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Freshwater resources and changes in those resources have been identified as one of the most important global change issues in the arid and semi-arid regions of sub-Saharan Western Africa. In these regions, most surface waters are temporary and exhibit a high spatial and temporal variability associated with seasonal rains. Wide-field-of-view satellite sensors allow mapping and monitoring of the changing surface water extent every 10 days, at a 1 km spatial resolution, at a regional scale. The accuracy of these water body detections was assessed by a time series analysis, allowing the production of a map that represented a synthesis of 10-daily water body detections from 1999 to 2007. The map included, in particular, temporary water bodies, which showed the potential of wide-field-of-view satellite sensors to add novel information to existing surface water databases. The high accuracy obtained for the regional scale water body map was confirmed during a field survey in the Republic of Niger, West Africa.
The fact that water bodies can be monitored in near-real time, at low cost, at a regional scale, with a high reliability, makes them ideal ecological indicators. Relationships and interactions exist between the seasonality and extent of temporary water bodies, rainfall, and vegetation cover, and changes in one factor lead to changes in one or more of the other factors. When these changes are quantified, localized and the relative contribution of each factor is evaluated with statistical analyses, it is possible to give indications about the ecosystem state at both a catchment and a regional scale. This integrated assessment of remotely sensed rainfall, vegetation cover, and water body extent showed the potential of detected temporary water bodies to function as ecological indicators in West African drylands.

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Thèse présentée en vue de l'obtention
du grade de docteur en sciences

Faculté des sciences
École doctorale en sciences

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Eva Maria Haas

Thèse présentée en vue de l'obtention
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Louvain-la-Neuve, Avril 2010

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Ce qui embellit le désert c'est qu'il cache un puits quelque part.

What makes the desert beautiful is that somewhere it hides a well.

Le Petit Prince; Antoine de Saint-Exupéry

Summary

Freshwater resources and changes in those resources have been identified as one of the most important global change issues in the arid and semi-arid regions of sub-Saharan Western Africa. In these regions, most surface waters are temporary and exhibit a high spatial and temporal variability associated with seasonal rains. These temporary water bodies provide important ecosystem services to the local populations. The availability of water resources is one of the major obstacles to poverty alleviation and sustainable development in West African drylands.

The reliability of a time series of 10-daily water body detections, based on a wide-field-of-view satellite sensor, was assessed. A time series analysis enabled the creation of a map that represented a synthesis of 10-daily water body detections from 1999 to 2007. A cost- and time-efficient regional scale accuracy assessment proved the high quality of this mapping approach and of the water body detections. The map included, in particular, temporary water bodies, which showed the potential of wide-field-of-view satellite sensors to add novel information regarding such water bodies to existing surface water databases. This method allows frequent updating of the maps for different time intervals and regions. In addition, humid areas were also mapped, which provided indirect evidence of surface and sub-surface water in drylands. The high accuracy of the regional scale water body map was confirmed during a field survey in the Republic of Niger. A typology of detected water bodies and humid areas was derived that gave an insight into their characteristics on the ground.

The fact that water bodies can be monitored in near-real time, at low cost, at a regional scale, with a high reliability, makes them ideal ecological indicators. Good indicators of environmental conditions need to be easily observable over large areas, must be amenable to quantitative measurement, and must be suitable for regular updating. In arid and semi-arid regions, complex relationships exist between hydrological and biotic processes and there is a need for more integrated research at the interface of ecology and hydrology.

The occurrence of temporary water bodies is not only related to the amount and distribution of rainfall, but also to the catchment characteristics that influence runoff. Relationships and interactions exist between the seasonality and extent of temporary water bodies, rainfall, and vegetation cover. Changes in one factor lead to changes in one or more of the other factors. When these changes are quantified, localized and the relative contribution of each factor is evaluated with statistical analyses, it is possible to give indications about the ecosystem state at both a catchment and a regional scale.

Results of these statistical analyses showed that temporary water body detections at a 1 km spatial resolution reflected climatic variability, expressed by rainfall, during the period 1999 to 2008. The length of the detected water bodies' emptying phase was related to their maximum extent in surface area reached during the rainy season. This allowed a prediction of surface water availability throughout the subsequent dry season to be made at the end of the preceding rainy season. Additionally, a positive relationship between vegetation cover and water body extent that goes beyond the influence of the common driver, rainfall, was observed during an eight year study period between 2001 and 2008. This period was characterised by higher intensity rainfall than previous decades, which supported the replenishment of water bodies and reduced the influence of vegetation cover on runoff, and at the same time increased vegetative growth through increased rainfall. In addition to increased rainfall, changes in land-use and land-cover can also increase runoff. However, to disentangle the effects of climatic fluctuations from the effects of land-use and land-cover change on the replenishment of water bodies, more than eight years of water body monitoring data would be needed.

Sahelian climate and environment are constantly changing and thus the hydrological regimes continue to evolve with great consequences on the available freshwater resources. This integrated assessment of remotely sensed rainfall, vegetation cover, and water body extent shows the potential of detected temporary water bodies to function as ecological indicators in West African drylands.

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Mama, Papa und die beste Schwester der Welt, Kati: Danke für alles, sternenlieb.

List of Abbreviations

ACP	African Caribbean Pacific
ASTER GDEM	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model
AVHRR	Advanced Very High Resolution Radiometer
AWRD	African water resource database
CILSS	Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel
DCW	Digital Chart of the World
DRE	Direction Regionale de l'Environment
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecast
EVI	Enhanced vegetation index
FAO	Food and Agriculture Organization
FEWS	Famine Early Warning System
FP	Framework Programme
GLWD	Global Lakes and Wetland Database

GMES	Global Monitoring for Environment and Security
GPS	Global positioning system
GTS	Global Telecommunication System
IIASA	International Institute for Applied Systems Analysis
ITCZ	Intertropical Convergence Zone
IWRM	Integrated Water Resources Management
JRC	Joint Research Centre
Landsat TM	Landsat Thematic Mapper
MODIS	Moderate Resolution Imaging Spectroradiometer
MVC	Maximum value composites
NDVI	Normalised difference vegetation index
NDWI	Normalised difference water index
NIR	Near infrared spectrum
NOAA	National Oceanic and Atmospheric Administratio
PSU	Primary sampling unit
RED	Red spectrum
RFE	Rainfall estimates
RUE	Rain Use Efficiency

SIEREM	Système d'information environnementales sur les ressources en eaux en Afrique pour leur modélisation
SPOT	Satellite Pour l'Observation de la Terre
SRTM	Shuttle Radar Topography Mission
SSU	Secondary sampling unit
SWB	Small water bodies
SWBD	Shuttle Radar Topography Mission water body data
SWIR	short-wave infrared
TSWB	Temporary small water bodies
USGS	United States Geological Survey
VGT	VEGETATION
WBR	Water Body Ratio
WMS	Web Map Service
WRS-2	Worldwide Reference System 2
WWF	World Wildlife Fund

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Chapter 1 Introduction

Freshwater resources and changes in those resources have been identified as one of the most important global change issues in the arid and semi-arid regions of sub-Saharan Western Africa (Gash, 1999; Oyebande, 2002). The vulnerability of natural and socio-economic systems, as well as land-use and land-cover changes, were identified as major issues. Thus, a sound scientific base for the development of policies for the sustainable use of water and natural resources is required for these regions. There is a need to assess water resources and their vulnerability, and to determine the driving forces behind ecosystem change (Gash, 1999). Both scientists and decision makers acknowledge the need for integrated studies of the interactions between land-cover/land-use and climate, which address not only natural, but also social systems (Gash, 1999).

1.1 Freshwater resources and climate change

At the close of the World Water Week 2009 in Stockholm, the participants unanimously stated in the so-called Stockholm Statement that water must be included in the COP-15 United Nations climate change deliberations which were to be held in Copenhagen in December 2009. The Stockholm Statement claims that future global commitments on climate change measures - both mitigation and adaptation - are crucial in order to secure future water resource availability, and thus the importance of water must be properly and adequately reflected within the COP-15 agreement and in processes beyond COP-15[1]. Since water is a key medium through which climate change will be felt, the effective management of water resources is central to successful adaptation planning, which is a prerequisite for sustainable development and poverty reduction.

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[1]http://www.worldwaterweek.org/documents/WWW_PDF/
Stockholm_Statement_090821.pdf (last accessed 11th November 2009)

Climate change and variability, population growth, the overexploitation of natural resources, and environmental degradation have significantly contributed to the deterioration of freshwater resources and their worldwide decline (Meybeck, 1998; Zalewski, 2002). Climate change is expected to accelerate water cycles and thereby increase available renewable freshwater resources. However, this effect may be offset by changes in seasonal patterns and the increasing probability of extreme events like floods, droughts and storms (Oki and Kanae, 2006; Bates et al., 2008).

Wetlands, with their limited capacity for adaptation, are amongst the ecosystems most vulnerable to climate change. The Ramsar Convention on Wetlands defined wetlands as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine water the depth of which at low tides does not exceed six metres*"[2].

Temporary, endorheic (i.e. terminal or closed) water bodies are particularly vulnerable due to their sensitivity to changes in the balance of inflows and evaporation. Changes in inflows to such water bodies can have very substantial effects. Under some conditions, they can disappear entirely, which will have profound effects on ecosystem services including the maintenance of biodiversity (Bates et al., 2008). Of all ecosystems, wetlands appear to have the highest proportion of species threatened with extinction by climate change (Millennium Ecosystem Assessment, 2005; Bates et al., 2008).

Wetlands also form a vital part of a natural infrastructure needed to counteract climate change. Some sources estimate that wetlands account for about one-third of the terrestrial carbon stocks (Ramsar Secretariat, 2002). Their degradation and loss is a major cause for increased carbon emissions and thus contributes to the worsening of climate change, leaving communities more vulnerable to its impacts (Ramsar Secretariat, 2007; Pritchard, 2009).

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[2] http://www.ramsar.org (last accessed 11th November 2009)

Globally, climate change will have an impact on freshwater resources and the negative impacts are expected to outweigh the benefits (Bates et al., 2008). Conservation, restoration and safeguarding wetlands are therefore effective climate adaptation strategies (Erwin, 2009). An integrated land and water resources management scheme, as agreed upon in the Nairobi Statement[3], is key to an effective climate change adaptation because land and water resources are fundamentally linked.

Management of water resources is a key component for growth, social and economic development, poverty reduction and equity of communities and countries. These humanitarian requirements and sustainable environmental services are essential for achieving the Millennium Development Goals for 2015, set up by the United Nations (World Water Assessment Program, 2009). There is also a need for higher-quality information that is more effectively shared. Knowing where and how the impacts of climate change will affect populations and ecosystems through the water cycle is important for the identification of hotspots, which are especially located in arid regions of developing countries.

1.2 Freshwater resources in West African drylands

Water stress is a major societal challenge. During the first half of the 21st century, water shortages will be amongst the world's most pressing problems, and will also affect issues such as food security, international diplomacy, poverty alleviation, public health, energy production, ecosystem management and the preservation of biodiversity (Vörösmarty et al., 2000; Vörösmarty et al., 2005; World Water Assessment Program, 2009). The availability of freshwater resources and their management are determinants of a country's growth strategy, since growth requires natural resources, and thus they can impose limits to growth. In Africa, both growth and water are major challenges.

[3] http://cms.iucn.org/about/union/members/resources/news/?uNewsID=3053 (last accessed 11th November 2009)

About 25% of the contemporary African population experiences water stress with an additional 15% experiencing drought-related stress at least once each generation, while 60% live under conditions of relative water abundance (Vörösmarty et al., 2005). However, this relative abundance does not take into account the potability nor the accessibility of water. Despite considerable improvements in accessibility to water resources in the 1990s only 62% of the African population had access to improved water supplies in the year 2000 (WHO/UNICEF, 2000; Bates et al., 2008). The African heads of state recognised the importance of water and sanitation as a key to sustainable development and the prerequisites for Africa's human capital development as well as social, economic and environmental development (World Water Assessment Program, 2009).

In particular, sub-Saharan Western Africa lags behind in achieving the Millennium Development Goals. Here, the percentage of the population living in absolute poverty is essentially the same as it was 25 years ago (World Water Assessment Program, 2009). The major obstacle to poverty alleviation and sustainable development is the availability of water resources (OSS/UNESCO, 2004; UN-Water/Africa, 2006). In an increasing number of countries in sub-Saharan Western Africa, water demand exceeds available resources (UNEP/AEO-2, 2006). Although Africa as a whole has abundant water resources, there are great disparities in water availability and use between the African countries due to an uneven distribution of water resources (GEO-2000, 2000; UN-Water/Africa, 2006).

1.2.1 Study area and physical environment

The focus of this thesis is on the Sahel region in sub-Saharan Western Africa, an arid and semi-arid transition zone between the Sahara desert in the north and the humid savanna lands in the south (Le Houerou, 1980; Graetz, 1991). This region has the lowest amount of natural water resources in Africa, both in absolute terms and in relation to its population (OSS/UNESCO, 2004; UN-Water/Africa, 2006).

The Sahel stretches approximately 5500 km across Northern Africa from the Atlantic Ocean in the west to the Red Sea in the east, covering an area of approximately 2.5 million km^2 (Le Houerou, 1980). Researchers have previously chosen various isohyets to define the limits of the Sahel (Grove, 1978) but for practical purposes Nicholson (1994) suggested defining the Sahel as the region bound between 15° W to 20° E and 13° N to 20° N. The Sahelian belt crosses the African continent almost parallel to the equator, with the isohyets running roughly parallel in a west-east direction inclining 4% towards the south-east (Le Houerou, 1980). The present study concerns the Sahel as a whole and selected sub-regions (Figure 1-1).

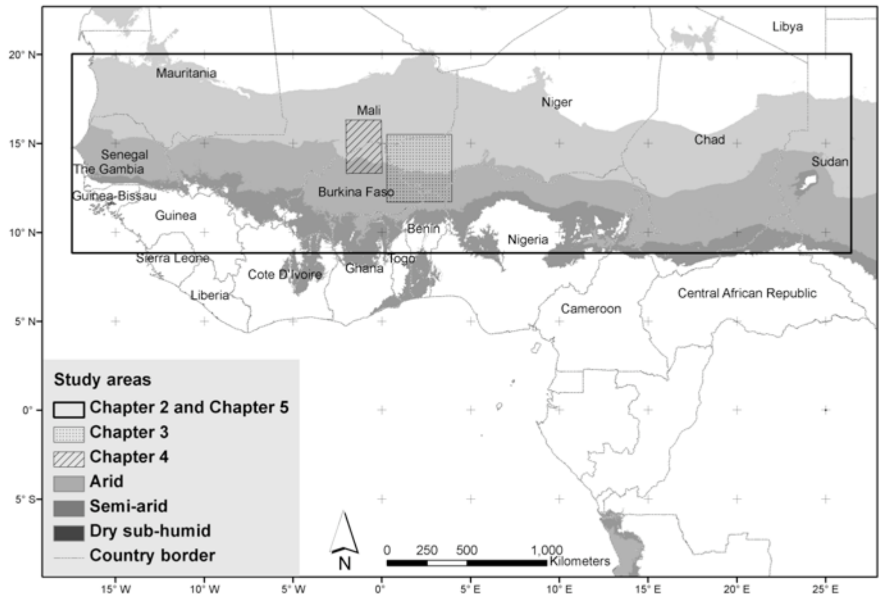

Figure 1-1: Study areas covered in the thesis. Water body detections were validated and analysed in the arid, semi-arid and adjacent dry sub-humid climate zone (WorldClim database, Hijmans et al., 2005).

As part of this research, water bodies were mapped for the African continent but the accuracy of the mapping approach was assessed only between 17° W to 26° E and 8° N to 20° N in the arid, semi-arid, and adjacent dry sub-humid climate zones (Chapter 2). The same area was considered in the regional assessment of water and natural resources, presented in Chapter 5.

This area that ranges from the Atlantic coast to the Republic of Chad corresponds to the geopolitical UN definition of Western Africa[4] and covers the CILSS (Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel) countries. The field survey described in Chapter 3 was carried out in the south-western part of the Republic of Niger (11° 37' N to 23° 23' N) in the northern half of a circle of approximately 125 km in radius centred on the capital city Niamey. In Chapter 4, a detailed study was carried out in two regions located between 14° N to 16° N and 3° W to 0° W, in Mali and Burkina Faso respectively.

Strong seasonality characterises the dry tropical climate of the Sahel with a mono-modal, short, rainy season and a long, intense dry season (Grove, 1978). During the rainy season, which is usually between June and September with the peak in August, the Intertropical Convergence Zone (ITCZ) carries moisture from the Gulf of Guinea into the Sahel. The Sahelian rainy season is therefore a consequence of the south–north and north-south movement of the ITCZ. In the Sahel, 95% of the annual rainfall is produced by Mesoscale Convective Systems (Laurent et al., 1998). Squall lines form convective cells that produce north-south orientated bands of intense rainfall travelling across the Sahel from east to west (Desconnets et al., 1997; Amani, 1999). The rainfall in the Sahelian environment has a patchy character (Dolman et al., 1997), and daily rainfall maxima can sometimes exceed annual rainfall amounts. The highly variable rainfall ranges annually between 100 to 200 mm in the north and 400 to 600 mm in the south of the Sahel (Grove, 1978). Three ecoclimatic zones can be identified along the latitudinal gradient of annual rainfall level from north to south: the Saharo-Sahelian zone (100 to 200 mm), the Sahelian zone "sensu stricto" (200 to 400 mm) and the Sudano-Sahelian zone (400 to 600 mm) (Le Houerou, 1980).

Mean annual air temperature is around 28° C with minimum temperatures around 10 to 15 °C from December to January and maximum temperatures of 40 to 45 °C from April to May (Le Houerou, 1989). Air humidity is below 40% during the dry season and can drop to less than 10% in the afternoons

[4] http://www.un.org/unowa/ (last accessed 11th November 2009)

from March to May. From July to September the average air humidity is above 70% (Le Houerou, 1980). Air temperature, air humidity, wind speed, and irradiation all influence evaporation. Potential evapotranspiration is extremely high at 1800 to 2300 mm per year. Class A pan evaporation is 3000 to 3500 mm per year (Le Houerou, 1980).

During the last three decades of the 20th century the Sahel was subject to one of the largest climatic changes observed worldwide, leading to decreasing rainfall and devastating droughts (Bates et al., 2008). From the mid 1960s to the late 1980s, the region has experienced a systematic decrease in rainfall. Widespread droughts affected large areas in the Sahel, which peaked in the period 1982 to 1985, and caused large-scale food shortages and famine (Olsson, 1993; Glantz, 1994). Since the late 1990s the region has experienced an increase in rainfall compared to the late 1960s, although the conditions are still dryer than the conditions that prevailed in the region from 1930 to 1965 (Hulme, 2001; Nicholson and Grist, 2001; Anyamba and Tucker, 2005; Lebel and Ali, 2009).

Climatic constraints such as the scarcity and variability of rainfall are the most important controlling factors of the Sahelian ecosystem. The vegetation cycle closely corresponds to the seasonality of the rainfall and the general gradient of the long-term average rainfall that declines from south to north is followed by the vegetation gradient (D'Herbes and Valentin, 1997). White (1983) mapped the vegetation throughout the region as Sahel Acacia wooded grassland and deciduous bush land. In the north, annual grasses and scattered bush steppe prevail, which gradually merge into Sudanian savannas in the south that are characterised by perennial grasses, scattered trees, and extensive rain-fed cultivation (White, 1983). Annual herbaceous plants cover about 20 to 80% of the soils, while bushes occupy up to 20%, and small trees cover only about 1 to 5% of the soils (Le Houerou, 1989).

Besides rainfall, the soil type significantly influences vegetative production. Three types of soil can be identified in the Sahelian landscape, which is mostly characterised by a low relief of between approximately 200 to 600 m in altitude, interspersed by occasional high mountain ranges (Penning de Vries and Djiteye, 1982; Hoogmoed and Stroosnijder, 1984).

Sandy soils (luvic arenosols) are present in the form of dunes or eroded dune fields that are yellowish-red in colour and cover about 50% of the region. Dark grey clay soils (vertisols) from recent or fossil river and lake deposits extend over 20% of the area. Shallow stony soils (ferric luvisols) that develop on laterite or sandstone occupy the remaining 30% (Le Houerou, 1980; Hoogmoed and Stroosnijder, 1984). Soils in the southern parts of the region are more acidic than those in the north. Large areas of soils are covered with recent quaternary eolian deposits that range from deep and coarse in the north to very fine sandy and loamy in the south (Hoogmoed and Stroosnijder, 1984). On sandy soils most of the rainfall infiltrates and becomes available for plants. Clay and loamy soils are characterised by low infiltration rates that lead to increased runoff and thus less water is available for vegetative growth resulting in slower growth rates. In addition, the different moisture retention characteristics of sands and clays cause differences in growth rates, particularly at the beginning of the rainy season (Kumar et al., 2002). The deep sandy and loamy soils in the south, which have a dense topsoil that is soft when wet and very hard when dry, are the best suited for growing crops. Soils in the Sahel are generally characterised by low fertility, low organic matter content and most of the agriculture in this region is rain-fed. Arable crops can be grown only in the south of the Sahel since at the 400 mm isohyet the risk of crop failure is high and cropping is already marginal (Hoogmoed and Stroosnijder, 1984). Local agriculture is therefore vulnerable to changes in rainfall, and is often severely compromised by periods of prolonged droughts and floods (Mendelsohn et al., 2000; Stige et al., 2006).

The patterns of population distribution in the Sahel depend on environmental factors such as climate and soils but also on long-term and recent history (Raynaut, 2001). The Sahel is extensively utilised by humans and three main zones can be identified. In the north, nomadic and transhumant pastoralism dominates and agriculture only exists locally according to water availability. The central Sahel is predominantly rangeland with some cultivation and is used by the nomadic transhumant groups from the north (Le Houerou, 1980). The south is the privileged domain for agriculture and more settled mixed herding.

Since the early 1950s population growth and increased demand for agricultural land has led to the movement of sedentary agriculture into the central Sahel, an area that was previously regarded as unsuitable. The competition between these two modes of resource use, rangeland versus cropland, often generates strong conflicts that are reinforced by the effects of drought (Raynaut, 2001).

The 16 Western African countries located in the Sahel are prone to experiencing water stress and scarcity, which is likely to increase by the year 2025 (GEO-2000, 2000; UNEP/AEO-2, 2006). Throughout the Sahel, surface water resources are distributed unequally between the countries and the type of available surface water resources varies greatly. Some of the most extensive wetlands are situated in this zone, such as the Niger Inner Delta, and Lake Chad, as well as many small temporary water bodies.

1.2.2 Characteristics of temporary water bodies

The extreme spatial and temporal variability of rainfall, combined with high potential evapotranspiration, makes water resources and plant productivity in arid and semi-arid regions hard to predict and leads to a general low conversion of rainfall to runoff (Schulze, 1999). Rainfall that reaches the soil is subject to infiltration. The rate of infiltration depends on the type, structure and texture of the soil as well as on surface crusting, and water and organic matter content. Temporary water bodies facilitate infiltration deep into the soil and thus constitute a major contributor for the upper aquifer recharge (Desconnets et al., 1997; Leduc et al., 1997).

In arid and semi-arid regions commonly Hortonian type overland flow occurs due to rainfall intensities exceeding the infiltration rates of the soil (Yair and Lavee, 1985). On average, 25% of the rainfall is transformed to runoff in the Sahel (Hoogmoed and Stroosnijder, 1984). Locally, high runoff can be observed during the rainy season even though large-scale drainage does not exist (Peugeot et al., 1997). Reasons for the lack of large-scale drainage are the almost permanent water deficit, a flat landscape with slopes of only 1 to 3% and the local blocking of valley bottoms by fossil sand dunes and sand deposits. During the dry season the predominant Harmattan winds blow from the Sahara desert and transport large amounts of dust.

Locally, these winds also move sand and form dunes, which block the ancient drainage network that developed in the Pleistocene when wetter climatic conditions prevailed (Desconnets et al., 1997). Under the present dry climatic conditions, surface water flow seldom occurs for more than approximately one hundred metres and water accumulates in depressions along the ancient drainage network. As a result, temporary water bodies form in the depressions like “a string of pearls”. In the present climatic conditions, these temporary water bodies are rarely, if ever, connected as the runoff resulting from rainfall events is not sufficient to provide a continuous water flow (Desconnets et al., 1997). Only large, temporary rivers have a continuous water flow during the rainy season because they accumulate water from tributaries originating in wetter regions. A small number of large, permanent rivers have a continuous water flow due to their headwaters being situated in wetter regions. The surface hydrology of the study area is a juxtaposition of hundreds of small endorheic hydrologic systems where surface runoff collects and forms temporary water bodies.

Different types of temporary water bodies can be distinguished due to their dependence on climatic fluctuations. Chamaillé-Jammes (2007) found rain-fed water bodies to be sensitive to climatic fluctuations while groundwater-based water sources (springs, seeps) showed no response to changes in rainfall and generally had a much higher probability of retaining water during the dry season. In this thesis, the focus is on natural temporary water bodies that are dependent on rainfall and thus are likely to respond to climatic variability. Temporary surface waters linked to a river system and its floodplains with headwaters in more humid regions, permanent water bodies, and water bodies associated with large dams, are excluded from this study due to their different hydrological regimes.

The functioning of dynamic temporary water bodies was little studied before the setting up of HAPEX-Sahel in the 1990s, an international experiment designed to provide field data to model the climate of the Sahel and its dependence on land surface conditions (Goutorbe et al., 1994; Prince, 1995; Goutorbe et al., 1997). Current research on surface processes and the water cycle in Western Africa is carried out in the framework of the AMMA-CATCH project (Redelsperger and Lebel, 2009).

Temporary accumulations of surface water in the Sahel are generally named ponds, pools, temporary water bodies, shallow lakes or Sahelian lakes. In French, they are called *mares* or *mares temporaires*. Locally, a cultural nomenclature is used, which shows the heterogeneity and socio-economic importance of the wetlands (Cooper et al., 2006).

1.2.3 Ecosystem services of temporary water bodies

Wetlands provide a wide range of ecosystem services (defined as "*benefits people obtain from ecosystems*") that contribute to human well-being (Costanza et al., 1998; Millennium Ecosystem Assessment, 2005).

The Ramsar Convention on Wetlands (2002b) recognised the critical importance of temporary water bodies for the maintenance of biodiversity through the highly specialized plant and animal communities that depend upon them (Boutin, 1982; Williams, 1997; Zedler, 2003) as well as their provision of breeding and roosting sites for birds (Green, 2000; Dodman, 2006) and drinking water for herbivores (Redfern et al., 2005; Chamaillé-Jammes, 2007). Temporary water bodies also have important cultural and socio-economic values, as they provide freshwater, grazing areas and other ecosystem services to pastoral communities (Thebaud and Batterbury, 2001; Brouwer, 2003; Hein, 2006). Around isolated temporary water bodies in the Sahel, dry season cropping takes place and the subsequent high value food crops provide food and income for local communities. These temporary water bodies are important for watering livestock because meeting the water demand from surface water requires less physical effort than drawing it from wells. The wet soil of water bodies is also used for the production of bricks (Figure 1-2). A common practice is the stocking of water bodies with desired fish species. In drought years, water bodies can provide foods like water lily tubers and lungfish (Brouwer, 2003).

Figure 1-2: Ecosystem services of a water body in south - western Niger.

There is a concern that temporary water bodies are often neglected due to their ephemeral character and are disappearing worldwide because of unsustainable management practices, including permanent flooding, and land-filling for agricultural and urban developments (The Ramsar Convention on Wetlands, 2002b). Temporary water bodies are designated as wetlands of international importance and their inclusion in national wetland inventories and a better representation of this wetland type in the Ramsar List of Wetlands is encouraged (The Ramsar Convention on Wetlands, 2002a).

1.3 The importance of ecohydrological studies in drylands

The occurrence of temporary water bodies is not only related to the amount and distribution of rainfall but also to the catchment characteristics that influence the generation of runoff. In freshwater ecosystems of arid and semi-arid regions, complex relationships exist between hydrological and biotic processes, whilst interactions are especially intense due to water scarcity and its intermittent and unpredictable appearance (Peugeot et al., 1997; Beven, 2001; Porporato and Rodriguez-Iturbe, 2002; Zalewski, 2002; Candela et al., 2005). The complex interactions between these processes are not completely understood and there is a need for more research at the interface of ecology and hydrology (Rodriguez-Iturbe, 2000; Zalewski, 2002; Hannah et al., 2004; Popp et al., 2009).

Ecohydrology, to which this thesis contributes, is an evolving field of research. It aims at better understanding the interrelated characteristics of climate, soil, vegetation and hydrological dynamics at catchment and regional scale (Rodriguez-Iturbe, 2000; Zalewski, 2002). This understanding provides the basis for Integrated Water Resources Management (IWRM) that contributes to the sustainable use of water resources (Porporato and Rodriguez-Iturbe, 2002).

1.4 The potential of remote sensing in ecohydrology

Earth observation is an important tool used in gathering information about ecohydrological dynamics across spatial and temporal scales and to study relationships between land, vegetation and hydrology (Meijerink, 2002). Commonly, information such as rainfall, vegetation condition, surface water bodies, fires, soil moisture and evapotranspiration are detected by remote sensing as well as derived information such as land-cover change and landscape degradation. Other forms of rapid land-cover change that are thought to be widespread, like the alteration of wetlands, are still poorly documented at regional and global scales even though studies on local to national scales have proven those changes to be important and of ecological significance (Lambin, 2003).

A large body of research was conducted to investigate the influence of seasonal and inter-annual climate variability, primarily expressed by rainfall and air temperature, on vegetation behaviour at continental to sub-continental scales (Prince and Goward, 1995; Yang et al., 1997; Holm et al., 2003; Kaurivi, 2003; Wang, 2003; Martiny et al., 2006; Camberlin et al., 2007). Vegetation behaviour was depicted with vegetation indices such as the Normalised Difference Vegetation Index (NDVI) (Tucker, 1979; Sellers, 1985; Tucker et al., 1985; Myneni et al., 1995). For the Sahel, a significant response of NDVI to inter-annual rainfall variations was identified at local to regional scales (Tucker et al., 1985; Hielkema, 1986; Malo, 1990; Nicholson, 1990; Diouf and Lambin, 2001; Diello et al., 2005; Herrmann et al., 2005). A strong spatial and temporal relationship between rainfall and NDVI was detected for open grasslands and croplands in semi-arid regions with mean annual rainfall between 200 and 600 mm (Camberlin et al., 2007). Spatial patterns of land-cover change identified with the Enhanced vegetation index (EVI) (Huete, 2002) were linked with short-term rainfall variability (Vanacker et al., 2005). Relating NDVI and rainfall data (Holm et al., 2003) gave an indication about landscape degradation.

Furthermore, a large body of research exists on land-atmosphere feedbacks. Charney (1975) hypothesised a positive feedback loop whereby albedo increases due to removed vegetation and subsequent desertification, that then causes a reduction in rainfall and thus inhibits the recovery of the vegetation. Since then a large body of research was conducted on the influence of changes in land-use, vegetation cover and surface albedo on rainfall variability in Western Africa (Xue and Shukla, 1993; Nicholson et al., 1998; Zeng et al., 1999; Wang and Eltahir, 2000; Clark et al., 2001; Fuller and Ottke, 2002; Taylor et al., 2002; Brunsell, 2006; Lauwaet et al., 2009). These studies confirm the sensitivity of the Sahelian rainfall to land surface conditions and highlight the importance of other feedback mechanisms such as soil moisture (Entekhabi et al., 1996; Eltahir, 1998; Zheng and Eltahir, 1998) and regional to global sea surface temperature patterns (Giannini et al., 2003).

Recent studies have proven the existence of relationships at local to regional scales between rainfall and trends in vegetation dynamics, land-cover change, soil moisture, sea surface temperature, surface albedo, fires (Koffi et al., 1995), forest fire scars (Jupp et al., 2006), ENSO effects (Plisnier et al., 2000) and disease outbreaks (Anyamba, 2001). However, no studies currently exist at these scales that relate rainfall and vegetation cover to available surface water. Indeed, until now, it was not possible to monitor surface water dynamics in near-real time with a high temporal resolution at the regional scale.

The Joint Research Centre of the European Commission developed a method to map and monitor small water bodies (SWB) in arid and semi-arid regions using the wide-field-of view SPOT VEGETATION (VGT) sensor at 10-day time resolution (Gond, 2000; Gond et al., 2004). It was demonstrated that the 1 km spatial resolution of SPOT VGT is sufficient to accurately map and monitor the presence of water in natural and artificial ponds and swamps at sizes of approximately 1 km² and greater. This is considered to be small compared to the sub-continental scale on which the data are acquired. The fact that water bodies can be monitored in near-real time, at low cost, at a regional scale, with a high reliability, makes them ideal ecological indicators. Good indicators of environmental conditions need to be easily observable over large areas, must be amenable to quantitative measurement, and must be suitable for regular updating (Mabbutt, 1986; Segnestam, 2002).

The mapping and monitoring of temporary water bodies is important for studying the water balance in the Sahel. In this region water bodies are the only reliable integrators of hydrological processes (Desconnets, 1994; Desconnets et al., 1997) and thus are likely to indicate ecosystem changes in a catchment. The biophysical variables in a catchment are interconnected in complex ways. Hence, changes in any of these variables can lead to changes in other variables, with magnitude depending on the nature of the relationship. If relationships between rainfall, water bodies and vegetation cover can be established and quantified, it will be possible to obtain information on the state of the ecosystem from the observed temporal and spatial behaviour of water bodies, and vice versa. This ecological indicator can be used to assess short-term changes in climate and ecosystem processes of arid and semi-arid regions such as the Sahel in Western Africa.

1.5 Objectives of the thesis

The overarching aim of the thesis was to understand the potential of water body detections by a wide-field-of-view sensor to indicate ecosystem status in West African drylands. An ecological indicator needs to be based on reliable input data. Thus, the first step was to assess the quality of the novel remote sensing derived water body dataset that is key to this research. In the second step the water body detections were related to rainfall and vegetation cover at a local and a regional scale. The objectives were addressed with two research questions:

(1) Are water body observations by wide-field-of-view satellite sensors reliable?

Hypothesis: Water bodies can be reliably detected with an optical remote sensing time series at a regional scale. Their maximum extent can be mapped and information about inter- and intra-annual seasonal changes can be identified based on a time series of water body detections.

(2) What are the relationships between surface water, vegetation cover and rainfall at the ecosystem (or catchment) scale and at the regional scale?

Hypothesis: Relationships and interactions exist between the seasonality and extent of temporary water bodies, rainfall, and vegetation cover. Changes in one factor lead to changes in one or more of the other factors. These changes can be quantified, localized and the relative contribution of each factor can be evaluated.

1.6 Outline of the thesis

The methods used to answer the research questions are time series analysis, statistical analysis, an accuracy assessment of regional scale maps and a field survey. An overview of the employed methods, the results, the scale of the study and the respective research question to be answered is provided in Figure 1-3.

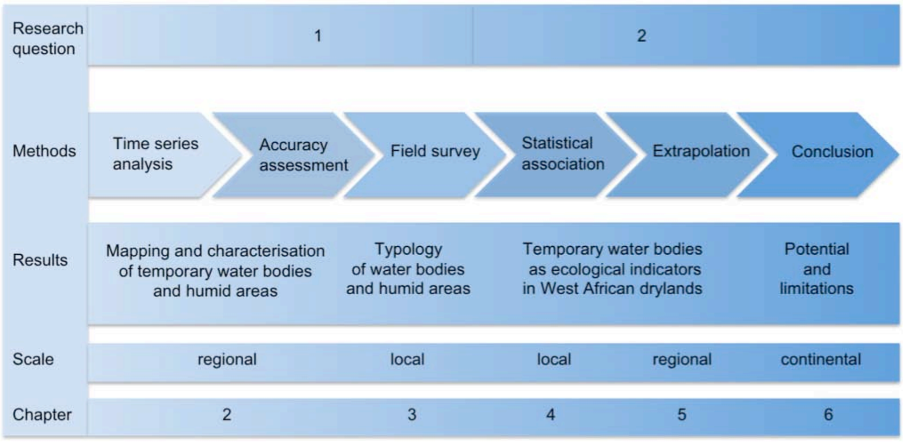

Figure 1-3: Outline of the thesis indicating methods used and results.

The two research questions are addressed in the six chapters of the thesis as follows:

Chapter 2 refers to the first research question by introducing a method of mapping temporary water bodies based on a novel optical remote sensing time series of water body detections. A time series analysis enabled the creation of a novel map of water bodies for sub-Saharan Western Africa that includes in particular small temporary water bodies. Each mapped water body was then characterised based on a time series analysis. This provided important environmental information about the hydrological behaviour of temporary water bodies and allowed their dynamics to be incorporated into a map form. A regional scale accuracy assessment showed the reliability of the water body detections. In addition, a map of humid areas that provided indirect evidence of available surface water was developed for sub-Saharan Western Africa. This map, however, could not be validated at a regional scale because, unlike water bodies, humid areas could not be clearly identified on the high resolution satellite images that were used as a surrogate for ground observations.

Chapter 3 describes how the remote sensing derived water body and humid area detections were linked for the first time to ground observations during a field survey in the Republic of Niger, West Africa. The accuracy and typology of water bodies and humid area detections was assessed and differences between them were identified.

Chapter 4 aims to answer the second research question by providing an insight into ecosystem processes in the arid and semi-arid regions of sub-Saharan Western Africa. Based on knowledge of the water balance, the statistical associations between surface water extent, vegetation cover and rainfall were studied at the ecosystem (or catchment) scale for 11 catchments in two regions of Mali and Burkina Faso.

Chapter 5 focuses on testing the findings obtained in Chapter 4 at the regional scale. To understand the potential of the regional scale water body dataset to indicate ecosystem status, the statistical associations between water body extent, vegetation cover and rainfall identified in Chapter 4 were tested within a 1° grid covering Western Africa. Furthermore, the trend of the developed Water Body Ratio (WBR) that describes the relationship between surface water extent and rainfall was determined.

Chapter 6 presents the main conclusions and essential findings of this thesis as well as the limitations and potential future applications of the research work.

Chapter 2 Time series analysis of optical remote sensing data for the mapping of temporary surface water bodies in West African drylands[5]

Abstract

This chapter contains the methodology to assess the reliability of the small water body (SWB) dataset at a regional scale. A map of temporary small water bodies (TSWB) at 1 km resolution was derived for the arid, semi-arid and dry sub-humid regions of sub-Saharan Western Africa to assess the quality of the SWB observations. Water bodies and humid areas were mapped and characterised by the analysis of a time series of 10-daily SWB maps based on SPOT VGT data for the period January 1999 to September 2007. Further analysis of the SWB time series provided additional information on the seasonal recurrence of water bodies and their hydrological function. A map derived from a continuous time series assures the inclusion of temporary features, a clear advantage compared to other datasets, which are based on several single date observations. The method described in this chapter targets a rapid creation of TSWB maps based on the SWB time series for different time intervals and regions. An accuracy assessment was carried out for the TSWB map with a stratified random sampling approach and a one-stage cluster analysis that relies on high resolution satellite data. The overall accuracy, considering only the commission error, is 95.8% for the whole study area, with the highest accuracy obtained in the arid and semi-arid climate zone. The method to map water bodies delivers satisfactory results, particularly for sparsely vegetated and flat areas of the study area. In more humid, more vegetated areas and in mountainous areas, the possibility of false detections increases due to surface characteristics.

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[5] Adapted from: Haas, E. M., Bartholomé, E., & Combal, B. (2009). Time series analysis of optical remote sensing data for the mapping of temporary surface water bodies in sub-Saharan Western Africa. Journal of Hydrology, 370 (1-4), 52-63.

2.1 State of the art water body datasets and the potential of remote sensing

Until now, knowledge of surface water resources in the arid and semi-arid regions of sub-Saharan Western Africa was based on maps of perennial water bodies, maximum extents of wetlands, well-known rivers, potential drainage networks and on fragmentary knowledge of temporary surface water. Especially in these regions, where a high inter- and intra-annual variability of surface water resources can be observed, temporary water bodies appear to be missed in mapping due to their short and erratic appearance. There is a need for the mapping in particular of temporary water bodies at a regional scale in West African drylands, because they provide important ecosystem services to the local population.

Existing datasets provide a valuable collection of surface water maps based on topographic map sheets, in-situ or remote sensing observations for Western Africa. These maps accurately portray perennial and well-known temporary water bodies. However, particularly small temporary water bodies are often missed due to their nature. Currently, the most comprehensive dataset of lakes and wetlands on a global scale is the Global Lakes and Wetlands Database (GLWD) (2004). It combines the best available data sources on water resources and is mainly based on the Digital Chart of the World (DCW) (ESRI, 1993). Although, temporary or intermittent water bodies are not included in the GLWD "lakes" class, seasonality in the wetlands class is provided, which includes 12 types of lakes and wetlands (Lehner and Döll, 2004). However, for the arid and semi-arid regions of sub-Saharan Western Africa in the GLWD, there is an absence of temporary water bodies, with mainly permanent or well-known temporary features mapped. The surface water body component of the African Water Resource Database (AWRD) (Jenness et al., 2007) includes amongst others the VMap0 (Government of Canada, 2008), which is a slightly updated and improved version of the DCW and the Shuttle Radar Topography Mission (SRTM) water body data (SWBD) (Slater et al., 2006). The SWBD generally displays surface water as depicted in February 2000, which corresponds to the dry season in the study area. In the rare cases of missing SRTM data, the SWBD relies on Landsat Thematic Mapper (TM) data from the 1990s.

There is an increased realisation that remote sensing can add valuable information to surface water datasets (The Ramsar Convention on Wetlands, 2002a; Jones et al., 2006). Most of the current continental scale datasets partly contain data based on remote sensing. Remote sensing allows for the multi-temporal mapping and monitoring of large areas covered with surface water, which may otherwise be inaccessible. The importance of remote sensing for wetland inventory and monitoring at all scales was emphasised several times by the Ramsar Convention on Wetlands based on studies, e.g. by Finlayson et al. (1999) and Lowry and Finlayson (2004). Various Earth observation systems can provide information about surface water resources and are employed depending on the specific application. Radar imagery provides information at any weather condition and can detect water under closed vegetation in specific circumstances (Rosenqvist et al., 2007). Nevertheless, there are temporal resolution and operational exploitation constraints. Radar altimeters can monitor reservoir and lake water heights in an operational manner with a higher time resolution, but there are limitations on the minimum size of detectable objects and their location under the satellite overpass (Alsdorf et al., 2007; Reynolds et al., 2007a). Optical remote sensing techniques have been widely used for mapping and monitoring wetlands (Phinn et al., 1999; Davidson and Finlayson, 2007). Single or multi-date high resolution optical imagery provides accurate local information (Coste, 1998; Harvey and Hill, 2001), but does not allow frequent monitoring over large regions. Coarse resolution sensors are an option for regional coverage at high time resolution (Verdin, 1996; Roshier and Rumbachs, 2004), but until now no operational surveillance of water resources was established.

The novel SWB dataset that is key to this study allows monitoring SWB and humid areas in near-real time in an operational manner at a high temporal resolution of 10 days. A time series of water body detections is available for the African continent starting from January 1999 until present (Bartholomé and Combal, 2006). In this chapter the time series between January 1999 and September 2007 was employed. The time series permits the extent and occurrence of temporary water bodies to be mapped and updated frequently, thus the TSWB map was named accordingly even though permanent water bodies are included as well.

Mapping based on this time series is a clear advantage compared to other mapping methods of water resources, which are mainly based on single date satellite observations or historical maps. Rather than being a new water resources dataset, the TSWB map aims to display the dynamics of surface water by incorporating both recurrent and erratic temporary water bodies.

This chapter addresses (i) the development of a mapping approach based on the SPOT VGT SWB time series, which is independent of ancillary datasets and is especially focused on mapping temporary SWB, (ii) the creation of a temporary small water bodies (TSWB) map for the arid, semi-arid and dry sub-humid regions of sub-Saharan Western Africa and (iii) the attribution of seasonal recurrence and hydrological function information to each pixel in the TSWB map.

2.2 Study area and datasets

2.2.1 Study area: arid and semi-arid sub-Saharan Western Africa

The study area comprises the arid and semi-arid zones of sub-Saharan Western Africa and the adjacent dry sub-humid zone. These zones were derived from a 1 km resolution aridity index map (Hartley et al., 2007) based on monthly temperature and rainfall layers in the WorldClim dataset (Hijmans et al., 2005) and climate zone thresholds (UNESCO, 1979; Estrela et al., 1997). Water bodies were mapped for the whole African continent but were validated only when they occurred between 17° W to 26° E and 8° N to 20° N in the arid, semi-arid and adjacent dry sub-humid climate zone (Figure 1-1).

2.2.2 The SWB dataset

Information about SWB is derived from the SPOT VGT sensor that provides daily global information of the Earth surface at 1 km spatial resolution (CNES, 1999). The first satellite component VGT 1 was launched on 24 March 1998 onboard the SPOT 4 satellite, while the second instrument VGT 2 was launched on-board SPOT 5 on 4 May 2002.

Operational exploitation is currently planned to continue at least until 2012 providing a homogeneous data set covering a 15 years period (Bartholomé, 2006).

The SWB identification is based on SPOT VGT-S10 (10-day synthesis) Maximum Value Composites (MVC) in which the “best” ground reflectance values are retrieved if they correspond to the highest Normalised difference vegetation index (NDVI) (Equation 1) value during the 10-day period, i.e. a dekad[6] (CNES, 1999). The starting day of each dekad is set to the 1st, 11th and 21st of each month.

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$

The NDVI is determined from measurements in the red spectrum (RED) and the near-infrared spectrum (NIR) and can be directly related to the photosynthetic activity and energy absorption of plant canopies (Tucker, 1979; Sellers, 1985; Tucker et al., 1985; Myneni et al., 1995). Atmospheric influences increase the spectral value of the RED more than the NIR, thus the highest NDVI value will lead to the “best”, least contaminated signal. The same MVC method is employed to derive the SPOT VGT-S1 (daily synthesis) images on which the VGT-S10 images are based. VGT-S1 images include the “best” ground reflectance measurements of all segments received during one day for the same geographical area. Since the areas distant from the equator have more overlapping parts the choice for the “best” pixel will be out of more data for these regions (CNES, 1999).

Clouds were identified and masked on the VGT-S1 images until 10 May 2001 through a set of empirical thresholds. Based on the extensive analysis of VGT data during these first three years of operation, this method was replaced on 11 May 2001 by a new algorithm (Lissens et al., 2000). The information about clouds is stored in a separate file and provided with the data (Bartholomé, 2006).

[6] The term dekad is used hereafter in relation to SPOT VGT products for which it was designed.

To remove remaining clouds in the SWB data that occur, in particular, during the rainy season in the study area, a water body pixel is only confirmed if it was already detected on the previous 10-day SWB map. Thus, an influence of clouds on the regional averaging, which leads to the detection of a water body pixel as explained in the following section, was minimised.

The dekadal MVCs clearly show water bodies and humid vegetation, yet simple image classification does not provide sufficient results, because the spectral signatures vary together with the ecological conditions of these surfaces. To overcome these limitations Gond et al. (2004) developed a robust contextual algorithm, which takes into account local contrast and is described briefly hereafter. Figure 2-1 shows a representation of the algorithm to derive the dekadal SWB maps using the Gond et al. (2004) methodology. Since surface water highly contrasts with the surrounding in arid and semi-arid regions Gond et al. (2004) generated an index of local contrast with values ranging from zero to one determining the difference between the regional average (i.e. the mean value computed on a moving window of 45 by 45 pixels - about 2025 km²) and the actual pixel value of either the original short-wave infrared (SWIR) channel or derived channels like the NDVI and the Normalised Difference Water Index (NDWI) that is used for remote sensing of vegetation liquid water from space (Equation 2) (Gao, 1996).

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \qquad (2)$$

The SWIR is absorbed by water, which is present as water bodies or as water contained in plant cells. The NDWI increases with vegetation water content and from dry soil to free water, and can detect also drainage patterns in green vegetation areas, which indicates its sensitivity to liquid water in vegetation (Gao, 1996). A 20 km coastline buffer was used to ensure that only land surface values were included in the moving window since sea surface values would lead to unwanted detection.

Values of local contrast close to zero show surfaces that are typical for the region whereas values different from zero show anomalies, such as water bodies or humid areas. With simple thresholds, these specific surfaces are selected in the image and depending on the value the state of surface water is defined for each pixel of each of the 36 dekads in a year (Gond et al., 2004; Bartholomé and Combal, 2006). Detected pixels can belong to three categories: free water, humid area or a mixture of free water and humid area. Free water is defined as an open water surface in contrast to humid area, which describes waterlogged ground with a high amount of vegetation content, either floating or growing inside or on the fringe of the accumulated water.

The difference between the average and the original value of the difference between NDVI and NDWI are computed and compared with a threshold to extract free water (Figure 2-1, Level 1). The same procedure is applied on the SWIR channel. If both procedures indicate the presence of water (Figure 2-1, Level 2) the pixel is flagged as free water (Figure 2-1, Level 3). To extract humid areas with vegetation, the same procedure is applied, but for NDVI and NDWI independently. In this way each 10 days SWB map is produced that results in a SWB time series marked in grey in Figure 2-1 (Level 4).

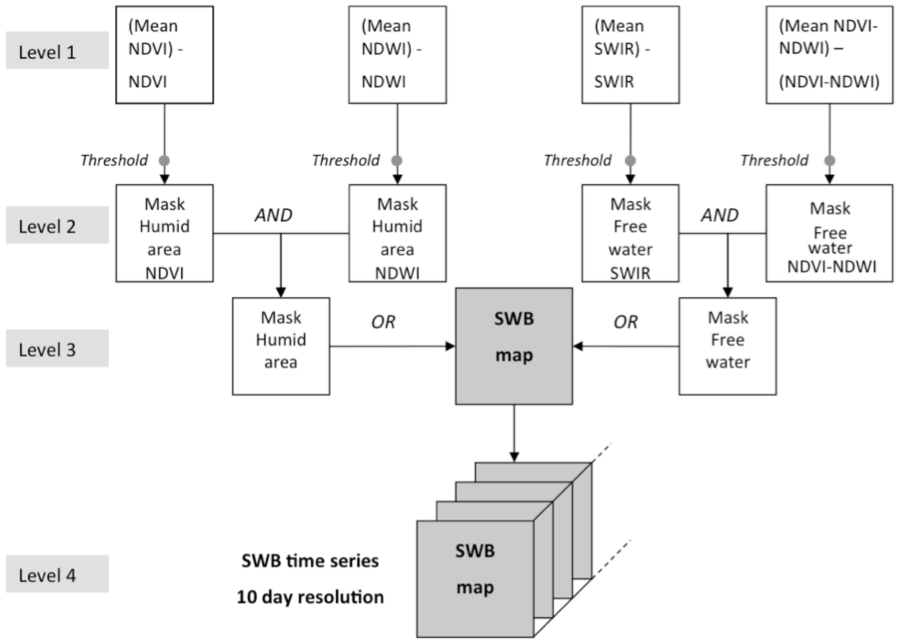

Figure 2-1: The visual synopsis of the algorithm to derive the dekadal SWB maps based on the method description in Gond et al. 2004.

The geometrical accuracy of the SPOT VGT data of less than 160 m co-location accuracy for VGT 2 allows construction of a reliable time series. However, potential errors caused by the change from VGT 1 to VGT 2 and inherent geometrical errors have to be taken into account that can influence the accuracy of the SWB detection and thus the time series (Bartholomé, 2006). The satellite location can be estimated normally with a location accuracy of 10 m while the absolute altitude measurements can lead to a 0.5 km RMS location error in the images. This relatively large error was corrected with ground control points for the VGT 1 instrument onboard SPOT 4, whereas for VGT 2 more accurate measurements provided by a star tracker mounted onboard the SPOT 5 platform allowed to reach a 50 m accuracy without the use of ground control points. The star tracker uses stars measured position to estimate the satellite's attitude with an accuracy better than 0.01°. The satellite relative attitude movements during the viewing can be neglected on a short viewing but lead to a location error of 0.5 km between the first and last lines of very long segments.

Also, mis-registration of the four cameras can lead to an error of about 0.1 pixel. Segments or scenes can differ slightly over a long time period also due to the pre-processing and data treatment. A more detailed description of the geometrical modelling and potential errors can be found in the VGT4Africa user manual (Bartholomé, 2006).

The recurrent observation allows to determine the seasonality of each pixel, i.e. when replenishment started and when drying out was completed (Bartholomé and Combal, 2006). Figure 2-2 shows representative time series of different types of pixels detected by the SWB dataset.

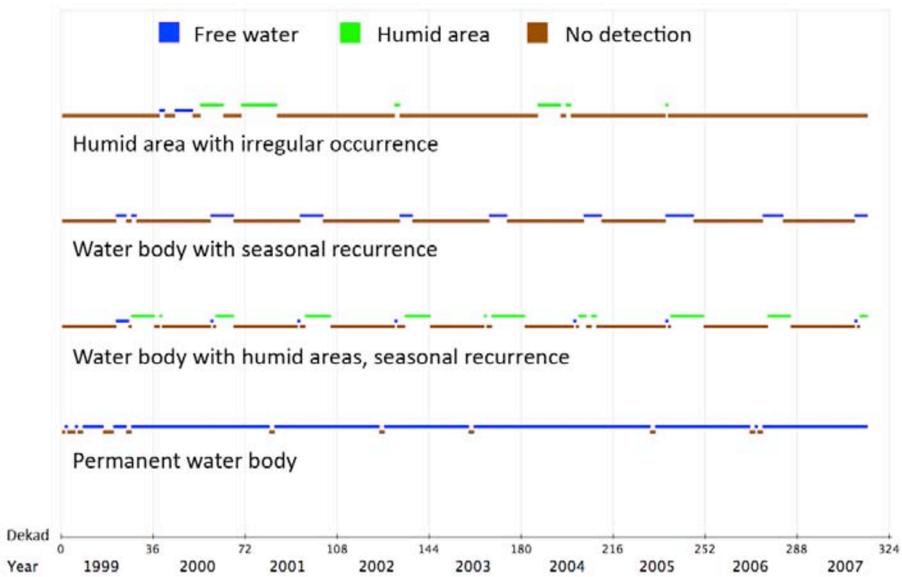

Figure 2-2: Time series of representative types of pixels detected by the SWB dataset between January 1999 (dekad 1) and September 2007 (dekad 315). Pixels can be detected as free water, humid area or a mixture of free water and humid area. The latter is rarely detected.

It can be seen that the type and temporal behaviour of detected pixels displayed in Figure 2-2 clearly characterise the detected water body. Water bodies that are mainly detected as free water (blue) are either permanently present or reveal a temporal pattern, characterised by alternating periods of detection and no detection (brown) during the dry season. Water bodies that are mainly detected as humid areas due to their vegetation content (green) can reveal seasonality, too, indicating that they are replenished frequently. More infrequent detections characterise erratic temporary water bodies and humid areas. The evolution over time clearly shows the type of water body or humid area detected. Changes in this behaviour can indicate changes in the ecosystem that influence the seasonality.

SPOT VGT SWB maps are available for each dekad for the African continent from January 1999 until present. The water body detection and the seasonality products are updated in near-real time and distributed in an operational manner by the VGT4Africa (DevCoCast) project[7]. The SWB time series between the first dekad of January 1999 and the last dekad of September 2007 was considered (315 dekads) for the development of the TSWB map. This time series covers nine rainy seasons and ensures that early rain events are included in the wet year 1999 as well as the flood events that took place in August and September 2007 in sub-Saharan Western Africa (FAO/GIEWS, 1999; FAO/GIEWS, 2007).

2.2.3 Datasets for accuracy assessment

Medium to high resolution satellite images are a good surrogate for costly and difficult field surveys and are frequently used in sub-continental scale studies (Congalton and Green, 1999; Foody, 2002). Landsat TM quicklook images do not provide the same high spatial resolution and geometrical accuracy like the original images. However, cost efficiency, the easy availability and the possibility to choose the date when water bodies can be observed justified the choice for their use in this study. For a nine year time series, not one single acquisition date but rather a period of time was chosen for selecting the quicklook images. Since 1999 was an especially wet year most of the water bodies were expected to be replenished. To obtain cloud-free quicklook images a period after the rainy season between October and December 1999 was selected (Gond et al., 2004). Georeferenced quicklook images from various high resolution sensors were obtained from the USGS Global Visualization Viewer archive[8], as well as Landsat TM quicklook

[7] http://www.devcocast.eu (last accessed 11th November 2009)
[8] http://glovis.usgs.gov/ (last accessed 11th November 2009)

images from the USGS EarthExplorer database[9] that were roughly geometrically corrected. Another high resolution dataset was accessible via Google Earth[10]: the Global Mosaic[11], which is a high resolution global image mosaic of Landsat TM scenes between the years 1999 and 2003. Google Earth provides a mosaic of images of different origin, resolutions and acquisition dates. Temporary water bodies are therefore not necessarily present at the time of acquisition but the distinct traces of water can be identified, which turns Google Earth into a useful decision support tool for the accuracy assessment. Ancillary information was also used to provide interpretation confidence. Level 3 of the Global Lakes and Wetlands Database (GLWD-3) is a global raster map of lakes and wetlands, which includes reservoirs and rivers at 30 arc second (about 1 km) spatial resolution (Lehner and Döll, 2004). This dataset was completed by the potential river network from WWF HydroSHEDS (Lehner et al., 2008), which is based primarily on elevation data obtained during NASA's Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick, 2000). It gives an indication about the potential drainage network and good co-registration was found with the TSWB map.

2.3 Time series analysis for the mapping and classification of temporary water bodies: Overview of methodology

There are five components to the methodology and corresponding results:

(1) Mapping temporary small water bodies (TSWB) from the SWB time series.

(2) Accuracy assessment of the TSWB map.

(3) Mapping the seasonal recurrence of each TSWB pixel from the SWB time series.

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[9] http://earthexplorer.usgs.gov/ (last accessed 11th November 2009)
[10] http://earth.google.com (last accessed 11th November 2009)
[11] http://onearth.jpl.nasa.gov/WK/ (last accessed 11th November 2009)

(4) Classification of each TSWB pixel according to its hydrological function from the SWB time series and ancillary datasets.

(5) Mapping humid areas from the SWB time series.

The process of mapping and characterisation is shown in Figure 2-3.

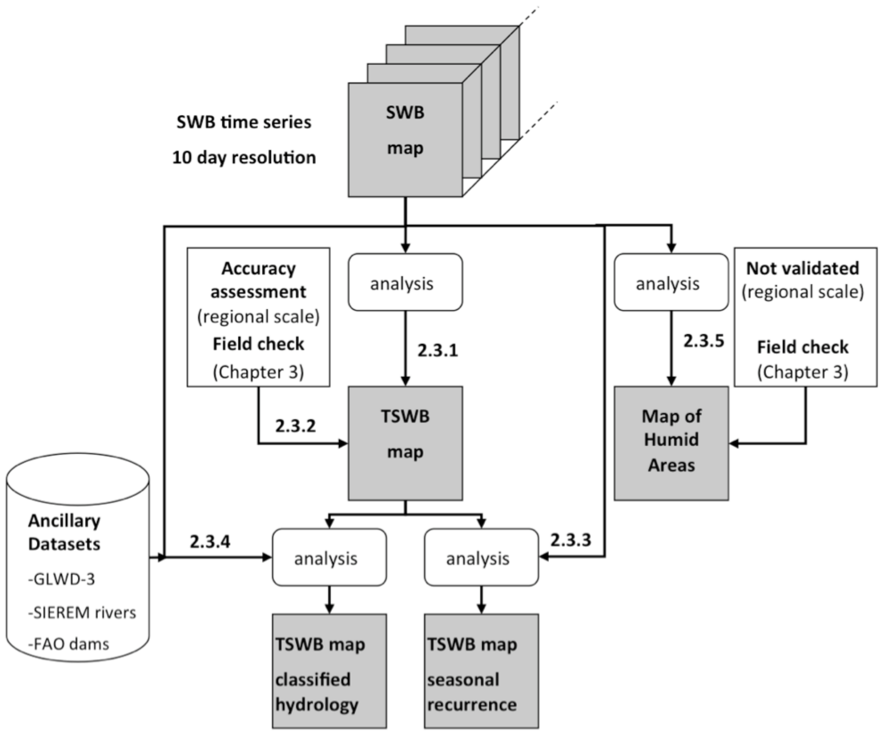

Figure 2-3: Overview of the methodology to derive the TSWB map and the map of humid areas. For each pixel in the TSWB map the seasonal recurrence and the hydrological functioning are identified by SWB time series analysis. For the classification of the hydrological functioning also ancillary datasets are used. The numbers in the flowchart refer to the sections of this chapter.

In a first step, the SWB time series was analysed twice with different criteria to identify temporary water bodies and humid areas. The first analysis resulted in the TSWB map, the second in the map of humid areas (Figure 2-3). Only the TSWB map was validated at a regional scale.

Based on the validated TSWB map the SWB time series was analysed again to attribute the seasonal recurrence and the hydrological function to each pixel in the TSWB map. Ancillary datasets were employed in addition for the identification of the hydrological function. The resulting maps are marked in grey in Figure 2-3.

2.3.1 Mapping temporary small water bodies (TSWB)

In a previous study (Haas et al., 2006) the SWB time series was analysed over most of Western Africa to derive an initial TSWB map. This map was then systematically validated by visual interpretation of high resolution satellite data. In the thesis, an advanced method to extend the mapping geographically and to exploit the SWB time series until 2007 was developed, which differs from the previous study in the following points:

- The validation is based on a rapid assessment of the detected water bodies as opposed to a time-consuming systematic visual validation.
- Short duration water bodies are now included whereas they were discarded in the previous study to remove potential false detections.
- The type of detected water body is characterised.

The analysis of the time series is concentrated on “free water” detections, for which a high accuracy could be assumed based on findings of the previous study. A water body is likely to change the state of surface water over its seasonal presence and over several years. This changing state of surface water was implemented in the method to derive the TSWB map, where humid areas were considered as water bodies if they were identified at least once as free water. Pixels only detected as humid areas were mapped separately in the map of humid areas (see 2.3.5).

False detection due to the confusion between cloud or atmospheric contamination and short-term flooded areas is a key issue in the SWB dataset. This is particularly true during the rainy season when cloud cover occurs more frequently. The underlying assumption for removing false detections from the TSWB map was that cloud cover occurs randomly. The probability of a false detection, due to clouds, to be observed twice at the same place is very low. A short term flooded area is likely to be flooded again at some point in the time series between 1999 and 2007, which includes two very humid years. Therefore, every pixel detected only once in the 315 dekads of the SWB time series was considered as noise and was removed.

Water body pixels were identified using the following criteria (Equation 3):

If $n > 1$ and $nf \geq 1$ then

$$Vp = \frac{100nf}{nf + nh + nm} \qquad (3)$$

Where n is the number of dekads the pixel is detected in the time series; Vp is the percentage of free water occurrence during the period the pixel was observed in the time series; nf the number of dekads the pixel is detected as free water in the time series; nh the number of dekads the pixel is detected as humid area in the time series and nm is the number of dekads the pixel is detected as mixture of free water and humid area in the time series.

The result is a raster map representing surface water bodies at 1 km resolution with a spatial extent between 17° W to 26° E and 8° N to 20° N in the arid, semi-arid and dry sub-humid regions of Western Africa (Figure 2-4). The value of each pixel indicates the percentage of detection as free water and humid area in the time series between 1999 and 2007 (Figure 2-4).

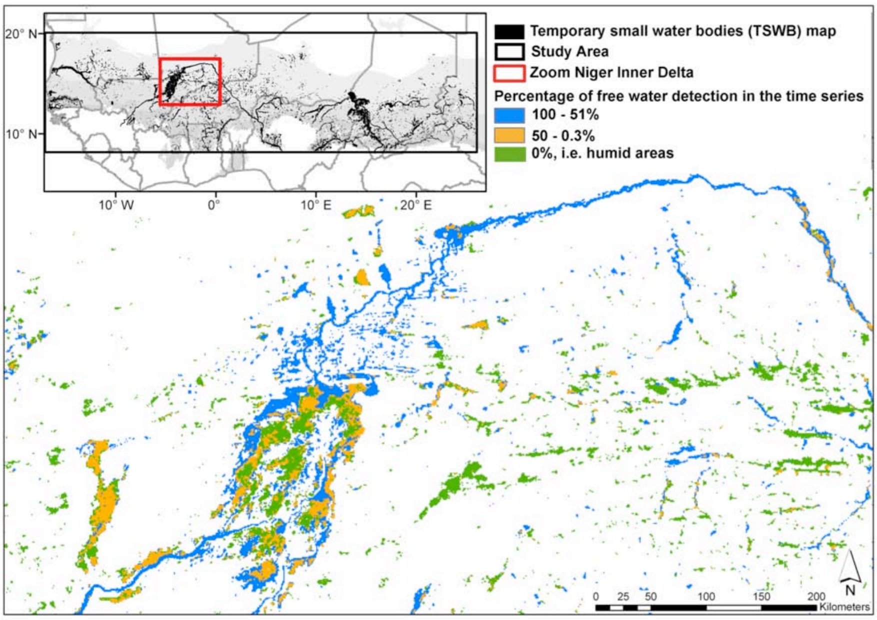

Figure 2-4: The TSWB map of sub-Saharan Western Africa, including in particular small temporary water bodies. A zoom to the Niger Inner Delta, Mali, shows the percentage of detection as free water and as humid area in the time series for each water body pixel between January 1999 and September 2007.

Figure 2-4 shows the potential of the TSWB map to characterise mapped water bodies in open water surfaces (blue) and areas with increased vegetation growth (orange). This environmental information is especially important in large wetland complexes like the Niger Inner Delta where areas of surface water alternate with humid areas. The map of humid areas (green) is complementary to the water body observations because it provides information about increased vegetation cover in relation to surface water that is not directly detected as such.

2.3.2 Regional scale accuracy assessment of the TSWB map

A combination of cluster sampling and stratification was proven to achieve cost-effectiveness and precise class-specific estimates (Stehman et al., 2003), therefore a stratified random sampling approach with one-stage cluster sampling was chosen to access the accuracy of the TSWB map.

2.3.2.1 Sampling design

The primary sampling unit (PSU) is a cluster (hereafter called grid cell) of 0.5° x 0.5° (about 56 km x 56 km). The secondary sampling unit (SSU) is the 1 km x 1 km water body pixel. In a one-stage cluster sampling, all SSUs within each sampled PSU are selected in the sample (Stehman, 1999). Two strata were defined: (i) the climate zone and (ii) the percentage of surface water coverage per PSU.

A climate zone stratum was chosen since the water body detection algorithm works best in sparsely vegetated areas. The three climate zones (arid, semi-arid and dry sub-humid) were overlaid by the 0.5° grid, leaving out grid cells where no water bodies were detected. A grid cell belongs to the climate zone stratum in which its centre is located.

Water bodies are not equally distributed throughout the region. Therefore, the second stratum level is based on the percentage of surface water coverage per grid cell. This second stratification imposed on each climate stratum assured the availability of a sufficient amount of pixels for validation by avoiding an over-sampling of grid cells with few water bodies. In each climate stratum the percentage coverage values of the grid cells were divided into four classes according to quartile thresholds established separately for each of the strata. In this way extremely sparsely and extremely widely covered grids were regarded separately (Figure 2-5). As there is only one category to be verified, the sample size was defined as approximately 10% of the total amount of grid cells per climate zone stratum, which led to 100 samples as recommended for large areas by Congalton and Green (1999). The ratio between the grid cells in the strata is 40:40:20 for the arid, semi-arid and dry sub-humid zone, respectively.

Thus, there are ten randomly selected samples for each of the four classes of the arid and semi-arid strata and five samples for each class of the dry sub-humid stratum. Figure 2-5 shows the distribution and properties of the PSUs and selected sample sites.

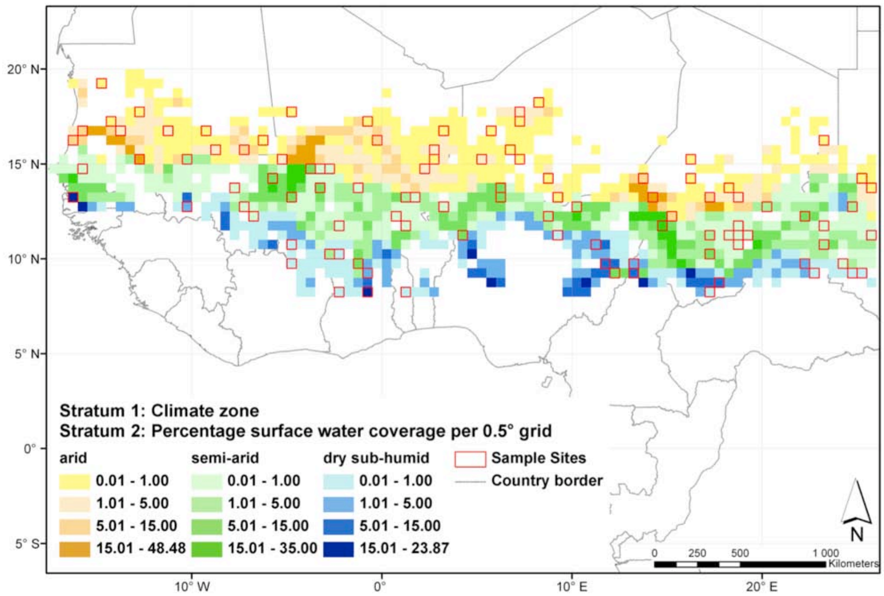

Figure 2-5: Sample sites defined by two strata, the climate zone and percentage surface water coverage per 0.5° grid. The latter is subdivided into quartiles, which provide four equally populated classes according to the maximum percentage of water body coverage in the climate zones.

2.3.2.2 Results of the accuracy assessment

Knowing that the algorithm for the detection of water bodies works best for the arid and semi-arid regions of sub-Saharan Western Africa (Gond et al., 2004), also the dry sub-humid zone was validated to verify this assumption and to understand to which extent the map can be used in this climate zone. The results derived in the accuracy assessment, regarding only the commission error, are shown in Table 1.

The high percentage of valid pixels confirms the initial assumption that the detection algorithm works best in arid and semi-arid regions with a sparse vegetation cover and no topography.

Table 1: Results of the accuracy assessment for the arid, semi-arid and dry sub-humid climate zones (first stratum) regarding only the commission error.

Climate zone	Validated pixels: total	Validated pixels: correct	Validated pixels: false	Percentage of valid pixels
Arid	4457	4399	58	98.7
Semi-arid	4838	4590	248	94.9
Dry sub-humid	2637	2447	190	92.8

Only the commission error was determined because the TSWB map is a synthesis of the SWB input data that was validated considering both the commission and omission error. The validation of the SWB data was carried out in a region representative for the study area, using 32 Landsat-7 ETM+ scenes and experts knowledge (Gond et al., 2004). Approximately one third of the water bodies present in the high resolution images used for the validation were not detected with the contextual algorithm and the method delivers a higher omission than commission error. However, most of the non-detected water bodies identified in the high resolution images were smaller than the 1 km SPOT VGT spatial resolution (Gond et al., 2004). This corresponds to the findings obtained at a regional scale during the accuracy assessment. The omission error was accepted since the aim was to reduce the commission error in order to assure a reliable detection of surface water (Gond et al., 2004). Since every pixel detected with the SWB input data was included in the TSWB map apart from singular detections the omission error can be expected to correspond to the one observed by Gond et al. (2004) even though it is likely to vary throughout the region. The results showed that the removal of singular detections to derive the TSWB map is a good measure to remove false detections caused by clouds. The low commission error obtained by the regional scale accuracy assessment supports this.

However, potentially valid singular water body detections are removed as well, thus contributing to the omission error. The high accuracy obtained at regional scale could be also due to the fact that a binary class (water body or non water body) was validated and no further distinction was made. Most observed false detections had other causes than clouds such as soil properties, topography or increased vegetation cover that cannot be removed because they exhibit various temporal profiles. Possible reasons for false detections and the influence of the second stratum, the percentage surface water coverage per 0.5° grid, became clear when regarding the detailed results obtained for the arid and semi-arid climate zone (Table 2). In these climate zones the highest accuracy was obtained and the algorithm was expected to work best.

Table 2: Results of the accuracy assessment for the arid and semi-arid climate zone (first stratum) regarding the percentage surface water coverage per 0.5° grid (second stratum), considering only the commission error.

Percentage grid coverage Arid / Semi-arid	Validated pixels: total	Validated pixels: correct	Validated pixels: false	Percentage of valid pixels
Very sparsely covered	26 / 32	9 / 22	17 / 10	**34.6 / 68.7**
Sparsely covered	101 / 209	98 / 196	3 / 13	**97.0 / 93.7**
Widely covered	472 / 1009	438 / 850	34 / 159	**92.7 / 84.2**
Very widely covered	3858 / 3588	3854 / 3522	4 / 66	**99.8 / 98.1**

The percentage of detected valid pixels varies among the four classes of the second stratum but shows the same sequence for both, the arid and the semi-arid climate zone. The lowest percentage of valid pixels was found for very sparsely covered grids. This class indicates very dry areas where only some single water bodies were found. It is likely that detections in such regions are false detections, often caused by differences in soil colour due to duricrusts. Sparsely covered grid cells with several small water bodies are most common in the study area. In this class, a high percentage of detected pixels were valid, which showed the reliability of the detection algorithm. Grid cells covered widely with surface water are an indication for more humid and thus more vegetated areas. There, the detection of densely vegetated areas that contrast from the surrounding can lead to increased false detections, as expressed by a declined percentage of valid water body detections. The still high amount of correctly detected pixels is due to larger water bodies present in these grid cells. Very widely covered grid cells indicate the presence of large water bodies like permanent rivers or wetland complexes. Since they are detected correctly, a large amount of valid pixels led to a high accuracy in this class. The overall accuracy of 96.7% obtained for the arid and semi-arid climate zone can be therefore also explained by the composition of the sampling sites. However, apart from the very sparsely covered class, the percentage of valid pixels derived for each class was in the range of the overall accuracy.

2.3.3 Mapping the seasonal recurrence of each TSWB pixel

The seasonal recurrence of each pixel in the TSWB map was derived from the SWB time series, thus identifying frequently and infrequently recurring water bodies. Seasonal recurrence is understood as the return frequency of a water body pixel across several years. A water body that recurs frequently during rainy seasons has different implications for the ecology of a habitat than a water body that occurs only in relation to extreme rainfall events. Nine seasons of SWB detections between March 1999 and February 2008 were observed. A season was defined according to the hydrological season in the study area rather than to the rainy season, since water bodies can last beyond the rainy season.

As most of the water bodies are drained before the end of February, the hydrological season was defined for each year from the first dekad of March until the last dekad of February of the consecutive year. For each pixel, the presence or absence in a hydrological season was determined. The result is the TSWB map of seasonal recurrence with values ranging between 1 and 9 as shown in Figure 2-6.

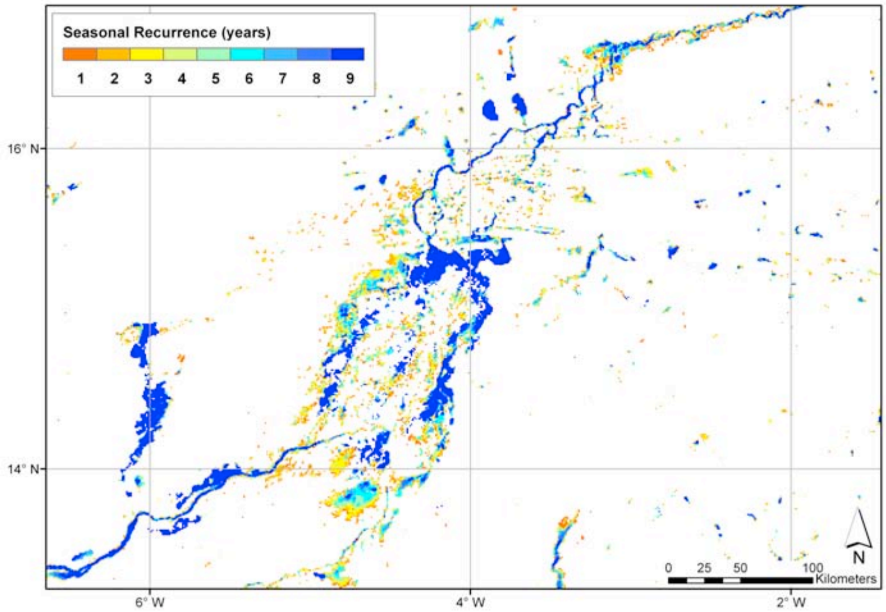

Figure 2-6: Example of the TSWB map of seasonal recurrence displayed for the Niger Inner Delta, Mali. Areas that are replenished every year are clearly visible (dark blue) as well as infrequently replenished areas (dark orange) such as floodplains. The varying extents of the delta, and especially areas that are not replenished in every season, can be seen in the southern section of the map.

Most of the pixels that are detected only in one out of nine observed seasons appeared in 1999 (results not shown). This year was one of the wettest years since 1950 (Balme et al., 2006). This finding confirms the potential of the TSWB map of seasonal recurrence to detect erratic water bodies that occur in relation to extreme rainfall events.

2.3.4 Hydrological classification of each TSWB pixel

The TSWB map contains surface water bodies with two different hydrological functions. *Class 1* comprises temporary features that are directly linked to local rainfall. *Class 2* comprises features that are influenced by large perennial river systems and their temporary floodplains with water coming from headwaters next to local rainfall. *Class 2* also comprises small and large permanent lakes and reservoirs where the hydrological regime is artificially influenced.

Four different sources of information were used to classify the TSWB map:

(1) The SWB time series provides information about the temporal characteristics of each pixel. Since some of the permanent features might not be mapped in the ancillary datasets, filtering was carried out based on the time series of each water body pixel. The criterion for a permanent water body is its presence during a year from January to December. The calendar year was chosen, since a temporary water body would not be visible during one entire year. A water body was considered as permanent when it was detected 11 to 12 months per year in at least one year. The analysis was carried out on monthly aggregates rather than on the dekadal SWB data to smooth the time series and remove noise, e.g. due to missing detections caused by cloud cover. For each month, the three dekads were checked for the pixels occurrence. No moving window was used. If the water body pixel was detected in one of the three states of surface water in at least one dekad it was mapped for this month and a raster map representing "permanent" surface water bodies was produced from the SWB time series.

(2) GLWD-3 lakes, reservoirs, freshwater marshes and floodplains were used to classify the TSWB map.

(3) The African dams database[12] provides information about large dams (height ≥ 15 m) and smaller dams if available. Even though an artificial water body might change its size according to the available rainfall amount, its hydrological regime differs from a natural water body. Therefore, any object linked to a dam was filtered from the TSWB map.

(4) The SIEREM database[13] attributes to each river its regime, temporary or perennial. This information must be regarded cautiously, because river regimes can change over time. The database was derived from various data sources of different dates, but the main perennial rivers can be clearly identified and were filtered from the TSWB map.

A key question is if pixels or objects should be filtered. The TSWB map is a raster map with each pixel being an independent detection. However, it is clear that neighbouring pixels form a water body and should be considered as a unique water body object. Transformation into vector format ensured that neighbouring pixels were grouped together.

The vectorised TSWB map was classified based on GLWD-3, the SIEREM rivers and the African dams database. A water body object in the TSWB map was labelled as *Class 2* if it either contained a GLWD-3 object, a permanent SWB, an African dams point or was crossed by a perennial river line from the SIEREM database. Every object that was not defined as *Class 2* was automatically labelled as *Class 1*. The TSWB map classified by hydrological function is shown in Figure 2-7.

[12] http://www.fao.org/nr/water/aquastat/damsafrica/index.stm (last accessed 1st April 2009)
[13] http://www.hydrosciences.org/sierem/ (last accessed 1st April 2009)

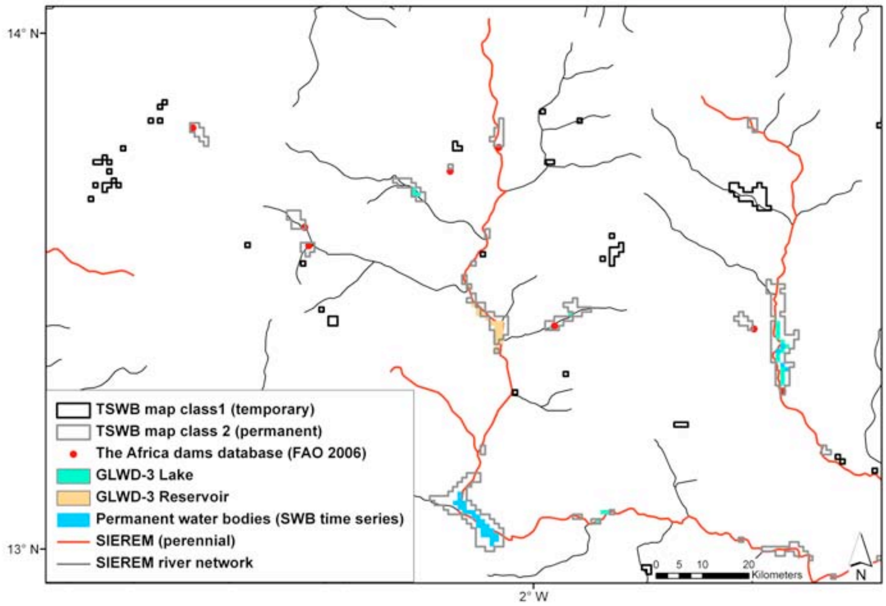

Figure 2-7: Example of the TSWB map classified according to hydrological functioning in temporary water bodies that are directly linked to local rainfall (Class 1) and permanent water bodies that are not solely linked to local rainfall (Class 2).

2.3.5 Mapping humid areas from the SWB time series

In arid and semi-arid regions humid areas indicate the presence of water, because water bodies are temporary and can drain quickly, leaving only a wet soil surface on which vegetation might develop. This indirect evidence of water is accurately detected in the dekadal SWB dataset. It was integrated in the TSWB map up to a maximum tolerance in the case of a water body being detected only once as free water. To identify pixels that were detected only as humid areas, the same method as applied for the free water detection was used (see Equation 3, 2.3.1). The number of dekads a pixel was detected as humid area (*nh*) was compared to the total amount of detections for this pixel. Singular detections were discarded in order to remove noise. If the value was 100% the pixel was included in the map of humid areas.

The resulting map provides useful information in addition to the TSWB map in areas composed of both surface water types, such as the Niger Inner Delta in Mali (Figure 2-4) or Lake Chad. It also shows humid areas that are not linked to a water body but indicate the presence of water. The map of humid areas has the same spatial resolution and extent as the TSWB map. No accuracy assessment was carried out since humid areas could not be validated with a high enough confidence rate at the regional scale. A local scale accuracy assessment of detected humid areas during the field survey in Niger, which is described in Chapter 3, provided useful information about the typology of humid areas that could be used for a future validation approach at a regional scale.

2.4 Comparison between the TSWB map and other surface water datasets

A comparison between the TSWB map and the map derived in the previous study (Haas et al., 2006) indicated that 24313 additional pixels were found with the current mapping approach. This increase might be attributed to the longer time frame used in the current study and the more restrictive criteria employed in the previous study. On the other hand, 30% of the pixels from the previous map were not mapped in the TSWB map. In the previous map, large wetland areas, which were detected entirely as humid areas in the SWB time series, were included. They were excluded in the TSWB map and stored in a separate map of humid areas. The combination of the TSWB map and the map of humid areas corresponds to 99% to the previous map. The high quality in mapping can be seen in Figure 2-8, where the TSWB map is displayed on a geometrically corrected Landsat TM quicklook image of October 1999. From this figure small water bodies are clearly visible. Most of them were not referenced in the other surface water databases.

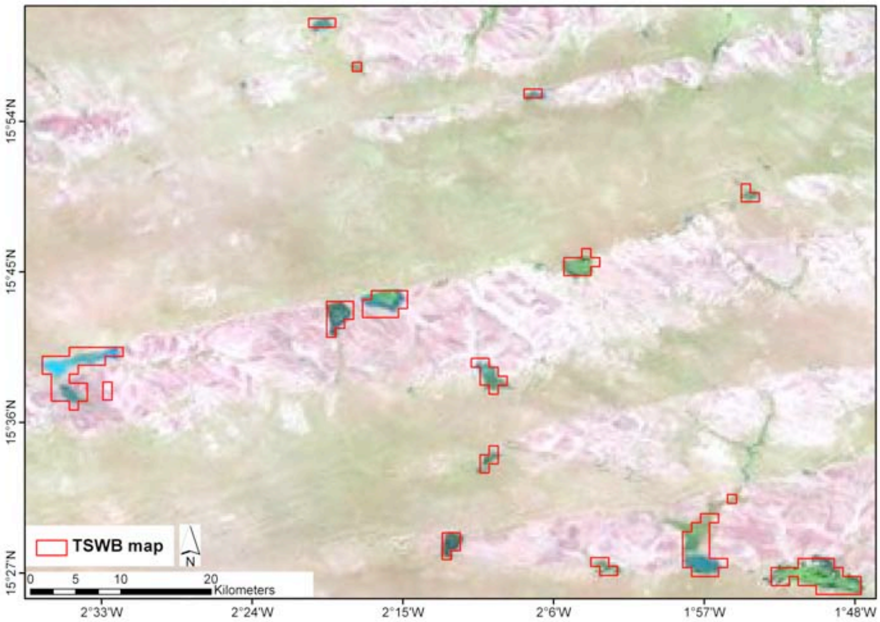

Figure 2-8: The vectorised TSWB map displayed on a geometrically corrected Landsat TM quicklook (Path 196, Row 49) of 20th October 1999. Detected small water bodies are clearly visible. Most of them were not referenced in the other surface water databases (Figure 2-9).

The particular area shown in Figure 2-8 (dashed box in Figure 2-9) is endorheic, the surface water is entirely dependent on rainfall and hence has high spatio-temporal variability. A comparison with other surface water databases showed that most of these temporary water bodies were only mapped in the TSWB map (blue areas in Figure 2-9).

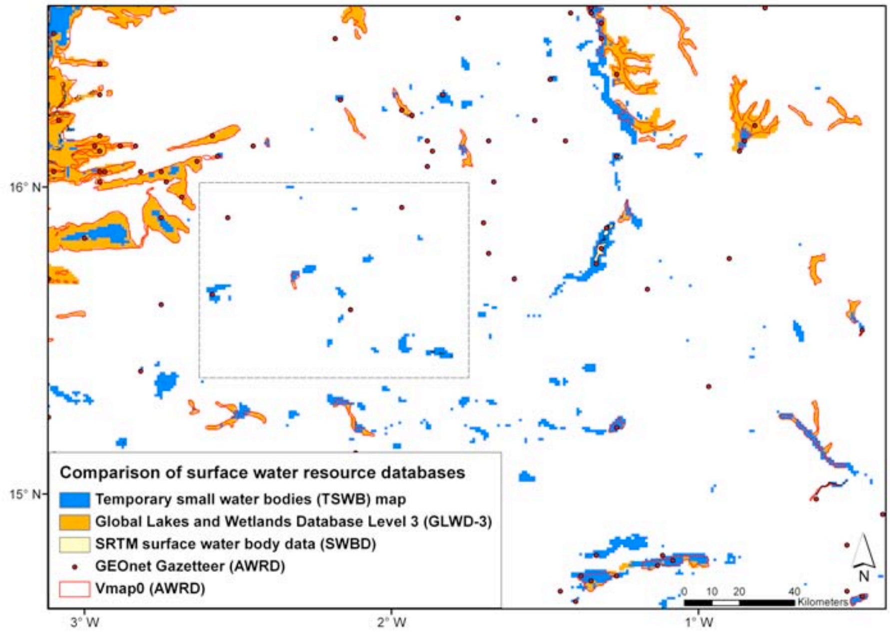

Figure 2-9: Comparison of small temporary water bodies as depicted in different databases: Temporary small water bodies map (TSWB map), SRTM surface water bodies (SWBD), Global Lakes and wetlands database Level 3 (GLWD-3), African water resource database (AWRD). Location: the southern endorheic part of the Niger Inner Delta, Mali). The dashed box marks the area displayed in Figure 2-8.

The TSWB map does not depict large features to the same extent as GLWD-3, because the latter includes information from historic maps produced during a wetter period than what could be observed during the 1999 to 2007 period used for the TSWB map. In addition, several sources of input data were overlaid, leading to an inclusion of the respective maximum extent in GLWD-3 (Lehner and Döll, 2004). From this point of view GLWD-3 provides a map of potential extent as it could be observed over the last century, whereas the TSWB map provides the actual extent observed during the last decade.

Of all features detected throughout the study area, small features prevail, with a majority detected in the range of the VGT pixel resolution of 1 km and, from 1 km to 10 km (Figure 2-10a). Like many other natural phenomena this distribution follows the Rank-Size distribution or power law (Newman, 2005), which shows a log-linear pattern. It is derived by a calculation of the natural logarithm of the water body size and rank (Figure 2-10b), where the largest objects have the lowest rank and the smallest objects have the highest rank. This finding shows the potential of the SWB dataset to depict in particular water bodies close to pixel resolution of 1 km while covering a large region like Western Africa.

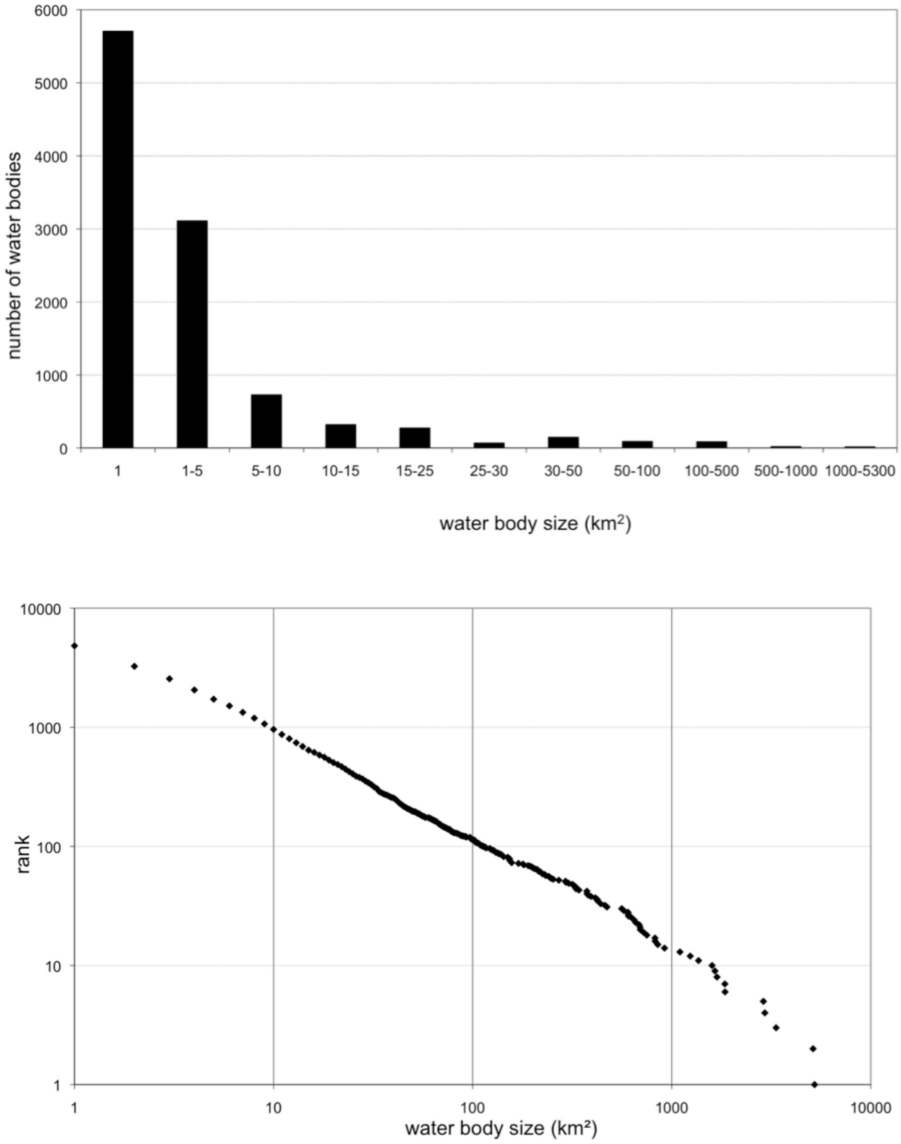

Figure 2-10 a and b: Distribution of the size of water bodies detected in the TSWB map.

2.5 Discussion

A 1 km resolution map of surface water bodies was derived for the arid, semi-arid and dry sub-humid regions of sub-Saharan Western Africa from dekadal water bodies detection between January 1999 and September 2007. The methodology tested here allows a frequent update of the map based exclusively on the SWB time series. The map comprises many small temporary water bodies that were not referenced in any other dataset before. This provides evidence of the usefulness of mapping based on the time series of a wide-field-of-view sensor. The focus of the SWB detection is on the seasonal occurrence of surface water in a 1 km pixel rather than on its exact shape and extent. For this reason no direct areal comparison was carried out with the AWRD surface water component, GLWD-3 or the SWBD. The latter would be the most suited but an elaborate methodology is needed that goes beyond the scope of this study. The map produced does not aim to substitute existing comprehensive datasets but adds valuable information about temporary water bodies to them. Used as a mask for an analysis of the SWB time series (see Chapter 4), the TSWB map increases the reliability of the results. It was demonstrated that the analysis of the SWB time series adds additional information to the TSWB map. The developed accuracy assessment, which is based on stratified random sampling and regards only the commission error, enables a rapid assessment of the TSWB map. Easily accessible and cost-efficient ancillary validation material was used as a surrogate for field surveys.

2.6 Conclusion

The need to improve existing global databases with new remote sensing products, expressed by Lehner and Döll (2004), could be met for the mapping of maximum extents of temporary water bodies in the arid, semi-arid and dry sub-humid regions of Western Africa. The findings obtained in this chapter show that new remote sensing products can add valuable information about temporary surface water to existing surface water datasets at a regional scale. The TSWB map was derived from one source of input data with worldwide coverage, thus a consistent picture of surface water in sub-Saharan Western Africa can be given for the period 1999 to 2007. It is suggested that the introduced method is also applicable to other arid and semi-arid regions in Africa and beyond.

In conclusion, the first research hypothesis addressing the reliability of water body observations by wide-field-of-view satellite sensors was not rejected for the regional scale. To understand if the high mapping accuracy also holds true for the local scale, a field survey was carried out in the Republic of Niger.

Chapter 3 Associating remote sensing detections of water bodies and humid areas with field observations in the Republic of Niger, Western Africa

Abstract

This chapter reports on the findings obtained during a field survey in the Republic of Niger, Western Africa. It adds to the first research question by testing the reliability of water body observations by a wide-field-of-view satellite sensor at a local scale. The remote sensing derived water bodies and humid areas were linked to ground observations for the first time. This provided an understanding of the typology of observed water bodies and humid areas and showed the potential and limitations of the remote sensing derived signal. The documentation of the test sites with georeferenced photos led to an inventory of water bodies in south-western Niger.

3.1 Introduction

The original development of the SWB algorithm to detect surface water bodies and humid areas was focused on Burkina Faso and areas in Mali and Niger between 9° N to 16° N and 3° E to 6° E (Gond et al., 2004). There, the validity of the water body detections was systematically assessed with high resolution satellite imagery, ancillary datasets and expert knowledge. The same type of validation material was used for the accuracy assessment of the TSWB map in Chapter 2, employing a stratified random sampling approach to cover a large region such as the arid and semi-arid sub-Saharan Western Africa. In arid and semi-arid regions, water bodies have a distinct shape and clearly differ in appearance from the surrounding land surface. Therefore, they can be reliably distinguished by visual interpretation of high resolution satellite images. On the contrary, humid area detections, which provide indirect evidence of locally available surface and sub-surface water, could not be validated with confidence using this same technique (see Chapter 2).

Humid areas comprise environmental features that cannot be identified clearly on high resolution satellite images. However, high resolution satellite images are commonly used as a surrogate for field surveys in regional scale studies (Congalton and Green, 1999) as they provide a coherent overview of the environment at a certain time, compared to the limited areal extent and overview of ground truth approaches. Nevertheless, knowledge of the attributes of the detected features on the ground is indispensable to fully understand and interpret the signal that is detected by the satellite.

To associate the remote sensing detections of water bodies and humid areas with field observations, a field survey was carried out in the Republic of Niger from 3rd to 18th December 2008, at the beginning of the dry season. The remotely sensed detections of surface water bodies and humid areas were then compared to the field observations. The Republic of Niger was selected for the field survey because it is representative of the Sahel region in terms of climate, vegetation cover, and type of surface water. The south-western part of Niger is characterised by the Niger River, its tributaries and temporary water bodies that reach sizes larger than 1 km^2. Since the focus of this thesis was on mapping and monitoring small temporary water bodies, Niger provided an ideal location to test the potential of the detection algorithm for different water body types. The algorithm was developed using the same geographical region, and information about the functioning of the extremely dynamic temporary water bodies in the study area existed due to extensive studies carried out by the HAPEX-Sahel project in the 1990s (Goutorbe et al., 1994; Prince and Goward, 1995; Goutorbe et al., 1997) and by the AMMER-CATCH observing system (Redelsperger and Lebel, 2009). In addition, the ability of the AGRHYMET centre[14] to provide scientific and technical support for the field survey led to the decision to carry out the local scale accuracy assessment of the regional SWB dataset in Niger. The objectives of the field survey were (i) to assess the accuracy and typology of water bodies and humid areas detected using remote sensing, (ii) to identify differences between water body and humid area detections, and (iii) to understand the reasons for and limitations of the detections.

[14] http://www.agrhymet.ne/eng/index.html (last accessed 11th November 2009)

3.2 Study area and datasets

3.2.1 Study area: south-western Niger

The field survey was carried out in the south-west of the Republic of Niger, in sub-Saharan Western Africa. The study area comprised the northern half of a circle, approximately 125 km in radius, centred on the capital city Niamey (Figure 3-1).

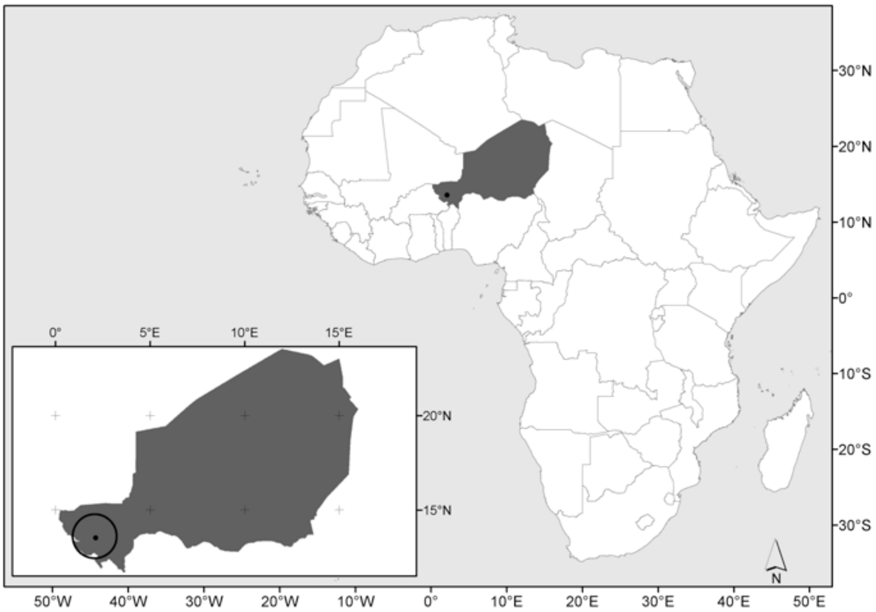

Figure 3-1: The location of the Republic of Niger in sub-Saharan Western Africa. The circle around the capital city Niamey marks the area observed during the field survey.

Both water bodies and humid areas were surveyed in three regions of south-western Niger. These regions all exhibit different landscapes and land surfaces, which has implications for the local ecological and hydrological regimes. The regions are listed below along with the survey dates. The surveys were documented with GPS tracks that were named according to the survey date and are shown in Figure 3-2.

- The region of eastern and western Niamey (03. 12. – 06. 12. 2008)
- The region of Tillaberi (10. 12. – 13.12. 2008)
- The region of Tera (15. 12. – 17. 12. 2008)

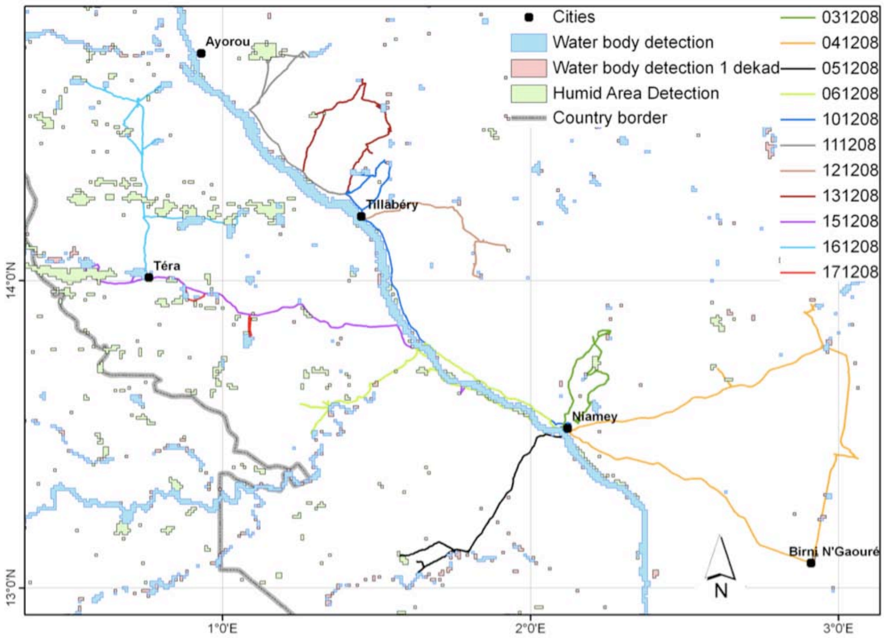

Figure 3-2: The water bodies and humid areas observed during the field survey. The numbers of the GPS tracks correspond to the survey date.

Situated in the heart of the Sahel at 16° N and 8° E, the Republic of Niger is characterised by a hot, continental climate with an average annual temperature of 29° C. Between mid-March and mid-May, maximum daily temperatures can reach over 40° C, and remain continuously above 32° C except during the peak rainy season in August (Cappelaere et al., 2009).

Mostly of convective origin, 90% of the annual rainfall occurs during the rainy season between June and September, with rainfall varying greatly between years within the 400 to 600 mm range. In the capital city Niamey, the mean annual rainfall is 557 mm (1943 to 2007, Niamey airport) (Favreau et al., 2009). Towards the north the amount of rainfall decreases along a gradient of approximately 1mm/km (Le Barbe and Lebel, 1997). The annual rainfall in the Niamey region is typically produced by 15 to 20 squall lines that each provide between approximately 15 to 40 mm of rainfall and around 20 smaller mesoscale convective events (Cappelaere et al., 2009). Niger is prone to drought conditions with the latest crisis occurring during 2005 and 2006 following the very dry year of 2004. In other years, for example 1999, 2007 and 2009, above-average rainfall occurred, which led to devastating floods in the area.

Two major landscapes dominate the study area: lateritic plateaus linked with sandy valley bottoms, and fossil sand dunes stabilised by vegetation. The region on the east bank of the Niger River, between Niamey and Tillaberi, and the region on the west bank up to Tera consist of repeated toposequences from the plateaus to the sandy valley bottoms, where temporary water bodies form during the rainy season. North of Tera the landscape changes and recent and fossil dune systems prevail (AGRHYMET, 1991b), which block the ancient drainage network provided by the valley bottoms. This results in endorheic water bodies forming at the foot of the sand dunes. These sand dune systems are also found on the east bank of the Niger River in the Tillaberi region but are less distinct (AGRHYMET, 1991b). In the eastern part of the Niamey region the ancient river valley of the Dallol Bosso, a long-inactive tributary of the Niger River, forms a distinctive landscape. The Dallol Bosso is associated with a 775 km long valley running southward from Mali and is characterised by a system of temporary and permanent water bodies that accumulate along the valley floor. Active temporary rivers originating in Burkina Faso dominate the landscape on the west bank of the Niger River that receives water from the six tributaries Gouroual, Dargol, Sirba, Gouroubi, Diamangou and Tapoa in the study area.

Figure 3-3 shows the detected water bodies and humid areas within the landscape of the study area, based on the 30 m ASTER Global digital elevation model (GDEM)[15].

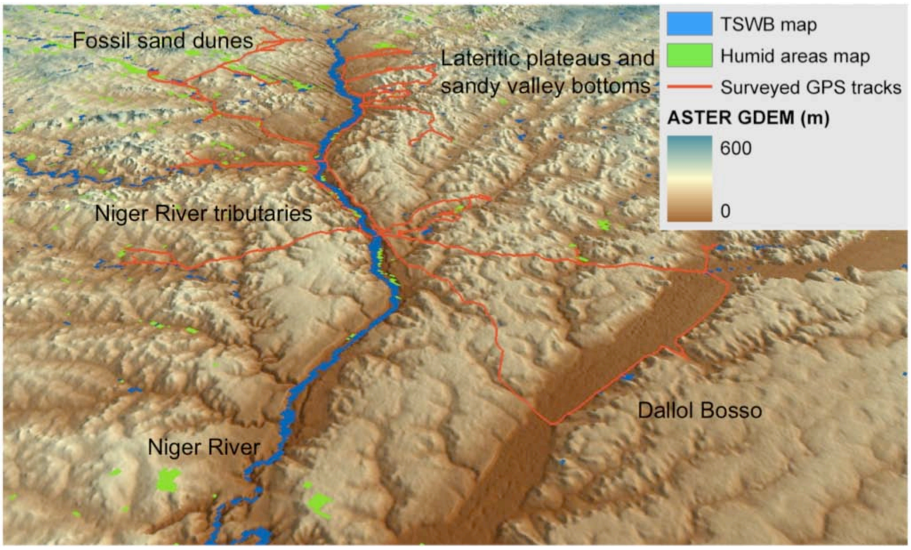

Figure 3-3: The landscape of the study area. Water body and humid area detections are displayed together with the surveyed GPS tracks on the 30 m ASTER GDEM (20 times exaggeration). The viewing direction of this figure is northward.

The natural vegetation in the study area is characterised by a herbaceous layer mainly composed of annual plants, mainly grasses, scattered bushes and low trees. Like elsewhere in the Sahel, the density and canopy cover of woody vegetation is generally low. The spatial distribution of woody vegetation is highly variable, with higher densities located along drainage networks, around water bodies, and in depressions between dunes. On shallow soils, such as is found on plateaus, bushes and trees can form a linear pattern known as tiger bush (White, 1970).

[15] http://www.gdem.aster.ersdac.or.jp/ (last accessed 6th November 2009)

The study area belongs to the cultivated Sahel that is roughly defined by the 400 to 800 mm annual rainfall isohyet. Local agriculture is mainly rain-fed and relies on traditional techniques (Cappelaere et al., 2009). The two major activities in the cultivated Sahel are mixed crop-livestock agriculture and wood harvesting for cooking, both of which modify the land-cover. Rapid population growth since the middle of the 20th century has led to an increase in rain-fed cultivated lands and fuel wood harvesting at the expense of the woody savanna habitat found naturally in the Sahel (Raynaut, 2001). In south-western Niger about 80% of the natural vegetation was cleared for agriculture, mostly rain-fed millet, and fuel wood between 1950 and 1992 (Leblanc et al., 2008). Cropped areas in south-western Niger have expanded at an annual rate of 2% since 1994 following, although with a declining rate, the Sahel-wide increase in cropped areas since the middle of the 20th century (Hiernaux et al., 2009). This trend is not only a result of plain area expansion of clearings, but also of changes in the relative extent of permanently cropped fields and fields under shifting cultivation, where fallow periods have been significantly reduced (Hiernaux et al., 2009). Sahelian soils are of low inherent fertility and require a long period of fallow to offset the negative impacts of a short period of cultivation (Valentin et al., 2004). In the absence of sufficient fertiliser input, reduced fallow periods lead to declining soil fertility, which threatens crop productivity. If fields are manured, livestock, rather than expensive inorganic fertilisers, are utilised (de Rouw and Rajot, 2004). Western Africa is the only part of the world where, overall, cropland expansion was accompanied by a decrease in fertiliser use (-1.83% per year) and just a slight increase in irrigation (0.31%) (Lambin, 2003). In the whole of the Republic of Niger, millet productivity was estimated to have decreased by one-fifth since the 1950s even though the amount of cultivated area increased. This led to increasing food supply difficulties for a fast-growing population (Cappelaere et al., 2009). Over the period 1994 to 2006 herbaceous yields decreased in the study area on cultivated and fallow fields, as well as on rangeland, at an overall mean annual rate of 5% due to factors such as declining soil fertility and increasing cattle pressure (Hiernaux et al., 2009).

Land-use and land-cover changes have severe hydrological implications since soil surface conditions, including soil crusts and vegetation cover, are key determinants for runoff generation (Casenave and Valentin, 1992; Cappelaere et al., 2009). Sahelian soils are characterised by crusted soils, low clay and organic matter content, and a low structural stability that leads to low infiltration and soil water-holding capacity, and the dominance of Hortonian type runoff (Descroix et al., 2009). Like natural vegetation, the presence of crops and cattle grazing commonly cause a reduction of the soil bulk density and an increased porosity, which triggers infiltration. However, since Sahelian peasants generally do not practice tillage and fallow periods have been reduced, this has resulted in soil compaction, which causes reduced infiltration and fosters runoff (Descroix et al., 2009). In south-western Niger the decrease in natural vegetation cover has modified the hydraulic properties of the topsoil leading to an increase in Hortonian type runoff (Valentin et al., 2004).

A given change in land-use and land-cover can lead to different hydrological responses, depending on the initial catchment characteristics. In some endorheic regions, such as in the study area, an increase in runoff provides an increase in available surface water. Recent research showed that the drainage density increased by approximately 2.5 times between 1950 and 1992 in south-western Niger. This included the development of more connected drainage systems with gullies and new water bodies, even though rainfall did not increase significantly during this time (Leblanc et al., 2008). An increase in the number of water bodies, and their extent and duration, was also observed in the Malian Gourma, although this is a pastoral area where few land-use changes have occurred. Recovered rainfall conditions since the end of the 1990s and the lasting impacts of the drought during the 1970s and 1980s, which reduced and changed the type of vegetation cover and led to increased runoff, could be reasons for this increase (Gardelle et al., 2009; Mougin et al., 2009). A continuous increase in runoff can even lead to endorheic catchments becoming exorheic. In originally exorheic catchments increased runoff causes increased discharge in rivers and a falling water table linked to the reduction of water infiltration. However, originally exorheic systems can also become endorheic due to an increase in transported sediments related to the increased runoff, which in turn leads to the silting up and closure of valleys by sand (Descroix et al., 2009). This increased sedimentation of the drainage courses and water bodies also prevails in the endorheic catchments of the study area. The mechanisms that lead to increased runoff and sedimentation were observed during the field survey and are described more in detail in section 3.5 in relation to the hydrological system in which they occur.

An increase in erosion and sediment transport due to land degradation is one of the major evolutions currently observed in Sahelian hydrology (de Marsily, 2003; Descroix et al., 2009). Favreau et al. (2009) identified the need to monitor and document the indirect impacts of land-use change on water quantity and quality in West African drylands as these were found to be of a greater influence than the direct influence of climatic variability.

3.2.2 Remote sensing derived datasets to be validated

During the field survey the following remote sensing derived datasets were validated:

- The TSWB map (see Chapter 2), including the seasonal recurrence.
- Singular free water detections not included in the TSWB map.
- The map of humid areas (see Chapter 2).
- SWB maps (see Chapter 2) of the last dekad of November 2008 and the first and second dekad of December 2008.

3.2.3 Supporting material

To locate the water bodies and humid areas to be validated and to gain additional understanding about their temporal behaviour and the surrounding catchment, the following supporting material was used during the field survey:

- A Global Positioning System (GPS) (Garmin GPSMAP 60Cx) for orientation and for mapping the locations of the surveyed water bodies, humid areas and the driven tracks. Inserting the TSWB map in the GPS assured that the targeted water bodies were observed and it allowed distinguishing the actual location in a detected pixel.

- High resolution satellite scenes of Landsat TM at 30 m spatial resolution that cover the study area (Table 3). The path and row numbers in Table 3 are based on the Worldwide Reference System 2 (WRS-2), a global notation system for Landsat 4, 5 and 7 data[16].
- Topographic map sheets Niamey, Gothéye, Dosso, Tera, Sebba and Ouallam at 1:200,000 scale produced by the French National Geographic Institute were scanned and georeferenced. The topographic maps rely on field surveys and aerial photos of the 1960s but are the only map sheets available for Western Africa. For the Tillaberi region a soil map at 1:100,000 that displayed water bodies was used in addition.
- SWB time series of water bodies and the humid areas under observation to assess their temporal profile as observed with remote sensing.

Table 3: The Landsat TM scenes employed for the field survey.

Path	Row	Acquisition date
192	50	15. 02. 2001
192	51	24. 11. 2002
192	51	09. 11. 1999
193	50	18. 09. 2001
193	51	02. 12. 1999
194	50	05. 08. 2000

The outlines of each water body and humid area under validation were superimposed on the respective close-up and regional scale satellite images and on topographic maps. These high spatial resolution satellite images and maps were printed and laminated. They provided useful support for orientation during the field data collection.

[16] http://landsat.gsfc.nasa.gov/about/wrs.html (last accessed 11th November 2009)

3.3 Field data collection at detected water bodies and humid areas

The aim of the field survey was to compare the remote sensing derived information about water bodies and humid areas to the ground reality. No specific quantitative measurement was performed at the water bodies or humid areas during the field survey. Instead, the focus was on visiting as many detected water bodies and humid areas as possible to get an overview of the typology and functioning of different hydrological systems in the study area. During an initial meeting with local experts from the AGRHYMET centre, the potential test sites were identified and the feasibility of reaching them was determined. The survey team consisted of Eva Haas, PhD candidate and author of this thesis, Dr. Etienne Bartholomé, senior scientist from the European Commission (EC) Joint Research Centre (JRC), and a number of local experts with backgrounds in hydrology, agronomy and geography. Each day two to three local experts accompanied the field survey team, and the following methods were used to obtain information about detected water bodies and humid areas:

- Semi-structured interviews with the local population based on a questionnaire.
- Test site documentation with photos, videos and a textual report.
- Mapping of locations with GPS.

A questionnaire was used during semi-structured interviews with the local population at each water body (see Annex). It was developed to identify the type of water body detected and the characteristics of its surrounding catchment. The most important questions targeted the water body size during the rainy season, its seasonality, the functioning of inflow and outflow, and the usage and typology of the observed water body. The interviews were carried out using the local language Hausa with the help of the local experts and also in French by the author and Dr. E. Bartholomé. For humid areas no specific questionnaire was developed although water availability, vegetation type and landscape features were documented at each site. The results of the semi-structured interviews were summarised for each test site in a textual report.

Each test site was also documented with photos and videos and was georeferenced with a GPS. The photo archive was then linked to the GPS tracks and locations to provide a comprehensive document of the observed water bodies and humid areas. To facilitate the visualisation the tracks and georeferenced photos were converted to a format that allowed a display on Google Earth. This georeferenced photo archive and the textual field report that document each surveyed water body and humid area, including the names of the relevant experts, are included with this thesis as an accompanying CD. A copy of the CD can also be obtained from the author at the contact email address provided underneath the questionnaire in the Annex. The photo archive and the textual report aided the subsequent analysis that focused on the typology of detected water bodies and humid areas and on the links between the ground observations and the remote sensing signal.

3.4 Potential and limitations of water body detections

The field survey gave an insight in the quality characteristics of both the TSWB map and the SWB maps that revealed the potential and limitations of a wide field-of-view sensor for the mapping of temporary water bodies. This local scale accuracy assessment of the TSWB map provided information about the minimum detectable size of water bodies and the quality of their detection.

3.4.1 Local scale accuracy assessment of the TSWB map

For the 36 water bodies detected with the TSWB map that could be reached during the field survey (Figure 3-2) their existence, or indications of their existence, was checked. As in the regional scale accuracy assessment (see Chapter 2), only the commission error was determined because no general mapping survey of water bodies could be carried out, nor did any independent water body maps exist that would allow identification of the omission error.

Only one detection turned out to be a false detection. This was a one-pixel detection located next to the town of Tera (14° 01' 32" N, 0° 46' 02" E) that was observed twice in the nine year time series. Figure 3-4 presents a photo taken during the field survey in the location of the false detection. It clearly shows the lack of surface or sub-surface water and the dark duricrust that caused the detection with the contextual algorithm due to its contrast with the paler, sandy surroundings.

Figure 3-4: The detected area that led to a false detection is characterised by a duricrust that contrasts from the sandy surroundings.

The local scale accuracy assessment confirmed the findings of the assessment carried out at a regional scale (see 2.3.2.2). However, the local scale assessment could not be regarded as exhaustive due to the limited spatial extent of the field survey compared to the regional scale of the TSWB map under validation. The results of the local scale accuracy assessment showed that the benefit of removing singular detections outweighed the risk of including false detections. Disregarding singular detections led to a low number of false detections and a successful inclusion of temporary short duration water bodies in the TSWB map, proven on both a local and a regional scale. In particular, clouds that occurred randomly and for a short period of time could be successfully removed with the singular detections.

However, relief and soil properties that did not show a specific recurrence pattern were more difficult to identify. To test the nature of singular detections that were not included in the TSWB map, a map of singular free water detections was validated during the field survey. It was found that singular free water detections corresponded to surface water when they were located on the potential river network from WWF HydroSHEDS (see 2.2.3). These detections were not added to the TSWB map since it would have required the inclusion of an ancillary dataset. This should be avoided to keep the TSWB map free from any errors that may already be present in the ancillary dataset. Singular free water detections that appear on the river network could be used in addition to the TSWB map to identify erratic water bodies. This aggregation would make the TSWB map even more complete.

The completeness of the TSWB map and the importance of remote sensing to detect surface water in remote regions became clear when the TSWB map was compared to a water body map of the Regional Environmental Service, or DRE (Direction Regionale de l'Environment) in Tillaberi (see Figure 3-2). The DRE is the local environmental service that is responsible, amongst others, for the inventory of water resources. Its database comprised only a fraction of the water bodies mapped in the TSWB map for the Tillaberi region. The further potential of a recurrent remote sensing detection became clear when considering the *Mare de Tem* (14° 43' 57" N, 1° 18' 02" E), an important temporary water body for pastoralists and the local population north of Tillaberi. This particular water body was not detected after 2005 using the SWB dataset. The local service was not aware of the fact that the large dam that created this temporary water body had burst during a period of extreme flooding in 2005.

3.4.2 Minimum detectable size of water bodies

The local accuracy assessment showed that all water bodies detected with the TSWB map existed on the ground apart from one false detection. However, the SWB algorithm did not detect several water bodies that were perceived as large by the local population. To understand how the size and shape of a water body influence the remote sensing detection, the TSWB map and the SWB map of the dekad covering the date of the respective field surveys were compared to ground observations. Since no quantitative measurements of size could be carried out during the field survey, the extent of the water bodies was visually assessed. Indirect evidence of the water body size during the rainy season was obtained by observing the landscape and from local farmers. In addition, the size of detected water bodies was determined from the high resolution satellite images. The size of water bodies observed on the ground and on the high resolution satellite images was found to correspond to the findings of Gond et al. (2004) who stated that water bodies close to the pixel resolution of 1 km could be detected. Water bodies that were approximately 600 m to 800 m in width and length could still be detected as at least half the 1 km pixel was covered by water. These are approximate dimensions since the size of water bodies was estimated visually, rather than measured. The minimum detectable size is expected to vary throughout the Sahel depending on surface characteristics.

Minimum detectable size also has consequences for the stability of the detection of a water body. The smaller the detected water body, the higher the possibility of losing the signal during the season due to changes in the surface water extent and limitations in the location accuracy of the satellite. A water body of a maximum size close to pixel resolution (1 km^2) would only be detected during its maximum extent and no information about its behaviour before and after it reached its maximum extent would be available. The inclusion of humid area detections that occurred in relation to free water detections (see 2.3.1) in the TSWB map allowed mapping of water bodies with a low water level. Even though they were not fully replenished the sediment and vegetation cover contrasted visually from the surrounding area, which allowed a detection using the SWB algorithm. Larger water bodies were found to provide more stable detections over time. Apparently temporary water bodies that were reliably detected with the SWB data could actually be permanently present on the ground, although the water surface remaining during the dry season was rather small (less than 1 km^2) compared to the extent reached during the rainy season. The local population considered such water bodies to be permanent. Based on these observations it should be emphasised that the SWB data should not be used on a per-pixel, but rather on a per-watershed or sub-section of large watershed, basis. This increases the stability of the detection and provides a framework for inferring the occurrence of water in small ponds.

The observed minimum detectable size was particularly critical for linear features such as rivers. These could only be detected during extreme events when the water also flowed in the flood plains alongside the river bed and the minimum detectable size close to the pixel resolution of 1 km was reached. It was discussed in Chapter 2 (see 2.2.2) that the SWB identification was based on SPOT VGT-S10 MVCs, in which the least atmospherically influenced, and thus highest, NDVI values were included. Therefore, the maximum vegetation cover was included rather than the maximum surface water area. As flooding is mostly related to local storm events, cloud cover present during this time that would diminish the NDVI value would also prevent the pixel from being selected in the MVC. For a flood event to be mapped with the SWB dataset, the flood waters must remain in place for more than 10 days. Hence, the SWB dataset was not suited to mapping short term flooding events. Since the TSWB map was based on a synthesis of nine years of dekadal SWB observations, the sections of a temporary river that were subject to longer-term flooding were displayed but mapping of an entire river was not possible (Figure 3-5). A different 10-day synthesis method would allow mapping of temporary flooding events if the removal of atmospheric noise could be assured. This would add valuable information to the existing TSWB map that was shown to successfully detect water bodies of 1 km^2 and larger.

3.5 Typology of detected water bodies and humid areas

Water bodies and humid areas observed with the SWB dataset exhibited different characteristics in the field, and as such were classified under a number of types. In the following section the environmental settings of observed water bodies and humid areas, their location in the landscape, and reasons for their detection with the SWB algorithm are discussed.

A typology of detected water bodies and humid areas was established based on field observations. Types A to C were distinguished according to the type of surface water flow exhibited and the landscape in which they occurred.

Generally, surface water flow occurs only temporarily in the study area during the rainy season except for the permanent Niger River. During the rainy season, water flow can be continuous (Type B) or erratic (Types A and C). Temporary water bodies (Types A and C) and temporary rivers (Type B) form during the rainy season in the ancient drainage network that was carved out during the wetter Holocene. Today, this drainage system is present as a network of sandy valley bottoms that are sporadically blocked by fossil sand dunes. These drainage courses are called *wadi* or *oued* in Arabic, *dallol* in the Djerma language, and *kori* in the Hausa language, which is predominant in the study area. Thus, the term *kori* is used in the following text to describe a drainage course that was originally formed by water but is distinguished from a river valley by the fact that surface water flow is only intermittent or temporary. Koris can vary greatly in size, ranging from large, temporary river beds to small gullies.

The following types of detected water bodies and related humid areas were identified during the field survey (Figure 3-5):

A. Temporary and permanent water bodies in koris

I. Ephemeral water bodies on the lowest parts of pediments (p. 71)

II. Temporary water bodies in koris (p. 73)

III. Areas of humid vegetation in koris (p. 77)

IV. Temporary and permanent water bodies in an ancient kori (p. 80)

B. Temporary rivers in koris

I. Large temporary rivers in koris (p. 81)

II. Small temporary rivers in koris dammed by roads (p. 82)

III. Areas of humid vegetation along small temporary rivers in koris (p. 83)

C. Endorheic temporary water bodies within fossil sand dunes

I. Endorheic temporary water bodies within fossil sand dunes (p. 85)

II. Areas of humid vegetation within fossil sand dunes (p. 86)

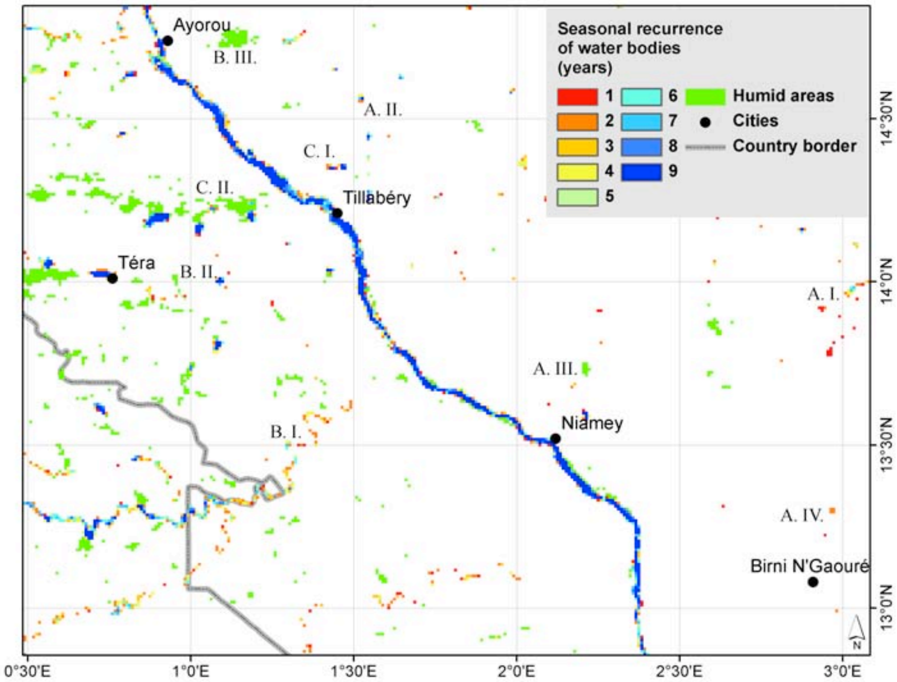

Figure 3-5: Types of water bodies and humid areas identified during the field survey in Niger. Water bodies are displayed with their seasonal recurrence (1 to 9 years) as attached to the TSWB map. Humid areas are displayed in green. The nomenclature corresponds to that used in the text.

A. Temporary and permanent water bodies in koris

The landscape in the Niamey region consists of dissected flat-topped lateritic plateaus that are often capped by thick, ferruginous duricrusts. This cemented ironstone or gravel can be covered with gravelly loam soils between 25 and 85 cm in depth or with up to 4 m of sand (D'Herbes and Valentin, 1997). A valley system starts below the relative steep plateau escarpments that can rise up to 100 m above the level of the Niger River (Leduc et al., 1997). Plateaus can be directly connected to the valley through sandy aeolian deposits that are continuous with the valley sands and are referred to as sandy skirts. Downslope iron-indurated layers are locally exposed. They are followed by a convex segment, which generally links the slope to the drainage network that lies in the sand-filled valley bottom or kori below (D'Herbes and Valentin, 1997).

A typical landscape of the Niamey region thus includes three main areas: the plateau, the sandy skirt and the sandy valley bottom or kori (Figure 3-6). The relief, together with the vegetation, determines the formation and location of the water bodies, which are found on the lowest parts of the pediment and as isolated water bodies within the koris during the rainy season (Figure 3-6).

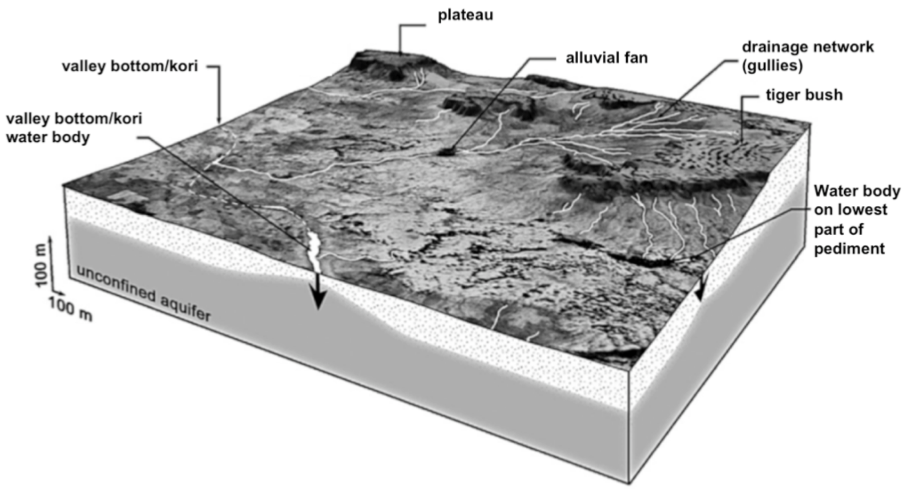

Figure 3-6: The main landscape and hydrological features of the study area (modified from Leblanc et al. 2008).

On the lateritic plateaus dense shrub vegetation alternates with strips of bare soil, which forms banded patterns and is therefore known as tiger bush (White, 1970). Tiger bush formations exhibit good infiltration capacities compared to the mostly bare areas on the plateau characterised by impervious soil crusts that generate intense runoff (Hiernaux and Le Houerou, 2006). The amount of runoff may be reduced on the escarpments as they are mainly covered with loose gravel, thus infiltration is relatively high despite the steep gradient (D'Herbes and Valentin, 1997). The sandy skirts are most vulnerable to soil crusting, which impedes infiltration. The sandy skirts have a steep slope and runoff concentrates in, often bush-filled, gullies. Mid-slope alluvial fans can occur that foster the infiltration of runoff to the groundwater (D'Herbes and Valentin, 1997). Little vegetation occurs between the gullies on the upper slopes but, commonly, millet is cultivated on the lower slopes that are prone to soil crusting. On the foot of the sandy skirts degraded hillslopes occur that are seriously affected by soil crusting.

These slopes are characterised by extremely low cover of both woody and herbaceous vegetation and are thus prone to erosion by both wind and water (D'Herbes and Valentin, 1997). The dominant woody species along the plateau to valley toposequence are *Guiera senegalensis, Combretum glutinosum* and *Combretum micranthum* (Hiernaux and Le Houerou, 2006).

Since the 1950s, the natural woody savanna vegetation within the study area has declined due to increasing demographic pressure that has led to the expansion of cultivated fields, especially millet. Other drivers to expand cropped areas have been the aim to reduce climate risks by spreading more fields over larger areas to profit from the patchy rainfall and to compensate for differing soil quality (Valentin et al., 2004). Initially the most favourable areas on the sandy skirts and in the koris were cultivated, followed by the more peripheral areas (Leblanc et al., 2008). As could be observed during the field survey, cultivated land now ranges from the valleys to the foot of the plateaus. The woody tiger bush vegetation on the plateaus has also been affected by clearing for use as fuel wood.

While natural vegetation, and to a lesser extent fallow, enhances the water-holding capacity of the soil and thus reduces runoff, cultivated areas with overexploited or crusted soils increase runoff (Descroix et al., 2009). Cultivation clears the soil and the almost bare soil is then prone to crusting when exposed to heavy rainfall. The water drop impact disrupts the finer mineral particles and the organic matter from the sand and the infiltrating water clogs the pores in between the sand grains with the finer particles, which causes soil crusts to form (Hoogmoed and Stroosnijder, 1984; Casenave and Valentin, 1992). On sandy soils a thin crust of about 0.1 mm develops, while on loamy and clayey soils thicker crusts of a few millimetres can develop (Hoogmoed and Stroosnijder, 1984). The thin soil crusts that develop on the mainly sandy soils of the cultivated fields significantly impede infiltration. Crusts destroyed by tillage are subsequently restored after a few rainfall events thus reducing the positive effect of tillage on infiltration capacity (Hoogmoed and Stroosnijder, 1984; Peugeot et al., 1997). Therefore, land-use and land-cover changes have important implications for the accumulation of surface water on the lowest part of the pediments and in the koris.

A. I. Ephemeral water bodies on the lowest parts of pediments

During extreme rainfall events runoff water from the plateaus and sandy skirts is collected in gullies and accumulates in ephemeral water bodies on the lowest part of the pediment, as observed near the town of Fandou-Mayaki (13° 54’ 58” N, 2° 55’ 30” E) (Figure 3-7). Figure 3-8 shows the ephemeral water body that had nearly disappeared in December 2008, two months after the end of the rainy season. It also shows that the water body had accumulated in a very shallow concavity. Due to the shallow water table, these ephemeral water bodies disappear quickly after the rainy season or even after the isolated heavy rain event that caused their formation. Hence, they are only detected rarely and exhibit a low seasonal recurrence of one to two years (Figure 3-5).

Within the study area, land clearance on the sandy skirts enhanced runoff and resulted in an increase in both the number and the length of the gullies, therefore increasing the drainage density and the number of water bodies, in particular of the type that occur at the bottom of pediments. Water level monitoring showed that more than 85% of the incoming surface water to these ephemeral water bodies rapidly infiltrates, which makes them main contributors to the groundwater recharge (Leblanc et al., 2008).

Figure 3-7: Ephemeral water bodies develop on the lowest parts of pediments in connection with extreme rainfall events like observed near the town of Fandou-Mayaki (13° 54’ 58” N, 2° 55’ 30” E).

Figure 3-8: The last signs of the presence of an ephemeral water body visible in December 2008. Water accumulated in a shallow concavity on the lowest part of a pediment near the town of Fandou-Mayaki (13° 54’ 58” N, 2° 55’ 30” E).

A. II. Temporary water bodies in koris

Runoff that does not accumulate as ephemeral water bodies on the lowest part of the pediment forms temporary water bodies in the elongated and disconnected depressions of the kori like "a string of pearls". In very wet years temporary streams can form in the kori that occasionally connect a series of normally independent water bodies. The observed seasonal recurrence of water bodies in koris was five to nine years out of the nine year monitoring period because they are replenished frequently and can reach large sizes (Figure 3-5). Figure 3-9 shows the *Mare de Kouana* (13° 35' 35" N, 2° 12' 49" E), which is regularly observed north of Niamey with the SWB dataset.

During interviews with the local population it became clear that 2008 was particularly wet and thus the *Mare de Kouana* was still well-replenished at the beginning of December during the dry season. Another reason that the *Mare de Kouana* was still well-replenished in December 2008 was due to a small dam that was able to turn the normally temporary water body into a permanent water body during wet years. To impede runoff from water bodies and to help retain water for longer periods during the dry season, small dams are often built that cross the koris in the study area. Figure 3-10 shows the small dam of the *Mare de Kouana,* which is located upstream on the left hand side of the dam. Water overflows the small dam and replenishes the water body downstream (shown in Figure 3-11) only in very wet years or as a result of heavy rainfall events. The difference between the upstream *Mare de Kouana* and downstream water body and sections of the kori are clearly visible in Figure 3-11. While upstream of the small dam a large stagnant water body is present only a small water body accumulates downstream and the kori is dry and densely vegetated. The replenishment of downstream water bodies from upstream in the kori is atypical as they are usually replenished from the surrounding catchment area.

Figure 3-9: The Mare de Kouana (13° 35' 35" N, 2° 12' 49" E) occurs naturally in the kori but is artificially retained by a small dam, which explains the large size at the beginning of December 2008 in the dry season. In the background the typical landscape of the study area consisting of plateaus and hillslopes is visible (photo: E. Bartholomé).

Figure 3-10: A small dam impedes runoff from the Mare de Kouana that is located upstream in the kori, on the left hand side of the dam. While upstream stagnant water is present, downstream, on the right hand side of the dam, the kori is already dry and densely vegetated (photo: E. Bartholomé).

Figure 3-11: View from the small dam that separates the Mare de Kouana upstream the kori from the water body downstream. The small size of the water body and the dry sand with dense green vegetation indicate that this part of the kori was flooded at some point during the rainy season but not continuously, since the water was retained by the dam (photo: E. Bartholomé).

Figure 3-12: The increased sedimentation of the kori and changes in the extent of the water body are visible, the latter indicated by dead trees located at the centre of the water body (13° 44’ 05” N, 2° 12’ 47” E).

Profound changes in the natural savanna vegetation caused by reduced rainfall during the drought of the 1970s and 1980s led to an increase in the amount of bare ground and areas of open vegetation within the catchments. As a consequence, runoff increased and collected in gullies and rills that became deeper and more numerous. The concentration of surface water in gullies reduced the water available for vegetation and thus hampered any recovery (Hiernaux and Le Houerou, 2006). This evolution of the drainage network was accelerated by recovered rainfall conditions from the 1990s onwards, leading to even more runoff. In addition to the lasting impacts of the drought on natural vegetation, increased levels of cultivation also led to increased runoff. Cultivated hillslopes are prone to soil crusting that reduces infiltration rates, triggers runoff and hence increases water erosion. Loss of natural vegetation and its clearance for cultivation also reduced the amount of soil protection provided by standing vegetation and litter, triggering wind erosion that causes a loss of fine particles from the topsoil. Moreover, cultivation breaks soil crusts and the detached material is then removed during storms by wind and rainfall (de Rouw and Rajot, 2004).

The increased erosion and sedimentation that occurred, together with the formation of more gullies and rills, led to several changes of temporary water bodies in the koris, which were observed over the field survey period. Increased transportation of fine clay and silt particles from the catchment by the increased runoff led to the silting up of water bodies and koris. The result were split water bodies and the closure of koris by natural sand dams. This led to larger water bodies with higher water levels that also lasted for longer time periods. This process was indicated by a number of dead trees, previously located on the water body shores that, in later years, were recorded standing deep in the water (see Figure 3-12, which shows a water body in the kori upstream of the *Mare de Kouana* and Figure 3-15*)*. A continuous increase in sediment load can also lead to the disappearance of water bodies when the concavities in the kori, where the temporary water bodies form, are filled in and runoff does not accumulate but instead infiltrates into the kori bed.

Potential anti-erosive measures such as sand trapping on the hillslopes were not observed within the study area. Existing measures against erosion observed in the field took the form of half moon or straight structures built on the plateaus out of stones or sand. In the right locations, such structures retain water and thus allow vegetation to develop, which helps to prevent further erosion. However, these structures did not appear to be well-adapted to preventing or even mitigating against erosion as they were located too high on the plateaus to be effective.

Changes in land-use and land-cover that alter the hydrodynamic soil surface behaviour and increase runoff levels, and thus the accumulation of temporary surface water, were also indirectly observed in south-western Niger. Since temporary water bodies disappear after the rainy season through evaporation and infiltration into the groundwater they act as important contributors to the upper aquifer recharge (Leduc et al., 2001). The observed increase in the groundwater level in south-western Niger over the last 30 years, despite an increase in rainfall, was attributed to the increased accumulation of surface water in temporary water bodies (Leduc et al., 2001).

A. III. Areas of humid vegetation in koris

Due to the temporary availability of water, the koris show abundant vegetation, mostly along the shores of the temporary water bodies. Woody vegetation like *Piliostigma reticulatum*, *Acacia nilotica*, *Mitragyna inermis* and *Ziziphus mauretania* are mixed with herbaceous vegetation like *Zornia glochidiata* and *Schoenefeldia gracilis* along the shores (Hiernaux and Le Houerou, 2006). Man-made vegetable gardens add to the vegetation cover in the valleys.

If this vegetation covers the surface water to a large extent a humid area, rather than a water body, is detected in the kori. The surface water in humid areas is shallow and thus often covered with aquatic vegetation that needs to have its roots in the ground. Humid areas showed clear signs of the presence of surface water, such as small water surfaces, soil crusts and flood tolerant humid vegetation (Figure 3-13).

Figure 3-13: A humid area that is attached to a temporary water body in a kori. The vegetation is characterised by flood tolerant species like Acacia nilotica. During the dry season the local population digs holes in the ground to obtain water and these zones are often used for the production of bricks.

The extent of the surface water in the kori is critical for the distinction between a humid area and a water body by the SWB algorithm. The narrower and longer the water body, the closer the opposing vegetation stands are located on the shores. This leads to an increased humid vegetation signal in the 1 km resolution pixel that results in the detection of a humid area rather than of a water body, such as for the area shown in Figure 3-14.

Vegetation can also cover the shores of a large water body but due to the large area of the water surface, the vegetation does not influence the signal as the contrast between water and vegetation can be sufficiently detected. The greater the body of water the less influence shore vegetation will have on the signal. Shoreline vegetation had no influence on detections of large water bodies of several kilometres in size (see Figure 3-15). These findings support the validity of the humid areas map to provide important information about available surface and sub-surface water.

Figure 3-14: Detection of a humid area rather than surface water due to the shape and size of the water body in the kori. The dense green vegetation related to the availability of surface water causes the detection of a humid area.

Figure 3-15: A water body of sufficient size to be detected as surface water by the SWB algorithm even though dense vegetation occurs on the shore. Large trees that were previously standing on the shore are now in the water, even during the dry season in December, indicating a change in the hydrology of the water body.

A. IV. Temporary and permanent water bodies in an ancient kori

Humid areas, like water bodies, were only detected with the SWB algorithm when they contrasted with the surrounding area. Since water bodies and humid areas in the ancient kori Dallol Bosso in the Dosso department (13° 57' N, 3° E) were replenished by a near-surface aquifer in addition to rainfall, the whole area was densely vegetated. Together with the vegetation, a number of both small and large water bodies occurred, which exhibited almost no water flow or suspended load (Figure 3-16). The small temporary or permanent water bodies that occurred in this densely vegetated ancient kori could not be detected with the SWB algorithm. A limited number of larger water bodies were sporadically detected when they reached a sufficient size to contrast with the surrounding area as indicated by the low seasonal recurrence of only one or two years (Figure 3-5). The Dallol Bosso that is recognised as a wetland of international importance by the Ramsar Convention of Wetlands (Ramsar site number 1382) is characterised by an undulating land surface where soils rich in clay and organic matter are intensively cultivated.

Figure 3-16: A temporary water body detected in the Dallol Bosso (13° 57' N, 3° 00' E).

B. Temporary rivers in koris

Like most surface water resources in arid and semi-arid regions, rivers occur only temporarily during the rainy season unless they are provided with water from more humid regions upstream like the Niger River. Temporary rivers typically exhibit a continuous water flow during the rainy season. After the rainy season has finished they dry out. Firstly leaving separate temporary water bodies in the concavities of the kori bed and then drying out completely. Temporary rivers of different size were detected with the SWB algorithm and are described below.

B. I. Large temporary rivers in koris

The Niger River is permanently supplied with water from headwaters originating in wetter regions, but also by temporary tributaries that exhibit variations in the water levels of 10 to 20 m during the rainy season. The Niger tributaries observed during the field survey were Goroubi, Sirba and Dargol. They are all similar in character and were detected in the same way by the SWB algorithm. Differences between the koris that host temporary water bodies (Type A) and the koris of temporary rivers (Type B) were the deeply carved kori bed of the latter, due to the continuous water flow during the rainy season. On both sides of the temporary rivers large flood plains can develop (see Figure 3-17). Only when the flooding covered a sufficient area close to the pixel resolution of 1 km, it was detected with the SWB algorithm as a water body (see 3.4.2). After the retreat of water from the flood plains, water-demanding plants like maize are cultivated and detected as humid areas.

The large, temporary tributaries of the Niger River were detected frequently with the SWB algorithm, but never entirely (see 3.4.2 and Figure 3-5). Most sections of the tributaries were detected in the years 1999 and 2001, which were reported by the local population to have been very humid years. Once the rainy season has ended these large temporary rivers dry up and form a series of independent water bodies holding stagnant water, similar to the water bodies observed in the smaller koris (Type A). The kori bed is then used for counter-season cropping of vegetables that are able to profit from the capillary rise of soil moisture.

Figure 3-17 shows the Sirba River in December 2008, at the beginning of the dry season, when the water flow had ceased.

Figure 3-17: The Sirba River during the dry season in December 2008. The high water levels during the rainy season can be perceived by the boats that are available at the shore and the dense green vegetation on the flood plain.

B. II. Small temporary rivers in koris dammed by roads

Smaller temporary rivers that flow towards the Niger River tributaries carry high volumes of water during the rainy season. These smaller rivers were not detected by the SWB dataset due to the issue of a minimum detectable size (see 3.4.2). Roads that cross these small temporary rivers function as dams, helping to retain the seasonal water. As a result temporary water bodies are formed that remain long into the dry season and are of a sufficient size to be detected with the SWB dataset. Figure 3-18 shows an example from one of the Dargol River tributaries where the road towards Tera also functions as a dam, which leads to the formation of an upstream water body. These temporary water bodies were detectable only when a large amount of water had accumulated during the rainy season, which leads to recurrent detections of two to six years out of nine observed years (Figure 3-5). Downstream of the road dams, humid areas often developed in the kori bed, which could be detected with the SWB algorithm.

Figure 3-18: A road dam on the road to Tera in the town of Dargol (13° 55' 20" N, 1° 14' 57" E) that retains water arriving in a small tributary of the Dargol River.

B. III. Areas of humid vegetation along small temporary rivers in koris

If the water in a small, temporary river is not retained artificially it will flow at a high level during the rainy season (see Figure 3-19), creating inundated areas characterised by increased vegetation growth. An example of a large area (27 km^2) such as this was detected near the town of Boni (14° 43' 59" N, 1° 09' 00" E). This detected area was not entirely inundated, but was also used for agricultural activities due to its location in a depression and its proximity to temporary rivers. The presence of surface water in an area allows increased agricultural production, in particular of water-tolerant plants such as sorghum and maize. The water stored in the soil remains available, even after the rainy season, through capillary rise whereby it contributes to long-lasting, green vegetation (see Figure 3-20). The large humid area detected near the town of Boni was therefore a mixture of inundated zones, humid vegetation, and agriculture, which contrasted with the sparsely vegetated surroundings enabling detection with the SWB algorithm.

Figure 3-19: The inundated area is pervaded by small koris that temporarily carry large amounts of water during the rainy season visible by the accumulated material.

Figure 3-20: Inundated areas are used for agricultural production. Green vegetation in the dry season (picture taken in December 2008) indicates high soil moisture content that was accumulated during the rainy season.

C. Endorheic temporary water bodies within fossil sand dunes

The landscape in the northern part of the study area comprised fossil sand dunes. When fossil sand dunes, as detected with the high resolution ASTER GDEM, crossed ancient drainage networks they were found to cause the accumulation of temporary surface water, as shown in Figure 3-21.

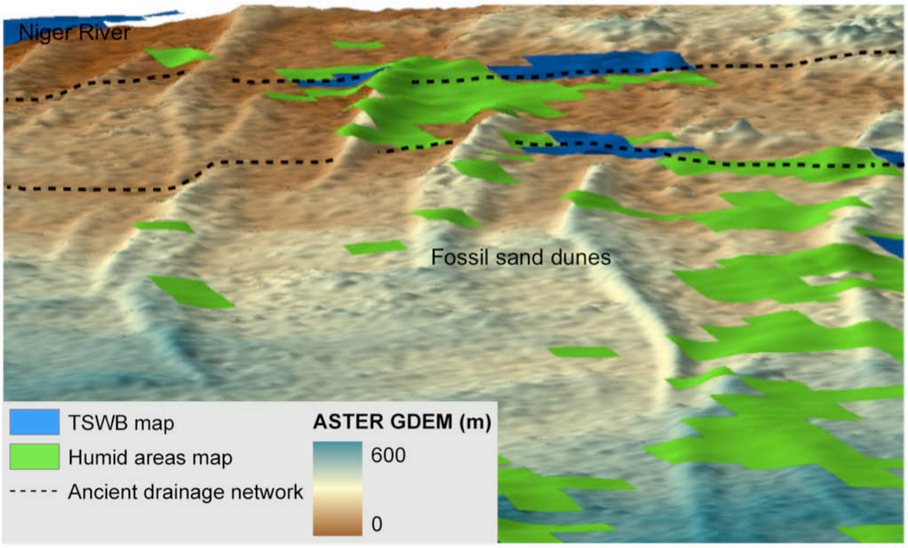

Figure 3-21: The detected water bodies accumulate on the foot of the fossil sand dunes, which block the ancient drainage networks, and can be detected with the high resolution digital elevation model ASTER GDEM (20 times exaggeration). The viewing direction of this figure is eastward.

C. I. Endorheic temporary water bodies within fossil sand dunes

Endorheic temporary water bodies are found in depressions along fossil sand dunes formed in the Pleistocene and Holocene, which intersect the ancient drainage networks or koris and constitute a natural dam for inflowing water. Locally, water from the dune slopes also drains into the inter-dune depressions although runoff is limited on sandy soils. Endorheic water bodies that occur in relation to fossil sand dune systems were frequently detected with the SWB algorithm, as can be seen in the seasonal recurrence map (Figure 3-5).

The blocking of the kori was evident in the Tillaberi region at the *Mare Hogore* (14° 20’ 47” N, 1° 28’ 05” E), an endorheic water body visited during the field survey. The force of the runoff water arriving during the rainy season was not sufficient to carve an outflow in the fossil sand dune, which was approximately 30 m high and covered with vegetation (see Figure 3-22).

Figure 3-22: The endorheic Mare Hogore (14° 20’ 47” N, 1° 28’ 05” E) in the Tillaberi region has no outflow since the ancient drainage network is blocked by a fossil sand dune. The viewing direction of this image is eastward.

C. II. Areas of humid vegetation within fossil sand dunes

Fossil sand dunes in the study area were covered with annual herbaceous vegetation (*Cenchrus biflorus, Aristida sp., Schoenfeldia gracilis*) and dense woody vegetation dominated by *Combretum* and *Acacia sp.* (Chevallier, 1985). Due to the increased extension of agricultural fields, millet crops are often found at the foot of the sand dunes.

Since the vegetation on the fossil sand dunes is larger, greener and denser compared to the sparse surroundings, sand dunes were often detected as humid areas, such as the area shown in Figure 3-23. Even though no obvious sign of surface water was present in this area, the presence of the vegetation indicated available sub-surface water. The humid areas detected were often located in depressions at the foot of fossil sand dunes or on their slopes (see Figure 3-21). Fossil sand dunes cut across ancient drainage networks and thus groundwater can accumulate that becomes available to the vegetation through capillary rise. Another reason for the increased vegetation growth can be due to the different infiltration capacity of the fossil sand dune compared to the surrounding environment.

Figure 3-23: The vegetation that occurs related to fossil sand dunes is greener, higher and denser compared to the sparse surroundings.

The typology carried out in this section showed that areas of humid vegetation differ but commonly indicate available surface and sub-surface water. Their detection with the SWB dataset was comprehensible but more insight in the characteristics of humid areas is needed to provide information about the validity of the detection.

3.6 Characteristics of detected humid areas

Areas of humid vegetation are indicators of the availability of surface or sub-surface water in arid regions. The field survey showed that humid areas detected with the SWB algorithm provide indirect evidence of available surface or sub-surface water but are of a different nature. To understand the reasons why a vegetated area is detected as a humid area rather than vegetation cover, the time series of SWB humid area detections was compared to the green cover time series (see 4.2.2.3 for a detailed description of the dataset) for the respective humid areas. Humid areas were assessed in the field based on a map of humid areas (see 2.3.5) that also provided the basis for this analysis. For each humid area the number of pixels detected for each dekad between the first dekad of June 2001 and the last dekad of August 2008 was determined. For the same time-span the average green cover within each humid area was calculated. The results were time series of humid area and green cover detections for each humid area observed during the field survey. The analyses of the time series data focused on the timing of humid area detections and on the amount of pixels detected as a humid area or the green cover value respectively.

All detected categories of humid areas revealed similar characteristics when the time series data of green cover and the humid area detections were compared. The dates in the following figures represent the year, month and dekad of the observations. In the case of large humid areas in koris (A. III.), most humid area pixels are detected at the beginning of September during the peak of the vegetation activity and the rainy season (Figure 3-24). As can be seen in Figure 3-24, vegetation cover is present throughout the year in this humid area located within a kori, which indicates the availability of sub-surface water.

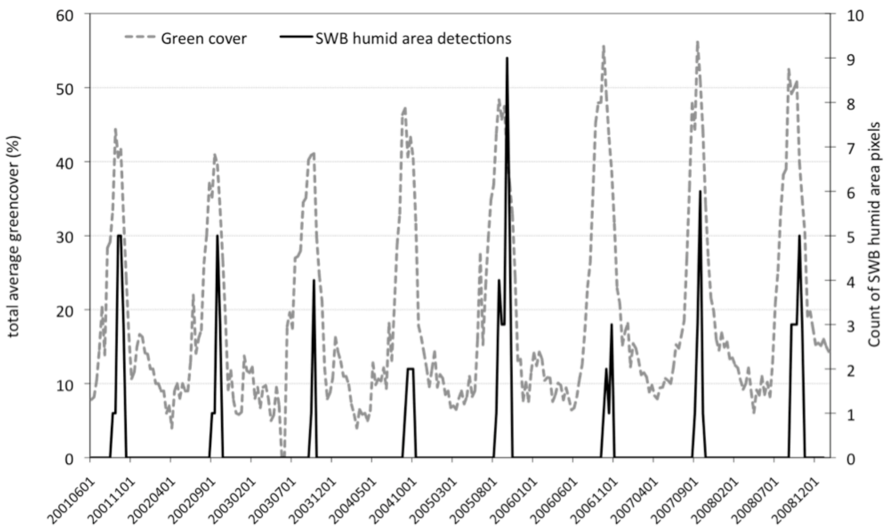

Figure 3-24: The time series of humid area detections (SWB algorithm) compared to the green cover time series for a large area of humid vegetation in a kori (A. III.).

Compared to areas comprising humid vegetation in koris (A. III.), inundated areas with humid vegetation alongside small temporary rivers (B. III.) did not show continuous vegetation cover. However, both areas revealed the same pattern for the SWB humid area detection with a peak in the rainy season (see Figure 3-25). Inundated areas that contain agricultural fields were only detected in years with above average green cover, which is an indication of available surface water. For inundated areas with humid vegetation cover (B. III.), the analysis showed that the smaller the area the less often it was detected with the SWB algorithm (see Figure 3-26). A similar pattern was revealed for areas of humid vegetation that occur in relation to fossil sand dunes (C. II.). As can be seen in Figure 3-27, the general low green cover signal is accompanied only by erratic detections of humid area pixels.

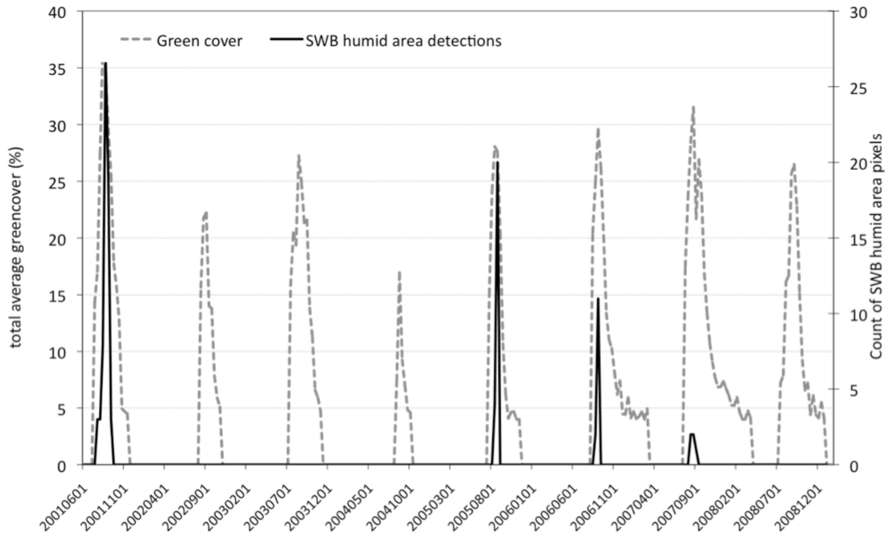

Figure 3-25: The time series of humid area detections (SWB algorithm) compared to the green cover time series for a large (27 km^2) inundated area of humid vegetation along a small temporary river (B. III.).

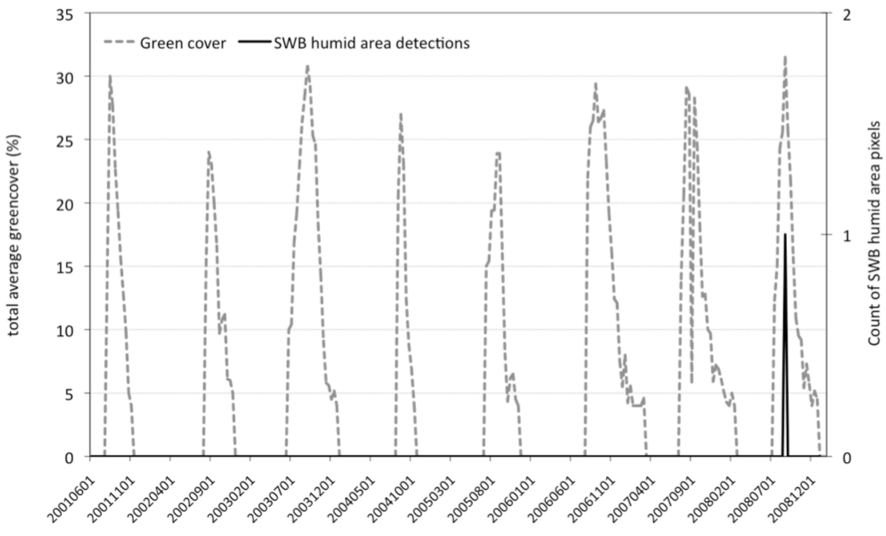

Figure 3-26: This small (1 km^2) inundated area of humid vegetation (B. III.) is only detected in the year with the highest amount of green cover.

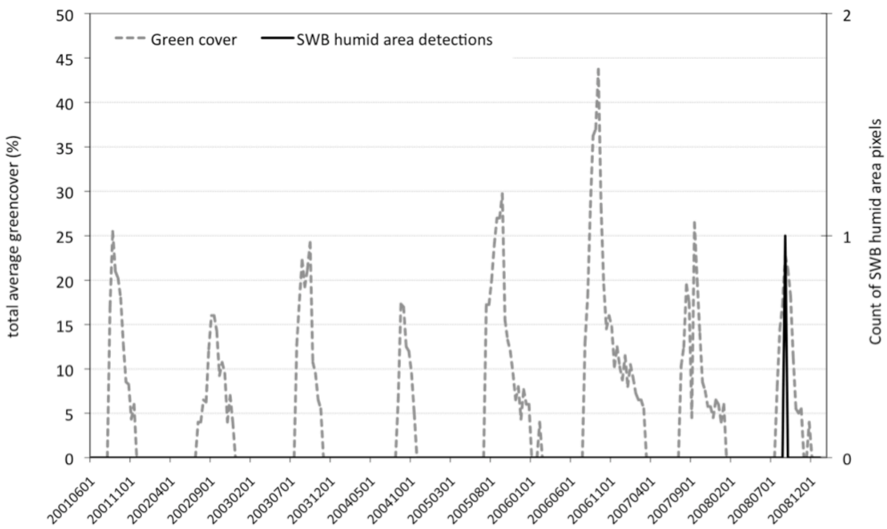

Figure 3-27: Areas of humid vegetation that are characterised by dense green vegetation related to fossil sand dunes (C. II.) are not frequently detected and reveal a similar pattern like a small inundated area of humid vegetation along a small temporary river (B. III.).

The humid area detections produced different time series results to the green cover detections even though both were based on NDVI. This indicated that the SWB algorithm was suitably designed to detect only humid vegetation rather than vegetation cover in general. In arid regions, humid vegetation can be defined as vegetation that occurs in relation to abundant surface water such as bushes, trees and aquatic vegetation. Humid vegetation can be natural or associated with agricultural activities and is characterised by higher water requirements than steppe vegetation, leading to denser and greener vegetation. The reason for the difference between the green cover and humid area detections was the additional extraction of NDWI to detect humid areas using the SWB algorithm (see 2.2.2). NDWI is sensitive to dense green vegetation and to liquid water in vegetation (Gao, 1996) also when derived from coarse spatial resolution data such as SPOT VGT (Verbesselt et al., 2007).

The detections of all types of humid areas in all categories occur during the peak of the rainy season in August or September (Morel, 1981) and always correspond to the maximum green cover value. This finding indicates that humid vegetation, and surface water located on the ground between the vegetation, was successfully detected using the SWB algorithm. These findings confirmed that the map of humid areas, as developed in section 2.3.5, provides important environmental information about available surface and sub-surface water in arid regions.

3.7 Discussion

The findings obtained in this chapter complete the first research question regarding the reliability of wide-field-of-view sensors for the detection of surface water bodies. They also show the potential for detected humid areas to provide indirect evidence of surface and sub-surface water in arid regions. The validity of the regional scale SWB dataset and derived products such as the TSWB map and the map of humid areas was confirmed at a local scale by a field survey. The exploitation of field data provided the following results: (i) a local scale accuracy assessment of the TSWB map, (ii) a typology of water bodies and humid areas including a description of the reasons for the detection with the SWB algorithm, and (iii) a description of water body and humid area detection characteristics. The documentation of the field survey with georeferenced photos completed this inventory of surface water bodies and humid areas in south-western Niger.

All water bodies detected with the TSWB map were confirmed on the ground, apart from one pixel that was identified as a false detection related to particular soil properties. This particular area was detected twice in the nine year time series. The results of the local scale accuracy assessment confirmed the finding at the regional scale that the removal of singular detections when deriving the TSWB map leads to high detection accuracy (see 2.3.2). The risk of including short duration false detections, such as those observed during the field survey, is outweighed by the benefit of including temporary short duration water bodies. Singular free water detections were found to be valid when they were located on the potential river network as obtained from WWF HydroSHEDS (see 4.2.2.4 for a detailed description of the dataset). This will allow a map of valid singular free water detections to be derived that could add valuable information about erratic water bodies to the TSWB map. The importance of remote sensing for the mapping of surface water in remote and inaccessible areas was highlighted for the study area, where the regional scale TSWB map added important information regarding water bodies of 1 km^2 in size and larger to existing local water body maps. The minimum detectable size of water bodies was found to be approximately 600 m to 800 m in width and length, which is less than the pixel resolution of 1 km. However, these estimates of the minimum detectable size are only valid for this particular study area and would, presumably, be different for other regions depending on their surface characteristics. Water bodies of 1 km^2 were reliably detected but there are limitations for the detection of smaller linear features such as rivers. Rivers were only detected during flooding events of sufficient duration when they exceeded the minimum detectable size of 1 km in width. This was also true for flooding events that were independent of rivers that occurred in connection with heavy rainfall produced locally by convective cells.

The SWB algorithm detected open water surfaces correctly as water bodies and correctly detected surface water occurring between vegetation or covered by vegetation as humid areas. A typology of detected water bodies and humid areas, developed in this chapter, assisted the understanding of the environmental characteristics of detected features and the reasons for the detection with the SWB algorithm. The composition on the ground within a pixel was found to influence the detection by the SWB algorithm. All detected humid areas were related to the associated, potential river network, which indicates the reliability of the detection.

Three types of humid area were identified: (i) areas of humid vegetation in sandy valley bottoms or koris, (ii) inundated areas of humid vegetation in relation to small temporary rivers, and (iii) humid vegetation related to fossil sand dunes. While an indication of available surface or sub-surface water was found in all area types, humid areas in koris were the most highly associated with surface water bodies because they actually contain open water surfaces. Humid areas were always detected at the peak of the vegetation and rainy season and the detection characteristics differed from pure vegetation cover detections.

3.8 Conclusion

This chapter has discussed the research conducted and the understanding gained from the association of remote sensing derived maps of water bodies and humid areas with actual ground observations. The findings obtained in this chapter provide a novel insight in the nature of remotely sensed water body and humid area detections and have important implications for the analyses carried out in the following chapters. A local scale accuracy assessment confirmed the reliability of the regional scale TSWB map. Employed as a mask in the SWB time series analyses carried out in the following chapters, the TSWB map assures the quality of the analyses. The finding that water bodies close to the pixel resolution of 1 km can be reliably detected allows the integration of small water bodies into the analyses. However, larger water bodies were found to provide more stable detections over time. As a conclusion, several small water bodies should be regarded collectively for a region rather than individually to increase the stability of the detection. Since water bodies were studied in the context of their environment during the field survey, a basis was provided for the integrated ecosystem assessment carried out in the following chapters. The gained understanding about characteristics of water body detections also provides important information for a potential future application of the SWB algorithm on higher spatial resolution satellite data that goes beyond the scope of this thesis.

It has been shown in Chapters 2 and 3 that a wide-field-of-view sensor can be a reliable tool to map, monitor and report on the changing surface water resources at local to regional scales. The proven reliability of the regional scale water body dataset allows for an integrated assessment of remote sensing derived surface water extent, rainfall and vegetation cover, which is described in the following two chapters. This integrated assessment will answer the second research question that aims to identify the potential of remote sensing derived temporary water bodies as ecological indicators in West African drylands.

Chapter 4 Remotely sensed surface water bodies as ecological indicators in semi-arid Western Africa

Abstract

In the light of ongoing changes in the hydrology, climate and land-cover of the Sahel, there is an increased interest in the integrated assessment of ecosystem processes at local to regional scales. While vegetation cover and rainfall are commonly monitored to assess ecosystem changes in West African drylands, it has not been possible until now to monitor temporary surface water at high temporal and spatial resolution at a regional scale. Temporary water bodies represent the integrated hydrological response of a catchment as they are not only influenced by rainfall but also by catchment characteristics such as vegetation cover. Changes in their extent involve complex interactions at the catchment scale. Due to the direct link between temporary water bodies and the ecosystem in which they appear, there is an interest to understand how far the monitoring of the changing extent of surface water can give indications about the ecosystem state.

This chapter highlights the integrated assessment of water body extent, rainfall, and vegetation cover for two regions in Mali and Burkina Faso. The anomalies of the annually integrated water body extent in relation to a corresponding rainfall dataset, for the time period 1999 to 2008, were analysed. The meteorological signal was found to be reflected by the replenishment of temporary surface water bodies of 1 km^2 and larger. The emptying phase of the water bodies was related to their maximum extent during the rainy season. Changes in the extent of water bodies during a rainy season were positively related to the amount of vegetation cover in the catchment. These observed relationships between remotely sensed variables provide a basis for the development of environmental indicators that can indicate short-term changes in arid and semi-arid ecosystems at local to regional scales.

4.1 The water balance of arid and semi-arid ecosystems

The availability of surface water in arid and semi-arid regions is determined by rainfall amount and intensity, evaporation, transpiration rates, topography, soil permeability and vegetation cover. Ecohydrological processes in arid and semi-arid ecosystems are difficult to quantify due to their extreme spatial and temporal variability and a lack of in-situ data. Simplifying assumptions that preserve the most important characteristics of those ecosystems should therefore be employed (Porporato and Rodriguez-Iturbe, 2002). As this study focused on seasonal and inter-annual variability in ecohydrological processes, the temporal variation in rainfall, vegetation cover and the spatial extent of the water bodies were considered as proxies for the components of the water balance in a water-limited arid and semi-arid ecosystem. All these variables can be estimated from remote sensing data. The temporal changes in the volume of water in the water body, which are the result of the interaction between rainfall, evapotranspiration, runoff generation and infiltration and thus a proxy of ecohydrological processes, cannot be directly measured remotely. Thus, it was assumed that the spatial extent of the water body is a direct function of the volume of water in the water body.

Figure 4-1 shows a conceptual model of the most important ecohydrological components and their relationships in a water-limited ecosystem during the rainy season and the dry season.

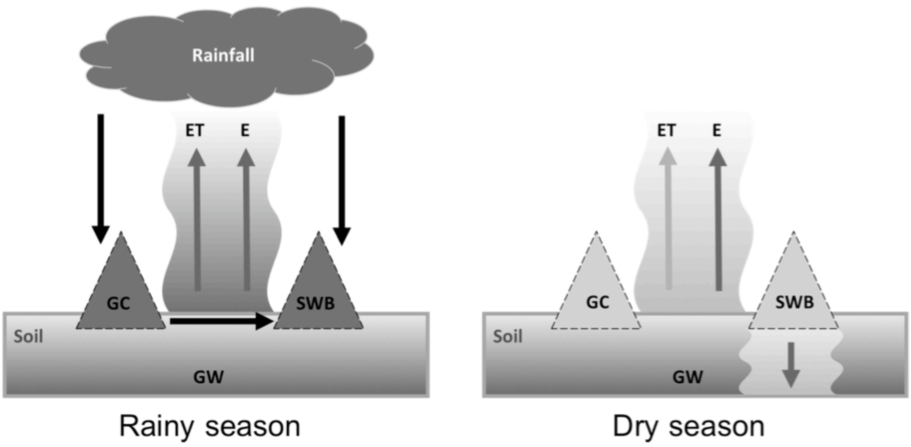

Figure 4-1: A conceptual model of the most important ecohydrological components and their relationships (black arrows) in a water-limited ecosystem during the rainy season and the dry season. Rainfall influences green vegetation cover (GC) and the extent of temporary water bodies (SWB). The timing and amount of GC influences runoff generation and thus SWB. The soil synthesises the action of rainfall and vegetation cover on the water balance. The variables are influenced by evapo(transpi)ration (E and ET) and are connected to the groundwater (GW) by infiltration and deep percolation.

Most components of the water balance in arid and semi-arid regions have been studied using hydrological models, separately or in combination with rainfall (Cappelaere et al., 2003; Peugeot et al., 2003; Candela et al., 2005; Balme et al., 2006; Paturel, 2007; Vischel and Lebel, 2007). Rainfall, which is the driving factor behind ecosystem processes in arid and semi-arid regions, is partitioned into interception, evapotranspiration, runoff, and infiltration into the soil. Such infiltration leads to the recharging of groundwater (GW). During the rainy season between June and September intense rainfall of short duration coming from convective cells produces Hortonian type runoff. In the study area rainfall levels exceed potential evaporation (E) only in the peak rainy season in July and August (Desconnets et al., 1997).

The fraction of rainfall water that does not infiltrate or evaporate produces runoff and eventually reaches temporary water bodies (SWB) (Desconnets et al., 1997). Peugot et al. (2003) estimated that, in the Sahelian climate, only about 8% of the annual rainfall is transferred to water bodies through surface runoff, while the remaining 92% is returned to the atmosphere through evapotranspiration (ET). Thus, the given volume of a water body, which can be assessed trough changes in the water body extent, is a measure of the balance between rainfall, evapotranspiration, infiltration and runoff in a catchment (Combal et al., 2009). The formation of these temporary water bodies facilitates infiltration and deep percolation, which makes them a major contributor towards the groundwater (GW) recharge process (Desconnets et al., 1997; Leduc et al., 1997; Leduc et al., 2001). In turn, groundwater does not usually influence water body volume since, in the study area, the water table is typically located approximately 20 m underneath the surface (Martin-Rosales and Leduc, 2003).

Evapotranspiration is an important component of the water balance in arid and semi-arid regions and was assessed via the vegetation cover (GC). Vegetation cover, which is driven by rainfall and soil conditions, exerts control over the entire water balance process and is responsible for many feedbacks to the atmosphere in water-limited ecosystems (Sanchez and Puigdefabregas, 1994; van Wesemael et al., 1998; Rodriguez-Iturbe, 2000; Porporato and Rodriguez-Iturbe, 2002). Vegetative productivity depends on soil moisture distribution (Galle et al., 1999) and soil type (Sala et al., 1988; Kumar et al., 2002; Huxman et al., 2004b). In the Sahel the predominant soils are Alfisols, Entisols and Inceptisols (Eswaran et al., 1996) that are characterised by low inherent fertility, low organic matter content, the presence of hardened iron and manganese concretions, and are prone to soil crusting and surface sealing. In general, important soil properties include the infiltration capacity, plant-available water reserves and saturated and unsaturated hydraulic conductivity (Lal, 1991). If more water is supplied to the soil than can be held, as determined by the field capacity, the excess water drains out. In the coarse-textured Sahelian soils with low water holding capacity, low soil moisture levels are quickly reached. Soils can temporally store water in the rainy season, but are likely to dry out completely during the dry season in arid and semi-arid regions.

Soils present in the study area have low plant-available water reserves and vegetation development depends on the permanent wilting point, which is the minimal level of soil moisture the plant requires not to wilt. To assure growth and survival, plants need to maintain an adequate level of water in their tissues. They also require a continuous flux of water to perform vital processes such as photosynthesis and nutrient uptake. Since water is absorbed from the soil, it is obvious why soil moisture deficit has such an essential control on plant conditions (Porporato et al., 2001). This process, together with the fact that over large spatial scales (in the order of kilometres such as employed in this study) the spatial variability of soil moisture is decreased (Rodriguez-Iturbe et al., 2001), led to the assessment of soil moisture content via the vegetation cover.

Soil moisture levels also have an important influence on plant transpiration (ET) and evaporation (E) directly from the soil. At very low levels of soil moisture, below the wilting point, plants stop transpiring, while at very high levels the evapotranspiration rate is high, depending on plant type and climatic conditions such as wind speed, air temperature and humidity (Laio et al., 2001). Since vegetation cover is sparse throughout the Sahel, direct evaporation from the soil surface represents a major component of the water balance equation. Even on cropped land soil evaporation is likely to contribute at least 30% of the total water lost by evaporation during the growing season (Monteith, 1991; Wallace and Holwill, 1997).

Inter-annual variations in vegetation cover often result from variations in soil moisture, which are driven by fluctuations in rainfall amount and distribution (Webb et al., 1978; Gutierrez and Whitford, 1987; Knapp and Smith, 2001; Huxman et al., 2004b). The intensity and distribution of annual rainfall was found to be more important for the development of vegetation than the total amount of rainfall, with low rainfall intensities producing more vegetation and smaller amounts of sediment and runoff (Smithson et al., 2002; Wheater, 2008). The amount of vegetation cover is also a major factor that determines runoff and erosion rates (Blackburn, 1992), with runoff increasing as the amount of vegetation cover decreases (Thurow, 1986; Hofmann, 1991; Eldridge, 1993; Gutierrez and Hernandez, 1996; van Wesemael et al., 1998).

Under high intensity storms, a large proportion of rainfall is transformed to runoff especially at the onset of the rainy season when vegetation cover is scarce. In the general, rather bare, environments of arid and semi-arid regions most of the rainfall is transformed to runoff and flash floods are common (Dingman, 1994; Wheater, 2008). Thus, there is a potential link between the timing and amount of vegetation growth, which influences runoff generation, and the timing and extent of water body formation. This link between rainfall, vegetation cover and runoff may also occur inter-annually, with runoff production lower in a year that follows a wet year, due to enhanced vegetation cover (Wheater, 2002; Hughes, 2008).

The objective of this chapter was to test whether remote sensing derived estimates of surface water extent, vegetation cover and rainfall were statistically associated. Based on principles of the water balance in arid and semi-arid regions, the three following hypotheses were tested:

Hypothesis 1: Temporary water bodies are vulnerable to climatic variability as measured by rainfall. Anomalies in the extent of temporary water bodies are therefore expected to be associated with rainfall anomalies.

Hypothesis 2: The length of the emptying phase of a temporary water body is expected to be positively related to its maximum extent. If this hypothesis is verified, the maximum extent of water bodies could be used as an indicator for water availability during the dry season.

Hypothesis 3: Temporary water bodies represent the integrated catchment response to rainfall. Changes in vegetation cover – either degradation or increase - that influence evapotranspiration and runoff are expected to be reflected in the storage of runoff water in temporary water bodies.

The three hypotheses were tested in 11 different endorheic catchments located in Mali and Burkina Faso. Each catchment was between 76 and 586 km^2 in area and contained an endorheic temporary water body.

4.2 Study area and datasets

4.2.1 Study areas: Mali and Burkina Faso

The study areas belong to the arid and semi-arid Sahelian climate zone where rainfall occurs during a single rainy season between June and September, with a mean annual rainfall of between 350 and 450 mm (AGRHYMET, 1991a). Two suitable study areas that each contained several endorheic water bodies were identified in Burkina Faso and Mali (Figure 4-2).

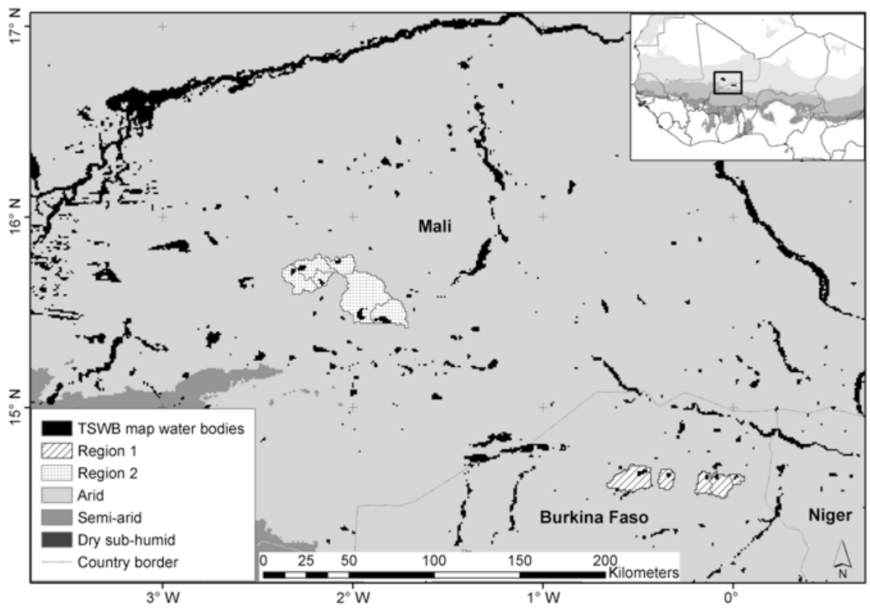

Figure 4-2: The studied endorheic catchments in Burkina Faso (Region 1) and Mali (Region 2). Water bodies are detected with the TSWB map, which is especially suited to mapping temporary accumulations of surface water (Haas et al., 2009).

The Sahel region experienced a prolonged drought during the 1970s and 1980s that resulted in significantly below average annual rainfall (Lebel and Ali, 2009). Rainfall levels have not yet returned to the pre-drought conditions although wetter conditions were observed during the last two decades in the central part of Western Africa that hosts the study areas (Lebel and Ali, 2009). Both study areas considered in this chapter are located within the Sahelian eco-climatic zone (White, 1983). The land-use within the study areas is pastoral with some limited agricultural production of rain-fed crops such as millet.

The study areas form part of a large sedimentary basin with bedrock mainly composed of Precambrian sandstones and schists that have eroded to peneplains surrounded by a few hard sandstone plateaus. These plateaus are locally capped by duricrusts. Fossil sand dunes that have segmented a system of valleys formed during wetter periods are the second main landscape feature (Gardelle et al., 2009). These landscape features exhibit large differences in the type and amount of vegetation cover and in the soil properties, which leads to two different hydrological systems (Mougin et al., 2009). On sandy soils, high infiltration rates limit runoff, which flows over short distances from dune slopes to inter-dune depressions where it accumulates as endorheic water bodies. In the peneplains, between the sand dune systems, shallow soils on rocky outcrop prevail. These soils are characterised by low infiltration capacities leading to concentrated runoff over larger areas that accumulates in depressions as mostly temporary endorheic surface water bodies. The vegetation in both study areas is typical for the Sahel, with a herbaceous layer almost exclusively composed of annual plants among which grasses dominate, plus scattered bushes, shrubs and low trees (Hiernaux and Le Houerou, 2006; Mougin et al., 2009). Vegetation cover on the shallow soils is extremely low and patchy, with large areas remaining bare throughout the year in the northern study area (Region 2, Figure 4-2). The southern study area (Region 1, Figure 4-2) is characterised by abundant grassland savanna.

Representative water bodies for this study were temporary, endorheic and of a sufficient size to assure a stable detection, since water bodies close to pixel resolution of 1 km are only detected during the short period in which they are fully replenished.

Region 1 encompasses the catchment that drains into the well-studied site of the *Mare d'Oursi*, a designated Ramsar Site (number 490) of importance for trans-Saharan migratory birds (The Ramsar Convention on Wetlands, 2008). The *Mare d'Oursi* is located in northern Burkina Faso between 14° 33' N to 14° 41' N and 0° 26' W to 0° 40' W, with a catchment of approximately 263 km^2 (Chevallier, 1985). The catchment slopes downward towards the north, where the ancient drainage network carved during wetter periods is blocked by a fossil dune system, a typical morphological feature of the Sahelian zone. This leads to the temporary accumulation of surface water in the *Mare d'Oursi* that can be permanently present during rain-laden years. Towards the east along this fossil dune system, four additional endorheic temporary water bodies were identified. Their respective catchments ranged between 93 and 146 km^2. Altogether, these five water bodies composed the study area in Burkina Faso (Region 1). A similar water body system was identified in Mali (Region 2) where six temporary surface water bodies regularly formed along fossil dune systems, with respective catchments of between 76 and 586 km^2. The identification of the water bodies was based on topographic maps and visual interpretation of high resolution satellite imagery (Landsat TM and Google Earth). In addition, the characteristic ascending slope at the outlet of endorheic water bodies was verified using a 90 m horizontal resolution digital elevation model (Lehner et al., 2008).

4.2.2 Datasets

Remote sensing datasets of vegetation cover, rainfall and water bodies were used as proxies for the components of the water balance (Figure 4-1). Topography was not explicitly integrated into the analyses due to the general flat terrain of the study area. Not all components of the water balance (e.g., evapo(trans)piration and soil moisture) could be included directly in the analyses due to differences in the temporal resolution and time-spans of the existing datasets. The components of the water balance analysed in this study are described hereafter.

4.2.2.1 SWB dataset

The SWB time series for the period January 1999 to April 2009, covering 10 complete rainy seasons, and the TSWB map were used in this chapter (see 2.2.2 for a detailed data description).

4.2.2.2 Rainfall dataset

10-daily rainfall estimates (RFE) from NOAA's Climate Prediction Center processed for the Famine Early Warning Systems Network (FEWS NET) and disseminated by U. S. Geological Survey (USGS) were used in the present study. The RFEs provide a continuous time series from 1995. The original RFE data, with a spatial resolution of 8 km, were resampled to 1 km for the period 1999 to 2008, for Western Africa. Since the original rainfall estimation algorithm (known as RFE1.0) changed in 2001 (to become known as RFE2.0) it was necessary to assess the differences and potential implications of this change for the rainfall time series employed here. However, only one set of analyses was based on the time series for the period 1999 to 2008. In the remaining analyses, time series data between 2001 and 2008 were used, which were exclusively based on the RFE2.0 algorithm.

In the first algorithm, RFE1.0, which was operational from 1995 to 2000, Meteosat 5 geostationary satellite data, rain gauge reports, model analyses of wind and relative humidity, and orography were used for the computation of rainfall estimates (Xie and Arkin, 1996; Herman et al., 1997). Based on half-hourly Meteosat 5 thermal infrared data the fractional coverage of clouds with cloud top temperatures below 235 K and warmer top temperatures between 235 K and 275 K were determined. The cold cloud duration (CCD) was then used to derive the GOES Precipitation Index (GPI) rainfall amounts, where a value of 3 mm/h of rainfall was assumed. Rain gauge reports were obtained every six hours from between 400 to 800 stations via the WMO Global Telecommunication System (GTS) and were accumulated daily. An interpolation method was used to combine GPI and GTS data for daily rainfall estimates.

Orographic rainfall was estimated based on warm cloud information and model analyses of surface wind and surface relative humidity acquired from the Environmental Modeling Center (EMC) Global Data Assimilation System (GDAS) (Xie and Arkin, 1996; Herman et al., 1997).

On 1st of January 2001 RFE1.0 was replaced by RFE2.0, which used two additional satellites to better estimate rainfall while continuing the use of GPI and GTS station rainfall data (Love et al., n.d.; NOAA, n.d.). Half-hourly GPI rainfall amounts were derived from Meteosat 7 geostationary satellite infrared data using the CCD method to estimate rainfall as in the RFE1.0 method. The two new satellite rainfall estimation instruments that were incorporated into RFE2.0 were the Special Sensor Microwave/Imager (SSM/I) on board Defense Meteorological Satellite Program satellites, and the Advanced Microwave Sounding Unit (AMSU). Both rainfall estimates were acquired at six hour intervals with a resolution of 0.25°. GTS station data provided accurate rainfall totals, which were assumed to represent the true rainfall near each station. A two step merging process leads to the daily rainfall estimates. Firstly, data from all three satellites is combined linearly. Then, the satellite estimates are merged with GTS station data to remove bias. While the spatial shape of the rainfall event is given by the three combined satellite estimates, the magnitude is inferred from the GTS station data. To produce the dekadal estimates the daily totals are summed (Xie and Arkin, 1996; Love et al., n.d.).

Initial validation for the RFE2.0 product showed that outputs have reduced bias and mean error compared to RFE1.0. This was attributed to the increased input data and a modified algorithm (Love et al., n.d.). A cross-validation of the RFE2.0 rainfall estimates was performed for the December 1999 data. The four inputs GTS, GPI, SSM/I, and AMSU produced the highest correlation between estimated rainfall and actual station rainfall amounts, with a relatively small bias. Using only GTS and GPI input data produced similar results, although a slightly lower correlation was obtained (NOAA, n.d.). This adequate accuracy of GTS and GPI allowed the inference that RFE1.0, which was mainly based on these two inputs, provided comparable rainfall estimates.

A comparison of GTS rain gauge data with satellite derived rainfall estimates such as TRMM MPA-RT, CPC CMORPH and RFE2.0 showed similar trends of the mean bias and standard deviation for the African continent. Since GTS station data was used as input to the RFE algorithm a special method was designed to allow for an independent comparison. Depending on the estimated rainfall amount the products either underestimated (for daily rainfall amounts of 1 to 20 mm and of more than 100 mm) or overestimated (for daily rainfall amounts of 21 to 50 mm) the rainfall amounts (Laws et al., 2004).

Over large areas with inadequate rain gauge networks, such as the Sahel, satellite rainfall estimates were found to perform similarly to, and in some cases better than, rain gauge data (Symeonakis et al., 2009). An extensive validation of several satellite-derived rainfall products over the Sahel with independent rain gauge data for the rainy season 2008 showed that the RFEs performed best relative to having the highest correlation with considerably low bias, which suggests less systematic errors (Novella and Thiaw, n.d.). RFEs showed a good performance in terms of detecting rain events and identifying the magnitude of rainfall for weak and extreme rainfall amounts. A supposed problem of RFEs in detecting orographically induced rainfall could not be assessed since the Sahel does not have a complex topography or high terrain (Novella and Thiaw, n.d.).

In order to assess the differences between RFE1.0 and RFE2.0 for the study area, data from the year 2000 that had been treated with both algorithms was obtained from The International Research Institute for Climate and Society (IRI)[17]. The integrated rainfall during the rainy season as detected with RFE1.0 and RFE2.0 between June and September 2000 is shown in Figure 4-3.

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[17] http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP/.CPC/.FEWS/.Africa/ (last accessed 15th March 2010)

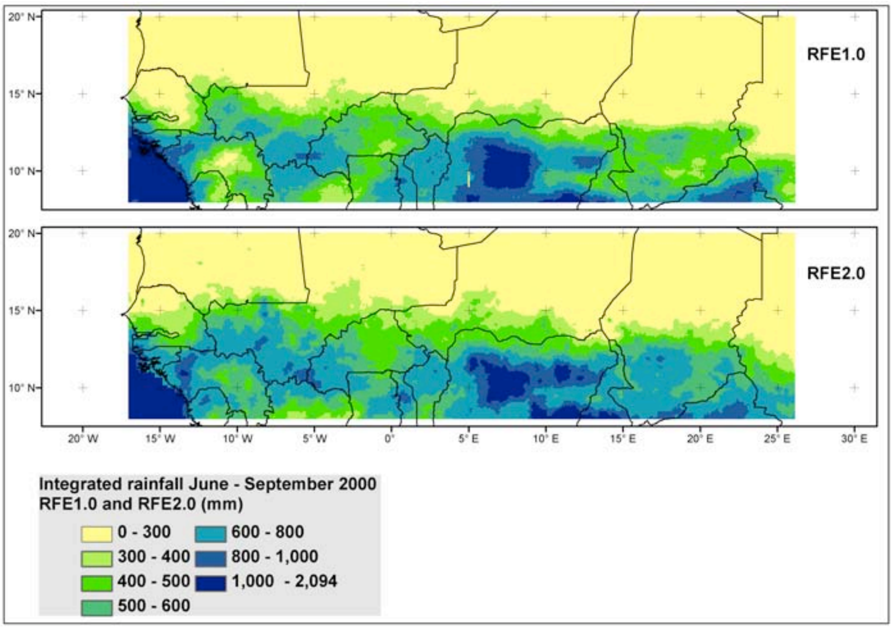

Figure 4-3: The integrated rainfall as detected with RFE1.0 and RFE2.0 during the rainy season between June and September 2000 for Western Africa.

The ranges of rainfall values are similar for RFE1.0 and RFE2.0 but show different patterns throughout the Sahel. Subtracting RFE1.0 from RFE2.0 showed the magnitude and spatial distribution of differences between RFE1.0 and RFE2.0 (see Figure 4-4). A linear regression between both datasets, carried out for the 1° grid employed for the statistical analyses in Chapter 5, showed a significant correlation of 0.93 ($p<0.01$, $n = 28590$) for the rainy season of 2000 (see Figure 4-4). Even though both datasets were highly and significantly correlated, the changed algorithm introduced a slight bias as indicated by the offset of 96.62. Overall, RFE2.0 reveals higher rainfall values compared to RFE1.0, indicated by the slope of 0.94. In the rainfall range of 0 to 200 mm RFE1.0 produced higher rainfall values. For the rainfall range between 200 and 800 mm, which covers most of the study area, both algorithms show comparable values. For rainfall above 800 mm RFE2.0 tends to detect higher values.

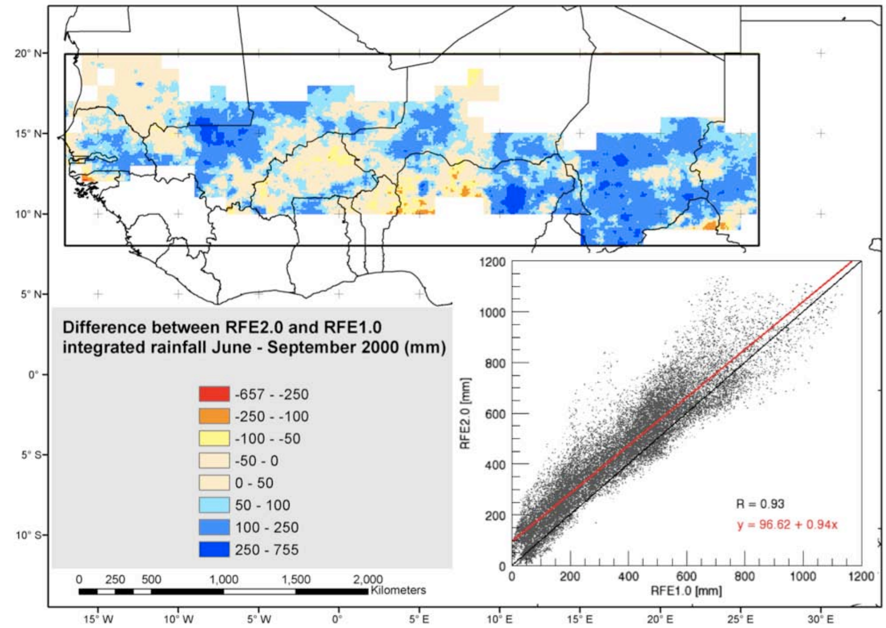

Figure 4-4: Magnitude and spatial distribution of differences between RFE1.0 and RFE2.0 for the rainy season 2000.

Due to data availability, this regional scale assessment could be only carried out for the year 2000. However, a local scale accuracy assessment for the regions studied in Chapter 4 showed that derived annual FEWS rainfall totals for each year, from 1999 to 2008, agree with those reported in the literature (Mougin et al., 2009). The comparison between rainfall estimated with RFE1.0 and with RFE2.0 between June and September 2000, for both Regions 1 and 2, is shown in Figure 4-5. Rainfall totals and overall patterns for the rainy season were similar for RFE1.0 and RFE2.0 in both regions.

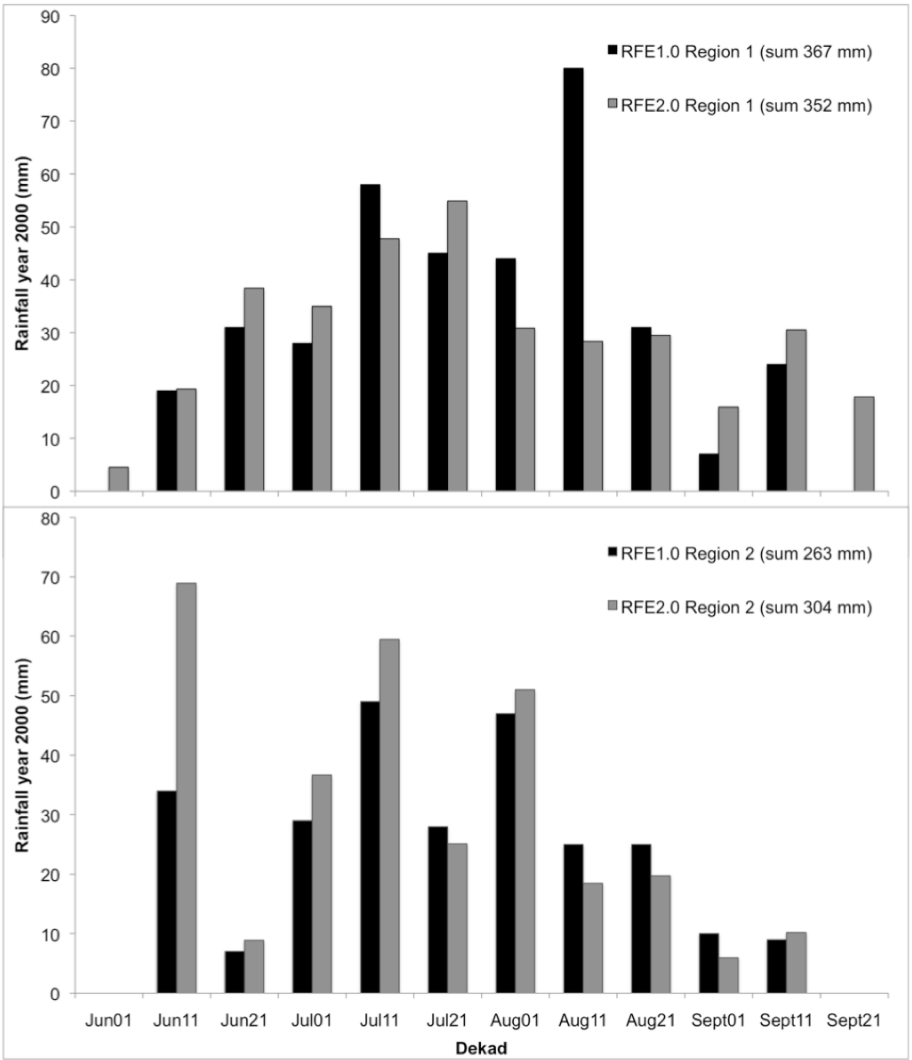

Figure 4-5: Rainfall estimated with RFE1.0 and RFE2.0 between June and September 2000 for Region 1 and Region 2.

In addition, the average rainfall in both study areas, for each year between 1999 and 2008, was correlated with rainfall estimates from the European Centre for Medium-Range Weather Forecast (ECMWF) gridded rainfall data, at 1° ground spatial resolution (Pearson correlation coefficient 0.69 and 0.82 respectively, $p<0.05$, $n = 10$). The ECMWF data is based on an atmospheric circulation model that is continuously corrected with data from several satellites. The comparison showed that both datasets capture the same pattern, but while FEWS RFEs generally overestimate the total rainfall amount, the ECMWF rainfall estimates show a slight underestimation. These findings are in agreement with a study that compared these rainfall datasets for the Sahel (Rojas et al., 2009). In conclusion, the rainfall time series data between 1999 and 2008 was considered to be sufficiently consistent over the study area to be employed for the analyses at both a local and a regional scale.

4.2.2.3 Green cover dataset

The green cover dataset was originally designed to detect the start of the vegetation growth period in arid and semi-arid regions, in order to support desert locust monitoring activities (Cherlet et al., n.d.). To derive the green cover percentage (0-100%), Normalised Difference Vegetation Index (NDVI) data based on SPOT VGT 1 and VGT 2 S10 (10-daily maximum value composite synthesis) images were rescaled and corrected for soil effects (Cherlet et al., n.d.). Removing the soil effect from the vegetation signal is especially suited to arid and semi-arid regions with a generally low vegetation cover. A detailed description of this method can be found at http://www.devcocast.eu. The green cover data are available from June 2001 on a 10-daily time step. The entire time series that covered eight growing seasons (until May 2009) was used in this study. Based on the green cover time series, also the maximum green cover detected between 2001 and 2008 was mapped.

4.2.2.4 Hydrological conditioned digital elevation data

Delineation of the catchments was performed on data obtained from WWF HydroSHEDS (Lehner et al., 2008), which provided hydrographical information based on elevation data obtained during NASA's Shuttle Radar Topography Mission (SRTM) (Farr and Kobrick, 2000). The original SRTM terrain data was provided as hydrological conditioned, which involved the removal of artefacts and anomalies originating from the radar-derived input dataset.

This hydrological conditioning improves the elevation data for hydrological applications. The derived datasets used in this study were: the drainage directions, the flow accumulation, and the potential river network, all at a spatial resolution of approximately 450 m.

4.3 Methods

The methodology includes three components:

(1) Catchment delineation based on hydrological conditioned digital elevation data.

(2) Time series extraction of biophysical variables.

(3) Statistical associations between biophysical variables.

4.3.1 Catchment delineation

The catchments around the selected water bodies were derived based on hydrological conditioned digital elevation data from WWF HydroSHEDS (Lehner et al., 2008). A pour point (confluence point) was placed manually at the outlet of the water body on the potential river network and adapted automatically to the lowest point in the surrounding terrain. Based on the flow accumulation and flow direction data obtained from WWF HydroSHEDS, the catchment for each water body was delineated and then resampled to match the resolution of the rainfall and green cover data.

In arid regions, where surface water only occurs temporarily, changes in the extent of a water body cause changes in catchment boundaries. To account for these changes, the catchments used in this study were based on the maximum extent of the water bodies as derived from the TSWB map (Haas et al., 2009).

4.3.2 Time series derivation of biophysical variables

Water bodies are integrators of hydrological processes (Desconnets et al., 1997) that accumulate rainfall from different parts of the catchment. The correlation between biophysical variables was performed based on surface average values of rainfall and green cover for a given catchment for each dekad. To assure the reliability of the water body detection, the TSWB map was used as a mask for the extraction of time series data of SWB and green cover. For the water body analysis, every pixel detected within the TSWB map was extracted regardless of its category (free water or humid area). When extracting the green cover, the water body, as represented on the TSWB map plus a one pixel buffer, was masked out to retrieve only the natural vegetation cover of the catchment. The buffer accounts for the vegetation in the surroundings of a water body that is mainly influenced by leaking surface water, and for man-made gardens and agricultural fields. These vegetated areas do not follow the growth cycle of natural vegetation because they rely on small-scale irrigation and/or capillary rise of infiltrated water from the water body. During the emptying phase, vegetation develops in the water bodies and these areas are sometimes used for agriculture. For each catchment, a time series of the water body extent, catchment-average vegetation cover and catchment-average rainfall were derived with a 10-daily time step.

4.3.3 Statistical associations between biophysical variables

Primary and secondary biophysical variables were extracted from the time series of rainfall, water bodies and green cover. Because all variables were continuous, standard statistical analysis could be used. Univariate statistical associations between the biophysical variables were studied using Spearman correlation analyses, and were tested for statistical significance. Spearman´s rank correlation coefficient is often used for modelling grassland vegetation dynamics (Balzter, 2000). In addition, a multivariate linear regression model was employed. The statistical analyses were conducted at two levels of spatial aggregation: (i) the catchment level (n = 11 catchments) and (ii) the geographic region (n = 2).

4.3.3.1 Extent of water bodies and rainfall

The hydrological regime of temporary water bodies can be divided in two phases: the replenishment phase (RP) and the emptying phase (EP) (Figure 4-6).

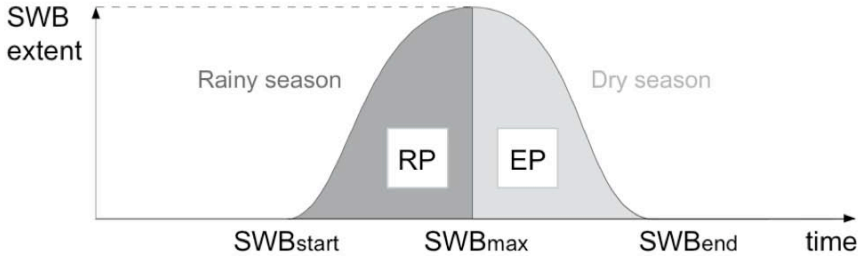

Figure 4-6: The water body evolution from the first detection (SWB start) until its last detection (SWB end) can be split in the replenishment phase (RP) and the emptying phase (EP). The division is placed when the water body first reaches its maximum extent (SWB max) during a rainy season. The ecohydrological processes that influence the extent of the water bodies during the replenishment phase (rainy season) and emptying phase (dry season) are shown in Figure 4-1.

During the rainy season, temporary water bodies are replenished by runoff water. The factors influencing the replenishment of the water body at this stage are the intensity and temporal distribution of rainfall, the vegetation cover and the soil characteristics (see Figure 4-1) (Desconnets et al., 1997; Hughes, 2008; Wheater, 2008). The start of the replenishment phase (RP) was defined as the first non-zero detection of a water body in a rainy season (SWBstart) (Figure 4-6). The end of the replenishment phase was defined as the first maximal extent of the water body (SWBmax). This definition was used in preference to the end of the rainy season in order to keep the observations of the water bodies independent from the rainfall data. A heavy rainfall event at the end of the rainy season might cause an increase in water body extent whereas a low rainfall amount would be evaporated and thus would not change the maximum extent of the water body.

However, in most cases, the end of the rainy season corresponds to the maximum extent of the water bodies as they rely entirely on temporary inflow from runoff water and no permanent stream flow occurs.

The relationship between rainfall and water body extent was investigated by correlating z-scores of the integrated values of both these variables during the replenishment phase. The z-score is a dimensionless quantity derived by subtracting the population mean from the individual raw score in the population and then dividing the difference by the population standard deviation (Snedecor and Cochran, 1980; Larsen and Marx, 2000), as given in Equation 4:

$$z = \frac{x - \mu}{\sigma} \qquad (4)$$

where:

z = the z-score of the raw score

x = the raw score to be standardised

μ = the population mean

σ = the standard deviation of the population.

The z-score describes, for each raw score, its deviation from the mean value and therefore indicates the anomaly from normal (average) behaviour at a given time. The anomalies are measured in units of standard deviation. The z-score is negative when the raw score is below the mean and positive when above the mean. This method has been successfully employed in environmental studies to estimate temporal variability of various ecological and climatic variables (Helldén and Eklundh, 1988; Prince et al., 1998; Helldén and Tottrup, 2008).

4.3.3.2 Extent of water bodies and length of their emptying phase

The processes that influence the emptying of a water body include infiltration, which leads to water percolation into the groundwater, and evaporation from the water body surface. The partition of water between evaporation and infiltration is dependant on the filling stage of the water body. After a flood event has replenished a water body, a stage of fast decrease in the water level can be observed. During this stage the dominant process is infiltration. This is followed by a period of slow emptying since sediments clogged the bottom of the water body, which impedes infiltration. At this stage, evaporation plays a larger role and the longer the water body is present the higher the influence of evaporation compared to infiltration (Desconnets et al., 1997; Martin-Rosales and Leduc, 2003). The presence of infiltrated water allows the growth of denser vegetation around the water body. Evapotranspiration by this vegetation is not thought to influence the water body in any way (Desconnets et al., 1997). The emptying phase of a water body, as indicated by Figure 4-6, was defined as the time period from the first dekad after its maximum extent (SWBmax) until the last non-zero detection of the water body (SWBend). To test the relationship between water body extent and the length of the emptying phase, the maximum extent of the water body (given in km^2) was correlated with the length of its emptying phase (given in dekads). The residuals of the relationship were extracted and analysed for a possible trend that could indicate ecosystem changes such as sedimentation or human usage.

4.3.3.3 Rain Use Efficiency (RUE) and Water Body Ratio (WBR)

To analyse the possible association between the extent of water bodies and vegetation cover in a catchment, the Rain Use Efficiency (RUE) and the Water Body Ratio (WBR) were computed, to control for the effect of rainfall. The RUE is the ratio of annual net primary production (NPP) to annual rainfall (Le Houerou, 1984). Under constant conditions RUE tends to decrease with increasing aridity and the increase of potential evapotranspiration. However, it strongly depends on the soil condition and the dynamic vegetation condition.

The RUE is a good indicator of ecosystem productivity and allows comparisons between ecosystems from various climatic zones with different botanical structures (Le Houerou, 1984). In extremely dry years when water is most limiting, deserts, grasslands and forests exhibit the same rate of biomass production per unit rainfall, despite differences in physiognomy and site-level RUE (Huxman et al., 2004a). NPP was shown to increase across biomes with increasing mean annual rainfall although there are different sensitivities of NPP to inter-annual variability in rainfall across biomes. Grasslands, which are the main vegetation cover in the Sahel, are generally more variable in yearly patterns of RUE (Huxman et al., 2004a). At the local scale addressed in this study, a number of factors can influence the RUE value, and these should be carefully considered when interpreting the results.

Monteith (1972) showed that NPP is closely related to the amount of absorbed photosynthetic active radiation (APAR) integrated during a time interval, multiplied by the growth efficiency (gram dry matter per megajoule). The growth efficiency is influenced by temperature, light, availability of water and nutrients, respiration costs for maintenance, and the growth needs of the plant, which must all be considered when modelling plant productivity (Prince, 1991; Prince and Goward, 1995; Fensholt et al., 2006). Thus, the relationship between NPP and APAR is valid for a specific site and during the growing season time scale, but can vary for different sites and for successive years (Mougin et al., 1995).

When NPP is estimated remotely, with empirical approaches based on vegetation indices, growth efficiency is not taken into account as well as other important factors that influence biomass at a local level. Indices based on reflectance, measured with satellites in the red and infrared bands such as the NDVI, were found to be positively linearly related to absorbed photosynthetic active radiation (APAR) and thus to NPP (Tucker, 1979; Sellers, 1985; Tucker et al., 1985; Prince, 1991). However, this relationship is not linear over the entire range of NPP. For biomes with high NPP it becomes saturated, while it is weak for biomes with low NPP (Box et al., 1989). Grasslands are the most suitable biome to derive quantitative estimates of NPP from NDVI data (Paruelo et al., 1997). Residuals of the NDVI - NPP relationship are likely to be caused by: the spatial aggregation of heterogeneous landscapes in coarse resolution pixels; the soil contribution in the signal since vegetation cover is generally low in arid regions; and by atmospheric and angular effects (Diouf and Lambin, 2001). For arid and semi-arid regions such as the Sahel that are mainly covered with grasses NDVI was found to be a good surrogate for NPP (Prince, 1991; Prince et al., 2009). However, there can be large inter-annual variations in the strength of the relationship between NDVI and NPP. Integrated NDVI values over a growing season were found not to be a very robust proxy variable for biomass, in particular at a local scale (Diouf and Lambin, 2001).

Scale is also important when the relationship between NPP and rainfall is considered, on which the RUE is based. In arid and semi-arid regions, NPP generally shows a strong linear relationship with rainfall (Le Houerou, 1989). At the scale of the Sahel, a strong relationship between rainfall and NDVI was demonstrated (Tucker et al., 1985; Hielkema, 1986; Malo, 1990; Nicholson, 1990; Diouf and Lambin, 2001; Diello et al., 2005; Herrmann et al., 2005). Yet, rainfall is not the only factor controlling NPP, as indicated by the variability in the relationship (Prince et al., 1998), which is considerable at the local scale (Diouf and Lambin, 2001). Several factors can cause a lack of direct response of vegetation to rainfall when considered on an annual basis. Gaps between rainfall events during the growing season, which are common in semi-arid regions, can change NPP even when the same annual rainfall amount is measured. Also, soil fertility and nutrient limitations influence NPP (Prince, 1991), but are stable between years. Other reasons are the slow turnover rate of populations of longer-lived species, differences between plant functional types in physiological variability and acclimation, as well as human and natural interventions (Goward and Prince, 1995).

Since the ratio of NPP to rainfall is an estimate of the RUE of an ecosystem it greatly relies on climatic, human, and animal impacts on the ecosystem (Le Houerou, 1984). Although water availability limits the maximum cover of woody species in many African savanna ecosystems, disturbances such as fire and herbivory control the savanna structure below this maximum and thus influence NPP (Sankaran et al., 2005). These factors operate at different spatial and temporal scales leading to abrupt or gradual changes in the vegetation cover (Mazzoleni et al., 2003). A reduction in RUE was associated with land degradation in the Sahel (Nicholson et al., 1998; Prince et al., 1998).

Changes in RUE can also be caused by a shift from grassland to woodland and changes in species composition. Such fine scale changes in vegetation communities cannot be measured at the spatial resolution of 1 km^2 as obtained with remote sensing. However, Fensholt et al. (2009) confirmed an agreement between in-situ NDVI measurements and, amongst others, the SPOT VGT NDVI product for homogenous landscapes, such as grasslands of northern Senegal. Since green cover is a rescaled NDVI that has been corrected for soil influences, the RUE employed in this analysis was defined as (Equation 5):

$$RUE = \sum GC / \sum R \qquad (5)$$

where:

$\sum GC$ is the integrated seasonal green cover and

$\sum R$ is the integrated seasonal rainfall, both a spatial average for the catchment.

Literature suggests that low values of RUE (low vegetation production per unit of rainfall) are associated with less vigorous and a less dense green cover and thus potentially higher runoff coefficients that could result in an enhanced supply of runoff water to water bodies (Prince et al., 1998). In a degraded environment, the RUE is expected to decrease due to a decreasing amount of vegetation produced for the same amount of rainfall, caused by physical and chemical degradation of the soil (Diouf and Lambin, 2001). This leads to an increase in runoff and soil evaporation (Prince et al., 1998). To disentangle the impact of land degradation from that of short-term fluctuations in rainfall, several decades of observations are required (Prince, 2002; Herrmann et al., 2005). To assess whether the response of the water body to the available rainfall is above or below normal, the ratio of the water body extent to the rainfall, both integrated for the season, was established. This is possible since in an endorheic catchment, the extent and duration of a water body is directly dependent on the rainfall intensities and patterns.

To normalise the water body detection by the rainfall amount, a Water Body Ratio (WBR) was defined as (Equation 6):

$$WBR = \sum SWB / \sum R \qquad (6)$$

where:

$\sum SWB$ is the integrated seasonal amount of detected water body pixels in a catchment and

$\sum R$ is the integrated seasonal rainfall averaged for the catchment.

A correlation between RUE and WBR would suggest that a statistical association between vegetation cover and water body extent would not simply result from the fact that they both depend on rainfall.

4.4 Results

4.4.1 Water bodies as indicators of climatic variability

A transformation into z-scores allowed the identification of years comprising above and below average rainfall amounts and water body extent. Figure 4-7 displays the z-scores (the deviation from the average value) during the replenishment phase for Regions 1 and 2.

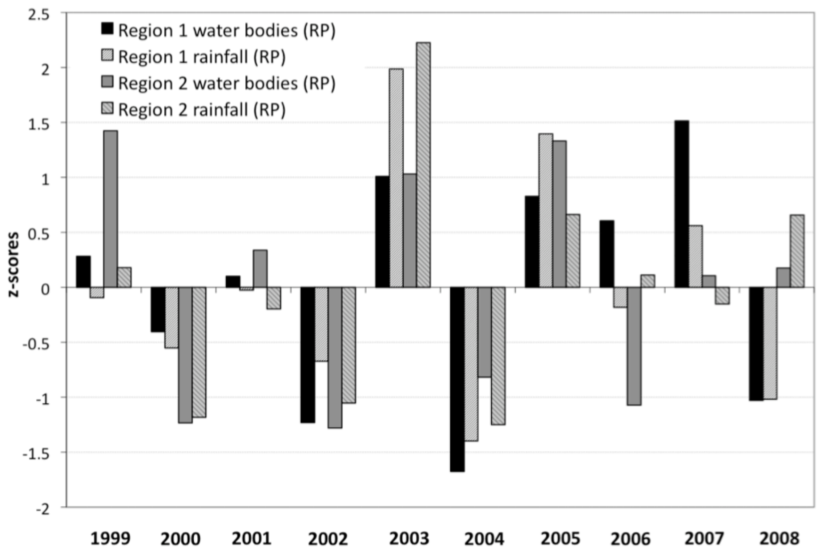

Figure 4-7: The anomalies of water body extent and rainfall amount for Regions 1 and 2 during the replenishment phase (RP).

In both regions the two variables exhibit similar patterns during extreme climatic years such as the very dry year of 2004 and the very wet years of 2003 and 2005. However, as Figure 4-7 shows, these variables can each exhibit different responses during more normal years.

During the replenishment phase of a water body, the strong linear relationship between rainfall anomalies and water body extent anomalies indicates that temporary endorheic water bodies of 1 km^2 and larger reflect the climatic variability in an ecosystem. The Spearman correlation coefficient for Region 1 (0.90, $p<0.01$, $n = 10$) was slightly higher than that for Region 2 (0.70, $p<0.05$, $n = 10$), with both being statistically significant. When data from the two regions were pooled, the correlation was still significant: 0.80 ($p<0.01$, $n = 20$) (Figure 4-8).

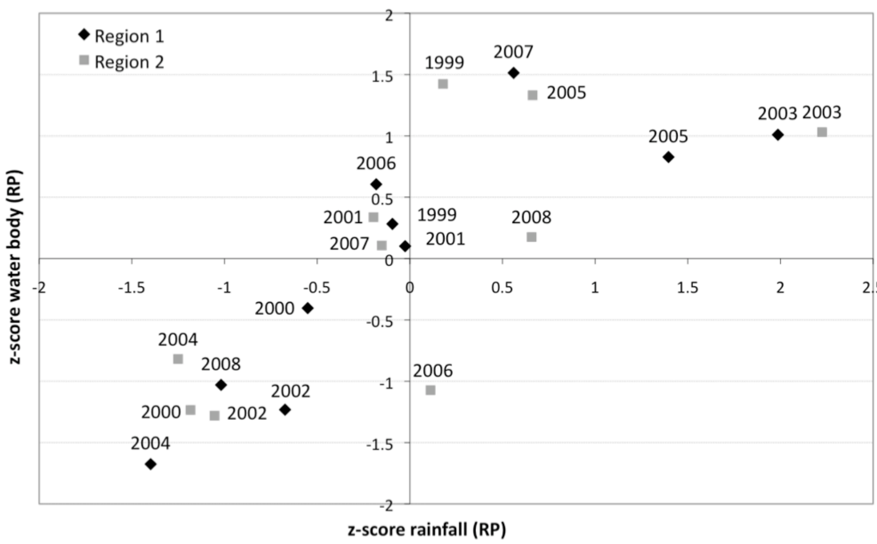

Figure 4-8: Correlation between the z-scores of rainfall and water bodies detected during the replenishment phase in Region 1 and Region 2; Spearman correlation coefficient 0.80 (p<0.01, n = 20).

To increase the number of observations, the z-scores of rainfall and water body extents within the 11 individual catchments were analysed together, which resulted in a significant Spearman correlation coefficient of 0.56 ($p<0.01$, $n = 110$) (Figure 4-9).

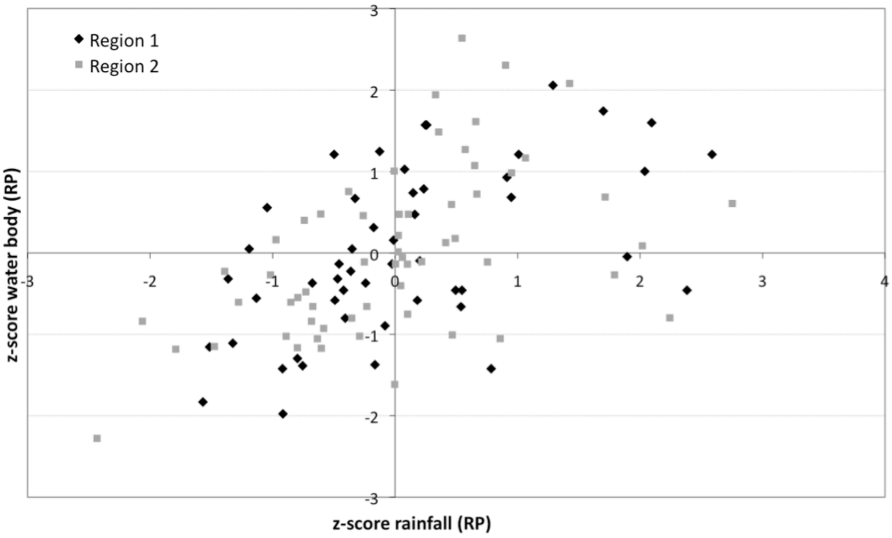

Figure 4-9: Correlation between the z-scores of rainfall and water bodies detected during the replenishment phase (RP) in the 11 individual catchments of Region 1 and 2. Spearman correlation coefficient 0.56 (p<0.01, n = 110).

The Spearman correlation coefficients for the individual catchments vary between 0.49 and 0.75 for Region 1, and between 0.33 and 0.82 for Region 2. Low correlations were obtained for catchments with small water bodies close to the pixel resolution of 1 km^2. Even though these water bodies could be detected reliably, the stability of the detection was less than for larger water bodies (see 3.4.2). The conclusion from section 3.4.2, that several small water bodies should be regarded collectively for a region rather than individually, was confirmed by this finding.

4.4.2 Water bodies as indicators for water availability during the dry season

The relationship between the maximum extent of the water bodies and the length of their emptying phase was significant in both study areas. The Spearman correlation coefficient for Region 1 (0.84, p<0.01, n = 10) was slightly higher than for Region 2 (0.71, p<0.05, n = 10) with both being significant. When the exceptionally dry year of 2004 was not included for Region 1, the Spearman correlation coefficient was still 0.77 (p<0.05, n = 9), which confirmed the strength of this relationship. When data from the two regions were pooled, the correlation was not significant and decreased to 0.20 (n = 20), suggesting that respective water bodies in the two regions exhibit different emptying characteristics (Figure 4-10). For a similar maximum extent of the water body, the length of the emptying phase was much shorter for Region 2, which is located to the north of Region 1. Region 2 also exhibits greater differences in surface water availability between the years than Region 1.

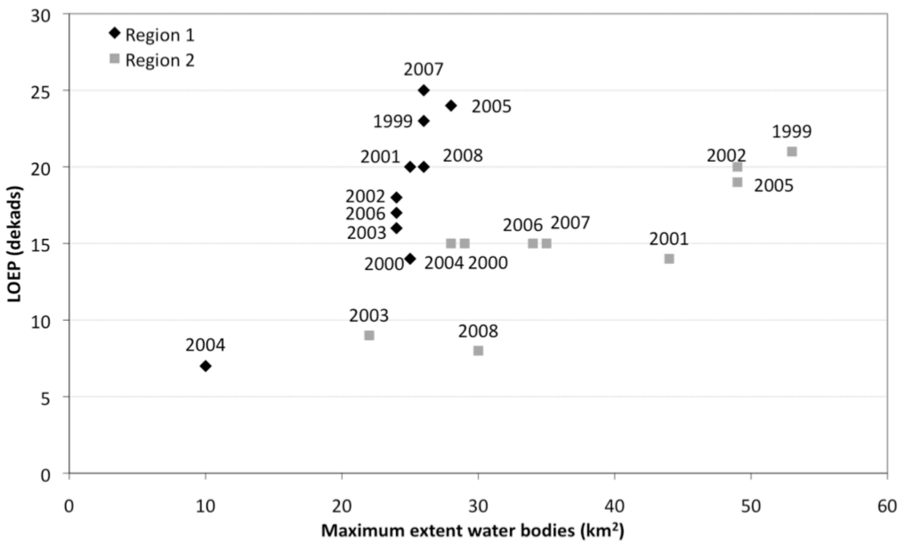

Figure 4-10: The maximum extent of surface water in Region 1 and Region 2 is significantly related to the length of the emptying phase (LOEP). The Spearman correlation coefficient is high for Region 1 (0.84, p< 0.01, n = 10) and Region 2 (0.71, p< 0.05, n = 10).

For the 11 individual catchments of both study areas, the relationship between the maximum extent of the water body and the length of the emptying phase ranges between 0.42 and 0.86. Two exceptions were for catchments with smaller water bodies that exhibited only a weak relationship (0.16 and 0.24 respectively). Analysis of the residuals did not reveal any significant trend that might indicate the presence of ecosystem changes (Figure 4-11).

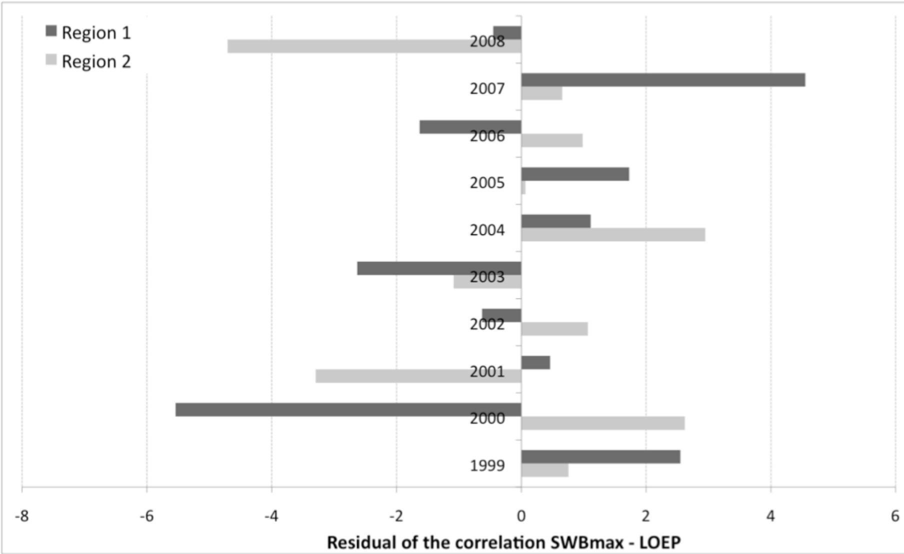

Figure 4-11: The residuals of the correlation between the maximum extent of water bodies (SWBmax) and the length of their emptying phase (LOEP) did not show a significant trend for either region.

4.4.3 Water bodies as indicators for the state of an ecosystem

Rainfall influences runoff generation, the filling of water bodies, and vegetation growth. A multivariate linear regression analysis of the z-scores of the integrated water body extent, green cover and rainfall during the replenishment phase between 2001 and 2008 revealed statistically significant correlations between the variables in both Regions 1 and 2. For Region 1 the predictor variables, rainfall and green cover, were less significantly correlated (0.51, $p<0.1$, $n=8$) than rainfall to the dependent variable water body extent (0.83, $p<0.01$, $n=8$) and then water body extent to green cover (0.84, $p<0.01$, $n=8$). In Region 2 rainfall and green cover showed a slightly higher correlation (0.75, $p<0.1$, $n=8$) than rainfall and water body extent (0.74, $p<0.1$, $n=8$), although the latter correlation was less significant than in Region 1. Water body extent was also correlated to green cover in Region 1 (0.67, $p<0.1$, $n=8$).

The overall goodness-of-fit for each regression model was evaluated by the R-square that indicates the proportion of the observed variation in the dependent variable (water body extent), which could be statistically significantly explained by the multivariate linear regression model. In Region 1, 93.6% ($p<0.01$, $n=8$) of the observed variability in water body extent could be statistically explained by rainfall and green cover. While in Region 1 the inclusion of green cover increased the goodness-of-fit of the model, it decreased in Region 2. Thus, only rainfall was regarded as a predictor that could explain 55% of the variability in the water body extent ($p<0.1$, $n=8$).

Since the variables were standardised for each individual catchment, they remained continuous and thus could be pooled for each region. When the observations from the five individual catchments in Region 1 were pooled, rainfall and green cover together explained 42.6% ($p<0.01$, $n=40$) of the variations in water body extent. In the six catchments of Region 2, green cover was statistically a more important predictor than rainfall and explained 41.7% ($p<0.01$, $n=48$) of the total variations in water body extent. When the individual observations from both regions were pooled, the model showed a similar predictive power of 42% ($p<0.01$, $n=88$), including rainfall and green cover as predictors of water body extent variability.

Possible reasons for the lower correlations and goodness-of-fit of the multivariate linear regression models, in the individual catchments, were the stability of the detection of small water bodies during the replenishment phase (see 3.4.2), and also the variability of the rainfall. Smaller water bodies were not frequently, or not at all, detected in very dry years since the size of the water bodies was approximately equal or smaller than the minimum detectable size of 1 km^2. At the same time, during dry years rainfall occurred that led to the development of green cover. The finding that green cover better statistically explained the variability of the water body extent in Region 2 than rainfall could result from the fact that rainfall is more variable than green cover. Both water body extent and green cover depend on rainfall. Since both these variables evolve continuously during the rainy season they are better related to each other than to rainfall, which is more variable and is based on an estimate.

The multivariate analysis showed significant relationships between the variables. However, the correlation matrices showed multi-collinearity between the predictor variables rainfall and green cover. Even tough multi-collinearity does not reduce the predictive power or reliability of the model, correlated predictors in a multivariate model may not give valid results about an individual predictor. Since there were only two predictors, and the development of green cover was dependent on rainfall, it was difficult to estimate the direct influence of green cover on water body extent using multivariate regression analysis.

Computing the RUE and WBR allowed water body extent to be related to the vegetation cover of a catchment independently of variations in annual rainfall amounts. High vegetation productivity was related to a large total extent of water bodies for Region 1 (0.90, $p<0.01$, $n = 8$). This relationship was not significant for Region 2 (0.31, $n = 8$) (Figure 4-12).

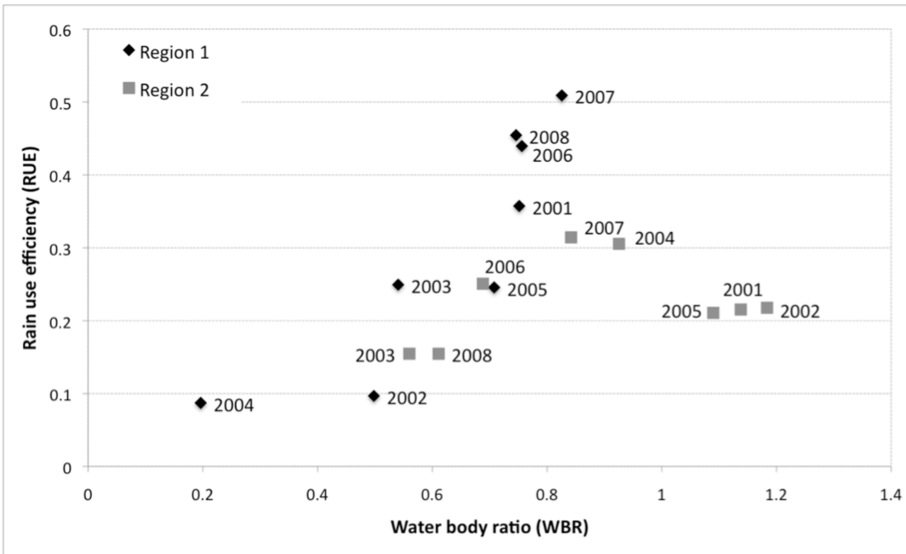

Figure 4-12: Correlation between the WBR and RUE for Region 1 (Spearman correlation coefficient 0.90, p<0.01, n = 8) and Region 2 (Spearman correlation coefficient 0.31, non significant, n = 8).

4.5 Discussion

4.5.1 Water bodies as indicators of climatic variability

Hypothesis 1, that endorheic temporary water bodies reflect climatic variability, was not rejected in this chapter. A strong positive relationship between rainfall anomalies and temporary water body extent anomalies was measured for both study areas. This finding is in agreement with a study that compared the differences between rainfall and SWB observations between 2006 and 2007 for all administrative regions of the CILSS countries, and that found most of the regions with abundant rainfall in 2007 also showed more water bodies in that year (Combal et al., 2009). The fact that the evident relationship between rainfall and water body extent can be observed, shows the potential of the 1 km spatial resolution SWB dataset to indicate climatic variability.

The rainfall and water body extent relationship was established for closed hydrological or endorheic systems. The general surface hydrology of the Sahel region is a juxtaposition of hundreds of small endorheic systems that are only connected during very wet years (Desconnets et al., 1997). Thus, the relationship between rainfall and water body anomalies is expected to be transferable to temporary water bodies throughout the Sahel. Field observations in south-western Niger confirmed that temporary water bodies that occur along a temporary drainage network are only connected during extreme rainfall events and thus have no significant outflow (Haas and Bartholomé, 2009). This relationship would presumably be different for temporary water bodies with a significant outflow during the rainy season. In this case, the water balance is not closed and the inflow (rainfall) cannot be directly compared with the water body extent, as the outflow from the hydrological system is unknown.

4.5.2 Water bodies as indicators for water availability during the dry season

In a closed hydrological system, the emptying of a water body is caused by evaporation and infiltration. A statistically significant, positive relationship between the maximum extent of temporary endorheic water bodies at the end of the rainy season and the length of their emptying phase was found for both regions. Thus, Hypothesis 2 was not rejected. When observations from both regions were pooled, no significant relationship was identified, indicating that the two regions exhibit different hydrological characteristics. This is probably linked to regional differences in climate, geomorphology, or the permeability of the underlying rocks. The dryer environment in Region 2 located further north, favours evaporation and thus emptying. However, other environmental factors may play a role such as regional differences in the morphology of the water bodies. Water bodies with a higher area-depth ratio will be much more sensitive to evaporation.

The residuals of the observed relationships did not reveal any significant trends that would indicate long-term ecosystem changes. The years with a longer-than-expected emptying phase of the water bodies in relation to their maximum extent did not occur in chronological order (see Figure 4-11).

If this had been the case, it could have indicated increased sedimentation and clay clogging of the water body bottom and thus degradation in the catchment (Martin-Rosales and Leduc, 2003). There was also no evidence of a systematic shortening of the emptying phase over the years that could indicate increased human water extraction or increased evaporation due to increased temperatures (Figure 4-11). Such processes can probably only be detected at finer spatial and temporal scales or for longer time series (Martin-Rosales and Leduc, 2003).

4.5.3 Water bodies as indicators for the state of an ecosystem

Vegetation cover influences runoff generation and thus the spatial and temporal behaviour of the water body extent. Hypothesis 3 stated that degraded or increased vegetation growth in a catchment could be indicated by changes in the water body extent. Rather than finding a negative relationship between vegetation cover and water body extent, the short time series employed suggests that the RUE was positively related to the generation of runoff water during the period 2001 to 2008. Some differences in the hydrological responses between the northern (Region 2) and southern (Region 1) study areas were observed. The catchments in the northern Region 2 were generally characterised by a lower RUE and higher WBR than those in the southern Region 1. Vegetation cover in the southern Region 1 can reach a maximum green cover of 35% during wet years, while the vegetation in the northern Region 2 is very sparse and reaches a maximum of 10% green cover during wet years. Cultivation of millet is more common in the southern region. Differences in runoff generation might be related to regional differences in soil type, as the southern Region 1 is dominated by sandy soils where a large percentage of rainfall infiltrates and becomes available for vegetation. The northern Region 2 is dominated by shallow soils on rock outcrop that foster runoff and limit vegetation growth.

However, the association between RUE and replenishment of the water bodies observed in the study areas should be interpreted with a certain level of caution. Within the relatively short time series (< 10 years) employed in this study, the observed trends may occlude long-term changes in ecohydrological conditions.

The 8 years of observation data included in this study were characterised by a slight improvement of rainfall conditions in the central Sahel after the prevailing dry conditions since the Sahelian drought during the 1970s and 1980s (Lebel and Ali, 2009). Various authors have shown that the surface hydrology of the Sahelian catchments changed profoundly as a result of land-use changes during the last decades leading to increased runoff at the field scale despite decreased rainfall. This led to more discharge in Sahelian rivers and an increase in the extent and duration of temporary water bodies in some regions, such as south-western Niger (see 3.2.1) (Leblanc et al., 2008; Descroix et al., 2009; Favreau et al., 2009; Gardelle et al., 2009). Seasonal greenness has also increased since the 1980s in the Sahel (Herrmann et al., 2005; Prince et al., 2007; Helldén and Tottrup, 2008). The causes for greening are not completely understood but the resilience of natural vegetation and human activities such as the extension of the cultivation of the rain-fed, water-efficient millet crop are likely to have contributed to the long-term positive rainfall-independent deviations of greenness and RUE (Herrmann et al., 2005; Helldén and Tottrup, 2008).

The data on the temporal evolution of the green cover and RUE (2001 - 2008) shown in Figure 4-13 conformed to previous studies. The WBR did not reveal a significant trend for either region but positive anomalies prevailed in the second half of the observed time period between 2001 and 2008, although 2008 alone revealed below average values in Region 2 (Figure 4-13).

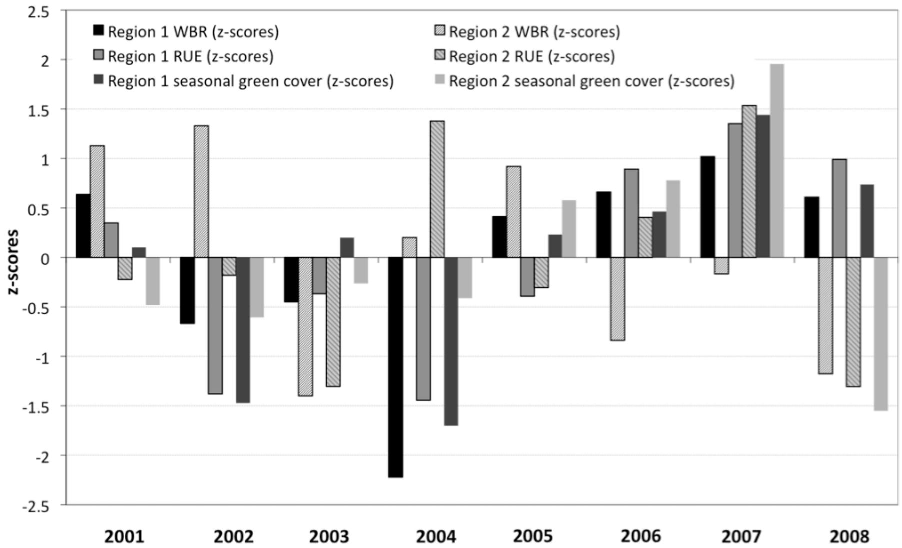

Figure 4-13: The z-scores of the WBR, the RUE and the seasonal green cover of both regions between 2001 and 2008.

To what extent changes in surface water extent are caused by land-cover changes, or are a result of improved rainfall conditions since the end of the 1990s, cannot be identified with a short time series covering only this time frame. The changes in rainfall intensity and distribution since the end of the 1990s were favourable for runoff generation and thus could increase runoff and water body replenishment. The statistically significant relationship between rainfall anomalies and water body extent anomalies observed between 1999 and 2008 indicates a direct impact of rainfall on temporary water body extent. This effect can be reinforced by land-cover changes that foster runoff.

4.6 Conclusion

The hypothesis that time series of temporary water bodies detected with the SPOT VGT SWB dataset have the potential to be used as ecological indicators for short-term ecohydrological changes in semi-arid ecosystems of Western Africa was tested in this chapter. The findings in two regions of Mali and Burkina Faso suggest that the dynamics of temporary water bodies reflect both rainfall and vegetation variability. The observation of their maximum extent at the end of the rainy season can indicate future water availability during the following dry season. Since water bodies indicate a positive balance between rainfall and evaporation they can provide information beyond a purely climatic (i.e. rainfall) dataset. These results suggest that observations of temporary water bodies by remote sensing at a 1 km spatial resolution can be used to monitor the availability of surface water during the dry season at ecosystem level, and to indicate inter-annual rainfall variability. At the same time it allows us to infer, from available rainfall and green cover observations, the condition of water bodies in an ecosystem.

The integrated assessment of rainfall, vegetation cover and water body extent suggested strong statistical relationships between the three variables. Rainfall in the arid and semi-arid regions of sub-Saharan Western Africa drives both vegetation development and the replenishment of water bodies, which explains their strong relationship. Beyond the influence of rainfall a positive relationship between vegetation cover and water body extent was observed. A possible cause for the positive relationship was more high intensity rainfall observed during the time frame of the study between 1999 and 2008 compared to previous decades (Lebel and Ali, 2009). High intensity rainfall supports the replenishment of water bodies and reduces the influence of vegetation cover on runoff, which is generally low due to the sparse vegetation cover in arid and semi-arid regions. Land-cover changes that impact on the soil and vegetation composition can reinforce this effect. At the same time, vegetation cover profits from the increased rainfall. To disentangle the effects of climate fluctuations and land-use change on the replenishment of water bodies, a long-term monitoring period is needed.

Additionally, higher time and spatial resolution datasets that include more ecosystem variables such as soil moisture could provide a better insight in the complex ecohydrological processes of semi-arid environments. The regional scale on which the data were acquired, which hindered a detailed identification of processes, is an advantage when monitoring large areas. If long-term monitoring confirms the positive link between surface water extent and vegetation cover, information regarding foraging potential, in addition to available surface water, could be provided as a practical consequence of the obtained results. This is especially important for pastoral communities in the Sahel. The possibility of being able to forecast the duration of surface water availability, which can relate to foraging potential, can also prevent conflicts between herders and farmers. An integrated assessment of remotely sensed rainfall, vegetation cover, and water body extent provides an understanding about ecohydrological relationships in semi-arid ecosystems. Continuous monitoring will reveal if the observed positive relationship between vegetation cover and water body extent remains and will thus allow the identification of any short-term changes in ecosystem status.

In conclusion, the second research hypothesis addressing the links between surface water extent, vegetation cover and rainfall was not rejected for the ecosystem (or catchment) level. To understand the potential of the regional scale water body dataset to indicate ecosystem status at the regional scale, the findings obtained in this chapter at ecosystem level were tested for the whole of sub-Saharan Western Africa in the following Chapter 5.

Chapter 5 Potential and limitations of the regional scale water body dataset to indicate ecosystem status in West African drylands

Abstract

The objectives addressed in this chapter are (i) to test the three hypotheses regarding water bodies as ecological indicators that have been developed at an ecosystem level for Western Africa and (ii) to assess the potential, and limitations, of the regional scale SWB dataset to indicate ecosystem status in West African drylands. The three hypotheses in respect of temporary endorheic water bodies as indicators for ecosystem status, developed at a local scale in Chapter 4 (see 4.1), were tested here at a regional scale. In addition, seasonal vegetation cover anomalies were directly compared to seasonal rainfall and water body anomalies to assess the quality of the observed biophysical variables. To understand if the hypotheses also apply for non-endorheic temporary water bodies they were tested for a 1° grid that covered Western Africa. The Water Body Ratio developed in Chapter 4 (see 4.3.3.3) is the ratio between seasonally integrated water body extent and rainfall amount, which indicated rainfall-independent surface water occurrence. In this chapter, it was adapted to cover only the replenishment phase (WBRrp) and was calculated for each 1° grid cell. A trend analysis of the WBRrp showed no significant trend between 1999 and 2008 for the study area. This indicated that during the last decade the available surface water in a 1° grid cell was related to the available rainfall. The fact that the WBRrp did not exhibit a trend from 1999 to 2008 allowed the identification of a median WBRrp value for each grid cell. Based on this median WBRrp value, the water body amount during the replenishment phase could be estimated from rainfall data and vice versa. Important findings of this chapter are that the relationships observed at a local scale also hold for the regional scale. Thus, temporary water bodies have the potential to indicate ecosystem status in West African drylands. Limitations are the varying qualities of the observed relationships throughout the region.

5.1 Introduction

At a regional scale, wide-field-of-view satellite sensors allow monitoring of the changing state of surface water and natural resources at a high spatial and temporal resolution. This is important in understanding and quantifying ongoing processes that can affect countries, regions and global climate. An important scientific question for the Sahel is to understand if the lasting drought that peaked in the 1970s and 1980s was the first regional scale display of global climate change, or if it was predominantly caused by specific, regional, land-use changes observed in Western Africa (Redelsperger and Lebel, 2009). Since the 1960s, agriculture has replaced natural savanna ecosystems, and trees have been cut for fuel wood in order to satisfy a growing population living under extreme climatic conditions. Such land clearance is the main explanation for the "Sahelian paradox" that describes the increased runoff in most of the Sahel despite less rainfall during the drought and the following decades (Leblanc et al., 2008; Descroix et al., 2009). While the drought impacted the Sahel rather uniformly, a complex pattern of recovery was observed. Wetter conditions have been observed in the eastern and central Sahel in particular since the end of the 1990s (Lebel and Ali, 2009), which is the time period covered in this study. For the same time period in the western Sahel, dry conditions have prevailed (Lebel and Ali, 2009). Future climate scenarios for this region show high uncertainties and predict increased rainfall as well as increased drought by the end of the 21st century. Such conditions will further stress this region, which has already undergone the largest climate anomaly observed worldwide during the last century (Bates et al., 2008).

Due to continuous changes in regional land-use and climate, the factors influencing the variability of the Sahelian hydrology remain difficult to grasp. In the face of climate and environmental changes, the hydrological regimes will most likely continue to evolve, with great consequences on available water resources (Descroix et al., 2009). The integrated assessment of regional scale changes in surface water extent, vegetation cover and rainfall performed in this chapter contributes to the development of regional scale environmental indicators. These indicators facilitate monitoring of ecosystem changes at a regional scale and provide an insight into the complex relationships between biophysical variables.

5.2 Study area and datasets

The study area for this regional scale assessment comprises sub-Saharan Western Africa, which ranges from the Atlantic coast to the Republic of Chad, according to the geopolitical UN definition of Western Africa (see Figure 1-1). The same datasets of rainfall, vegetation cover and water bodies that were used in Chapter 4 (see 4.2.2) were used in the regional scale study in order to assure consistency.

5.3 Methods

The following methods were applied to test the potential of water bodies to indicate ecosystem status at a regional scale:

(1) Derivation of a 1° grid covering Western Africa.

(2) Time series derivation of biophysical variables for each 1° grid cell.

(3) Statistical associations between biophysical variables.

(4) Trend analysis of the Water Body Ratio (WBRrp).

5.3.1 Derivation of a 1° grid covering Western Africa

A 1° grid, which includes all 0.5° grid cells validated in the accuracy assessment of the TSWB map (see 2.3.2), was derived for Western Africa. This 1° grid contains several hydrological features. While in the local scale study in Chapter 4 only endorheic water bodies were chosen, at the regional scale a number of different temporary hydrological features were included that have been described in detail in section 3.5. The nomenclature of these water body types has been used in this chapter, in particular in the results section. Large permanent rivers and freshwater systems such as the Niger Inner Delta and Lake Chad were excluded. These large hydrological features exhibit a different behaviour to those that were targeted for this analysis since they receive discharge from different upstream climatic regions after a significant time lag.

5.3.2 Time series derivation of biophysical variables

For each 1° grid cell, the time series of the biophysical variables rainfall, water body extent and vegetation cover were derived using the same method as was employed in section 4.3.2. From these time series, primary and secondary biophysical variables were extracted based on the same definitions as in section 4.3.2. In addition, the integrated seasonal extent of water bodies, rainfall and vegetation cover were also extracted and standardised to z-scores (see 4.3.3.1).

5.3.3 Statistical associations between biophysical variables

The statistical associations between the biophysical variables rainfall, water body extent and vegetation cover were tested with the Spearman correlation coefficient when four or more years of valid detections were available for a 1° grid cell. A detection was considered as valid if more than one water body pixel was detected during a rainy season, if water bodies were not permanently present, and if rainfall was not equal to zero.

The three hypotheses introduced in Chapter 4 (see 4.3.3) and two new hypotheses, discussed below, were tested for each 1° grid cell at the regional scale. The two new hypotheses support the validity of the third hypothesis about the relationship between Rain Use Efficiency (RUE) and the Water Body Ratio (WBR).

Rainfall and water body extent anomalies (z-scores) during the replenishment phase (RP) were correlated to test Hypothesis 1, regarding water bodies as indicators of climatic variability, expressed by rainfall. The maximum extent of water bodies (SWBmax) at the end of the replenishment phase was correlated with the length of their emptying phase (LOEP). This provided an understanding of whether water bodies can be used Sahel-wide as indicators for water availability during the dry season, as stated in Hypothesis 2. Hypothesis 3 tested the potential of water bodies to indicate ecosystem status, by the correlation of the RUE and WBR ratios at the regional scale. Both these ratios are based on the seasonal integrals of rainfall, vegetation cover and water body extent.

Correlating the seasonal integrals of water body extent and green cover (which were transformed to z-scores to assure comparability), a potential, direct relationship between water body extent and vegetation cover was investigated. To test if the commonly pixel-wise detected relationship between rainfall and vegetation cover can also be detected for 1° grid cells, the seasonal integrals of rainfall and green cover were transformed to z-scores and then correlated.

5.3.4 Trend analysis of the Water Body Ratio (WBRrp)

The WBR, as developed in Chapter 4 (see 4.3.3.3), was adapted to the replenishment phase by using the integrated water body extent and rainfall values relating to the replenishment phase only, rather than of the whole season. To identify a trend in water body replenishment that goes beyond the influence of available rainfall during the last decade (1999 to 2008), the trend of the WBRrp was computed for each 1° grid cell in the study area using a linear regression t-test. The slope and direction of the regression line indicated the trend that was mapped, together with the significance level. Extracting the years of the maximum WBRrp between 1999 and 2008 for each grid cell revealed years of especially large surface water extent compared to available rainfall, indicated by a high WBRrp.

5.4 Results

5.4.1 Extent of water bodies and rainfall at the regional scale

Rainfall anomalies recorded during the replenishment phases from 1999 to 2008 were reflected by the water body extent anomalies throughout the study area, although not all grid cells showed significant correlations, as can be seen in Figure 5-1.

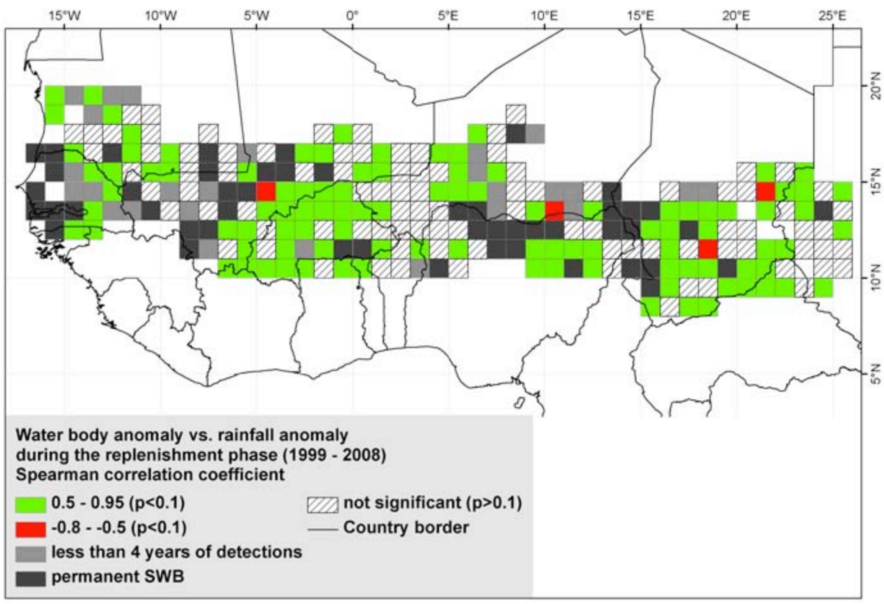

Figure 5-1: Spearman correlation coefficients of rainfall and water body anomalies (z-scores) during the replenishment phase for 1° grid cells in Western Africa.

The positive relationship between the respective rainfall and water body extent anomalies was confirmed at the regional scale but the same quality was not seen throughout the region. Significant positive relationships between rainfall and water body extent anomalies were found in 106 out of 279 grid cells, which were distributed throughout the Sahel.

No clear spatial pattern emerged, although the grid cells showed some clustering. In particular in the central Sahel (5° W to 0° W, 12° N to 15° N) a large region showed significant positive correlations between the anomalies. The northern part of this region in the central Sahel comprises a large endorheic area located within the Niger River loop, where temporary surface water bodies of all sizes (Types A and C) are replenished entirely by local rainfall. Grid cells in other parts of the study area also exhibited significant positive correlations. These grid cells contained, in particular, a number of both small and large temporary water bodies of the types that occur in koris (Type A) and in relation to fossil sand dunes (Type C), as well as smaller temporary rivers that depend on local rainfall (Type B). The grid cell covered during the field survey in south-western Niger (1° E to 2° E, 13° N to 14° N), where such water bodies were observed, showed a positive correlation between rainfall and water body anomalies. However, in a neighbouring large area of south-western Niger (2° E to 5° E, 12° N to 15° N) no significant relationships were observed. This latter area, like other areas where no significant correlations were observed, was characterised by a low number of small temporary water bodies (Type A) with a size close to the pixel resolution of 1 km, large temporary rivers (Type B), or floodplains of large permanent rivers. Permanent hydrological features, such as large wetland complexes and large rivers, were masked out as their behaviour is not directly related to seasonal rainfall. Such large wetland complexes showed some seasonality, such as the southern part of the Niger River Inner Delta (5° W to 4° W, 14° N to 15° N), which exhibited a significant negative correlation between rainfall and water body extent anomalies. Three additional grid cells exhibited a significant negative correlation, which were all very sparsely covered with small water bodies (Types A and C) close to the pixel resolution of 1 km. This confirmed the finding at the local scale that the stability of the detection increased with the size of the water body (see 3.4.2). Small water bodies of a size close to pixel resolution (1 km) are only infrequently detected, which causes a negative or no correlation with observed rainfall.

The validity of the SWB dataset to display climatic variability became evident when the integrated seasonal water body anomalies were regarded for the very wet year 1999 and the very dry year 2004, as shown in Figure 5-2.

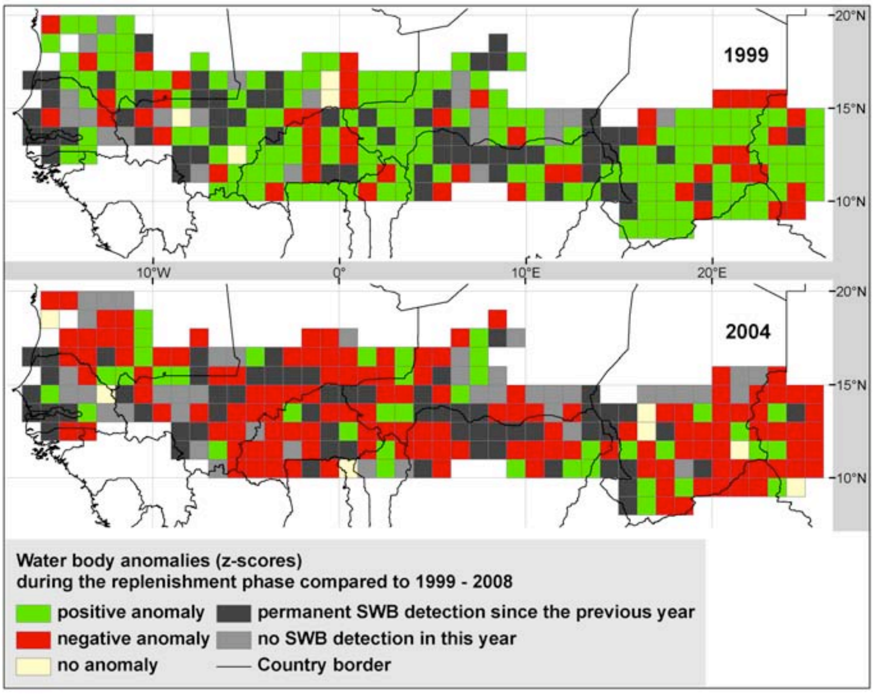

Figure 5-2: Water body anomalies in Western Africa for the year 1999 and 2004.

In most of the grid cells shown in Figure 5-2, the observed rainfall anomalies of both years, positive in 1999 and negative in 2004, were reflected in the water body anomalies during the replenishment phase. In both years, large rivers and wetland complexes were permanently present. Such permanent features receive water throughout the year from headwaters located in wetter regions and, unlike temporary water bodies, are not dependent on local, seasonal rainfall. However, temporary water bodies may occasionally remain present during the dry season before their replenishment starts in the following rainy season. As can be seen in Figure 5-2 the number of grid cells with a permanent detection of water bodies was higher in the dry year 2004 than in the wet year 1999.

This was due to the fact that 2003 was extremely wet and water bodies did not dry out. They were continuously present throughout the dry season, although at a reduced size, until they were replenished again when the rains started in 2004. In this very dry year, a higher amount of grid cells showed no SWB detections compared to the wet year 1999. This pattern of water body replenishment in the climatically extreme years of 1999 and 2004 was observed throughout Western Africa. This confirmed that water bodies can be used as indicators of climatic variability expressed by rainfall, at a regional scale.

5.4.2 Extent of water bodies and length of their emptying phase at the regional scale

The assumption that the length of the emptying phase is dependent on the maximum extent of the water bodies was significantly detected in 67 grid cells out of 279 in Western Africa as displayed in Figure 5-3.

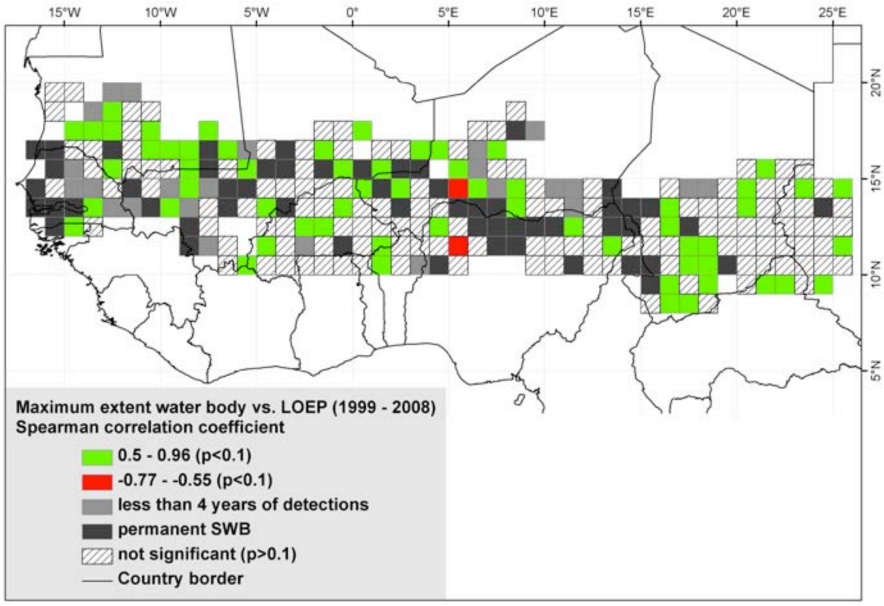

Figure 5-3: Spearman correlation coefficients of the maximum extent of water bodies in a catchment and the length of their emptying phase for 1° grid cells in Western Africa.

A positive relationship was confirmed at regional scale, but its quality varies throughout the study area. Grid cells in endorheic and non-endorheic areas densely covered with larger temporary water bodies (Types A and C) revealed the highest significant positive correlations. The presence of small water bodies close to pixel resolution of 1 km, of the same types that occurred in sparsely covered grid cells, led to a significant negative correlation in two of the grid cells and in most of the cases, to no significant correlation. This could be related to the stability of the detection that was found to increase with the size of the water body (see 3.4.2). Additionally, in grid cells that contained larger semi-permanent water bodies (Type A) and large temporary rivers (Type B), no significant relationship between the water body extent and the length of the emptying phase could be established. The maximum extent of a large temporary river is influenced by the geomorphology of the river bed and by inflow from headwaters. Thus, the actual surface area of a river does not influence its emptying pattern. Large, semi-permanent water bodies can become permanent during rain-laden years and will then persist until the start of the next rainy season. These water bodies are often rather deep and influenced by dams. Their emptying pattern is not, therefore, related to their maximum extent. Particularly in the southern and eastern regions of the study area, correlations were not found to be significant. This could be due to the presence of large temporary rivers and the fact that large areas were often only sparsely covered with small water bodies that were infrequently detected.

5.4.3 Rain Use Efficiency (RUE) and Water Body Ratio (WBR) at the regional scale

The relationship between water body extent and the amount of vegetation cover, which goes beyond the influence of the common driver rainfall, was tested by correlating the seasonal Rain Use Efficiency (RUE) with the Water Body Ratio (WBR) as shown in Figure 5-4.

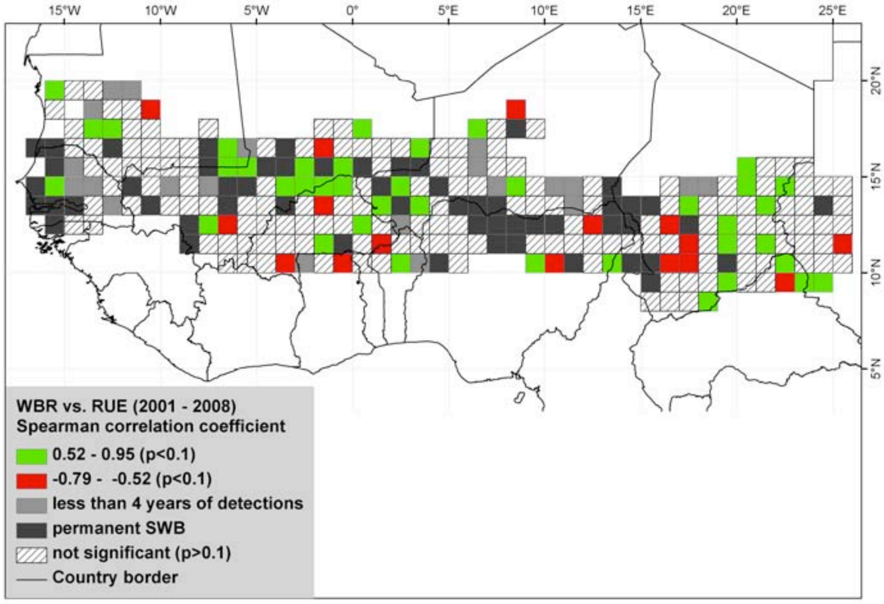

Figure 5-4: Spearman correlation coefficients of the Water Body Ratio (WBR) and the Rain Use Efficiency (RUE) for 1° grid cells in Western Africa.

A significant, positive, rainfall-independent relationship between water body extent and amount of vegetation cover was observed for 39 grid cells out of 279. These grid cells were clustered, indicating that continuous surface conditions, such as the type of land-cover, are influential. A comparison to the Global Land Cover (GLC) map of Africa for the year 2000 (Bartholomé et al., 2002) showed that these grid cells were all located in areas classified as sparse or open grassland. However, such clusters of grid cells that exhibited positive correlations were distributed throughout the study area. Not all grid cells classified as sparse or open grassland exhibited a significant correlation between RUE and WBR. Therefore, the type of surface water that occurs in the grid cell must also influence the relationship. A cluster of grid cells that showed a positive correlation between RUE and WBR was located within the Niger River loop, between 14° N to 16° N and 4° W to 0° W. This region was characterised by larger endorheic temporary water bodies (Types A and C) that showed a strong correlation between local rainfall (see 5.4.1) and the length of their emptying phase (see 5.4.2).

Grid cells with similar land-cover types, where no significant relationship between RUE and WBR was detected, were sparsely covered with small temporary water bodies close to the pixel resolution of 1 km (Types A and C) or large temporary rivers (Type B). A number of different reasons for this lack of relationship are possible. Like vegetation cover, small temporary water bodies are influenced by local rainfall but are not frequently detected due to their small size (see 3.4.2). This can lead to erroneous WBR values. Large temporary rivers are influenced by headwaters that collect rainfall from other regions, and do not depend on the local rainfall in the same way as vegetation cover. This makes the RUE and WBR values incomparable. Additionally, grid cells that were mainly covered with bare rock, according to the GLC 2000 map, did not reveal significant relationships because no vegetation cover was detected that could be related to the water body extent. The water bodies occurring in the 16 grid cells that showed a significant, negative, correlation between RUE and WBR were mainly located in the southern part of the study area, with land-cover classified as cropland, shrub land and woodland. No clear pattern emerged from the distribution of the grid cells that were not clustered. A low number of small temporary water bodies (Type A) or large temporary rivers (Type B) and semi-permanent water bodies (Types A and C) were located in these grid cells. A possible reason for the negative correlation between RUE and WBR could be that less water bodies were detected in these more humid, and thus more densely vegetated, areas due to the design of the SWB detection algorithm (see 2.3.2.2). Additional reasons could be that, unlike water body extent and annual grassland vegetation, the amount of vegetation cover in more humid regions was not directly related to rainfall, and also that the detected water bodies were often semi-permanent or were related to temporary rivers. Such hydrological features were detected in the two grid cells that exhibited a negative correlation but were located in the grassland region in the northern part of the study area. This finding indicates the importance of the water body type for the establishment of a relationship between RUE and WBR.

5.4.4 Extent of water bodies and green cover at the regional scale

In arid and semi-arid regions, water body extent and the amount of vegetation cover are both driven by rainfall. While in section 5.4.3 their relationship, independent of rainfall, was analysed by correlating the seasonal RUE with the WBR, here, the direct correlation between water body extent and the amount of vegetation cover is assessed. A correlation between the seasonally integrated anomalies (z-scores) of water body extent and green cover revealed that the strength of the relationship varies throughout the Sahel but, overall, positive correlations prevail, as can be seen in Figure 5-5.

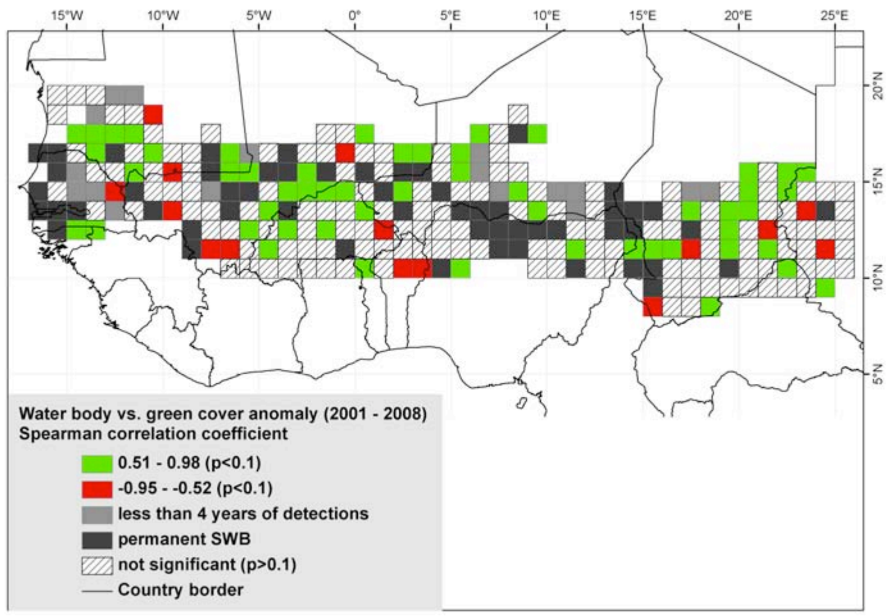

Figure 5-5: Spearman correlation coefficients of seasonal water body and green cover anomalies (z-scores) for 1° grid cells in Western Africa.

A significant, positive relationship between anomalies in water body extent and green cover, which includes the effect of rainfall, was found in 53 out of 279 grid cells compared to 39 grid cells exhibiting a rainfall-independent positive relationship (see Figure 5-4).

In Figure 5-5, the grid cells are more clustered and are mostly located in areas classified as open grassland in the GLC 2000 map. In particular, the area of the Niger River loop (14° N to 16° N, 4° W to 0° W), where strong correlations between surface water extent and rainfall (see 5.4.1), and length of water body emptying phase (see 5.4.2) were observed, showed positive correlations. Here, large endorheic temporary water bodies (Types A and C) are the main hydrological features. Small temporary water bodies (Types A and C) were found in the other grid cells that exhibited a positive correlation. This indicates that a relationship between both surface water and annual vegetation cover could be established since both were driven by rainfall. Negative relationships were found for 15 grid cells, which occurred without a clear pattern, mostly in areas that were classified by the GLC 2000 map as cropland, shrub land or bare rock. These grid cells were only sparsely covered with small water bodies. No significant correlations were found in grid cells characterised by bare areas, cropland, or grassland, which also contained either large temporary rivers (Type B) or only a sparse covering of small temporary water bodies (Type A).

5.4.5 Rainfall and green cover at the regional scale

Commonly, vegetation anomalies measured with NDVI are related to rainfall anomalies on a per-pixel basis, which has revealed positive correlations, particularly in arid and semi-arid regions (Nicholson, 1990; Poccard, 1996; Richard and Poccard, 1998; Olsson et al., 2005; Pettorelli et al., 2005; Martiny et al., 2006). The grid cell based correlations between the anomalies of seasonally integrated rainfall and green cover, showed significant positive relationships for certain parts of the study area, in particular in the semi-arid climate zone, as displayed in Figure 5-6.

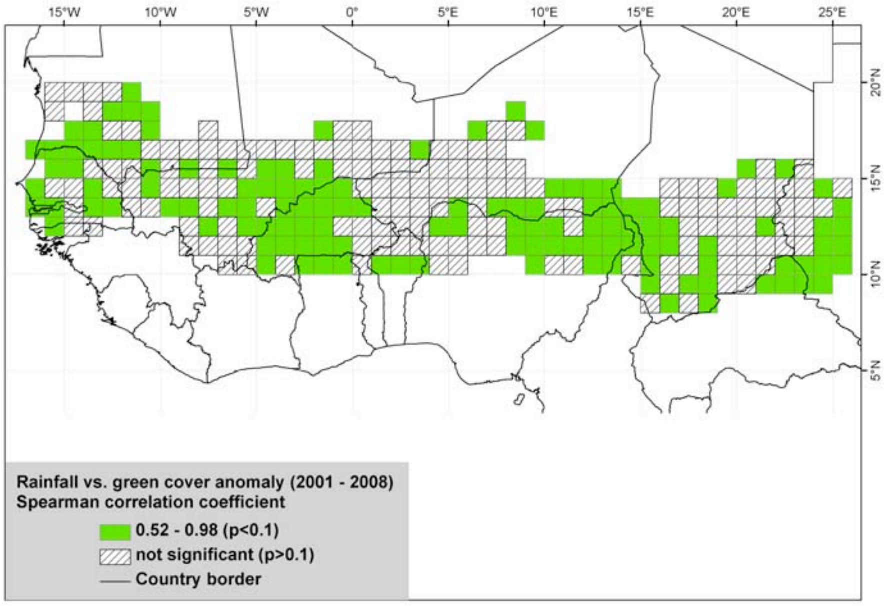

Figure 5-6: Spearman correlation coefficients of seasonal rainfall and green cover anomalies (z-scores) for 1° grid cells of Western Africa.

Commonly, a correlation coefficient of 0.3 is an accepted threshold indicating a relationship between vegetation cover and rainfall (Helldén and Tottrup, 2008). If this threshold is taken into account, 196 catchments exhibit a positive relationship between rainfall and green cover anomalies. Due to the limited number of observations (n = 8) and the variability in the relationship between rainfall and green cover (see 4.3.3.3), only correlation coefficients of 0.5, which were found in 127 grid cells, were significant ($p<0.1$). This finding assures the good quality of the rainfall and green cover input datasets used for the RUE derivation.

5.4.6 Trend of the Water Body Ratio (WBRrp)

The trend analysis of the WBRrp for the years 1999 to 2008 revealed no significant trend for most of the study area, as shown in Figure 5-7. Negative trends (see the red grid cells in Figure 5-7), where the WBRrp value decreased over time, were observed for large freshwater systems, such as the Senegal River, the Niger Inner Delta, Lake Chad and their larger tributary rivers, as long as they were not masked out due to the permanent occurrence of surface water (given as dark grey grid cells in Figure 5-7). Grid cells with less than four years of SWB detections were also masked out.

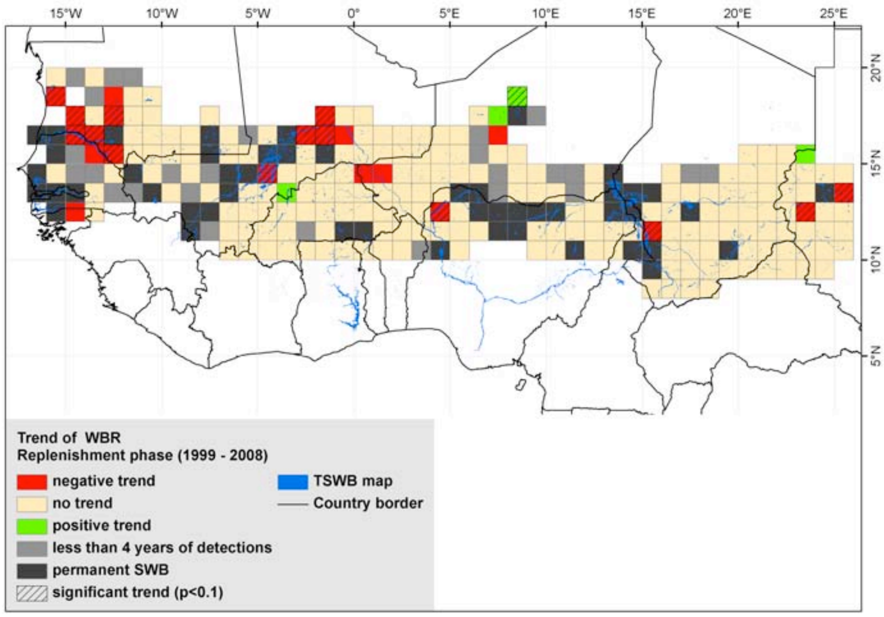

Figure 5-7: Trend of the Water Body Ratio during the replenishment phase (WBRrp) for the years 1999 to 2008 in the arid and semi-arid regions of Western Africa.

The trend analysis showed that over the 10-year period 1999 to 2008, no significant trends in respect of WBRrp were observed in the majority of grid cells. In grid cells that do not exhibit a trend over the 10-year period, the median value of the WBRrp, calculated for each grid cell, gives an indication of the most typical ratio between surface water extent and rainfall. As can be seen in Figure 5-8, the range of median WBRrp values varies throughout the region, with high values in grid cells that are densely covered with surface water, and low values in sparsely covered grid cells.

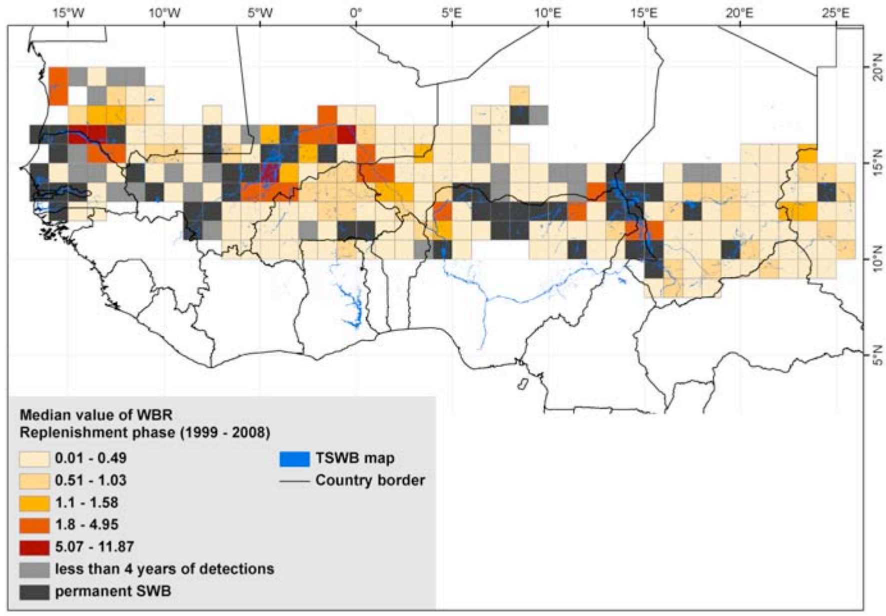

Figure 5-8: The median value of the WBR represents the typical value for the ratio between surface water and rainfall in a 1° grid cell. High values are observed in grid cells that are densely covered with surface water, while low values characterise sparsely covered grid cells.

To understand in which years the WBRrp was the highest, a maximum value of the WBRrp was identified from the whole 10-year period for each grid cell. Figure 5-9 shows how many maximum values were observed in each year, showing that the maximum WBRrp value for each grid cell was mostly observed in 1999 and 2007.

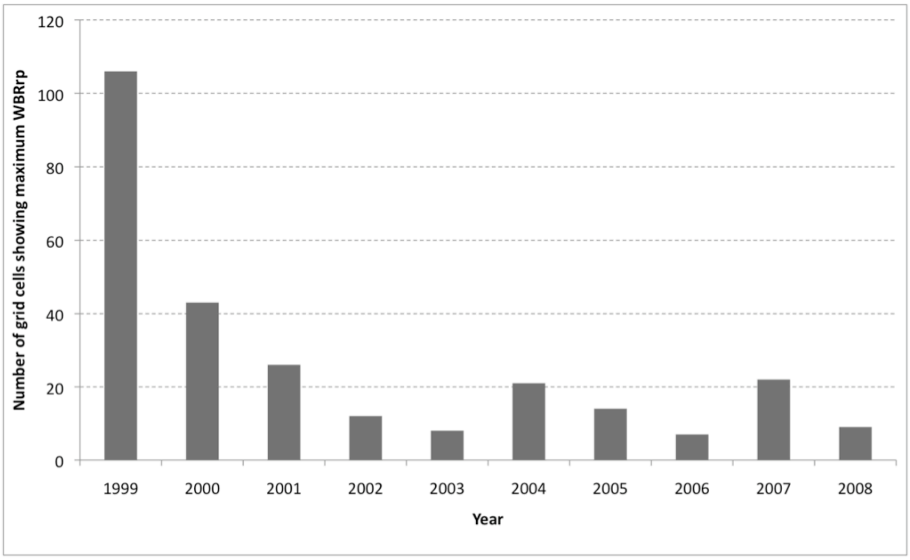

Figure 5-9: The years of the maximum WBRrp for all (279) 1° grid cells in the study area. In most of the grid cells the maximum WBRrp was observed in 1999 or 2007.

In 25% of the grid cells, the maximum WBRrp was detected in 1999, followed by 2007 with 8%. The least often the maximum WBRrp was detected was in 2006. A high WBRrp indicates that more water bodies were replenished than could be expected from the available rainfall. This is typical for flooding events where high amounts of rainfall occur over a short period of time. This high intensity rainfall, even of short duration, results in Hortonian type overland flow when the rainfall rate exceeds the infiltration rate that is typical for semi-arid zones (Candela et al., 2005). This can cause floods constituting serious threats for agriculture and people, which was the case in 1999 and 2007 in the Sahel (FAO/GIEWS, 1999; FAO/GIEWS, 2007). These findings show the sensitivity of the WBRrp to rainfall variability. The potential and limitations of the obtained results are discussed in the following section.

5.5 Discussion

The SWB dataset is a regional to continental scale dataset that provides information about available surface water in near-real time and at a high temporal resolution, making it ideal input data for the development of an ecological indicator. Beyond the value of the surface water detection *per se*, it was shown in this chapter that the findings regarding water bodies as indicators for ecosystem status at the local scale were also confirmed at the regional scale. However, the observed relationships between extent of surface water, vegetation cover, and rainfall are of a different quality throughout the region and for each tested hypothesis. A reason for this is that the 1° grid cells exhibit different climatic, hydrological, and geological characteristics. It was shown that the type of water body influences the quality of the observed relationship. Therefore, each 1° grid cell had to be regarded independently and no overall correlation for Western Africa could be identified for the tested hypotheses. Another aspect that limits the statistical analysis is the low number of observations over 8 or 10 years depending on the observed variables.

The finding at a local scale that water body detections of 1 km and larger reflected climatic variability, expressed by rainfall anomalies, was confirmed at a regional scale. Remote sensing derived rainfall estimates provide information about potentially available rainfall that, if it actually rains, is prone to evaporation and land surface processes before it is available as surface water on the ground. In turn, the SWB dataset provides information about the actual available surface water on the ground, which has been proven to represent climatic variability. The maximum extent of temporary water bodies at the end of the replenishment phase was related to the length of the emptying phase. This relationship was confirmed for several 1° grid cells in Western Africa. This finding allows an indication of the likely amount of available surface water during the subsequent dry season to be given at the end of the preceding rainy season, based on the 1 km regional scale water body detections.

The ratio between available surface water and rainfall during the replenishment phase indicates rainfall-independent changes in the replenishment of water bodies. This Water Body Ratio (WBRrp) did not exhibit a trend in most of the 1° grid cells over the last decade from 1999 to 2008. The observed positive relationship between rainfall and water body anomalies confirmed this finding. The stable relationship allowed a median WBRrp value for each 1° grid cell to be established. Thus, it is possible to infer from rainfall amount to water body extent, and vice versa, during the replenishment phase. Figure 5-10 shows the synergetic use of water bodies as environmental indicators.

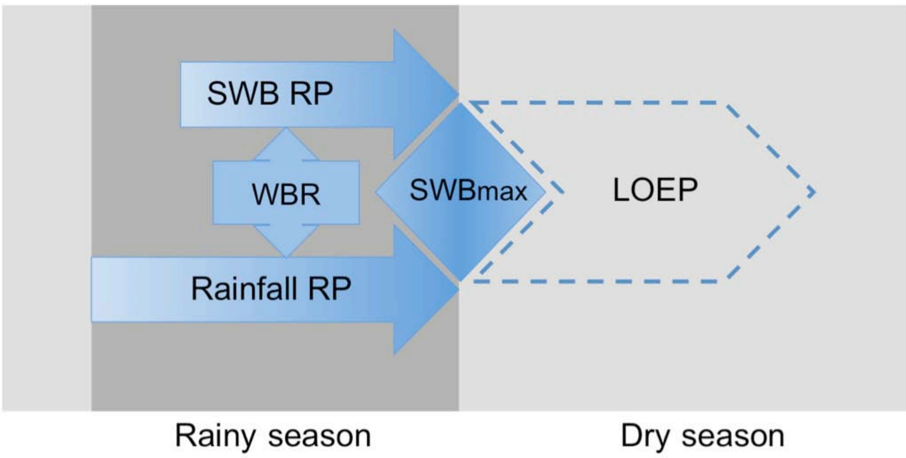

Figure 5-10: The synergetic use of water bodies as environmental indicators. Rainfall and water bodies (SWB) accumulate during the rainy season until the water body surface reaches its maximum extent (SWBmax) at the end of the replenishment phase (RP). Based on SWBmax, which can be estimated from the Water Body Ratio (WBR) or observed, the length of the emptying phase (LOEP) can be estimated.

A trend in the WBRrp indicates rainfall-independent changes in surface water extent in a 1° grid cell. Mostly negative trends were identified for sections of large freshwater systems such as the Niger Inner Delta, the Senegal River, parts of Lake Chad, and their tributaries that are not permanently present. Permanent parts of these large freshwater systems were masked out since this study focused on small temporary water bodies.

However, the observed negative trend in large freshwater systems is in line with studies that describe the spatio-temporal variability of hydrological systems in Western Africa (Descroix et al., 2009). In Sahelian basins, runoff has increased during the last three decades despite a decrease in rainfall that persisted until the beginning of the current decade. This current decade has been characterised by improved rainfall conditions, although the conditions have varied according to the region within the Sahelian climate zone (Lebel and Ali, 2009). In the Sudanian climate zone, located south of the Sahel, the decreased rainfall during previous decades resulted in a decrease in runoff, as was expected (Descroix et al., 2009). Although rivers such as the Niger and the Senegal flow mainly within the Sahelian climate zone and thus should profit from the observed increase in runoff, they show decreased runoff because most of their discharge originates from regions within the Sudanian climate zone (Descroix et al., 2009).

Land-cover and climatic changes were found to significantly impact on Sahelian hydrology. The mechanisms causing the so-called “Sahelian paradox” that has been observed since the drought of the 1980s were explained in detail in Chapter 3 (see 3.2.1). The “Sahelian paradox” describes the increased runoff measured at the field scale caused by a reduction of the water-holding capacity of the soil. This is closely linked to the degradation of vegetation cover by human induced land clearing, and also the impacts of the lasting drought on natural vegetation (Descroix et al., 2009). Two visible effects of the “Sahelian paradox” in the Sahelian hydrology were that were visible as a consequence in the Sahelian hydrology were increased discharges of large Sahelian rivers, and an increase in the extent, amount, and duration of temporary water bodies.

The first effect, the increased river discharges, which resulted from the increased field scale runoff that accumulated in large rivers, could not be detected with the SWB dataset. The increased runoff water did not result in large-scale flooding, but was transported into the river network. The SWB dataset would only be able to depict changes in the discharge of large rivers if this were to result in a significant increase in their extent. The second effect, the increase in the extent, amount, and duration of temporary water bodies could, in principle, be detected with the SWB dataset. However, this evolution was most marked from the mid 1970s until the mid 1990s.

Since then, during the 1999 to 2008 time frame covered by this study, recovered rainfall conditions have mitigated this effect. As a result, changes in the extent, amount and duration of temporary water bodies cannot be attributed to one single factor. Thus, it is not the regional scale and spatial resolution of the SWB detections that hinders the detection of the "Sahelian paradox" but the short time frame of data that covers exactly the period of recovered rainfall conditions since the mid 1990s. Since the vegetation cover has greatly changed over the last decades, and in particular many trees have disappeared, the rainfall-runoff relationship will be affected for a long time, even if rainfall conditions recover.

Such ecosystem changes can alter the relationship between surface water and rainfall, leading to variations, and thus to a long-term trend in the WBRrp. The potential of the WBRrp to indicate changes in the relationship between rainfall and water body extent was shown when the years of the maximum WBRrp values for each grid cell were extracted. The years with the highest number of maximum WBRrp values, 1999 and 2007, were characterised by heavy flood events resulting from above average rainfall within a short time period in several regions of the Sahel (FAO/GIEWS, 1999; FAO/GIEWS, 2007). This finding indicated that the WBRrp has the potential to show changes in the relationship between rainfall and water body extent, which originate from changes in climatic conditions as well as from land-cover changes that alter runoff characteristics. To disentangle these effects on the Sahelian hydrology, a long-term monitoring period is needed. The simultaneous observation of the vegetation cover will add to the identification of hotspots of land-cover change in the long-term.

For the 2001 to 2008 time frame, a positive relationship between seasonal vegetation cover and seasonal water body extent beyond the influence of rainfall, expressed by the WBR and the RUE, was found at a local scale (see 4.4.3) and was partially confirmed at a regional scale (see 5.4.3). Since the climatic, hydrological and geological environments were not homogeneous, the characteristics within a 1° grid cell vary and thus also the quality of the relationship between WBR and RUE. Significant positive relationships between the WBR and RUE were particularly found in grid cells located in semi-arid regions and covered with annual grasses.

The relationship between WBR and RUE was supported by positive, direct relationships between water body extent anomalies and vegetation cover anomalies. Although these direct relationships did not show the same quality throughout the study area, the positive relationships prevailed. This finding allows an indication to be given, not only about the availability of surface water, but also about vegetation cover. Productive regions and areas of decreased ecosystem services can therefore be identified. On a national scale, the availability of surface water and vegetation are the main drivers for the movements of pastoralist, who are often in conflict with local farmers depending on rain-fed agriculture (Raynaut, 2001), and such indications could support the policy-making process for the Sahel region.

5.6 Conclusion

The findings discussed in this chapter confirm that the relationships identified at the ecosystem level, between remotely sensed surface water extent, vegetation cover, and rainfall, could also be observed over a large region such as Western Africa. However, the rather short time series of 10 years employed in this study, due to data availability, limited statistical analysis and the detection of long-term trends. The findings obtained in this chapter have given an initial indication that regional scale ecosystem changes could be detected using the SWB dataset. Therefore, in the long-term, the SWB detections and the possibility of a continuous monitoring period, over large regions, will potentially allow the identification of ecosystem and hydrological changes within the Sahelian region.

This chapter completes the second research question addressed in this thesis. The findings obtained in this chapter showed that the spatial and temporal behaviour of temporary water bodies is a reliable ecological indicator for the state of an arid and semi-arid ecosystem. Remote sensing derived detections of temporary water bodies were found to be valuable ecological indicators in addressing national to sub-continental scale environmental issues. Potential limitations and future applications are discussed in the following and ultimate chapter of this thesis.

Chapter 6 Conclusion of the thesis

Two research questions have motivated this study. The first research question challenged the reliability of wide-field-of-view satellite sensors for use in mapping and monitoring temporary surface water bodies in the arid and semi-arid regions of sub-Saharan Western Africa.

The second research question emphasised that there are potential relationships between remotely sensed surface water body extent, vegetation cover, and rainfall. The aim was to identify the potential of using detected temporary water bodies as ecological indicators in West African drylands.

Until now, no studies exist that have related remotely sensed surface water extent, rainfall, and vegetation cover at local and regional scales, although the importance of integrated assessments of ecological and hydrological variables is widely recognised (Rodriguez-Iturbe, 2000; Zalewski, 2002; Hannah et al., 2004; Popp et al., 2009).

6.1 Main findings and contributions

Two main contributions of this thesis can be emphasised. The first contribution is the quality assessment of water body detections based on a wide-field-of-view satellite sensor, which led to a novel map of temporary water bodies and humid areas in West African drylands. This methodology allows for frequent updating and accuracy assessments of temporary water body maps in arid and semi-arid regions of Africa and beyond. The second contribution is the statistical association of remotely sensed surface water body extent, rainfall, and vegetation cover, which shows the potential of detected water bodies to be used as indicators for the state of arid and semi-arid ecosystems in sub-Saharan Western Africa.

6.1.1 Mapping, characterisation and validation of temporary water bodies

In the arid and semi-arid regions of sub-Saharan Western Africa, the spatio-temporal distribution of surface water exhibits high inter- and intra-annual variability depending on rainfall. A novel regional to continental scale remote sensing dataset was key to this study and provided information every 10 days (= dekad) at a 1 km spatial resolution regarding the occurrence and extent of small water bodies (SWB) based on the wide-field-of-view SPOT VEGETATION satellite sensor.

To assess the quality of the dekadal SWB detections, a map of temporary small water bodies (TSWB) was derived for the arid, semi-arid and dry sub-humid regions of sub-Saharan Western Africa at a 1 km spatial resolution. The TSWB map is a synthesis of the SWB time series displaying the maximum extent of surface water between January 1999 and September 2007. A time series analysis that aimed to minimise false detections was performed to derive the TSWB map. False detections are caused mainly by clouds and differences in soil properties and are inherent in the dekadal SWB detections. The water body time series analysis also provided additional information regarding the seasonal recurrence of temporary water bodies detected with the TSWB map, as well as their hydrological function. This characterisation allows the incorporation of temporary surface water dynamics, as monitored with a dekadal regional scale remote sensing dataset, into a surface water map. An accuracy assessment enabled a rapid validation of the regional scale TSWB map, using easily accessible and cost-efficient ancillary validation material as a surrogate for field surveys. The overall accuracy of the derived TSWB map, considering only the commission error, is 95.8% for the whole study area, with the highest accuracy obtained in the arid and semi-arid climate zone. In addition, a map of humid areas was derived from the SWB time series data that yielded important indirect information about available surface and sub-surface water in drylands. However, this map could not be validated at a regional scale because the type and characteristics of humid areas could not be clearly identified on the high resolution satellite images used for validation.

A local scale accuracy assessment carried out during a field survey in Niger confirmed the high quality of the water body detections and provided novel information about the typology of detected water bodies and humid areas. Their documentation with georeferenced photos led to an inventory of surface water bodies and humid areas in south-western Niger. The field survey confirmed a regional scale assessment that showed the potential of the SWB algorithm to depict, in particular, water bodies close to the pixel resolution of 1 km, while covering a large region like Western Africa.

In the first part of the thesis (Chapters 2 and 3), it was shown that wide-field-of-view satellite sensors such as SPOT VEGETATION reliably detect water bodies. Analysing a continuous time series of water body detections, such as those provided by a wide-field-of-view satellite sensor, assures the inclusion of temporary water bodies in particular. This is a clear advantage compared to other surface water databases, which are based on several single date satellite observations or on topographic maps. The need to improve existing surface water databases by using remote sensing techniques, expressed by both the research community and by policy makers, could be met for the mapping of temporary water bodies in West African drylands. It was demonstrated that remote sensing adds valuable information, in particular in respect of temporary water bodies, to existing surface water datasets at a regional scale.

The novel TSWB map is derived from one source of input data with worldwide coverage, thus a consistent picture of surface water in sub-Saharan Western Africa can be given for the period 1999 to 2007. The developed methodology allows a rapid creation of TSWB maps from the SWB time series data for different time intervals and regions, and also a cost-efficient and rapid validation at the regional scale. This method is likely to be applicable to other arid and semi-arid regions of Africa and beyond.

6.1.2 Temporary water bodies as ecological indicators in West African drylands

Fluctuations in water body extent are a measure of the balance between rainfall, evapotranspiration, infiltration and runoff in a catchment. A statistical association of remotely sensed water body extent, rainfall and vegetation cover, carried out Chapters 4 and 5, revealed the potential of the spatial and temporal behaviour of detected temporary water bodies to indicate the state of an arid and semi-arid ecosystem.

Relationships between the biophysical variables observed at a local scale were tested for a 1° grid covering sub-Saharan Western Africa. The relationships did not exhibit the same strength throughout the Sahel but the findings obtained at a local scale were confirmed at a regional scale. This implies that detected water bodies are diagnostic elements in detecting short-term changes in ecosystem processes at a regional scale.

This novel ecohydrological assessment showed that water bodies detected with a 1 km remote sensing dataset reflected climatic variability, expressed by rainfall. If it actually rains, the rainfall is prone to evaporation and other processes on the land surface before it is available as surface water on the ground. While remote sensing derived rainfall estimates provide information about potentially available rainfall, water body detections can indicate climatic variability and additionally provide information about the actual available surface water on the ground.

Detected water bodies can also indicate the availability of surface water during the dry season. The maximum extent of detected temporary water bodies at the end of the rainy season was related to the length of their emptying phase. The possibility of being able to forecast available surface water during the following dry season makes temporary water bodies detected using the 1 km resolution SWB dataset important ecological indicators for the seasonal ecosystem state.

The developed Water Body Ratio (WBR) relates integrated seasonal water body extent with rainfall and thus indicates rainfall-independent changes in surface water extent. Adapted to the replenishment phase, the WBRrp provides information about rainfall-independent changes in the replenishment of surface water bodies. Such changes can be caused by land-cover changes that may alter runoff coefficients, and by climatic changes. Various factors influence the Sahelian hydrology and, in the face of climate and environmental change, it is important to monitor the evolution of hydrological regimes. In the long-term, the WBRrp has the potential to recognise rainfall-independent changes in surface water extent that can indicate ecosystem changes. In the short period between 1999 and 2008 covered in this study, no significant trend in the WBRrp was observed for most of the 1° grid cells in the Sahel. This allowed the identification of a median WBRrp value to be made for each grid cell, from which the amount of surface water or rainfall can be estimated for the replenishment phase.

The seasonal WBR was positively related to the Rain Use Efficiency (RUE) in vegetated catchments. The RUE is the ratio between seasonally integrated vegetation cover and seasonal rainfall that can be used to indicate rainfall-independent changes in vegetation cover. This positive relationship of water body extent and vegetation cover, beyond the influence of rainfall, was found at both a local and a regional scale and shows the potential of remotely detected water bodies to indicate changes in ecosystem status that are related to vegetation cover.

A potential cause of the positive relationship between vegetation cover and water body extent, and the fact that no trend was observed in the WBRrp, was the wetter conditions that prevailed during the observed time frame between 1999 and 2008 compared to the lasting drought of the 1980s and beyond in the Sahel. High intensity rainfall, which has been observed more often during the last decade, supports the replenishment of water bodies and reduces the influence of vegetation cover on runoff. Land-cover changes can reinforce this effect and, at the same time, vegetation cover profits from the increased rainfall. To disentangle the effects of climatic fluctuations and land-use changes on the replenishment of water bodies, long-term monitoring is needed.

6.2 Limitations and perspectives for future research

6.2.1 Long-term SWB monitoring

Since the SPOT VEGETATION programme started in 1998, products such as the SWB dataset have become available. Although 10-daily water body detections over a time span of 10 years provide a wealth of information, when the long-term changes of surface water resources, such as those observed in the Sahel since the drought of the 1980s, are considered, this archive is not sufficient. Currently, with 10 years of observations, an assessment of the ecosystem state and the development of analysis methods are possible. However, the findings obtained during this decade will have to be tested and applied on a longer period of time series data to provide more statistically significant information. Thus, it would be important to adapt the SWB algorithm to high spatial resolution satellite data with a long-term monitoring perspective.

The European Space Agency (ESA) is developing five new missions called Sentinels specifically for the operational needs of the joint European Commission-ESA Global Monitoring for Environment and Security (GMES) programme[18]. The Sentinel-2 mission that is envisaged to fly as a pair of satellites, with the first planned launch in 2013, would be especially suited to high spatial resolution, surface water body monitoring. Each Sentinel-2 satellite carries a Multi-Spectral Imager (MSI) with a swath of 290 km. It provides a set of 13 spectral bands spanning from the visible and near infrared (VNIR) to the SWIR, featuring four spectral bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolutions. In full operational phase, the pair of Sentinel-2 satellites will deliver data every 5 days under cloud-free conditions, and every 15 to 30 days under cloudy conditions. This polar-orbiting, multispectral, high resolution imaging mission is designed to monitor land in order to provide information regarding, for example, vegetation, soil and water cover, inland waterways and coastal areas.

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[18] http://www.esa.int/esaLP/SEMM4T4KXMF_LPgmes_0.html (last accessed 3rd March 2010)

Sentinel-2 will provide enhanced continuity of the multispectral imagery provided by the SPOT series of satellites. However, the suitability of the repeat cycle for cloud-free monitoring over the African continent would have to be tested. Furthermore, data policy issues such as the cost and availability of data need to be taken into account, since they are a prerequisite for an operational pre-processing chain that would allow the near-real time monitoring of water bodies to be carried out.

The SPOT VEGETATION system will continue after 2013 using the PROBA V sensor that will provide daily global monitoring at 100 to 300 m resolution. The focus will be on land-use and land-cover changes, vegetation behaviour, detection of fires and surface water bodies, as well as biophysical variables for models devoted to water budget and primary productivity. The absolute geometric error across track will be 38.7 m for the central pixels and 108.8 m for the peripheral pixels, with both errors being just 36.2 m along track, which will allow a reliable times series to be built[19]. However, for this system the data quality, accessibility, and the potential to establish an automatic processing chain for near-real time water body monitoring will also have to be evaluated.

6.2.2 Spatial and temporal resolution of the SWB dataset

High time resolution sensors like SPOT VEGETATION provide daily global coverage at a spatial resolution of 1 km. The results obtained in this thesis support the fact that water bodies close to the pixel resolution of 1 km can be reliably detected using the SWB dataset. This spatial resolution can be considered as small when compared to the continental scale of the dataset. However, if the maximum extent of the water body corresponds to the pixel resolution, the water body cannot be monitored continuously. Thus, only rather large water bodies can be reliably detected. Mapping of water bodies at a 1 km resolution can only provide general information about major changes in available surface water and important information regarding small changes in surface water availability cannot be provided.

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[19] http://directory.eoportal.org/get_announce.php?an_id=10001905 (last accessed 11th November 2009)

Binary information only, regarding the presence or absence of water in a pixel, is provided and no volume or precise extent can be provided. Currently, very small ponds can only be mapped using several single date high resolution satellite images. Continuous near-real time monitoring such as SPOT VGT, which provides information about the seasonality of water bodies, does not exist.

A promising approach is a new SWB algorithm applied on data from the Moderate Resolution Imaging Spectroradiometer (MODIS). The originality of the developed approach is the simultaneous exploitation of the MIR, NIR, and RED wavelengths throughout a new qualitative index (Pekel et al., 2010). Based on this index, a complete automatic and near-real time processing chain, combining the daily observations of MODIS (Aqua & Terra), was designed to provide a SWB map at 250 m resolution every 10 days. This methodology is currently implemented over the whole of Africa at the ENGE unit of the Earth and Life Institute (ELI) at the Université catholique de Louvain (UCL) in Belgium. A publication regarding this new methodology and product is currently in preparation.

The future development of the SWB dataset and new SWB algorithms, based also on findings obtained in this thesis, will allow regional scale studies to be carried out at higher spatial and temporal resolutions. This will be especially suitable for exploring health and socio-economic issues in relation to surface water. There is also increased interest from the hydrological and climate modelling community in remote sensing derived water body observations.

6.2.3 Impact on thematic applications

6.2.3.1 The SWB dataset and health issues

Infectious diseases are a serious threat to human health and are evolving in response to global environmental changes. As these diseases are closely related to intermediate hosts and special environmental conditions, the spatial distribution of such diseases strongly depends on the environment.

Since there is a close association between vectors and their habitat, it is possible to draw conclusions about vectors by using remote sensing methods to detect environmental characteristics. Water bodies of any size are focal points for people and livestock that favour the development and transmission of diseases (Lacaux et al., 2007). The SPOT VGT SWB data was tested within the framework of a study that assessed disease outbreaks in relation to surface water presence in the Ferlo Valley in North Senegal. The small water bodies that were monitored locally were too small to be detected by the SWB algorithm (Soti et al., 2009). However, the observation of large water bodies would allow the replenishment of small water bodies to be inferred, and thus provide indirect evidence of surface water presence that could be linked to disease development. Linking surface water observations to health information is a promising field of future research that needs to be developed in the face of continuous population growth. The use of remote sensing in epidemiology is common, although there is still a need for accurate disease early-warning systems to be developed. These could potentially be established with the help of new high temporal and spatial resolution remote sensing time series data that allow the detection of water bodies and other biophysical variables to be made in near-real time.

6.2.3.2 The SWB dataset and socio-economic issues

Another future emphasis should be on the interpretation of results from the analysis of biophysical variables in terms of impacts (direct or indirect) on human activity. These include, in particular, agriculture and the vulnerability of societies within the Sahel region to surface water availability. An integrated approach for livelihood support and ecological management is needed for drylands, which combines the fundamentally interwoven biophysical and social issues (Reynolds et al., 2007b).

Food provision for a large and growing population will place increasing demands on both rain-fed and irrigated agriculture in the future. In the Sahel, most of the agriculture is rain-fed and thus susceptible to climate change. In these regions, large-scale irrigation is not practiced. Increased rain-fed agricultural production would depend on available surface water, thus knowledge about the location and replenishment of water bodies could provide a systematic framework for more effective rain-fed agricultural production. The coupling of remote sensing derived information regarding available surface water with models and systems such as the Agro-Ecological Zones (AEZ) water balance, a method developed by IIASA and FAO over the past 30 years (Fischer et al., 2008), and with the spatially explicit GIS-based Environmental Policy Impact Calculator (GEPIC) model (Liu et al., 2007), would allow the identification of areas suitable for a potential increase in crop yields, and of crop yield gaps. Simulations using GEPIC showed that crop yields in many African countries could increase substantially with a sufficient water supply and fertilizer application (Liu et al., 2007).

Currently, temporary, natural water bodies are not used for large-scale irrigation purposes. Local populations practice small-scale irrigation for high value crops and market gardening around these temporary water bodies, and use them for counter-season cropping during the dry season. Based on water body maps, the potential extent of areas suitable for use for market gardening purposes could be determined. Seasonal recurrence information of water bodies could refine this information. Coupled with information about the population density, an estimate regarding this economically important, small-scale, agricultural practice could be given.

Apart from rain-fed agriculture, the population in the Sahel depends on pastoralism and there is a need to reliably assess the variables of ecosystem productivity in order to develop appropriate management tools in these fragile environments. Research on pastoralist movements and rangeland management approaches can profit from knowledge of available water resources. The proximity to rare water points is the main driving force behind these activities and the pastoralist system depends largely on the availability of water and pasture land productivity (Breman et al., 2001).

Future research on the links between available surface water, vegetation cover and pastoralist movements could support a variety of strategies. An operational system put in place by the JRC and local institutes such as the AGRHYMET centre in Niger, could potentially aid the mitigation of conflicts related to surface water, which constitutes the main source of water for the population.

Groundwater is the second major water resource for populations in arid regions. Since temporary water bodies were found to directly, and almost uniquely, to contribute to the upper aquifer recharge in the Sahel (Leduc et al., 1997), their mapping and monitoring is of major importance in estimating future changes in groundwater levels over large regions.

6.2.3.3 The SWB dataset and global climate modelling

The comparison of the TSWB map with other surface water databases showed the potential of the SWB time series data to detect, in particular, temporary water bodies in Western Africa. Reliable regional scale maps of temporary water bodies are useful for global climate modelling and scenario exercises. The World Commission on Water for the 21st Century developed a set of scenarios that describe several possible developments in the world water situation by 2025. In the “business-as-usual” scenario, the number of areas affected by severe water stress will increase, as will the number of people living in these areas, in particularly in Western Africa (Alcamo et al., 2000). There are numerous dynamic external drivers that influence water resources and are continually evolving. It is therefore difficult to draw a comprehensive picture of future water resources if drivers are examined independently, as they often have more impact collectively than individually. Thus, future scenarios that consider these interactions offer a more holistic picture than existing global water scenarios, which have been found to be outdated, incomplete, or sectoral, and do not fully incorporate each of the external drivers (World Water Assessment Program, 2009). Research such as that carried out in this thesis, that highlights links between biophysical variables, can aid the development of future scenarios. The ultimate objectives of future-oriented world water resource assessments are to show the international community what will happen if the world continues to manage available water resources as it does today, and to indicate what actions may be needed to prevent undesirable outcomes (Oki and Kanae, 2006).

6.2.3.4 The SWB dataset and hydrological modelling

Hydrological modelling aims at assessing the availability of, and any changes in, surface water. There is increased interest from the hydrological modelling community in near-real time observations of surface water. Initially designed for the detection of small water bodies in arid and semi-arid regions, a field survey in the Yaere floodplain of North Cameroon showed the advantages and disadvantages of the SWB dataset for the monitoring of large floodplains (Delclaux et al., 2010). The Yaere floodplain is subject to annual flooding caused by local rainfall and the overflow of the Logone River. Difficulties in reconstructing the surfaces of very large water bodies were observed, whilst a good ability for reproducing water spreading and irrigation conditions over the rice-growing areas were shown. Observed water levels at the outlet of the floodplain were fully consistent with remotely monitored flood waters spreading across the whole plain. Annual SWB composite maps coupled with DEM information were found to provide consistent information on the water path across the floodplain. Remote sensing derived information about surface water can thus aid hydrologic modelling for large areas with sparse in-situ data coverage.

Approaches towards carrying out hydrological modelling based entirely on remote sensing data are also promising (Stisen, 2007) but are still limited. Unless all components of the water balance in arid and semi-arid regions can be reliably monitored using remote sensing datasets, there is a risk of accumulating errors when working entirely with remote sensing derived biophysical datasets. The spatial and temporal resolution, as well as the regional scale on which the water body dataset is acquired, has to be considered when measurement accuracy is assessed. Significant information can be missed when dataset scale does not correspond to the ecological process being monitored. However, a more in-depth study of the observed variables, including information about land-cover change and other variables, such as soil moisture, would provide further insight into ecosystem processes. For example, remote sensing derived soil moisture data indicates surface wetness conditions in the upper soil layer (Bartsch et al., 2009).

Furthermore, higher time resolution rainfall estimates are needed since the intensity and distribution of rainfall events was found to be more important for runoff generation than the seasonally integrated rainfall amount that was employed in this thesis.

Remote sensing derived datasets such as digital elevation data, land-cover and land-use, rainfall, land surface temperature, and soil properties are commonly used for the parameterisation of hydrological models in order to rapidly acquire synoptic land surface information. Remote sensing can potentially close some of the gaps in data availability and provide a means for the spatial calibration and validation of distributed hydrological models (Stisen, 2007). An increased spatial and temporal resolution of remote sensing datasets, in particular the SWB dataset, will expedite the use of remote sensing in hydrological applications.

6.3 Policy implications

Freshwater ecosystems are under increasing pressure from natural resource extractions, pollution from land-use change associated with growing populations, and climate induced changes that influence the quantity and seasonality of hydrological flows (Oki and Kanae, 2006). Effective management of water resources is a prerequisite for sustainable development and poverty alleviation that requires improved monitoring systems to track changes in surface water availability. Remote sensing provides a synoptic view of ongoing processes and allows for an assessment of pressures placed on aquatic ecosystems (Goetz et al., 2008). Regional scale water body maps will contribute to the ambitious Millennium Development Goal to halve, by 2015, the proportion of people lacking adequate drinking water and sanitation. This will require, in particular, information on the physical access to water (Vörösmarty et al., 2005). In the face of a growing population, water can be a source of conflict and knowledge about its distribution and temporal availability is crucial in order to detect potential conflicts and to design political instruments that encourage cooperation between native tribes and countries. The pressure related to water resources will increase with climatic change.

The understanding developed in this thesis that water bodies can indicate climatic variability and are linked to vegetation cover provides a tool with which potential drought conditions can be identified. If information regarding continental scale patterns of the above-mentioned highly localised issues can be provided to policy makers, potentially in near-real time, it will be possible to pinpoint areas of emerging problems and to implement suitable interventions.

The best way to present research findings is distilled into meaningful aggregates in the form of indicators that can be conveyed to the policy and management communities (Vörösmarty et al., 2005). The environmental indicators developed in this thesis are useful for water management, early warning systems for the prevention of natural hazards such as floods and droughts, the prevention of conflicts, and human and social development. The findings will support policy and decision-making by providing synthetic information about environmental status.

The infrastructure to implement research findings, such as those developed in this thesis, directly and in an operational manner in conjunction with African partners is made available by the Joint Research Centre of the European Commission (EC), where this research was carried out, within the framework of the African Caribbean Pacific (ACP) Observatory for Sustainable Development. The ACP Observatory[20] provides scientific information, diagnostics and scenario building for the development of policies regarding information sharing, increased co-operation and co-ordination of response strategies.

[20] http://acpobservatory.jrc.ec.europa.eu/ (last accessed 11th November 2009)

This research benefited from products developed in the FP4 “improvement of the VGT mission” projects, the **geo**land project, an FP6 integrated GMES project[21], and the FP6 VGT4Africa project that is continued with the FP7 DevCoCast project[22]. Within the framework of the VGT4AFRICA (DevCoCast) project, SPOT VEGETATION data products were distributed to all non-commercial users in Africa within the PUMA Network of Meteorological Stations built up in every African country based on a telecommunication satellite of EUMETSAT. The aim was to set up an operational and near-real time distribution system of SPOT VEGETATION data and high-level derived products to all African countries in order to support sustainable development policies in Africa. Within the framework of the AMESD (African Monitoring of the Environment for Sustainable Development) project, in which all the sub-Saharan ACP countries participate, this network is currently expanded, assuring the usage of research findings for policy support.

Future research will have to aim towards a more complete understanding of the human–water interactions as policy intervention to alleviate water stress requires a broad, interdisciplinary approach. Thus, the development of geospatial indicators that link biophysical, socio-economic and engineering perspectives constitutes an important next step in global water assessment (Vörösmarty et al., 2005). The aim of this thesis was to contribute towards a better understanding of the complex relationships between biophysical variables in drylands, detected using remote sensing techniques. The understanding that temporary water bodies can be used as ecological indicators in West African drylands contributes to the scientific base needed for the development of policies regarding the sustainable use of water resources in this region.

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[21] http://www.gmes-geoland.info/ (last accessed 11th November 2009)
[22] http://www.devcocast.eu (last accessed 11th November 2009)

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Annex: Questionnaire

Type of test site: o Water body o Humid area

Name: **Location:**

Approximate size (diameter):

Shape:

Description of the Water body

Type of water body:

o pool along an endorheic river o independent water body

o other:

Hydrological regime:

o natural o mini barrage o dam

Source of water:

Inflow: o rainfall only o river and rainfall o GW

Description of inflow:

Outflow:

o endorheic (no outflow)

o outflow

Type of outflow: o river o known GW outflow o Evaporation

Description of outflow:

Water body dynamics: The behaviour of the water body during the season

When does it appear normally?

Years when it did not appear?

Is the way it appears always the same?

Is there a difference in appearance according rainfall intensity?

How long does it normally last?

What are the main reasons for its drainage?

Characteristics of water

Colour of the water:

Sediment load:

Water plants:

Depth of water body

Surrounding: o smaller water bodies o other hydrological features

Description of the catchment

Vegetation

Riverine Vegetation:

Type of vegetation:

Vegetation composition:

Density:

Crops (Land-use and Land-use practices):

Vegetation dynamics:

How does the vegetation develop?

How long is the time lag between rainfall and occurrence of vegetation?

Different time lags for different vegetation types:

Soil type and characteristics

Surface crusts:

Geology

Type of bed rock:

o Aquifer o Aquiclude

Topography

o Lateritic Plateau

o sandy skirt

o valley bottom (kori)

o River valley

Slope:

State of the catchment

Degradation/Desertification visible?

Fires/ Burned areas:

Land-use change:

Land-cover change:

Human impact:

o grazing o drinking water o general water usage

General comments:

Contact information of the author to obtain the textual field report and the georeferenced photo archive: haaseva@googlemail.com