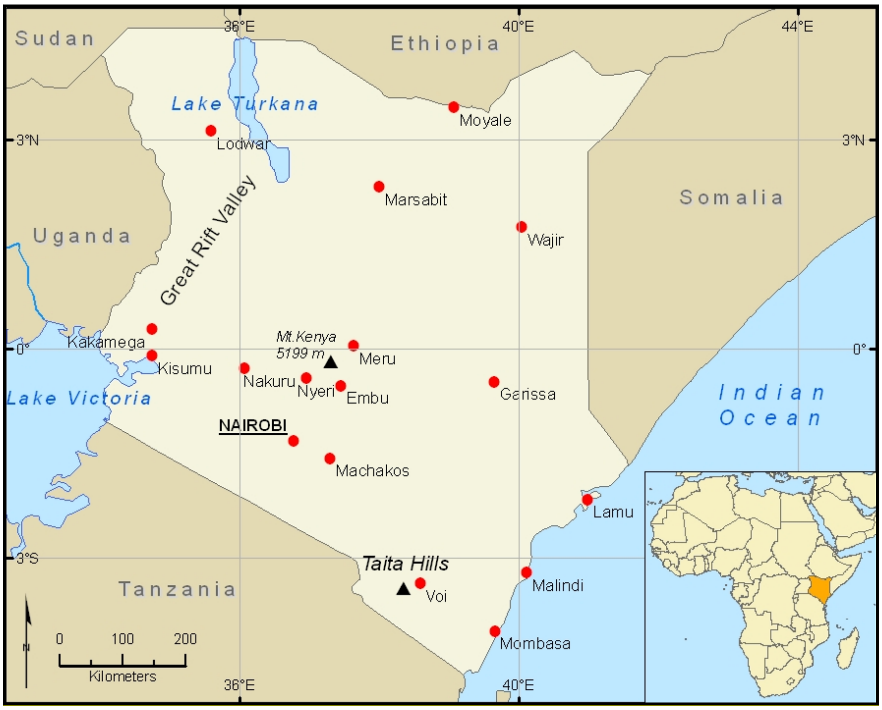


Figure 6. Location of Kenya.

The climate of East Africa has two particular features: the marginal nature of the rainfall over much of the area and the remarkable modifications induced by relief (Morgan 1973: 29-47). The climate of Kenya is influenced by two positional factors: the location at the equator and in the vicinity of the Indian Ocean. The climate is dominated by the intertropical convergence zone (ITCZ) which produces two intense seasonal rainfalls annually. Furthermore, the regional effects of the differences in altitudes affect the general climate patterns. Climate varies from tropical along the coast to arid in the inland plateaus and even to arctic-like at the highest summits of Mount Kenya. Generally speaking, temperatures decline along the increasing elevation from the coastal plains and lowlands to the plateaus and highlands. Rainfall is heaviest in the highlands and particularly at the coast in the vicinity of Mombasa from where it declines northward and southward (Soja 1968: 6). The driest regions are low inland plateaus of large areas of semi-deserts where rainfall is very sparse and uneven (Hazlewood 1979: 2). In addition, several small distinct highland regions - such as the Taita Hills - obtain higher rainfall rates due to the higher altitudes (Soja 1968: 6). Kenya is predominantly a dry country of frequent droughts where most of the land does not regularly receive sufficient rainfall. The rainfall may be unreliable even in places where the rainfall on average is adequate for cultivation. The uneven distribution of rainfall – wide variations between the seasons and the different regions over the country, and around the average from year to year - and its overall inadequacy are fundamental to the economy of Kenya. 82 % of the area of Kenya is defined as arid and semi-arid lands (ASAL), and land use is greatly determined by the influence of land and its agro-ecological potential to various purposes (Mwagore 2002). Furthermore, the climate has a considerable effect on the transport conditions in Kenya too. Two annual rain seasons make the maintenance of road infrastructure a challenging task which needs to be performed regularly and during the certain, limited periods of year.

Climate is considered the most important factor on soil formation (Lundgren 1975: 53). In East Africa, rainfall has the predominant influence on soil (Morgan 1973: 82) which together with other soil forming factors form the typical soils of East Africa. The iron oxides give the characteristic red colour to many tropical soils found in Kenya. However, depending on the soil formation factors, there are large variations in the characteristics of these latosolic soils of Kenya from highly leached and deeply weathered soils lacking of all mineral nutrients to very fertile red loams, and coarse soils with rock fragments (Lundgren 1975: 54). Only the highlands, Lake Victoria borderlands, the coastal plain and a few isolated enclaves such as the Taita Hills have reliable rainfall and fertile soils to sustain a dense agricultural population and permanent agriculture (Soja 1968: 8).

There are diverse major vegetation types in Kenya (Trapnell & Langdale-Brown 1961, cit. Morgan 1973: 48-69) due to the different regional climate patterns induced by varying topography. Hence, the climate has a strong influence on the vegetation which varies significantly along the region and the altitude and that makes the land cover of Kenya a mixture of different vegetation types. However, climate, topography and soil are not the only key factors determining the current vegetation of Kenya. The very intense activities by human land use have modified the vegetation and led to degradation of vegetation and a number of critical environmental issues (Virtanen 1989).

Soil erosion, either caused by water or wind, is a major land use problem in Kenya. It causes major drawbacks to productive soil in agricultural land use, vegetation cover, water infiltration, transport and human settlements. Lundgren (1975: 185) identifies two types of areas in East Africa which are very vulnerable to erosion: the semi-arid savanna lands or drylands with sparse vegetation, or the cultivated steep slopes of the deforested mountains. The process of soil erosion is facilitated by the destruction of vegetation which makes the ground susceptible to the eroding forces of water and wind leading to the degradation of land. The main causes of land degradation are a consequence of human actions that lead to soil erosion and loss of soil productivity (Lundgren 1975: 185).

In summary, the physical features of Kenya are very challenging to the conditions of road transport. The climate of two heavy rainy seasons combined with the other factors, varying topography, leaching soil, loss of vegetation due to the very intense, unsustainable land use and soil erosion, have great influences on the road transport and infrastructure of Kenya, and these factors also cause obstacles to the effective development of the road transport sector.

2.1.2 HUMAN GEOGRAPHY

Kenya, former known as British East Africa, became independent in 1963 after being a colony of Great Britain. The pre-existing era under the domination of colonial policies and forces had a great influence on the development of the Kenya. The colonial legacy still exists and plays a significant role in many fields and conditions of the current independent state. Despite the noteworthy continuity with the past, the period since the independence has also seen major changes of the society that have been undergone in many sectors of the economy, thus affecting substantially to such issues as the population, land use and transport of Kenya.

Nowadays, the total population of Kenya is approximately 34 million (2005 estimation), and the average annual population growth rate is 2.6 (2005 estimation) % (CIA 2006). The average population density is 56.1 inhabitants per km² (in 2003) (Statistics Finland 2006).

Approximately 42 % of all inhabitants live in urban areas and the estimation of the average annual growth rate of urban population (in 2000-2005) is 4.4 % (ibid.). The capital and the main hub of Kenya and East Africa is Nairobi, and the second biggest city is Mombasa which is the most important seaport in East Africa. Kenya is becoming more and more urbanised, but still having the majority of its population living in rural areas. Therefore, the management of rural transport is a central issue at the road transport sector of Kenya.

The Gross Domestic Product (GDP) of Kenya, on a purchasing power parity basis per capita, is 1100 USD (2005 estimation), and Kenya was ranked 22nd poorest country in the world on GDP per capita (CIA 2006). The Figure 7 shows that services encompass majority (65.1 %) while agriculture and industry sectors both carry approximately one-thirds of the total GPD. Merely a small part of Kenya's land area is suitable for permanent agriculture or intensive animal husbandry. At the same time, as much as 75 % of the labour force works within the agriculture sector (CIA 2006) that evidently represents the ineffective and small-scale nature of the agricultural activities. Moreover, the informal sector accounts for a great share of the economy. In consequence, the unemployment rate is 40 % (2001 estimation) (CIA 2006) that is a result of the distortion of the economy.

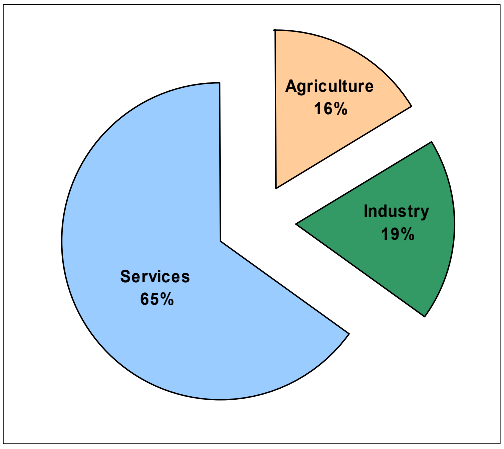


Figure 7. The composition of GPD in Kenya by sector in 2004 (CIA 2006).

The disparities of living standard between the various regions of Kenya, in many cases between rural and urban areas, are great and wealth is accumulated to a minority of inhabitants - to the small elite usually located in urban areas. Meanwhile, droughts, famine and diseases combined with the effects of general poverty are often serious threats especially to the inhabitants of rural areas. The inhabitants of the most remote, peripheral regions often lack business and industry, resources and proper infrastructure, and they also have the hardest physical conditions for agricultural activities. Thus, development of the general conditions of rural areas such as local and regional infrastructure is a fundamental task for the economic and social development. Functional transport connections is a prerequisite for the trade of groceries, raw materials, manufactured goods and merchandise which are either imported to or exported from the rural areas. Even in the most remote, highly self-sufficient communities of small-scale production, the functional transport connections are usually needed to ensure the marketing to the local business centres.

In general, the economy of Kenya has been more successful than many other countries of East Africa. Nowadays, Kenya is the regional hub for trade and finance, and the export and import values are clearly higher than its neighbouring countries have. A significant part of the export in Kenya is directed at other East African countries and to UK and US (CIA 2006). Respectively, most merchandise is imported from outside Africa, from Asia and other continents. However, a number of obstacles to the economy such as the inefficiency of the governance and the practise of corruption since independence have come in for great criticism. It is therefore essential to promote the factors of external trade such as to improve the regional and international transport connections.

2.2 BASIC FEATURES OF THE TAITA HILLS

2.2.1 PHYSICAL GEOGRAPHY

The Taita Hills (03º20’S 38º20’E) are located in Taita Taveta District (17 000 km²) of Coast Province, in south-east Kenya (Figure 8). The Taita Hills cover an area of approximately 1000 km², and together with Sagala Hills and Kasigau they form the northernmost part of the Eastern Arc Mountain chain in East Africa. The average altitude of the Taita Hills is 1500 meters, the highest point being Vuria at 2208 m a.s.l. and the surrounding Tsavo plains at about 700 m a.s.l.

The climate of the Taita Hills varies substantially with altitude and aspect. The rainfall pattern in the region is bimodal with two intense rainy seasons, the long rains occurring between March and May and the short rains between October to December. Figure 9 shows the rainfall pattern at two rainfall stations of the Taita Hills region. The mean annual rainfall varies from 500 mm in the lowlands to over 1400 mm in the highlands. The lowlands belong to the ASAL areas experiencing a maximum of 450 to 700 mm precipitation per year (Vogt & Wiesenhuetter 2000: 12). In addition, the north and north-west facing slopes of the Taita Hills are relatively dry due to their location in the so-called rain shadow region of the moisture-laden south-east trade winds (Krhoda 1998: 27). The temperature range is between 16°C and

30°C and the average temperature of the district is 24°C (Krhoda 1998: 27; Taita Taveta district development plan 2002-2008… s.a.: 8).

The Taita Hills region has varying land cover and land use patterns due to the different physical conditions and distribution of population as well. There are few indigenous forest fragments and patches in the region which have rich and unique biodiversity including several endemic species of birds, plants and insects. The largest forest remnants are Mbololo, Ngangao and Chawia located on the highest peaks of the hills. The highlands are generally characterised by woodland, dry forests, whereas the lowlands are mainly covered by wooded bushland, grasslands, riverine forests and swamps (Vogt & Wiesenhuetter 2000: 36). The highlands are mostly verdant and abundant in vegetation, while the lowlands are drier and more sparsely vegetated.

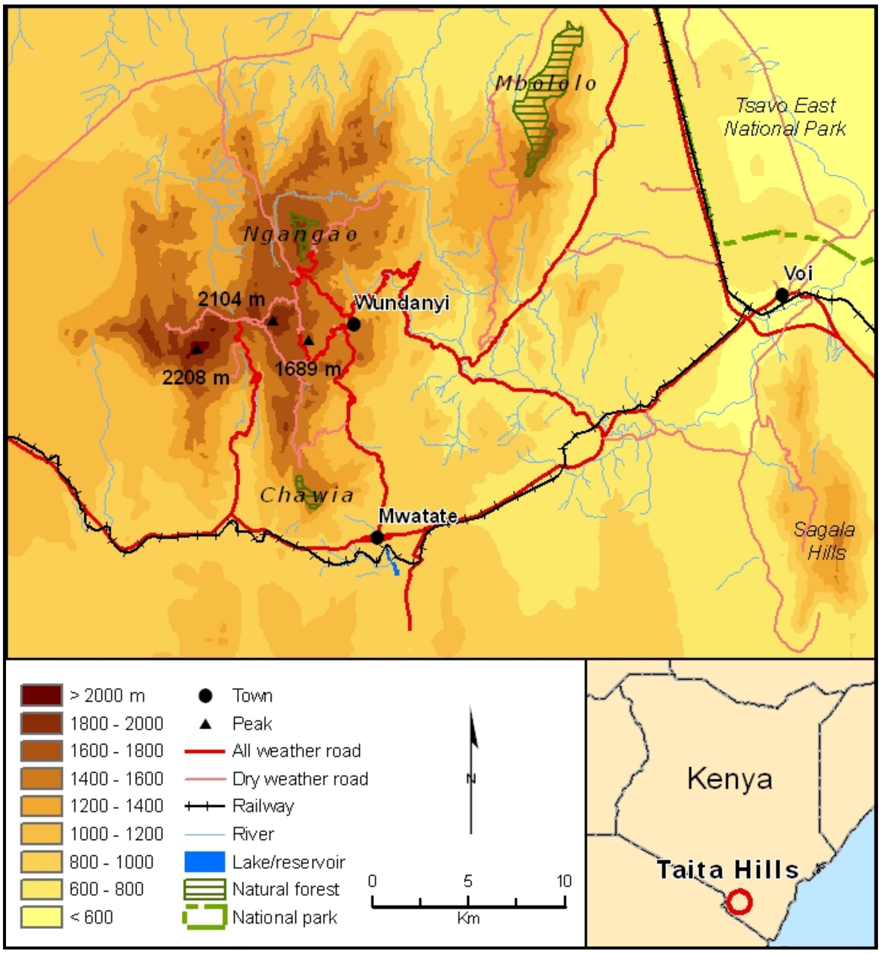


Figure 8. Location of the Taita Hills.

In the highlands the dominant soils are well drained, moderately deep and highly fertile while the adjacent foothills have generally soils of lower fertility (Krhoda 1998: 27). In particular, the soils of the lowlands and the steep slopes of the hills are sensitive to soil erosion with their high permeability and low water holding capacity (Vogt & Wiesenhuetter 2000: 23). In addition, such factors as the climate of heavy seasonal rainfalls, varying topography with steep slopes, degradation of vegetation, intense land use, population growth and spreading settlements have led to the rampant problem of soil erosion in the Taita Hills region. Gully erosion is a serious hazard in the Taita Hills region damaging agriculture and infrastructure such as roads and settlements and causing siltation of rivers and reservoirs (Hermunen et al. 2004; Sirviö et al. 2004). Erosion sites have increased in the Taita Hills region in the recent decades, especially in a number of lowland areas adjacent to the hills (Masalin 2005).

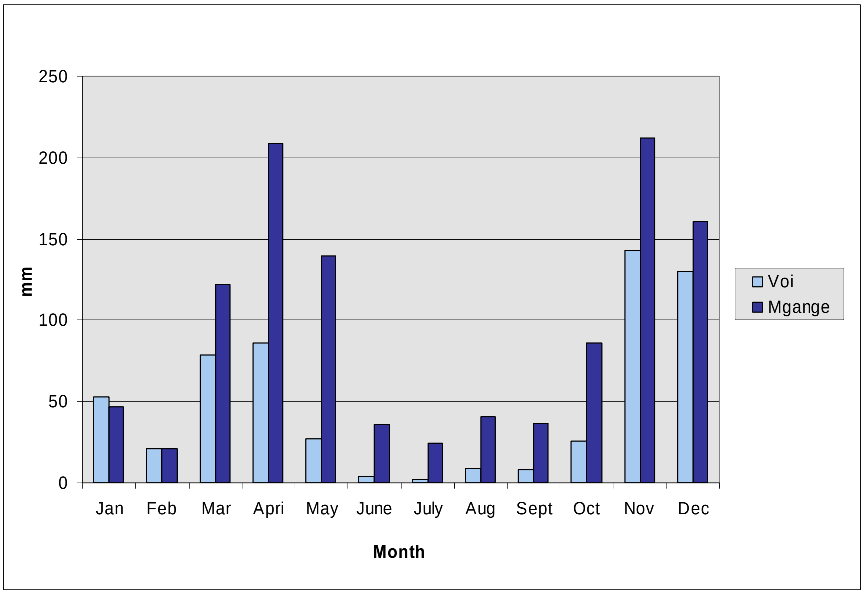


Figure 9. Average monthly rainfall in period 1986 - 2003 in Voi (560 m a.s.l.) and in Mgange (1770 m a.s.l.) (Kenya Meteorological Department data 2004, modified).

2.2.2 HUMAN GEOGRAPHY

The Taita Hills have a strategic location, and this has had a great importance on the development of the region. The Taita Hills were initially located in the vicinity of early coastal trade centres (e.g. Mombasa, Malindi and Kilifi) and by traditional caravan trails and explorer's routes (Soja 1968: 27-28). Thereafter, the alignment of Kenya-Uganda railway (1895-1902) and the parallel main road from Mombasa to Kibwezi and further to Nairobi followed approximately these caravan trails with a number of modifications (Molesworth 1899, cit. Morgan 1973: 344-345). Furthermore, the construction of the railway from Voi to Taveta (1918) for strategic purposes during the war and the road (1920) paralleling this branch line assisted the development of the region (Soja 1968: 27-32).

Morgan (1973: 346) describes the remarkable parallelism of railways, main roads and electric power lines - the three important services to industry and trade - as “a spine of economic development” in Kenya which has created a certain bulk of urban centres along the line from the coast to Nairobi. The administrative headquarters of the Taita Taveta District is Wundanyi located in the core of the highlands and being the centre of the agricultural area. The biggest urban centre and market town of the district is Voi, lying on the edge of the Tsavo East National Park, in the lowlands approximately 30 km east from Wundanyi by “the spine of economic development". Voi has attracted people for a long time from the Taita Hills and its surrounding plains to look for a job at the railway or sisal estates (Hurskainen 2005: 31). Voi has logistically a central position at the junction of Nairobi-Mombasa and Voi-Taveta-Moshi railway lines, and at the crossroads of the Nairobi-Mombasa highway and Voi-Taveta main road, also leading to Wundanyi. The railway traffic along the Voi-Taveta-Moshi branch line has diminished substantially in recent decades, but the other major routes still have an important role in local, regional and international transport of manufactures, agricultural products and people.

The total population of Taita Taveta District is approximately 260 000 (in 2002), the average density 40 people per km² and the annual population growth rate 1.7 % (Taita Taveta district development plan 2002-2008… s.a.: 8). However, the average density rate is misleading, since there are great variations in the population distribution of the district and people are distributed unequally among the different divisions of the district (Table 1). Majority of people live in the agricultural high potential areas of the Taita Hills and Taveta sub-district, at the footslopes of the hills and in the urban centres (Krhoda 1998: 47). The least occupied areas are located in the lowlands with inadequate rainfall, poor infrastructure and limited activities (Taita Taveta district development plan 2002-2008… s.a.: 7). The Tsavo National Parks (Tsavo East and Tsavo West), that count over half of the total area of the district, are almost uninhabited restriction areas for spreading settlements.

The business hub Voi is the largest city of Taita Taveta with approximately 33 000 inhabitants, and district's capital Wundanyi has a population of 4000 (1999 census) (Republic of Kenya 2001). Despite the strategic location of the Taita Hills and the major urban centres of Voi and Wundanyi, the Taita Hills is generally defined a rural region due to its agricultural-oriented livelihoods and rural population living in villages and dispersed by their small farms. The majority of the district’s population is rural and agriculture contributes 95 % of household incomes (Taita Taveta district development plan 2002-2008… s.a.: 8-9). A number of mountainous areas have to some extent peripheral status and they are seen as remote and poorly accessible by transport (Krhoda 1998: 38).

Table 1. Population densities and distribution by division in Taita Taveta District in 2002 (Taita Taveta district development plan 2002-2008… s.a.: 7, modified).

Division	**Area (km²)**	**Population**	**Density**
Wundanyi	701.9	57 706	82.2
Mwatate	1766.1	59 386	33.6
Voi	2975.0	57 486	19.3
Tausa	318.9	21 361	66.9
Mwambirwa	43.3	5191	119.8
Taveta	654.4	55880	86.6
Tsavo National Parks	10680.0	2879	-
Total	**16959.0**	**259 889**	**40.3**

The agricultural high potential areas are essential for productive agriculture in the Taita Hills (Krhoda 1998). Morgan (1973: 345) states that the Taita Hills is as “an oasis of water and population”. Indeed, the highlands and footslopes have abundant resources and favourable agro-ecological conditions for intensive agriculture and consequently the region is densely populated. Horticulture and agriculture are the main economic activities and source of income in the hills, and the district is one of the major suppliers of vegetables and fruits to Mombasa (Krhoda 1998: 14). Population pressure in the highlands has resulted in the expansion of agriculture and people into the lowlands, which are agriculturally more marginal regions (Soini 2005: 4).

The Taita Hills region has a poor physical infrastructure comprising of basic services and public facilities essential to the economy and the rural population of the region. Water and sanitation infrastructure, health services and educational facilities are insufficient and unequally distributed. In addition to the disadvantages of the poor road infrastructure, very few telephone services and post offices, power failures as well as a lack of electrification and incomplete mobile phone network – particularly in the rural areas of the highlands – impede efficient communication within the district and with the outside world. Road transport and road infrastructure of the Taita Hills region are considered with more detail in Chapter 3.2.

3. ROAD TRANSPORT IN KENYA AND IN THE TAITA HILLS

3.1 ROAD TRANSPORT IN KENYA

3.1.1 THE INFLUENCE OF COLONIALISM

The implementation of the different modes of transport has greatly influenced the development of Kenya. It is stated that modern Kenya was created by the railway (Hazlewood 1979: 1). Indeed, mainly the construction of railways facilitated the development of Kenya and improved the connections between the hinterlands and the coastal seaports, from where the raw materials and goods were able to be exported to the mother country. The expansion of the railways also consolidated the ground of British administration in Kenya (Mäkelä 1989: 143). Railways were built and expanded solely for colonial purpose of the monarchy but this had a great influence on the regional structure, general development and expansion of other transport networks - particularly the road network as well. The railways were well exploited in the passenger services but particularly in the freight transport where they contributed the major part of the total revenue (Hazlewood 1979: 96). Afterwards, the predominant role of the railways has been replaced by the development of the road transport.

The development heritage from the colonialism has played a major role in the emergence of the current road transport system in Kenya. Soja (1968) describes the early development of the road transport network in Kenya, emphasising the meaning of the past colonial purposes, the railway construction and the location of the seaports on the coast. The road network was designed and expanded due to the colonial needs in order to serve primarily the interest of the mother country rather than the needs of the indigenous peoples of Kenya. Roads were built as feeders to the railways to facilitate the stream of export to the mother country. Furthermore, roads were constructed to serve the growing areas of European settlements and to provide additional administrative connections (Soja 1968: 31). However, the British administration generally favoured rail transport at the cost of road transport (Mäkelä 1989: 145). At that time, roads existed over most of the country and the total road network was expanded but the road maintenance was often neglected and seen subsidiary to that of rail transport and especially at the cost of rural roads. As a result, the road network of the colonial legacy was relatively extensive and outward oriented at international scale but irregular and insufficient in terms of the regional and local needs (Mäkelä 1989: 143-152).

3.1.2 SHIFT OF THE ROAD POLICY FRAMEWORK

The road transport of Kenya was little developed before the 1960s. Since independence in 1963, the road transport has changed significantly in Kenya, in terms of both road policy framework and the physical infrastructure itself. An extensive review of the post-independence roads infrastructure policies in Kenya is presented by Wasike (2001) who reviews the trends in Kenyan road policy framework under the three different phases: the first era (1963-1972) of rapid economic growth, the second period (1973-1982) of continuous decline and the third and fourth decades (1982 to now) of structural adjustment and reforms. Since independence, there has been a major shift of the road infrastructure development towards the more privatised, decentralised road sector management through more public-private partnerships and with more commercialised policies and purposes. There are several benefits of privatising road contractors: private firms build highways faster and more efficiently than government agencies, users are more likely to accept to pay for roads owned by the private sector, and franchising should prevent the implementation of inadequate building plans (Wasike 2001: 10). Moreover, decentralisation is considered essential to minimise costs and to optimise road service delivery (ibid: 7).

On the other hand, the shift of the road policies has also had negative effects, since the institutional framework of the road transport sector has fragmented among different governmental ministries, departments, levels of government and other parties. Hermunen (2004) emphasises the issues of the whole current land use policy and administration of Kenya. The present national land use policy and administrative system of Kenya inherited from the colonial era is still heavily centralised, deeply sectoral and bureaucratic. The poor performance of the road infrastructure management may be a consequence of the fragmented nature of the institutional framework for the road sector, as it is difficult to coordinate the responsibilities, activities and financial requirements of the various road agencies (Wasike 2001: 42). Therefore, there is a need for more intensive collaboration between the distinct administrative bodies of the road sector in order to rationalise the management of the road transport in Kenya.

To date, there have been a number of efforts and activities to strengthen the institutional framework of road sector and to rationalise the management of roads in Kenya. With the Africa Road Maintenance Initiative (RMI) by UNECA, World Bank SSATP and the Government of Kenya the Road Maintenance Levy Fund (RMLF) Act was enacted in 1992 to promote the funding of the maintenance of the road network, and the Kenya Roads Board

(KRB) was established in 1999 to oversee and coordinate the development, rehabilitation and maintenance operations and activities of the road network in Kenya undertaken by various road agencies. KRB is the administering body of the funds derived from the RMLF and any other sources and it distributes funds to different road agencies, among others to District Road Committees (DRC). KRB involves individual and corporate members from both the private and public sectors of the economy. Generally speaking, the actual planning, construction and development of roads takes places at the national level, whereas the district level (mainly DRCs) is involved in routine maintenance of the road infrastructure.

In addition, the idea of using labour-intensive construction methods (Simon 1996; ILO 2006b) rather than conventional labour-replacing machinery has been applied in the road sector. A number of labour-based road maintenance programmes – such as Rural Access Roads Programme (RARP), Minor Roads Programme (MRP) and Roads 2000 have been implemented with the involvement of the International Labour Organization (ILO) (de Leen 1980; ILO 2006a). Major construction projects have been undertaken by domestic contractors and moreover, foreign parties of financing (e.g. EU, Danida) have been participated in the management of the road sector in Kenya. China Road & Bridge Corporation is involved in various road projects in Kenya, such as the rehabilitation of the Nairobi-Mombasa highway and the improvement of Mwatate-Taveta main road (Figure 10).

Figure 10. The improvement of Mwatate–Taveta road project (Keskinen 2004).

The administering agencies and the road classification of Kenya are presented in Table 2. At present, routine maintenance of classified trunk road network is still undertaken by the Roads

Department of Ministry of Roads and Public Works (MRPW). Other major implementing agencies in the road sector are e.g. DRCs, City and County Councils and Kenya Wildlife Service (KWS) which are responsible for the maintenance of rural road network and the unclassified roads.

Table 2. The road classification and the administering agencies of Kenya (KRB 2006)

Classified road network	
Trunk road network (Class A, B, C)	MRPW
International trunk roads (A)	
National trunk roads (B)	
Primary roads (C)	
Rural road network (Class C, D and others)	DRC
Secondary roads (D)	
Minor roads (E)	
Special purpose roads	
Unclassified road network	
Urban roads	Municipal Authorities
	(City and Municipal Councils)
Rural roads and tracks	County Councils
National park and game reserve roads	KWS
Forest roads	Forest Department

3.1.3 PRESENT STATE OF THE ROAD TRANSPORT

Nowadays, road transport is the dominant transport system in Kenya, and it has a substantial influence on the nation's economy. The road transport sub-sector accounts for approximately 34 % share of the total annual output of the transport services (in 1998), which is the highest contribution to national output among all transport modes (Wasike 2001). Moreover, the road transport contributes over 80 % of the country's total passenger and 76 % of freight traffic (GoK 2002).

The road infrastructure of Kenya is fairly well developed in terms of its extent but not of its operation condition that has suffered from inadequate maintenance and the disjointed institutional framework of the road sector. In the recent decades resources for the maintenance tasks have been declining though more financial resources have been allocated to the construction of rural and urban road infrastructure (Irandu 1996). Since the replacement of railway traffic and the independence, the expansion of road network has been rapid, mainly focusing on the construction of the classified roads. The main paved road network more than doubled from 4 480 km to 8 940 km between 1977 and 1999 (Figure 11), and the total length of the classified network increased from 50 400 to 63 000 km (Wasike 2001: 41). At the same time maintenance tasks have been undervalued and above all, the management of the rural road network has been neglected in many ways. The emphasis was firstly placed on the upgrading of the main trunk road network but since the early 1970s, more emphasis has shifted towards the construction of secondary, minor and rural access roads. However, the rural road network of Kenya is still inadequate in coverage and quality, that has several negative impacts on marginal areas of rural regions such as low productivity, high access costs to the market and poor management of natural resources (Obare et al. 2003; Mwakubo et al. 2004).

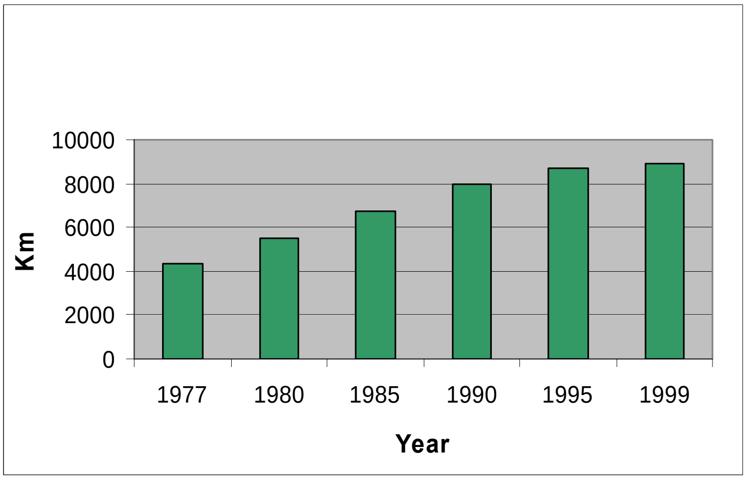


Figure 11. Development of the paved road network in Kenya 1977-1999 (Wasike 2001: 41).

In general, the extent and the state of road network can be described with various absolute and relative indicators. There is varying statistical information about the classified road network of Kenya (Heggie 1995; Wasike 2001; CIA 2006; IRF 2006; KRB 2006). In particular, no reliable data exists of the unclassified rural road networks.

The road transport sector in Kenya comprises 899 000 registered vehicles of which over 38 000 are public service *matatus* (a pickup truck or minibus used as share taxis) (Republic of Kenya 2003b: 19), and a road network of 177 500 km length (in 2004), of which the classified road network covers 63 000 km, representing approximately 35 % of the total road network (CIA 2006). Main unpaved (gravel and earth roads) roads cover 78 % of the classified roads while tarmac roads encompass the minority of the total classified road network (ibid.). The composition of the total road network and the unclassified road network data are shown in Figures 12 and 13. All roads except the unclassified roads form the classified road network.

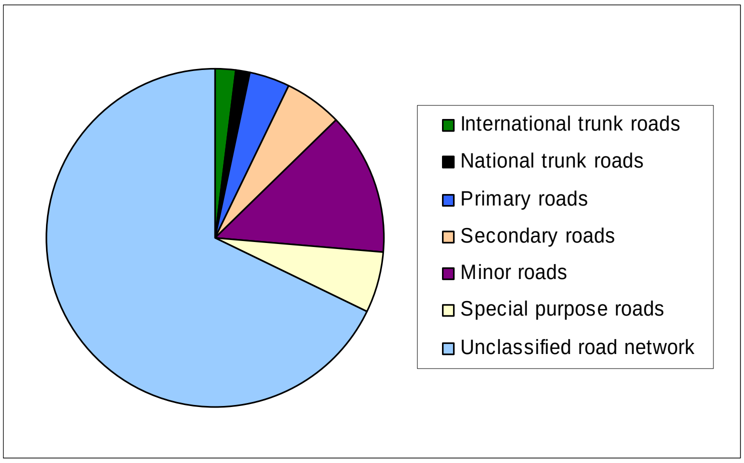


Figure 12. Composition of the total road network in Kenya (KRB 2006).

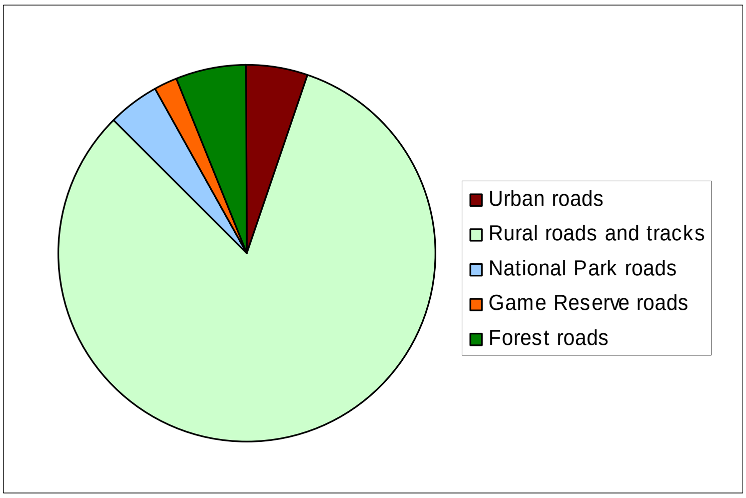


Figure 13. Composition of the unclassified road network in Kenya (KRB 2006).

Road density is a road-to-population ratio, a relative development indicator representing the average potential access or potential use of transport. In 1995, road density of the classified road network was 2.3 (1000 km per one million persons) in Kenya, which is similar to most SSA countries where the average value is 2.9 (World Bank 2000: 256). By 2004, the road density of Kenya had fallen to 2.0. Road density of the classified road network per land area has increased from 0.09 (in 1977) to 0.11 km / km² (in 2004). However, there is great variation in the road density rates of different areas in Kenya and roads are generally concentrated in the areas of high population and economic activity in Kenya while many rural, more peripheral regions are lacking proper main roads. The Figure 14 demonstrates the unequal distribution of roads in Kenya based on Digital Chart of the World Server data (DCW 2007). Notice that the very simple road classification of the source data differs from the Table 2 road classification which is the formal classification in place in Kenya. In particular, northern, eastern and southern parts of the country have inadequate road networks, tarmac roads and badly maintained road infrastructure (Republic of Kenya 2003b)

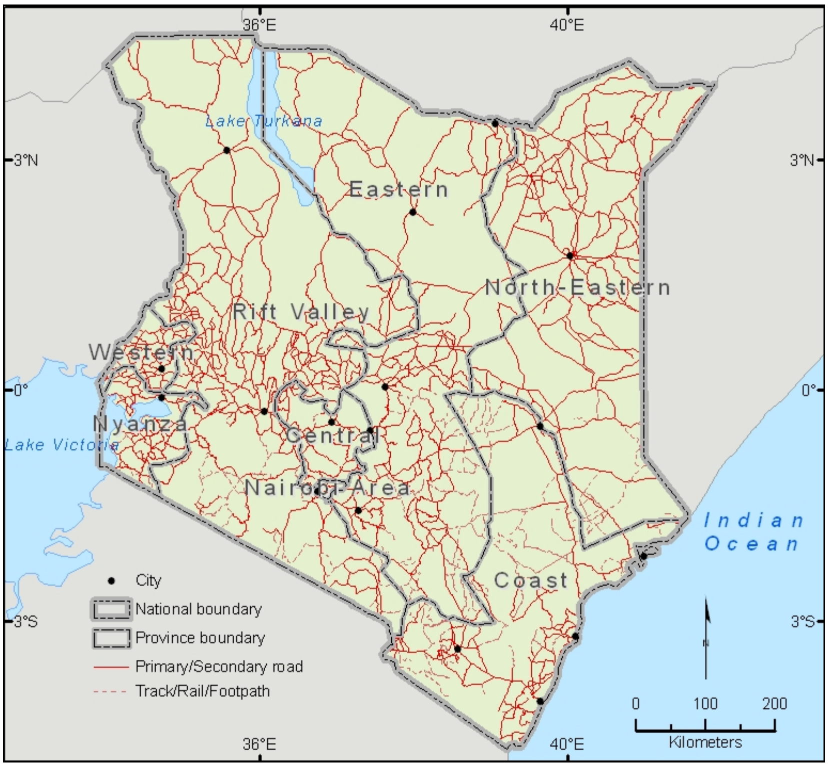


Figure 14. The main road network of Kenya based on the Digital Chart of the World Server database 1991/1992 data.

The primary problem of the road sector in Kenya is not the quantity but the quality of the infrastructure: there exists a relatively extensive road network in places but it has a poor state, since conditions on the main roads have deteriorated significantly due to the heavy growth of road transport and due to the lack of periodic, routine maintenance. Buys et al. (2006) describe the state of main road networks in SSA countries with a road transport quality indicator, and the index value of Kenya is 16.3, normalised to 100 for the highest-quality road transport in South Africa. A large proportion of the road network in Kenya is in poor condition, and this is a major constraint to economic and social development. The bad condition of the road infrastructure has an influence on the whole transport, which means that rapid movement of vehicles and the effectiveness of transport connections are often impeded if there exists a poor infrastructure of roads. The proportion of paved roads has stagnated at approximately 12 % of all classified roads since the 1980s (IRF 2006), and only a minority these roads are in good condition. 32 % of paved roads were in good condition in 1989 (World Bank 2000: 257) and respectively, 66 % of unpaved roads were of good quality, but conditions on these roads, particularly earth roads, can change quickly over time during intense rains. In 2002, MRPW estimated that only 17 % of the classified road network were in good condition, 39 % in fair condition due to periodic maintenance, 27 % in poor condition requiring rehabilitation, and the remaining 16 % was failed and required reconstruction (KRB 2006). However, these numbers represent only a small proportion of the total road network, since unclassified roads comprise the majority of all roads in Kenya.

Unclassified roads and especially rural roads are generally in even poorer condition than classified roads. The maintenance of these roads has been left to poorly funded and/or ineffectively coordinated local authorities, and the rural road network is often neglected in the prioritisation, whereas the classified main roads are seen as more important by administrative and financier parties and in terms of national and international interest. In 2005, 58 % of all inhabitants of Kenya were classified as rural (Statistics Finland 2006), indicating that rural roads are directly more relevant to the majority of the population by providing access to markets and basic services and increasing the mobility of rural people. 98 % of the rural people do not own their own motor vehicles and over 85 % of the movements in the rural areas usually take place of the road using tracks and paths (Republic of Kenya 2003a: 9).

On the one hand, rural roads are often more important in terms of their non-motorised meaning to increase accessibility and mobility of rural people by supplementing motorised transport with non-motorised modes of road transport. Improving paths or tracks can ease the transport burden of rural people and reduce time spent on water and firewood collection. On the other hand, the development of the motorised and public road transport facilities in the rural areas and the maintenance of the rural road network are also important factors to improve the food security, cheaper health care and educational services and to generate employment (Irandu 1996).

3.2 ROAD TRANSPORT IN THE TAITA HILLS

3.2.1 CONSTRUCTION AND EXTENT OF THE ROAD NETWORK

The Taita Hills have an extensive road infrastructure which is, however, seasonally and in certain places in poor condition. The great scope of the network and the poor state of the infrastructure have several effects on the development of the region, that are discussed later in this chapter. Taita Taveta District has a total classified road network of 955 km (in 2001) (Taita Taveta District Development Plan 2002-2008… s.a.: 11). The classified road network of the Taita Hills comprises of international trunk roads, and there are also a number of primary, secondary and minor roads connecting rural access roads and tracks to higher class roads and linking different agriculture areas and market centres to each other. Figure 15 shows the road network of the Taita Hills region based on Survey of Kenya (1991) topographic map data (Broberg & Keskinen 2004). Notice that the road classification differs from the Table 2 road classification.

The road density rates of the Taita Taveta District are 0.06 km / km² and 3.7 (1000 km per 1 million persons) in 2001. Hence, there are almost half less roads per km² but nearly double the amount of roads per population in the district than on average in Kenya (equivalent rates 0.11 and 2.0 in 2004). These ratios indicate, that the extent of the road network is generally lower in the district – with great variations - but the potential access and use of roads is higher than the national level. The Taita Hills is a highly mobilised periphery within the Nairobi-Mombasa core region (Krhoda 1998: 37). Roads are concentrated in areas of high population density and economic activities: towns, market places and other urban areas, and important agriculture regions. Fewer roads are situated in less populated and less productive lowland areas, remote places, conservation areas and areas of extremely difficult topography. By 2008, the road density per land area is estimated to increase to 0.10 and the road density per population to 6.2 in Taita Taveta District. It should be noticed that these rates involve only the classified road network.

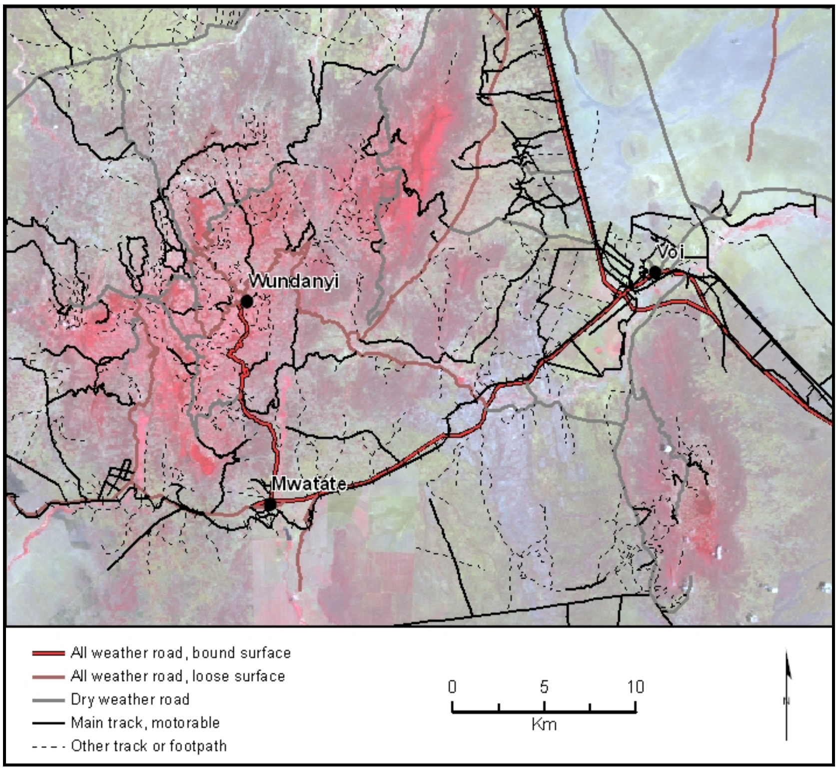


Figure 15. Road network of the Taita Hills. The SPOT 2003 image is shown in the background.

In recent decades, there has been a heavy growth of population that has led to increased population density, dispersed distribution of the inhabitants and dynamic chances of land use patterns in the Taita Hills region. Under the circumstances of the intensive agriculture and high population pressure, and despite the hard physical geography for road construction - difficult rolling terrain of steep slopes and great altitude variations - roads have been built extensively all around the region. Hence, the current road infrastructure reaches to almost every corner of the Taita Hills, with the exception of just the highest and steepest hillsides, dense indigenous forest areas and the most remote parts of the region. Roads have been constructed - or paths and tracks have been formed - to more remote places that have earlier remained untouched but then, along the road construction become prone to such human influences as firewood collection, hunting and settlement building. This has led to degradation of the land and loss of vegetation and biodiversity of ecosystems. In addition, road construction has encouraged gully erosion problems by laying bare surfaces open to erosion that can damage productive land of agriculture or grazing nearby the road construction site and also the road itself. Figure 16 shows a gully erosion site along the north side slopes of the Taita Hills. Gully erosion has taken place and damaged the earth road running from Werugha to Kishushe. Most of the erosion takes places along the roads and tracks cutting across very steep slopes of the Taita Hills, and this occasionally makes road construction hazardous to the sustainable land use of the area (Muya & Gicheru 2005: 6).

Figure 16. Gully erosion site along the road (Keskinen 2005).

3.2.2 MAINTENANCE AND CONDITION OF THE INFRASTRUCTURE

The road infrastructure of the Taita Hills is to some extent of poor quality and in need of routine, seasonal maintenance operations. The Mombasa-Nairobi highway and the main road from Mwatate to Wundanyi and the road section between Voi and Mwatate are the only tarmac roads in Taita Taveta District. The majority of roads are unpaved, either gravel or earth roads (Figure 17), and these roads are more vulnerable to damage caused by heavy rains, soil erosion and traffic of heavy, overloaded vehicles. In total, there were 152 km of tarmac roads, 311 km of gravel roads and 955 km of earth roads in the district in 2001 (Taita Taveta District Development Plan 2002-2008… s.a.: 11). The poor state of the road infrastructure is a consequence of hard physical features of the region, population growth and dispersion into sensitive areas, increased quantities of the road transport and lack of financial resources for road maintenance. In addition, there is a need for tighter supervision and there should a more favourable regime for locally based contracting and local purchasing of materials for road maintenance operations (Danida 2004).

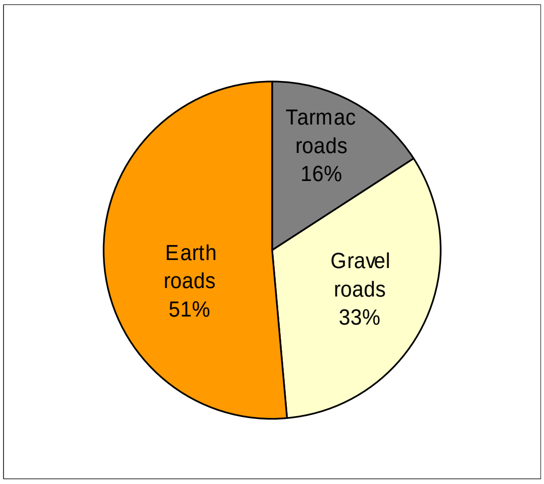


Figure 17. Composition of the classified road network in Taita Taveta District in 2001 (Taita Taveta District Development Plan 2002-2008… s.a.: 11).

Occasionally, many roads in the district become in poor condition and even impassable by motor vehicles. In addition to the hard conditions for road construction in the Taita Hills, conditions for road maintenance are very challenging as well. Hilly topography, intensive land use on the slopes, serious gully erosion problem in places and seasonal, heavy rainfalls together with leaching soil and degradation of vegetation make the maintenance of the road infrastructure a very difficult task. The whole concept of the road maintenance is troubled by the lack of financial allocation, particularly in terms of rural roads and other roads that do not take the first priority in the national or district level road policies. These roads do not carry the heaviest transport quantities or are the busiest in traffic volume either but, however, basic access and mobility of local people by non-motorised means of transport or by matatus should be ensured with the regular maintenance operations.

Because of the varying physical features of the Taita Hills, roads differ from each other in their nature of construction material and conditions, according to where they run and how they have been constructed and maintained. In the highlands, roads have been generally built to snake among the intensive agriculture land of terraced fields, small settlements and vegetation areas. On the deep hillsides roads follow a winding, serpentine routes of great variation in gradient - that makes them prone to soil erosion. Road paths are usually relatively narrow without or with marginal roadsides so that a road path may be bordered by adjacent steep descents or craggy cliffs. The majority of the roads are earth roads composed of either reddish or brownish laterite sand or bright gravel. A few very steepest sections have been paved either with tarmac or concrete surface to allow motor vehicles to better deal with the tough gradient, especially during the intense rains (Figure 18). Hence, roads in the highlands are generally clearly defined with their relatively sharp boundaries in terms of the different building material from the adjacent, vegetated, land use and the great variation in gradient.

Figure 18. A steep road section paved with concrete surface (Keskinen 2004).

Meanwhile, borders of the roads in the lowlands are often less clearly defined. Composition of these roads is usually very similar to the adjacent land use and the road paths are not as strictly defined by the gradient as on the steep slopes of the Taita Hills. The majority of these roads are composed of bright red, reddish or red-brownish laterite sand. Roads run among settlements, arid agriculture land of sparsely vegetated fields, bare ground, erosion sites, and they are not as well "organised" to run by the gradient as on the hillsides of the Taita Hills.

Soil erosion and road infrastructure have a great influence on each other in the Taita Hills region. They have a mutual interrelationship that has an effect on the state of the road infrastructure and its maintenance operations. On the one hand, road building itself has been a factor increasing the erosion risk, in particular in places where there has been unmanaged road construction activities with other boosting factors of erosion. Roads are likely to cause increased rates of erosion because, in addition to removing vegetation that covers the ground from heavy rains, they can significantly change drainage patterns of water. The high amount and intensity of precipitation and the texture of the soil cause soil erosion on many roads in the highlands and, moreover, the steep gradients increase soil erosion risk on the slopes where roads run. Erosion risk is increased by the degradation and the loss of vegetation adjacent to roads. The exiguous vegetation cover is dominant especially in certain dry lowland regions of Mwatate and Msau where gully erosion is prevalent. In addition, many hillside areas of the Taita Hills - where winding roads run on the slopes - suffer from soil erosion.

On the other hand, soil erosion affects the road infrastructure and its maintenance operations as well. The existence of the soil erosion problem decreases the condition of road network by damaging roads, making roads poorly passable both by motorised and non-motorised means of transport and even preventing completely mobility and access of the local people to markets and basic services, especially during the rainy seasons. Hence, soil erosion increases the need for long-lasting road infrastructure and continuous, effective maintenance operations. The soil erosion and its effects need to be taken into deep consideration during the road construction and the maintenance operations. In addition to the road maintenance operations themselves, proper and adequate culverts and drainage are needed to take care of drainage patterns of the rainwater so that the flow of water is not hindered and funnelled straight onto the road surface but rather into the ditches from where it is funnelled further into the surroundings of a road. This will protect and extend the life cycle of roads and reduce the need for road maintenance operations themselves since there is less water on a road area damaging the structure of a road. In addition, the risk of soil erosion and its effect on access and mobility can be reduced by upgrading a road to a tarmac surface, gravelling or paving the way so that the soft laterite soil is better bounded to hold the agent of water for erosion. Moreover, the environment surrounding the roads has to be taken into consideration to prevent soil erosion risk on those sites. This has been executed on the slopes of the Taita Hills traditionally by terraced fields and vegetation and lately, by road gabions (embankments) which are constructed from stones that are set under a metal net are used to prevent the gully erosion on the roads (Figure 19). The more intensive land use of the present-day Taita Hills with the loss of vegetation cover is increasing the erosion risk in the region.

Figure 19. A road embankment (Keskinen 2005).

In addition, other routine and periodic maintenance operations such as spot patching and spot improvement of paved surfaces, other improvements of carriageways, concrete bridge construction, roadside clearance, shoulder rebuilding and road furniture maintenance activities are essential to maintain and improve the quality of the road infrastructure in the Taita Hills.

3.2.3 DEVELOPMENT OF THE ROAD INFRASTRUCTURE

In recent years, there have been several major road construction and maintenance projects developing the state of the road infrastructure in the Taita Hills. In particular, recent activities have been focused on the maintenance of the classified road network as shown in Figure 20. Earth roads have been upgraded to gravel roads and earth and gravel roads to tarmac roads as well. The section of the Mombasa-Nairobi international trunk road passing the east side Taita Hills region is in good condition with a fairly new tarmac surface, and the road is generally suitable for heavy freight traffic of lorries and trucks. On the other hand, further in the direction of Mombasa the road was of extremely bad quality in 2005 and under comprehensive rehabilitation so that these sections were barely passable with rugged, broken off surfaces of coarse gravel, and there was heavy congestion of both passenger and freight traffic. The international trunk road section from Voi to Mwatate was of moderate condition in 2004 and a year later, the road had been improved with spot patching activities. The following gravelled road section from Mwatate to Taveta was in bad condition and in need of re-gravelling, considering the large amount of freight traffic along the road of large potholes and rough, worn-out surface causing vibration of vehicles. The third paved road of the region, leading from Mwatate to Wundanyi was in good condition of proper tarmac so that the district headquarters, Wundanyi, is well connected with the lowlands regions and the principal market town Voi. However, patching of the potholes on the tarmac is needed on some sections of the road. Better connections are also required from Wundanyi to the north side regions of the Taita Hills.

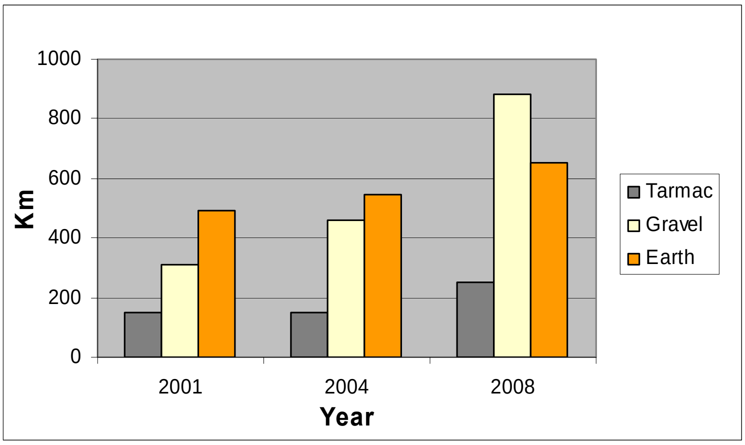


Figure 20. Development of the classified road network in Taita Taveta District 2001 – 2008 (Taita Taveta District Development Plan 2002-2008… s.a.: 76).

The most obvious road infrastructure developments during the study period were focused on the two secondary roads in the south side of the Taita Hills, the one leading from the junction of the Voi-Mwatate road to Msau and further all the way to Wundanyi, and the one from Bura to Mgange Nyika. The first one was improved during 2004, first from the direction of Voi to Msau and thereafter from Msau up to Wundanyi so that although the hillside section was hardly passable during the intense rains in January 2004, it was in good condition a year later. The road maintenance activities along this road were noticed to be very comprehensive with such improvement as road embankments and drainages. The other important road from Bura to Mgange Nyika was under maintenance at the beginning of 2005, and the road was partly in good condition.

On the other hand, many roads of the classified road network are still in poor condition and in need of urgent and regular maintenance operations to improve the state of the road infrastructure and road transport in the Taita Hills region. The secondary road from Wundanyi to Werugha and up to Mwanda is in moderate condition: some sections are of good quality but respectively, in places the road is in poor condition with deep ruts that make the road hardly passable on the deepest sections, especially during rains. Other classified roads are as well of poor quality particularly in rain seasons when intense rains make many of these earth roads very slippery, muddy and loose, occasionally impassable by any motor vehicles. In addition, unclassified roads are in need of maintenance since they are usually the most important connections of the local people in their daily lives.

3.2.4 DIMENSIONS AND MEANS OF THE ROAD TRANSPORT

In general, the use of roads, the quantities and the means of road transport vary substantially according to different classes of roads. Consequently, the whole meaning of road transport can be considered with functional classification of roads, in which a road class is used to specify the standard of service and the principal function of a road in relation to other elements of road infrastructure. The road transport in the Taita Hills has four different dimensions that are all relevant to influence the development of the region. Most of the roads are unclassified, rural roads that have the greatest meaning to serve local people and *local* transport connections. Several primary and secondary roads are important as well to enable *regional* transport connections within the Taita Hills and the Taita Taveta District and to neighbouring regions. Respectively, the *national* and *international* dimensions of road transport are achieved by few international trunk roads which are essential transport links to other regions and neighbouring countries, big cities, and to the coast which is linked to the other world with large-scale sea transport connections from the Mombasa harbour.

The road transport in the Taita Hills vary from pedestrians, cycling, carts and other non-motorised means to motorised transport: motor vehicles including mopeds, cars, pickups, lorries, trucks, and matatus handling a great part of the public transport in the region. Motorised road transport of local people by cars is exiguous since only few local people can afford to have a private car. On the contrary, freight transport by lorries and trucks is significant, and public passenger transport mainly by matatus is common as well. The public service facilities of the district consist of 40 buses, 50 matatus, 10 pickups and 20 taxis (Taita Taveta District Development Plan 2002-2008… s.a: 11). Generally speaking, non-motorised means of road transport are still the most important mode in terms of the mobility of the local people.

3.2.5 IMPORTANCE OF THE FUNCTIONAL ROAD TRANSPORT

Inaccessible roads, poorly maintained roads, inadequate roads and corruption in contract tendering are the main problems of road infrastructure in Taita Taveta District (Taita Taveta District PRSP… 2001: 28). The poor state of the road network is a major obstacle to agriculture and development of the region (Vogt & Wiesenhuetter 2000: 56). In (Taita Taveta District Development Plan 2002-2008… s.a.) the emphasis of road infrastructure development is on improvement on existing roads in order to upgrade them to all-weather roads so that they are better accessible to local farmers. Earth roads need to be improved to gravel standard and roads in steep sections will require concrete slabs so that they are passable throughout the year (Taita Taveta District Development Plan 1994-1996… s.a.: 67). In particular, the roads of rough terrain in the hills need to be maintained regularly to guarantee the access along these important local routes. It will facilitate cheaper, more efficient marketing of agricultural produce and enable the provision of other essential services to the rural population of the Taita Hills (Dijkstra & Magori 1994: 14).

The proper road infrastructure and consequently functional road transport have also had a great influence on the economic and social development of the Taita Hills - at local, regional, national and international scales. The extensive network of rural roads plays the most important role in daily living of the local population. Local markets are important to rural households that get their major sources of income in horticultural production (Dijkstra & Magori 1994). Farmers need good roads to access local market centres, agricultural inputs and basic services such as health care and education, either by motorised vehicles or by non-motorised means of road transport. Personal travel generally predominates on rural roads of the developing countries, and transport of goods is less (Irandu 1996). When rural roads are of good quality, less time is needed for collecting firewood and carrying drinking water and hence, more time can be used for other daily activities such as education and agriculture. In addition, development of rural roads can generate employment by increasing labour activities for women, not only in agricultural sector but also outside their farms, such as small-scale industries and other ways of earning extra income (Irandu 1996).

On the other hand, certain regions in the Taita Hills are occasionally poorly accessible or even isolated due to the bad road infrastructure. In particular, narrow earth roads passing steep sections on the slopes get in substantially worse condition during the rainy season. Therefore, it is essential to have an extensive network of roads, tracks and paths of good quality to serve better the need of local people in the Taita Hills.

At the regional and national scale, functional transport of the Taita Hills is an important factor in reducing regional isolation throughout the coast province by providing a more efficient connection to the inland of Kenya. Indeed, the strategic location of the Taita Hills and the major transport routes in the neighbourhood of this distinct fertile highland area have had a great influence on the development on the region. The Taita Hills is a unique region with its favourable conditions for agriculture and with its abundant resources to serve regional markets and business activities. The Nairobi-Mombasa highway and the Voi-Mwatate-Taveta trunk road constitute major routes for road transport from and to Taita Hills. The highway traversing through the district has opened markets for regional trade of agricultural products to the major urban centres of Voi and Nairobi and, above all, to Mombasa where there exists a high demand of urban consumers and a massive tourism industry (Dijkstra & Magori 1994: 78-89; Krhoda 1998: 37-38). Moreover, the highway has enabled the delivery of goods from the Mombasa seaport to the Taita Hills and further to the inland. In addition, good connections to Wundanyi are essential since it is the headquarters of the district and the principal market centre of the highlands with its basic services for local people.

The Taita Hills region also benefits from its beautiful scenery and the biodiversity of the nature, that create possibilities for a tourism industry of various activities and at different scales. The functional road infrastructure is a crucial prerequisite for all tourism services to connect tourist attractions and other places of interest to accommodation and travelling services. Tsavo East and Tsavo West national parks as well as LUMO Wildlife Sanctuary are the most important tourist attractions on the surrounding plains of the Taita Hills. The potential of the Taita Hills highlands should be noticed by placing more emphasis on the improvement of the road infrastructure connecting the lowland and the highland regions such as the road from Maktau to Mwanda. In addition, the Taita Hills have potential for small-scale ecotourism (Himberg 2006) that can be promoted with the development the rural roads leading to small villages, tourist attractions and the most remotest parts of the region.

As described, a few main roads of the south side of the Taita Hills have already been improved with comprehensive maintenance operations to better connect different parts of the Taita Hills region. However, connections to the north side of Taita Hills (e.g to Kisushe) and rural roads within the highland areas are still inadequate and occasionally of poor quality too. Moreover, there are secondary roads such as the one from Wundanyi to Werugha and Mwanda, and the one from Msau to the direction of Mbololo forest, that are in need of maintenance operations, not only to facilitate tourism but also for the daily life of the local people as well. Himberg (2006) states that proper roads at the entrance points in the west and north-west side of the Taita Hills, and in Chawia and in Mbololo destinations are essential to improve the potential of ecotourism in the Taita Hills region.

The Nairobi-Mombasa highway and the Voi-Mwatate-Taveta road have been of great international stature, to boost the trade with other countries of East Africa. The manufacturing sector of Kenya has benefited from increased trade with Tanzania, Uganda and the COMESA region, particularly in agro-industrial products, plastics and engineering goods (OECD 2006). The Mombasa-Nairobi highway is one of the main transit corridors of the COMESA network operating as an essential link between the ports and hinterlands. Likewise, the road from Voi to Taveta is an essential link to connect Taveta market place with the Taita Hills region and Voi trade centre. Regional and international passenger traffic of labour and tourists has been enabled by these two international trunk road connections. There are several sisal plantations along these major routes of which Teita Estate is the largest one in the world. These estates employ hundreds of people and produce a huge amount of raw material for sisal products that are transported all over the world. However, the rich horticultural production area of Taveta sub-district is occasionally cut-off due to the deteriorated Mwatate-Taveta road section, which also impedes the international transport connections between the district and Tanzania (Vogt & Wiesenhuetter 2000: 56).

4. THEORETICAL FRAMEWORK

In this chapter, the theoretical framework of the thesis is introduced. The theoretical framework is formed around the combination of a remote sensing and GIS methodology that is applied to the field of road transport, in particular road infrastructure mapping. The concept of road transport is generally reviewed in Chapter 1 and at the Kenyan and Taita Hills scales in Chapter 3. At first, the main principles of remote sensing (RS) in road studies are considered and thereafter, background of the selected methodology is presented.

4.1 REMOTE SENSING – BASIC PRINCIPLES

Remote sensing is defined as the science of acquisition, recording and analysis of information about an object area or phenomenon from a distance without being in direct physical contact with the object of interest (Lillesand & Kiefer 2000: 1). RS is based on the propagation of electromagnetic radiation and its interactions with atmosphere and earth surface features. The reflected or emitted radiation is recorded by RS devices, which are generally divided into passive and active systems depending on their mode to collect data. While passive systems (e.g. cameras and multispectral scanners) measure naturally available sunlight energy reflected or emitted from terrain, active systems (e.g. radar and microwave sensors) use their own source of energy to record objects of interest. Terrain features have varying reflectance characteristics at different wavelength regions and with each other, and consequently, RS devices have varying abilities to measure different features and portions of the electromagnetic spectrum.

Currently, there is a wide variety of RS systems that acquire data at different resolutions from low to very high spatial resolution and from multispectral to hyperspectral, and at varying repetitive temporal cycles. Choosing an appropriate data depends on phenomenon itself and the resources available for that particular application. Generally speaking, with RS devices the cost-effective and up-to-date data may be obtained systematically, regularly over very large geographic areas rather than just single point observations and for a wide number of applications. The integration with GIS improves the management and use of data, extending the range of applications which the information can be used for. An example of applying RS and GIS methodology to various purposes in the developing world is introduced by Pellikka (et al. 2004).

4.2 SCALE AND RESOLUTIONS

Remote sensing systems collect data either in analog or digital form, and they have different resolution properties to detect signals. The resolution characteristics of a RS sensor describe its ability to distinguish between signals that are spectrally similar or spatially near (Jensen 1996: 3). In general, spatial, spectral, temporal and radiometric resolutions are used to define the accuracy of a RS system and the scale at which a phenomenon can be described (Hay & Marceau 2004). Spatial resolution is often used to represent the scale of measurement when RS data are processed in a digital format (Atkinson 2004). While spatial resolution expresses the accuracy of a sensor to record spatial detail of an image observation on the imagery in form of arbitrary pixel units, scale describes the magnitude or the level of aggregation on which a certain phenomenon can be described (Definiens 2004). Each scale reveals information specific to its level of observation (Marceau 1999) and therefore, it is advantageous to have a multi-scale approach to study different levels of information.

The use of spatial resolution as a representation of scale is problematic in a remote sensing context. In particular, many urban areas have a complex nature and discreet patterns which brings along the mixed pixel problem, a case when a pixel is composed of several pure components and the resulting pixel information is a combination of the spectral responses of these individual pure materials (Ben-Dor 2001: 244). The coarser the spatial resolution and the more increased fragmentation of the landscape, the more complex is the problem of mixed pixels and less objects are to be detected clearly (Foody 2004).

On the other hand, it is not always appropriate to use data at the highest spatial resolution to avoid the mixed pixel problem. Unnecessary details of remote sensing imagery may become apparent if data at very high spatial resolution are utilised for the purposes of general analysis (e.g. land use studies). In some cases, data at very high spatial resolution are needed to reach the very accurate results of an analysis, whereas low or medium resolution data are adequate to the purposes of many applications. Furthermore, a fully pixel-based method is not always the best solution for effective analysis and thus other techniques, not only those based on the pixels and the spatial resolution of data, need developing.

4.3 REMOTE SENSING OF ROADS

Roads constitute an essential geospatial layer in many applications, and roads are one of the most important classes of topographic objects. It is therefore of fundamental importance to develop effective methods to obtain accurate, up-to-date data of road infrastructure. However, it requires that certain basic principles of roads in a remote sensing context are followed.

4.3.1 URBAN CHARACTERISTICS

Roads are man-made, built objects usually associated with urban surfaces of infrastructural features and artificial, urban materials. The terms “man-made” and “artificial” refer to objects artificially created using synthetic or natural materials. Man-made objects are usually composed of distinct points, lines and regions related to each others and forming the ensembles of structures (Trinder & Wang 1998). In terms of their existence, however, roads are not only urban objects, but they are placed nearly in all kind of environments: urban, suburban, rural, natural surroundings etc.

There are several essential criteria concerning remote sensing of urban environment and urban objects. In an urban environment two major aspects can be remotely sensed: natural targets and man-made targets (Ben-Dor 2001). Environmental aspects in urban areas can be grouped into two categories: short-term and long-term aspects (ibid.: 245). Short-term aspects are defined as an environmental change that occur within days (e.g. air pollution and traffic load), whereas long-term aspects refers to spatial change which take place over months or years, such as built-up area or road changes.

Jensen & Cowen (1999) state that, besides having a sufficient spectral contrast between the object of interest and the background, it is more important to have high spatial resolution rather than high spectral resolution when extracting urban or suburban information from remote sensing data. Furthermore, the authors propose a spatial resolution standard of less than 5 meters for detailed urban area mapping. On the other hand, in many applications the spectral resolution of existing multispectral remote sensing sensors is still inadequate, and this is a great limitation on the effective RS of diverse urban environment and urban objects.

4.3.2 PHYSICAL CHARACTERISTICS

Roads are geometric, linear features which appear in varying ways on remotely sensed images, depending on sensor sensitivity and resolutions, scale and surrounding as well as the characteristics of roads themselves. Roads are mainly found as “twisting” structures forming solid networks between the nodes and routes between junctions. Linear features are very complex in a remote sensing context as their spectral and spatial characteristics generally vary along their extent (Wang et al. 1992). For example, the contrast along one linear feature against its background may vary from one location to another.

Spectral reflectance curves of urban surfaces differ substantially from each other, as shown in Figure 21. These general urban spectral reflectance characteristics are valid for the road surfaces too. Hence, roads have high within-class variability of spectral characteristics since they are constructed from different materials which produce a broad range of spectral signatures. Roads have spectral properties similar to other urban features, partly due to the fact that they are composed of similar materials. Consequently, it may result in spectral confusion between roads (e.g. asphalt-paved road) and specific roofing materials (Noronha et al. 2002). Asphalt roads also appear to have similar spectral trend to urban features such as paved parking lots, runways or sideways (Herold et al. 2004). Furthermore, gravel or concrete roads may be indistinguishable from bright targets of bare soil surfaces.

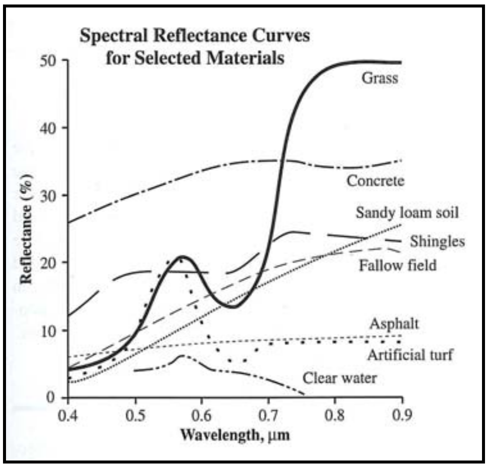


Figure 21. Typical spectral reflectance curves for selected urban-suburban phenomena (Jensen 1989, cit. Jensen 2000: 47).

In the developing countries, the problem of spectral similarity between roads and other land cover may be even more problematic than in the developed countries where concrete and asphalt surfaces are more prevalent. Natural building materials (e.g. clay, mud bricks and thatch) are often used in the construction of buildings in urban areas (Hurskainen 2005: 16). Likewise, especially rural roads in the developing world are more often constructed from materials found locally in the nature than using concrete or asphalt surfaces. The use of soil components (e.g. gravel or coarse sand) for road construction and the coexistence of dry, bare soil surfaces may increase the spectral confusion of roads and other land cover.

The existing methods in the remote sensing of roads are usually based on road models where roads are assumed to follow a number of generalities and where roads are described in terms of geometry, spectral characteristics, topology and context. However, there is a wide variety of roads of diverse properties due to their different functions and construction materials, and environments where they exist. Furthermore, the characteristics of roads vary at different resolution levels (Mayer & Steger 1998). Road models are described in several papers (e.g. Bajcsy & Tavakoli 1976, cit. Auclair Fortier et al. 1999; Barzohar & Cooper 1996; Gruen & Li 1997), in which, roads are usually defined with the following assumptions and generalities about their physical characteristics in remote sensed imagery:

- Roads are represented by continuous, narrow lines / regions of higher brightness values than their neighbour pixels on both road-sides. The brightness values of road pixels stay rather constant within a short distance and within the certain pavement material while the variation between road and background pixels, different road surface materials and over long distances is likely to be larger.
- Road are linear features composed of long, continuous, horizontal segments with smooth curves and straight lines. Neighbouring road segments are topologically linked to each other to form routes between nodes; a road network.
- In general, roads are straight locally but not globally. Roads are smooth in terms of their local curvature, and roads do not have small local wiggles. The local change of direction is limited and is likely to be gradual, although the upper limit is highly dependent on the classification of a road and the physical geography of a region where the road runs.
- Road width change is likely to be gradual. The width of a road has an upper bound, which likewise depends on the classification of a road.
- The steepness of roads has an upper bound, and that is why in mountainous or hilly terrain regions roads are likely to be winding and serpentine.

The physical characteristics influence on the visual characteristics of roads which define the appearance of roads in remote sensing imagery. Vosselman (1996) and Gerke (et al. 2003) criticise that roads are often described only by their geometrical and spectral properties which may confuse them with other linear objects (e.g. rivers or railways). Hence, context and topology should also be taken into consideration with other physical properties in the analysis. Besides, it is essential to pay attention to other factors affecting the appearance of roads in remote sensing imagery: sensor sensitivity and resolutions, scale, background, etc.

4.3.3 INFLUENCE OF SCALE

The appearance of roads depends substantially on the image scale represented by spatial resolution of the digital imagery. In low resolution imagery, roads are smooth objects modelled as lines of one-to-two pixels in width. Roads usually have higher intensity than their background (Trinder & Wang 1998), but however, brightness values of different construction materials can vary greatly. In medium resolution images, roads appear as homogenous areas bounded by two parallel boundaries within which the properties of the surface are measurable and lane lines may be visible. In high resolution images, roads are long, "rectangular-like" objects which cover narrow areas represented by several adjacent pixels. Roads are defined as elongated areas bounded by two parallel edges. The edges between road and neighbouring pixels are fairly sharp, and it is usually relatively easy to locate and assign a specific road class pixel.

A multi-resolution approach for road extraction is more successful than a single resolution one (Heipke et al. 1995). In general, digital camera data or other high spatial resolution imagery can be used to study the current status and change of road networks at a large scale, while satellite imagery of low or medium spatial resolution are principally applied to detect general features of road networks, direction of expansion and changes at small scale. The 1-30 m spatial resolution data is suited for general road centreline extraction while 0.25 m – 0.5 m data makes possible precise road width examination (Jensen 2000: 410). Each scale has its advantages, which often correspond to the drawbacks of the other (Heipke et al. 1995; Auclair-Fortier et al. 1999). In low-resolution images, small disturbances such as shadows by adjacent buildings or cars on a road are not so prominent or may even not be visible at all due to the averaging of the grey-scale values. Moreover, general road network structure can be seen clearly. In high resolution images, the geometric accuracy is much better, which usually makes possible a more accurate detection of roads. There are generally different algorithms for road detection at each resolution level due to the different appearance of roads in different scales.

4.3.4 INFLUENCE OF BACKGROUND

Roads appear differently on remote sensing images depending on the background where they exist. The most important condition for an acceptable result in the road detection process is a good contrast between roads and their background (Baumgartner et al. 1999). However, roads may have reflectance values similar with their background as already described above. Difficulties may arise when a road passes through or close to an area of bare ground, a settlement or a construction site. In addition, background may have a strong, disturbing influence on the appearance of roads due to the elongated characteristics of roads. Roads are usually represented by narrow lines or regions of not more than few pixels and thus, road pixels may get erroneous value from their neighbours instead of getting the proper values.

As a “bottom layer” of three-dimensional land surface structure, roads are often covered or shadowed by surrounding surfaces such as tree canopies, other vegetation, buildings or cars (Herold et al. 2003b). Other objects can fully or partially cover a road segment which results in a spectrally indistinct response with a high amount of spatial variability.

This brings along the mixed pixel problem (Campbell 2002: 277), in this case a value of a road pixel is inaccurately represented and mixed with the surrounding land cover or land use. The spectral continuity of the road is then interrupted and the contrast eliminated between road and its surroundings.

The extent of interruption by background depends on the surrounding land cover or land use itself. Usually, in rural areas there are only few disturbing background objects, e.g. single buildings or trees that influence the appearance of roads in the imagery (Baumgartner et al. 1999). On the contrary, in urban environment the level of disturbance becomes more complex (Hinz et al. 2001). Other urban objects may be spectrally similar due to similar material composition (e.g. roads and roofs) or spectral confusion between specific urban materials and bare soil surfaces (Herold et al 2004). In addition, shadows by high buildings and cars may disturb the appearance of roads. Furthermore, in forest areas roads are often not visible due to tree canopy as a “top layer” of land cover. Thus, only fragments of the road network may be detected.

4.3.5 REMOTE SENSING IN ROAD STUDIES

Since there is a wide range of roads of diverse characteristics and they exist in nearly all type of environments, road detection is a very challenging operation. Roads have been of great interest in the last few decades, and there has been much intensive research to automate the process by applying different automatic or semiautomatic techniques for road extraction. The existing techniques are often inadequate, complicated or time-consuming to implement, or suitable only for certain environments, road types or resolutions. These methods are often based on relatively simplistic road models, and most of them make only insufficient use of prior information, such as data from maps and GIS (Zhang 2001). The diversity of road extraction strategies is probably due to the fact that none of them are reliable in all circumstances (Auclair-Fortier et al. 1999)

Road extraction approaches can be classified in several ways (Mena 2003). Firstly, road extraction tasks are generally categorised according to the degree of automation (Zhang 2004). A traditional way for road detection is manual interpretation, which may still be the most functional and reliable way to extract road information in many applications. Semi-automatic methods can also be viewed as knowledge-based methods, in which the existing knowledge can be used to ease and speed-up object extraction (Baltsavias 2004). Fully automatic methods attempt to achieve true operational autonomy (Agouris et al. 2001). While methods fail to provide good quality results and are very slow, semiautomatic methods are often more successfully applied to various purposes (Eidenbenz et al. 2000).

Secondly, road extraction approaches are classified according to their technical aspects: the basic principle and functionality of a road extraction algorithm (Auclair-Fortier et al. 1999; Mena 2003). Among others, segmentation is one type of method discussed in the latter paper. The segmentation technique is essential in the context of this study (see Chapter 4.7).

Thirdly, road extraction approaches are classified based on the functionality; the context where they operate successfully. As roads exists in nearly all kind of environments and as background has a great meaning in road detection processes, road algorithms have been designed with a high level of details for that environment from which they are supposed to be extracted. Several papers (Hinz & Baumgartner 2000; Hinz et al. 2001; Butenuth et al. 2003) note that most of the approaches are focussed on the extraction of roads in a limited environment, usually in rural areas. Thus, road extraction mainly relies on road models that describe the appearance of roads in an open, relatively undisturbed environment, where roads are not obscured by buildings or trees and are relatively easy to detect. Meanwhile, the more complex urban environment has often been neglected, although there have been a number of efforts in recent years towards the more comprehensive extraction of roads in urban environments. Therefore, certain techniques are needed for the effective extraction of urban objects and roads in an urban environment and in other areas of heterogeneous land cover and land use.

4.4 SELECTED METHODOLOGY

The initial selection of the remote sensing (RS) and GIS methodology for this thesis is guided by the principles introduced above. In addition, the following issues are considered when choosing the methods suitable for this context:

- Methodology is suited for the diverse road infrastructure of the heterogeneous land use of the Taita Hills. The methods, however, are developed with a view to apply them generally to road mapping in the developing world.
- Methods are practical, straightforward and cost-effective, so that they could be appropriate, feasible and effectively utilised in the developing countries.
- There are data at different scales and resolutions available for this study. Thus, the methodology on trial is developed from the viewpoint of selecting best options for each “level” of examination, then discussing generally different approaches in the road mapping, and comparing their pros and cons. The emphasis is placed on the multispectral remote sensing approaches due to the multispectral nature of the RS data available.
- The focus is on the general road mapping applying a certain level of automation and novel techniques in the procedure. Above all, object-oriented approaches of *eCognition* software are considered, since segmentation-based classification along with automatic vectorisation could have potential for efficient, automated road extraction to substitute manual interpretation of roads and to generate practical vector format output. The data could be then completed by manual editing and used for updating the existing road data layer of the Taita Hills geodatabase
- Despite the emphasis on the digital analysis techniques, visual interpretation is implemented as well, since it is still assumed to be the most reliable method for accurate road detection and delineation.
- Pixel-based approach is also taken into consideration, since it is commonly used and relatively easily applied to the RS context.
- Field spectrometry is applied to analyse the spectral characteristics of the different road surfaces with the existing spectral libraries, and to discuss the potential of these approaches for detailed road mapping purposes.

4.5 VISUAL INTERPRETATION

Image interpretation is defined as the examination of images to identify objects and to assess their significance (Philipson 1997). The image interpretation tasks are classification, enumeration, measurement and delineation (Campbell 2002: 124-125), and the image interpretation may be either visual or digital. In the last few decades, there has been much effort to automate the process of image interpretation. However, visual or manual interpretation has still kept its significance in many remote sensing applications, and this traditional, qualitative way of image interpretation is often applied at least to evaluate and visually check the results of more automatic, sophisticated methods. In many cases, the visual analysis is still the most successful method to obtain reliable and accurate information from remote sensing imagery.

Visual interpretation is a very user-dependent process, which is carried out based on the skills and experience of interpreter to detect, identify, describe and assess object information. The analysis is based on the *elements of visual interpretation* which include location, size, shape, shadow, tone and colour, texture, pattern, height and depth, and site, situation, and association (Jensen 2000: 119-136). The benefits of the visual interpretation are that it is a simple, concrete method and it needs inexpensive equipment while automatic interpretation usually requires high-priced tools and expertise of staff to perform the process. Instead of using automatic methods, it is often possible to obtain reliable results more rapidly performing visual interpretation. The chances of misinterpretation of objects are very less due to the expertise, experience and local knowledge of the field. On the other hand, visual interpretation is a very subjective method and highly depends on the interpreter, in terms of the success or failure. It may also be time-consuming for less experienced interpreters, whereas digital methods may be more cost-effective for large areas and for repetitive studies and they may also result in more consistent results.

Visual appearance of roads in digital images may be improved performing image enhancement techniques to data (Jensen 1996: 139-195; Mather 2001: 97-111). Image enhancement techniques are designed to modify the appearance of an image in such a way that the information is more readily interpreted visually in terms of a particular need. Image enhancement is an arbitrary way to modify the content of an image and thus, enhanced images should not be used as an input for automated techniques of image interpretation. On the contrary, image enhancement techniques are often applied in context of visual interpretation. These techniques alter the original pixel brightness values of the digital image data and may emphasise the visibility of roads from their background.

Image enhancement techniques can be classified as either point or local operations (Jensen 1996:139-195). Point operations modify the brightness value of each pixel in the image data set independently while local operations change the value of each pixel based on neighbouring brightness values (ibid.) Image enhancement approaches can be categorised as contrast manipulation, spatial feature manipulation and multi-image manipulation (Lillesand & Kiefer 2000: 488-532). The selection of the proper methods and the choice of the right parameters depend on the quality of the original image data and on the application itself.

Contrast enhancement, also referred to as histogram stretching, modifies the original input brightness value range of the image. A new histogram will then have the same number of the brightness values available as the old one but they will simply be situated at different locations (Richards & Jia 1999: 92-93). Contrast enhancements can be considered as linear and non-linear stretch techniques (Jensen 1996: 145-152; Gibson & Power 2000: 35-40). While linear stretch expands equal digital number (DN) ranges by equal amounts, non-linear enhancement gradually stretches DN ranges by different amounts.

Spatial filtering is a local operation in which pixel brightness value is modified on the basis of the brightness values of neighbouring pixels (Lillesand & Kiefer 2000: 499). This approach makes possible to extract, reduce or amplify specific frequency components of a digital image. Spatial frequency enhancing can be performed either using spatial convolution filtering or Fourier analysis (Jensen 1996: 153-171). Convolution filtering is accomplished using a particular convolution kernel, a matrix of weighting factors which average the value of each pixel with the values of surrounding pixels (Erdas 2003: 158). High-pass filters emphasise the detailed high frequency components of an image called "image sharpening" and de-emphasise the more general, slowly varying low frequency information. Low-pass filters operate just the reverse way, thus “blurring” the image.

High-pass filters serve as edge enhancers, since they emphasise the edges within an image. An edge is a discontinuity or an abrupt, sharp, change in brightness value between two adjacent pixels of an image. Edges are generally formed by long linear features such as geological structures or rivers but however, urban landscapes also contain edges formed by cultural features such as roads, railways and the outlines of buildings (Gibson & Power 2000: 50). Edge enhancement delineates these edges and makes the shapes and details comprising the image more evident and easier to interpret (Jensen 1996: 158).

Roads – as well as coastlines, river systems and other linear structures - are usually identified relatively easily from remotely sensed data by their spatial character and then delineated through digitising. Roads are either delineated as lines or polygons that depend on the spatial resolution of remote sensing data and the purpose of the actual visual interpretation task. Digitising of roads along their centre lines is applied when using data of low resolution and/or if there is a need for a relatively rapid delineation process. Respectively, roads described by polygons are a more realistic and accurate representation when using high resolution data but, however, are a more time-consuming operation to carry out and not necessarily the most practical output either. Classification and other additional tasks such as building topology of a road network are carried out in the context of the digitising process.

4.6 PIXEL-BASED APPROACH

Pixel-based techniques are a quantitative approach to digital image analysis (Richards & Jia 1999: 75-88). So far, supervised and unsupervised classification methods have been the most common types of automatic image interpretation they offer a valid method for automatic classification purposes. The pixel-based methods have routinely been applied to remote sensing data since the first spectral classifiers developed in the 1970s. However, these purely spectral-based approaches have their limitations (Blaschke & Strobl 2001). In the pixel-based approaches, pixels are assigned to spectral classes according to their brightness values, and informational objects classes are then derived from the spectral classes and their subclasses (Campbell 2002: 321-323). Pixels having similar spectral characteristics are consequently assumed to belong to the same class. The classification process is carried out without any further information, such as spatial context or texture. Therefore, in many ways this type of classification is very inadequate and the obtained results may be rather inaccurate. In particular, the problem may be outstanding in cases of a coarse spatial resolution and spectrally complex urban environment, resulting in the mixed pixel problem. Townshend et al. (2000) point out that in the pixel-based characterisation of land cover a substantial proportion of the signal apparently coming from the land area represented by a pixel comes from the surrounding pixels. Consequently, spectral response of individual pixels is often inadequate to guarantee the success of a classification process.

Pixel-based classification techniques are often rather limited methods for the road extraction of different road types in diverse, urban environments. The characteristics of roads make the concept of road extraction a challenge, because roads are very diverse both spatially and spectrally. The methodology based on the pixel-based classification and one spatial scale does not make sufficient use of spatial concepts of neighbourhood, proximity or homogeneity (Burnett & Blaschke 2003). Therefore, new classification concepts are required which could be implemented more effectively in challenging remote sensing applications of road extraction. These concepts should pay more attention to additional information and scale issues, exploiting contextual information and road characteristics and not be limited to one-scale, pixel-based examination.

4.7 OBJECT-ORIENTED APPROACH

Segmentation is an innovative object-oriented approach and it is a prerequisite for object-based classification (Baatz & Schäpe 2000), which is a promising and superior approach to traditional pixel-based classification methods (Blaschke & Strobl 2001; Schiewe et al. 2001). The common image segmentation techniques were initially reviewed by Haralick & Shapiro (1985). Available image segmentation approaches are generally grouped into three categories: pixel-, edge- and region-based techniques (Blaschke et al. 2004). Image segmentation can be viewed as a clustering process in which the basic processing units are segments, clusters instead of single pixels. Segmentation is defined as the search and subdivision of neighbouring pixels of an image into separated, homogenous regions based on certain similarity criteria (Mather 2001; Definiens 2004) and the basic objective of the segmentation is to generate meaningful, homogenous objects for the following classification. In an urban environment sharp, discrete boundaries and a high-frequency change of different built objects with similar reflectance properties occur more often than in many natural environments (Blaschke & Strobl 2001).

The segmentation-based classification procedure in *eCognition* software offers a sophisticated method that is implemented at a segment level with additional, contextual information. The key to *eCognition*'s region-based approach is that the internal heterogeneity of a segmentation parameter under consideration is lower than the heterogeneity compared with its neighbouring regions (Blaschke et al. 2004). In *eCognition*, the multi-scale segmentation procedure can be performed through the two reverse approaches: top-down and bottom-up methods segmentation techniques (Hofmann & Reinhardt 2000; Definiens 2004: 65-67). Hofmann (2001a) places the emphasis on the distinction between the two approaches and on the order of segmentation that affects the results of the segmentation. Hence, the approach should be determined by the main focus of the classification and by the image data features.

The region growing segmentation should be appropriate for linear object extraction since shape information can be included in the similarity criteria of region growing. As roads are typically elongated features, spatial characteristics are better suited to describe them than their spectral properties (Hofmann 2001b). On the other hand, in terms of their shape characteristics, roads appear similarly with other linear object (e.g. rivers and railways) and there is a chance for confusion between these linear elements.

Object-oriented approach is expected to be suitable for the purposes of this study, in order to extract meaningful road object information from the remote sensing imagery. The multi-resolution segmentation and supervised classification conducted by fuzzy logic with the following automatic vectorisation procedure offer potential methods for the mapping and updating of the road infrastructure.

4.8 FIELD SPECTROMETRY AND HYPERSPECTRAL REMOTE SENSING

The weak knowledge of urban spectral properties is one of the major disadvantages of remote sensing (RS) of urban environment and transport infrastructure. There is an inadequate understanding about the spectral nature of different road surface types and their characteristics at varying age and condition. The complex nature of urban environment exacerbates discriminations between different urban surfaces (e.g. roads, buildings and parking lots) and decreases the effectiveness of the multispectral sensors. The existing multispectral devices have significant spectral limitations in mapping urban environment and road surfaces due to the location of the spectral bands and the broadband character of these sensors (Herold et al. 2003b). The spectral heterogeneity and the distinct spectral characteristics of urban materials and land cover types need to be taken into consideration in the discrimination and mapping of road surfaces. The spectral characteristics of urban features can be investigated with three different approaches: 1) applying *in situ* spectral measurements, 2) using existing spectral libraries of urban objects, or 3) acquiring and analysing hyperspectral RS data. The best results are achieved when data of these different approaches is analysed in the common context.

Field spectrometry is the quantitative technique to measure spectral reflectance, irradiance, radiance or transmission of surface materials to determine their spectral response patterns. The ground-based measurements are applied to calibration of remotely sensed data, prediction of best conditions for observing and acquiring data, and modelling the reflection from different surface structures (Barrett & Curtis 1999: 125). In addition, field observations provide detailed information about the spectral characteristics of individual materials for more precise, sophisticated image analysis techniques. Field spectrometry offers a technique for direct material identification instead of sample collection for later laboratory analysis.

Field spectrometry is usually conducted with spectroradiometer which is a hyper-spectral system with a very small spectral sampling interval (~1 nm), or with a radiometer that is typically a broad-band multispectral device with larger spectral sampling interval (~50 nm). The former allows collecting of continuous spectrum data with high spectral resolution and discrimination, whereas the latter has more limited capacity for spectral analysis.

Among others, field spectrometry may be applied to measure the reflectance of road surfaces and to acquire detailed information about the varying spectral characteristics of different road construction materials. At present, there are a number of urban spectral libraries constructed from *in situ* spectrometry measurements (Ben-Dor 2001: 243-281; Herold et al. 2004). These libraries consist of the individual spectra of urban materials, including roads, classified to different categories according to their spectral characteristics. The information of the libraries may be applied in detailed road studies including both rural and urban environment schemes and different road types. Spectral libraries enable comprehensive road analysis because they are able to derive very accurate information about the spectral separability and the spectral signatures of urban materials (Herold et al. 2004). In addition to existing spectral libraries, field spectrometry data may be analysed with laboratory measurements or with hyperspectral remote sensing data.

Hyperspectral remote sensing – also referred as imaging spectrometry - involves simultaneous acquisition of a large number contiguous spectral bands with hyperspectral sensors in order to make possible the construction of reflectance spectra at a pixel scale and the examination of these spectra with similar spectra measured either using field spectrometry or in a laboratory (Jensen 2000: 227; Van der Meer & Jong 2001). There are several reasons for applying hyperspectral imagery in various RS applications (Shippert 2004). Unlike common multispectral sensors, hyperspectral devices have the ability to image up to 224 bands and derive the complete reflectance spectrum of each picture element of an image (Jensen 2000: 226-231). The much increased spectral dimensionality enables substantially more precise investigations and more accurate discriminations of data, extending the range of applications and defining new concepts and analytical techniques (Landgrebe 2000; Campbell 2002: 407-417). Therefore, hyperspectral devices have great possibilities in urban applications and in RS of man-made structures. On the other hand, the hyperspectral image analysis needs to be performed outstandingly carefully due to the increased volume of data and the novel approaches to be applied (Lillesand & Kiefer 2000: 592-597).

On the other hand, Noronha (et al. 2002) argue that the discriminating ability of hyperspectral remote sensing is concentrated within a few wave bands. In addition**,** the classification accuracy can actually decrease if too many highly correlated spectral bands are applied so that the sensor derives “too much” spectral information (Landgrebe 2000). Furthermore, the current hyperspectral devices and techniques are criticised to be overly complex and expensive for most purposes and users, thus limiting the full benefits gained from hyperspectral remote sensing. Therefore, it is essential to develop specific multispectral sensor configurations and analytical techniques optimised particularly for the remote sensing of road infrastructure. This would improve general knowledge of the spectral properties of roads and the techniques available for road extraction.

Hyperspectral remote sensing may be combined with object-oriented image classification approaches to improve the accuracy of an analysis. Object-oriented approach as well as spatial, textural or contextual information may provide further significant improvements to analysis and help to overcome spectral confusion between specific classes such as asphalt roads and specific roof types (Herold et al. 2003a). In Noronha et al. (2002), the object-oriented approach is performed via segmentation using *eCognition* software.

5 DATA

5.1 REMOTE SENSING AND GIS DATA

The SPOT XS satellite imagery was applied to the preliminary examination of the Taita Hills, to increase basic knowledge of the study area and its road infrastructure and to prepare for the first field work period, conducted in January-February 2004. The satellite imagery was used in the visual interpretation (Chapter 6.6) and in the field spectrometry analysis (Chapter 6.8) as well. The main satellite image data of the study is from 2003, it has 20 m spatial resolution and spectral resolution of 4 bands: Green (G), Red (R), Near infrared (NIR) and mid infrared (MIR). The characteristics of the SPOT satellite image data are shown in Table 3.

Table 3. Characteristics of the SPOT satellite image (143-357).

Sensor	SPOT 4 HRVIR1
Year	2003
Date	October 15th
Bands	G, 0.50 - 0.59 µm
	R, 0.61 - 0.68 µm
	NIR, 0.78 - 0.89 µm
	(MIR, 1.58 - 1.75 µm)
FWHM	5 nm
Spatial resolution	20 m

The main remote sensing data of the study are airborne digital camera data acquired in January 2004 using a true-colour (B, G, R) NIKON D1X digital camera. The aerial photography was captured on January 27th 2004 between 10.25 and 11.13 GMT, and it consisted of total 599 digital images. The 11 flight lines had approximately 60 % overlap and 40 % sidelap, and a camera opening angle of 78º. The secondary data digital image mosaic was constructed in *EnsoMOSAIC* and *ERDAS IMAGINE* software from the primary airborne digital camera data. The characteristics of the original "raw" airborne data and aerial image mosaics are shown in Table 4 and Table 5. The main analysis of this study was based on the aerial image mosaic data.

In addition, the cartographic data produced by the Survey of Kenya (1991) were used in two ways in this study. Firstly, the two paper map sheets, *Kenya 1:50 000 Topographic Map* of the Taita Hills and Mwatate were exploited as such, mainly during the both field periods to assist the field work along with a paper print of the satellite image data. Secondly, six paper map sheets were scanned and digitised in order to generate a digital geodatabase of different map information in forms of vector data layers such as hydrography, administrative area boundaries and classified road network (Broberg & Keskinen 2004). The road network layer is the most essential auxiliary dataset of the geodatabase for this study.

Table 4. Characteristics of the NIKON D1X airborne digital camera data.

Camera focal length	DC Nikon D1X
Date	27th January 2004
Bands	B, G, R
Camera focal length	14 mm
IFOV	78°
Resolution	3040 x 2016 pixels
Ground resolution	~ 0.21 - 0.48 m
Type	JPEG image

Table 5. Characteristics of the NIKON D1X digital image mosaic.

Images	576
Flight lines	11
Type	TIFF (converted to IMG)
Resampled pixel size	0.8 m
RMS error	1.11
Projection	Transverse Mercator
Spheroid	Clarke 1880
Datum	Arc 1960
Scale factor at central meridian	0.999600
Longitude of central meridian	39:00:000000 E
Latitude of origin of projection	0:00.000000 N
False easting	500000.000000 m
False northing	10000000.000000 m

5.2 FIELD WORK DATA

An essential part of this study is the field work data collected during the two field work periods in the Taita Hills and Nairobi. The first field work was carried out in January-February 2004 in context of the field excursion to the Taita Hills (Pellikka et al. 2004) and the second was conducted in January 2005 with Professor Petri Pellikka, PhD student Barnaby Clark and MSc student Nina Himberg.

5.5.1 ROAD POINT DATA

During the first field period general knowledge was increased and detailed information was gained about the road infrastructure and transport of the Taita Hills. The field work was mainly carried out concurrently with MSc student Katja Masalin who was collecting various land cover data for her own Master's thesis (Masalin 2005). General observations and field notes about the road transport and more detailed field measurement about the road infrastructure were made on foot and utilising an off-road vehicle and GPS equipment that together enabled an extensive field study conducted in the study area.

The main aim of the first field work period was to collect an extensive *in situ* road verification dataset on a few selected study sites. The ground truthing dataset consist of 150 road points which encompass roads' spatial and attribute data, such as coordinate information, road width, surfacing material and condition, surrounding land use and terrestrial photograph. The road points were selected on the basis of the road classification of *Kenya 1:50 000 Topographic Map* data and according to different land use where roads exist, so that each road class would be represented within the various surrounding land use patterns. The initial purpose was to apply the field work data to the remote sensing analysis and evaluation of the results. However, the quite limited capacity of the hardware and software set up limits to the extent of the image mosaic applied to the digital analysis and hence, only a minority of the collected road data were used eventually. Instead, the analysis was implemented with samples and spectral signatures, since there was sufficient spatial and spectral resolution to identify objects on the imagery. In addition, the accuracy assessment was conducted with random sample points calculated by the software. The road point data were applied to assist the mapping and updating of the Taita Hills road infrastructure.

5.5.2 FIELD SPECTROMETRY

During the second field work period field spectrometry data were obtained to study the spectral characteristics of different road surface types. The reflectance values were measured for tarmac, concrete, gravel, and earth roads of varying characteristics and conditions. The field spectrometry was conducted using an ASD FieldSpec® HandHeld UV/VNIR (325-1075 nm, 3.5 nm spectral resolution) spectroradiometer, and the acquired data was post-processed afterwards.

5.3 OTHER DATA

Advantage was also taken of various qualitative data in this study. Field notes were collected and terrestrial photographs taken during the field periods. Furthermore, relevant literature and reports of Kenyan libraries were collected in Wundanyi, Voi and Nairobi. During the whole preparation phase of the thesis, various publications, journals and reports found in Finnish libraries and Internet were utilised as well.

6 METHODOLOGY AND ANALYSIS

6.1 SOFTWARE

This thesis is strongly methodology-oriented based on remote sensing (RS) and geographic information systems (GIS). Hence, the software utilised are a fundamental part of the whole process of this research, especially the methods and the analyses implemented. The RS and GIS software generally have different functions, operational principles and data formats to process and analyse data and therefore, it is required to select appropriate software for different purposes. The principal RS software applied to this context are *ERDAS IMAGINE (8.7)*, *EnsoMOSAIC (5.0)* and *eCognition Professional (4.0)*. In addition, the GIS software *ArcGIS (9.1)* was used in this study. Field spectrometry measurements were collected with FieldSpec® RS^2 software.

6.2 PRE-PROCESSING OF THE SATELLITE IMAGE DATA

When working with remotely sensed data, digital imagery usually needs to be pre-processed before the data can serve any useful purpose. Pre-processing operations normally precede further manipulation and analysis of the image data to extract specific information and to correct image data for distortions derived from the image acquisition process (Lillesand & Kiefer 2000: 470-488). Jensen (1996: 107) makes a difference between systematic and constant *internal* errors created by the sensor itself, and unsystematic *external* errors caused by platform perturbations and the modulation of atmospheric and scene characteristics. Radiometric and geometric errors are the two main types of errors encountered in remote sensing imagery. Radiometric errors present a problem of skewed DN values, and geometric errors bring about a distortion of the pixels' locations in relation to terrain. The aim of the geometric and radiometric corrections is to remove or reduce the source of errors in digital imagery that introduce distortions in quantitative studies such as land cover classifications and spectral analyses.

A number of pre-processing operations were implemented to the satellite imagery by PhD student Barnaby Clark and MSc student Katja Masalin. The visual interpretation and the field work were conducted with the imagery processed by Masalin. Respectively, the imagery pre-processed by Clark was applied to the spectrometry analysis. The pre-processing methods are more comprehensively described in Pellikka (1998), Clark & Pellikka (2005) and in Masalin (2005). The pre-processing of the airborne digital camera data is reviewed below.

6.3 PRE-PROCESSING OF THE AIRBORNE DIGITAL CAMERA DATA

The corrections of the airborne digital camera data were performed by the author himself since the digital camera data were the main data of this study. In this chapter, the background of the errors concerning digital airborne camera data is given and the principles of the correction methods are introduced. In addition, the implementation is presented with more detail on each step.

The principal aim of the pre-processing was to produce accurate digital image mosaics corrected from the various errors. In general, radiometric errors result in a mosaic with clearly seen seams of the individual images, and geometric errors occur as discontinuities of some terrain features such as roads (Holm et al. 1999). The corrections are a prerequisite for the further analysis of this study - both for quantitative classification techniques and for visual analysis. In addition, the accuracy of the digital image data is needed for the examination of the results with other data, such as the SPOT image data, the field work data and the vector layers.

6.3.1 RADIOMETRIC ERRORS AND CORRECTIONS

Radiometric errors of the remotely sensed data are caused by different factors: the remote sensing system or its detector may not function properly or the energy recorded by the sensor is intervened due to environmental attenuation (Jensen 1996: 107). The major sources of environmental attenuation are atmosphere attenuation caused by scattering and absorption in the atmosphere, and topographic attenuation (ibid.). In addition, such factors as viewing geometry, changes in scene illumination and instrument response characteristics affect the magnitude of radiance measured by the sensor and inflict errors in the data (Lillesand & Kiefer 2000: 477). In case of the airborne camera data acquired from low altitudes and using wide-angle lenses, the variations in the viewing geometry are typically greater and the data is less influenced by atmospheric effects than in case of satellite imagery (ibid.).

Topographic errors caused by slope and exposition of rough terrain or mountainous areas result in varying brightness values between the objects of same land-cover class due to their varying orientation and the sun angle (Teillet et al. 1982). The distortions cause remarkable problems e.g. to the forest classifications and, therefore, topographic correction methods such as illumination compensation are needed to improve quantitative classification results of the data (Pellikka 1998). On the other hand, a simple topographic normalisation may not necessarily improve significantly the results of the classification (Tokola et al. 2001). In addition, over-corrections may occur on poorly illuminated slopes, and the correction should be adjusted for each wavelength area individually which may be impractical against the overall benefits of the correction procedure. Consequently, no topographic corrections were implemented in this context due to the moderate quality of the digital elevation model (DEM) derived in *EnsoMOSAIC*.

The main problems in the digital analysis of aerial photographs are the effects of bidirectional reflectance distribution function (BRDF) and light falloff - also termed as exposure falloff - that cause brightness variations in aerial photographs and DN values of the image pixels to be dependent on their location in the image (Tuominen & Pekkarinen 2004). The presence of these effects induces errors in the brightness values of uncorrected remote sensing data. Without the corrections, different parts of the image are not spectrally comparable and, respectively, the corrections increase the classification accuracy of the data (Pellikka 1998). Therefore, it is necessary to use the BRDF and light falloff corrections for the purpose of the quantitative analysis applied to this context.

The light falloff effect is a combination of various optical and geometric factors, and vignetting effects caused by internal shadowing within the camera optics, film or charge-coupled devices (CCD) sensor (Pellikka 1998: 12). Modern lens designs have been able to reduce the concentric effect (ibid.). The light falloff is associated with the distance of an image point from the image centre, and the exposure is at maximum at the centre and decreases with the radial distance from the centre towards the borders of the image (Lillesand & Kiefer 2000: 66). Hence, edges and corners are darker than the centre areas of the image and similar surfaces may not have uniform values in different parts of the uncorrected image. The light falloff exposure can be reduced e.g. by placing anti-vignetting filters in front of camera lens or by using a correction model to normalise the light falloff effect. The latter was applied to this context.

The BRDF effect is the occurrence of brightness variations of similar objects in different parts of the image due to the different illumination conditions, the geometrical and spectral characteristics of sensor, the atmospheric conditions and the target characteristics. The BRDF is a mathematical description of the distribution of radiance at all possible different observation and illumination angles (Slater 1980). The magnitude of the BRDF effect is a combination of the different sensor, sun and target characteristics. The BRDF varies for all different combinations of wavelength areas, illumination and viewing angles, and with different surface characteristics and topography (Lillesand & Kiefer 2000: 31; Pellikka et al. 2000; Tuominen & Pekkarinen 2004). The BRDF effect causes the phenomenon that similar objects may have different spectral characteristics in different parts of the image. Objects in the direction of incoming solar radiation expose their shadowed parts to the sensor, and those in the opposite direction expose their well-illuminated sides (Holopainen & Wang 1998). As a result, the objects in the solar side of the image appear darker than the objects in the opposite side of the image.

The BRDF effect can be reduced with a variety of the correction models (e.g. empirical, physical or regression models) implemented on airborne or satellite image data. The Pellikka BRDF correction procedure (Pellikka 1998: 45-49), that is a mixture of physical and empirical correction models, was applied to this study.

6.3.2 GEOMETRIC ERRORS AND CORRECTIONS

In general, geometric errors of the remote sensing data are caused by different characteristics of sensor, imaging and environment. Geometric errors usually involve a range of systematic, predictable distortions and non-systematic, unpredictable distortions (Jensen 1996: 124). Normally, the systematic distortions are first considered and random errors afterwards (Lillesand & Kiefer 2000: 474). Geometric distortions derive from different sources; from sensor characteristics, aerial photography and environmental factors such as topography and atmospheric conditions. Geometric correction is defined as the process of “transformation of a remotely-sensed image so that it has a scale and projection properties of a map” (Mather 2001: 75). Geometric corrections are necessary for the purpose of applying remote sensing data to further analysis and GIS operations. Jensen (1996: 124) makes a difference between the errors that can be corrected using data and knowledge of internal sensor distortion, and those that must be corrected with a sufficient number of ground control points (GCP) on the terrain. In this study, however, GCPs were not applied to the correction procedure.

The geometric corrections were performed with the camera calibration parameters including the focal length and the principal point of the digital camera and the distortion coefficients of the CCD sensor of the camera. These parameters were applied to the image rectification from image coordinates to map coordinates to correct the geometric errors caused by internal sensor distortions. The actual image rectification was performed in the Bundle Block Adjustment (BBA) of the *EnsoMOSAIC* software. The geometric distortions of scale and location caused by aircraft roll, yaw, pitch and decrease of pixel size frame nadir point to the edges and off-axis areas (Pellikka 1998: 5) were not taken into consideration since these data were not available in this context.

6.3.3 IMPLEMENTATION OF THE CORRECTIONS AND MOSAICKING

The airborne digital camera data pre-processing was implemented in *ERDAS IMAGINE* and *EnsoMOSAIC* software through the different stages of the radiometric correction methods, image rectification and mosaicking. The pre-processing work flow is shown in Figure 22. The procedure resulted in a geo-referenced, radiometrically corrected digital image mosaic.

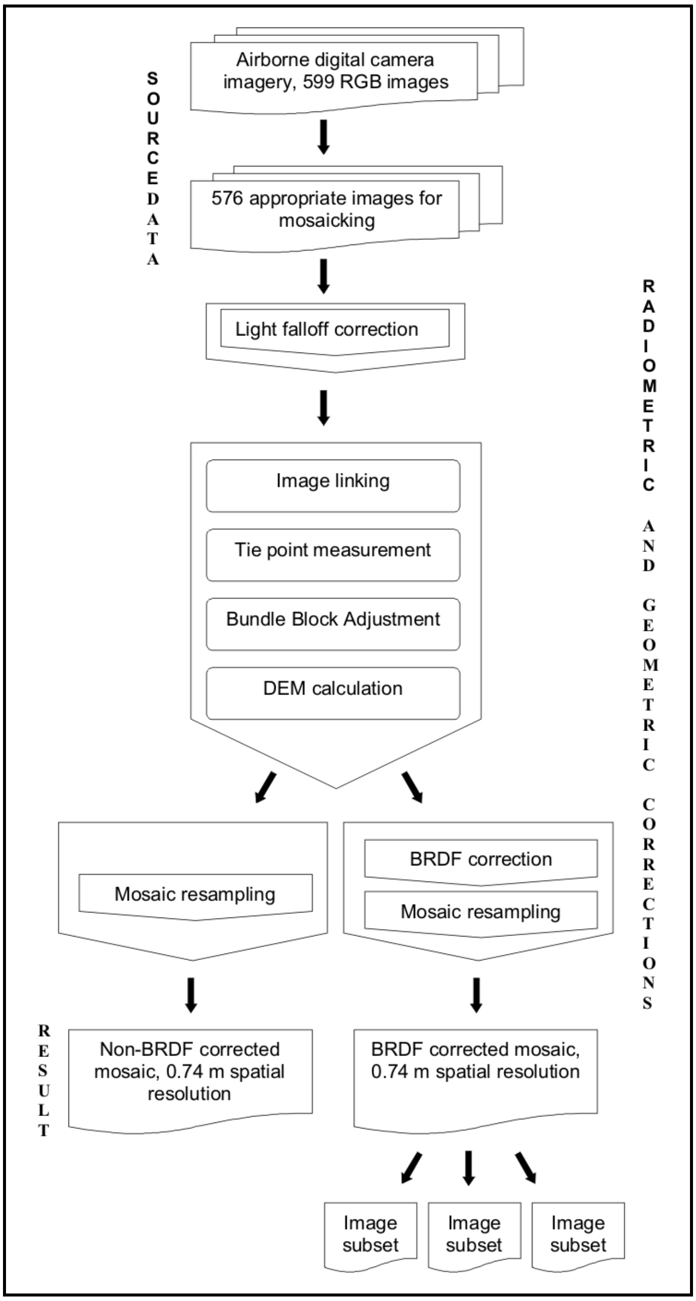


Figure 22 The work flow the of airborne digital camera data pre-processing.

The airborne digital camera data acquired in the aerial photography were in the digital compressed format of JPEG images. The first step of the pre-processing was to select appropriate images for the image mosaic construction and to discard inappropriate images. In total, 576 digital images were approved for the mosaicking while 23 images were discarded since they had poor quality due to cloud cover. Meanwhile, the original CRD file was set up and verified so that the flight line and image information details were correct and logical with the imagery chosen for the actual image mosaic construction. The CRD-file is an output file of aerial photography using NavCam software, and it includes flight information which is the input coordinate file for block creation in *EnsoMOSAIC* software (StoraEnso 2003).

The next step was to conduct the light falloff normalising method for the individual images with a modified correction procedure after Pellikka (1998: 39-41). The two phases of the correction were implemented in the *ERDAS IMAGINE Model Maker* using the unpublished model created by Janne Heiskanen & Petri Pellikka and further modified by Pekka Hurskainen and Pertti Parviainen (Hurskainen 2005: 54-55). At the first stage, the zenith view angle (θ) was derived for each pixel of one raw image from the equation:

$$\theta = \arctan\left(\frac{r}{f}\right)$$

, where θ = viewing angle between the optical axis and the ray to the off-axis point
f = focal length
r = distance between the pixel in the off-axis position and that at the optical axis
(Pellikka 1998: 40).

The focal length (f) of the camera was obtained from the camera calibration parameters. The zenith view angle is the viewing angle between the optical axis and the ray to the off-axis point, in other words the angle between the sensor, the zenith and the target pixel. The zenith view angle image models the increase of the light falloff effect from the principal point to the borders of the image (Figure 23).

Since light falloff is a systematic lens-related effect, the calculation of one zenith view angle image can be applied to all images taken during that flight and with the same camera. Hence, the correction of the whole imagery was implemented in a batch created by Hurskainen (2005) which reduced the processing time of the first phase.

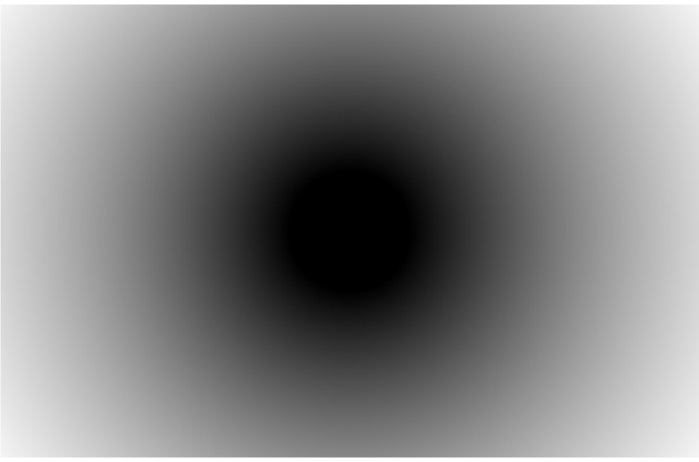


Figure 23. The zenith view angle image calculated for the DC Nikon D1X camera and for the actual light falloff normalising method.

At the second stage, the actual removal of the light falloff effect was conducted for each digital image in a batch applying the correction algorithm for normalising the brightness values of each pixel:

$$E_{\circ} = \frac{E_{\theta}}{\cos^{n} \theta}$$

, where $E_{\circ}$ = DN of the pixel in the off-axis position

E_{θ} = DN that would have resulted if the pixel had been located at the optical axis

$\cos^{n}$ = correction factor for the different aperture setting (Pellikka 1998: 41; Lillesand & Kiefer 2000: 68).

The original raw image, the zenith view angle image and correction factors for each image band were us as input parameters. Since the light falloff effect varies between different wavelength areas, correction parameters had to be defined separately for each channel of the multispectral images (Pellikka 1998: 41). The correction factors 0.63 (R), 0.29 (G) and 0 (B) were derived from the experiment of Hurskainen (2005: 55) since the same digital camera device was utilised in his study.

The following steps were implemented in *EnsoMOSAIC* which is a special software designed for semi-automatic creation of geo-referenced, orthorectified aerial image mosaics from a group of individual images consisting of several flight lines (Holm et al. 1999; StoraEnso 2003). *EnsoMOSAIC* is a complete set of hardware and software from flight planning to mosaics creation, and it enables the user to produce image mosaics without GCPs in the case that accurate GPS data has been collected during the flight operation (StoraEnso 2003: 3). In this study, the mosaic creation was implemented with GPS data, whereas optional GCPs were not applied to the correction procedure.

The image linking provides the initial orientation of two image coordinate systems in relation to each other (StoraEnso 2003: 19, 27). An ideal link between two images is a formation of the nearest large, open triangle of image coordinates of three objects so that the objects are detectable on both images and located on the entire overlapping area of the images (ibid.). Hence, a practical link is a distinct object such as building, road junction, edges of different land uses etc. In this study, the image linking that connects all adjacent image pairs together, was performed as a manual operation, since no camera orientation parameters (roll, pitch and yaw) were available for automatic linking. In general, automatic linking by means of a mean ground altitude is well suited for the purpose of relatively flat target areas whereas the support of a DEM is a more appropriate method for hilly or mountainous areas (StoraEnso 2003: 25). However, manual image linking is often the most reliable – but also the most time-consuming – method to define functional links separately for low and high altitude areas.

Good links are a prerequisite for the next working step which is the tie point measurement (StoraEnso 2003: 28). Tie points are clearly identifiable objects on at least two overlapping images and usually between three and six tie points per image pair, and their function is to connect separate images together and provide image coordinates for the actual image rectification of the Bundle Block Adjustment (BBA) (ibid.). Figure 24 shows the tie points of four images of two adjacent flight lines. The distribution of the tie points indicates common points of the images and consequently the success of the following image rectification process. In *EnsoMOSAIC*, tie points can be measured either manually or by means of automatic tie point computation with optimum search parameters. In this case, the result of the automatic tie point measurement was improved afterwards with the manual tie points that were added to several image pairs of the block, especially to the most problematic areas that failed the automatic tie point search observations. All in all, 136947 tie points were derived from the automatic and manual tie point measurement.

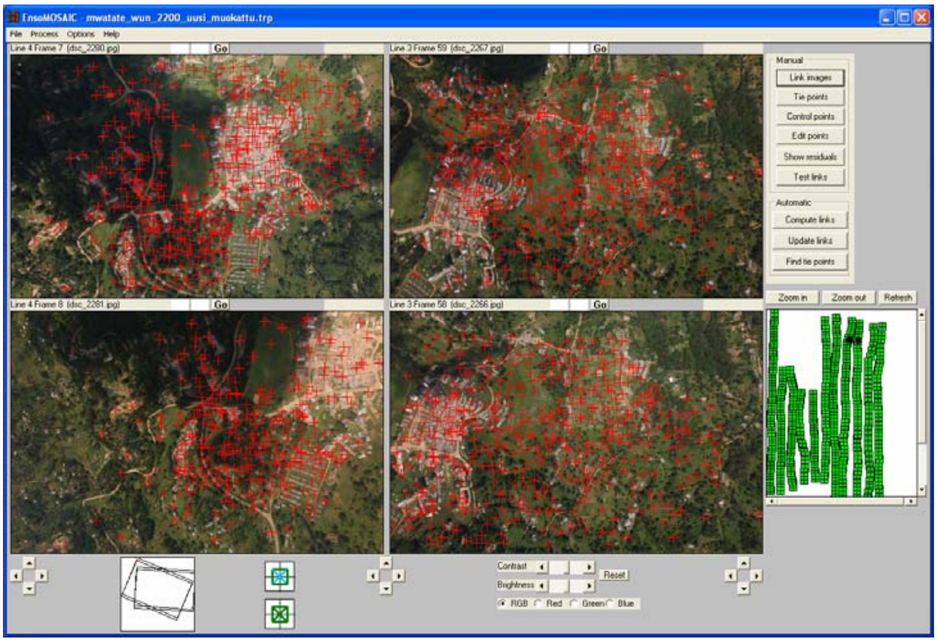
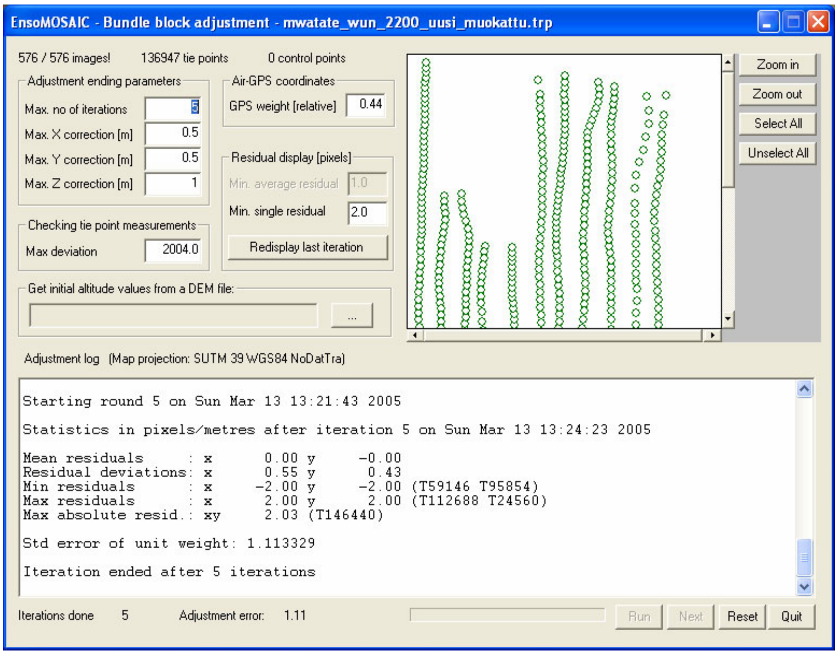


Figure 24. Tie points (red crosses) of the four images of two adjacent flight lines in *EnsoMOSAIC* software. The flight lines and the position of the individual images are shown on the right side in the image index window.

After an adequate amount of the tie points was measured using both the methods described above, the actual image rectification was run by the BBA. The BBA is “an iterative mathematical process to solve the orientation of the images and the location of the perspective centres simultaneously for a large image block” (StoraEnso 2003: 2). The process combines the bundles of adjacent images through the common object points seen on these images resulting in one large block of images (ibid.). The camera calibration data is a prerequisite for the success of the BBA. Furthermore, The BBA process enables image rectification into a ground coordinate system and creation of the image mosaic. After each iteration round of the BBA, tie points with the highest residuals are deleted and new tie points are added simultaneously to the spots of lacking observations where necessary. The block adjustment and these other steps are then repeated and the value of minimum single residual parameter reduced until the acceptable adjustment error is obtained (Figure 25). In the creation of this image mosaic, the block adjustment was started with the minimum single residual parameter of 10 and reduced to the value of two. The adjustment error, root mean square error (RMS) of the final block for the creation of the image mosaic was 1.11 and maximum residual 2.0.



EnsoMOSAIC - Bundle block adjustment - mwatate_wun_2200_uusi_muokattu.trp

576 / 576 images! 136947 tie points 0 control points

Adjustment ending parameters
Max. no of iterations: 5
Max. X correction [m]: 0.5
Max. Y correction [m]: 0.5
Max. Z correction [m]: 1

Air-GPS coordinates
GPS weight [relative]: 0.44

Residual display [pixels]
Min. average residual: 1.0
Min. single residual: 2.0

Checking tie point measurements
Max deviation: 2004.0

Get initial altitude values from a DEM file:

Adjustment log (Map projection: SUTM 39 WGS84 NoDatTra)

```
Starting round 5 on Sun Mar 13 13:21:43 2005

Statistics in pixels/metres after iteration 5 on Sun Mar 13 13:24:23 2005

Mean residuals      : x      0.00 y     -0.00
Residual deviations: x      0.55 y      0.43
Min residuals       : x     -2.00 y     -2.00 (T59146 T95854)
Max residuals       : x      2.00 y      2.00 (T112688 T24560)
Max absolute resid.: xy     2.03 (T146440)

Std error of unit weight: 1.113329

Iteration ended after 5 iterations
```

Iterations done 5 Adjustment error: 1.11

Figure 25. The BBA process after the last iteration round that led to an acceptable result for DEM calculation and mosaic formation.

One of the most essential parameters of the BBA is the relative GPS weight value of air-GPS coordinates which has a great influence on the speed of the whole BBA iteration process. High weight means high accuracy and reliability of the coordinates, and vice versa (StoraEnso 2003: 36). In this case - as there were no GCPs available to improve the accuracy of the mosaic - it was necessary to use a relatively high weight value of the GPS coordinates. The GPS weight value is derived from the equation:

$$W = \left(\frac{1}{\sqrt{x}} \right)$$

, where W = GPS weight value
x = accuracy of the air GPS coordinates

The accuracy of the air-GPS was estimated to approximately 5 meters which means that:

$$W = \frac{1}{\sqrt{5}} = 0.447$$

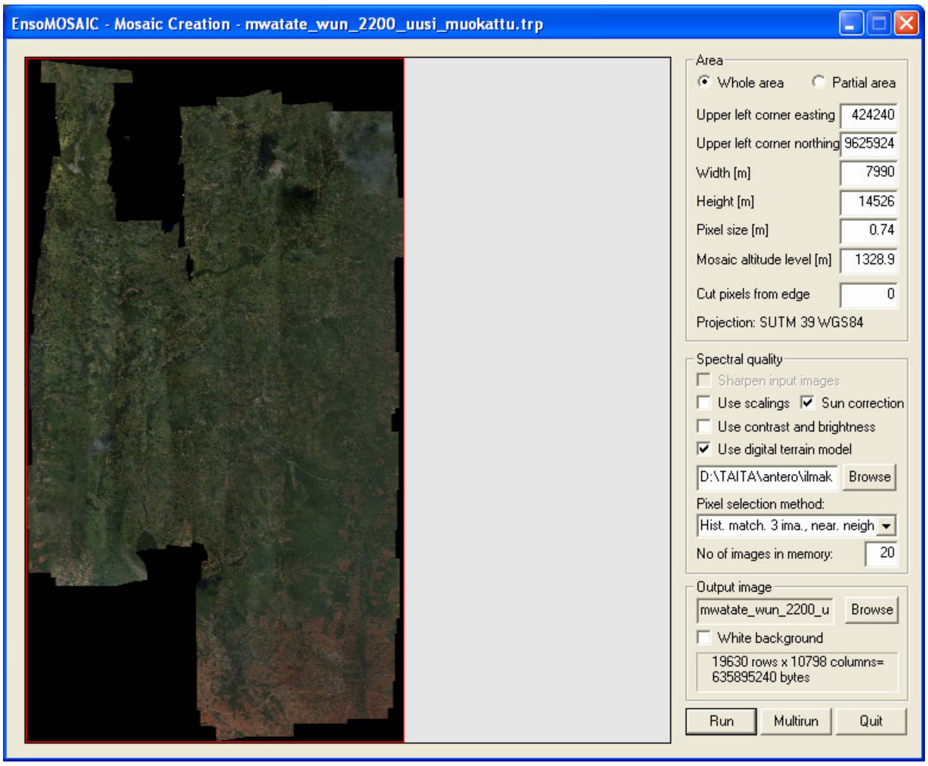
Since the value of *x* was an estimate, the GPS weight value was set to 0.44 so that the calculated maximum value of the GPS accuracy was not exceeded.

After the block adjustment, a DEM with 1-meter ground resolution was derived in *EnsoMOSAIC* based on the elevation values of the 136947 tie points measured in the automatic and manual tie point search. The computation of the DEM has a supportive function to improve the mosaic quality in the mosaic resampling in which the terrain high values are interpolated from the DEM file for each pixel of the mosaic (StoraEnso: 4).

The image mosaic formation was then performed from the original image data. The mosaic was created applying the DEM file and the BRDF correction method proposed by Pellikka (1998: 45-49). The input correction parameters were derived from the special sun correction file that specifies correction factors for each channel individually. The correction parameters were 1.20 (R), 1.00 (G) and 0.80 (B) specified for the circumstances of Kenya (StoraEnso 2003: 63). In addition, an image mosaic without the BRDF correction was generated but this mosaic was not applied to further image analyses.

It was found by using trial and error method that the maximum size of the image mosaic, that is possible to create in *EnsoMOSAIC (5.0),* is approximately one gigabyte due to the software and hardware limitations. Consequently, 0.74 meter pixel size was found to be the highest possible spatial resolution for the image mosaic of this amount of images. Hence, the mosaic was resampled to 0.74 meter pixel size using histogram matching between three images and bilinear interpolation methods (Figure 26). Afterwards, the mosaic was resampled to 0.80 meter pixel size. The total area of the created image mosaic is approximately 80 km^2, the greatest length approximately 14 km and the greatest width 8 km.

Finally, the image mosaic (TIFF file) was imported into *ERDAS IMAGINE* (IMG-file) where it was re-projected to the same coordinate system as the topographic maps, the satellite image data and the vector data (Transverse Mercator / Clarke 1880 / Arc 1960). It was later noticed that the entire image mosaic could not be used as such in *eCognition* software due to the very big size of the mosaic file, since the software cannot run segmentation and classification operations with such big data file. Hence, three smaller, more practical image subsets were made from the 0.80 pixel size image mosaic for the purpose of testing segmentation-based classification. The subsets were defined over the test sites of Mwatate (2.5 km x 2.0 km), Dembwa (3.0 km x 3.0 km) and Wundanyi (2.7 km x 3.5 km) (Figure 27).


EnsoMOSAIC - Mosaic Creation - mwatate_wun_2200_uusi_muokattu.trp

Area

● Whole area ○ Partial area

Upper left corner easting 424240

Upper left corner northing 9625924

Width [m] 7990

Height [m] 14526

Pixel size [m] 0.74

Mosaic altitude level [m] 1328.9

Cut pixels from edge 0

Projection: SUTM 39 WGS84

Spectral quality

☐ Sharpen input images

☐ Use scalings ☑ Sun correction

☐ Use contrast and brightness

☑ Use digital terrain model

D:\TAITA\antero\ilmak

Pixel selection method: Hist. match. 3 ima., near. neigh

No of images in memory: 20

Output image

mwatate_wun_2200_u

☐ White background

19630 rows x 10798 columns= 635895240 bytes

Figure 26. The final output derived from the *EnsoMOSAIC* mosaicking with the applied BRDF correction.

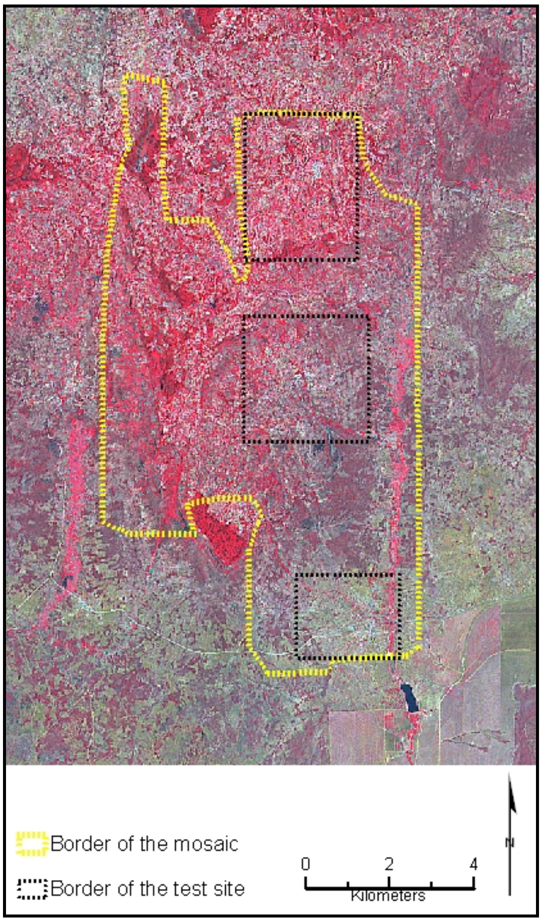


Figure 27. The extent of three test site subsets. The SPOT 2003 image is shown in the background.

The aerial image subsets of the test sites were subject to visual interpretation and pixel-based classification as well, to compare the results of these three different approaches with each other. The work flow of the different approaches for road extraction is presented in Figure 28.

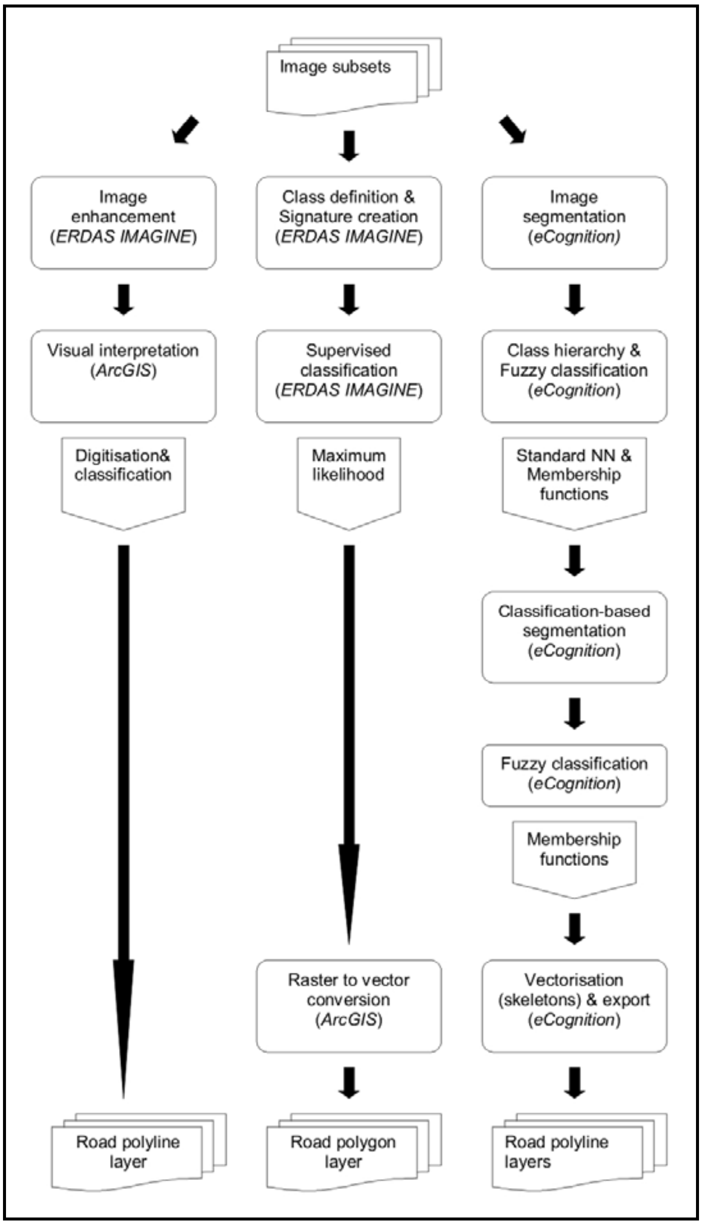


Figure 28. The work flow of the different road extraction methods applied to this thesis.

6.4 PIXEL-BASED ROAD EXTRACTION

The three aerial image subsets were classified in *ERDAS IMAGINE* applying its maximum-likelihood supervised classification function. Supervised classification is a pixel-based technique in which the image analyst controls the pixel categorisation by specifying of representative samples of known land cover types, called training areas. Generally, from five to ten samples is a minimum amount of samples to obtain reliable classification results (Campbell 2002: 336). The training sites are used to train the classification algorithm of the image to assign every pixel to the class of which it has the highest likelihood of being a member based on mathematical criteria (Jensen 1996: 197). A typical supervised classification procedure can be divided into the three basic steps: training stage, classification stage and output stage (Lillesand & Kiefer 2000: 535-566).

Since there were not enough ground truth data available for every class of the classification, the training stage was conducted from the imagery with the *Region Grow* –tool by defining 10 signatures of maximum 300 pixels area and less than 10.00 spectral Euclidean distance from the seed pixel for each predefined class. The signatures of the same class were then merged for the classification stage which was performed applying the maximum likelihood classifier. The maximum likelihood algorithm assumes that the training data statistics have normal distributions and it evaluates both the variance and covariance of the pixels, calculates probability density functions for each spectral category and then classifies the pixels by the highest probability value (Lillesand & Kiefer 2000: 541- 544). The maximum likelihood classifier is one of the most accurate and reliable so-called hard classification methods available nowadays. For the output stage, the classes of non-interest were combined by recoding them to the same class and the final output image was consisted of three informative classes: tarmac road, earth road and non-road. Furthermore, the data of the two road classes were converted into polygons in *ArcGIS*. The accuracy of the classification results was assessed in *ERDAS IMAGINE* (see Chapter 8.3).

6.5 OBJECT-ORIENTED ROAD EXTRACTION

The object-oriented road extraction was implemented through the different stages in *eCognition*: segmentation, building a class hierarchy and fuzzy classification. Furthermore, classification-based segmentation, vectorisation and export of the results were involved to the object-oriented image analysis.

6.5.1 SEGMENTATION

In *eCognition*, multi-scale segmentation is the first phase of the object-oriented approach to create meaningful, homogenous areas for the following classification that is conducted applying fuzzy logic of nearest neighbourhood (NN) classifier or membership functions to the procedure.

The hierarchical structure of image objects is created in *eCognition* applying different scale parameter and composition of homogeneity criterion, so that the image information can be represented in several scales simultaneously by different object layers. The scale parameter determines the maximal allowed heterogeneity of the objects and it is used to adjust the average size of image objects (Baatz & Schäpe 2000). The homogeneity - also referred as minimised heterogeneity - criterion is a combination of colour and shape properties, and it is used to control the similarity of the adjacent image objects (Definiens 2004).

Multi-scale segmentation was not used for this study since there were only various roads in focus and one segmentation level (Level 1) was sufficient for the purpose of representing these object classes. The segmentation involved a lot of experiment, and several segmentations with different combinations of scale parameter and homogeneity criterion were performed before the final settings were selected. The segmentation settings were adjusted mostly by trial and error so that emphasising of the shape factor would generate as large elongated regions as possible representing roads but still separating different road type segments from each other and from surrounding land cover.

Table 6 and Figure 29 present segmentation results of different combinations of homogeneity criteria with scale parameter 8 tested in the segmentation process of Mwatate subset. Consider the effect of increasing shape factor from A to B: when more value is given to the shape of the segments, less weight is put on the spectral information and for instance, the road segments do not follow the edges of roads but rather consist of other land cover as well. In the end, two segmentation levels were created since the second one (Level 2) was constructed at the later stage for the purpose of segmentation-based classification (see chapter 6.5.3).

Table 6. Segmentation parameters tested in Mwatate subset.

	Scale parameter	**Shape factor**	**Compactness**	**Smoothness**
A	8	0.1	0.5	0.5
B	8	0.9	0.5	0.5
C	8	0.5	0.9	0.1
D	8	0.5	0.1	0.9

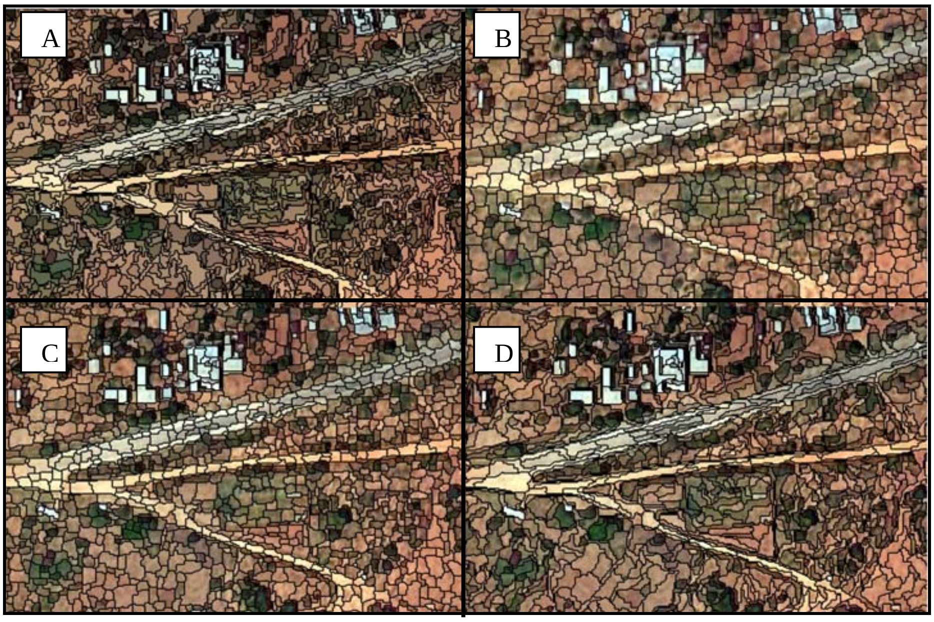
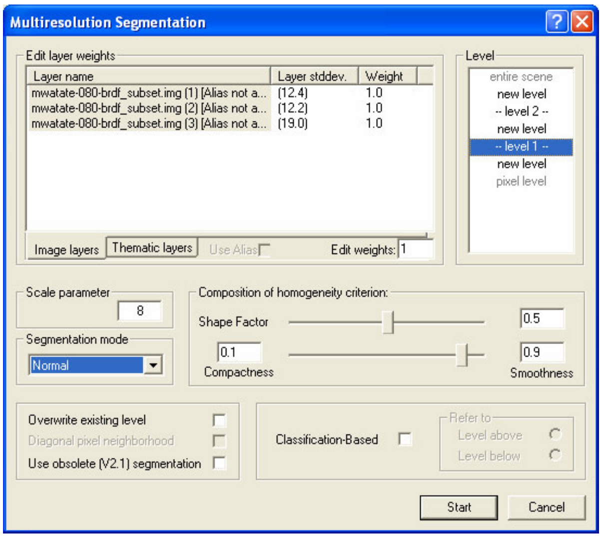


Figure 29. Segmentation test results using different combinations of homogeneity criteria. Scale parameter of each option is 8. See also Table 6.

Each of the three subsets was segmented mainly with the same final settings that were found appropriate in every case to generate meaningful road segments. Only the scale parameter was adjusted slightly between the three subsets: the segmentation of the Wundanyi and Dembwa subsets were performed with the scale parameter 10 whereas the Mwatate with scale parameter 8 (Figure 30). Each subset was segmented with the shape factor 0.5 and the smoothness 0.9. In general, the shape criterion consists of two parts: compactness and smoothness. When shape criterion is given more value, the shape homogeneity of the image objects is improved and the smoothness and the compactness are optimised which results in a more compact form objects with smoother borders (Definiens 2004: 79).



Multiresolution Segmentation

Edit layer weights

Layer name	Layer stddev.	Weight
mwatate-080-brdf_subset.img (1) [Alias not a...	(12.4)	1.0
mwatate-080-brdf_subset.img (2) [Alias not a...	(12.2)	1.0
mwatate-080-brdf_subset.img (3) [Alias not a...	(19.0)	1.0

Use Alias ☐

Edit weights: 1

Level: -- level 1 --

Scale parameter: 8

Segmentation mode: Normal

Composition of homogeneity criterion:

Shape Factor: 0.5

Compactness: 0.1

Smoothness: 0.9

Overwrite existing level ☐

Diagonal pixel neighborhood ☐

Use obsolete (V2.1) segmentation ☐

Classification-Based ☐

Refer to
Level above ○
Level below ○

Figure 30. The final segmentation settings chosen for the segmentation of the Mwatate subset.

6.5.2 CLASS HIERARCHY AND IMAGE CLASSIFICATION (LEVEL 1)

Once segmentation was performed, the next step was to build a class hierarchy for the classification scheme. In *eCognition*, the class hierarchy of all classes and their class descriptions is the knowledge base for the supervised classification, in which the objects derived from the segmentation can be classified by their physical properties and/or semantic relationships using a fuzzy approach of nearest neighbour (NN) classifier or membership functions (Hofmann 2001a; Definiens 2004). Each class of the class hierarchy can be described by fuzzy rules based either on one-dimensional membership functions or on multidimensional NN classifier using training areas called sample objects which the user has to determine. In this context, the class hierarchy was built with three abstract parent classes and seven active child classes. In addition, the eighth object class "railway" was created for the Mwatate subset based on the imported thematic layer (Figure 31).

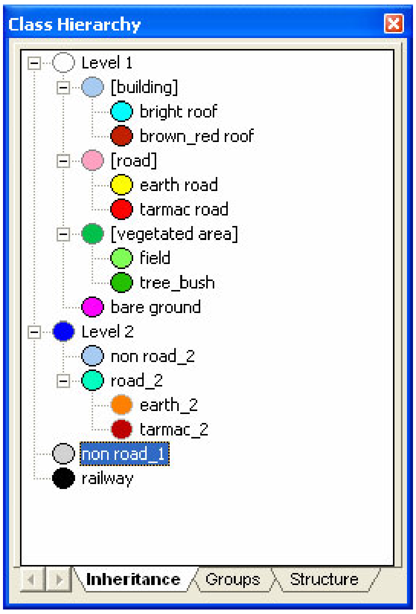
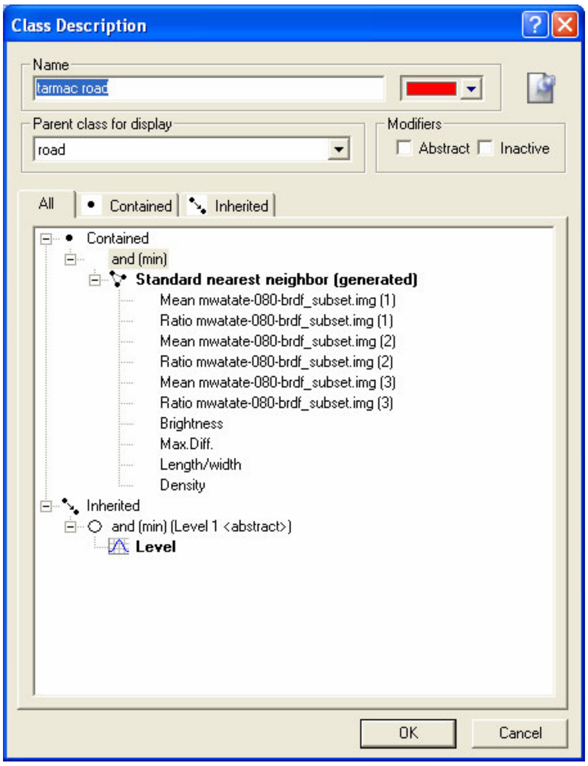


Figure 31. The inheritance class hierarchy of the Mwatate.

The feature view function of the software was taken advantage of while creating the class hierarchy and considering the most suitable class descriptions for the classification. Feature view allows one to display, analyse and compare one feature at a time for all objects in the scene in order to know which attributes are suitable for separating the classes to be specified (Definiens 2004: 218). Beforehand, it was hypothesised that the generic shape features would be the most suitable features for distinguishing elongated road segments from the other object classes. For instance, road objects should have large values of *shape index* and small values of *density* (Song & Civco 2004). Furthermore, it is useful to classify elongated road objects by describing their shape by form criteria and subsequently their different spectral properties (Hofmann 2001b). However, with the feature view and with the other tools of *eCognition* (e.g. sample editor and 2D feature space plot) it was noticed that the shape features would not be sufficient alone to separate roads from the other segments of their surroundings. Hence, several other features were considered and the best options were then selected for the classification scheme.

Since the NN classifier can operate more effectively in multidimensional feature space than membership functions and because in many cases the classes can be distinguished more effectively when operating in the same feature space, the standard NN classifier was selected for the classification process. The feature space of the standard NN is defined for the entire project and thereby for all classes to which the expression is assigned (Definiens 2004: 230). The membership function was only applied to distinguish the railway based on the thematic layer. The features chosen for the Standard NN classification scheme are shown in Figure 32.


Class Description

Name: tarmac road

Parent class for display: road

Modifiers: ☐ Abstract ☐ Inactive

- Contained
  - and (min)
    - **Standard nearest neighbor (generated)**
      - Mean mwatate-080-brdf_subset.img (1)
      - Ratio mwatate-080-brdf_subset.img (1)
      - Mean mwatate-080-brdf_subset.img (2)
      - Ratio mwatate-080-brdf_subset.img (2)
      - Mean mwatate-080-brdf_subset.img (3)
      - Ratio mwatate-080-brdf_subset.img (3)
      - Brightness
      - Max.Diff.
      - Length/width
      - Density
- Inherited
  - and (min) (Level 1 <abstract>)
    - **Level**

Figure 32. The Standard NN classification scheme.

The classification process of the subsets was conducted selecting 50 representative sample objects for each object class of the Dembwa subset and 40 samples for each class of the Mwatate and Wundanyi subsets. The sample objects were inserted equally throughout the image subsets and for each object class. At the beginning, only a few samples were set per object class and the first classification was then run. Thereafter, more samples were inserted so that some misclassified samples were moved into their proper class and the classification was run again. This step was repeated and the classification was run iteratively until the results were satisfactory.

In *eCognition*, it is possible to group even very different classes to a superior class of common *semantic* meaning (Definiens 2004). After the classification process was finished, the semantic grouping was applied to combine the classes of non-interest into a common "*non road*" object class. Finally, the clarified classification results were exported to *ERDAS IMAGINE* where the accuracy assessment was conducted (see Chapter 8.4).

6.5.3 CLASSIFICATION-BASED SEGMENTATION AND IMAGE CLASSIFICATION (LEVEL 2)

Since the results of the Level 1 classification were not satisfactory, the classification-based segmentation was carried out by defining structure groups. A structure group is a collection of classes representing the same structure in an image and can consist of classes defined for different levels in the image object hierarchy (Definiens 2004: 148). Firstly, separate structure groups were built for both road classes and the classification-based fusion was then conducted to create new segmentation level of merged road image objects. In the classification-based object fusion, all adjacent segments of the same road structure group were merged into one new image object representing an entire road area. Meanwhile, the segments of other object classes remained as before Notice that in Figure 33 merged road segments on Level 2 are considerably larger than on Level 1 whereas all other segments have remained unchanged

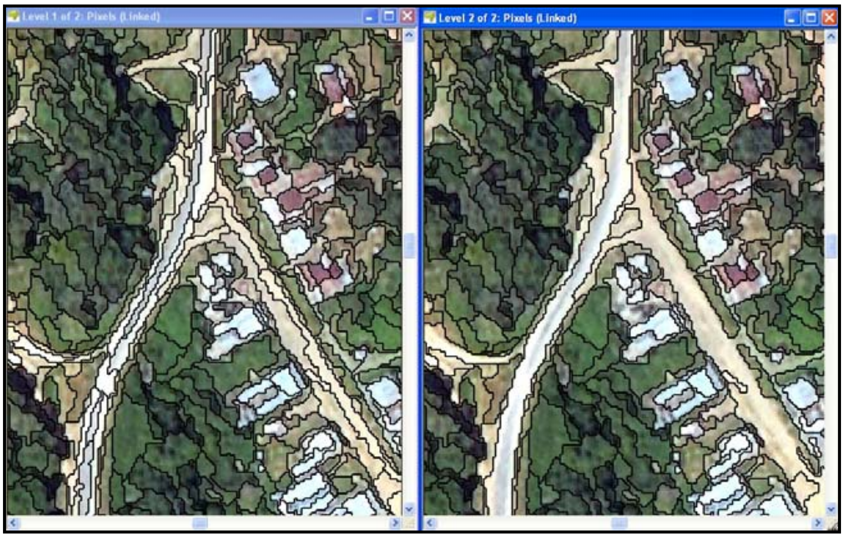
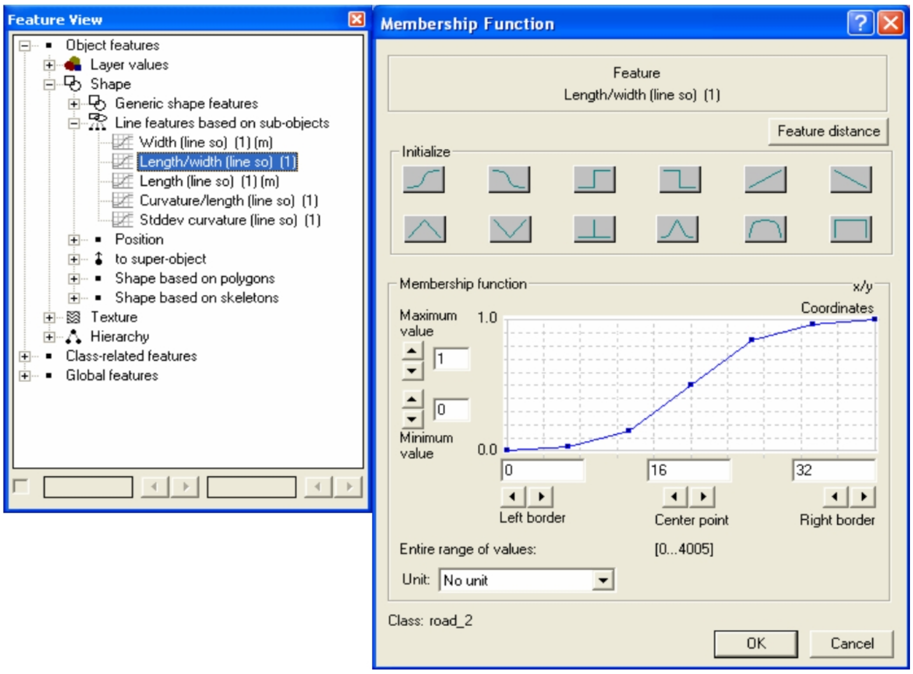


Figure 33. Segmentation results of Level 1 (left) and Level 2 (right).

The class hierarchy similar to the semantic structure of the Level 1 was created (see Figure 31, Level 2) and the fuzzy membership functions were defined for each parent and child class of the inheritance hierarchy. The road parent class was differentiated from the "non road" class by the line features based on the sub-objects of the Level 1 (Figure 34), and the road child classes (tarmac road and earth road) by the existence of sub-objects of Level 1 (Figure 35). The Level 2 segmentation was then classified using contextual information of class-related features so that the Level 1 was taken into account in the classification process. Class-related features refer to the classification of other image objects situated at any location in the hierarchy, and this approach makes possible classifications defined by vertical distance relationships of super- and sub-objects or by horizontal distance to neighbour objects (Definiens 2004).



Feature
Length/width (line so) (1)

Maximum value: 1

Minimum value: 0

Left border: 0

Center point: 16

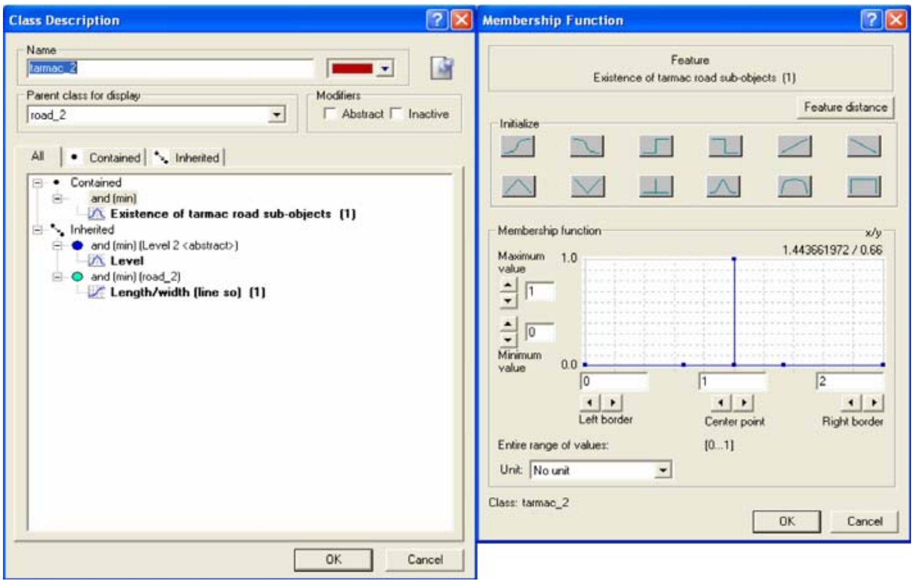
Right border: 32

Entire range of values: [0...4005]

Unit: No unit

Class: road_2

Figure 34. Line features of the Level 2 road parent class.



Name: tarmac_2
Parent class for display: road_2
Modifiers: ☐ Abstract ☐ Inactive

Contained
and (min)
Existence of tarmac road sub-objects (1)
Inherited
and (min) (Level 2 <abstract>)
Level
and (min) (road_2)
Length/width (line so) (1)

Feature
Existence of tarmac road sub-objects (1)

x/y
1.443661972 / 0.66
Maximum value: 1
Minimum value: 0
Left border: 0
Center point: 1
Right border: 2
Entire range of values: [0...1]
Unit: No unit
Class: tarmac_2

Figure 35. The existence of tarmac sub-objects of the Level 1.

6.5.4 AUTOMATIC VECTORISATION

Once the second classification was finished, *eCognition's* automatic vectorisation was performed for the vector representation of the export results by creating polygons from the objects of Level 2. In *eCognition*, it is possible to create polygons after the segmentation procedure for each image object to display their outlines, to compute different shape features with them or to export them to GIS. In this case, the main aim was to create polygons for the objects of the two road classes. Thereafter, skeletons were created in conjunction with polygons (Figure 36). Skeletons are advanced object features based on polygons and they are practicable for elongated object extraction where they are used for the detection of roads' centrelines and export to GIS (Benz et al. 2003). By creating skeletons, it is possible to describe the inner geometrical structure of an object more accurately (Definiens 2004).

Finally, the results of the Level 2 segmentation-based classification were exported for further analysis and use in GIS. Besides the classification result itself, the objects shapes of both road classes were exported in format of raster polygons based on the outlines of the pixel borders, and line objects based on the skeleton lines. The classification accuracy assessment was conducted in *ERDAS IMAGINE* the same as the Level 1 classification evaluation (see Chapter 8.4).

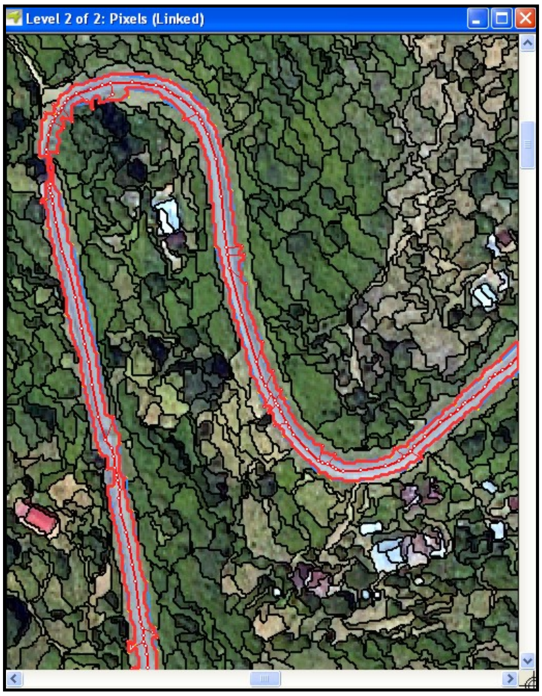


Figure 36. Skeletons of the tarmac road polygons.

6.6 VISUAL INTERPRETATION

The image enhancement operations were implemented in *ERDAS IMAGINE* and the actual visual interpretation in *ArcGIS.* The contrast adjustment and filtering operations were applied to the satellite image data to improve the appearance of the roads for the visual analysis. By contrast, the digital image mosaic subsets were not enhanced, since the spatial resolution of the original image data was adequate for the accurate detection of roads.

Various contrast enhancements, such as histogram equalisation and linear contrast stretch, were tested by trial and error method on the SPOT image data. A number of convolution filters were tested alone and along with different contrast enhancement options. In Figure 37, the option A shows the image without any enhancements. The option B is the data with linear contrast stretch and 3x3 summary filter. The option C shows the data with 3x3 edge detector filter, and the option D with histogram equalisation and 3x3 edge enhance filter. A number of high-pass filters, edge enhancer filters and edge detector filters were tested while low-pass filters were excluded from the image enhancement operations.

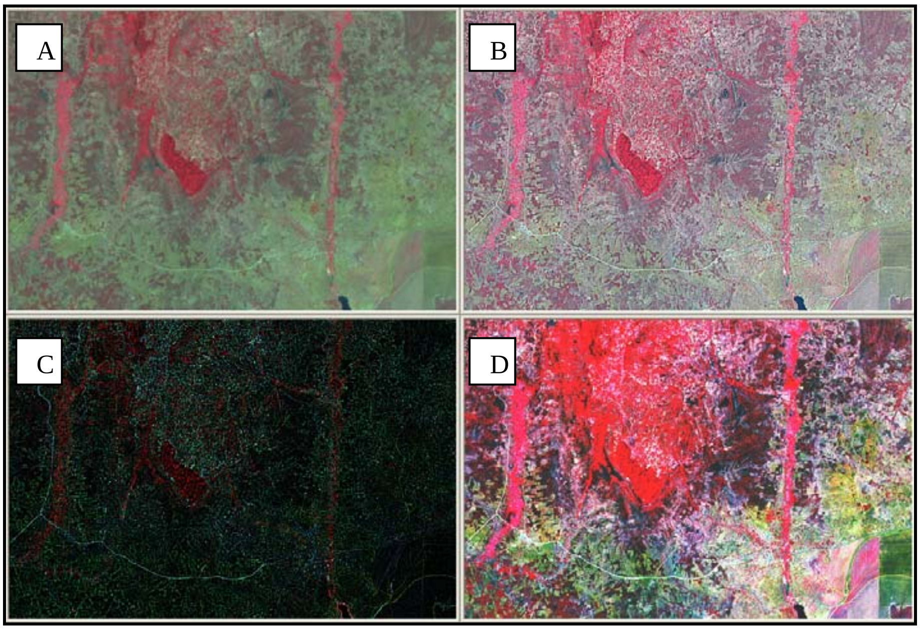


Figure 37. Various contrast enhancements tested on the SPOT image data.

After some experiment, the best options were chosen for the visual analysis of the roads. The linear contrast stretch with 3x3 summary filter was found to be the best combination to improve the appearance of the roads in the imagery. At this phase, the image adjustments were not done via lookup table operations as earlier but they were applied to the image file to permanently change the DN values of the original image data and to create appropriate image data for the visual analysis in *ArcGIS*. On the contrary, edge detectors were not exploited at all when producing the final raster image outputs for the visual interpretation.

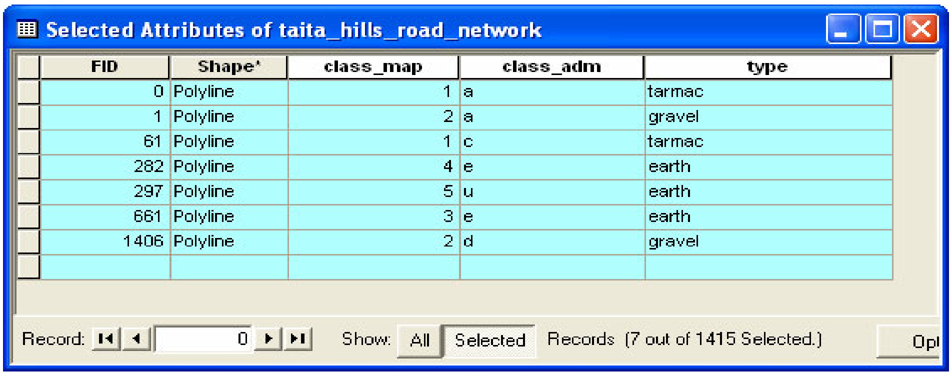
In practise, the visual interpretation was carried out by digitising roads manually on the image subset areas and storing the created data as ESRI Shapefile vector layers. Roads were digitised along the centre lines as polyline features that were connected to each others with the snap mode. At some locations only unconnected stretches were digitised if it was not possible to identify the road line completely. In case of the SPOT image analysis, roads were digitised at a very general level, when they were visible and identified at least somehow. The whole SPOT satellite image and the original aerial image mosaic over the Taita Hills were also considered in the visual interpretation. In addition, the scanned topographic maps, the existing GIS database road layer and the road point data were applied to assist and verify the detection process in spots where roads were not clearly identifiable.

6.7 GENERATING AN UP-TO-DATE ROAD INFRASTRUCTURE DATA LAYER

The mapping and the updating tasks were implemented to correct and modify the following weaknesses and errors of the existing road data:

- The existing vector road data layer is out-of-date since it was created (Broberg & Keskinen 2004) from the *Kenya 1:50 000 Topographic Map*s information that is based on aerial photography conducted in 1988 and 1989 (Survey of Kenya 1991).
- The existing road data is generalised and needs to be specified. The existing data was digitised from the smaller-scale maps (1: 50 000) that had already been generalised from the aerial photography source data.
- There are new roads and missing roads of the existing data that were possibly excluded from the 1: 50 000 maps and that need to be located precisely.
- There are wrongly located roads and paths in the existing road data
- Map classification is partly invalid and in need of modifications
- Administrative classification (see Table 2 on page 30) does not always follow the map classification
- Ancillary attribute information of roads (e.g. surface type, condition, width) gained in the field may be useful for some mapping purposes

The mapping process was implemented following the principles introduced in Chapter 6.6. The selection of this particular technique for the mapping is considered with more detail in Chapter 7.5. The digitisation was extended outside the aerial image subset areas and within the boundaries of the Mwatate-Wundanyi image mosaic. Visual inspection was made at a scale between 1: 3000 – 1: 5000 on the device screen. Together with the digitisation work, roads were classified and attribute information was given to each digitised road segment (Figure 38). In addition to the initial map classification, roads were categorised according to the administrative classification based on Roads 2000 Coast (s.a) reference map and by their surface type. The various classification methods are shown in Table 7. The map classification was made with the assistance of the existing road data layer and the original, scanned topographic maps as well as the visual analysis. Initial classes of the existing road were modified if necessary, and new roads were given a class number based solely on the visual interpretation.



FID	Shape*	class_map	class_adm	type
0	Polyline	1	a	tarmac
1	Polyline	2	a	gravel
61	Polyline	1	c	tarmac
282	Polyline	4	e	earth
297	Polyline	5	u	earth
661	Polyline	3	e	earth
1406	Polyline	2	d	gravel

Records (7 out of 1415 Selected.)

Figure 38. The attribute information of selected road objects.

Table 7. Three different classification types.

Map classification (class_map)	**Administrative classification (class_adm)**	**Surface classification (type)**
All weather road, bound surface (1)	International trunk road (A)	Tarmac
	National trunk road (B)	Gravel
All weather road, loose surface (2)	Primary road (C)	Earth
	Secondary road (D)	
Dry weather road (3)	Minor road (E)	
Main track, motorable (4)	Unclassified road (U)	
Other track or footpath (5)		

The next step was to update the attribute information of the existing road data of the outside regions of the mosaic, in other words the areas that were not included in the digitisation work of this study. The same attribute information types were given to the old road network when determined as were set to the digitised roads.

Finally, the data of the existing road data layer from the outside regions of the mosaic was appended into the new data layer. In future, it is possible to join more updated attribute information into the new data layer or add the road infrastructure of the Ngangao and Chawia image mosaics (Lanne 2007) to this dataset. In addition, more attribute information may be associated into the data layer, e.g. road width, upcoming or implemented maintenance operations, general conditions during the rains, etc.

6.8 FIELD SPECTROMETRY

Field spectrometry is a quantitative, sensitive technique and the results obtained are very dependent on environmental characteristics conditions, instrumentation available and sampling strategies applied in the field. Therefore, the measurement operations have to be designed and conducted with care and standardised procedures. In addition, further analysis of the spectra requires systematic, exact inspection techniques to reduce possible error sources and to gain reliable results in the analysis.

6.8.1 FIELD SPECTROMETRY MEASUREMENTS

A small-scale field spectrometry study was conducted during the second field work period in the Taita Hills between 23rd and 29th January 2005. The spectra of different road surfaces were acquired *in situ* with PhD student Barnaby Clark, in conjunction with his work to collect calibration site data for the Historical Empirical Line Method (HELM) correction of the SPOT imagery (Clark & Pellikka 2005). In total, 20 sets of reflectance measurements, each with a sample average of 15, were measured at 14 different sites using an ASD FieldSpec® HandHeld UV/VNIR (325-1075 nm, 3.5 nm spectral resolution) spectroradiometer. Spectra were collected in sets of one or two for each field target. The device was calibrated to a Spectralon® $BaSO_4$ 99% white reference reflectance panel before each single set of measurements. The spectra were acquired from a height of ~1.0 meter using the bare field optic cable, with a field of view of 25° (0.44 m at-nadir ground view at a height of 1.0 m). The field site descriptions are presented in Table 8 and the terrestrial photographs in Appendix 1.

The next step was to reduce noise by using median values in post-processing. If two sets were collected at the same site, average values of the both median value sets were calculated for further processing.

There are various methods of applying spectrometry measurements for further analysis. One approach is to compare the measured reflectance curves with each other and compile a spectral library of the data, which would give information about the spectral characteristics and discrimination of the different road surfaces. In addition, it is possible to apply the field spectrometry to imaging spectrometry with hyperspectral sensors, which have potential for more detailed and sophisticated analysis than conventional multispectral sensors. If there is only a limited amount of measurements, it is more practical to analyse the data with existing spectral libraries that usually contain pure laboratory, field or imaging-based spectral samples of different urban and natural surfaces with high spectral detail and additional information.

Table 8. Field site descriptions and collected spectrum sets.

Site 1	Red earth road	2 sets
Site 2	Bright red earth road	2 sets
Site 3	Light grey gravel road	1 set
Site 4	Light concrete road (ford)	1 set
Site 5	Glittering brown/grey earth road	1 set
Site 6	Brownish red earth road	1 set
Site 7	Light grey gravel road	2 sets
Site 8	Old, grey concrete road	2 sets
Site 9	Greyish brown earth road	1 set
Site 10	Reddish brown earth road	2 sets
Site 11	Bright red earth road	1 set
Site 12	Old, light tarmac road	1 set
Site 13	Old, light tarmac road	2 sets
Site 14	New, dark tarmac road	1 set

In this study, the results of the field spectra were compared with a few existing spectral libraries and literature to obtain wide-ranging information about the roads' spectral characteristics. The influence of the composition and the condition and the aging of paving were considered in the investigation. The results of the field spectrometry are presented in Chapter 7.6, and the comparison with the other research results is considered in Chapter 9.

6.8.2 SYNTHESISING MEASUREMENTS WITH THE SPOT IMAGE

The spectrometer measurements were further processed to synthesise the SPOT image data which, at least in theory, would make possible the concurrent analysis of the spectrometer derived reflectance values and the atmospherically corrected SPOT response for each spectral band. In this study, however, it was not a principal task since the spatial resolution of the SPOT image is not sufficiently high for getting pure reflectance values of the road surface pixels. Furthermore, it would be more practical to use field spectrometry with hyperspectral image data with a higher spectral resolution as well.

Due to the multispectral, broad-band characteristics of the SPOT sensor, it was necessary to process the spectrometer derived reflectance spectra to match with each spectral band of the sensor separately. The recorded, complete 325 – 1075 nm spectra had to be synthesised to the lower spectral resolution (of the SPOT data) and therefore, spectra were resampled into the

SPOT spectral configuration (4 channels with 5 nm FWHM). Total integrated spectral response values were calculated for Band 1 (green), Band 2 (Red) and Band 3 (NIR) based on the specific spectral sensitivities of each band (obtained from the SPOT website). Band 4 was not calibrated, since the mid infrared (MIR) wavelength (1580 - 1750 nm) is outside the wavelength domain of the FieldSpec® HandHeld UV/VNIR spectroradiometer. The synthesised SPOT reflectance response values were calculated for each of the 14 field spectrometry site measurements.

The next step of the spectrometry analysis was to compare the synthesised SPOT reflectance response of the spectrometry derived data with the actual reflectance values of the SPOT image pixels. The SPOT 2003 image was atmospherically corrected applying the Historical Empirical Line Method (HELM) by Clark (Clark & Pellikka 2005). The corresponding pixels of the field spectrometry sites were traced on the SPOT image on the basis of visual interpretation and the GPS coordinates recorded in the field. The per-band pixel reflectance values of the roads were determined; in most cases it was practical to calculate the mean value of two pixels locating in the position or in the direct vicinity of the road site.

The final step was to compare roads' reflectance values with their various surroundings. Similarly with the previous step of the procedure, a number of pixels representing surroundings of the road sites were defined on the SPOT image. These pixels represent various surrounding environments of the roads which may be considered at least somehow in Appendix 1. The adjacent pixels were selected so that they were both side of the earlier determined road pixel(s) in each field site location. The per-band reflectance values were then defined for the surrounding pixels and finally, the road pixels and surrounding pixels were considered in a common context.

7 RESULTS

In this chapter, the results of the pre-processing, the visual and digital analyses, the road mapping and the field spectrometry are introduced for each step of the procedure. In addition, the results and the methodologies beyond the results are considered in Chapter 8 from the viewpoint of accuracy assessment.

Object-oriented and pixel-based classification results are presented as raster mask images of simplified visualisations with three informative classes. In Appendices 2, 3 and 4 the digital classification outputs are presented with two classes: tarmac road and earth road that were the classes of interest for the purposes of this study.

7.1 PRE-PROCESSING AND MOSAICKING

In this context, mosaicking results of the airborne digital camera data are considered but not the SPOT satellite imagery since they were not pre-processed by the author. The original resampled image mosaics derived from the EnsoMOSAIC mosaicking are presented in Figure 39.

Figure 39. The resampled image mosaics: without the BRDF correction (left) and with the BRDF correction (right).

Given the fact that nearly 600 images of changing illumination conditions over the Taita Hills region of varying topography were applied to the mosaicking, the final output mosaic is considered to be of appropriate quality. The output could have possibly been of better quality if the mosaicking process had been implemented repetitively by creating several sub-mosaics of smaller areas and then combining them together. However, it was seen more practical to generate an unbroken, larger extent image mosaic covering the whole area from Mwatate to Wundanyi.

There are few clouds and shadows of the clouds in the mosaic that decrease the quality of the output image and generally negatively influence digital classification of the remote sensing data. In addition, visual analysis becomes more difficult if there exists clouds and shadows in the imagery. Both disturbing factors are concentrated mainly in the north-east corner of the image mosaic around the Wundanyi area. The influence of the implemented radiometric and geometric corrections is evaluated in Chapter 8.1.

The original BRDF corrected image mosaic was further subset to fix the irregular frames of the mosaic. Furthermore, three smaller subsets were produced for the digital classifications and visual analysis. The final mosaic subsets are shown in Figure 40.

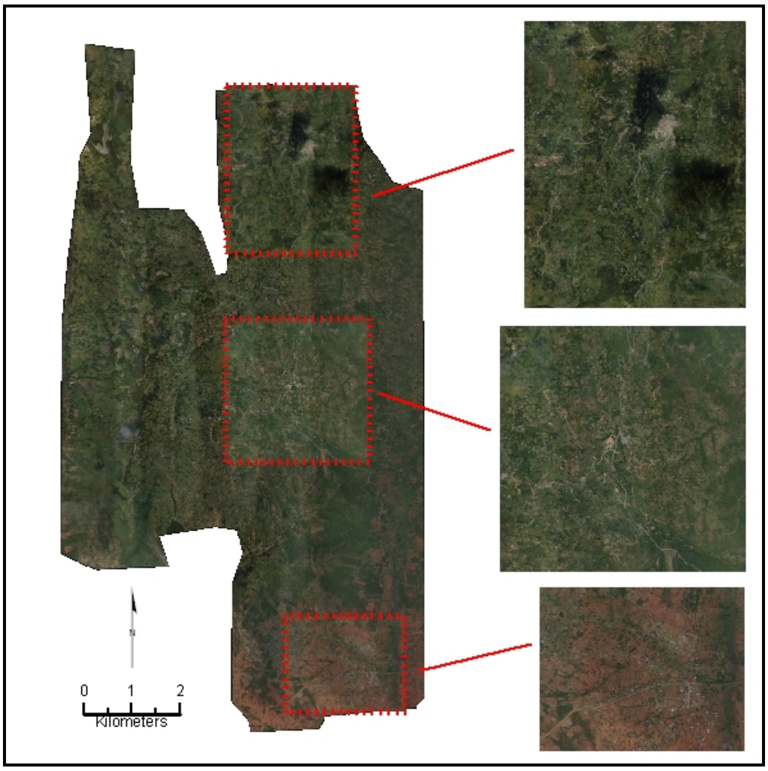


Figure 40. The Mwatate – Wundanyi mosaic subset (left) and the three small subsets of Mwatate (bottom), Dembwa (middle) and Wundanyi (top).

7.2 VISUAL INTERPRETATION

The results of the subset visual interpretations are presented with the source image data in Figure 41. Although the inspection of the SPOT image was extended beyond the subset areas to the highlands and the southward lowlands of the Taita Hills, only the subset areas are shown in this context. The analysis was easier to perform as the road network was considered at the scale of the entire SPOT image and not only at the scale of the subset areas.

The applied summary filter slightly sharpened up the edges between roads and their adjacent land use but generally, image enhancement operations did not make any significant improvements to the appearance of the roads on the SPOT image. The edge detection filter - that was expected to be the one in question to emphasise road edges - did not operate properly and it was thus abandoned from the enhancing of the imagery.

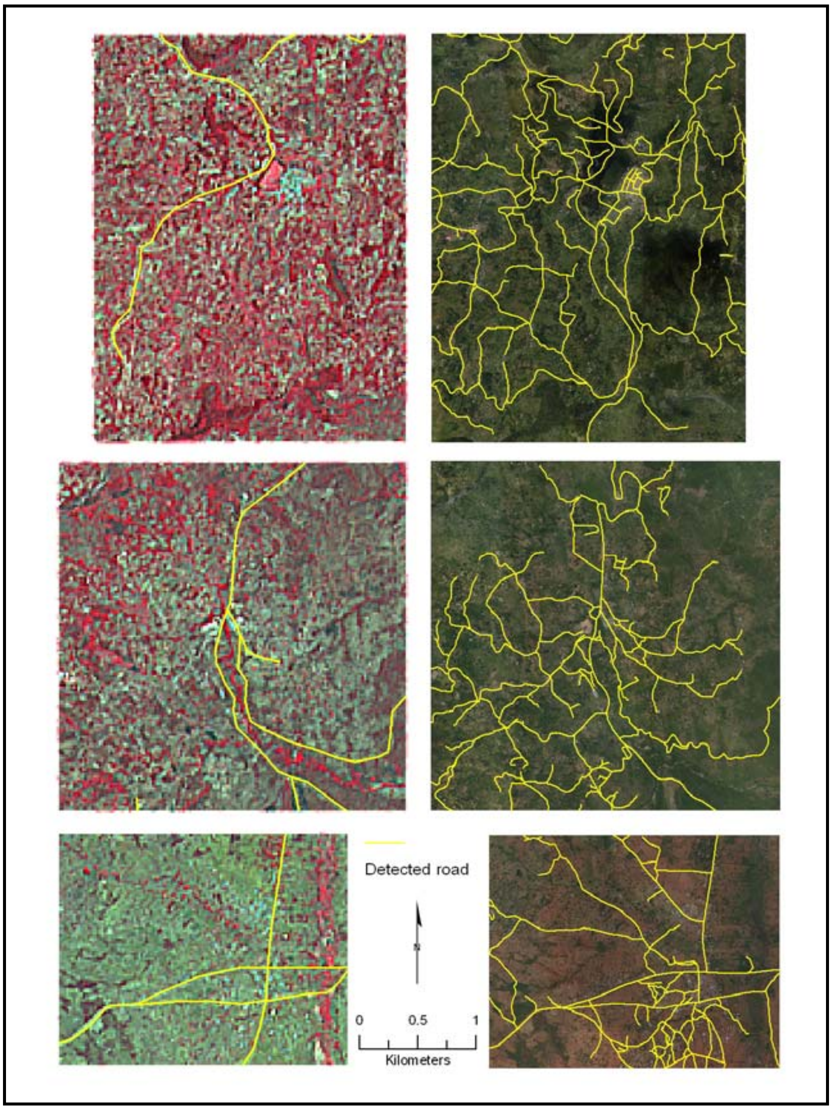


Figure 41. The visual interpretation of the SPOT image (left) and the mosaic subsets (right) of Wundanyi (top), Dembwa (middle) and Mwatate (bottom).

The SPOT image analysis was performed at a very general level and the results were not very accurate. It was possible to detect and delineate roads very generally, and only main roads or parts of them were identified at the subset areas while minor roads and paths were not identified at all. The interpretation results varied according to road characteristics and environment adjacent to roads. At the scale of the whole SPOT image, several trunk roads and secondary roads were identified properly in the lowland areas. Furthermore, even narrower roads and tracks were visible in these areas. However, roads located in the highlands were not primarily distinguishable, not even the wider main roads.

On the contrary, nearly all roads were detected accurately on the digital image mosaic subsets and digitised along their centre line. Main roads were detected most accurately, and moreover, minor roads and paths were identified on the imagery. In addition, it was possible to identify the construction materials of roads, whether a road had a tarmac or earth surface. There were slightly differences between the analyses results of the different subsets due to the different road and adjacent land use characteristics and the disturbance of shadows and clouds.

7.3 PIXEL-BASED ROAD EXTRACTION

The pixel-based supervised classification results are presented so that they are first considered generally and then class-specifically, especially in terms of the road classes. In addition, the results are assessed in Chapter 8 with error matrices that give more exact information about the overall and class-specific accuracies of the various classification techniques. The pixel-based classification results are also presented in Appendices 2, 3 and 4 with the segmentation-based classification results.

In this context, it is not meaningful to describe the classification results with area variables. The visual analysis was implemented by digitising roads as polyline objects – not as polygons – and thus, it would not make sense to compare classification area variables with the line features that have no area attribute information. Therefore, quantitative area-based examination and comparison is excluded from the study, and the examination is done by comparing the classification results with the original aerial image subsets, the “ground truth”. Alternatively, length values were calculated for the generated vector skeletons (see Chapter 8.4).

Generally speaking, all three pixel-based classifications are characterised by over-emphasising of both the road classes. There are erroneous pixels classified as either tarmac or earth road class, although they actually belong in the non-road class in most cases. When visually comparing the classifications, it can be seen that only the tarmac road class of Dembwa is classified fairly well; all the other road classes of each classification contain numerous misclassified pixels. In other words, *commission* error - which defines misclassification of other pixels to that particular inappropriate class – is prevalent in the road classes of these classifications. Respectively, the *omission* error – which tells omitted pixels from the correct category - is common predominantly in the non-road class, since these pixels were classified as both road classes. The omission – commission aspect is considered in Chapter 8.3 in context of the accuracy assessment error matrices.

The supervised maximum likelihood classification result for Mwatate is presented in Figure 42. Most tarmac road pixels are classified to their appropriate category, and major earth roads likewise, but substantial errors of commission in non-road pixels occurred in these categories as well. In particular, northwest and eastern parts of the subset region have broad areas of tarmac pixels at inappropriate locations. Wide areas were misclassified into the earth road class in the southern and southwest part of the image subset.

In Dembwa (Figure 43), tarmac road was classified well and only few areas were mixed into this category. Wider earth roads were also classified quite successfully but the earth road class contains plenty of misclassified non-road pixels as well.

The Wundanyi classification output (Figure 44) has a significant amount of misclassified tarmac class pixels, especially in the vicinity of Wundanyi centre. Similarly, there are many pixels inappropriately classified as earth road. The major tarmac road was classified mostly correctly.

Since the classification results were not promising at all, the pixel-based classification outputs were excluded from the further analysis. However, the raster image data was converted into polygon data but the vector output was of poor quality as well. Therefore, it was not attempted to modify the polygon data such that it would be appropriate for the primary road infrastructure mapping of the study area. In this context, the converted polygon data are not shown due to their very poor quality and uselessness.

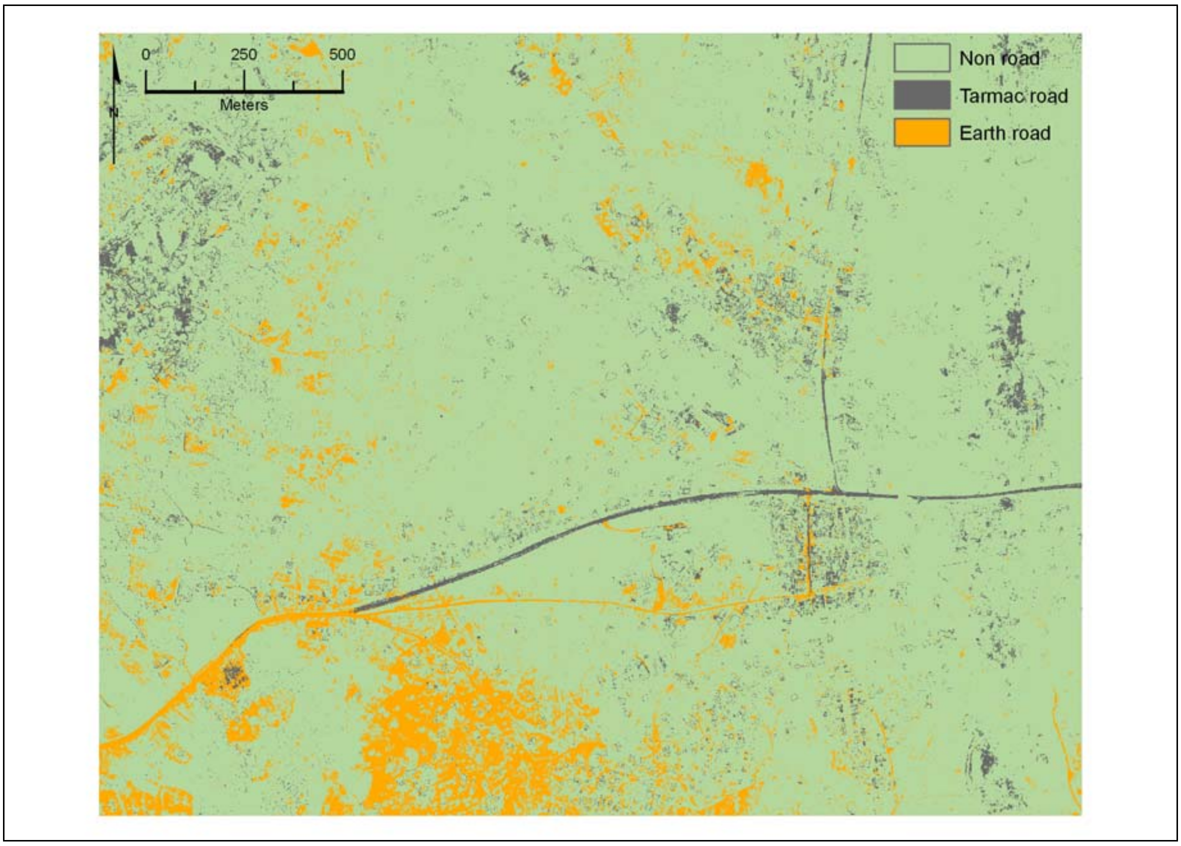


Figure 42. The pixel-based classification of Mwatate.

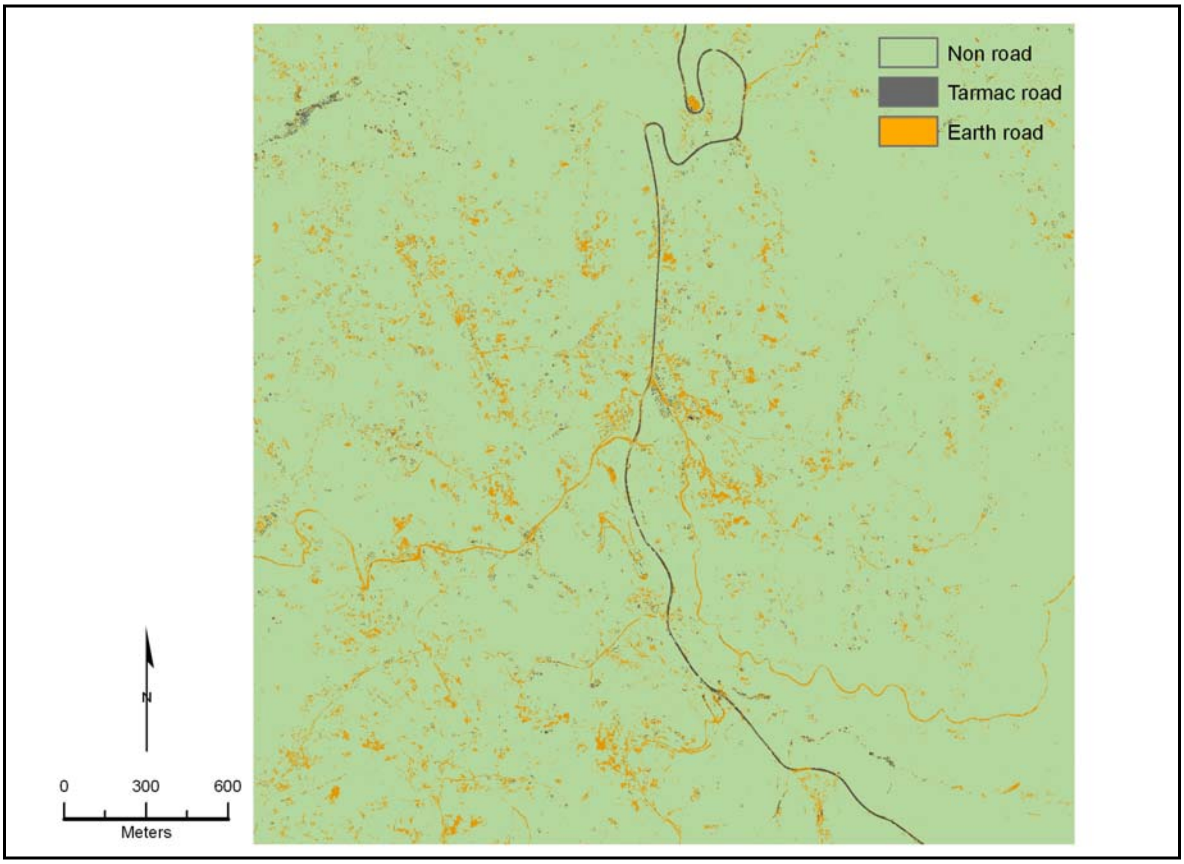


Figure 43. The pixel-based classification of Dembwa.

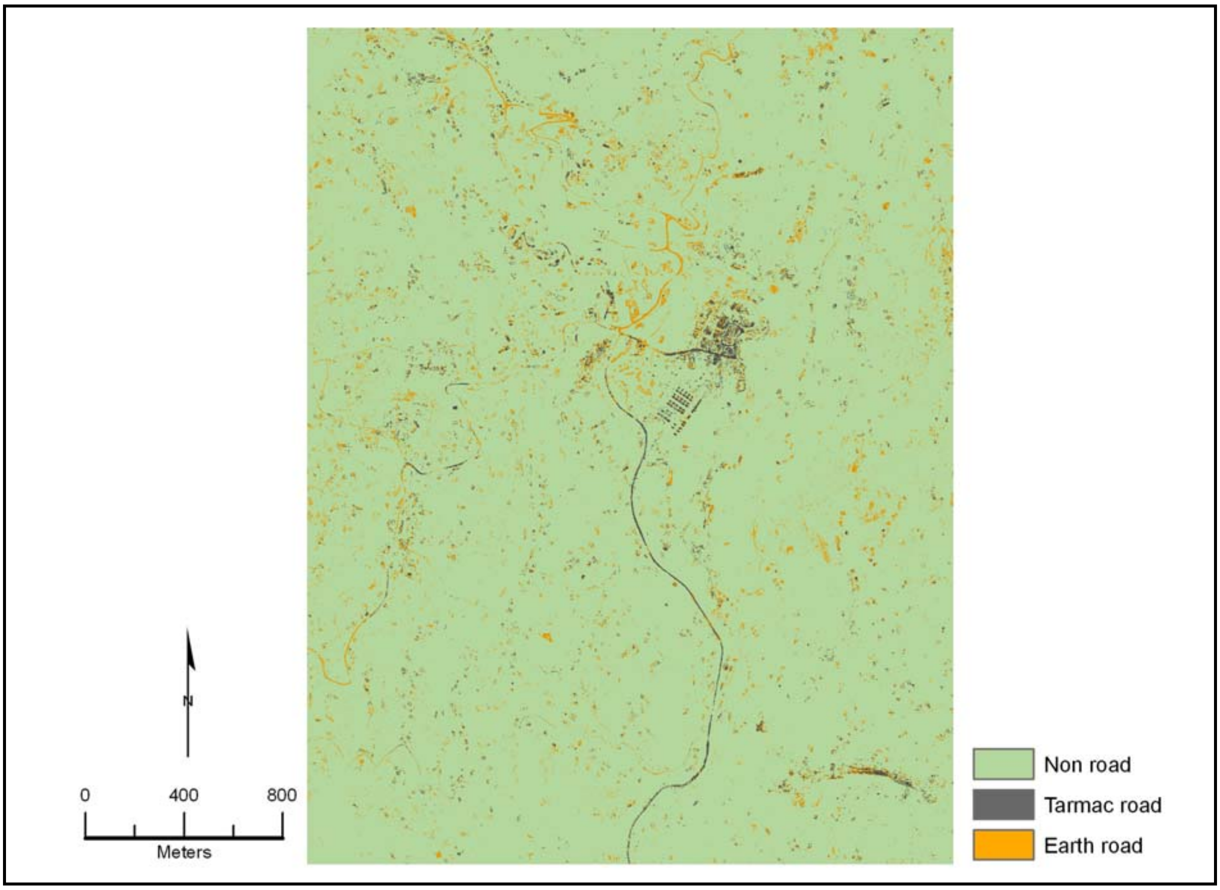


Figure 44. The pixel-based classification of Wundanyi.

7.4 OBJECT-ORIENTED ROAD EXTRACTION

The object-oriented classification results and the following vectorisation results are presented in this chapter. The segmentation-based raster masks are also shown in Appendices 2, 3 and 4 with the pixel-based classification results.

7.4.1 CLASSIFICATIONS

Quite similarly with the pixel-based classifications, the Level 1 classifications generally over-estimate both road classes. In particular, Mwatate and Wundanyi classifications have plenty of commission errors in the road classes. Respectively, considerably less misclassifications occur in these categories in the Level 2 classifications.

Figure 45 shows the classification results for Mwatate. In the Level 1 classification, the tarmac road class encompasses most tarmac roads but also other areas, especially in the western parts of the region and in the surroundings of Mwatate. Most main earth roads are in their appropriate category, but there are also many misclassified objects in this class, particularly in the southern parts of the image. In the Level 2 classification, most tarmac roads are classified properly and there are fewer over-classified features in this category. Earth road class has less non-road features in its class, although many minor roads, tracks and paths were misclassified as the non-road class.

The classification result for Dembwa is presented in Figure 46. In the Level 1 classification, tarmac was classified properly, although a few other features were misclassified as this category too. Earth roads were classified either as their appropriate category or as the non-road class. At Level 2, the classification of tarmac and earth roads was more successful and fewer segments were misclassified into the non-road class.

Figure 47 shows the results of the Wundanyi subset classifications. At Level 1, the tarmac road class encompasses appropriate tarmac roads but also several other objects, especially around the Wundanyi population centre and in the south-east rock area. Earth roads were either classified properly or misclassified as non-roads. In the Level 2 classification, several non-road segments were classified as tarmac, but considerably less of them ended up in the earth road class.

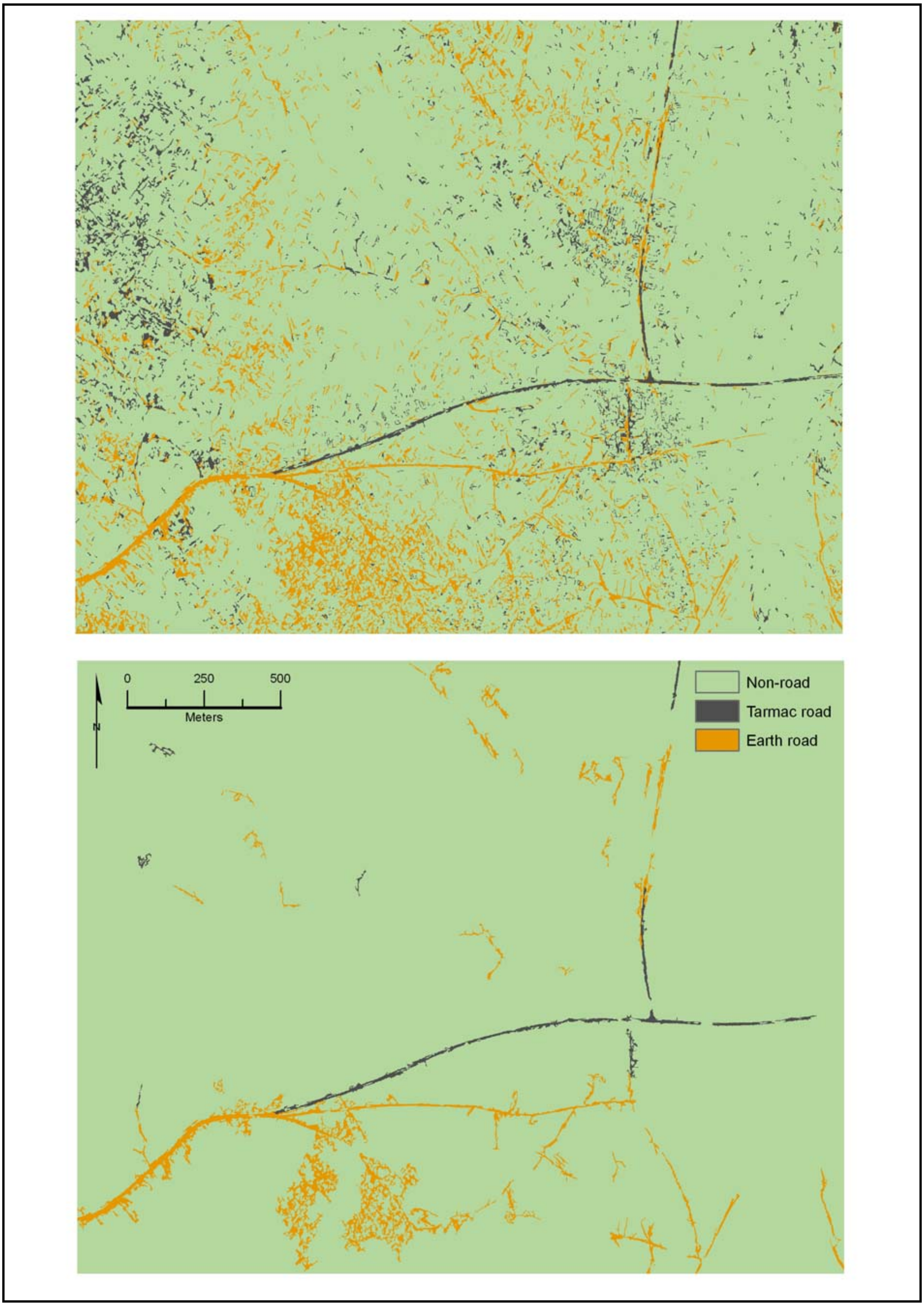


Figure 45. The object-oriented classification of Mwatate applying Standard NN (Level 1, top), and applying membership functions (Level 2, bottom).

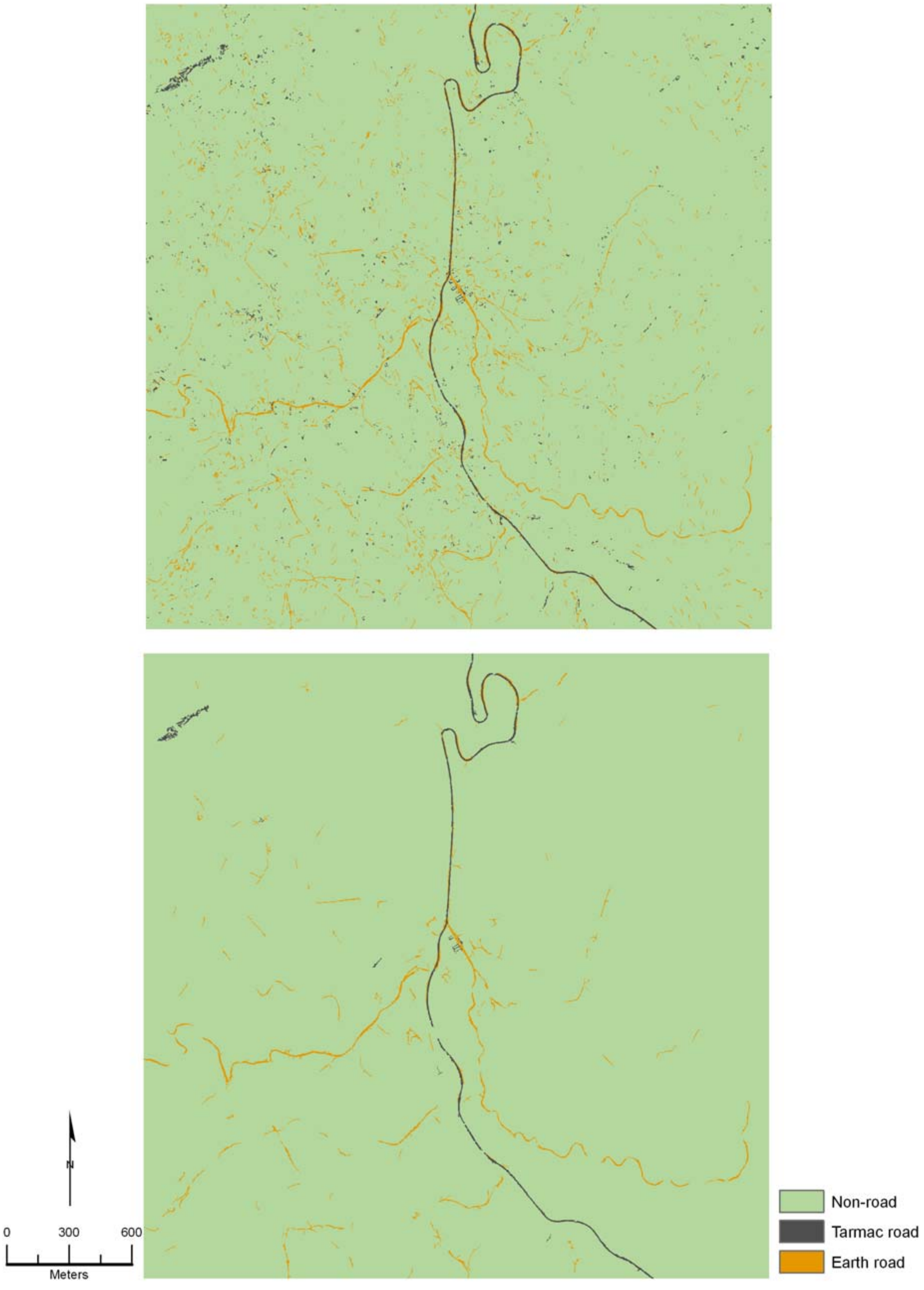


Figure 46. The object-oriented classification of Dembwa applying Standard NN (Level 1, top), and applying membership functions (Level 2, bottom).

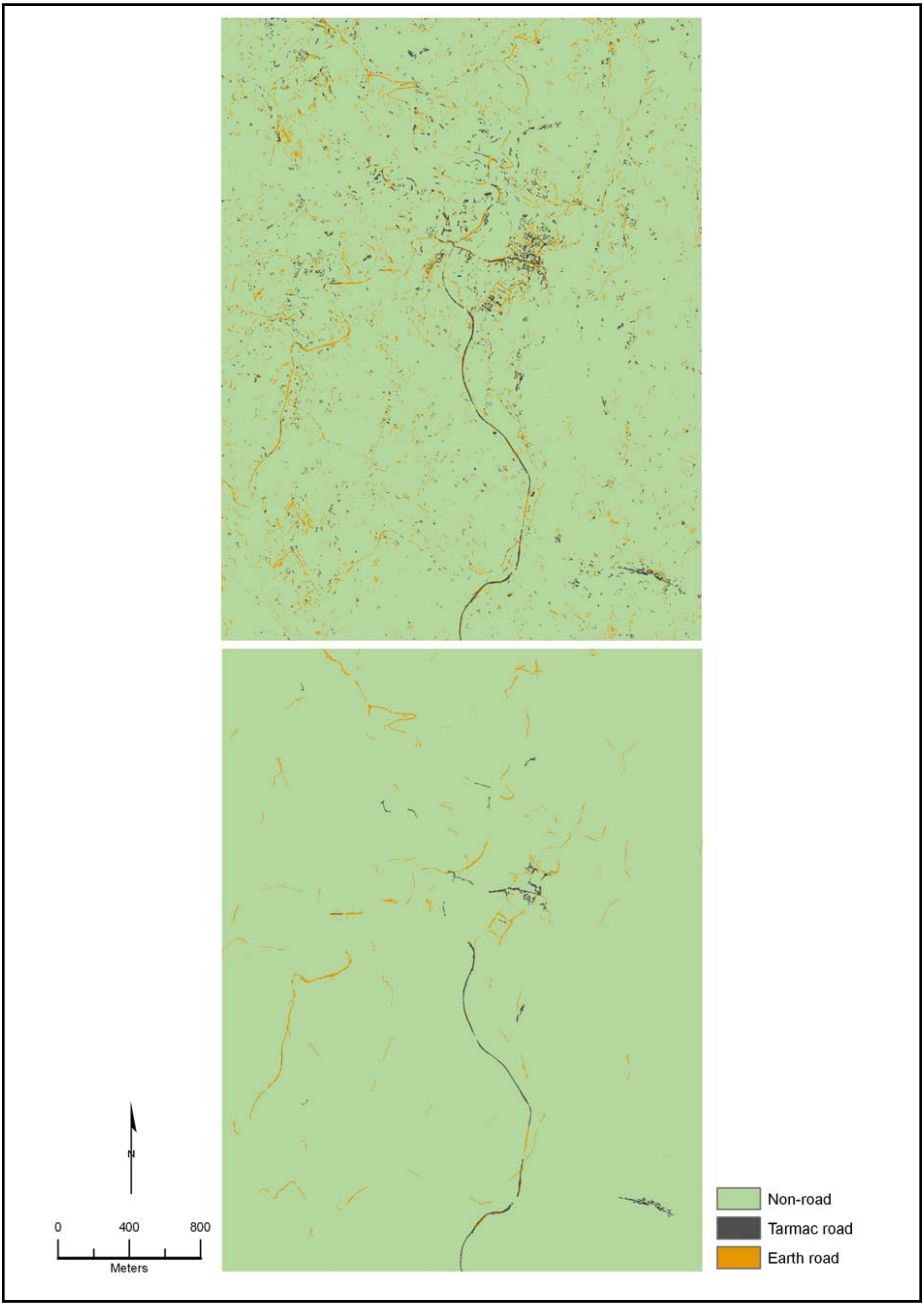


Figure 47. The object-oriented classification of Wundanyi applying Standard NN (Level 1, top), and applying membership functions (Level 2, bottom).

7.4.2 AUTOMATIC VECTORISATION

The skeleton outputs of the *eCognition*'s automatic vectorisation are visualised with the visually interpreted, manually digitised roads. Here, both layers are visualised by their surface type, since the exported skeletons have this type of classification directly based one the *eCognition's* classification results. Furthermore, the main aim of the vectorisation was to study the possibilities of the vectorisation procedure to generally convert raster classification results to vector outputs and different road types to their proper categories.

The skeleton layers presented below are based on the Level 2 object-oriented classification results. In addition, skeletons were created from the Level 1 classifications, but the results were notably worse than Level 2 outputs. In Level 1, there were plenty of redundant, fragmental skeletons all over the classified areas, only a minority of actual roads were covered by proper skeletons and generally the skeletons were of extremely poor quality. Therefore, these skeletons were discarded from further consideration and they are not presented here.

Figure 48 presents manually digitised roads versus automatically generated skeletons representing the roads of the Mwatate area. In places, the skeletons follow strictly the digitised main roads but there are many skeletons missing in particular on the minor roads and tracks, and there are also unnecessary skeletons in the area.

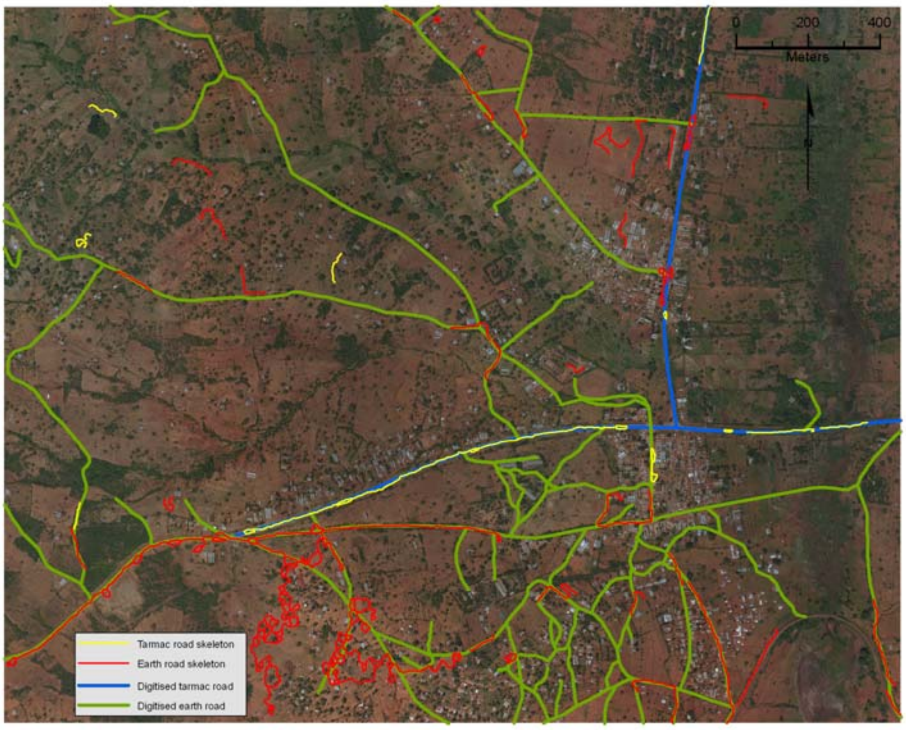


Figure 48. The skeletons and the digitised roads of the Mwatate subset.

In Dembwa (Figure 49), nearly the whole length of the tarmac road is covered with skeletons. A few main earth roads have also continuous skeletons overlaid but many other earth roads have no skeletons at all.

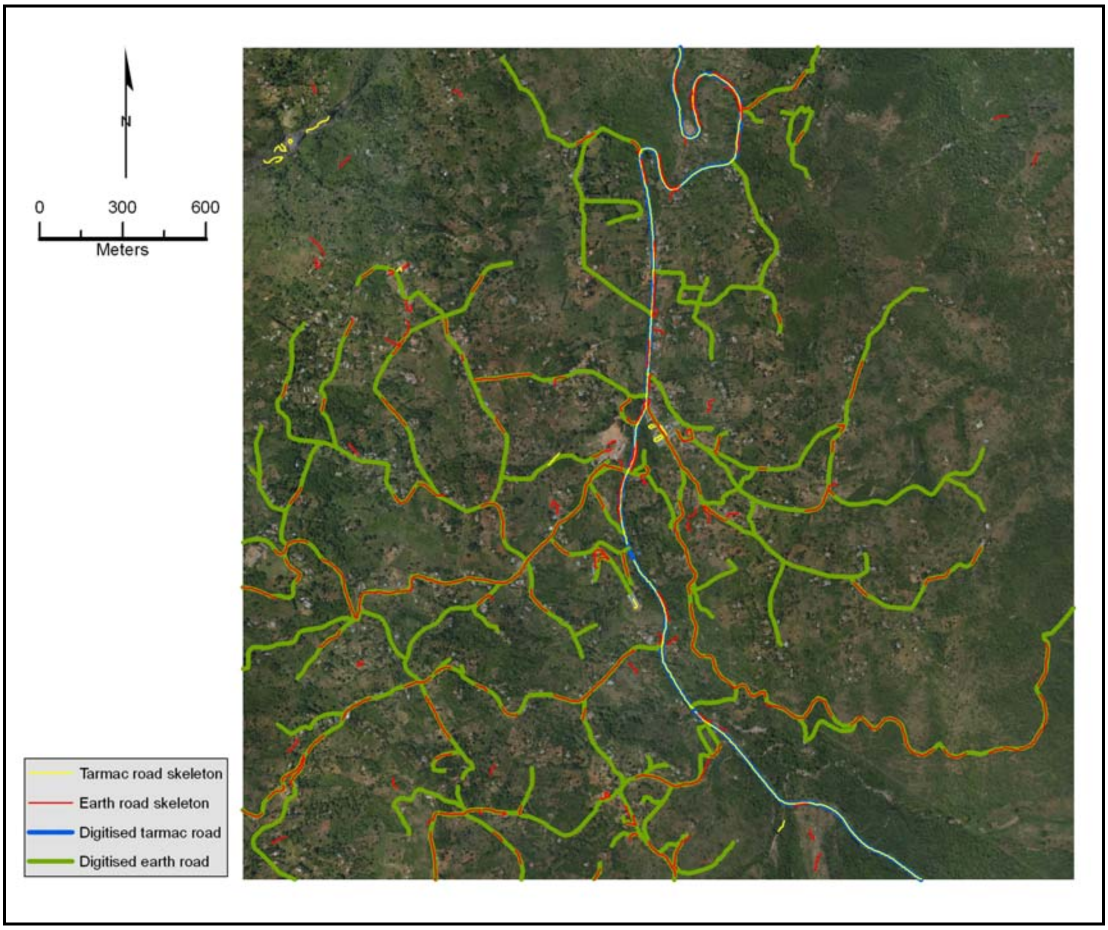


Figure 49. The skeletons and the digitised roads of the Dembwa subset.

Figure 50 shows skeletons in the Wundanyi area. There are only few continuous skeletons in the area; most of the roads are lacking skeletons or just have short pieces of them. The tarmac road from south to Wundanyi is the only road that is fairly well covered by the skeletons.

In addition, the vectorisation results are considered in Chapter 8.4, in which the accuracy of the procedure is assessed through calculating different length variables for the generated skeletons.

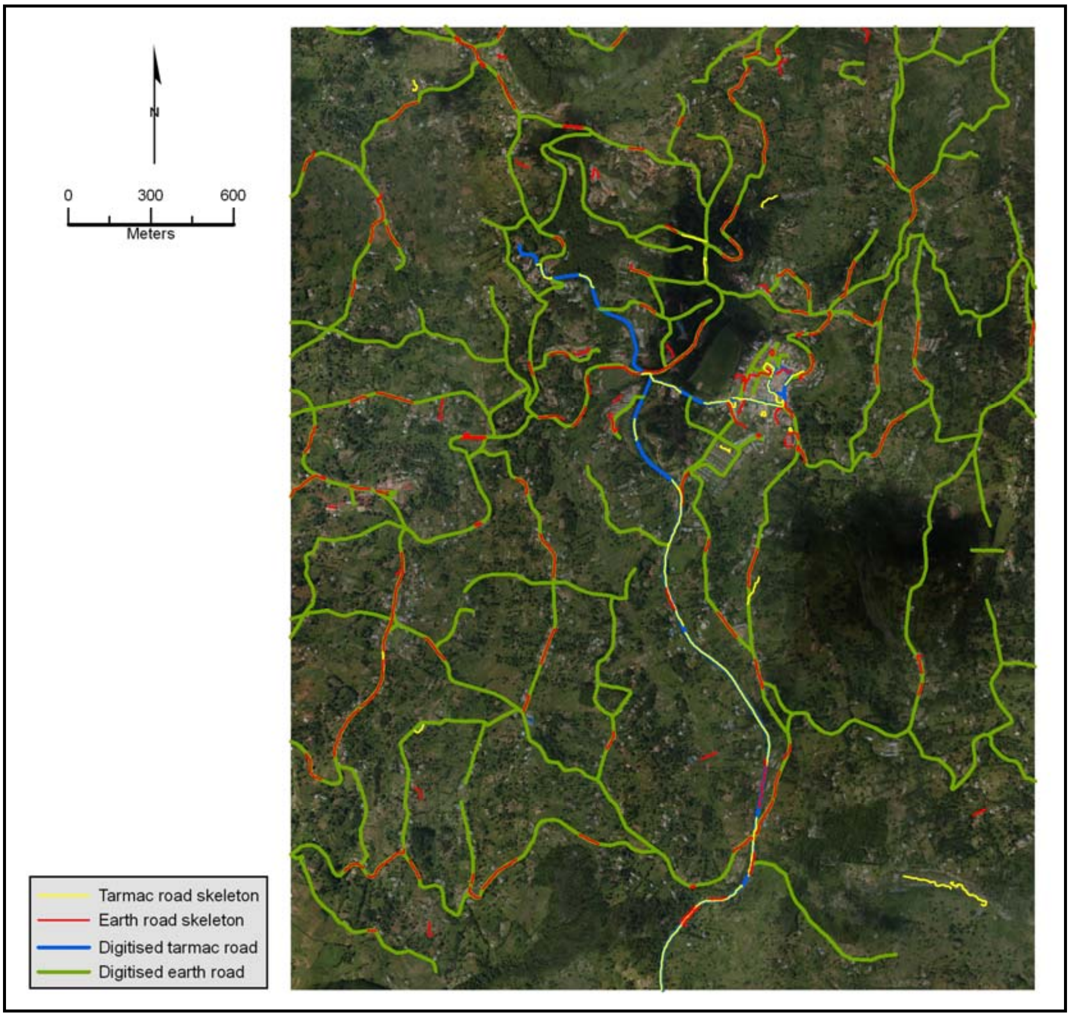


Figure 50. The skeletons and the digitised roads of the Wundanyi subset.

7.5 GENERATING AN UP-TO-DATE ROAD INFRASTRUCTURE DATA LAYER

The results of the road mapping and updating are introduced below. The mapping was concentrated mainly in the aerial image mosaic area, but some results will also be shown at a broader extent in Appendices 8 and 9, although the outside regions of the image mosaic were not mapped otherwise than adding the attribute information about the administering and surface type classifications to the existing road network.

The initial purpose of this study was to implement object-oriented classification and vectorisation for the road infrastructure mapping of the Taita Hills region. Beforehand, it was assumed that automated road vectorisation results of the *eCognition* software could be improved by manual editing and completion of the skeletons and to generate a practicable vector layer for the updating of the Taita Hills geodatabase. Since the results of the segmentation-based classification and vectorisation were not satisfactory at all, the original concept was abandoned. It would have been an unreasonable and time-consuming task to generate a proper road layer based on the skeletons that were not of appropriate quality. There was not only an absence of these skeletons in most classified places, but there were also plenty of redundant, fragmental skeletons in the wrong locations. Even the skeletons in the road locations may be erroneous and inappropriate for further use if they are not located precisely at roads' centrelines as they should be. Hence, the mapping and updating of the Taita Hills road infrastructure was conducted on the basis of visual interpretation and manual digitisation.

The road infrastructure of the Taita Hills mosaic area by the map classification is represented at two different dates, in 1991 and in 2004 (Figure 51 and Appendix 5). The 1991 dataset was created by Broberg & Keskinen (2004). It can be noticed that there are obvious differences in the extent of the road networks between the two dates. In particular, there are plenty more tracks and footpaths and the road network is denser in the 2004 map than in the 1991 map. Regardless of reasons, which are discussed in Chapter 9, evident changes are seen in many areas, such as in the surroundings of Dembwa and Wundanyi between the different years. In places, there are fewer roads generally whereas some parts of the mosaic region - especially northern and middle ones - are more densely covered by roads in the 2004 output.

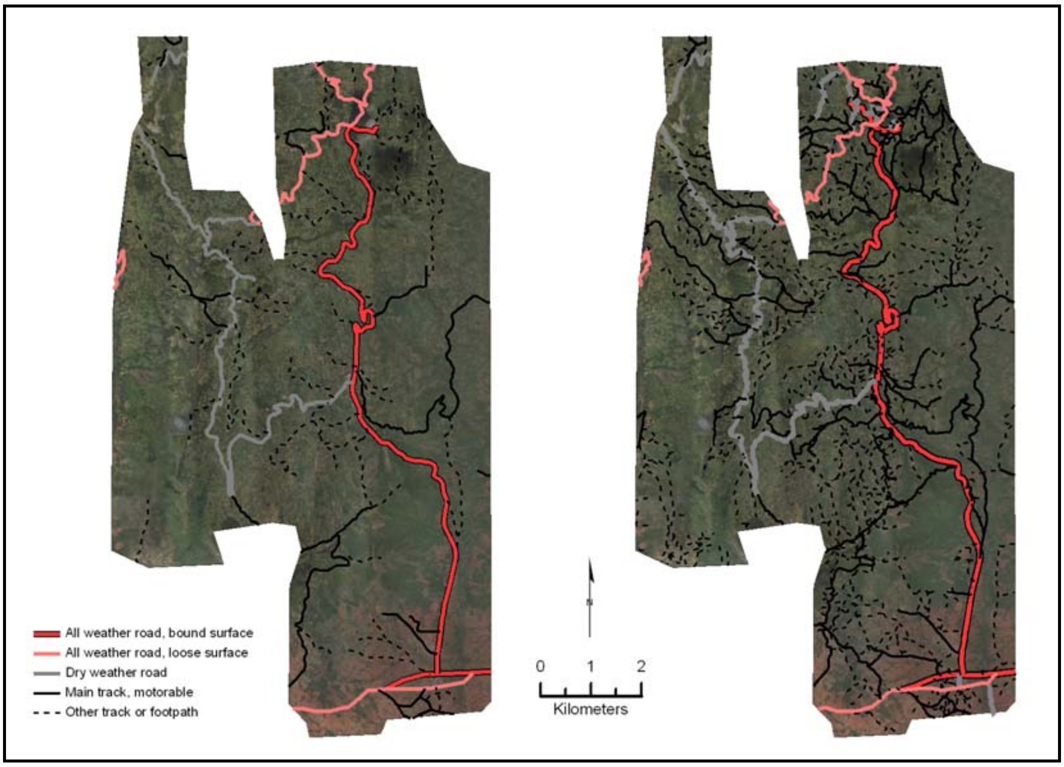


Figure 51. The road infrastructure of the Taita Hills by the topographic map classification in 1991 (left) and 2004 (right)

The road infrastructure by the administering classification is presented in Figure 52 and in Appendix 6. The administering classification is based on the Roads 2000 Coast (s.a.) reference map data. Most of the roads in the Taita Hills are unclassified roads, whereas a few minor roads and other roads of "higher" categories are located in the region.

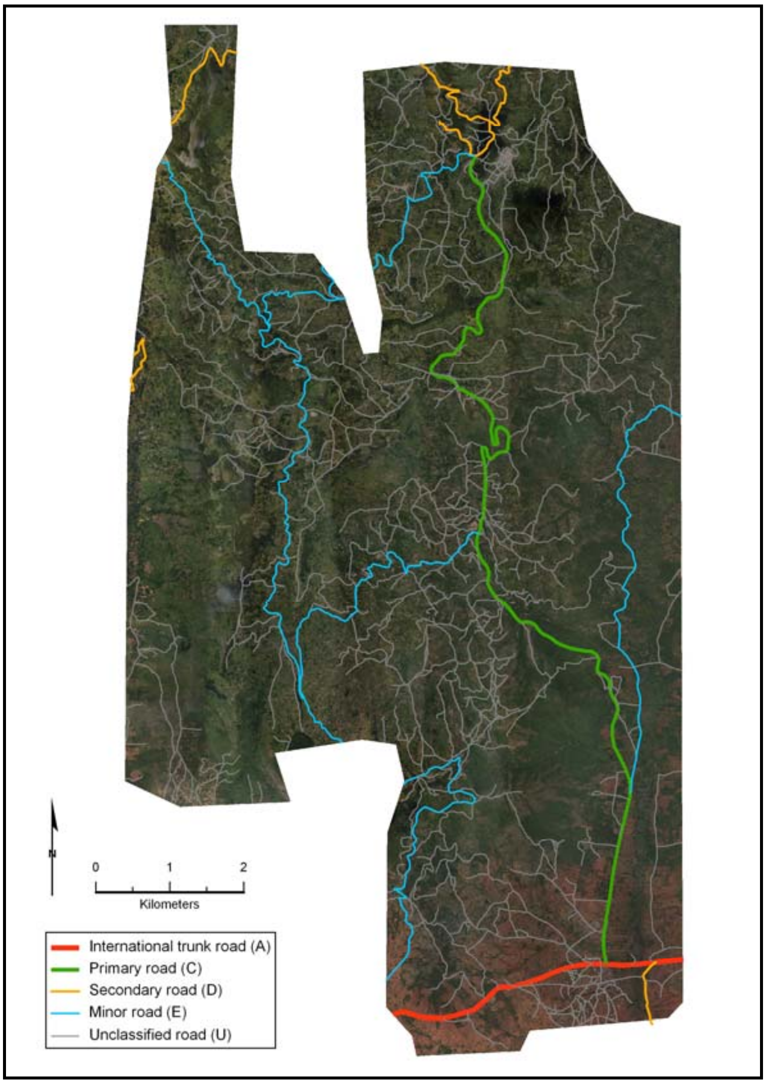


Figure 52. The road infrastructure of the Taita Hills by the administering classification in 2004.

The road infrastructure of the Taita Hills classified by surface type is shown in Figure 53 and in Appendix 7. Earth road is clearly the most widespread road type in the region, whereas tarmac and gravel are more uncommon, rarely used surface materials in road construction. However, this surface classification is very generalised in terms of the earth road class which contains all colour tones and composition of red, reddish, brownish-red, brown etc. earth roads.

Appendix 8 shows the updated road infrastructure of the mosaic area combined with the vector data of the surrounding regions generated from the *Kenya 1:50 000 Topographic Map*s (Broberg & Keskinen 2004). The SPOT image is visualised in the background. It should be noticed that data of the mosaic area and the surroundings were created using data of different degree of generalisation and varying accuracy. The map shows that the road network is denser within the mosaic area and in particular, there is more extensive coverage of tracks and footpaths in the highland area than in the surrounding plains. In Appendix 9, the road infrastructure of the Taita Hills and the surrounding plains is visualised by the administering classification. At the scale of the whole region, minor roads are concentrated within the mosaic area, and several minor roads lead to or pass through the core area of the Taita Hills. Generally, there are secondary and minor roads all around the region but with a rather scattered distributed and less to the south side of the Voi – Taveta international trunk road. The whole region is bounded by the two international trunk roads.

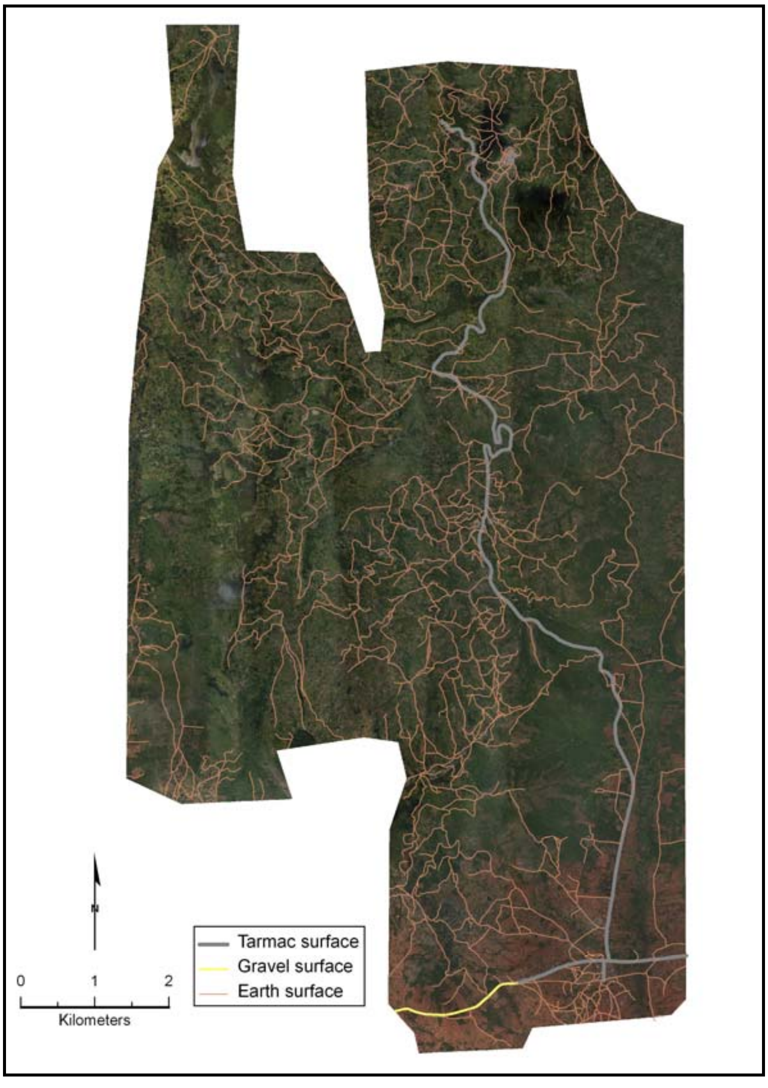


Figure 53. The road infrastructure of the Taita Hills by the surface type in 2004.

7.6 FIELD SPECTROMETRY

7.6.1 FIELD SPECTROMETRY MEASUREMENTS

The field spectrometry reflectance values of the different road surfaces are presented in Figures 54 and 55. Note that all reflectance values for the Taita Hills road surfaces are less than 70 %. Over the measured spectrum, concrete and gravel roads have the highest reflectance while tarmac surfaces have the lowest values. Generally speaking, variation between the reflectance values of various road surfaces increases towards the longer wavelength regions (NIR). Only tarmac roads have level spectral responses across the measured spectra while others show significant variation across their spectral range. All road surfaces have reflectance with an increasing signal towards the longer wavelength regions (NIR), however in the case of the tarmac roads the increase is minimal. Furthermore, no significant absorption troughs can be observed on any road surfaces and all roads experience the sharpest increase of their reflectance between 500 and 600 nm (~VIS green). While earth roads have another slightly sharp rise from 900 nm upwards, the increase is less in case of other roads.

The greatest within-class variation occurs between the different concrete sites: while the light concrete surface (Site 4) has reflectance between 15 to 60 % across the measured spectrum, the grey concrete (Site 8) has considerably lower reflectance between 8 and 28 %. Earth road surfaces show moderate separation particularly within the NIR region where the reflectance values are between 20 and 40 %. Tarmac surfaces have the lowest within-class variability: dark colour tarmac (Site 14) has the lowest reflectance of all roads measured, but it is only slightly lower than the spectra of lighter dark colour tarmac roads (Sites 12 and 13).

It should be noticed that in this context, the term “dark (colour)” is used to describe the tarmac road of new, good condition tarmac, whereas the term “lighter dark colour” defines the deteriorated road of poorer surface condition and older tarmac. The age, condition and composition aspects are considered with more detail in Chapter 9.

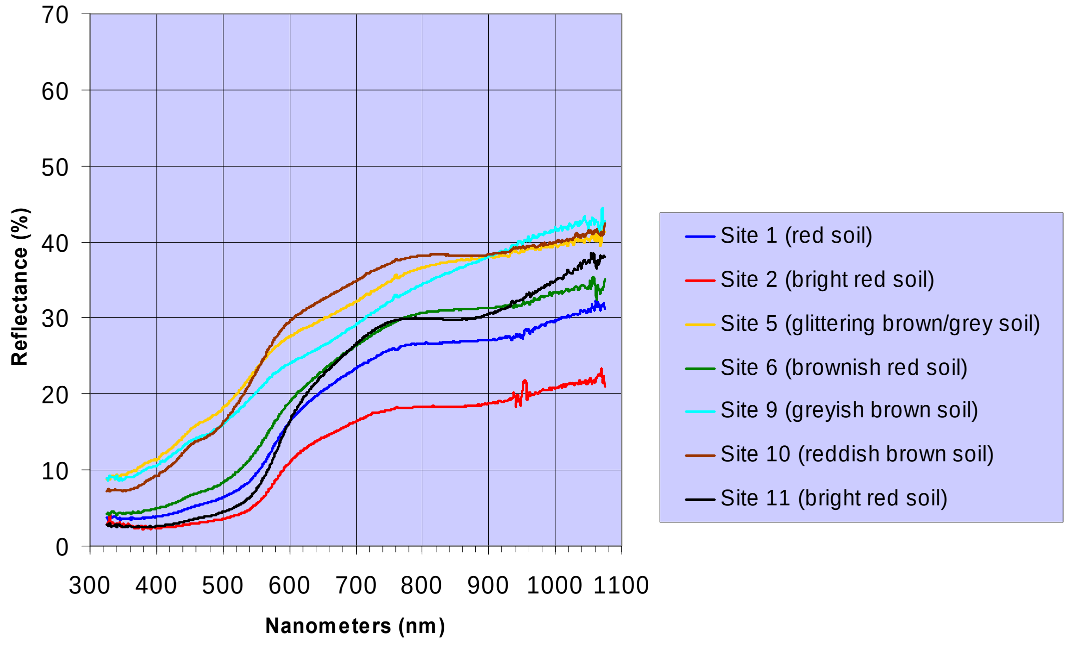


Figure 54. Spectral plots of the earth road surfaces.

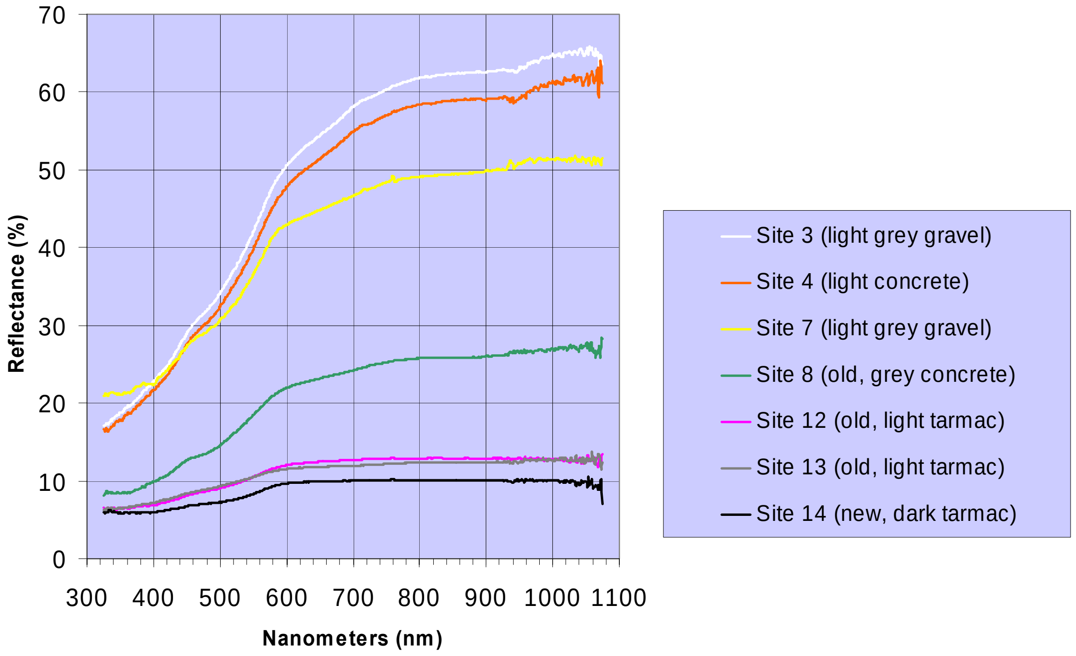


Figure 55. Spectral plots of the tarmac, concrete and gravel road surfaces.

7.6.2 SYNTHESISING MEASUREMENTS WITH THE SPOT DATA

The results of the SPOT 2003 image pixel reflectance values and synthesised SPOT reflectance response comparison are shown for each band individually in Figures 56, 57 and 58, and in the measured values in detail Appendix 10 and 11. All compared reflectance values are less than 70 %. Generally speaking, there are not any evident trends that one dataset would regularly give higher or lower reflectance values than the other. On the contrary, the corresponding points seem to locate at the reflectance scale quite randomly. When comparing all values of all three bands, 59 % of the corresponding values are located within the 10 % units of each other. When comparing the results band-specifically, it can be summarised that in Band 1 eight values out of 14 (57 %) were within 5 % reflectance units of each other, four (29 %) in Band 2, and five (36 %) in Band 3. The greatest variation between the pixel reflectance values and synthesised SPOT reflectance values occurs in Sites 3 (gravel) and 4 (concrete) in every band.

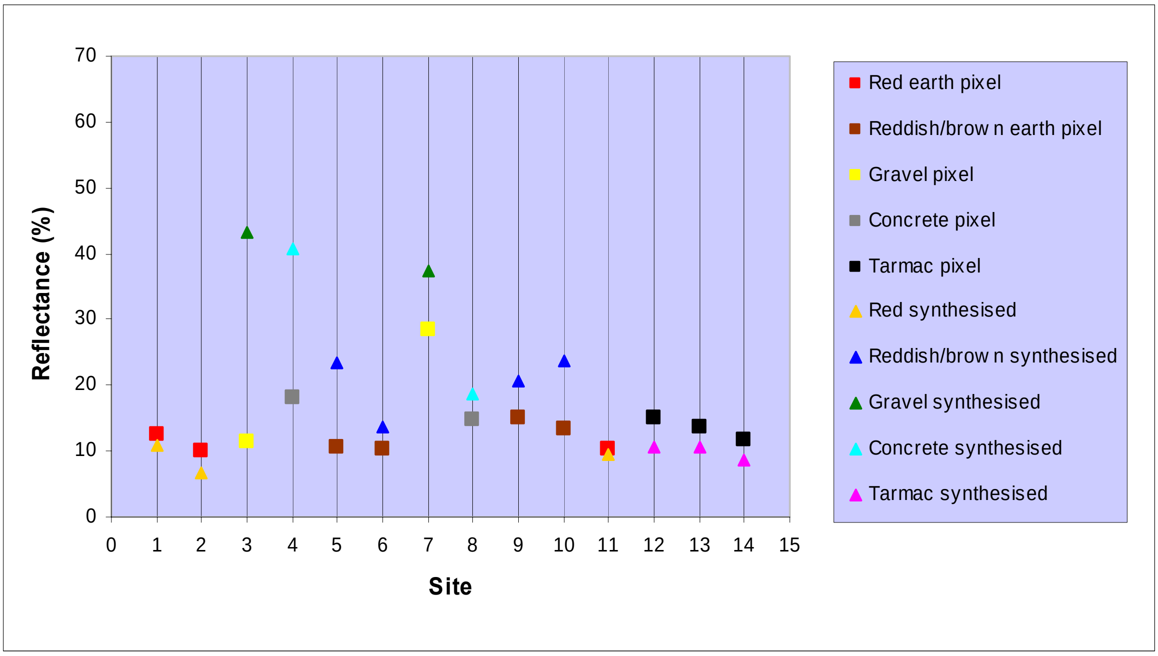


Figure 56. Comparison of the SPOT pixel reflectance values and the synthesised SPOT reflectance response for Band 1 (G).

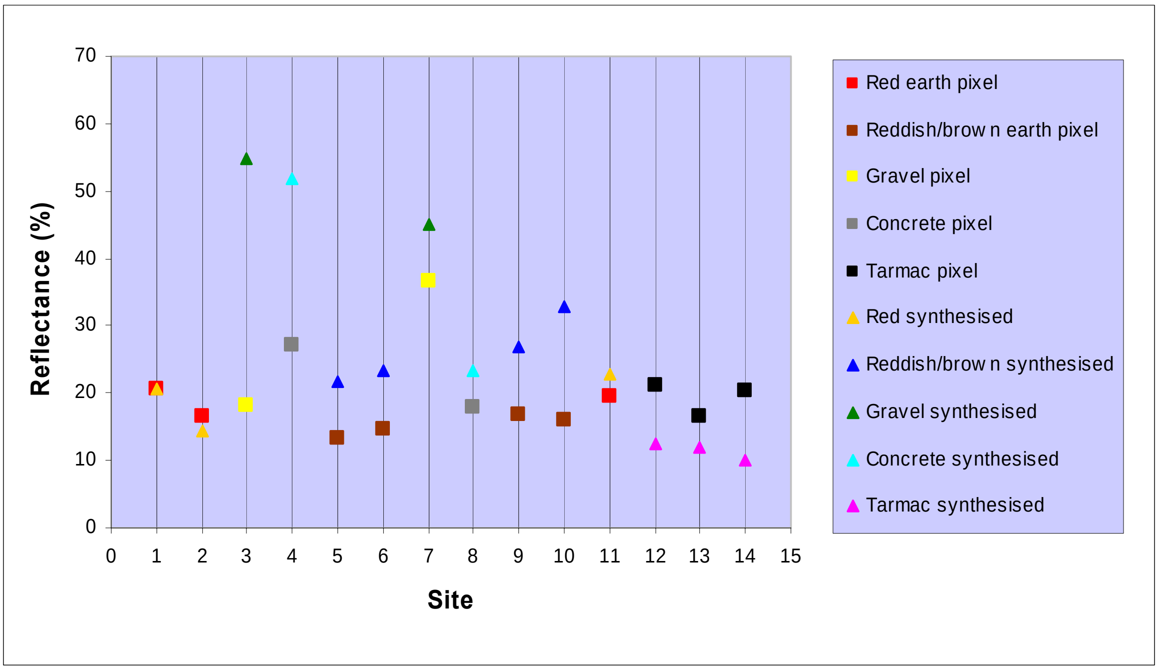


Figure 57. Comparison of the SPOT pixel reflectance values and the synthesised SPOT reflectance response for Band 2 (R).

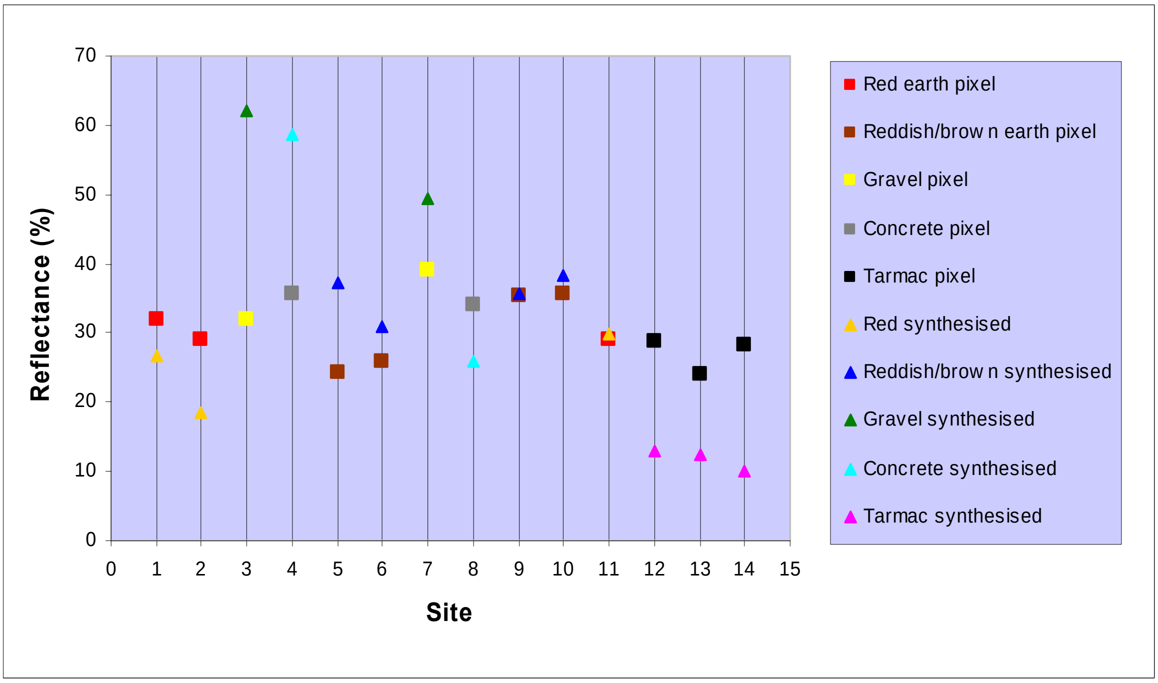


Figure 58. Comparison of the SPOT pixel reflectance values and the synthesised SPOT reflectance response for Band 3 (NIR).

The results of the SPOT 2003 road pixels and surrounding pixels comparison are presented for each band individually in Figures 59, 60 and 61, and the measured values in detail in Appendix 12 and 13. All compared reflectance values are less than 45 %. The surrounding pixels have reflectance values above and below the roads' values, mostly within 5 % units to both directions from the road reflectance values. Hence, there is very little variation between the reflectance values of the road sites and their surroundings. Furthermore, there are not any obvious differences between the different road surfaces. It should be noticed that the tarmac roads have similar reflectance values with their surroundings as well – this is a fact that emphasises the meaning of the spatial resolution characteristics and the mixed pixel problem occurred frequently on the SPOT image.

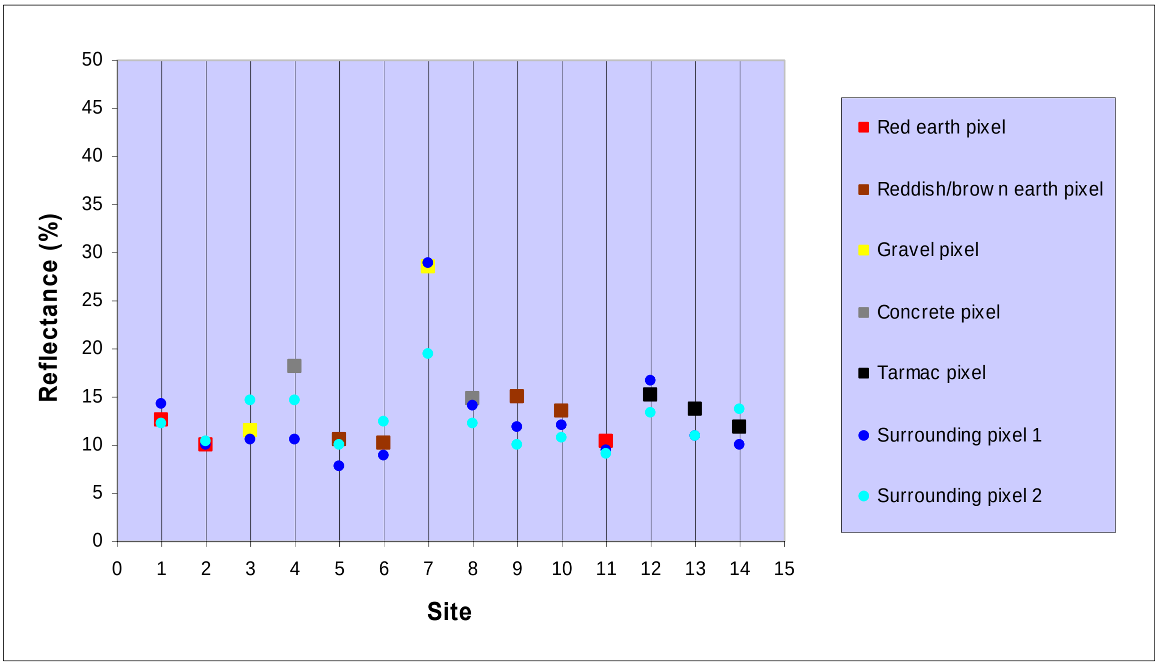


Figure 59. Comparison of the SPOT road and surroundings reflectance values, Band 1 (G).

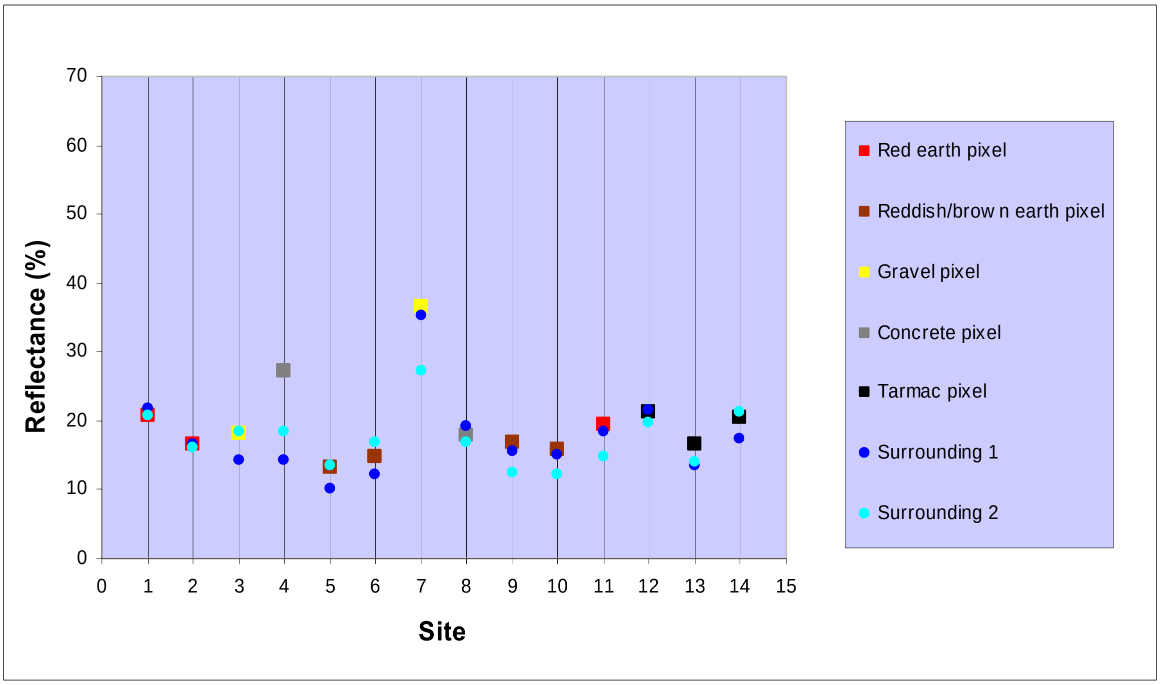


Figure 60. Comparison of the SPOT road and surroundings reflectance values, Band 2 (R).

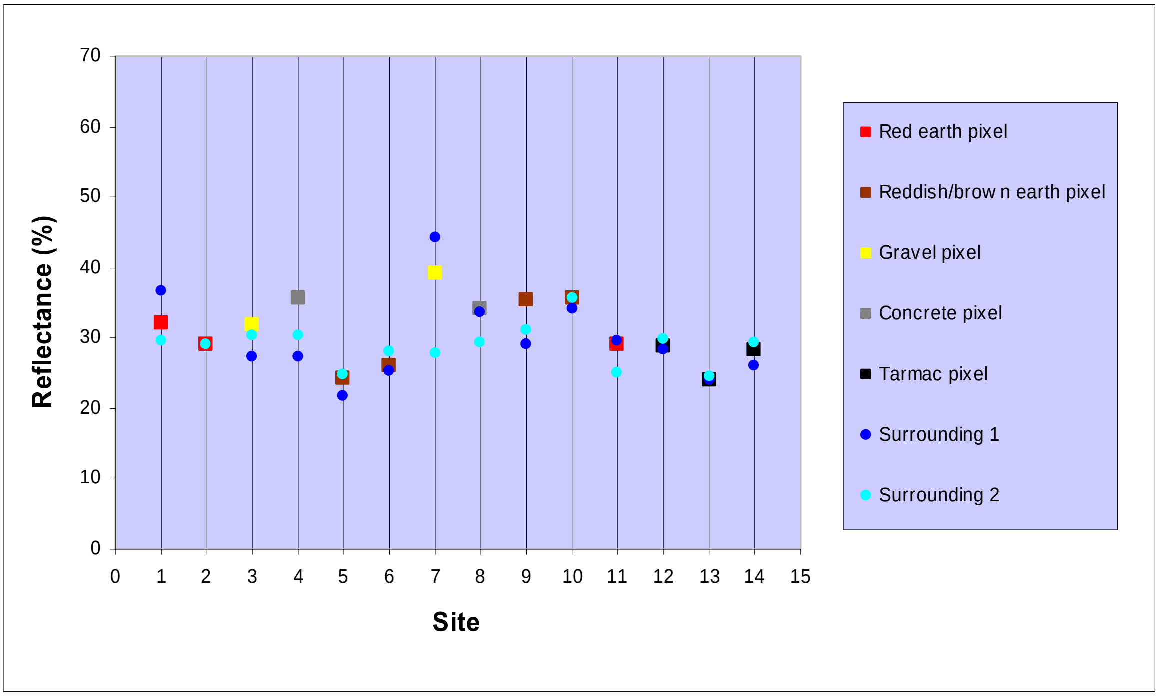


Figure 61. Comparison of the SPOT road and surroundings reflectance values, Band 3 (NIR).

8 ACCURACY ASSESSMENT

In this chapter, the quality and the reliability of the results and methods are evaluated. Accuracy is assessed for each main step of the pre-processing and the analysis procedure. Both quantitative and qualitative evaluation is implemented.

8.1 PRE-PROCESSING AND MOSAICKING

In this context, the accuracy of the BRDF correction is assessed briefly, but the light fall-off correction is not evaluated. Geometric corrections are considered at each step of the procedure.

8.1.1 RADIOMETRIC CORRECTIONS

In general, colour variations appeared in the imagery due to radiometric errors and different illumination conditions during the flight (Thurston 2003). The applied radiometric and geometric corrections reduced but not totally remove the volume of the errors encountered in the imagery. Radiometric errors are seen as vertical striping between adjacent flight lines on the image mosaic. The stripes are not precisely vertical but slightly twisting due to the varying orientation of the flight lines. The applied BRDF correction parameters reduced the intensity of the BRDF effect on the mosaic but the correction did not succeed in removing the brightness variations completely.

The optimum approach would have been to define correction factors for each individual image of the mosaic and for every band of the images. In addition, different quantification factors are needed for different land cover types to avoid over-correction or under-correction (Mikkola & Pellikka 2002). In this context, the correction model was only applied to the different bands of the entire image mosaic but not to different land cover types to avoid an unreasonable amount of pre-processing work. It should also be noted that the applied correction parameters were generalised values for the circumstances of Kenya, and thus they are not specified for this particular area, which may have had an influence on the final result.

8.1.2 GEOMETRIC CORRECTIONS

The geometric accuracy of the mosaics depends on the aerial photography, the original “raw” images and the corrections applied to the mosaicking procedure. The changes of the aircraft in-flight such as flight direction, speed and altitude may cause differing flight line orientation and varying overlap of the images (Thurston 2003).

In this study, the geometric corrections were implemented in the *EnsoMOSAIC* orthorectification process by the iterative Bundle Block Adjustment (BBA). The standard mean error of unit weight is a function of all the residuals and all the weights, and it is used to estimate the overall accuracy of the image rectification (StoraEnso 2003: 37-39). The adjustment error, the root mean square error (RMSE) of the final block for the creation of the image mosaic was 1.11 and maximum residual 2.0. In general, an overall adjustment error close to two pixels is a good and approximately one pixel is an excellent result of the BBA (StoraEnso 2003: 46). Thus, the mosaic is considered to be at least of good quality.

The optional ground control points (GCP) were not used to improve the geometric accuracy of the image mosaic. GCPs are not a necessity for the mosaicking procedure if accurate GPS data is registered during the flight (StoraEnso 2003: 3). The accuracy of the air-GPS was estimated to approximately 5 meters (Chapter 6.3.3) which was considered to be adequate for solely GPS data-based mosaic generation.

The overall geometric accuracy of the image mosaic was evaluated with the road GPS points collected in the field, and against the existing vector road data layer. The latter was only a very approximate evaluation since the digitised roads had been generalised from the once already generalised *Kenya 1:50 000 Topographic Map* information, and thus, they only fit partially when overlaid with the image mosaic. Generally speaking, vector roads fit regularly over the aerial image mosaic. When comparing with the GPS points, the geometric accuracy of the mosaic is considered to be good.

With a closer look at the image mosaic, it may be noticed that there are few visible seams between the individual images of the image mosaic and, consequently, discontinuities between the features of adjacent images, in particular roads and buildings. In Figure 62 minor discontinuities can be seen most clearly within the yellow boundaries at the locations of the artefacts. The geometric distortions stem from various reasons. Firstly, the changes of the aircraft in-flight cause distortions to objects captured in two adjacent flight lines due to the differences in photography, flight direction, speed etc. (Thurston 2003). When these objects are mosaicked using the “raw” images of varying ground pixel size and orientation, the outcome may be a visible seam in the image mosaic. In general, seams origin from the inconsistencies and inaccuracies of the DEM applied to the orthorectification and from the - height differences of the terrain (Hurskainen 2005: 97). The tie points located on top of buildings instead of the ground may cause distortions to the appearance of buildings due to the inaccurateness of the generated DEM in these particular spots. The quality of the generated DEM is discussed later in this section. In addition, distortions of buildings stem from the *relief displacement* of photogrammetry. The magnitude of relief displacement depends on the flying altitude, the distance from the principal point to the feature, and the object height (Lillesand & Kiefer 2000: 127). Hence, the effect causes the top of a vertical feature to lie farther from the principal point of the image than its base resulting in a leaned appearance of the object (ibid.: 148).

Figure 62. Geometric errors occurred in the image mosaic.

There is a clearly observable discontinuity error in the very north-west corner of the image mosaic where roads and fields are not at consistent locations (Figure 63). The area is located at the northernmost end of the flight line 11, at the place of the last individual "raw" image utilised for the mosaicking. The error of that image origins from the *EnsoMOSAIC* orthorectification process, since the overlap and sidelap with other images were inadequate and there were not sufficiently tie points located on that area of the "raw" image successful image rectification. However, this part of the mosaic was excluded from both visual and digital analyses.

Figure 63. Geometric errors occurred in the image mosaic

8.1.3 DEM

Geometric distortions of the image mosaic stem from the DEM quality and the great height variations of the undulating terrain of the Taita Hills. The DEM was computed with the 136947 tie points based on the elevation values generated for the tie points during the BBA (Figure 64). The accuracy of the DEM depends on the number of tie points measured (StoraEnso 2003: 42). Respectively, the amount, distribution and accuracy of the tie points affect the accuracy of the final mosaic (Sarmento & Sarkeala (2005).

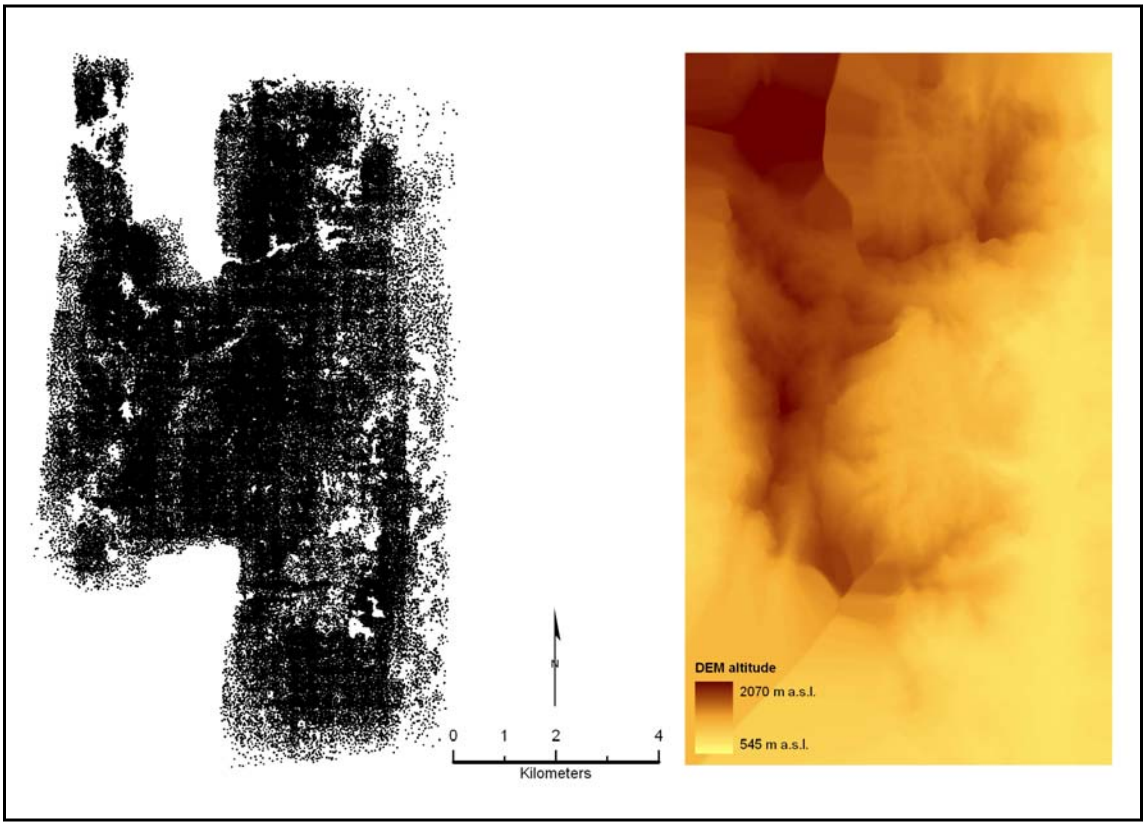


Figure 64. Tie point distribution map (left) and DEM derived from the tie point elevation values (right).

Table 9. GPS elevation values of 10 road points and DEM values at the corresponding locations.

Road point	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
GPS elevation	866	967	881	1169	1119	1373	1424	1475	1767	1817
DEM value	873	967	886	1171	1111	1374	1439	1484	1788	1816

In places, the unequal distribution of the tie points and the misplacement of some points to represent object height instead of true terrain elevation may have decreased the quality of the DEM. For instance, along the road from Mwatate to Wundanyi and in the surroundings of Wundanyi, the tie point distribution is more unequal and sparse than generally in the mosaic area. Since the DEM is based on the tie points that are not necessarily lain on the ground but on the top of trees and buildings as well, the output may not be the actual digital terrain model (DTM). Consequently, this has a distorting effect on the quality of the final output mosaic. In addition, the computation of the DEM at one meter resolution due to the software and hardware limits may have caused inconsistencies in the mosaic, since the mosaic was resampled at a slightly different resolution. The accuracy of the DEM was checked against the GPS height coordinate data of the road point data collected in the field. Elevation values of the two datasets were rather uniform and within 10 meters in all except two of ten chosen locations (Table 9).

8.2 VISUAL INTERPRETATION

Unlike in the pixel-based and object-oriented classifications, the accuracy of the visual interpretation was not determined with an error matrix but qualitatively in this context. The visual analysis of the SPOT satellite image data is only indicative and at a very overall level and, hence, it was not seen necessary to evaluate the accuracy of the results. On the contrary, the visual interpretation of the high spatial resolution image mosaic is assumed to represent the ground truth and to have an accuracy of almost 100 per cent. However, the accuracy is estimated to be at a lower level in places. There are obfuscatory objects such as tree canopy, clouds and shadows covering roads and, moreover, low contrast between roads and their background – particularly in bare ground areas – which made the detection task more difficult to conduct.

The accuracy assessment of the visually generated results were not seen practical, since the delineation was conducted by digitising roads as line objects, which was a generalised output covering basically only the centre lines of the whole extent of the roads. In addition, evaluation was seen worthless when conducted by the same person and against the same image data from which the original interpretation was made.

8.3 PIXEL-BASED AND OBJECT-ORIENTED CLASSIFICATIONS

A digital classification of remotely sensed data is not complete until the reliability of the results has been evaluated. Classification results of remotely sensed data are commonly assessed against the reference data that is assumed to be true and usually derived from ground truth data and/or visual inspection. It is important to conduct the accuracy assessment using a different data set that is applied to the actual classification to avoid the overestimation of the classification accuracy. In addition, the correctness - or at least the very high accuracy - of the reference data is crucial to build a fair assessment scheme. The most common way to express the classification accuracy is in the form of an error matrix which offers both descriptive and analytical statistical techniques to inspect the data reliability (Congalton 1991).

Since there was not a sufficient amount of ground truth data to conduct the assessment with test points, the classification results were evaluated against the aerial image mosaic. The visual inspection of the high spatial resolution image data was assumed to be the most appropriate and correct assessment method for this purpose. The visually interpreted road layer was used as an additional dataset on the top of the image. Accuracy assessment was performed in *ERDAS IMAGINE*.

A practical accuracy assessment is conducted with a set of randomly selected reference pixels that represents each pixel of the classification scheme. In general, a minimum of 50 samples for each vegetation or land use class should be collected to construct an appropriate error matrix (Congalton 1991). A more extensive sampling is needed if the classification has a large number of different categories and/or if categories show great variability (ibid.) In this context, 250 reference pixels per class were selected by using equalised random operation which determines an equal number of random points for each class (Erdas 2003: 262). Thus, the reference pixels were selected applying a 3x3 window size majority rule which set a minimum limit for “randomly” select reference pixels according to the class of the surrounding pixels within the square window. The accuracy assessment was performed for the recoded classification images, since there were only two classes of interest, namely "tarmac road" and "earth road", and one subsidiary class "non-road". Hence, all in all 750 reference pixels were selected for each classified image and then visually checked against the digital image mosaic.

The error matrices were compiled with the reference points. The error or confusion matrix is generally used to compute various descriptive statistics of the data: overall and class-specific accuracies of the data, and so-called producer’s and user’s accuracies. While producer’s accuracy is a measure of *omission* error and indicates the probability of a reference pixel being correctly classified, user’s accuracy is an estimate of *commission* measure and expresses the probability of a classified pixel actually representing that category on the ground and what has really been measured (Congalton 1991). It is important to describe the reliability of the data with both methods since the estimates answer completely different questions, and since a misclassification error is not only an omission from the correct class but also a commission into another category (Story 1986). In addition, Kappa statistics of the error matrices were determined. The Kappa coefficient describes “the proportionate reduction in error by a classification process compared with the error of a completely random classification” (Erdas 2003: 262). The estimator is commonly used to summarise the results of an accuracy assessment assignment (Stehman 1996).

The classification error matrices of the classifications are presented in Tables 10, 11 and 12. The overall accuracies for the supervised maximum likelihood (ML) classifications vary between 50 and 72 per cent, for segmentation-based fuzzy nearest neighbourhood classifications between 49 and 75 % (Level 1), and for fuzzy membership classifications between 74 and 91 % (Level 2). The best overall accuracy was achieved in the Level 2 Dembwa classification (91 %), and lowest accuracy in Level 1, Mwatate (49 %). The overall accuracies for Level 1 shows only slightly improvements from the ML classifications, except in case of Mwatate where the classification accuracy is even worse. On the contrary, the level 2 classifications have clearly the highest overall accuracies of the classification methods applied to the subsets.

In the pixel-based and the Level 1 classifications, user’s accuracies are notably worse than producer’s accuracies generally. That is to say, road classes were over-emphasised with redundant, misclassified features. Level 2 shows slightly opposite trend: producer’s accuracies are slightly higher than user’s accuracies, although the differences between the rates are smaller. In general, Level 2 classification reduced the over-classification into the road classes.

In Mwatate, the earth road class of each level is over-emphasised with misclassified features from other categories, whereas the tarmac road class shows significant improvement on the user’s accuracy of the Level 2 classification. In Dembwa, tarmac road is over-estimated in Level 1 classification while the ML and Level 2 classifications have less misclassification as tarmac road. Earth road was classified most accurately in Level 2. In Wundanyi, the tarmac road class has rather low user’s accuracy in every classification, though Level 2 has clearly the lowest commission error of tarmac class. Similarly, earth road class is least over-emphasised in Level 2 classification.

It is stated that a minimum of 85 % overall accuracy and 70 % per-class accuracy is required to attain reliable results in land cover classifications (Thomlinson et al. 1999). When comparing the digital classifications conducted, only one classification (Dembwa, Level 2) has overall accuracy better than 85 % (91 %) with per-class accuracies better than 80 %. Hence, this classification succeeded well according to these criteria while the others failed. Another classification (Wundanyi, Level 2) almost reached these criteria, having an overall accuracy of 83.87 % and lowest class-related accuracy 72.54 %. In the both classifications, there are many areas that are either misclassified into the road categories or missing from these. However, the criterion was developed for the land cover classifications and not specifically for the purpose of road extraction.

In general, the accuracy assessment conducted with the error matrix is only indicative and is overly optimistic occasionally as well. Therefore, the accuracies derived from the error matrix should not be kept as an unconditional truth but only as an indication of how well the classes are spectrally separable, how homogenous the training areas are, and how well the classification procedure is suited for that particular scene (Lillesand & Kiefer 2000: 570).

It should also be noted that since the accuracy of the segmentation-based classifications was assessed in *ERDAS IMAGINE*, the initial fuzzy classification concept of *eCognition* software was excluded from this stage onwards. Hence, image objects did not have any longer memberships in more than one class but they were “forced” to belong into one delimited category. However, this was an applicable assessment method for comparing the accuracy of the different classifications with each other.

Table 10. Classification error matrices of the pixel-based (ML), object-oriented Level 1 (L1) and object-oriented Level 2 classifications in Mwatate.

Classification (ML)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	85	6	159	98.84%	34.00%
Earth road	1	48	201	78.69%	19.20%
Non-road	0	7	243	40.30%	97.20%
Overall accuracy		50.13%	**Kappa statistics**		0.252

Classification (L1)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	59	13	178	93.65%	23.60%
Earth road	3	59	188	78.67%	23.60%
Non-road	1	3	246	40.20%	98.40%
Overall accuracy		48.53%	**Kappa statistics**		0.228

Classification (L2)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	216	4	30	95.15%	86.40%
Earth road	9	95	146	92.23%	38.00%
Non-road	2	4	244	58.10%	97.60%
Overall accuracy		74.00%	**Kappa statistics**		0.61

Table 11. Classification matrices of the pixel-based (ML), object-oriented Level 1 (L1) and object-oriented Level 2 classifications in Dembwa.

Classification (ML)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	227	4	19	100.00%	90.80%
Earth road	0	65	185	92.86%	26.00%
Non-road	0	1	249	54.97%	99.60%
Overall accuracy		72.13%	**Kappa statistics**		0.582

Classification (L1)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	166	1	83	98.22%	66.40%
Earth road	3	150	97	94.94%	60.00%
Non-road	0	7	243	57.45%	97.20%
Overall accuracy		74.53%	**Kappa statistics**		0.618

Classification (L2)	Reference data			Producer's accuracy	User's accuracy
	Tarmac	Earth	Non-road		
Tarmac road	226	0	24	98.69%	90.40%
Earth road	3	211	36	98.60%	84.40%
Non-road	0	3	247	80.46%	98.80%
Overall accuracy		91.20%	**Kappa statistics**		0.868

Table 12. Classification error matrices of the pixel-based (ML), object-oriented Level 1 (L1) and object-oriented Level 2 classifications in Wundanyi.

Classification (ML)	**Reference data**			**Producer's accuracy**	**User's accuracy**
	Tarmac	Earth	Non-road		
Tarmac road	83	10	157	92.22%	33.20%
Earth road	7	65	178	84.42%	26.00%
Non-road	0	2	248	42.54%	99.20%
Overall accuracy	52.80%		**Kappa statistics**	0.292	

Classification (L1)	**Reference data**			**Producer's accuracy**	**User's accuracy**
	Tarmac	Earth	Non-road		
Tarmac road	54	5	189	84.38%	21.60%
Earth road	10	117	123	89.31%	46.80%
Non-road	0	7	243	43.78%	97.20%
Overall accuracy	55.20%		**Kappa statistics**	0.328	

Classification (L2)	**Reference data**			**Producer's accuracy**	**User's accuracy**
	Tarmac	Earth	Non-road		
Tarmac road	170	14	66	95.51%	68.00%
Earth road	8	216	26	91.14%	86.40%
Non-road	0	7	243	72.54%	97.20%
Overall accuracy	83.87%		**Kappa statistics**	0.758	

8.4 AUTOMATIC VECTORISATION

The accuracy of the skeletons – or automatic vectorisation – can be assessed with various methods to describe the success of automated road mapping. The quality of the extracted road centreline from classified imagery determines the positional accuracy of the extracted road network (Zhang & Couloigner 2006). Three basic quality measures have been commonly used to evaluate extracted road networks: *completenes*s, *correctness* and *Root Mean Square Error (RMSE)* (Wiedermann 2003). In this context, however, the evaluation is performed slightly differently.

The skeletons are compared to the reference data set – the manually digitised road layer – with the *overall accuracy* index, also referred as producer’s accuracy. The overall accuracy indicates only *omission* errors but no *commission* errors. Therefore, the measure of *agreement* (Hodgson et al. 2004), that considers both types of error simultaneously, is applied to the evaluation process with a certain buffer scheme developed by the author. Finally, the correctly extracted skeletons are compared to the ground truth (digitised roads), which is considered as the most explicit measure of the applied three indexes to describe the actual success of the road mapping procedure performed by the automatic vectorisation and the preceding segmentation-based classification.

The overall accuracy is derived from the equation:

$$\text{Overall Accuracy (\%)} = \frac{\text{All skeletons}}{\text{All digitised}} \times 100$$

, where All skeletons = Total length of extracted skeletons

All digitised = Total road length of reference data set.

The overall accuracies and the total length of the skeletons and the digitised roads are presented in Table 13. The values were derived in *ArcGIS* by using its *Extract* and *Proximity* analysis tools. The table shows that each skeleton layer - except one - has the total length of skeletons less than the visual layer has, and that the overall accuracy values are substantially better for tarmac roads. The exception is the tarmac skeleton layer of Dembwa, in which the total length of skeletons exceeds the ground truth. The Dembwa tarmac case clearly indicates the problem that occurred in the vectorisation procedure: there may be redundant skeletons involved in the road classes. Respectively, other results indicate that some skeletons may be missing. Hence, although the total length comparison may indicate general trend of the vectorisation, there may be redundant skeletons harming and skewing the actual rates of the vectorisation.

Table 13. Accuracy assessment indexes of the vectorised skeletons.

Mwatate						
	All digitised	**All skeletons**		**Skeletons (≤ 5m distance)**		
	length (m)	**length (m)**	**Overall accuracy (%)**	**length (m)**	**Agreement (%)**	**% of All digitised**
tarmac	3105.57	2477.38	79.77	1725.84	44.74	55.57
earth	22669.23	11941.51	52.68	5142.87	17.45	22.69
Dembwa						
	All digitised	**All skeletons**		**Skeletons (≤ 5m distance)**		
	length (m)	**length (m)**	**Overall accuracy (%)**	**length (m)**	**Agreement (%)**	**% of All digitised**
tarmac	4660.59	5356.67	114.94	4633.57	86.07	99.42
earth	35494.99	16012.54	45.11	11324.39	28.18	31.90
Wundanyi						
	All digitised	**All skeletons**		**Skeletons (≤ 5m distance)**		
	length (m)	**length (m)**	**Overall accuracy (%)**	**length (m)**	**Agreement (%)**	**% of All digitised**
tarmac	4269.40	4189.19	98.12	2803.77	49.58	65.67
earth	48126.41	11815.47	24.55	9038.28	17.76	18.78

Consequently, a slightly different approach was developed to dissect *correctly* extracted skeletons which truly represent roads. Therefore, total length values were calculated for those skeletons that are located within a 5 metre distance buffer zone from centrelines of the visually digitised roads. In this context, both road classes were handled separately. However, this was a rough approximation based on the estimated maximum road width (i.e. 10 metre) in these subset areas. Therefore, specific buffer layers were generated from the visually digitised roads and the skeletons were then set against the per-class buffers to derive length attribute for those skeletons that fulfil the 5m distance criterion. It should be noted that since many of the roads, tracks and paths in the subset areas are narrower than 10 metres, the 5m buffer distance may be too much to represent the actual road width in many cases. Hence, the buffer estimate may skew and increase the measured accuracy rates, as there are skeletons within the buffer zone which fulfil the predefined criterion but do not truly represent roads.

The road feature agreement is derived from the equation (Hodgson et al. 2004):

$$\text{Road Feature Agreement (\%)} = \frac{\text{Skeletons (5m distance)}}{\text{All skeletons} + \text{All digitised - (Skeletons (5m distance))}} \times 100$$

, where Skeletons (5m distance) = Total length of skeletons within the 5 m buffer zone.
All skeletons = Total length of extracted skeletons
All digitised = Total road length of reference data set.

Table 13 shows that the road feature agreement index rates are substantially lower in every road class than in the former analysis. Only tarmac road skeletons seems to be generated well (86.07 %) in terms of omission and commission errors. All the other agreements values are below 50 % which may be considered as poor results according to this accuracy criterion. The earth road classes have in every case agreement value below 20 %.

The last evaluation variable indicates the ratio of the skeletons fulfilling the 5 m criterion to the all digitised roads. According to these accuracy rates, tarmac roads were vectorised moderately or well (Dembwa 99.42 %), but earth roads very poorly.

On the other hand, this approach does not take into account the fact, that although a skeleton would be within the set 5 metre criterion from the digitised road centreline, its quality may be erroneous and inappropriate for further use. A skeleton may be overly winding and it may be located elsewhere than at roads’ centreline, even outside the whole road area. The direction differences (Wiedermann 2003) were not included to this context either.

8.5 SPECTRAL SIGNATURE SEPARABILITY BETWEEN ROADS AND BACKGROUND

Various statistical methods are used to evaluate spectral separation between different classes and consequently, to define appropriate techniques and optimal bands to minimise commission and omission errors in a particular classification procedure (Jensen 1996: 218). *Transformed divergence* is used to measure the statistical distance between the signatures of different classes and that distance can be used to determine how distinct the signatures are from each other. As a consequence, this utility can be used to determine the best subset of spectral bands to apply to the classification process.

In this context, the emphasis was not to choose the most optimal bands for the classification, since the imagery was comprised of only three visible light channels (RBG). The transformed divergence utility was applied to statistically analyse spectral separability between roads and background objects on the airborne digital image mosaic. In total, 22 sample signatures were collected from the three subset image areas so that these signatures represented most common road types *(R)* and background surfaces *(BG)* found in the study sites (Table 14). The signatures were created with the *ERDAS IMAGINE Region Grow* –tool (maximum 150 pixels area and less than 10.00 spectral Euclidean distance). Statistical distance between the signatures was computed with all three bands of visible light channels applying the transformed divergence formula (Jensen 1996: 220).

Table 14. Spectral signature test sites.

R1	Tarmac road, very dark	***BG11***	Red (reddish brown) roof
R2	Tarmac road, dark	***BG12***	Brown roof
R3	Tarmac road, light	***BG13***	Grey roof
R4	Tarmac road, old	***BG14***	Light grey roof
R5	Tarmac road with red sand	***BG15***	White roof
R6	Gravel road, light (red)	***BG16***	Rock
R7	Earth road, reddish	***BG17***	Bare ground, light brown soil
R8	Earth road, red	***BG18***	Bare ground/open field, brown soil
R9	Earth road, light brown	***BG19***	Bare ground/open field, red soil
R10	Earth road, brown	***BG20***	Grass/vegetated field
		BG21	Bush
		BG22	Tree

In general, transformed divergence values are set between 0 and 2000, so that values of 2000 represent excellent between-class separation, above 1900 stand for good separation and values below 1700 for poor separation (Jensen 1996: 225). The results of the signature separability of different road types and various background objects using transformed divergence are shown in Table 15. The clearly lowest values are marked as bold font and orange colour.

Table 15. Transformed divergence with RGB bands between roads and background objects.

Sig	***BG11***	***BG12***	***BG13***	***BG14***	***BG15***	***BG16***	***BG17***	***BG18***	***BG19***	***BG20***	***BG21***	***BG22***
R1	2000	1954	1997	2000	2000	2000	2000	2000	2000	2000	2000	2000
R2	2000	2000	**1337**	1996	2000	1931	2000	2000	2000	2000	2000	2000
R3	2000	2000	2000	**1718**	2000	1966	2000	2000	2000	2000	2000	2000
R4	2000	2000	2000	2000	2000	2000	1982	2000	2000	2000	2000	2000
R5	1984	1994	2000	2000	2000	2000	2000	**1891**	2000	2000	2000	2000
R6	2000	2000	2000	2000	2000	2000	1995	2000	2000	2000	2000	2000
R7	1968	2000	2000	2000	2000	2000	2000	1991	1999	2000	2000	2000
R8	1933	2000	2000	2000	2000	2000	2000	2000	**1498**	2000	2000	2000
R9	2000	2000	2000	2000	2000	2000	2000	1961	2000	2000	2000	2000
R10	2000	2000	2000	2000	2000	2000	2000	1992	2000	2000	2000	2000

The table suggest that a few background classes are poorly separable from the roads due to the short statistical spectral distance between them, in other words their similar spectral characteristics. The clearly poorest separability is in two cases: between dark tarmac road *(R2)* and grey roof *(BG13)*, and between red earth road (*R8*) and bare ground area (*BG19*). This is undoubtedly true, since grey roofs and tarmac roads were mixed in the classifications, especially in Mwatate and Wundanyi centre areas. In addition, the lowest error matrix accuracies were derived from the Mwatate subset classifications, and the very same area is generally dominated by the red latosoil type that is found widely on the fields, bare grounds areas and roads of this lowland area. The third poorest return is between light tarmac road *(R3)* and light grey roof *(BG14)*. Indeed, a number of light grey roofs – that are common in the Taita Hills region – and light tarmac roads were problematic in the classification process, especially in the pixel-based and Level 1 object-oriented classifications.

The results of the transformed divergence are overly optimistic in comparison with the classification results and the error matrices, since there is only two returns below 1700 and all in all, four below 1900 suggesting that the classes have excellent between-class separation in most cases. For instance, according to the transformed divergence results the Rock *(BG16)* background would have at least a good separation from all tarmac road surfaces *(R1-R5)*, although the former was classified as tarmac road in the digital classifications, particularly in certain areas of Wundanyi and Dembwa. Under these circumstances, the table only shows an indication based on one spectral signature per object class solely.

8.6 GENERATING AN UP-TO-DATE ROAD INFRASTRUCTURE DATA LAYER

The accuracy of the visually interpreted, digitised data is assumed to be very accurate, since the aerial image mosaic has high spatial resolution and most roads and even minor tracks and paths were clearly detectable. At the same time, a few clouds, forest canopy on the top of some roads and low contrast between roads and the background made the analysis more difficult in certain places. Generalisation was made during the digitisation and especially when defining the smallest roads, tracks and paths. Hence, all tracks and paths do not follow strictly their centre lines, but more or less their course anyway.

A proper class for a road was determined on the basis of the original map information. The map classification may be partly outdated and moreover, road maintenance activities may have upgraded a few roads to a superior class. Therefore, visual inspection was applied to the classification as well - that is a slightly subjective method sometimes. In addition, conditions of many roads are dependent on seasons and they may change substantially between rain and dry seasons. Thus, it was sometimes difficult to define the appropriate categories for the roads of fluctuating conditions.

8.7 FIELD SPECTROMETRY

Due to the quantitative, sensitive nature of the field spectrometry technique, there are different sources of errors that influence the accuracy of the measurements conducted in the field. In addition, the accuracy of the analysis may vary according to what type of reference data measurements are compared with: spectral libraries, multispectral or hyperspectral data. The accuracy of the field spectrometry was not assessed quantitatively in this context but considered in terms of possible sources of errors and general success. In addition, the accuracy is discussed with the existing spectral libraries and other literature in Chapter 9.

8.7.1 FIELD MEASUREMENTS

Collection of field spectra requires particular attention be paid to the characteristics of natural illumination. Varying lighting conditions, different geometry of the sun in relation to target, cloud cover and shadows affect the process and result in errors in the resultant spectra. Parameters such as solar elevation angle and atmospheric conditions influence the intensity of direct solar illumination, whereas objects and shadows in the surroundings obscure diffuse illumination (Curtiss & Goetz 1994). Moreover, other atmospheric conditions such as humidity in terms of the absorbing effect of water vapour, wind and temperature may change the spectra characteristics.

In addition to variable illumination and atmospheric conditions, there are other factors affecting the accuracy of the resultant spectra measured in the field. The angle and height at which the fore-optics are held in relation to the target surface as well as the target materials (e.g. surface temperature) have effects on the measurement procedure.

In this study, the field spectra were collected during six days at different times of days and from a wide variety of solar angles and positions. Mainly, the field spectrometry spectra were collected under the illumination conditions of clear, cloudless sky, without shadows from topography or other disturbing objects and from a constant height of approximately one meter. In addition, the device was calibrated at regular intervals, before each single set of measurement. Therefore, the general measurement conditions were considered to be rather good, although the measurements were done at different times of days. The accuracy of the measurements could have possibly been improved in the performance of half-day long measurements, which was not possible within the time limits of the field work period.

8.7.2 SYNTHESISING MEASUREMENTS WITH THE SPOT DATA

The comparison of the field spectra and remote sensing (RS) imagery is influenced by different principal factors: the accuracy of the field spectrometry described above, and the absolute radiometric calibration accuracy of the RS imagery. In addition, the general spectral and spatial resolution characteristics of the RS data affect the analysis results and accuracy. The HELM corrected SPOT data is expected to have reflectance accuracy of better than 2 % for all bands retrieved with an average RMSE (Clark & Pellikka 2005).

It should be noted that only 14 site measurements were analysed with corresponding image pixel reflectance values. Indeed, this is not an extensive analysis but it gives an indication of the feasibility of this methodology to analyse field spectra with RS imagery.

The timing of conducting field spectrometry is important as well when field spectra are used for further analysis with other sources of data, e.g. hyperspectral or multispectral data. Therefore, field spectra should be retrieved simultaneously with image acquisition, since the variability between the time the reference is obtained and the field targets measured may be a source of errors and result in inconsistencies between the datasets. In this study, the timing between the field spectra and SPOT image acquisition was nearly one and a half years, since the image data originated from October 15th 2003, and the field spectra from the end of January 2005. However, this is a secondary matter in case of road surfaces which should be rather spectrally stable over this time span. On the other hand, certain road maintenance operations may change reflectance characteristics of roads. For instance, gravelling or covering the old surface with new sand of different composition may influence even substantially to the reflectance values of roads.

Due to the 20 metre spatial resolution of the SPOT image, the pixel analysis is not assumed to be accurate. The corresponding locations with the field sites were traced on the SPOT image but, however, roads in the region are narrower than the 20 m spatial resolution of the imagery and thus, mixed pixels commonly occur on the imagery. The reflectance values at the road locations are not pure spectral values of roads but mixed with the response from the surrounding environment. In addition, in some cases the field site points were located on the edge of image pixels and thus it was not evident which pixel might be the proper road location pixel. In that case, the mean values of the two pixels were calculated but, however, the resultant reflectance value was then composed of impure spectral responses.

Beforehand, the accuracy of the synthesising procedure was supposed to be only indicative, since the spectral and particularly spatial resolution characteristics of the SPOT data are not sufficient for the accurate discrimination of roads based on their spectral reflectance values. Therefore, it was assumed that there would be variation between the two datasets.

9 DISCUSSION

In this chapter, the road infrastructure mapping is discussed on the grounds of the data, methodologies and analysis applied to this study. At the beginning, the purpose of the thesis is summarised here from the viewpoint of how successfully the five principal aims (see Section 1.2) were achieved. Thereafter, the possibilities, limits and applicability aspects are discussed more specifically with the attained results, accuracy assessment and previous research work.

(1) The present state of the road transport in Kenya and in the Taita Hills was described fairly well by reviewing it extensively with the literature, background information and the experiences gained during the field work. The extent of road network varies according to regions from sparse to extensive but the condition of the road infrastructure is generally poor. It may also be argued that incongruities and absence of varying statistical information and map data - especially in terms of unclassified rural roads – cause uncertainties and questionablenesses to the results. Within the limits of this study it was not possible to acquire more knowledge of wider perspective, or data of larger scale and of longer period.

(2) The meaning of the functional road transport in developing countries was defined clearly, but on a very general scale of Africa, SSA, Kenya and with more detail in the Taita Hills. Road transport is the dominant mode of transport, and in particular, rural roads and non-motorised means of transport are most essential in local scale. Since Kenya is one of the most developed nations in SSA and the Taita Hills is an unique, to some extent favourable region, all results and conclusions of this study are not valid for every developing country at varying phase of development.

(3) The possibilities of GIS and remote sensing (RS) in the road mapping of the Taita Hills were experimented, analysed and evaluated by different methods and data. Visual interpretation and digitisation of the aerial image mosaic was found the most accurate and best technique available. The object-oriented road extraction succeeded moderately - or even well in ideal circumstances without obfuscatory objects and with high contrast between roads and background - whereas the pixel-based method worked out worst of all tested approaches. Both digital approaches were seen inappropriate and too time-consuming to be further implemented to the road mapping.

As a consequence, *(4) the mapping and updating of the Taita Hills road infrastructure* were conducted by visual interpretation along with manual digitisation and road class definition. The road infrastructure mapping succeeded well and roads were detected and delineated accurately. Since visual interpretation is a subjective method which is practical to conduct with some degree of generalisation, inaccuracies may occur in road centreline locations and in road class definitions. In addition, the road mapping covers only extensively the area of the generated image mosaic, whereas the infrastructure of the surrounding regions were only modified with the attribute information but not spatially.

(5) *The strengths and weaknesses of the applied GIS and RS based methods in the more general context* are discussed later in this chapter. Similar to the fulfilment of the second aim (see above) and due to the geographical peculiarities of the Taita Hills region, the results of the applied methodology and data are not entirely valid for every other regions of the developing world. However, the results may give general guidelines for the road infrastructure mapping in the developing countries. To summarise, the focal strength of the visual analysis is its accurateness and simplicity, whereas the digital methods are still fairly weak and inaccurate, although the segmentation-based road extraction may have potential for accurate road infrastructure mapping in different context.

Next, the field spectrometry results are discussed with the existing information about the roads' spectral characteristics based on a few existing spectral libraries (Ben-Dor et al. 2001; Herold et al. 2004). Figures 65 and 66 present spectra of typical urban materials representing roads composed of different materials and/or having different conditions. It should be noted that the graphs of the figures have slightly different scales and units with each other and with the applied methods of this thesis due to their different origins. For instance, in the graphs of the Figure 65 the spectral range is wider than the FieldSpec® measurements have.

When comparing Figure 65 with the field spectra acquired in this study, it is noticed that the corresponding tarmac surfaces have similar reflectance with each other, the lowest overall values of all roads, and increasing reflectance with aging and/or poorer surface condition. The spectra of concrete surfaces differ more from each other, but this originates from different composition of concrete surfaces, and there was also a great variation between the two measured concrete field spectra (Sites 4 and 8). Concrete roads have generally high within-class variability, and moreover, aging and poorer condition of the concrete results in decreased reflectance (Noronha et al. 2002). The gravel roads of the study area have clearly higher reflectance compared to the spectral library spectrum (Figure 65). This may stem from the fact that the freshly maintained gravel roads of the Taita Hills are very light colour surfaces, in other words they are good reflectors. The composition may also differ from the construction material of the reference (spectral library) road.

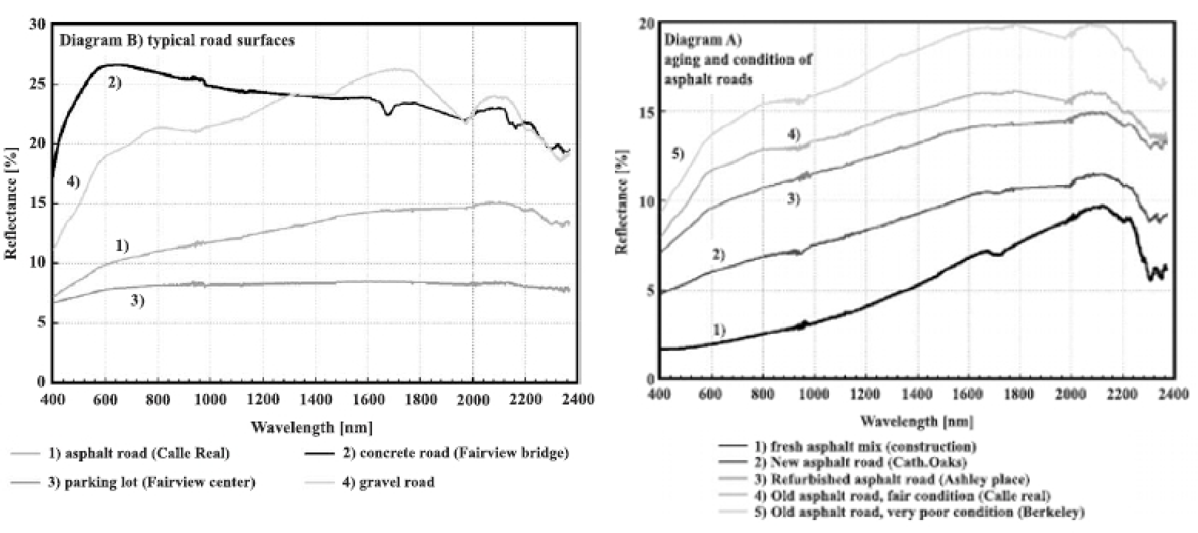


Figure 65. Spectra of typical road surfaces (left) and roads of different aging and condition (right) (Herold et al. 2004).

When comparing the earth roads' field spectra with the spectral libraries (Figure 66), it is noticed that the PUSH library reddish-brown soil surface spectrum (2757) matches fairly well with the field spectra of the various red-brown toned road surfaces. However, the field spectra values are at slightly higher level and with sharper increase of reflectance within the VIS green light region (0.50 – 0.60 µm). Furthermore, the field spectra are fairly similar with the CASILIB red-brown soil spectrum (25). In general, all spectra have typical soil spectrum shape: relatively low reflectance until the VIS green region from where it increases toward the red region. The relatively low reflectance of the red-brown colour earth roads compared with e.g. gravel roads of the Taita Hills stems from the composition of iron oxides and organic matter that give the dark colour for this soil as "colouring agents" (Ben-Dor et al. 2001).

On the basis of the field spectra and spectral libraries investigation, it can be summarised that road surfaces which have different composition, aging and conditions, show spectral reflectance variations within the VIS-NIR spectral regions , although there are no identifiable peaks which occur generally. In this spectrum region urban surfaces, such as roads, hold significant spectral fingerprints and this is likely to be sufficient for the discrimination of urban objects (Ben-Dor et al. 2001).

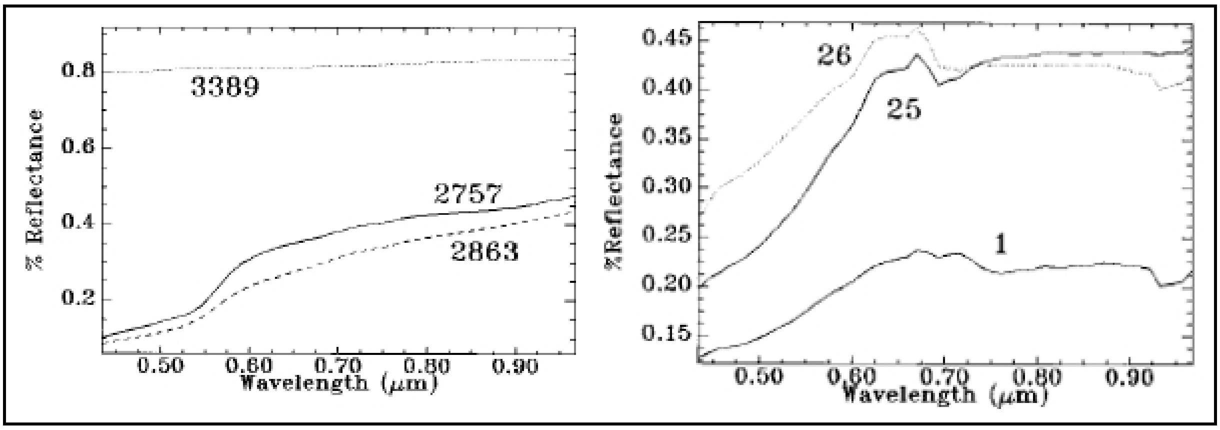


Figure 66. The PUSH spectral library (left) of reddish-brown soil (2863), and the CASILIB spectral library (right) of red-brown sandy soil (25) (Ben-Dor et al. 2001).

On the other hand, road surfaces have great variance in their spectral material separability and they may be confused them other land cover objects (Herold et al. 2004). Tarmac roads are spectrally similar to certain types of roof materials (Noronha et al. 2004). Furthermore, certain types of earth roads have similar spectral reflectance with bare soil surfaces. Current multispectral sensors are often limited to discriminate roads from their surrounding, since their spectral range does not entirely cover the locations of the optimal bands for urban mapping (Herold et al. 2004).

Indeed, when considering the analysed SPOT pixel reflectance values, it is found that roads and their surroundings have very similar reflectance values, which makes the discrimination of roads and other land cover hardly possible, particularly due to the coarse spatial resolution of the SPOT image and the resultant mixed pixels relative to the size of the roads. The higher spatial resolution may improve the separability of roads, but however, certain road types may still get mixed with the land cover having a similar spectral response in VIS-NIR region. The object-based classification results and the spectral signature separability test between selected road types background objects show that road surfaces are poorly separable from certain background features, especially from bare ground and roofs due to their very similar spectral characteristics. Hyperspectral data may have potential for very detailed road discrimination, but these data and techniques are still under development and not operationally applicable in developing countries.

Hence, both spectral and spatial resolution characteristics of data are essential for the road detection. It is considered that the spatial resolution of the RS imagery has the priority in the road detection. Although the SPOT imagery data is adequate for general land cover studies, it has major drawbacks in the road mapping of the Taita Hills, since roads - as linear objects – are narrower than the spatial resolution of the imagery. Mixed pixels occur frequently in the imagery and road pixels do not get pure but disturbed spectral values from their surroundings. Consequently, the amount of pixels representing pure reflectance values of roads is minimal in the imagery. In addition, tree canopies cause obstruction from the sensor direction, and bare ground similar to natural road construction materials result in low contrast between roads and their background. The very same difficulties may arise in the aerial imagery, but not at as high volume.

Pan-sharpened images are generally used for road mapping purposes, since they combine two essential elements required for detailed image interpretation. The colour information contained in the lower spatial resolution multispectral bands is merged with the geometrical information of the higher spatial resolution panchromatic band, and the result is a natural or false-colour pan-sharpened image having the spatial resolution of the panchromatic band.

The combination of the 10 metre panchromatic band and multispectral bands image, so-called pan-sharpened image would possibly improve the performance of road detection and their discrimination from the densely vegetated surrounding land cover. In case of the Taita Hills, the SPOT sensor was able to discriminate hardly any of the roads in the highland areas, not even the wider main roads. The spatial resolution of the SPOT image is, however, to some degree sufficient for general road mapping in sparsely vegetated territories such as in the lowland areas (e.g. Tsavo plains) of this particular SPOT scene. On the other hand, in these dryer regions roads may get mixed with bare ground. In addition to the SPOT sensor, Landsat 7 ETM+ has potential for general road detection purposes in developing countries, if its panchromatic band of 15 m spatial resolution is involved to the image analysis. Both sensors can offer relatively cost-effective data which are even obtainable in developing countries.

Alternatively, aerial image mosaics data have major benefits in road mapping due to their outstanding discrimination capabilities and high spatial resolution characteristics. The applied aerial image mosaic achieved the general requirements of at least 5 metre spatial resolution for urban mapping (Jensen & Cowen 1999). On the other hand, generating of an image mosaic may be a laborious and time-consuming process, as it was in case of the Taita Hills mosaic. Hence, it may be argued that it is not a cost-effective approach for general road mapping purposes in developing world. Besides, road mapping and updating is usually needed and implemented at large-scale business covering large territories and requiring extensive coverage of datasets. Therefore, very high spatial resolution satellite sensor, such as IKONOS or QuickBird would be suitable for these road mapping purposes, although the imagery are yet too expensive to be used other than in developed countries. On the other hand, Gianinetto (et al. 2004) emphasise that such imagery may offer a sustainable approach for mapping in developing countries. For small-scale purposes aerial image mosaics are generally the most practicable data source.

In this study, the applied corrections and the mosaicking succeeded reasonably well, and the output mosaic is practicable for various purposes. The generated aerial image mosaic is consistent, geometrically accurate and spectrally at least of moderate quality, which was considered sufficient for the road detection purposes. In particular, the mosaic is feasible for visual examination of various land use and land cover themes that are important in the Taita Hills region. One key benefit of the mosaic is its large extent which offers possibilities for relatively large-scale examination of the region. At the same time, the high spatial resolution and adequate spectral resolution make possible accurate image interpretation tasks. However, the absence of NIR-band is one disadvantage especially for detailed forest studies (Lanne 2007). In addition, NIR band is successful in the discrimination of man-made features and vegetation (Zhang & Couloigner 2006). The SPOT image involves the NIR band but for road detection the spatial resolution of the data was too coarse to benefit from the presence of the NIR band.

On the other hand, the mosaic may be considered to have overly radiometric inaccuracies for digital analyses and to be of too large extent for effective use in GIS. More specific correction parameters for each band and individual “raw” image and for every land cover type and for that particular region would have been needed to attain better results in the pre-processing. In addition, mosaicking procedure could have been implemented by creating several small-sized mosaics but then the joining of these smaller “sub-mosaics” together may have been problematic. Hence, generating one extensive image mosaic with relatively general correction parameters was seen the most practicable solution within the limits and for the aims of this study.

On the grounds of the experience gained in this thesis, it can be stated that visual interpretation with manual digitisation and classification is still the most accurate, reliable and expeditious procedure to conduct a feasible road mapping and to create practical output data for the use in GIS. The visual analysis succeeded well and most roads in the mosaic area were mapped and classified accurately and according to various criteria. On the contrary, the applied digital classifications did not succeed as well, and it was possible to classify roads only based on their surface type. The purely pixel-based classification was rather rapid to implement but the results were poor, particularly in terms of having plenty of commission errors and the vector output was impracticable and of poor quality too.

The object-oriented approach of *eCognition* was expected to have potential for more accurate detection of roads with the following road centreline extraction, conversion to practicable vector format and further completion by manual editing. In practice, the success was not that good and the initial concept had to be abandoned. Visual analysis and digitisation are generally considered as laborious, outdated techniques, but then *eCognition's* segmentation-based classification procedure is highly user-dependent and a time consuming task to implement without any prior knowledge of the software. It can be argued whether this procedure is automatic or semiautomatic, and more significantly, is it feasible to apply it to road mapping, if the traditional methods can be conducted more rapidly and with higher accuracy.

Ultimately, it was possible to implement the fuzzy classification of *eCognition* with the membership functions so that the derived classification results were at least of moderate quality. The shape properties of the software were used to define road objects in the classification procedure and it succeeded at least to some degree. However, there were still a plenty of commission errors in the road categories, especially in the earth road class that was mixed with bare ground surfaces. In addition, buildings were mixed with the tarmac road class and smaller roads and paths were omitted to non-road category.

Several studies underline the advantages of an object-oriented approach in road detection. Caprioli & Tarantino (2001) achieved overall accuracy over 90 % applying *eCognition's* nearest neighbourhood classifier to very high resolution Quickbird multispectral imagery. Compared with the results of this study, the former seem overly optimistic. They were attained in a small test area of flat terrain, no disturbance of shadows, tree canopy, etc.

However, similarly with the results of this thesis, tarmac roads got mixed with roofs and earth roads with arable land.

According to Hoffmann (2001b) there are several segmentation and classification possibilities for road detection in *eCognition*: pan-sharpening of IKONOS data enhances initial segmentation output by emphasising important boundaries, DEM improves urban area mapping, and shape properties can describe road objects in the classification. The last mentioned concept was attempted to exploit in this thesis. Various shape properties were used to determine elongated road objects of the segmentation output but these criteria – or spectral properties either - were not able to discriminate roads from other categories sufficiently. The initial problem in the whole procedure was that there were also elongated segments generated in the non-road class representing such objects as buildings and bare ground. Therefore, shape criteria could not be used effectively to describe and differentiate road classes. Spectral properties were not able to distinguish all road segments either since they had similar composition and/or spectral characteristics with other features.

Repaka & Truax (2004) compared various spectral and object-based classification methods for road mapping from high resolution multispectral imagery. Similarly with the results of this study, they found that the use of membership functions improves the classification result from purely pixel-based supervised classification, and from object-based nearest neighbourhood (NN) classifier. In this study, the results of the maximum likelihood classification and the standard NN classification were fairly similar and of poor quality, but the Level 2 classification results with membership functions showed obvious improvement from the first two classifications. However, plenty of narrower earth roads were still omitted to non-road class and non-road objects were also misclassified as roads.

The road centreline extraction through generating skeletons in *eCognition* is a practicable technique to convert raster data to vector format. Since the classification results were of fairly poor quality, the centreline extraction did not succeed well. In places, the extraction succeeded moderately, mainly in terms of tarmac roads and wider earth roads, whereas only a minority of narrow earth roads were extracted. It may be argued that although the vectorisation process itself is a fairly simple technique to implement, it is highly dependent on the classification results and it should not be perceived as a fully automated process. In context of the heterogeneous land use and land cover of the Taita Hills, the vectorisation output was rather useless, and much effort would have been needed to complete the vectorised skeleton layer into a feasible condition.

It would be interesting to experiment with *eCognition's* capabilities in a different context and compare the results with the results of this study. The auxiliary data layers and/or spectral bands would possibly improve classification results and moreover, a study area of different land use, land cover and road characteristics could bring about totally different segmentation, classification and vectorisation outputs and provide significant benefits in terms of saving time and effort in road mapping. In the context of this thesis, object-oriented approach was much slower to implement than visual analysis and digitisation.

The special characteristics of the study area and the spatial and spectral resolution properties of the applied data determine the methods suitable for the road mapping of the Taita Hills. First of all, a majority of roads are earth roads composed of natural materials similar to other land use areas, such as bare ground and sparsely vegetated fields, whereas only a minority of all roads are tarmac ones – that were better separated in the digital analyses. Roads are generally narrow and most of them are either small tracks or paths running among the fields and vegetation and on the slopes of the hills. Secondly, the Taita Hills have generally very heterogeneous land use, abundant vegetation in the highlands and bare ground areas on the lowlands. These facts make the separation of roads extremely difficult in the digital analysis, since there is wide variation of both roads' and their surroundings' spectral characteristics, low contrast occurred between certain road types and their adjacent land use, and narrow tracks and paths are shadowed and/or covered by tree canopy and vegetation. Thirdly, although the spatial resolution of the applied aerial image mosaic is very high, the spectral resolution is not sufficient for accurate road extraction conducted by digital methods.

As a consequence, the road infrastructure mapping of the Taita Hills was achieved with the visual interpretation, digitisation and classification that was the most reliable and rapid procedure to generate practicable road data of the region. Although the method is slightly subjective, the generated road data is considered to be very accurate, up-do-date and less generalised than the former dataset based on the generalised, partly outdated maps.

As described in Section 7.5, there are evident changes in the extent of the road networks between the two dates (1991 and 2004) data. There are plenty more tracks and footpaths and the road network is generally denser in the 2004 map. The road network is much denser in the highlands – the mosaic region – than in the surroundings. With the applied data, however, it is not possible to make definite conclusions on the real changes of the road infrastructure, since the changes stem from different reasons. On the one hand, real changes may have occurred, that is to say new roads constructed or paths formed. In the Taita Hills, the road network has extended in all likelihood, and it may be assumed that especially unclassified roads, tracks and paths have increased due to the growth and dispersion of the population during the last decades. On the other hand, the aerial photography (1988 – 1989) source data of the *Kenya 1:50 000 Topographic Map* had probably lower resolutions and poorer quality than the current digital image mosaic has. Moreover, different degree of generalisations made during the topographic map creation and in this study may have had substantial influence on the differences occurred in the output maps. It should also be noted that the surroundings of the image mosaic region were not mapped or updated otherwise than adding the road administering and surface type attribute information to the data.

In general, The Taita Hills have an extensive road infrastructure due to its peculiarities in geography and history, especially the favourable location, rich natural resources and abundant population. These facts have substantially influenced the development of the region and formed the present state of the road infrastructure. Moreover, road transport has different means and dimensions in the region, and this emphasises the importance of the functional road transport in the Taita Hills.

It can be stated that the road transport of the Taita Hills have better prerequisites for success than have many other regions in Kenya and in other developing countries. Principally, this stems from the peculiarities mentioned above. At the same time, the special features of the Taita Hills – particularly physical geography and the heavy growth and dispersion of population – make the road construction, maintenance and development operations very challenging as well.

Generally speaking, the road transport and the road infrastructure of the Taita Hills are in many ways similar to other *rural* areas of Kenya and other developing countries despite the influences of geography and other special features of the region. Several issues, that are valid for this case, may also be applied to more general context in the developing world.

First of all, the majority of the road network is unclassified rural roads and tracks that form the base of local transport connections, provide framework for access and daily life operations and are the most important transport services in the rural areas of the developing countries. A minority of all roads are classified trunk roads and other classified roads. In case of the Taita Hills, however, there are also several important classified road connections that provide transport services at different dimensions (Chapter 3.2). Therefore, it can be argued whether the Taita Hills is entirely a typical region to describe road transport patterns generally in the developing world.

Secondly, road transport contributes most of all transport in the Taita Hills, and in particular, non-motorised modes of transport and certain public transport modes are the most important transport activities in the region. On the contrary, private cars are few in number and motorised road transport occurs to a substantially lesser degree than the various non-motorised transport means.

Thirdly, although the extent of road networks may vary greatly in different territories and regions or even within the divisions or areas of one region, the condition of road infrastructure is generally poor. In particular, the rural roads of the unclassified road network are of poor quality. Roads are even occasionally impassable by motor vehicles, which hinders, for example, access to basic services, trade and tourism. Consequently, the poor quality of road infrastructure is considered as a major drawback for effective transport connections and for social and economic development in the developing countries. The poor quality of roads is caused by different factors. Most of the road infrastructure is unpaved earth roads that are vulnerable to soil erosion, heavy rains and heavy traffic. On the contrary, only a minority of the total infrastructure is paved tarmac roads that are generally less vulnerable to damage and are more durable. The maintenance of earth roads is an inadequate level, since these roads do not usually take the first priory in the road sector policies and thus lack periodic maintenance operations. Moreover, geographical features such as topography, heavy rains, degradation of roads adjacent vegetation and increase of population and transport induce and increase the problem, and consequently, plenty of earth roads are deteriorated seasonally and in places.

On the other hand, there were several maintenance operations planned, implemented or completed in the Taita Hills region during the research period. Various road administering agencies from national to district level actors and foreign parties were involved in the maintenance and improvement operations that mainly focused on the international and secondary roads. Less road maintenance operations were conducted on the classified minor roads and unclassified rural roads of the Taita Hills. In general, these roads have been neglected in the road maintenance operations whereas national and regional transport connections have been improved more regularly.

According to the results of this study, the unclassified rural roads are neither located and mapped accurately, since most of them were lacking from the topographic maps which were the source of the former vector data layer. The mapping of the Taita Hills road infrastructure demonstrated that although most of the main roads were actually present and even located fairly accurately in these former datasets, the unclassified rural roads were missing in many cases. This was due to different reasons, such as due to a real change occurred (a new road), poor quality of the aerial photography conducted for the topographic maps, or a high degree of generalisation from that aerial photography data. Regardless of reasons, it can be summarised that efficient methods are needed particularly for the mapping of unclassified rural roads in the developing countries. The comprehensive mapping of these roads would contribute to more effective management of the road sector, as the resources could then be allocated with more knowledge about the overall extent and condition of the road infrastructure including unclassified roads. The methods have to be simple and cost-effective and the data must have sufficient spatial and spectral resolution characteristics for the detection of these narrow, earth surface roads. Therefore, either very high spatial resolution satellite imagery or aerial image mosaics are required to implement accurate, up-to-date road mapping in the developing countries.

10 CONCLUSIONS

This Master's Thesis has reviewed the present state and significance of road transport and road infrastructure in Sub-Saharan Africa, with an emphasis on Kenya and the Taita Hills region in particular. This Thesis has discussed the possibilities of remote sensing (RS) techniques and applicability of geographical information systems (GIS) in mapping of roads of for developing countries. The road transport and infrastructure of Kenya were studied on a general scale. Subsequently, the Taita Hills region was studied with more detail. The road infrastructure mapping was performed specifically in the Taita Hills region. This was carried out applying RS and GIS based methodology including existing map data, all the while considering possibilities and limits of the applied data and methods in more general context – applicability of road mapping in developing countries.

In order to perform practical road infrastructure mapping, various data types and formats along with different methods were experimented, evaluated and compared with each other. The best available and applicable data along with methods were then selected for the actual road infrastructure mapping process. In addition, the spectral reflectance characteristics of various road surfaces were considered and scrutinised.

A high resolution digital image mosaic of the study area was generated with the appropriate radiometric and geometric corrections for the purpose of road infrastructure mapping. In addition, a SPOT 2003 satellite image was applied to the examination. Three image subsets were derived from the original image mosaic for trial procedures of the various image analysis techniques. The corresponding subset areas were interpreted visually from the SPOT image. The aerial image subsets were analysed by applying three different methods: visual interpretation including manual delineation, pixel-based supervised classification, and two different object-oriented supervised classification methods. The object-oriented raster classification results were processed further by a automatic conversion technique that transforms the appropriate pixels to skeletons representing road centrelines. Finally, the accuracy of the digital classification results and the skeleton outputs were assessed by various means.

Out of all the tested methods the visual interpretation coupled with manual digitisation and classification was concluded to be the most accurate, straightforward and rapid technique for road extraction. The poorest results were attained by the pixel-based classifications and by the object-oriented nearest neighbourhood classification methods. Both of these methods had a substantial amount of commission errors in both predefined road classes. When applying membership functions, the results of the object-oriented classifications were substantially improved at moderate level, particularly in case of tarmac road class.

The road centreline skeletons derived from the latter object-oriented classification in automatic vectorisation were of varying quality depending on the road class and subset area. While centrelines of the tarmac roads were represented fairly well by the skeletons, the earth road skeletons were of poorer quality.

The actual road infrastructure mapping of the Taita Hills was performed by applying visual interpretation and manual digitisation. All roads were delineated on the image mosaic area given various attribute information to categorise them according to map classes, administrating classes and surface types. In particular, plenty of “new” unclassified rural roads were digitised when compared with the old map and vector data.

The spectral reflectance characteristics of roads were investigated through the field spectrometry measurements, the synthesised SPOT reflectance response and a few existing spectral libraries of the reference literature. It was considered that roads of different composition, aging and conditions have great spectral reflectance variations within the VIS-NIR spectral region. In addition, it was noted that certain road surfaces within the Taita Hills region have similar spectral characteristics to their surroundings.

To summarise, road infrastructure mapping in the Taita Hills region - generalised along with the results of this study - in developing countries is a considerably challenging endeavour. These challenges area highlighted by issues such as the need for either high or very high resolution data and simple, cost-effective methods and the lack of reliable updated road infrastructure reference maps. Adding to these challenges is the fact that a majority of roads is narrow roads or paths composed of natural materials, which are easily mixed with other land use or land cover types with similar spectral characteristics. In addition, shadows and disturbance caused by rich vegetation cover creates difficulties in detecting roads from remotely sensed imagery.

In particular, unclassified rural roads and other minor roads, tracks and paths of rural areas have not been mapped accurately yet, and there is a need for effective road infrastructure mapping. Extensive mapping and accurate information would possibly contribute more funds and priority for the management of unclassified road network. Therefore, appropriate data and reliable methods are needed for a successful road infrastructure mapping schema for the developing countries.

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I would say that this thesis has taken such a long time in my life, continuing from the end of the year 2003 until this moment, May 2007. This incredibly extensive, but also rewarding, process period of studying, thinking, hesitating, performing, disappointing, asking, learning, discovering, succeeding and revising is nearly completed now. I must say that I am more than relieved – and grateful to many people who have made this possible with their invaluable encouragement, support, patience and knowledge during these *years*.

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APPENDICES

APPENDIX 1


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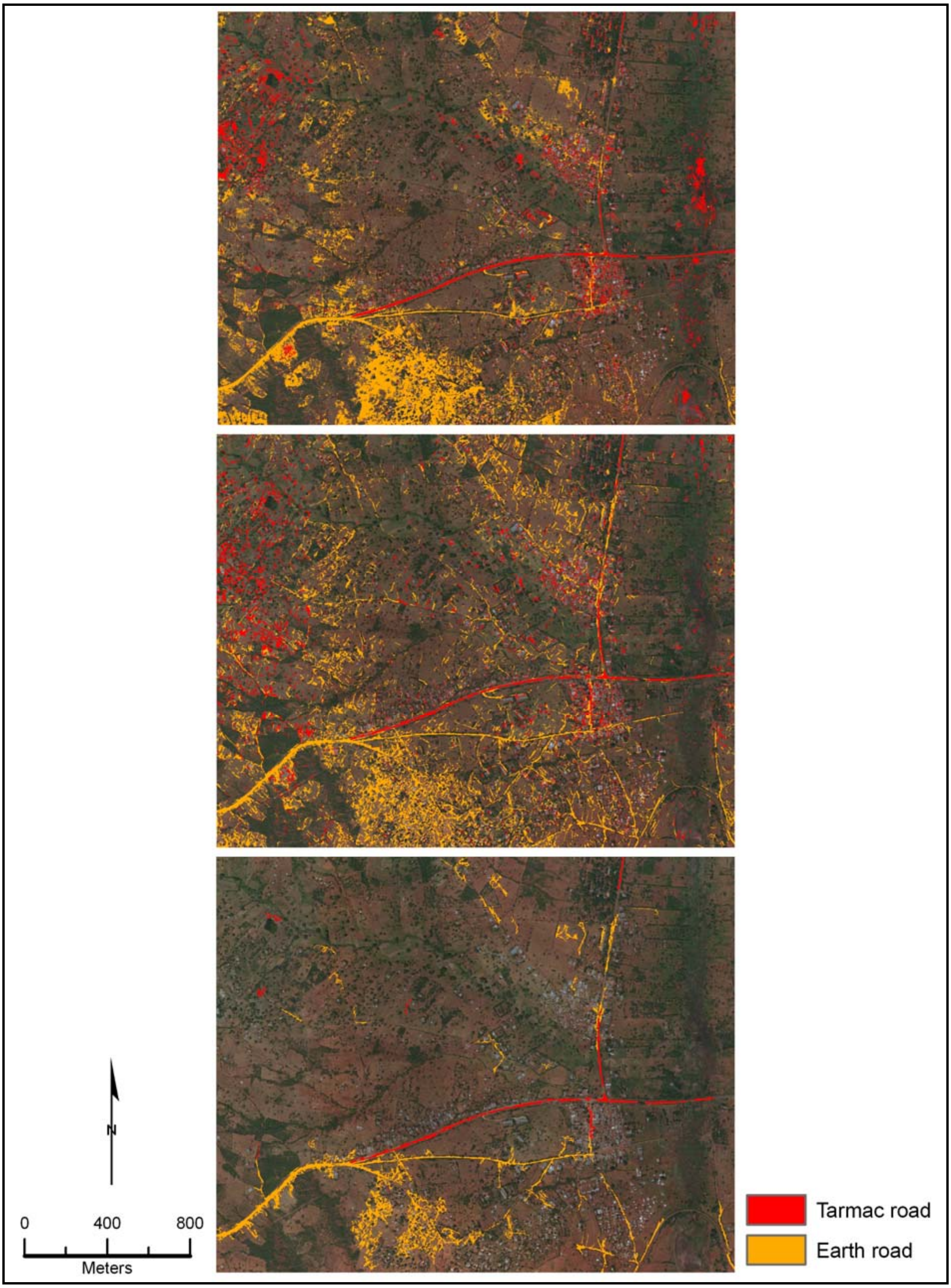
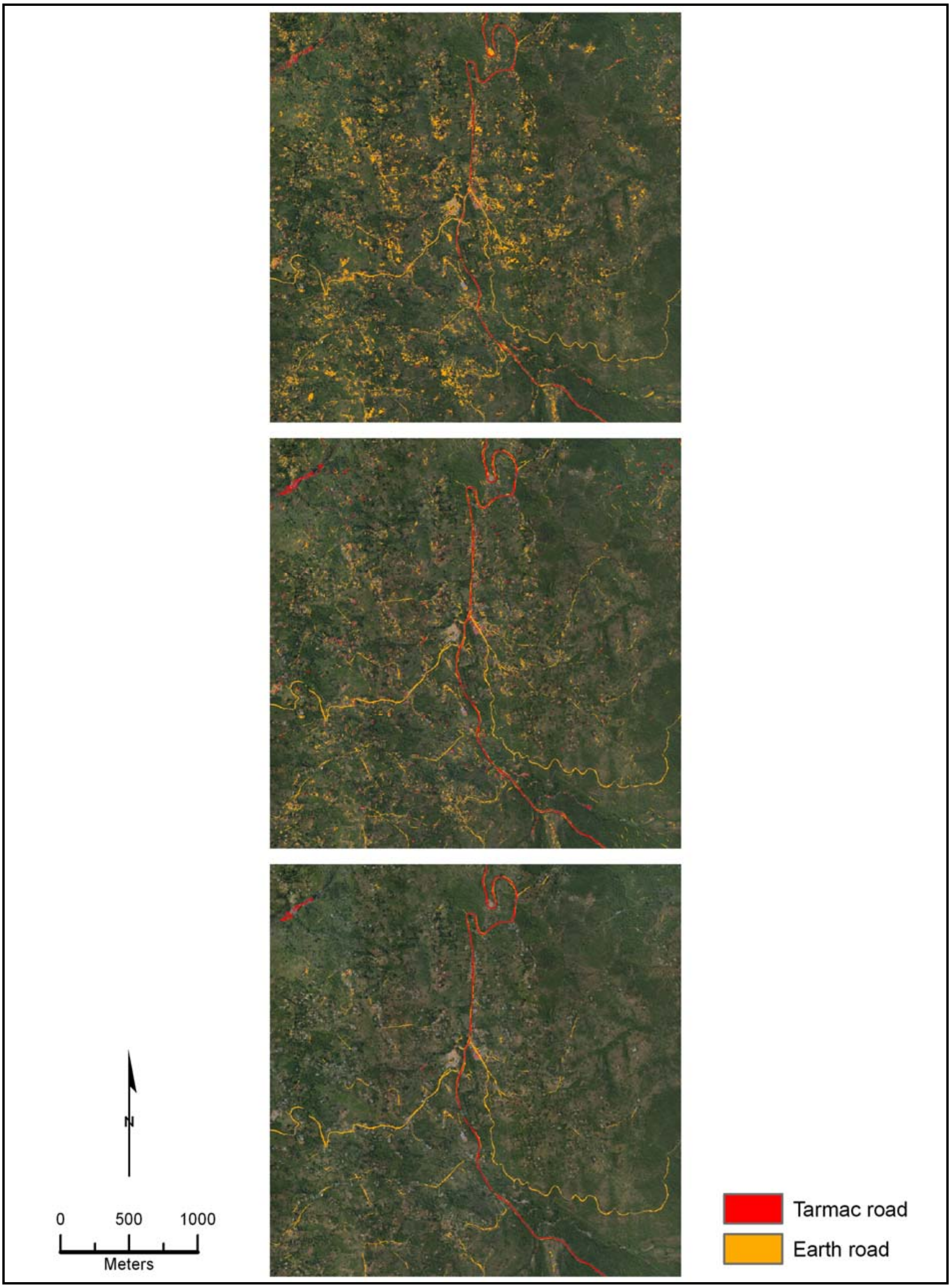
Appendix 1. The field spectrometry sites in the Taita Hills region.

APPENDIX 2



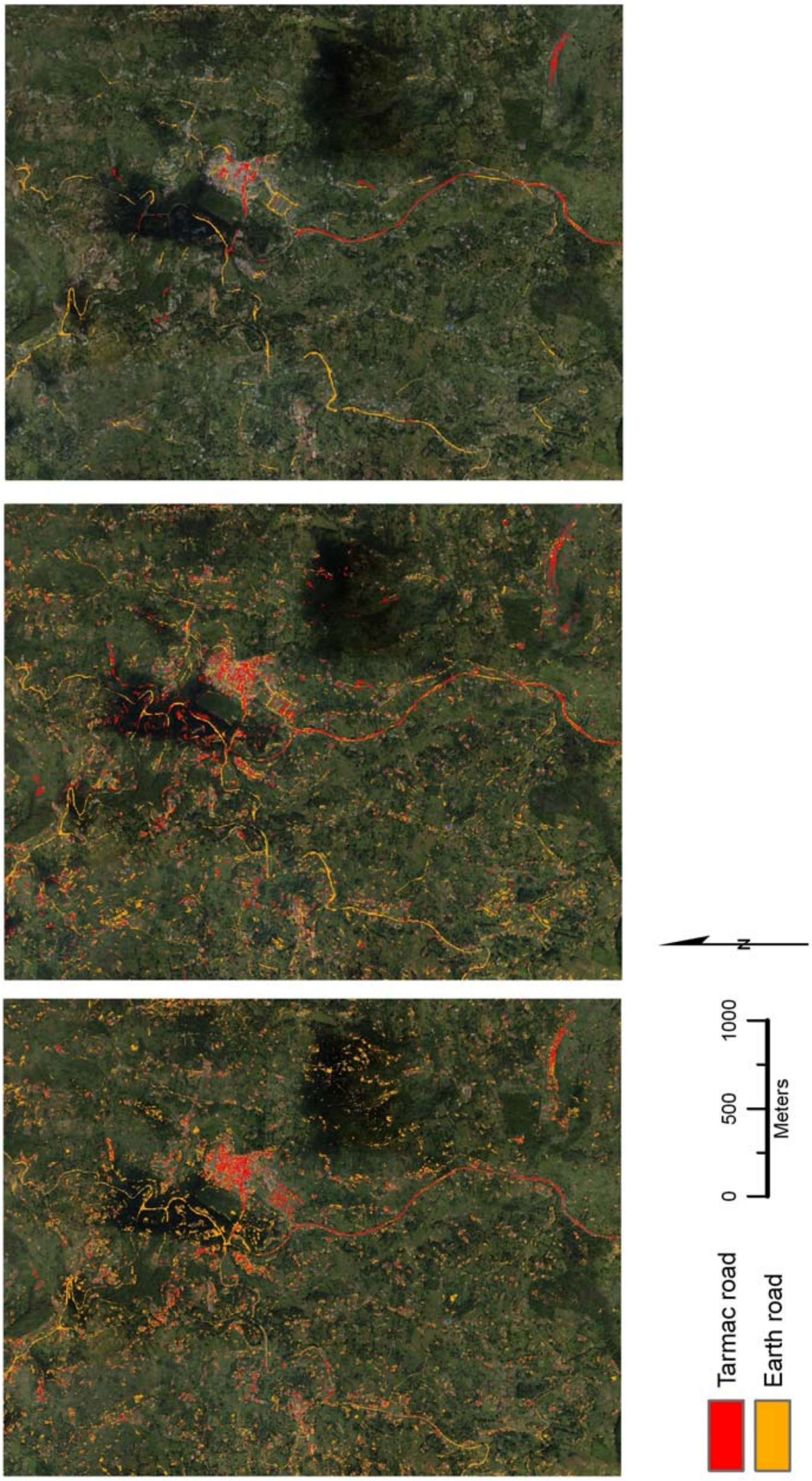
Appendix 2. The pixel based classification (top), the Level 1 object-oriented classification (middle) and the Level 2 object-oriented classification (bottom) of Mwatate.

APPENDIX 3



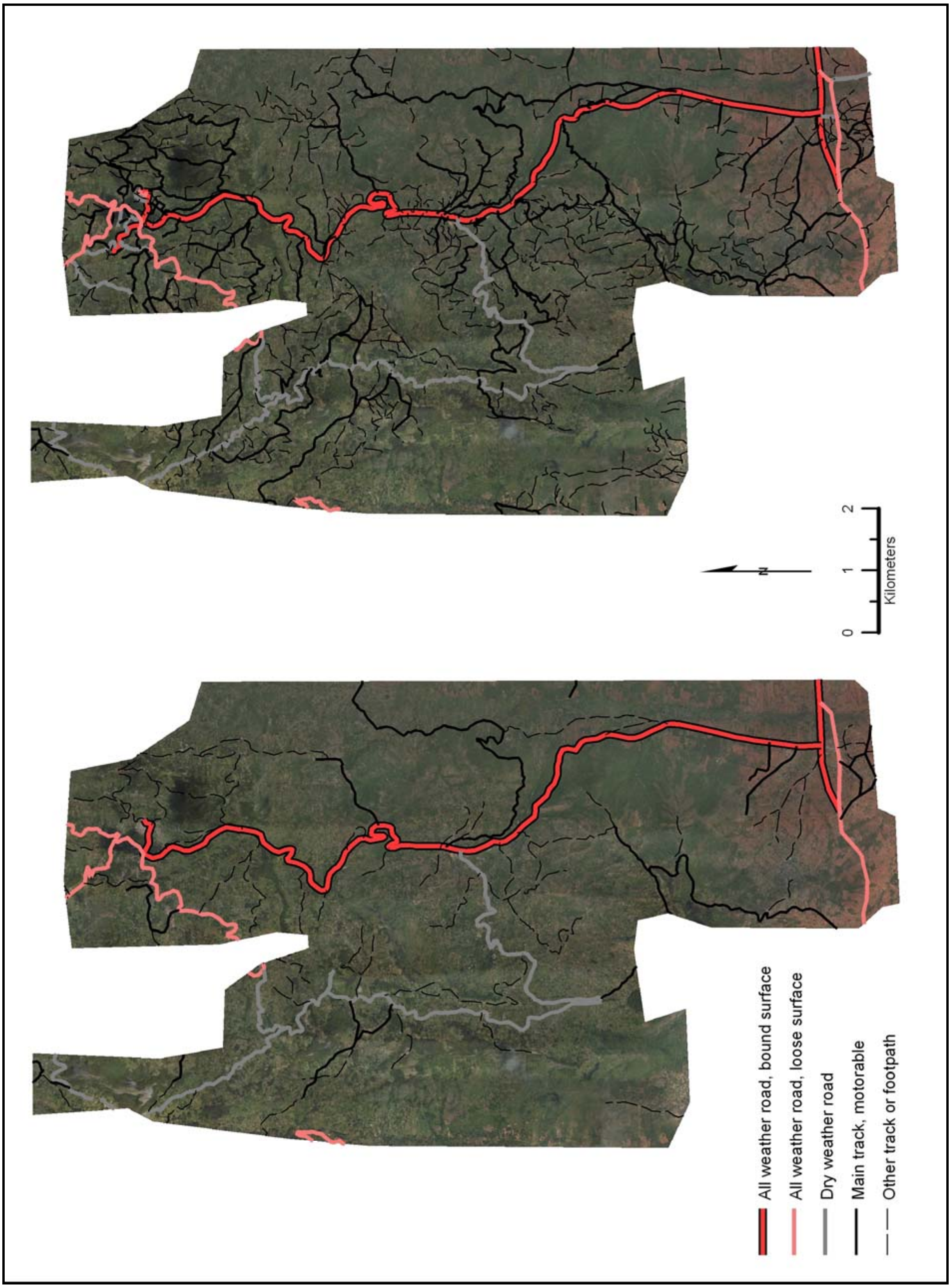
Appendix 3. The pixel based classification (top), the Level 1 object-oriented classification (middle) and the Level 2 object-oriented classification (bottom) of Dembwa.

APPENDIX 4

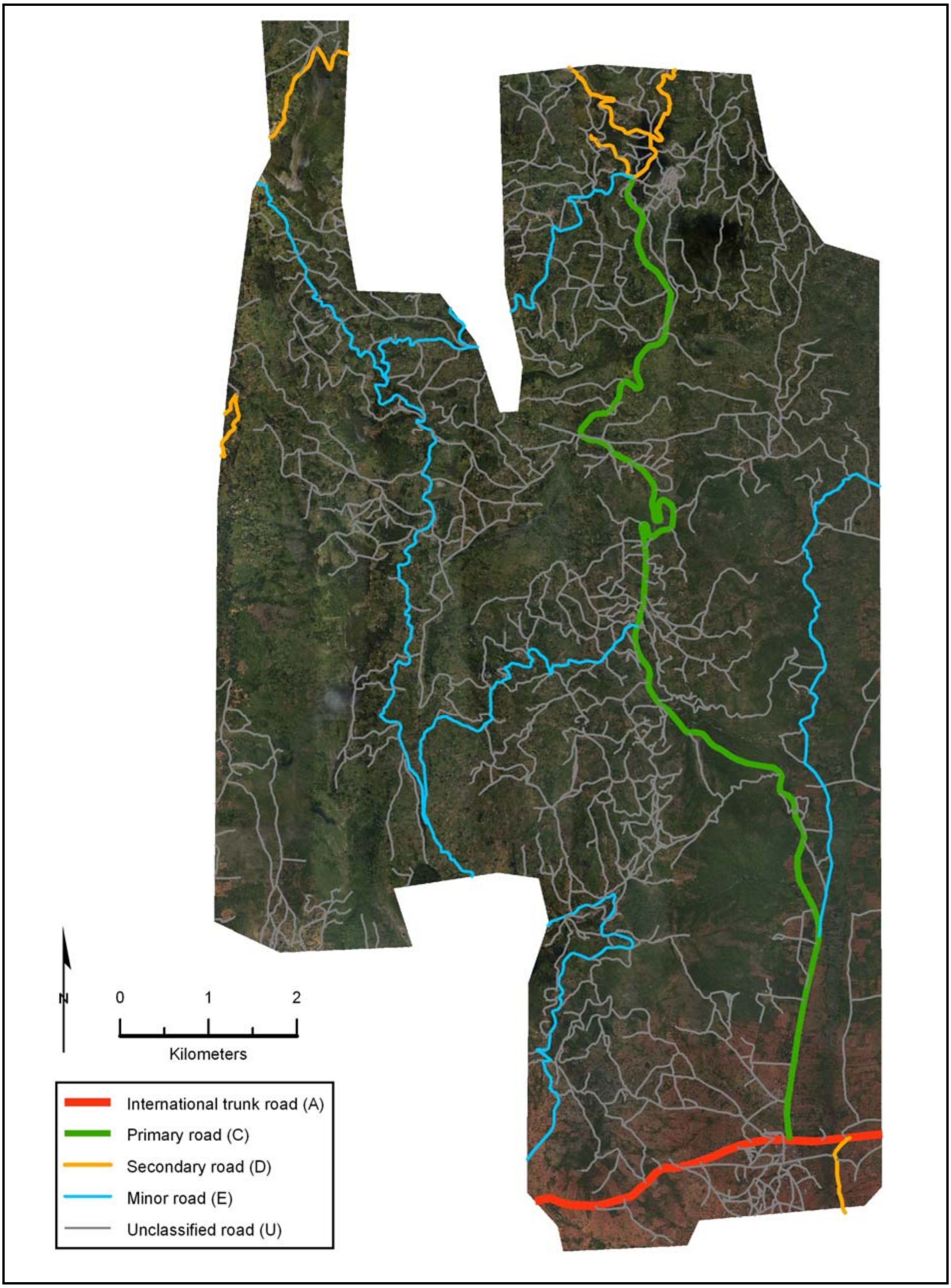


Appendix 4. The pixel based classification (left), the Level 1 object-oriented classification (middle) and the Level 2 object-oriented classification (right) of Wundanyi.

APPENDIX 5



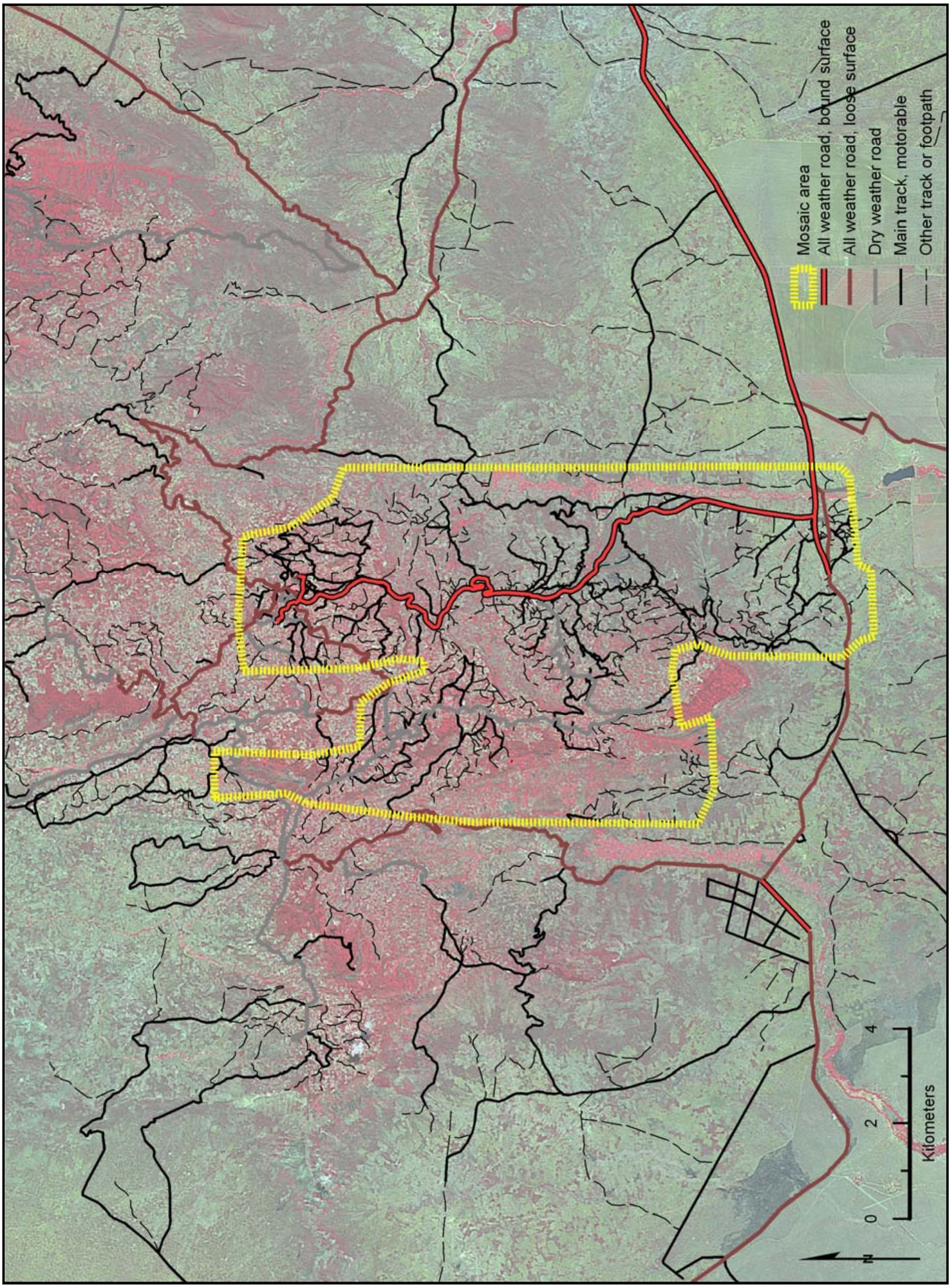
Appendix 5. The road infrastructure of the Taita Hills by the topographic map classification in 1991 (left) and 2004 (right).



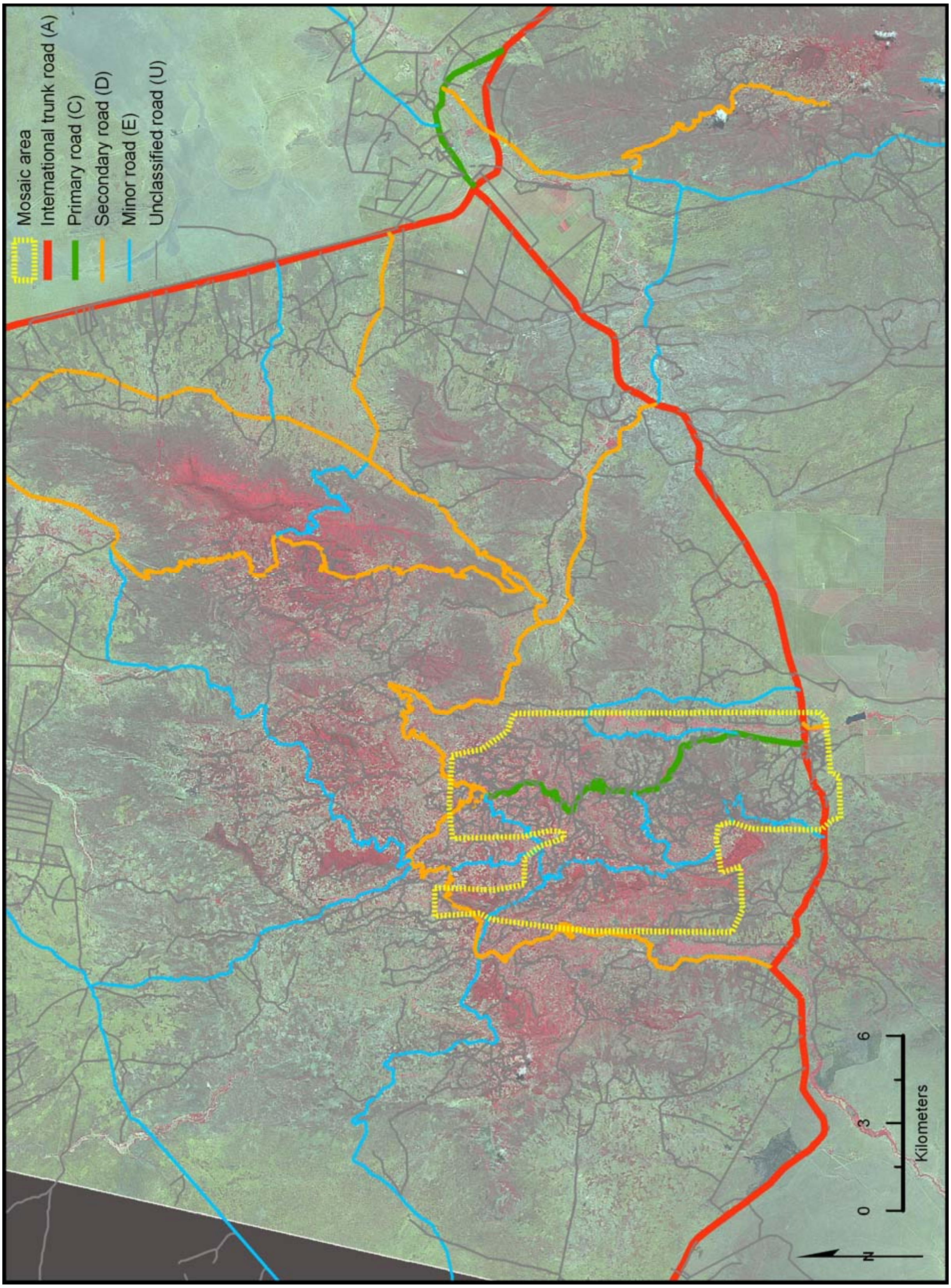
Appendix 6. The road infrastructure of the Taita Hills by the administering classification in 2004.

Appendix 7. The road infrastructure of the Taita Hills by the surface type in 2004.

APPENDIX 8



Appendix 8. The road infrastructure of the Taita Hills and the surrounding regions by the topographic map classification. The SPOT 2003 image is shown in the background.



Appendix 9. The road infrastructure of the Taita Hills and the surrounding regions by the administering classification. The SPOT 2003 image is shown in the background.

APPENDIX 10

Site 1

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	12.6525	1.08540891	11.885	13.42	**Band 1**	10.9241
Band 2	20.644	1.55280649	19.546	21.742	**Band 2**	20.6940
Band 3	31.9925	2.1899097	30.444	33.541	**Band 3**	26.7594

Site 2

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	9.9875	0.00212132	9.986	9.989	**Band 1**	6.7506
Band 2	16.485	0.00424264	16.482	16.488	**Band 2**	14.4154
Band 3	29.184	0.32244069	28.956	29.412	**Band 3**	18.3850

Site 3

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	11.3915	1.52522933	10.313	12.47	**Band 1**	43.1160
Band 2	18.184	3.40684047	15.775	20.593	**Band 2**	54.8444
Band 3	31.9225	2.8362053	33.928	29.917	**Band 3**	62.1026

Site 4

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	18.143	2.40557727	16.442	19.844	**Band 1**	40.8286
Band 2	27.155	0.54022958	26.773	27.537	**Band 2**	51.8467
Band 3	35.6135	2.54346309	33.815	37.412	**Band 3**	58.6595

Site 5

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	10.595	0.271529	10.403	10.787	**Band 1**	0.2355
Band 2	13.304	1.09318708	12.531	14.077	**Band 2**	0.2177
Band 3	24.308	0.19233304	24.444	24.172	**Band 3**	0.3714

Site 6

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	10.1835	0.20293965	10.04	10.327	**Band 1**	13.6294
Band 2	14.7065	0.50275292	14.351	15.062	**Band 2**	23.4042
Band 3	25.9545	0.03747666	25.981	25.928	**Band 3**	30.8806

Site 7

SPOT 2003 Image Pixel Values					Synthesised SPOT Reflectance Response	
	Mean	**Std**	**Min**	**Max**		
Band 1	28.435	3.24703434	26.139	30.731	**Band 1**	37.3974
Band 2	36.603	2.32638131	34.958	38.248	**Band 2**	45.0722
Band 3	39.1035	4.0665711	36.228	41.979	**Band 3**	49.3313

Appendix 10. Comparison of the SPOT 2003 image pixel reflectance values and the synthesised SPOT reflectance response of the field spectrometry measurements, Sites 1 – 7.

APPENDIX 11

Site 8

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	14.8045	2.44163972	13.078	16.531	**Band 1**	18.7800
Band 2	17.9605	3.67624816	15.361	20.56	**Band 2**	23.3028
Band 3	34.061	1.41421356	33.061	35.061	**Band 3**	25.8199

Site 9

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	14.939	2.25567063	13.344	16.534	**Band 1**	20.5618
Band 2	16.886	5.32027142	13.124	20.648	**Band 2**	26.7273
Band 3	35.471	2.41123412	33.766	37.176	**Band 3**	35.7223

Site 10

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	13.508	0			**Band 1**	23.5928
Band 2	15.885	0			**Band 2**	32.7120
Band 3	35.596	0			**Band 3**	38.2058

Site 11

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	10.3485	0.43345646	10.042	10.655	**Band 1**	9.4712
Band 2	19.4065	1.32582521	18.469	20.344	**Band 2**	22.8461
Band 3	28.9415	0.34011836	28.701	29.182	**Band 3**	29.9624

Site 12

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	15.1825	0.00070711	15.182	15.183	**Band 1**	10.6859
Band 2	21.1955	0.5211377	20.827	21.564	**Band 2**	12.4840
Band 3	28.8545	1.25935718	27.964	29.745	**Band 3**	12.8935

Site 13

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	13.678	0.43557778	13.37	13.986	**Band 1**	10.5944
Band 2	16.6545	0.2609224	16.839	16.47	**Band 2**	11.8199
Band 3	24.032	0	24.032	24.032	**Band 3**	12.3623

Site 14

SPOT 2003 Image Pixel Values					**Synthesised SPOT Reflectance Response**	
	Mean	**Std**	**Min**	**Max**		
Band 1	11.793	0			**Band 1**	8.5291
Band 2	20.442	0			**Band 2**	9.9245
Band 3	28.388	0			**Band 3**	10.1246

Appendix 11. Comparison of the SPOT 2003 image pixel reflectance values and the synthesised SPOT reflectance response of the field spectrometry measurements, Sites 8 – 14.

APPENDIX 12

Site 1 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 1 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	12.653	1.085	11.885	13.420	**Band 1**	14.345	12.198
Band 2	20.644	1.553	19.546	21.742	**Band 2**	21.723	20.699
Band 3	31.993	2.190	30.444	33.541	**Band 3**	36.665	29.608

Site 2 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 2 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	9.988	0.002	9.986	9.989	**Band 1**	9.983	10.300
Band 2	16.485	0.004	16.482	16.488	**Band 2**	16.477	16.124
Band 3	29.184	0.322	28.956	29.412	**Band 3**	28.948	28.976

Site 3 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 3 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	11.392	1.525	10.313	12.470	**Band 1**	10.619	14.632
Band 2	18.184	3.407	15.775	20.593	**Band 2**	14.292	18.363
Band 3	31.923	2.836	33.928	29.917	**Band 3**	27.216	30.344

Site 4 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 4 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	18.143	2.406	16.442	19.844	**Band 1**	11.206	16.143
Band 2	27.155	0.540	26.773	27.537	**Band 2**	18.300	20.157
Band 3	35.614	2.543	33.815	37.412	**Band 3**	30.254	33.394

Site 5 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 5 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	10.595	0.272	10.403	10.787	**Band 1**	7.801	10.080
Band 2	13.304	1.093	12.531	14.077	**Band 2**	10.171	13.584
Band 3	24.308	0.192	24.444	24.172	**Band 3**	21.739	24.826

Site 6 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 6 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	10.184	0.203	10.040	10.327	**Band 1**	8.836	12.467
Band 2	14.707	0.503	14.351	15.062	**Band 2**	12.178	16.878
Band 3	25.955	0.037	25.981	25.928	**Band 3**	25.191	28.101

Site 7 SPOT 2003 Image Pixel Values	Mean	Std	Min	Max	Site 7 Surrounding SPOT 2003 Image Pixel Values	Pixel 1	Pixel 2
Band 1	28.435	3.247	26.139	30.731	**Band 1**	28.914	19.392
Band 2	36.603	2.326	34.958	38.248	**Band 2**	35.356	27.262
Band 3	39.104	4.067	36.228	41.979	**Band 3**	44.225	27.804

Appendix 12. Comparison of the SPOT 2003 image road pixel reflectance values and two surrounding pixels reflectance values, Sites 1- 7.

APPENDIX 13

Site 8 SPOT 2003 Image Pixel Values					**Site 8 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	14.805	2.442	13.078	16.531	**Band 1**	14.093	12.267
Band 2	17.961	3.676	15.361	20.560	**Band 2**	19.224	16.917
Band 3	34.061	1.414	33.061	35.061	**Band 3**	33.691	29.332

Site 9 SPOT 2003 Image Pixel Values					**Site 9 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	14.939	2.256	13.344	16.534		11.882	9.948
Band 2	16.886	5.320	13.124	20.648	**Band 2**	15.439	12.371
Band 3	35.471	2.411	33.766	37.176	**Band 3**	29.074	31.061

Site 10 SPOT 2003 Image Pixel Values					**Site 10 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	13.508	0.000			**Band 1**	11.964	10.766
Band 2	15.885	0.000			**Band 2**	15.127	12.243
Band 3	35.596	0.000			**Band 3**	34.208	35.547

Site 11 SPOT 2003 Image Pixel Values					**Site 11 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	10.349	0.433	10.042	10.655	**Band 1**	9.444	9.098
Band 2	19.407	1.326	18.469	20.344	**Band 2**	18.529	14.707
Band 3	28.942	0.340	28.701	29.182	**Band 3**	29.682	25.059

Site 12 SPOT 2003 Image Pixel Values					**Site 12 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	15.183	0.001	15.182	15.183	**Band 1**	16.723	13.338
Band 2	21.196	0.521	20.827	21.564	**Band 2**	21.568	19.724
Band 3	28.855	1.259	27.964	29.745	**Band 3**	28.416	29.743

Site 13 SPOT 2003 Image Pixel Values					**Site 13 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	13.678	0.436	13.370	13.986	**Band 1**	10.901	10.907
Band 2	16.655	0.261	16.839	16.470	**Band 2**	13.516	13.893
Band 3	24.032	0.000	24.032	24.032	**Band 3**	24.024	24.485

Site 14 SPOT 2003 Image Pixel Values					**Site 14 Surrounding SPOT 2003 Image Pixel Values**		
	Mean	**Std**	**Min**	**Max**		**Pixel 1**	**Pixel 2**
Band 1	11.793	0.000			**Band 1**	9.953	13.640
Band 2	20.442	0.000			**Band 2**	17.496	21.184
Band 3	28.388	0.000			**Band 3**	26.151	29.286

Appendix 13. Comparison of the SPOT 2003 image road pixel reflectance values and two surrounding pixels reflectance values, Sites 8 – 14.