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Mapping small wetlands of Kenya and Tanzania using remote sensing techniques

E. Mwita[a,b,*], G. Menz[b], S. Misana[c], M. Becker[d], D. Kisanga[c], B. Boehme[d]

[a] Dar es Salaam University College of Education, Department of Geography, P.O. Box 2329, Dar es Salaam, Tanzania
[b] University of Bonn, Department of Geography, Remote Sensing Research Group, Meckenheimer Allee 166, 53115 Bonn, Germany
[c] University of Dar es Salaam, Department of Geography, P.O. Box 35049, Dar es Salaam, Tanzania
[d] University of Bonn, Institute of Crop Science and Resource Conservation (INRES), Bonn, Germany

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ABSTRACT

Although wetlands in Tanzania and Kenya have great potentials for agricultural production and a multitude of uses, many of them are not even documented on official maps. Lack of official recognition has done little in preventing there over utilization. As the wetlands continue to play remarkable roles in the movement of people and terrestrial species in the region, it is important that they are monitored and properly managed. This study was undertaken in Usambara highlands and the Pangani floodplain in Tanzania, the Mount Kenya highlands and Laikipia floodplain in Kenya to map the different types of wetlands in terms of their size, density, spatial distribution and use patterns. Remote sensing techniques and field surveys were adopted, and 51 wetlands were identified in flood plains within the semi-arid and sub-humid lowlands, and inland valleys in the region. The detailed maps generated showed the intensity of wetland use, inland valleys being the most intensively used, and are useful in monitoring changes in wetlands for their effective management. The use of multispatial resolution imagery, combined with field survey and GIS produced satisfactory results for the delineation and mapping of small wetlands and their uses.

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1. Introduction

Wetlands are valuable land resources that fulfil diverse natural, social and production functions. They also provide a range of ecosystem services. Even though wetlands occupy only about 6% of the earth's surface, they are among the most productive ecosystems (Turner and Jones, 1991). Their importance is due partly to the fact that they occupy a transition zone between purely aquatic and terrestrial ecosystems. They therefore, provide food and an important habitat for humans and a wide range of terrestrial and semi-aquatic animals and plant species. The mix of aquatic and terrestrial habitats within a wetland provides a variety of food sources and cover for nest sites for migratory birds. Wetlands are also of great use to humans because of the diverse nature of habitats they provide for different species. In many parts of the world, wetlands are used for recreation, cultivation, education and timber production. As such, wetlands provide areas for both consumptive and non-consumptive uses. Consumptive use involves hunting and fishing, while non-consumptive uses include canoeing, bird watching, and studying animals and plants. All of these activities benefit local economies through purchases of travel, lodging and recreational equipment. In addition, wetlands can buffer pollutants, recede floods and recharge aquifers.

The diversity of species aside, wetlands in the dry savanna lands of East Africa are potential areas for agriculture as they possess fertile soils and moisture conditions suitable for crop production (Roggeri, 1995). Wetlands are key resources for cultivators and pastoralists, providing a source of arable land or grazing during droughts or the dry season. The seasonal or all year moisture availability also makes them important sites for animal grazing, fishing and recreational activities in the region. Besides, they contain macrophytes, which are used as building materials, fuel, animal feed or for making handicraft (Dugan, 1990; Roggeri, 1995; Turner and Jones, 1991).

1.1. Small wetlands significance, potentials and threats

Small wetlands are particularly important in East Africa as they make up more than 80% of the total wetland area and cover some 12 million ha in Tanzania and Kenya alone (Kiai and Mailu, 1998; Sakané et al., 2011). They provide clean water and fuel wood to the communities living around them, and are important sinks for carbon. They present an enormous potential for agricultural production (von der Heyden and New, 2003; Franke et al., 2009), local hotspots for biodiversity (Cowardin and Myers, 1974; Chapman

* Corresponding author at: Dar es Salaam University College of Education, Department of Geography, P.O. Box 2329, Dar es Salaam, Tanzania. Tel.: +255 22 2850419; fax: +255 22 2850072.
E-mail addresses: emmyrh@yahoo.com, G.emi@duce.ac.tz (E. Mwita).

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et al., 2001; Dommain, 2004), and are important sites for a wide range of socio-cultural activities.

The wetlands of East Africa therefore continue to attract large populations of people with varied interests. In Kenya, for example, the current population of Laikipia District is 399,227 people (Kenya National Bureau of Statistics, 2010), an increase of 82% from the 1999 population. Rumuruti township in western Laikipia is currently more densely populated than the dry Mukogodo division in the northern parts of the Laikipia Plateau. In 1999, the population density around Rumuruti was about 30 persons per square kilometer compared to about 12 persons/km^2 in Mukogodo located in the dry region (Kiteme, 2006). By 2008, the population density for Rumuruti township had gone up to 53 persons/km^2 (Government of Kenya, 2008). The Nyahururu region recorded density of between 251 to 400 persons/km^2 with Nyahururu township recording over 900 persons/km^2 in 2008.

Because of their diverse ecological richness, wetlands have been intensively used for different human activities. Activities such as farming, grazing, fishing and settlement development are common in wetlands in sub-Saharan Africa, and have caused significant loss of wetlands and their riparian areas (Rebelo et al., 2009a,b; Haack, 1996). The majority of wetlands lost historically were drained or filled to create agricultural land. This has been the case for more than 80% of all wetland conversions since 1980 (Baker et al., 2007). Hydrological disturbance through drainage and vegetation clearance alters wetlands functionality leading to their loss and degradation.

With global warming and continuous dryness of the savanna belt in East Africa, the wetlands in the region have come under great pressure from the migration of people, birds and animals (Boko et al., 2007). Some of the diverse uses, such as crop cultivation, grazing, settlements and macrophyte harvest, are becoming conflicting, resulting in the loss of some ecosystem functions and land degradation. There are frequent user conflicts and the associated disputes could result in the potential destruction of the wetland ecosystems. As a result, the small wetlands in the region are vanishing at a rapid rate (Rebelo et al., 2009a,b; Schuyt, 2005). The consequences of wetland degradation to the local communities in East Africa, that highly depends on wetlands for their livelihood is great. Hunger, loss of livelihood options, water scarcity, salinization and degradation of soils are among the few impacts. In addition, the loss of plant and animal species with medicinal and other aesthetic values may negatively impact the communities and environment at large. Conflicts in resource use may escalate as well and cause insecurity and mass migration among the local people.

In view of their significance in terms of location and ecological functions and their rapid transformation under increasing pressure, there is a need for mapping such small wetlands for their proper monitoring and effective management. However, in spite of the loss of species and the significance of wetlands in the movement of people and in meeting the livelihood needs of the majority of communities in the region, the East African wetlands have received little research attention probably because many are small and highly diverse in terms of hydrology, soil type and the agro ecological zones in which they occur. It is the need for information about small wetlands in the East African region that this study fulfils.

This paper presents findings of field and remote sensing surveys covering the Usambara and the Pangani flood plain in Tanzania as well as Mount Kenya highlands and Laikipia flood plain in Kenya. The aim was to identify, map out and document small wetlands, and differentiate them in terms of their spatial distribution, size, density and land use and land cover patterns. We hypothesized that small wetlands can be detected and mapped using multi-spatial and multi-spectral resolution data sets.

1.2. Remote sensing and wetland mapping

Remote sensing provides critical methods for digital data capturing and mapping of wetland transformation and use dynamics because of the range of temporal and spatial resolutions of information contained in the data. The repetitive practice of using multi-sensors and multi-spectral imagery systems to capture information about land cover also provides valuable data for managing land-based resources (Ozesmi and Bauer, 2002). Remotely sensed data provides a standardized data-collection procedure and an opportunity for data integration and analysis within a geographic information system. The technique can thus be adopted to document not only the disappearance of wetland ecosystems but to also monitor the year-to-year changes that occur within their ecosystems (Murphy et al., 2007). Advancements in earth observation coupled with detailed ground analyses are believed to provide opportunities for identifying, describing and mapping the distribution and uses of wetlands at local, regional and global scales (Jones et al., 2009).

Application of remotely-sensed data for wetland mapping and classification has therefore gained momentum in the past two decades. The increased application is attributed to advances in remote data acquisition and sensor developments for mapping of earth resources (Nagabhatla and Galal, 2007). More recently, significant efforts to inventory and map wetlands using both optical and microwave remote sensing techniques have been made (Globwetland, 2004; Murphy et al., 2007; Owor et al., 2007; Jones et al., 2009; Bwangoy et al., 2010). For example, in 2003, the European Space Agency (ESA) in collaboration with the Ramsar Secretariat launched the Global Wetland project (Globwetland, 2004) to develop an earth observation-based information service to assist wetland managers and national authorities respond to the requirements of the Ramsar Convention. The project, which continued until 2007, involved 50 different wetlands distributed in 21 countries (Jones et al., 2009). The problem is that most of these wetland mapping activities using medium to low resolution or optical satellite data focus exclusively on large wetlands of national or international importance (Rebelo et al., 2009a,b; Nagabhatla and Galal, 2007).

Due to their size and their rapid transformation dynamics, small wetlands (<500 ha) require high to very high resolution data accompanied by field surveys for accurate mapping (Rundquist et al., 2001). Such data are unavailable for small wetlands that are abundant in Eastern Africa because they are too expensive to acquire. To fill this gap, intensive field and aerial surveys have been undertaken by the "Small Wetlands of Kenya and Tanzania Using Remote" Project. The project under which the research was undertaken is known as Agricultural Use and vulnerability of Small Wetlands in East Africa (it was abbreviated as SWEA which means Small Wetlands of East Africa) (SWEA, www.wetlands.uni-bonn.de) in four selected sites in Kenya and Tanzania for a semi-detailed mapping of small wetlands.

Wetland mapping involves most often the use of aerial photographs and satellite remotely sensed data due to their remoteness and inaccessibility (Baker et al., 2006). Landsat, SPOT, NOAA-AVHRR (Advanced Very High Resolution Radiometer), Indian Remote Sensing satellites (IRS) and radar systems such as European remote sensing satellite (ERS) 1–2, and TerraSAR-X are the most frequently used satellite sensors for wetland detection (Dehouck et al., 2011; Rundquist et al., 2001). Cowardin & Myers (1974) studied wetlands in Bemidji and Minnesota using field survey and historical aerial photographs. They found out that the use of multi-spectral aerial photographs and ecological knowledge was essential for wetlands mapping. Baker et al. (2006) used multi-season Landsat ETM+ imagery from 2001 combined with ancillary topographic and soils data, to map wetland and riparian systems in the Gallatin

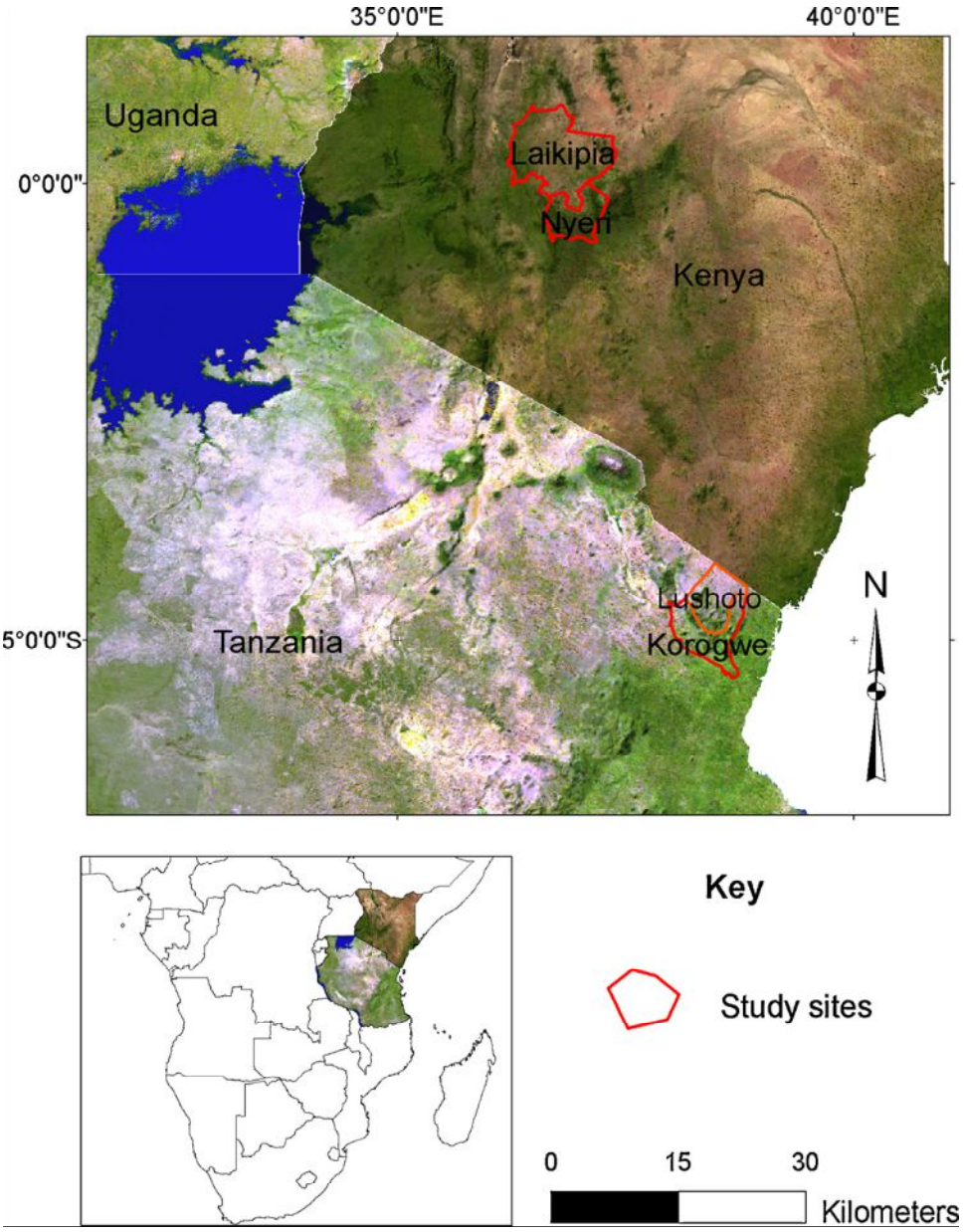


Fig. 1. Map of the study areas in East Africa (detailed study sites in red, false color LANDSAT image in the background). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Valley of Southwest Montana, USA. The technique was very useful in detecting a variety of wetlands and riparian zones present in the landscape. Hui et al. (2009), Davranche et al. (2010), Bwangoy et al., 2010 used high resolution SPOT-5 and Landsat Thematic Mapper (TM) images to detect and classify wetlands employing a decision tree technique, their findings revealed that combination of different knowledge and techniques is an effective and promising method of identification and classification of wetlands. Masarirambi et al. (2010) and Afework (1998) also attempted to map wetlands with remote sensing in Swaziland and Ethiopia, respectively. The wetlands covered in these studies were, however, larger and techniques used also varied from the current study.

Although there is increasing importance of monitoring wetland and their dynamics based on optical and radar satellite datasets, only some few studies have investigated the potential of very high to high resolution optical datasets for the detection of small wetlands in the dry savanna areas of East Africa (Haack, 1996; Kashaigili et al., 2006; Owor et al., 2007). Therefore this study is needed to contribute in improving our understanding on (1) delineation of small wetlands using high to very high resolution optical datasets and on (2) mapping of wetland's natural vegetation and agricultural use patterns by applying adapted classification methods.

2. Study sites, material and methods

2.1. Study sites

Four sites, the Mt. Kenya highlands and the Laikipia floodplain in Kenya, the Usambara highlands and the Pangani floodplain in Tanzania (Fig. 1) were selected for this study. These sites have a high diversity of wetlands and land-use and land-cover types. The Mt. Kenya highland study area extends from 36°53′28″ to 37°9′55″ E and from 0°23′56″ S to 0°33′5″ S around the towns of Nyeri and Karatina, 1570–1835 m above sea level. The area is classified as sub-humid highland. The rainfall of 900–1500 mm occurs in a bimodal pattern, with long rains between March and June, and short rains

between October and December. The undulating to mountainous landscape shows several streams, most of which are permanent with deep and narrow valleys, and swampy bottom lands. Valley bottoms are mostly intensively used for the cultivation of both horticultural and subsistence food crops.

The Laikipia floodplain site is located around the towns of Rumuruti and Nyahururu in the Rift Valley Province. It lies between 36°12′17″ and 36°45′16″ E and between 0°28′51″ N and 0°7′28″S with altitudes ranging from 1780 to 1835 m above sea level (Fig. 1). The area is classified as semi-arid to sub-humid savannah with mean annual rainfall ranging between 400 (Rumuruti) and 1000 mm (Nyahururu). The landscape is undulating in the West and flat in the East. Few larger rivers cross the area, most of them being seasonal and usually desiccate during dry spells. The Ewaso N'giro is the largest permanent river, receiving numerous tributaries in a drainage basin, thus forming a floodplain. The wetlands, such as the Ewaso Narok swamp, are either largely unused or covered by natural vegetation (*Cyperus papyrus*) or they are extensively used for food crop production or as grazing grounds. The population density has increased from 30 people per square kilometer in 1995 to 53 in 2008 (Government of Kenya, 2008; Thenya, 2001). Since the wetland is located in a semi arid area, low warfare conflicts arise during dry season between pastoralists and farmers over grazing on cultivated areas. Human versus wildlife conflicts are also prevalent as the wetland is an important dryland refuge for wildlife, which regularly feed on crops. There are also conflicts between the farmers and water and environmental protection authorities over the use of wetland resources.

The site in the Usambara highlands is located in Lushoto district, in Tanga region. The site extends from 38°13′17″ to 38°27′59″ E and from 4°37′38″ to 4°51′44″ S rising from 1320 to 1890 m above sea level. Like the Mt. Kenya highlands, the rainfall pattern is bimodal (900–1200 mm), with long rains between March and June and short rains between October and December. The district is drained by three permanent rivers (Umba, Sine and Lwengera) and numerous small seasonal streams exist in the undulating landscape with deep and narrow inland valleys. Most valley bottoms have water year round and are intensively used for irrigated market-oriented horticultural production. Lushoto is among the densely populated districts in the country with a population density of above 250 people per square kilometer (URT, 2003). Uplands degradation and unreliable rainfall patterns have exerted more pressure on inland valleys.

The site in the Pangani floodplain is located in Korogwe district in Tanga region (Fig. 1). It lies between 38°18′48″ and 38°35′49″ E and between 4°51′32″ and 5°6′56″ S, at 280–380 m above sea level on the leeward side of the Usambara Mountains. The mean annual rainfall of 500–1000 mm occurs in a bimodal pattern with long rains between March and June, and the short rains in September and October. The flat area is drained or inundated by the Pangani River and its tributaries Mbeza, Kizara and Vuluni. Several seasonal rivers flood the area during the rainy seasons and desiccate quickly with the onset of the dry season. The wetlands in the central floodplain are used for lowland rice production (wet season) or grazing (dry season), while wetland fringes are extensively cultivated with subsistence food crops.

The soils in the study sites vary with relief and parent material as illustrated in Table 1. The Pangani floodplain is dominated by unconsolidated sediment material, forming alluvial Luvisols and Fluvisols in the plain and Vertisols in the fringe areas. In Laikipia, on the other hand, the parent material is granite or tertiary basic igneous rocks, forming Lithosols and Xerosols in the uplands, while alluvial deposits form Fluvisols in the floodplains. The parent material around Mount Kenya is of volcanic origin, forming Andosols and Nitisols, while it is mainly gneiss in the Usambara Mountains, forming mainly Ferralsols. Both, in Mt. Kenya region and in the Usambara highlands, the soils in the valley bottom lands are classified as Gleysols.

In a nutshell the main activities in the study sites include crop cultivation, which involves field crop production as well as horticulture. Horticulture is prevalent in the highland areas and is intensively done with year round crop rotation. Extensive grazing is prevalent in the floodplains while in the highlands zero grazing is practiced. Other activities like fishing are also very common in the open water bodies of the wetlands. Macrophytes are harvested for thatching, fodder and handicrafts. In addition, the slopes in the highlands are cultivated with coffee and other food crops. Forests, both exotic and natural, also exist on the upland slopes. Conflicts on land-use evolve largely between the livestock keepers and farmers especially in dry season due to scarcity of grass for animal feeds, due to water abstraction for irrigation between the upland and lowland users and between environmental management authorities and farmers.

2.2. Data capturing, pre-processing and analysis

Fig. 2 illustrates the techniques used and steps followed in the detection and mapping of the wetlands. A preliminary study was carried out to identify, delineate and locate potential sites for the study. This included a study of the topographical maps of the study sites at a 1:50 000 scale and preliminary analysis of Landsat ETM+ of 2003 (scene 167/063 for Usambara highlands and Pangani plains, 168/060 Mt. Kenya highlands and 169/060 Laikipia Plateau). Maps were used to identify potential sites and locate them during field survey. Most of the topographical maps for the area dated back to 1970s and aerial photos were from early 1960s and hence outdated and unreliable particularly in locating the wetlands. Some wetlands shown on these old map and photographs no longer existed. Given the size of the small wetlands from 0.5 to 500 ha some could not be easily visualized in the analogue and digital data sets (e.g. Landsat images) and had to be physically located through field surveys. To accomplish this, river confluences were marked and traced for location of the wetlands. Since the maps were in digital format they later aided in georectification of other aerial photographs.

Radiometric and geometrically corrected Landsat scenes from the Global Land Cover Facility (GLCF) were selected and represented the dry season phenological status with pronounced spectral gradients between wetland and non-wetland vegetation. The geometrical quality of the satellite images was tested by superimposing maps and vector boundary files of the study areas on the different Landsat images with a root mean square error between 0,45 and 0,88 (equivalent to 13.5 to 26.4 m). The images were enhanced by combining ETM+ band 4, 3 and 5 bands to highlight and identify wetlands from other land uses and cover. According to Islam et al. (2008) and Ozesmi and Bauer (2002) combinations of ETM+ band 4, 3 and 5; band 7, 4 and 2, and band 3, 2, 1 displayed in false color composite (Red, Green and Blue) enhance wetlands depiction. ETM+ band 4 is the peak reflectance of green vegetation and ETM+ band 3 senses in a strong chlorophyll absorption region and strong reflectance region for soils. ETM+ band 5 is important for discrimination of vegetation and soil. Subsets were then created to cover the areas of interest for further analysis.

Wetland classification was performed in two consecutive steps. In a first step possible wetland candidates were classified with the Landsat images by using the unsupervised ISODATA (Iterative Self-Organizing Data Analysis) method within the software package ERDAS 2011. This technique is often used in a preliminary stage to aid in locating and mapping the wetlands either as a preprocessing step for a supervised classification and/or as a spatial reference dataset before going to the field. According to Kindscher et al. (1997) the ISODATA method allows natural spectral clusters to be defined with high degree of objectivity. The technique requires

Table 1
Parent material, soil types, landforms, and wetland types in the study areas.

Country	Tanzania		Kenya	
Site	Pangani	Usambaras	Laikipia	Mt. Kenya
Parent rock	Unconsolidated alluvial sediments	Granite & Gneiss	Granite & alluvial deposits	Volcanic & metamorphic
Soils	Acrisol, Vertisol, Luvisol & Fluvisol	Acrisol, Ferralsol Gleysol & Luvisol	Lithosol, Xerosol & Fluvisol	Nitisol, Andosol & Fluvisol
Landscape	Flat lowland plain	Undulating mountain highland	Undulating highland slopes & plain	Undulating mountainous highlands
Dominant wetland type	Floodplain	Narrow inland valleys with steep slopes	Floodplains and wide inland valleys	Narrow to wide inland valleys with gentle slopes

Source: De Puaw (1984), Jaetzold et al. (2006), Sombroek et al. (1982), (FAO, 1988) and IUSS Working Group WRB, 2006.

large number of clusters but since only subset images were used and the basic aim was to separate wetlands from other land uses, only 12 clusters were generated.

Based on the wetland masks from the previous unsupervised classification (step 1), land-use and land-cover patterns within the wetland polygons were derived by the supervised minimum-distance-to-means classification (step 2). At this stage a supervised classification was more preferable because of the high spectral similarity of some land-use and land-cover types of the wetlands (e.g. high similarity between wetland vegetation like young *Papyrus* and wetland crops like rice made it difficult to differentiate them) and because more distinct/discrete classes were obtained as compared to classification results that were attained with maximum likelihood that was tested earlier. Minimum-distance-to-means method

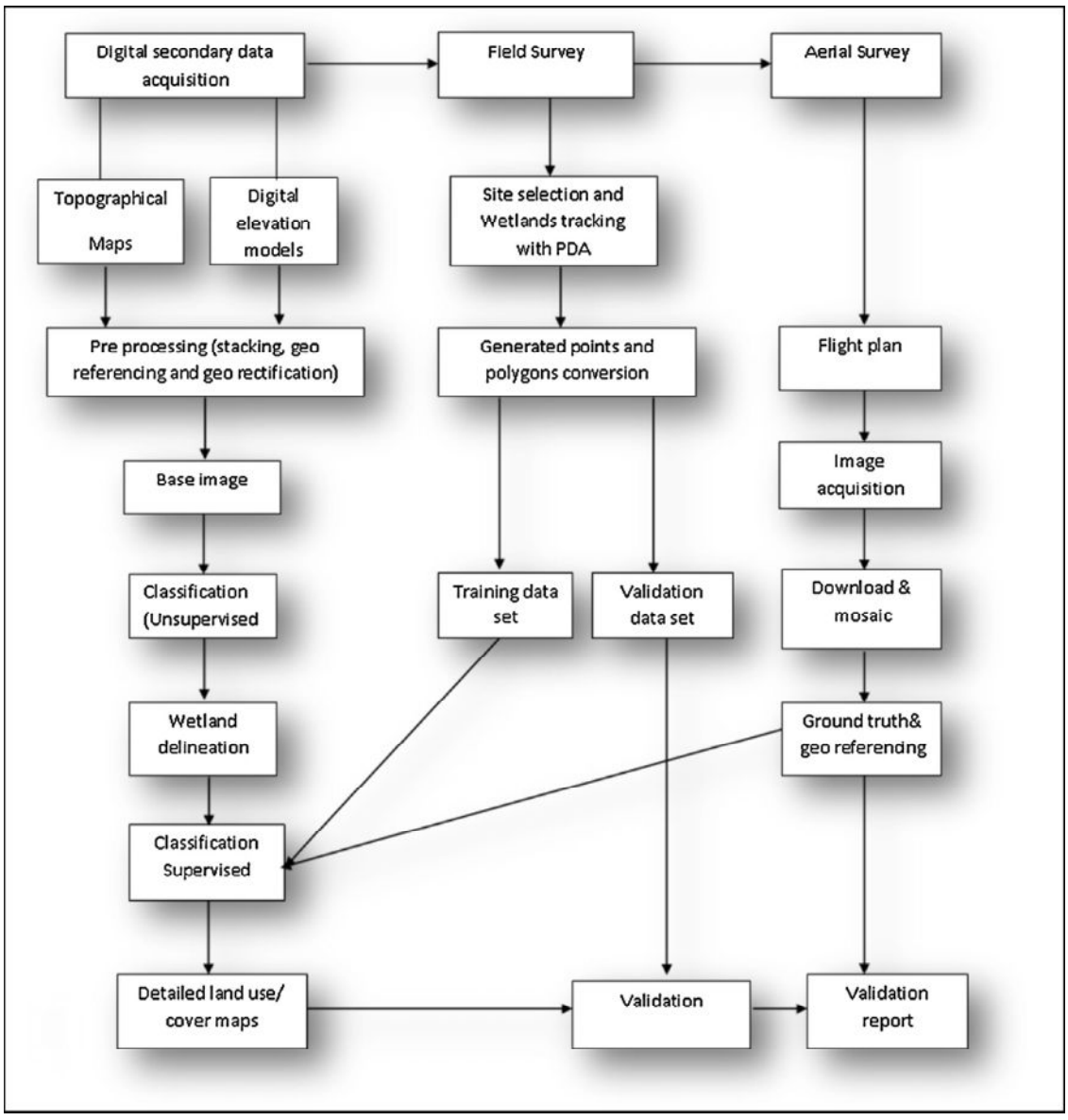


Fig. 2. Flow chart of steps and techniques used in mapping wetlands.

was finally applied to the Landsat images for the floodplains as well as the current aerial photographs that were particularly used for inland valleys (three bands of the aerial photographs (RGB) were used). A total of nine and ten classes were generated in the floodplains and inland valleys respectively. The overall accuracies were greater between 81 and 83% for Landsat and 69% for the aerial photographs.

Historical aerial photos from the early 60s' of the last century with nominal ground resolution of 15–30 m – dependent on the flight campaign and camera characteristics – were also used; these together with current aerial photographs from dry seasons 2008 and 2009 were visually interpreted to supplement the information obtained from Landsat and topographical maps. Texture, pattern, tone/color, association and shape are among the elements that were used in the interpretation. Tone, shape and pattern were the most distinguishing characteristics for wetland mapping. Ground truthing of the land uses was conducted through site visits.

Other data sets like ASTER digital elevation models (DEM) (ordered from Earth Remote Sensing Data Analysis Centre (ERSDAC) ASTER GDS (Japan) and downloaded from the United States Geological Survey (USGS) website) were used to calculate local slope in degrees using slope function in ArcGIS 9.3. Different slope threshold values were tested for delineation of wetlands and their fringe areas using raster calculator in ArcGIS critical slope values between 6° and 9° were chosen and used to separate floodplain and inland valley wetlands from other landforms.

Field surveys were conducted between January and June, 2009 to identify the location, size and use of these wetlands. Before the survey, identified potential sites for wetlands were digitized from the topographical maps and the polygons incorporated in personal digital assistant (Trimble PDA) with Arcpad 7.0 software to enhance tracking of the sites. Key informants i.e. village leaders and Agriculture Extension Officers were consulted where difficulties were encountered in accessing the sites. Wetland boundaries were set where the water table was within 60 cm of the soil surface. This was determined by soil augering up to a 60 cm depth. Areas such as bogs, permanently flooded swamps and the narrow inland valleys on the highlands, which could not be accessed during the field survey, were mapped using the Landsat images.

The polygons created in the field were over-laid on the maps, Landsat images and digital elevation models (DEMs) in an Arc GIS to delineate and generate location maps for the wetlands. The resulting ArcGIS shape files were further used to prepare a flight plan for aerial survey in three site clusters, namely, Laikipia plains and the Mt. Kenya highlands (Nyeri-Karatina) in August of 2008, Usambara highlands and Pangani plains in February, 2009. The surveys focused on specific wetlands selected in these areas.

The flight lines for the aerial survey were processed in ArcGIS software system with a side lap of 30% and an overlap of 40%. The start and end coordinates of defined flight lines were entered into the GPS-unit of the plane. A Nikon D-200 camera with a GPS-link was mounted outside the plane, from which the doors had been removed. The image capturing for each flight line was manually controlled. The camera used was equipped with a CCD-sensor with 23.6 mm × 15.8 mm at 10.9 Mio pixels. The image size of 3872 × 2592 pixels at a flight altitude of 670 m resulted in a ground coverage of about 775 m × 520 m per-picture. A direct link from the camera to a GPS device collected the center coordinates of the images. In addition a GPS track log was recorded to derive the flight path and altitude. Mosaics of the images were prepared using Nikon stitching software and geo referenced using ASTER images, as well as Landsat and topographical maps with root mean square error of between 0.6 and 0.98. Although the spatial resolution of the images used for geo referencing were a bit course compared to that of the aerial photos, there was no other data sources, which could have been used to accomplish the exercise. The aerial photographs produced (Fig. 3) had a spatial resolution of 0.25 m.

The size of each wetland was later determined by calculating the area of each wetland polygon created in the field using field calculator tool in ArcGIS. The accuracy analysis of the results was determined by overlaying a total of 80 out of 141 points that were collected in the field, the rest of the points were used as training data for supervised classification. The calculation was done using ERDAS imagine software system where the points were imported and their classes identified before the accuracy report was produced.

3. Results and discussion

A total of 51 wetlands, which covered 5% of the surveyed area, were identified (see Fig. 3a and b). As displayed in Fig. 3 the wetlands were located in either inland valleys or on floodplains. Using the morphological approach of inland valley classification first used by Windmeijer and Andriesse (1993), the wetlands in the area were further differentiated as (a) valley heads occupying 15.9% of the total wetlands area, (b) mid stream sections (64.3%) and (c) flood plains (about 19.8%). Valley heads had either concave shape with side slopes between 3 and 6% or convex shapes, with side slopes of up to 20%. Wetland sizes ranged between 0.5 and 458 ha, with valley heads and inland valleys occupying areas between 0.5 and 35 ha and flood plains from 10 to 458 ha.

The inland valleys in the Usambara Mountains were generally narrow with widths of <90 m. Floodplains were the dominant wetland type in the semi-arid and sub-humid zones and were sparsely distributed. Even though the area covered by flood plains was larger, the wetlands were not as dense as the narrow inland valleys in the highlands. Large parts of the flood plains are seasonally flooded thus in dry seasons they are completely dry except for some parts, which are covered by open water or where the water table is high and thus are moist throughout the dry season.

The major land use and cover types identified in the wetlands were open water, natural wetland vegetation (dominated by *C. Papyrus* and *Typha domingensis*), forest and shrubs, grazing land, bare land, cropland, and settlements. These land uses were, however, not uniform in all wetlands. In the floodplains, for example, the common land uses and cover were open water, floating vegetation, papyrus swamps, grazing and burnt areas (Fig. 4). The situation was different in the inland valleys where only few spots with natural vegetation still existed (Fig. 5). Unused parts were fallows, where grasses were being harvested as livestock feeds for zero grazing. Large parts of the inland valleys were intensively cultivated both for horticulture and subsistence crops like maize, beans and potatoes while floodplains were extensively used for rice cultivation.

Due to conflict in spectral signature, it was not possible to distinguish between natural vegetation and crop land with unsupervised classification. Thus, in the Pangani plains, it was difficult to distinguish lowland rice from young *Cyperus* spp. vegetation, while such differentiation was possible in the Laikipia floodplain at an accuracy of 83% (Table 2). The accuracy for the Pangani plains was 81%, and for the Usambara and Mt. Kenya highlands the accuracy was 69%. Field crops like maize and horticultural crops (i.e., cabbage and tomatoes) were easily distinguished on the aerial photographs (Fig. 5).

The information generated from this study revealed that inland valleys were generally more accessible than floodplains and were consequently more intensively cultivated. This cultivation was dominated by horticulture for commercial purposes because of good market access. While most inland valleys were cultivated all year round, flood plains were only extensively used, mainly for



Fig. 3. Examples of subsections of aerial photographs of (a) Usambara inland valley (intensively cultivated) and (b) Laikipia plains consisting of stitched images along the flight lines (pristine) (flight altitude: 670 m; spatial resolution: 0.25 m; date: February 2009).

the cultivation of subsistence field crops and cattle grazing during the dry season. The remaining portions of natural vegetation were widely encroached and used for dry season grazing but were also transformed into arable land following large-scale drainage. With land scarcity in the highlands and uplands, many people are turning to the wetlands where they drain them and convert them to agricultural lands. It is therefore likely that many of these wetlands will disappear in the near future.

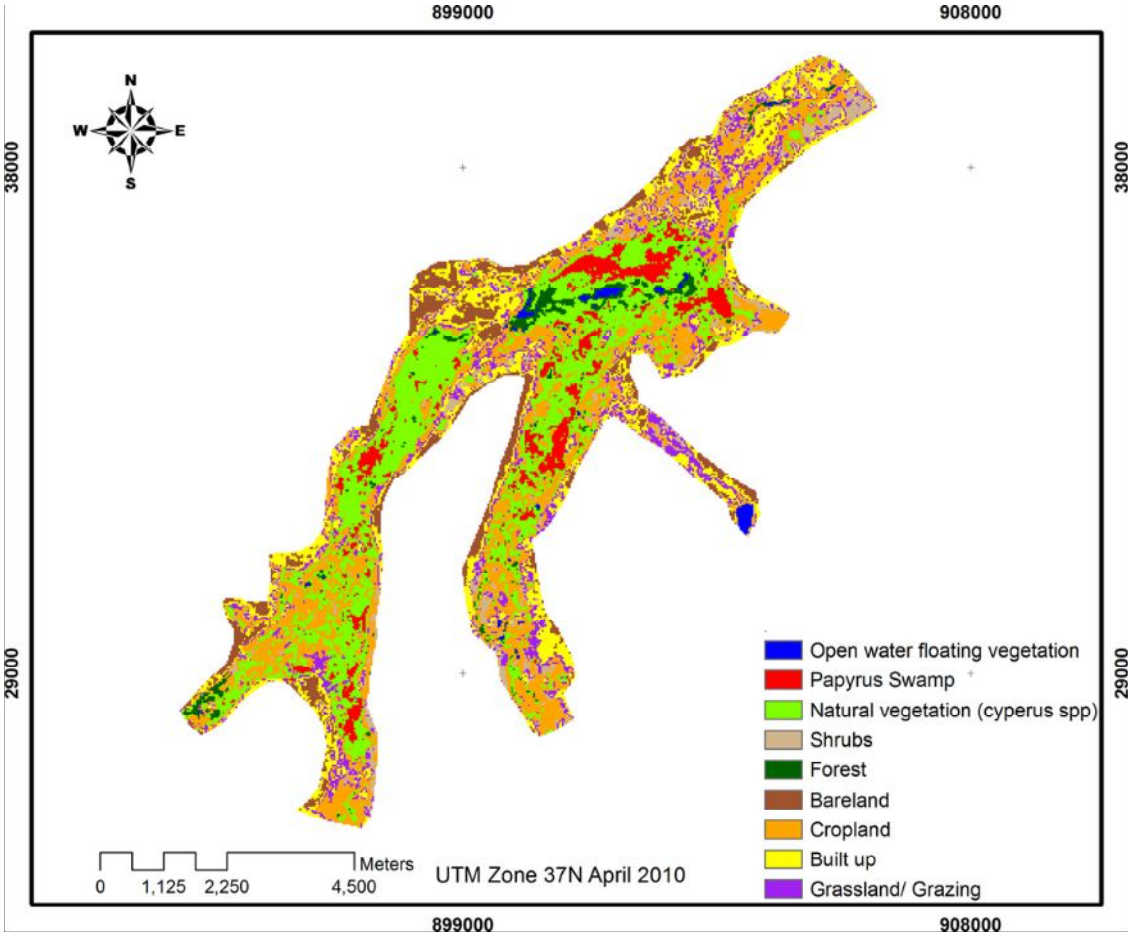


Fig. 4. Land use/cover map of the Laikipia flood plain derived from classification of Landsat image (ETM+, Jan 2003 169/063). *Source*: GLCF Lefrak Hall.

These results of this work correspond with the findings of a study done in Illubabor, Ethiopia where wetlands of similar types and more or less same sizes were found. The most common wetlands were valley heads (5–30 ha) and mid-valley (10–80 ha) while flood plains were extensive with sizes of several hundred hectares. This is, however, contrary to the small flood plains and swamps that occur along rivers and streams in the lower Middleveld and lowveld regions of Swaziland (Masarirambi et al., 2010). In Uganda, many of the small wetlands, narrow and elongated, were found in the valley bottoms and streams (WRI, 2010). Inland valleys (both valley heads and mid stream inland valleys) occurred predominantly in the highlands where population is high and arable land is scarce. Inland valley swamps, which correspond to the montane wetlands (vleis or dambos) of Swaziland (Masarirambi et al., 2010), dominated the humid highlands and they were densely distributed. Even though some of the inland valleys are drained for agricultural activities they remain wet for the most part of the year. Their location in humid areas makes them more resistant to drought.

In Illubabor, Ethiopia, the small wetlands, which are mostly dominated by *Cyperus latifolius*, are used mostly for thatching materials, domestic water, craft materials, medicinal plants, social ceremonial use of reeds while others are used for agriculture, mainly dry season grazing, water for stock and maize cultivation (Afework, 1998). In the more accessible locations near to the urban markets, however, with a demand for vegetables, it is likely that

Table 2
Accuracy assessment of the Laikipia floodplain.

Class name	Reference total	Classified total	Number correct	Producers accuracy, %	Users accuracy, %
Open water	17	7	7	41	100
Papyrus swamp	37	28	27	73	96
Natural vegetation	41	43	36	88	84
Shrubs	14	12	11	79	92
Forest	13	13	12	92	92
Bare land	27	25	25	93	100
Crop land	40	36	36	90	100
Settlements	18	20	17	94	85
Grazing	16	15	14	88	93
Total	223	199	185		

Overall classification accuracy = 83%.
Overall kappa statistics = 0.81.

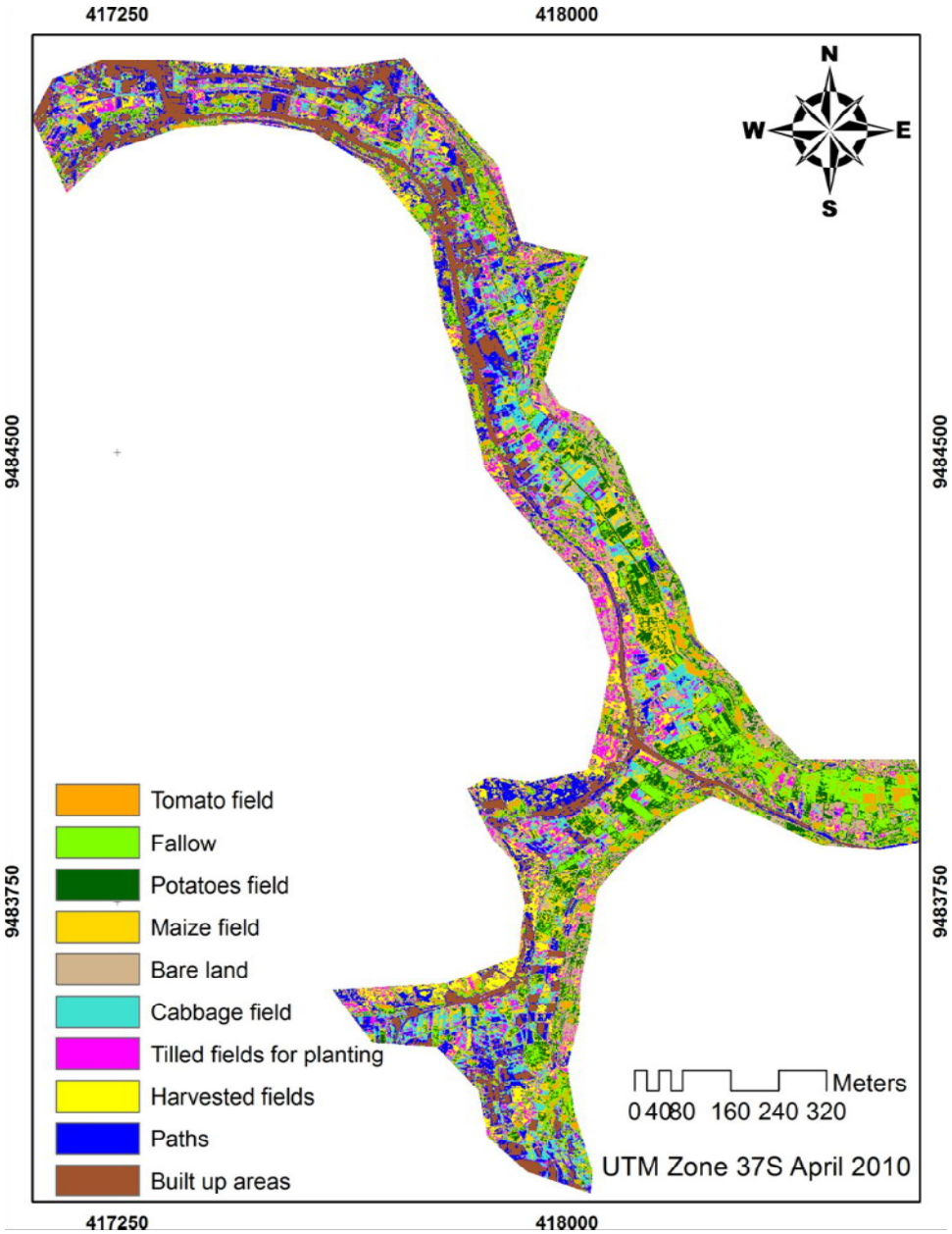


Fig. 5. Detailed land use map of a section of the Usambara highland derived from aerial photographs.

intensive use of the wetlands has already developed, as it is the case in the Usambara highlands.

The usefulness of remote sensing techniques in mapping wetlands has been discussed at length (Rebelo et al., 2009a,b; Islam et al., 2008; Ozesmi and Bauer, 2002; Rundquist et al., 2001). Remoteness, inaccessibility, and the presence of wild animals are the main reasons for the application of the remote sensing techniques. In addition, aerial photographs are very useful for high resolution mapping. All these situations were encountered in the present study of small wetlands in East Africa. Some areas were difficult to access because they were either permanently flooded, boggy, covered with thick shrubs or dense natural vegetation or were dangerous due to the presence of wild animals (hippos, elephants, buffalos and snakes). The small size of some wetlands, especially the inland valley swamps, made it difficult to identify them on Landsat images because of the poor spatial resolution. This necessitated the use of aerial photographs. Landsat images were only useful in the flood plains where the wetlands were big enough to be seen and identified. These findings confirm the observations made by Ozesmi and Bauer (2002) that the spatial resolution of most satellite imagery (20–30 m) makes it difficult to identify small or long, narrow wetlands.

Since small wetlands have not been documented in East Africa, this study is the departure point in efforts to document these vital resources, which have a lot of benefits to the ecosystem and the surrounding communities. The data and maps produced on one hand reveal a range of activities taking place in the wetlands and improve our knowledge on wetland transformation. They are of importance to decision makers as they can inform them where specific uses take place and help them determine where these uses should be further expanded or stopped. On the other hand, they can be used to guide land use planners on where to locate particular activities in the wetlands for sustainable use and conflict management. The maps will also help to create a decision support model, which will show which wetlands can be used and which ones to preserve depending on their resilience to human interference. In order to

do that, however, site-specific factors that affects a wetland's sensitivity to agricultural development and the chances of achieving sustainable use must be looked into. These factors include soil type, soil depth, surface gradient, size of the catchments and the nature of hydrological inundation (EWRP, 2010). Such factors determine whether or not a wetland is able to sustain drainage agriculture. The detailed aerial photographs, satellite data and maps will also be useful in monitoring activities and changes occurring in the wetlands for their sustainable management. Since the areas covered by this study were small in extent, it would be a good idea to extend the study to other parts of East Africa, and especially Uganda, where a multitude of small wetlands occur, so as to fill the knowledge gap on small wetlands.

4. Conclusion

This study applied remote sensing techniques to identify and map small wetlands in Tanzania and Kenya. The main purpose was to document the different types, their spatial distribution and use patterns, given that small wetlands are increasingly under pressure for agricultural production and might disappear undocumented. Within the four pre selected sites, three types of wetlands, mainly valley heads, midstream inland valleys and floodplains, were identified. These wetlands were covered by various land cover types and were used differently. The main land cover types and uses included natural wetland vegetation, forest, shrubs, grazing, cropland, settlements and bare lands. Inland valleys were intensively used for commercial horticulture production due to ease of physical and market access while flood plains were extensively used for agriculture and grazing.

The use of multi-spatial resolution imagery, including aerial photographs, combined with field survey data and GIS produces satisfactory results for the delineation and mapping of small wetlands and their uses. Landsat imagery, however, is insufficient to provide the required details and resolution for wetland use mapping. Its use, therefore, must be combined with other high resolution images complemented by field surveys for better results. It was for this reason that the current study had to acquire high resolution aerial photographs and conduct detailed field survey to supplement the information gathered from the Landsat images. The maps that have been generated in the present study improve our understanding of current use and transformation dynamics in small wetlands and may provide the quantitative basis needed to guide and predict future wetland uses in view of reconciling an increasing demand for food with growing concerns for wetlands conservation. The maps and aerial photographs produced from the aerial surveys will also be useful for monitoring the activities and changes occurring in the wetlands for their effective management.

Studies like this are needed in other parts of the East Africa and elsewhere and should cover larger areas for proper documentation of small wetland ecosystems and their monitoring. The results of such studies will help to inform the concerned authorities and guide them to make informed decisions for wise use of wetland resources.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jag.2012.08.010.

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