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Detection of surface water with SPOT/VEGETATION

Monitoring and assessing CILSS countries surface water availability

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List of acronyms

CILSS	Comité inter-État de lutte contre la sécheresse au Sahel
ITCZ	Inter Tropical Convergence Zone
MIR	Medium Infra Red, also named SWIR
NIR	Near Infra Red
NDVI	Normalised Difference Vegetation Index
NDWI	Normalized Difference Water Index
SWB	Small Water Body
SPOT	Satellite Pour l'Observation de la Terre
SWIR	Short Wave Infra Red
ADSW	Accumulated Small Water Bodies
WBS	Water Body Start (of replenishment)
WBE	Water Body End (of drainage)
WBF	Water Body Flag

Definitions

10-day period: The daily Spot/VEGETATION images are gathered into a synthesis every 10-day period. The 10-day periods are defined with respect to the day of the month, the 1st dekad starts on the 1st of the month and end on the 10th, the 2nd starts on the 11th and ends on the 20th and the third start on the 21st and end on the last day of the month. There are 3 10-day periods in a month, 36 dekads in a year.

Dekad: synonym of 10-day period.

Maps conventions

The maps presented in this document are all based on VGT4Africa products. These products are images in geographic projection (plate carrée, WGS84), with a pixel size of 1/112° in latitude and longitude, with geographic reference in pixel centre. At the equator, 1° contains 112 pixels, 2 overlapping the 1° grid edges, thus 1° has 111 pixels. At the equator, 1km equals 1/111°. A scale in kilometres is given on each figure to let the reader figure out the actual coverage and resolution of the displayed data. Although the conversion from degrees to kilometres is strictly valid only at the equator, the relation is reasonably correct (at the resolution of the printed material) on Africa.

All images are presented North-up, as it is the convention for plate carrée projection (and geographic projections in general). For this reason, neither the North arrow is represented, nor indications about the projection characteristics.

1 Introduction

In African arid and semi-arid regions a large amount of surface water is only available seasonally, in conjunction with the rainy season. At regional and sub-continental scales monitoring the surface water, i.e. detecting when surface water sites are filled by rainfalls and when they are drained out, is key information for the assessment of water availability and for deriving indicators of environment assessment, indicators of potential on vector borne diseases favourable breeding conditions, or managing sedentary and pastoral human activities.

The VEGETATION sensor on board satellites SPOT4 and SPOT5 provides an almost complete coverage of the Earth every day and the ground system generates a cloud free global composite image every 10-day.
A specific algorithm was designed by Gond et al. (2004) to retrieve seasonal and ephemeral water bodies in arid and semi arid regions. The detected water bodies correspond to free water and humid areas. The detection of the dates of first and last occurrence of the detection is also performed, making possible the assessment of dates of the beginning and end of surface water availability at regional scale.

The water bodies' detection and their seasonality assessment is a component of the VGT4Africa product portfolio also including additional products related to the monitoring of the vegetation and fires. More information is available from www.vgt4africa.org
Each component of the VGT4Africa portfolio is broadcasted to African and European users thanks to the Eumetcast digital video broadcasting system operated by Eumetsat. Users equipped with the Eumetcast receiving station are thus able to receive at no charge the VGT4Africa products, every 10 days. The VGT4Africa products are made available in the day of their production, which occurs usually two days after the end of the corresponding 10-days period of integration, allowing each user to monitor the evolution of surface water availability in a region in near real time.

The principle of the detection of water bodies and the assessment of their dates of availability is summarized in chapter 2. An assessment of the detection commission error is presented in chapter 3.

The water body detection considers two main types, free water and humid area, and a mixture of both in a third class. A classification of the water bodies, accounting for the seasonal transition from one class to another is detailed in section 4. Beside the water cover type of the pixel, the system also allows to assess the recurrence of the detection on long term, which is a proxy for the statement of the driest/most humid seasons. The timeliness of the detection is also used to assess the hydrological functioning of the water bodies, making distinction between permanent features (rivers, large lakes), seasonal and ephemeral bodies.

The recurrent detection of the surface water with Spot/VEGETATION coupled to the Eumetcast broadcasting system allows building an information system monitoring the progression of small water bodies replenishment on a seasonal basis. Section 5 shows some examples of such a reporting system.

2 Detection of water bodies with Spot/Vegetation

2.1 Detection of free water and humid areas

The VEGETATION sensor on board Spot 4 and Spot 5 provides 1.1 km resolution, 2250km large swath images, allowing the production of a daily mosaic of the Earth. In order to remove clouds and ensure the best quality of ground observation, the daily mosaics are assembled in 10-day maximum value composite synthesis (MVC). For each pixel, the best observation, defined as the one for which the NDVI is maximal, is retained in the synthesis (Passot, 2000).

Water spectral reflectance decreases from blue to medium infrared, which would correspond to the reflectance of a clear and deep (optically semi-infinite medium) lake. Surface water bodies are usually of different nature: the water depth is variable (up to a few centimetres) and can hold an important amount of floating material which has significant impact of the spectral signature, especially on the near and medium infrared bands. In addition, the presence of algae or aerial vegetation can cause absorption in the red band. In conclusion, there is no typical spectral signature of a water body.

Gond et al. (2004) demonstrated that surface water and humid areas can be classified in a Spot/VEGETATION image by using several indices based on the Short Wave Infrared and Near Infrared channels and their differences to the pixel neighbourhood in a 45x45 pixels window. Their approach relies mostly on the contrast between a water body and its surrounding in term of spectral properties. This spectral and contextual analysis of the image allows detecting free water and humid areas on a per pixel basis.
The product was named ‘small water bodies’ detection according to the fact that the smallest objects that can be detected have their size close to the pixel resolution.

The detection is done every 10-day for Africa in 5 classes (Figure 1), the code values being arbitrarily defined at the first code implementation:

Code	Land cover
70	Free water
150	Humid area
220	Mixture of free water and humid area
255	Land with no detection
0	Ocean

The term humid area corresponds to pixels which spectral signal show some evidence of water, although its NDVI indicates the presence of vegetation.

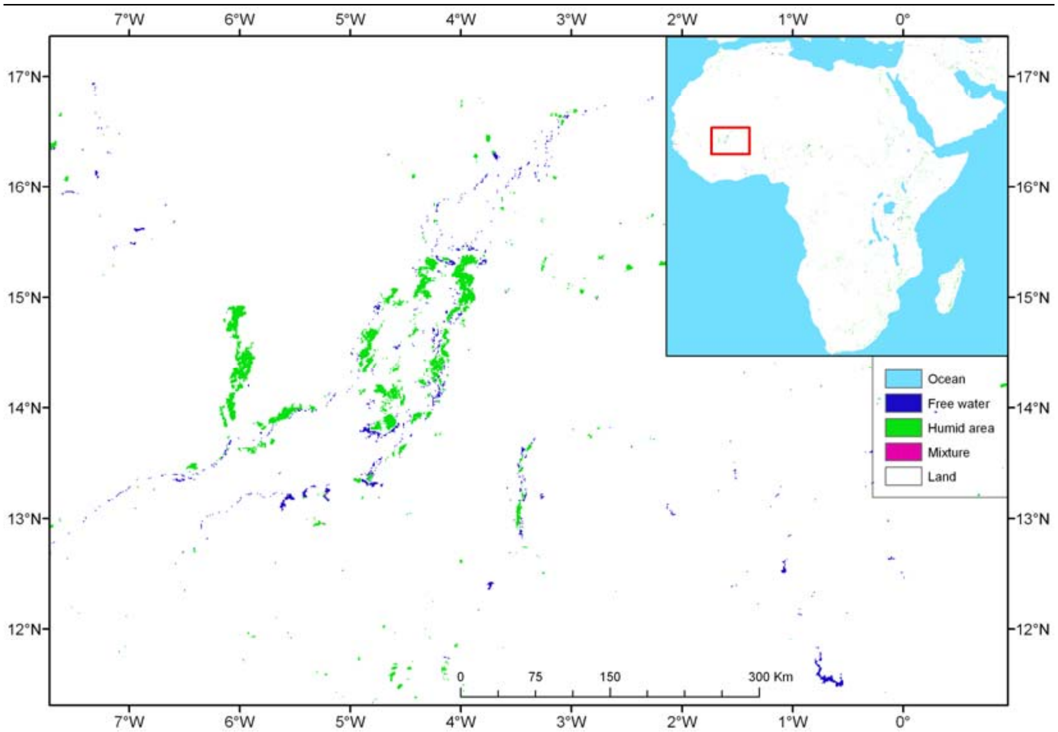

Figure 1. View of the small water body detection for the last 10-day composite of October 2007, full spatial extension and a close-up on the inner delta of Niger River.

2.2 Assessment of water bodies dates of availability

The accumulation of the 10-day detection allows defining a time series of observation for each pixel. The time series (1.25 year from the latest observation backward) are analysed to derive each pixel date of start of replenishment and date of drainage (Bartholomé and Combal, 2004). The season requires 2 positives detection out of 3 to be defined; this rule being set to avoid disruption in the signal due to long lasting cloud screening that may prevent for detecting a water body during the rainy season.

Figure 2 shows the synthesis of replenishment of the small water bodies at the end of season 2007, starting in April ending in late October. Most of the small water bodies in the loop of the river are rain fed. In the delta some areas are flooded later in the year, typically December in the northern margin of the river[1].

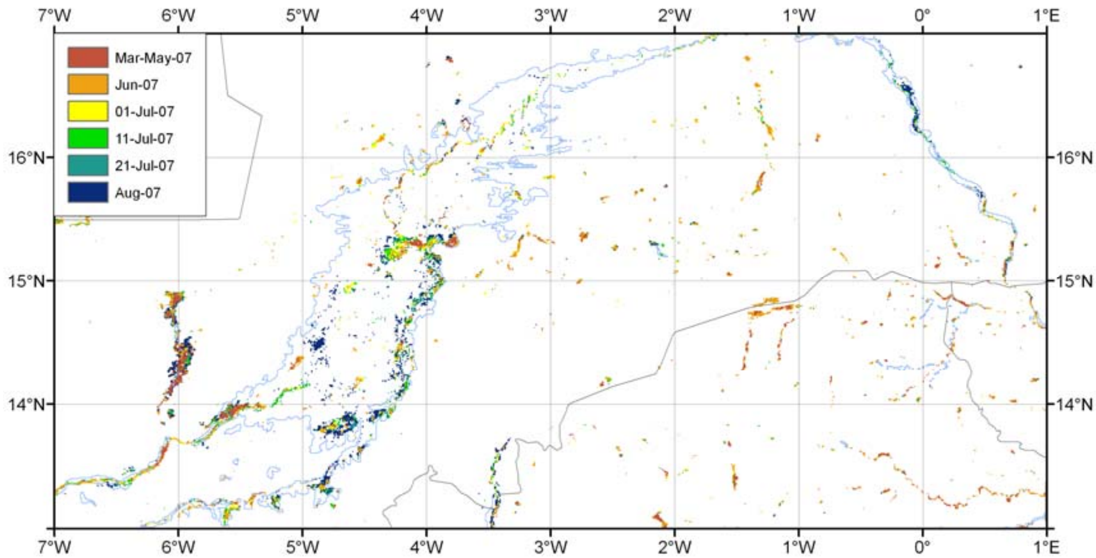

Figure 2. Synthesis of the date of appearance of small water bodies in 2007. Data has a time resolution of 10-day.

This seasonality assessment is coupled with a flag indicating the type and status of the season at the date of the latest observation (summarized on Figure 3):

1- The season is over (and thus the date of end is available);
2- The season is over and a new start (to be confirmed) is visible;
3- New start visible, no former season in the last year;
4- The season is going on;
5- Only single dates were visible in the last year;
6- In the last 1.25 year, no more seasons found, start of the latest season is out of scope

This flag was designed to help the users filtering data for their computations.
For example, to compute the duration of water availability, a user would only need to open the product broadcasted and season's end, and to compute for each pixel;

$$(\text{FLAG} == 1 \text{ OR FLAG} == 2) \times (WBS - WBS)$$

The logical operator (that worth 0 if false 1 if true) is used to set to 0 any pair (WBS, WBE) for which the end of the last season is not defined.
For monitoring activities, Flag=4 would be used to filter pixels that are currently filled, removing those found before the current season in the last 1.25 year at that have presently dried out (flag=1,2)

[1] www.nationalgeographic.com/wildworld/profiles/terrestrial/at/at0903.html

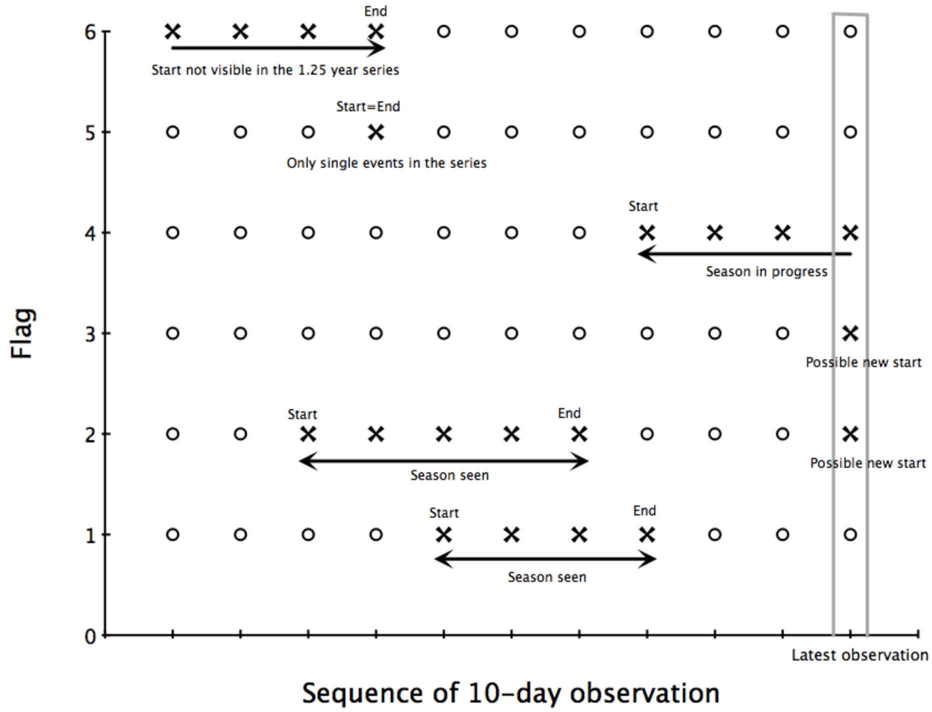

Figure 3. Values and interpretation of the flag related to the small water bodies seasonality.

3 Quality assessment of the detection

3.1 Detections in sub-Saharan Western Africa

The detection of small surface water bodies was designed in first place for arid and semi-arid regions (Gond et al. 2004).

Haas et al. (2009) shown that a mask of pixels showing at least two detections of free water during the first 9 years (1999 to 2007) of SPOT/VEGETATION acquisition time frame can be successfully validated against a set of high resolution images. The resulting map of accumulated detection of surface water (ADSW, named TSWB in Haas et al., 2009) is used a referenced validation mask, which indicates trusted detection. Because this map was done on only 9 years, valid detection out of it can occur in the next years. For this reason, the map will have to be updated in the next years. In addition, ADSW does not reference objects that were detected only as humid areas in 9 years.

Nevertheless, this first version of ADSW shows clearly that SPOT/VEGETATION can observe a range of surface water, most of them being seasonal or temporary that are neither referenced in the Global Lakes and Wetlands database (GLWD) nor detected by the SRTM surface water bodies. Figure 4 shows the loop of the Niger Inner Delta: The ADSW map does not depict large features to the same extent as GLWD, because this latter map includes information from historic maps produced during a wetter period than what could be observed during the 1999 – 2007 period. In addition, several sources of input data have been overlaid, leading to an inclusion of the respective maximum extent in GLWD (Lehner and Döll, 2004). At the same time many sites were found by SPOT/VEGETATION (and confirmed by validation against high resolution images) that were not referenced in GLWD.

The SRTM surface water bodies map generally displays surface water as depicted in February 2000 (although in the rare cases of missing SRTM data, the SWBD relies on Landsat 5 data from the 1990s), which corresponds to the dry season in the study region. Thus, most water bodies are not referenced that are depicted with SPOT/VEGETATION.

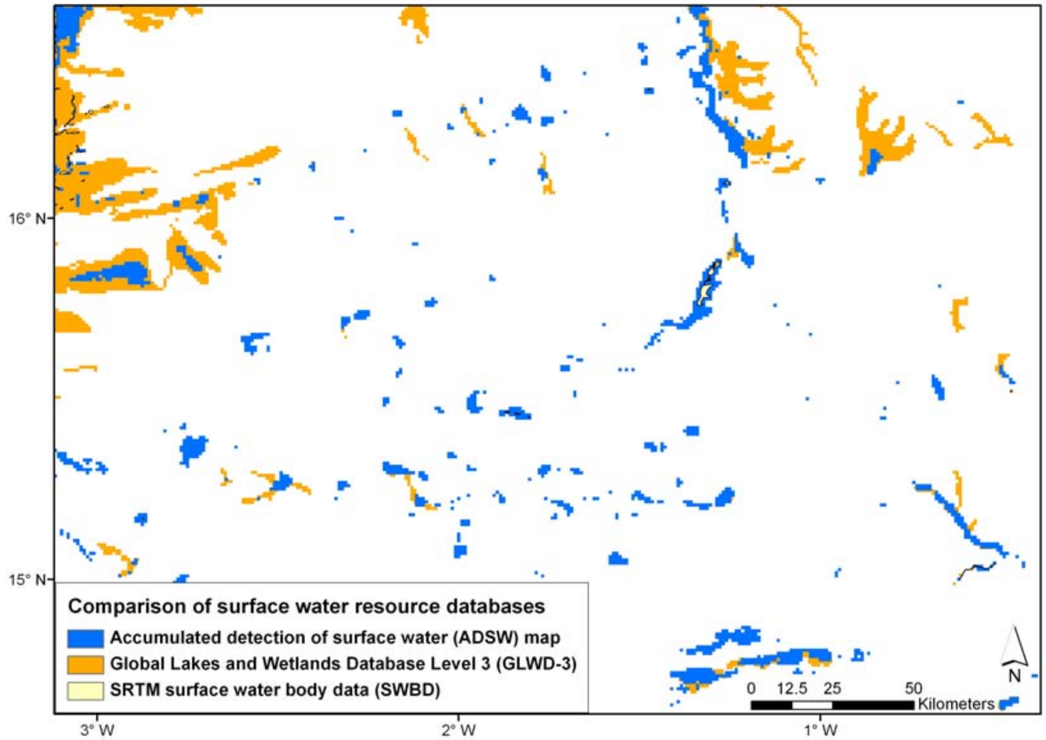

Figure 4. ADSW map shows temporary water bodies that are missed by other reference data bases, such as GLWD or SRTM.

3.1.1 Processing steps to derive the ADSW map

In a quality assessment carried out by Haas et al. (2009) the time series of SWB detections of each pixel between January 1999 and September 2007 was analysed. With 36 observations per year (every 10 days), the analysed time frame comprises 315 dekads for each pixel. This high time resolution allows in particular for the detection of temporary and erratic water bodies. Their inclusion in the ADSW map assures that even with an infrequent recurrence they will be mapped and thus correctly regarded as water bodies and not mistaken for noise.

A key issue in the water body dataset is indeed the possible false detection due to the confusion between noise because of cloud and atmospheric contamination and short-term flooded areas, in particular during the rainy season when cloud cover occurs more frequently. We assume that a false detection due to cloud cover occurs randomly and therefore would most probably be observed infrequently whereas a short term flooded area is likely to be flooded again at some point in time in the time series, which includes 2 very humid years (1999 and 2007). Every pixel with a total number of detections of 1 dekad in the 315 dekads long time series was therefore considered as noise and was removed before the analysis.

In a first validation approach the reliability of pixels detected as free water could be proven (Haas et al. 2006), thus the analysis was based on this class of the SWB detec-

tions. Haas et al. (2009) found that a pixel that has been at least detected once as free water is a correct detection in 98% of the cases.
As a result, every pixel that has not been a single detection and that has been at least detected once as free water was mapped in the ADSW map.

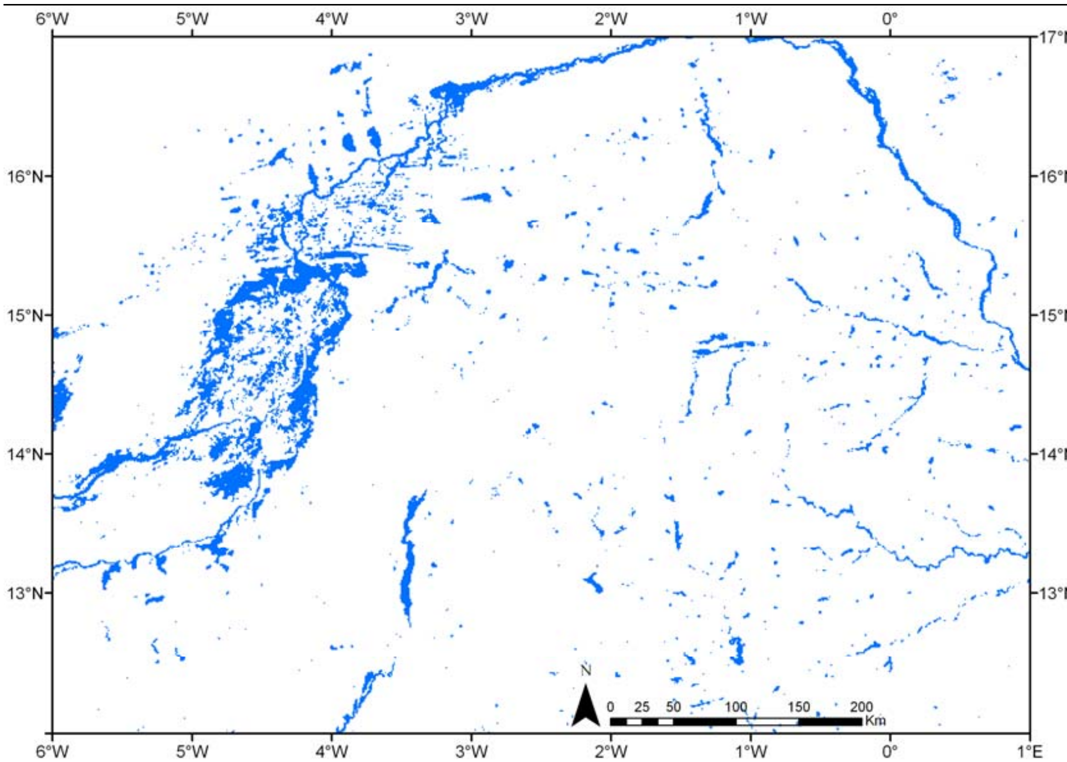

Figure 5. The ADSW map comprises water bodies of different size and hydrological functioning. Large wetland complexes like the Niger Inner Delta are detected as well as many small temporary water bodies and rivers.

The applied methodology allows for a frequent update of the map. It may be used on other arid regions with the same environmental properties.

3.1.2 Accuracy assessment

Water bodies have been mapped for the whole African continent but have been 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 6).

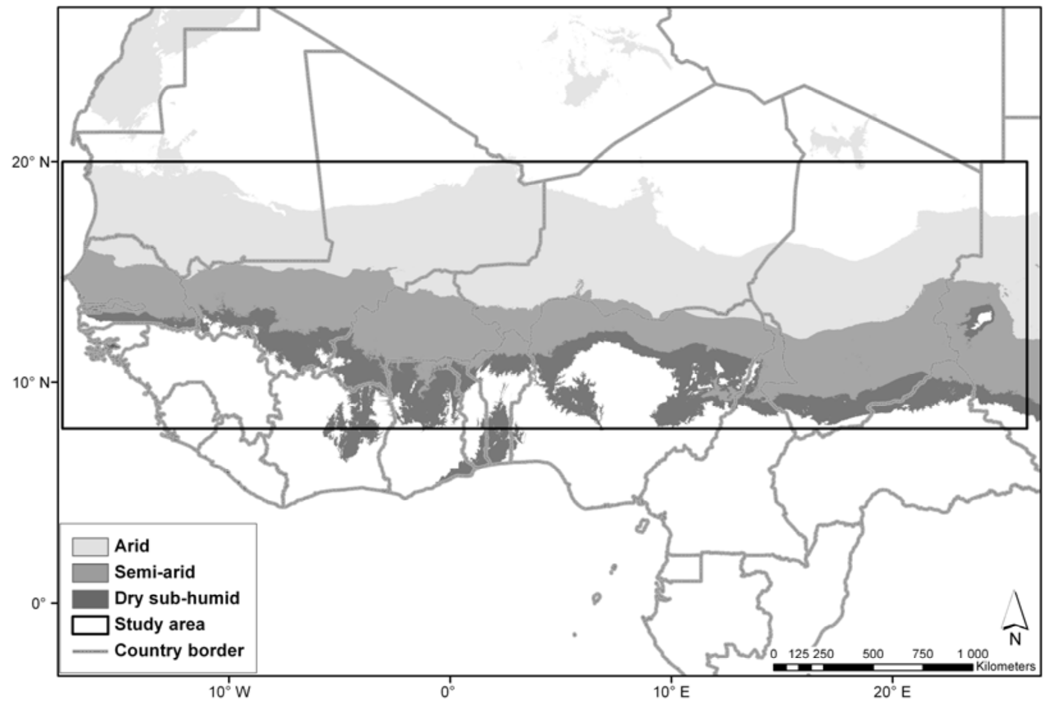

Figure 6. Water body detections have been validated in the arid, semi-arid and adjacent dry sub-humid climate zones when they occurred in the defined extent of the study area.

An extensive accuracy assessment has been carried out based on a stratified random sampling approach with a one-stage cluster analysis. High-resolution satellite data have been used to verify the detected water bodies. The overall accuracy, considering only the commission error, is 95.4 % for the whole study region, showing the best results in the arid (98.7 %) and semi-arid (94.9 %) climate zone (Haas et al. 2009).

3.1.3 Usage of the ADSW map

ADSW map is primarily used as a filter to keep small water bodies detections with a high rank of validity. Incorporating all potential sites of replenishment detected in the time series, the map can be used for statistical analysis of the small water bodies time series as well as for water body monitoring purposes.

At the same time, it is a synthesis of historical occurrence water bodies in Sahel.

The method design allows for a regular update of the map, which is important to capture the highly variable temporary features and it can be expected that by expanding the time series new water bodies will be detected. Another possibility is the limitation of the analysis to certain time intervals, when a synthesis of e.g. a rainy season is needed (see section 5).

3.2 Humid area detections in sub-Saharan Western Africa

In arid and semi-arid regions many water bodies are temporary and can drain quickly, leaving only a wet soil surface or shallow water on which vegetation can develop. The remaining humid area is thus an indicator allowing inference of surface water.

Therefore, not the actual water body but a result of its presence is detected as a positive anomaly and a map indicating areas with a potential presence of surface water can therefore provide valuable information. This positive anomaly is accurately detected in the dekadal water bodies dataset and integrated in the ADSW map up to a maximum tolerance in the case of a water body being detected only once as free water and the rest of time as humid area (see section **Error! Reference source not found.**).

All other pixels that have been identified entirely as humid areas have been mapped separately in a Map of Humid Areas (Haas et al., 2009) that can be used in complement to the ADSW map (Figure 6). Especially in large wetland complexes like the Niger Inner Delta or Lake Chad, where a composition of free water and humid areas can be found, the combination of the two maps provides the full picture about the surface water availability and composition.

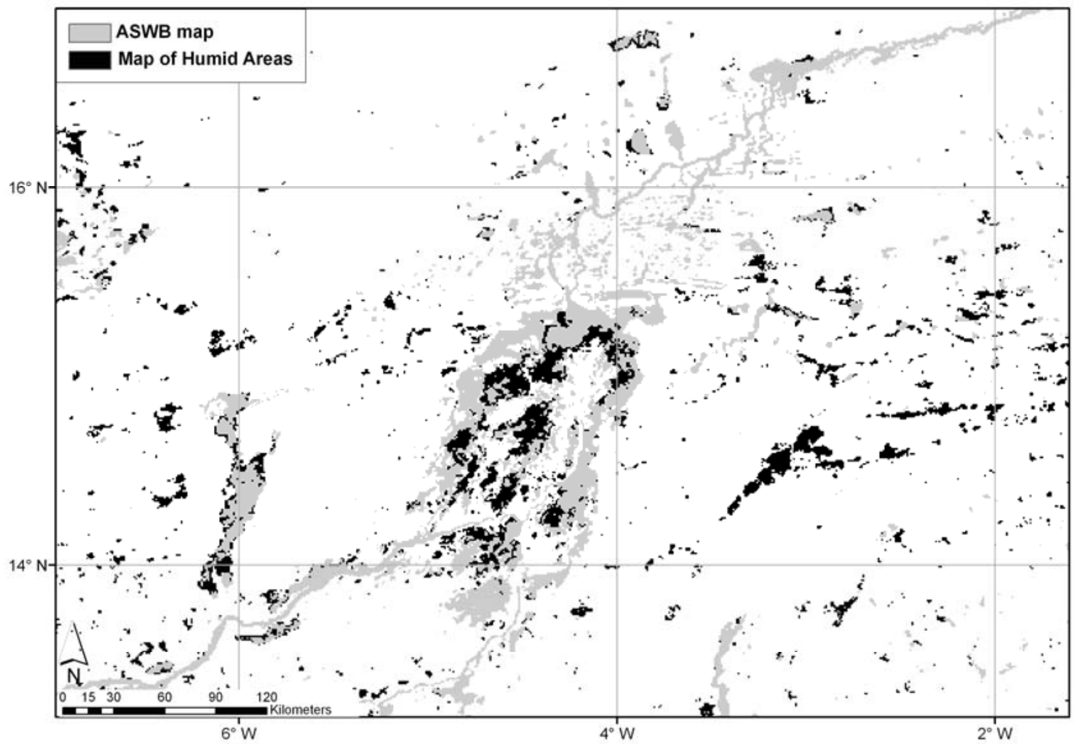

Figure 7. The Map of Humid Areas (black) displayed together with the ADSW map (grey) for the Niger Inner Delta, Mali.

3.2.1 Processing steps to derive the Map of Humid Areas

To derive the Map of Humid Areas the systematic analysis of the SWB time series was concentrated on the humid area detections.

In a first step, any pixel that was only detected once in the time series has not been considered for the analysis in order to remove possible false detections due to cloud and

atmospheric contamination, in particular during the rainy season when cloud cover occurs more frequently.
After the removal of single detections from the time series, for each remaining pixel the total number of detections during the 315 dekads has been extracted together with the number of detections in each state of surface water. Based on this extraction, the percentage of occurrence in the class humid area has been calculated. Pixels with a resulting value of 100%, which have been detected in all dekads as humid areas, have been mapped in the Map of Humid Areas.
The Map of Humid Areas is binary, with the value 1 representing an area entirely detected as humid area.

3.2.2 Accuracy assessment

The Map of Humid Areas has the same spatial resolution and extent like the ADSW map but has not been validated and therefore cannot be used as a reference map.
A large number of humid areas correspond to positive anomalies of vegetation growing due to the presence of surface humidity. Although this detection is of interest, for example for vector borne diseases warning system or locust breeding areas detection, they cannot be systematically validated with a high enough confidence rate. The information on humid areas has thus to be processed on purpose for each application and has to be used cautiously.

3.2.3 Usage of the map of humid areas

The best use of the map of humid areas is in complement to the ADSW map, especially in large wetland complexes where it provides additional information and the overall picture of the state of surface water. In other areas, the map shows humid areas that are not linked to a water body but can indicate the presence of water (Figure 7).

3.3 SWB detections in other arid and semi-arid regions

The method designed to map water bodies and humid areas allows for an expansion to areas with similar climatic characteristics. In Botswana a first test of the transferability of the ADSW map and the Map of Humid Areas delivered promising results.
The validity of water bodies detected with the ADSW map in arid and semi-arid areas of Botswana could be confirmed by high-resolution satellite imagery (Google Earth) and local expert’s field knowledge.
Likewise, many detections of humid areas were found to be related to the temporary presence of surface water.

4 Temporal properties of the surface water bodies

Surface water is detected every 10-day, allowing to analyse their time dependent properties.

4.1 Water bodies type as a function of time

The detection system allows distinguishing 3 types of surface water: free water, humid area and mixture of both, the latest being very rarely observed.

A humid area is a mixture of both water and vegetation, the mixture can have many forms, such as vegetation growing on a humid ground, a lake covered by some vegetation, or even in the surface covered by a pixel vegetation growing in between the meanders of a river.
A pixel classified as free water should not have a significant cover of vegetation.

Many of these surface water bodies are likely to be converted into what is seen as a humid area as soon as water is available. Actually, this conversion depends most likely on the water body properties, such as its depth of the underneath ground composition.

By counting the number of occurrence of detection in both classes 'free water' and 'humid area', among all detection from 1998 to 2007, the prevalent functioning of the system can be assessed.
Figure 8 shows a close up to the inner delta of Niger, where a fraction of the hydrological system is most of the time converted into a humid area, mostly in the inner delta itself. For the rest of the region, the water surface is usually (in more than 50% of the detections) seen as free water.
It should be noted that this computation only consider pixel from ADSW map, which means that surface water that were detected as humid areas in 100% of the cases are discarded. The case of surface only detected as humid areas is not considered.

The analysis of the frequency of conversion of surface water into humid area can play an important role for the understanding of the ecological functioning.

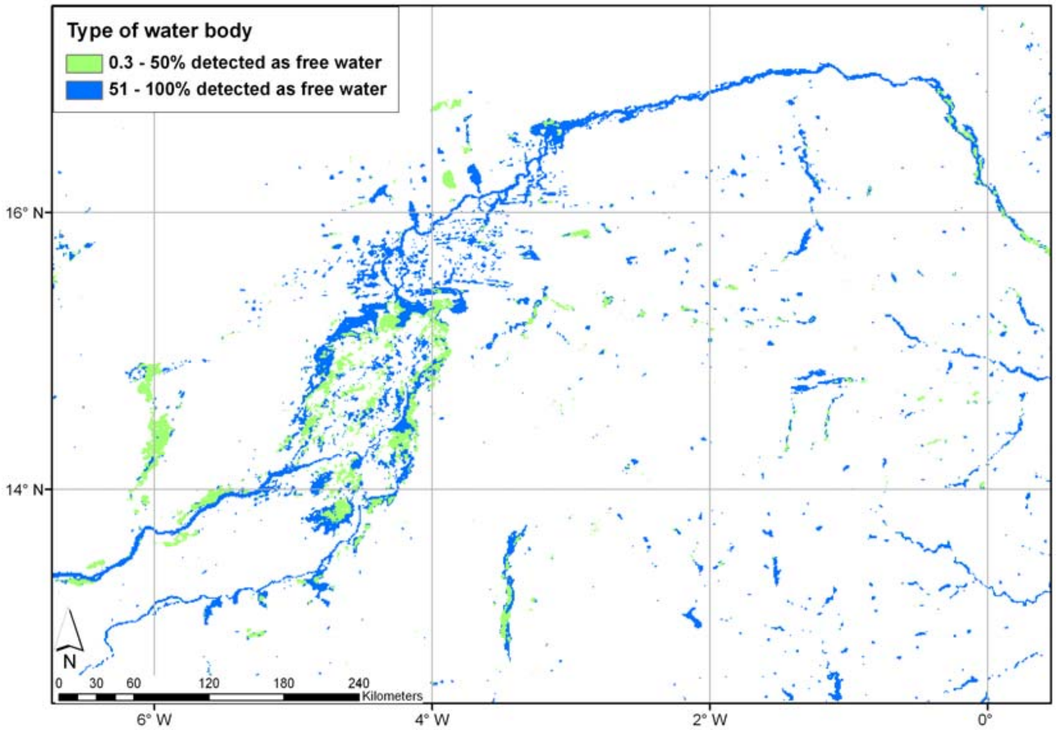

Figure 8. The ADSW map as derived from the SWB time series analysis displaying the percentage of occurrence as free water for each water body pixel in the Niger Inner Delta, Mali. Green areas have been detected mostly as humid areas whereas blue areas are mostly detected as free water.

4.2 Seasonal recurrence of water bodies

The apparition of temporary water bodies and their level of replenishment is directly linked to the rainfall condition of the current year. As a result, some water bodies can be detected every year, while others would be only rarely replenished.

Seasonal recurrence is understood as the return of a water body pixel in a rainy season on several years. A high seasonal recurrence denotes a water body that is replenished in most of the observed rainy seasons whereas a low seasonal recurrence indicates a water body with an infrequent recurrence. A water body that is recurring frequently during rainy seasons has another ecological meaning than a water body that occurs just in case of extreme events.

Haas et al. (2009) observed 9 years of detections between 1999 and 2007 in order to classify water bodies detected in the water body reference map by their seasonal recurrence, which allows to draw further conclusions about the type of water body observed.

Season was defined according to the hydrological season in the study region rather than to the rainy season, since water bodies can last beyond the end of rainy season.
The rainy season normally lasts from June to September but no common definition for a hydrological season is established for the Sahel region. Since most of the water bodies

dry before the end of February, the hydrological season has been defined for each year from the first dekad of March until the last dekad of February of the consecutive year.
The computation of the recurrence for each pixel in the ADSW map consists in counting in how many years it was detected during the hydrological season.
The count of years with detections between 1999 and 2007 is shown in Figure 9.

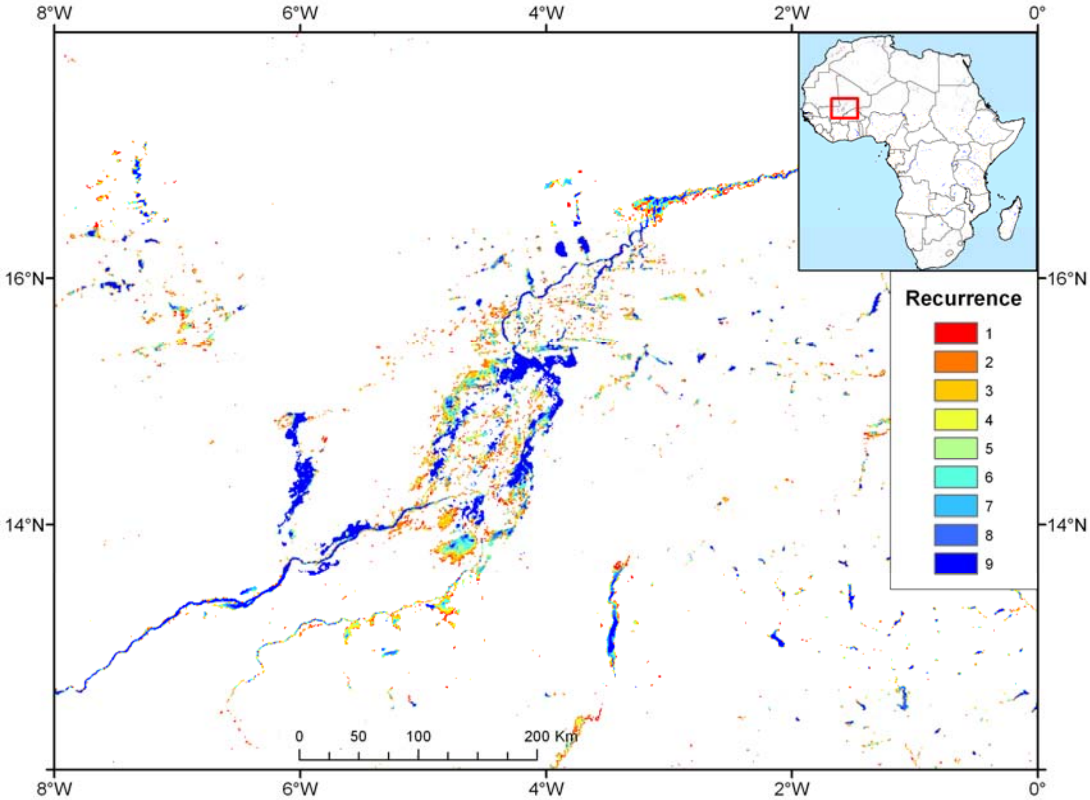

Figure 9. Number of seasons a pixel was detected in the Niger Inner Delta (Mali).

The map of seasonal recurrence displays water bodies that are recurring frequently (dark blue) as well as areas that are only infrequently replenished (red). The infrequently occurring water body pixels appear usually at the rim of water bodies and in floodplains along rivers (Figure 9).

Haas et al. (2009) showed that most of the 'one season' detections have been observed in 1999, which is known to be an extremely humid year with heavy rainfalls and floodings. On the contrary, in 2007 an other humid year, mostly areas that are also detected in other years have been replenished. This could indicate a very short duration for the 2007 floods in many regions, hindering the detection of water from standard 10-day VEGETATION composites.

Knowledge about the seasonal recurrence of water bodies can be useful for the understanding of the possible appearance of aquatic species in a temporary pool as well as the mapping of frequently recurring water bodies or areas that are infrequently flooded.

4.3 Permanent and temporary water bodies

In arid and semi arid regions, surface water availability is highly variable in space and time. A large number of water bodies would replenish only for a limited period depending on the current rainfall and drain as soon as the rainy season is over.
Such a temporary water body would be detected only within and shortly after the rainy season, while permanent water bodies, such as large lakes or rivers that are connected to another hydrological regime, would be detected almost during all year, with some missing detections due to noise (cloud screening, vegetation screening or temporary drainage).
The assessment of the surface water availability is a unique property of the SWB data, which provides information about the temporal characteristics of each pixel.

4.3.1 SWB time series analysis for the detection of temporary and permanent water bodies

The analysis of the temporal behaviour of a pixels time series gives a clear indication about its seasonality and thus the type of water body observed.
For the identification of temporary and permanent water bodies, the SWB time series was screened for each pixel according to a defined criterion.

The criterion used to select a pixel as a permanent water body is its presence during a year from January to December. The calendar year has been 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 or 12 month per year in at least one year between 1999 and 2007.
To smooth the time series and to remove possible noise, e. g. due to missing detections caused by cloud cover, the analysis was carried out on monthly aggregates rather than on the 10 day SWB detections. For each month, the three dekads were checked for the presence of a pixel, and no moving window has been used between the months. If in at least one dekad the water body pixel has been detected in one of the three classes it was mapped for this month.
The permanent features detected due to their specific seasonality have been mapped and as can be seen in Figure 10, the majority of water bodies are characterized by a temporary profile.

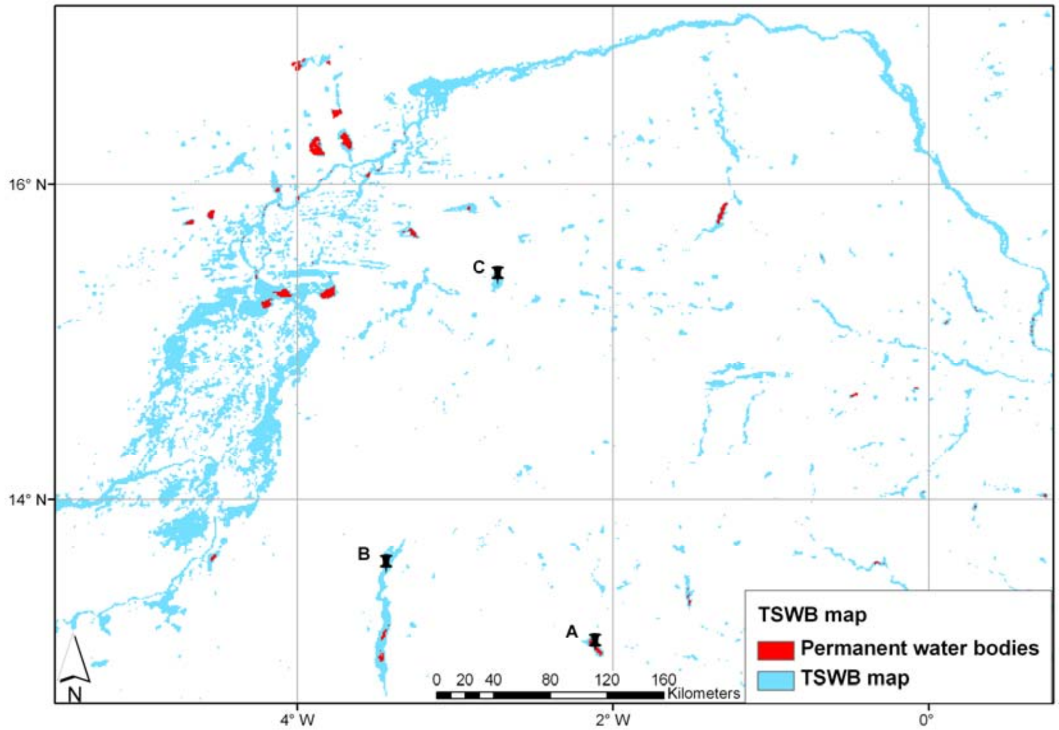

Figure 10. The majority of detected features in the ADSW map is only temporarily present, with permanent detections occurring only in larger lakes and some areas of the Niger Inner Delta. For points A, B and C the temporary profiles have been extracted and displayed.

The most persistent water bodies, like rivers and large lakes show an almost permanent detection of surface water (Figure 11) and were captured with the time series screening. A typical profile of such a permanent water body is displayed in Figure 11, showing detections in most of the dekads and years.

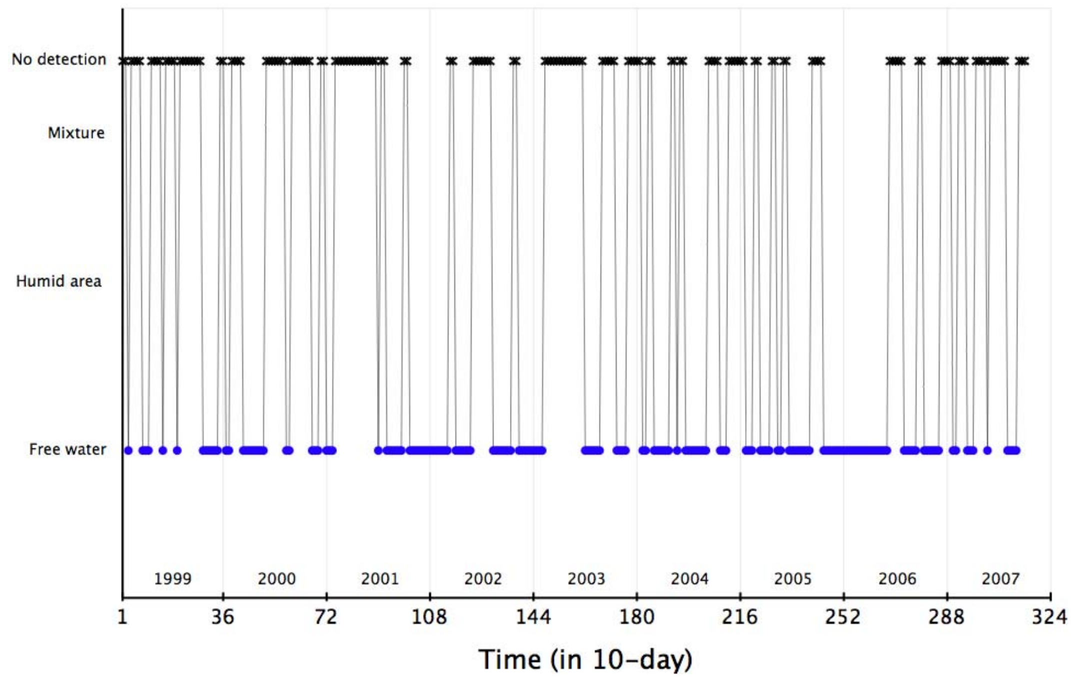

Figure 11. Time series of a permanent water body pixel (Figure 10, A) is characterized by an almost continuous presence as free water.

River banks, smaller lakes and the rim of large lakes may show seasonality related to the river or lake level and are not continuously present (Figure 12). In the very humid year 1999, this water body pixel that is located on the rim of a reservoir has been entirely detected as free water with a longer time of replenishment compared to the other years while in the dryer year 2004 is has been only present as humid area.

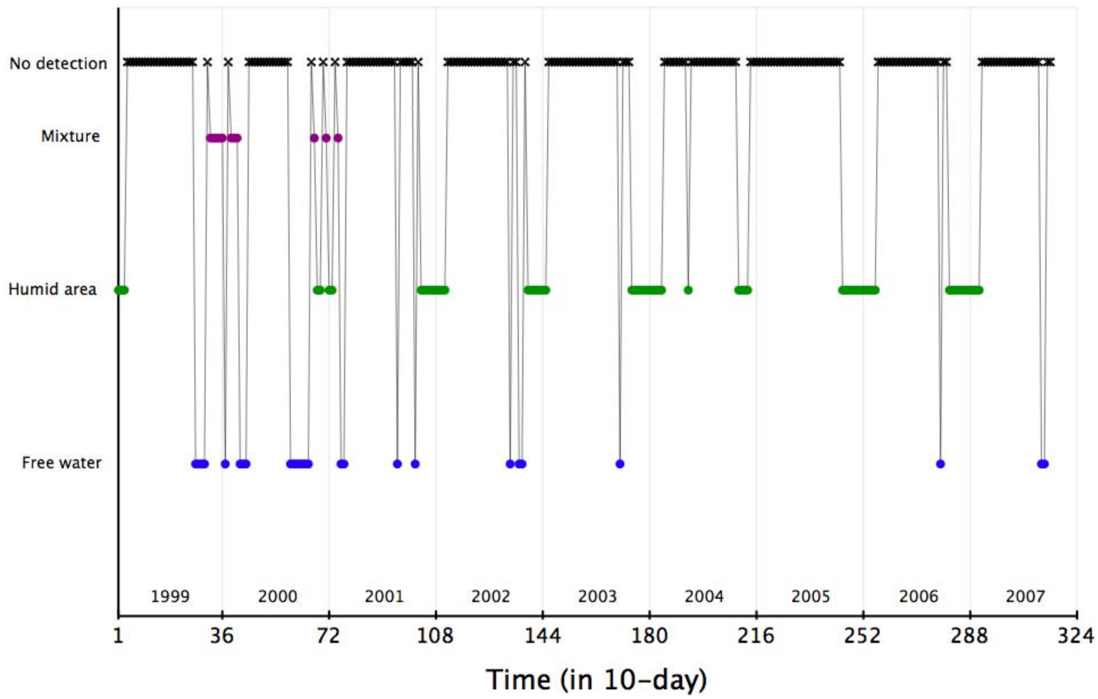

Figure 12. Time series of a water body pixel (Figure 10, B) located at the rim of a reservoir on the Sourou river (Mali) that is not continuously flooded.

Most of the surface water bodies in the Sahel show a distinct seasonality with a rather short duration of the replenishment. As can be seen in Figure 13, the change from free water to a humid area while drying out at the end of the season can be observed in the time series of a pixel. In the rather dry year 2004 the observed pixel didn't replenish sufficiently to be detected as free water, which can be seen from the profile.

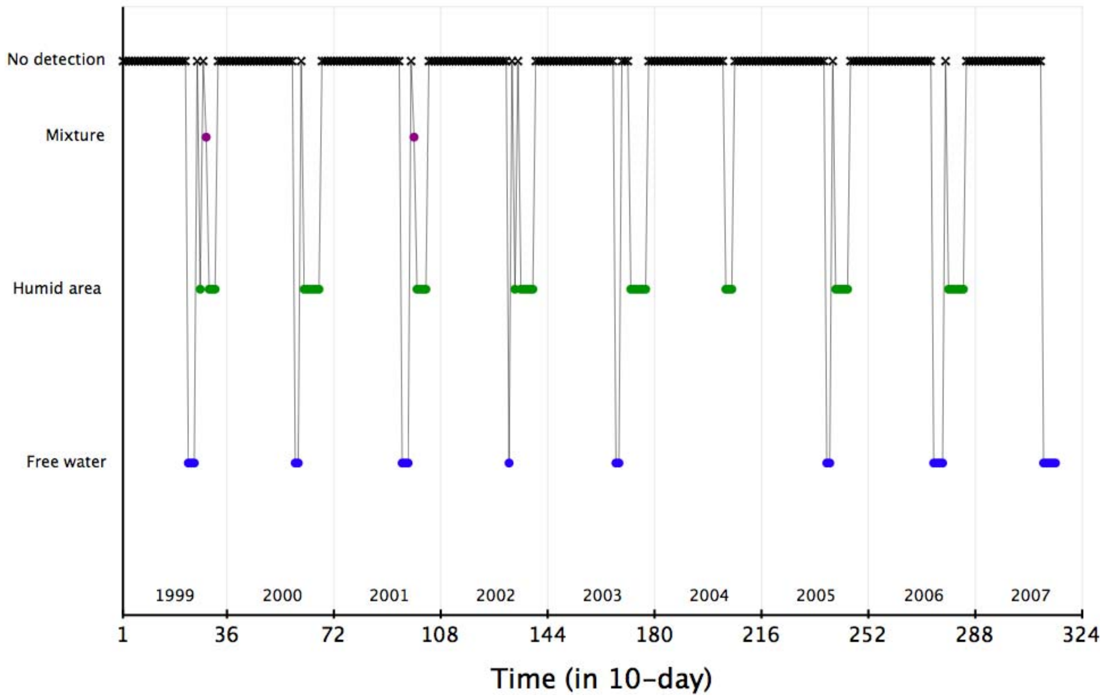

Figure 13. Time series of a temporary water body that is recurring frequently (Figure 10, C).

Knowledge about the permanent or temporary nature of a water body and its seasonal development is important for the planning of water resource usage (e.g. cattle management) as well as for environmental studies (e.g. monitoring of favourable conditions for disease outbreaks).

4.3.2 Classification of the ADSW map according to hydrological functioning

Most of the detected water bodies in the ADSW map are characterized by a distinct seasonality, but their functioning as well as the causes for the seasonal occurrence are diverse.

Haas et al. (2009) carried out a classification according to the hydrological functioning into features that can be related to local rainfall and features that are not solely influenced by local rainfall like large perennial river systems and their temporary floodplains, small and large permanent lakes as well as reservoirs whose hydrological regime is artificially influenced.

Ancillary datasets have been used to obtain information about permanent rivers, lakes and dams in combination with the information derived from the time series analysis.

A key question in the filtering process is, if pixels or features should be filtered. The ADSW map is a raster map with each pixel being an independent detection. However, it is clearly visible that neighbouring pixels form a water body that should be therefore considered as a unique water body feature.

Vectorising the raster dataset assures that neighbouring pixels will become one feature, not considering diagonal connections.

Using the vectorised ADSW map assures that neighbouring pixels, which form a water body, are filtered together so that water bodies will not be cut.

The resulting map is displayed on Figure 14.

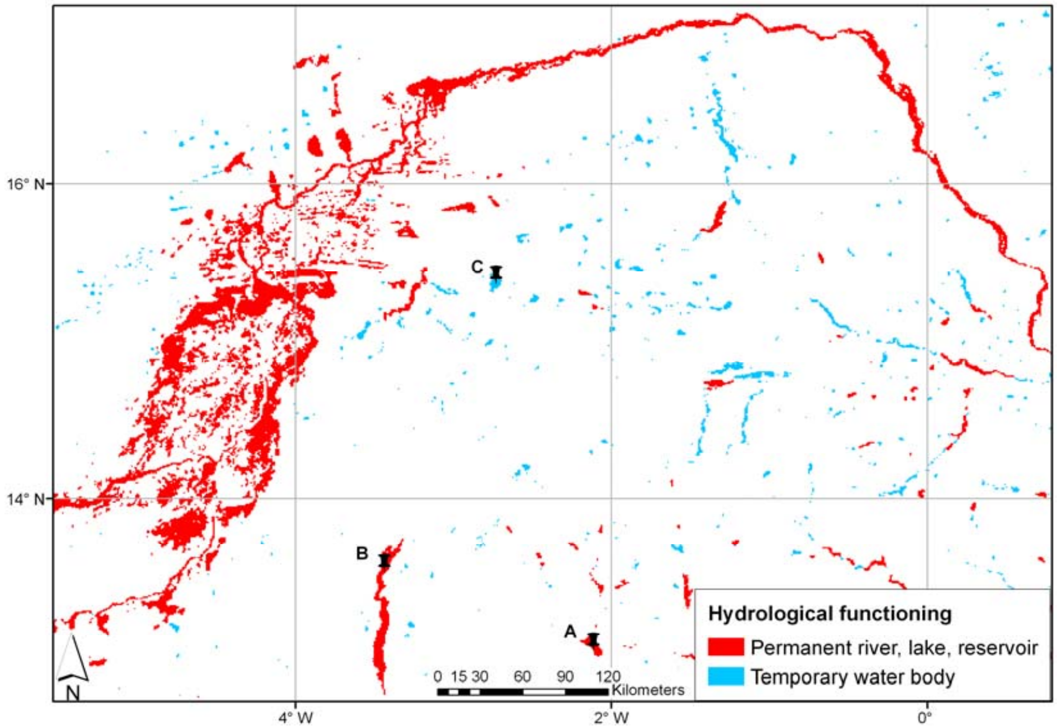

Figure 14. The ADSW map classified by hydrological functioning based on ancillary datasets and SWB time series analysis. Large wetland complexes like the Niger Inner Delta as well as reservoirs, permanent lakes and rivers are indentified as well as temporary water bodies.

The filtering with ancillary datasets enables the identification of water bodies with a hydrology that is not solely dependent on local rainfall.
Still, most of these water bodies show seasonality, especially at the rim of large lakes and reservoirs or in the floodplains of rivers.

In the ancillary datasets, this seasonality information is not implemented and a feature classified as permanent lake would be assumed to be always present even though it is partly absent. In Figure 12, the observation point B has been classified as permanent because it is linked to a reservoir. This is correct, but when the time series is regarded (Figure 10), it becomes clear that even though the water body pixel is part of a reservoir, it has a clear seasonality and is not permanently present.

According to the user's interest, the method to distinguish between temporary and permanent water bodies in the ADSW map has to be chosen.

The classification based on the SWB time series filters the water bodies according to their seasonal profile and does not provide further information about their hydrological functioning. This information represents well the variability of surface water in arid and semi-arid regions, where most of the water bodies are only temporarily present.

For some analysis, it might be useful to regard water bodies according to their hydrological functioning. To study temporary water bodies that are solely linked to local rainfall, the ADSW map that is filtered with ancillary datasets should be used.

5 Rainy season synthesis

The monitoring of surface water in western Africa is usually done during the rainy season. One goal is to assess the amount of available surface water and its progression along the season, summarized by grid cells or administrative regions. The assessment of inter season variability is also seeked.
This computation requires a reference map, called SeasonStatMask, for the statistical computation in order to:

- discard spurious detections
- have a counting reference for computing the percentage of available water bodies

The generation of SeasonStatMask for rainy season statistics follows the definition of ADSW (see section 3.1.1): by analysing the history of detection, pixels showing at least one detection in the whole history of free water are trusted.
In contrast with ADSW, the generation of this mask only consider detections occuring during the rainy seasons. The reason for this time frame restriction is that some water bodies would be replenished by rivers streams later than the small water bodies replenished by rain. The case is noticeable along the Niger River which brings upstream water after the end of the rainy season (October) as shown on Figure 15. In the inner delta, the floods level depends on the water levels coming from the Upper Niger and the Bani tributary which flows near Mopti. The flooded area can vary from a surface less than 9500 km^2 (1984) to 35000 km^2 (1967). The annual discharges go from 45.10^9 m^3 in Koulikoro to 30.10^9 m^3 in Ansongo, due to progressive disappearance and evaporation effects in the Delta (NBA and UNDESA, 2002). Flooding typically begins in the south in August or September and reaches the northern margins of the ecoregion in December. The total flooded area[2] can grow to be as large as 30000 km^2.

In many administrative units, a significant number of historical detections are found only several times in the history of detection (Figure 9). To give a more reliable idea of the percentage of possible surface water sites that were replenished in a given season, the water bodies corresponding to a low number of recurrence (less than 4 times in 9 years) in the history are also discarded.

[2] www.nationalgeographic.com/wildworld/profiles/terrestrial/at/at0903.html

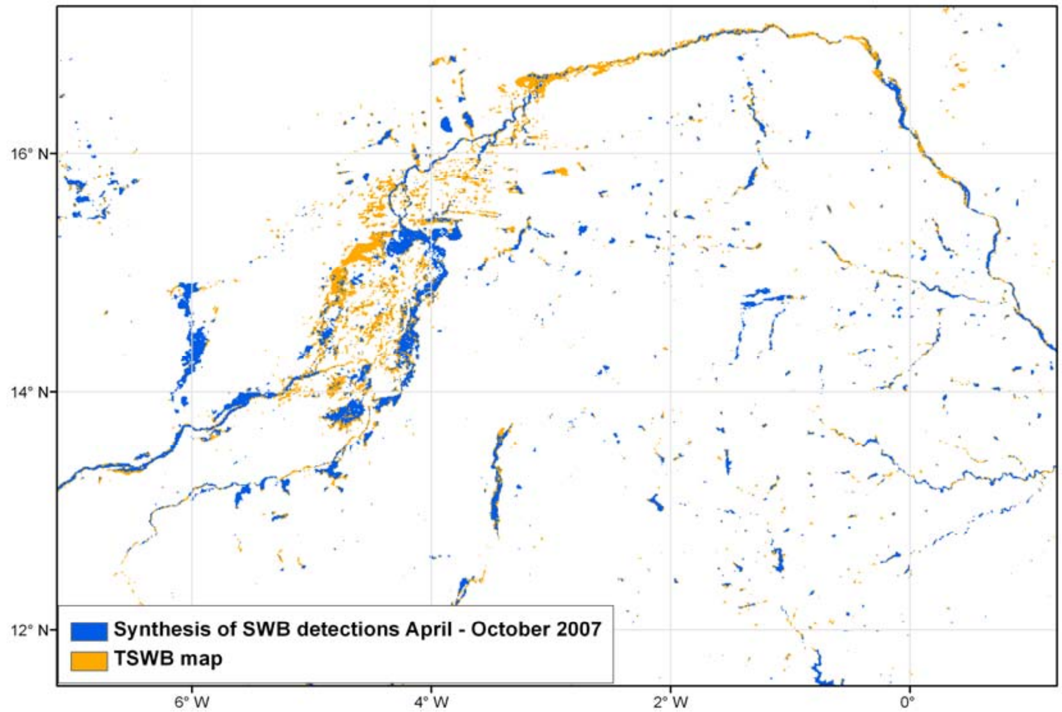

Figure 15. Pixels that were found with at least 1 free water detection in the history (blue and orange). The orange class shows those found during 2007 rainy season.

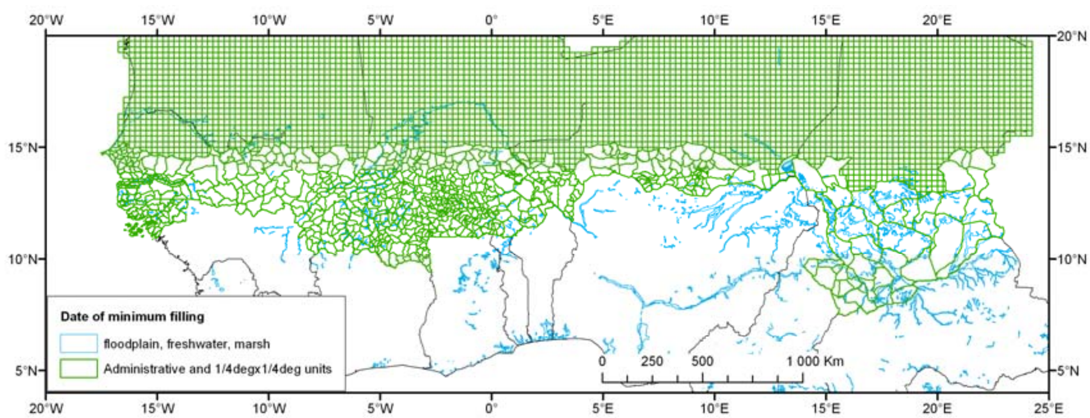

Figure 16. Units for computing the rainy season synthesis: the largest administrative units are exploded in ¼° × ¼°

5.1 Availability of surface water: quantitative assessment

The data statistics are represented by administrative unit (FAO level 3). Mauritania, Mali and Niger administrative units that are too large are subdivided in ¼°× ¼°.
Figure 17 to Figure 25 show the percentage of replenishment of those administrative units, as observed at the end of the rainy season (fixed at October, the 21st). The percentage of replenishment is computed with respect to the annual mask of detection (sea-

sonStatMask) and discarding rare occurrence of detection (occurrence number lower than 4 times in 9 years).
For each season, the relative count of detection, between the current season and the preceding one is computed as the percentage of detection of the former year:

$$\left(\sum_{year} SWB - \sum_{year-1} SWB\right) \Big/ \sum_{year-1} SWB$$

This indicator expresses the relative annual gain and loss of surface water at the end of a season.

At the end of October 1999, most of the recurrent water bodies (recurrence number above 3 times in 9 years) were in general filled. Figure 17 shows that most administrative units and ¼°× ¼° cells were replenished at more than 50%. The map indicates 1999 is rather a well humid year, which is confirmed by local observation of high rain fall amounts and floodings. Moreover, year 1999 is known for having a large number of detections with rare recurrence in the following years.

The proportion of replenished water bodies sensibly decreased in 2000 and 2001, especially in the north of Burkina Faso (Figure 18), showing clearly a loss of surface water with respect to 1999.
In 2001, a large number of administrative units, especially in north Burkina Faso, show a rather low amount of replenishment (Figure 19). However, comparing 2001 to 2002 does not show noticeable difference: the amount of replenishment is almost stable, with some increase along the Niger River, and some loss in other regions.
Year 2002 is clearly drier than 2001 (Figure 20), almost all administrative units showing a loss of surface water compared to 2001. The general level of replenishment in 2002 is rather low
The availability of surface water improves in 2003 (Figure 21).
Year 2004 is also a year of deficit (Figure 22).

These maps show that the tendency is not uniform at the scale of CILSS, since some administrative units can show gain while the rest of the region show a loss of filled sites.
Percentage of replenishments for 2006 and 2007 are shown on Figure 25.
North Burkina Faso and South of Chad seems to be the regions that are generally the most affected by droughts.

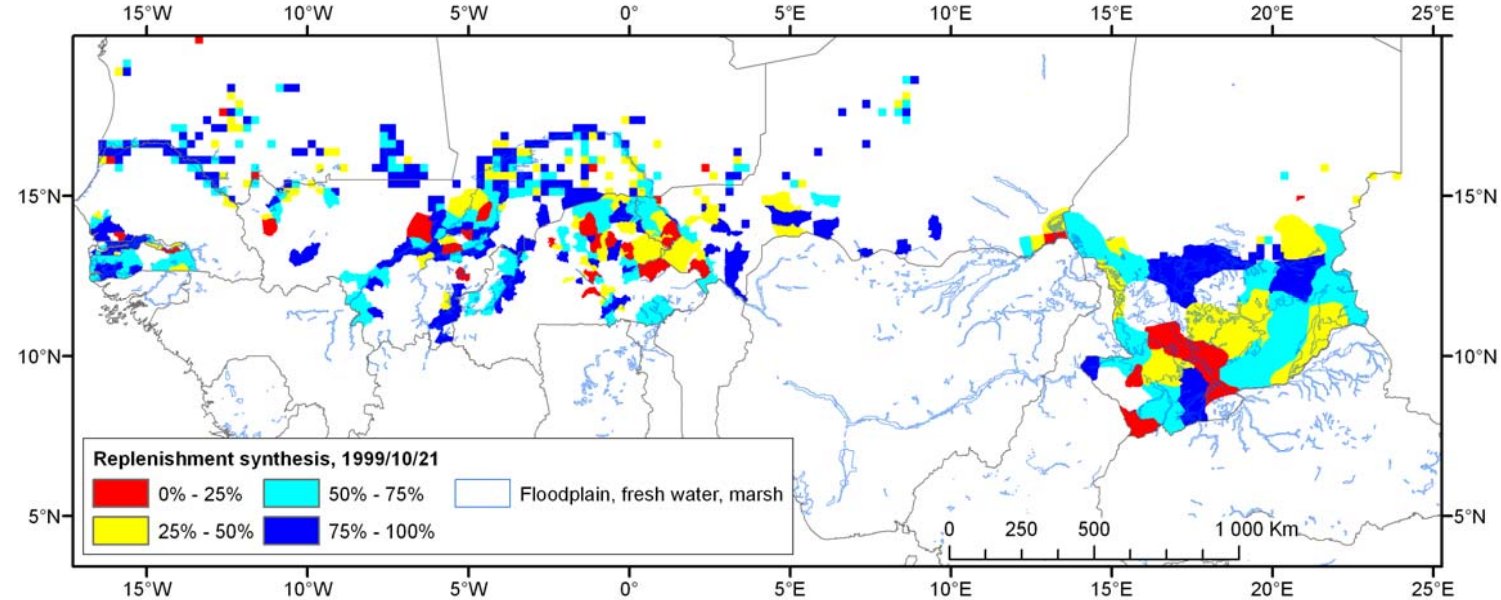

Figure 17. Synthesis of the replenishment of recurrent small water bodies, for season 1999

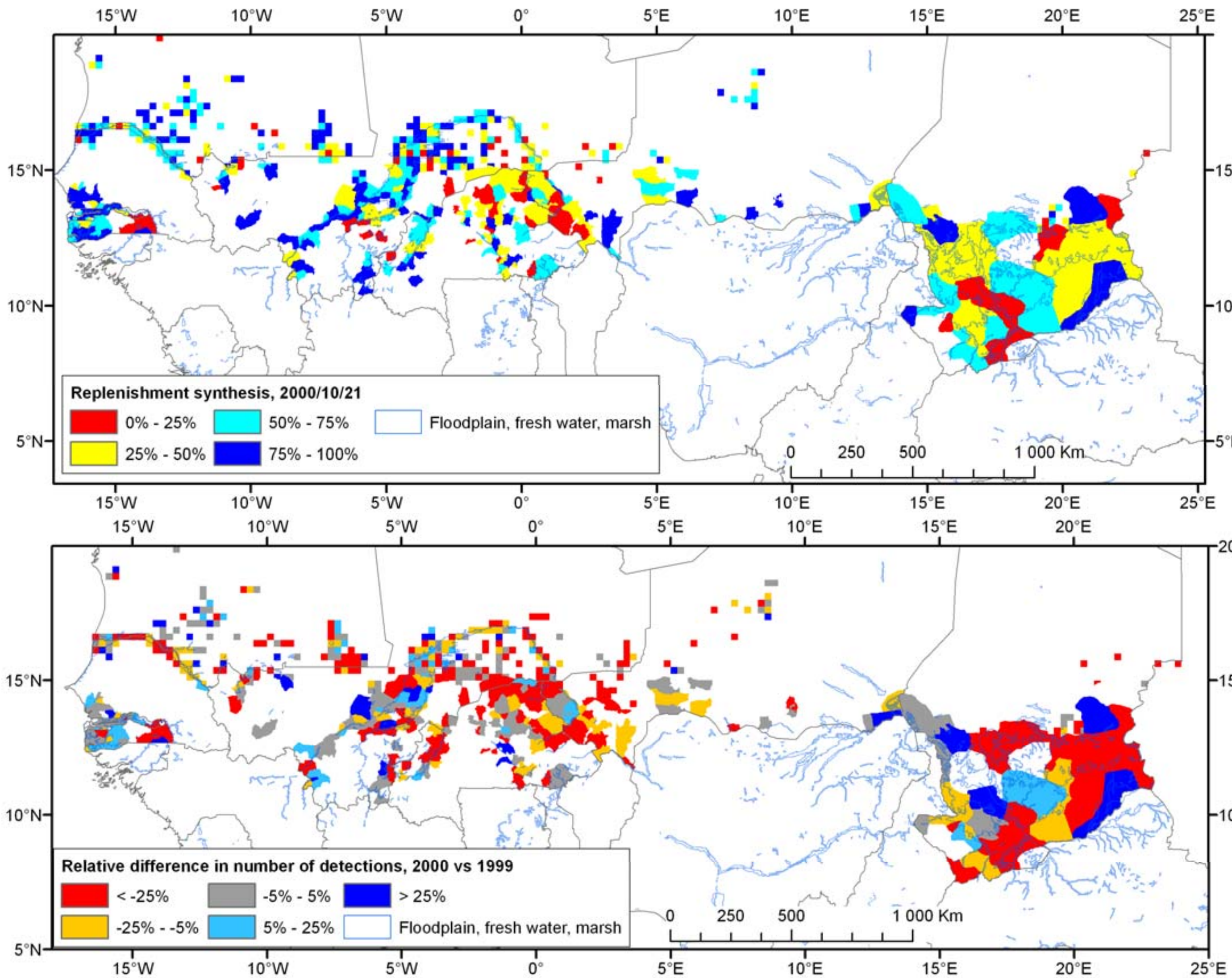

Figure 18. Synthesis of the replenishment of recurrent small water bodies, for season 2000

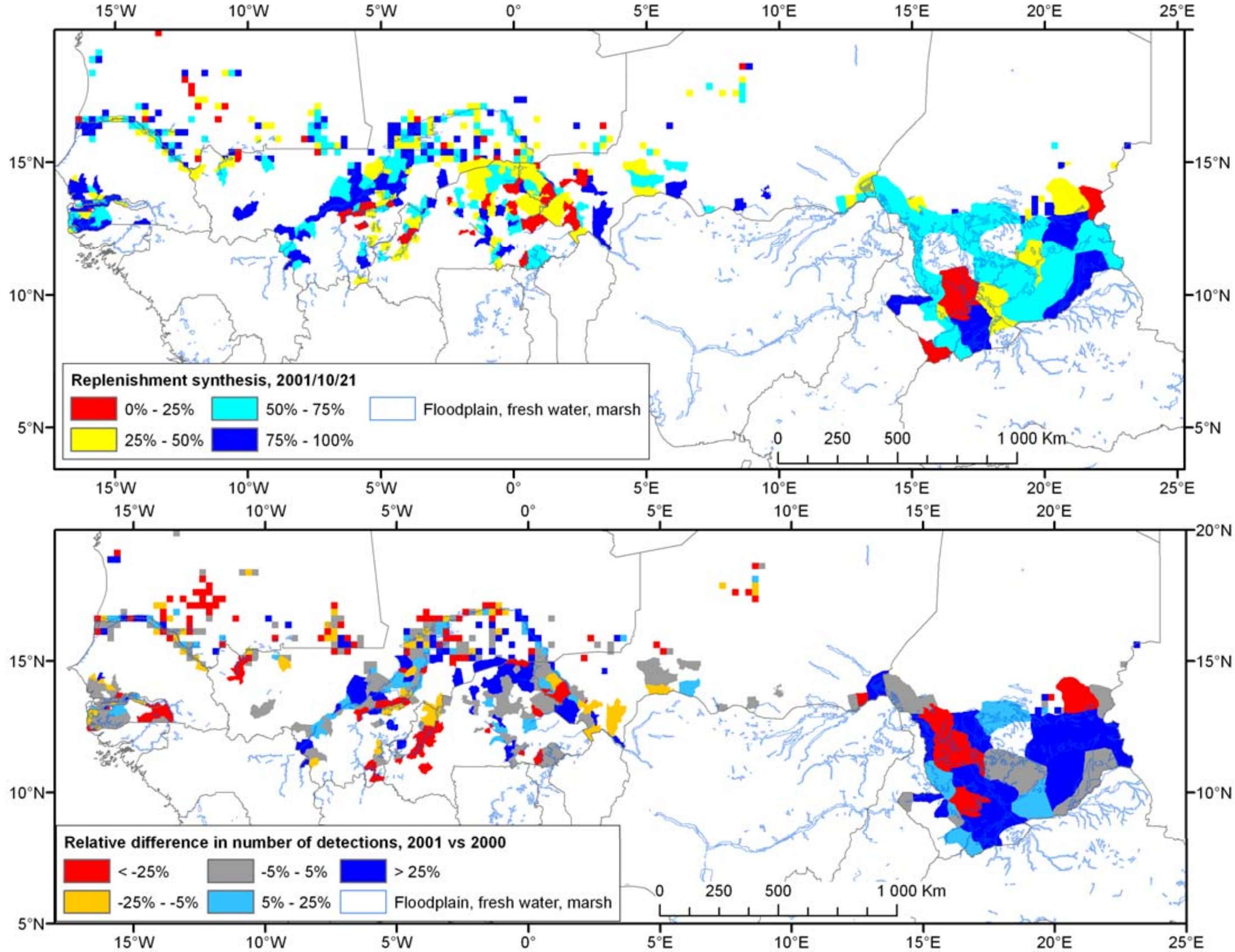

Figure 19. Synthesis of the replenishement of recurrent small water bodies, for season 2001

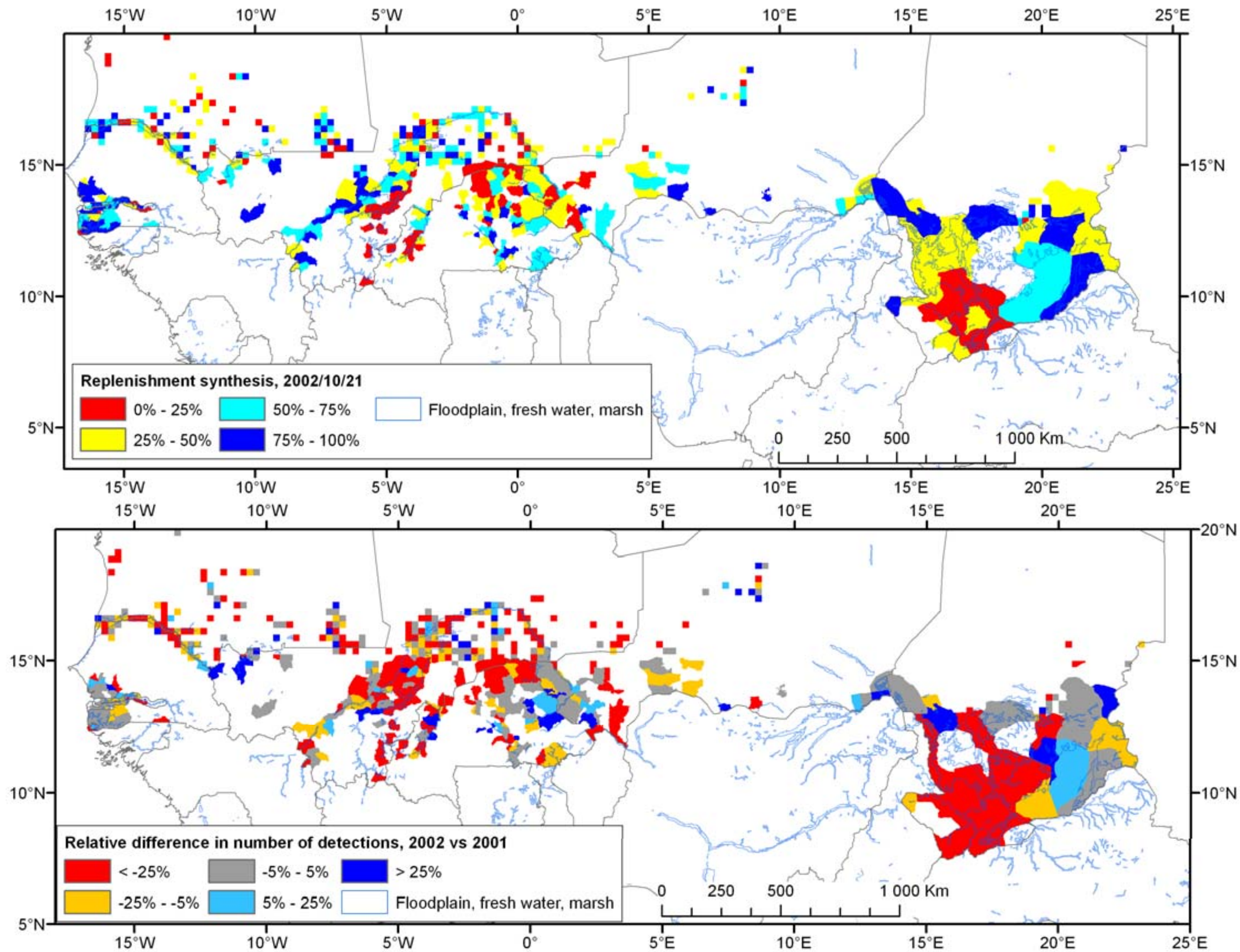

Figure 20. Synthesis of the replenishment of recurrent small water bodies, for season 2002

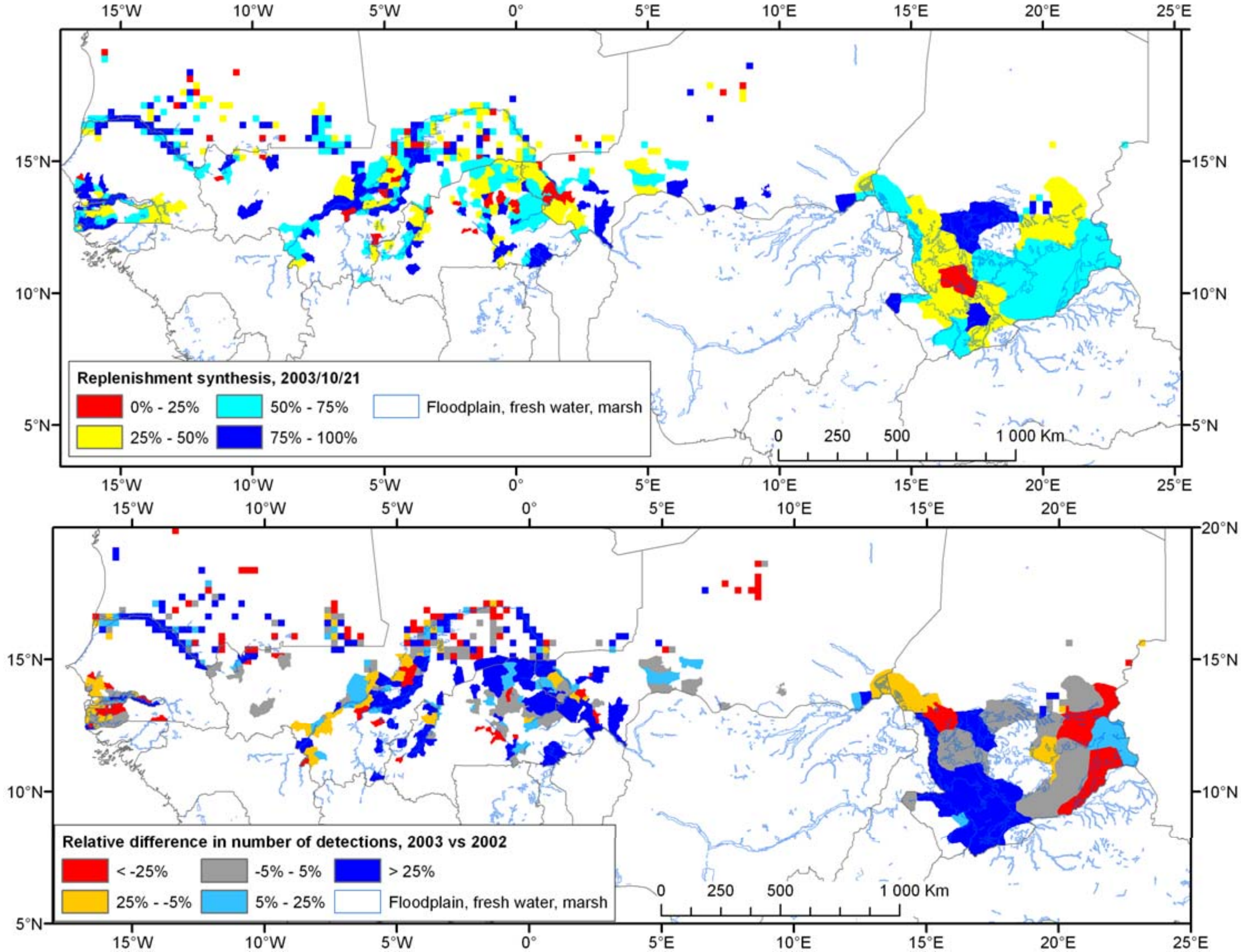

Figure 21. Synthesis of the replenishment of recurrent small water bodies, for season 2003

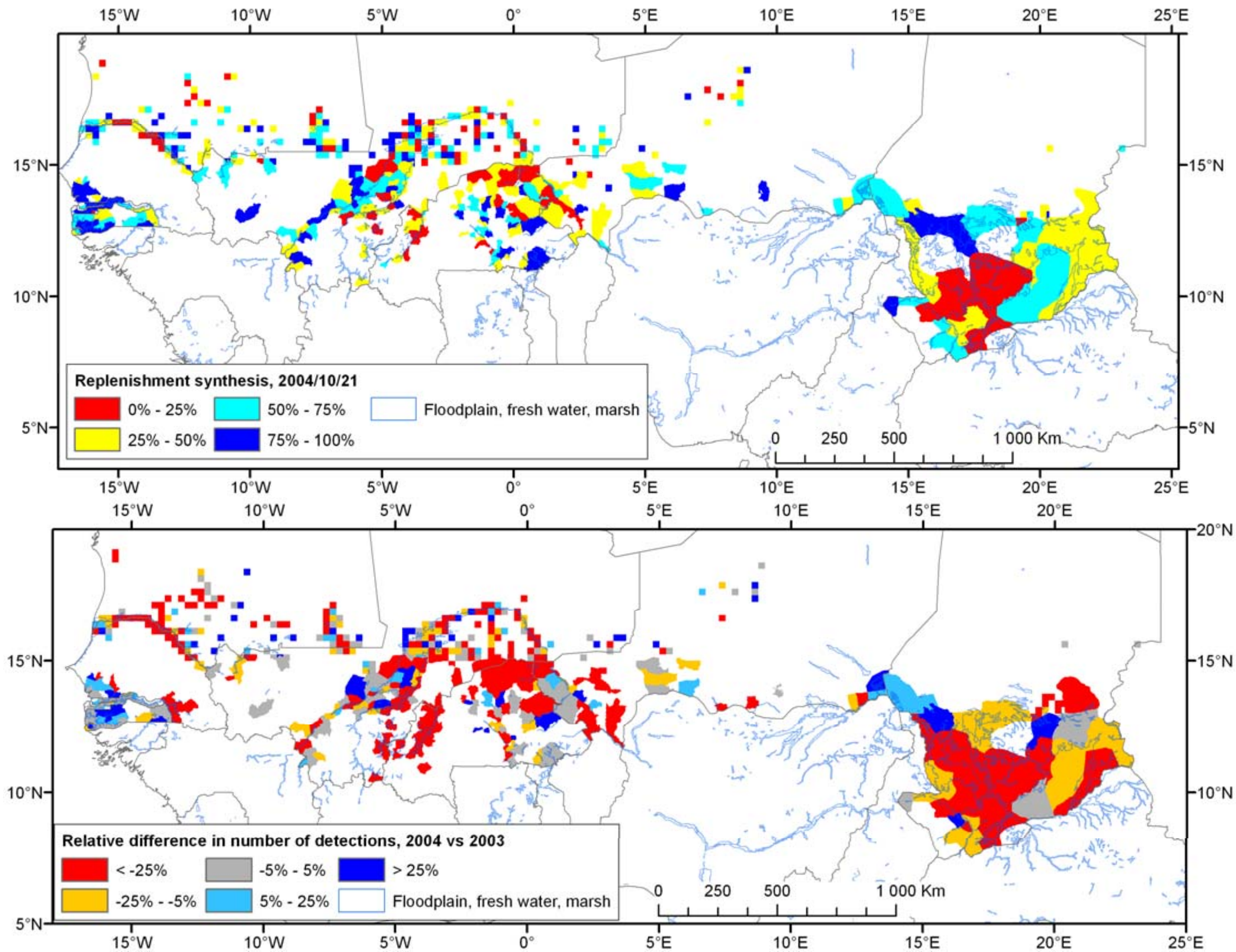

Figure 22. Synthesis of the replenishment of recurrent small water bodies, for season 2004

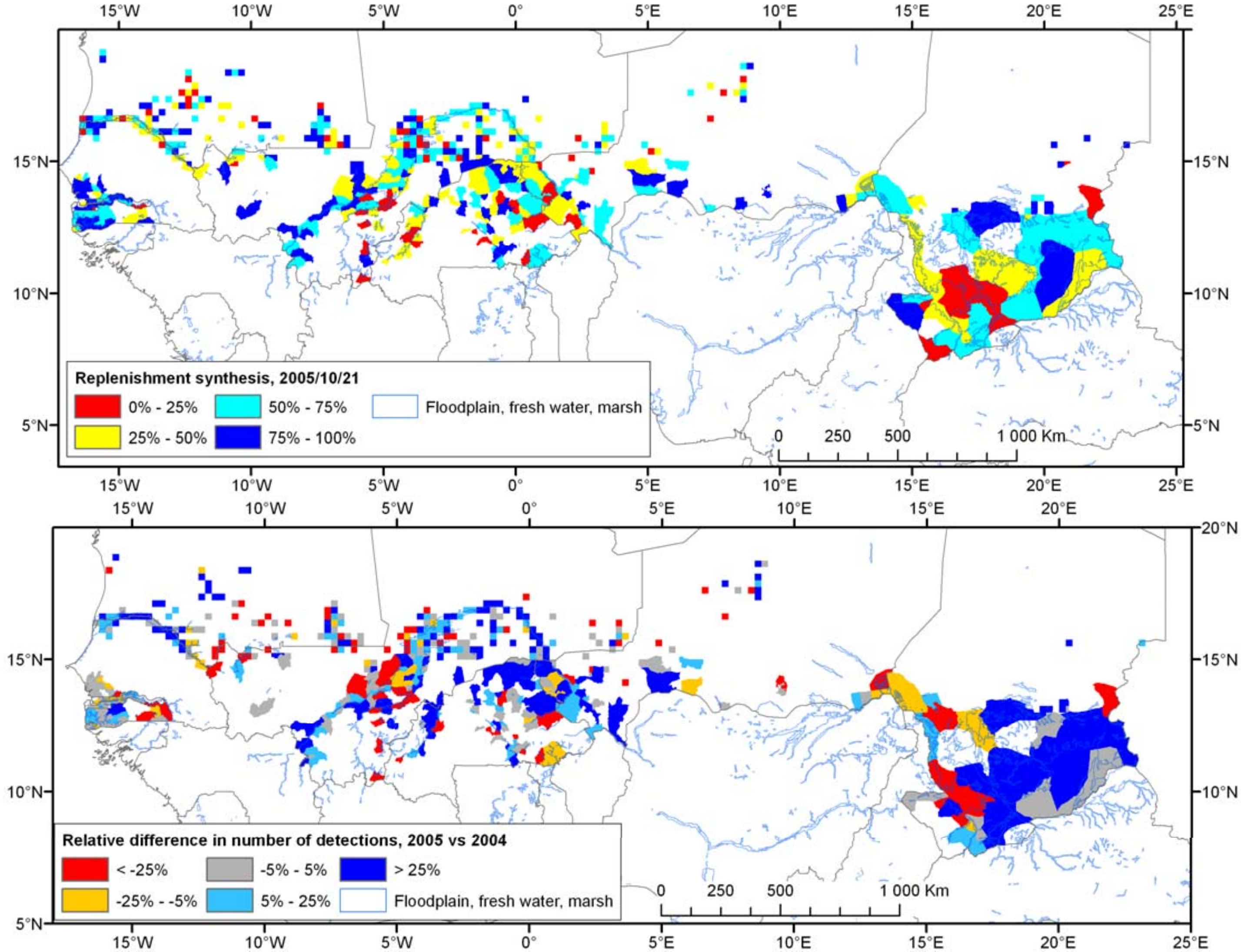

Figure 23. Synthesis of the replenishment of recurrent small water bodies, for season 2005

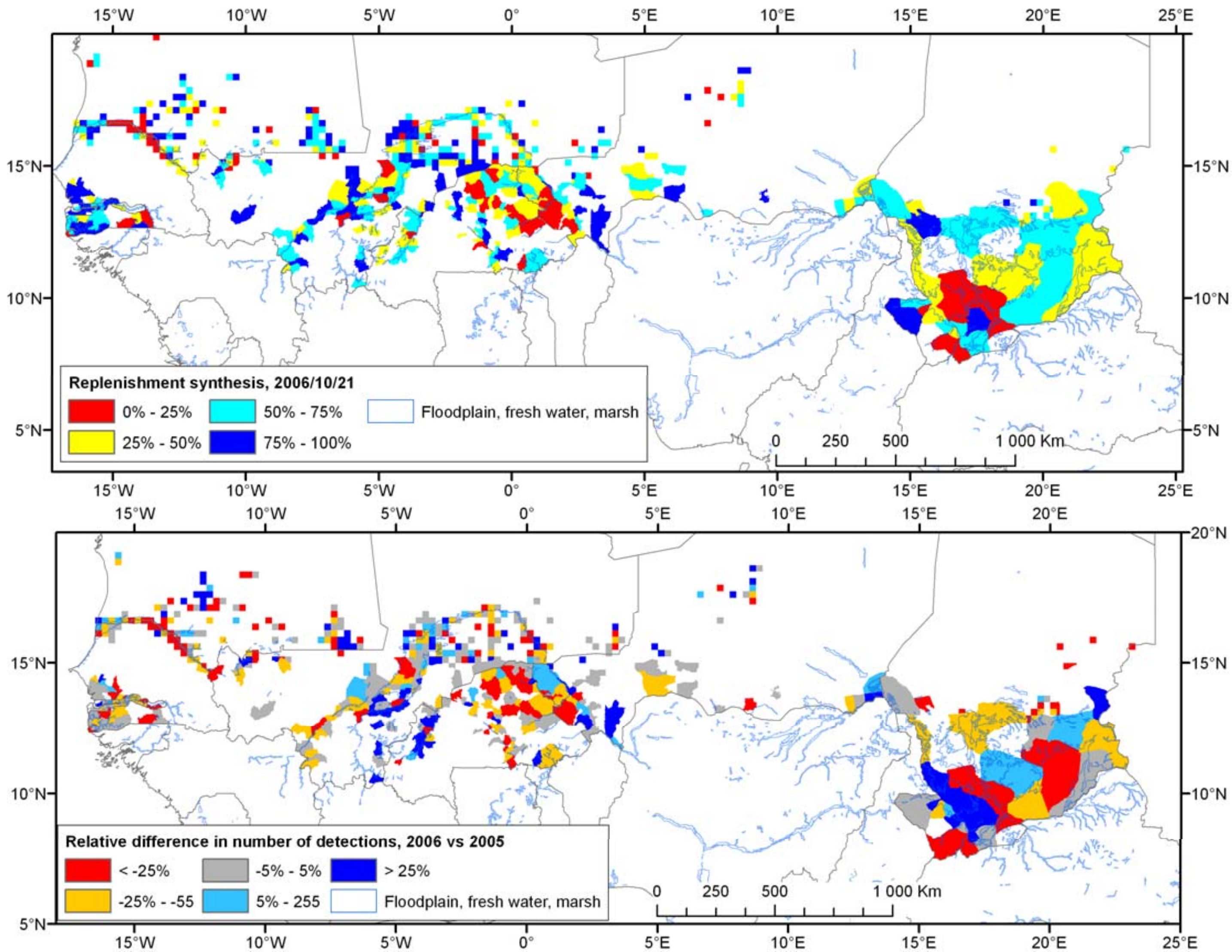

Figure 24. Synthesis of the replenishment of recurrent small water bodies, for season 2006

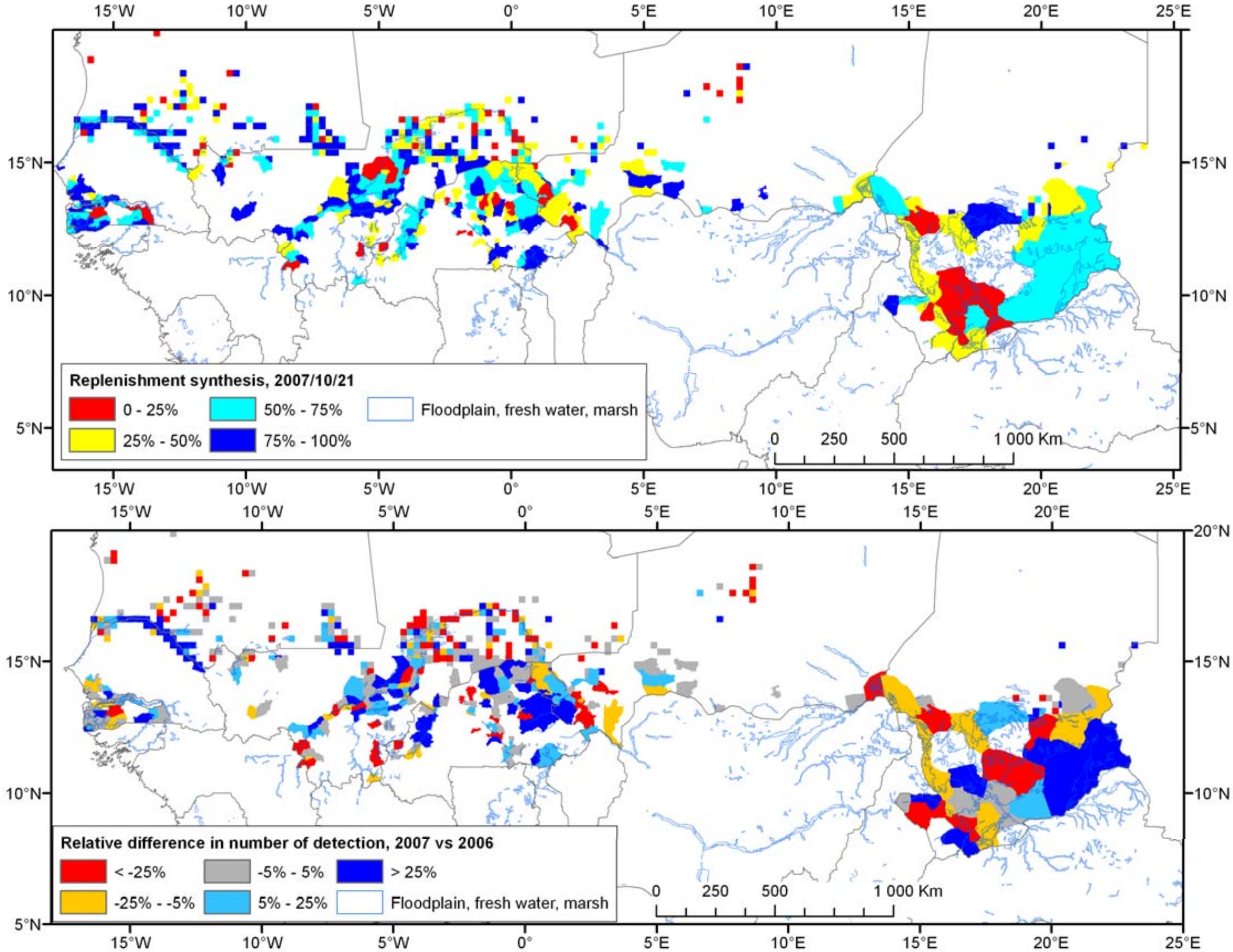

Figure 25. Synthesis of the replenishment of recurrent small water bodies, for season 2007

The 9 years of observation are summarized in Figure 26 and Figure 27 which show respectively the best and worse years in term of surface water availability, and the largest variation between the two extreme years.

In most administrative units, the best conditions were observed in 1999 and in some extend in 2007 and at a lesser degree 2003. It can be noticed that in the upper part of the Niger River the best year correspond mostly to 2001. The assessment of the driest year is more difficult to make, although 2000, 2002 and 2004 are often found as the driest years.

The maximal amplitude of variation is computed by comparing the largest amplitude to the maximal replenishment observable

$$\left(\max\left(\sum_{year}^{admin} SWB\right) - \min\left(\sum_{year}^{admin} SWB\right)\right) \Big/ \sum_{year}^{admin} SWB$$

In most administrative units, this amplitude can be larger than ¾ which means that in the 9 years ob observation a situation were ¾ of water bodies that were filled in the most humid season were found dry. The detection of the small water bodies is thus well related to the meteorological conditions.

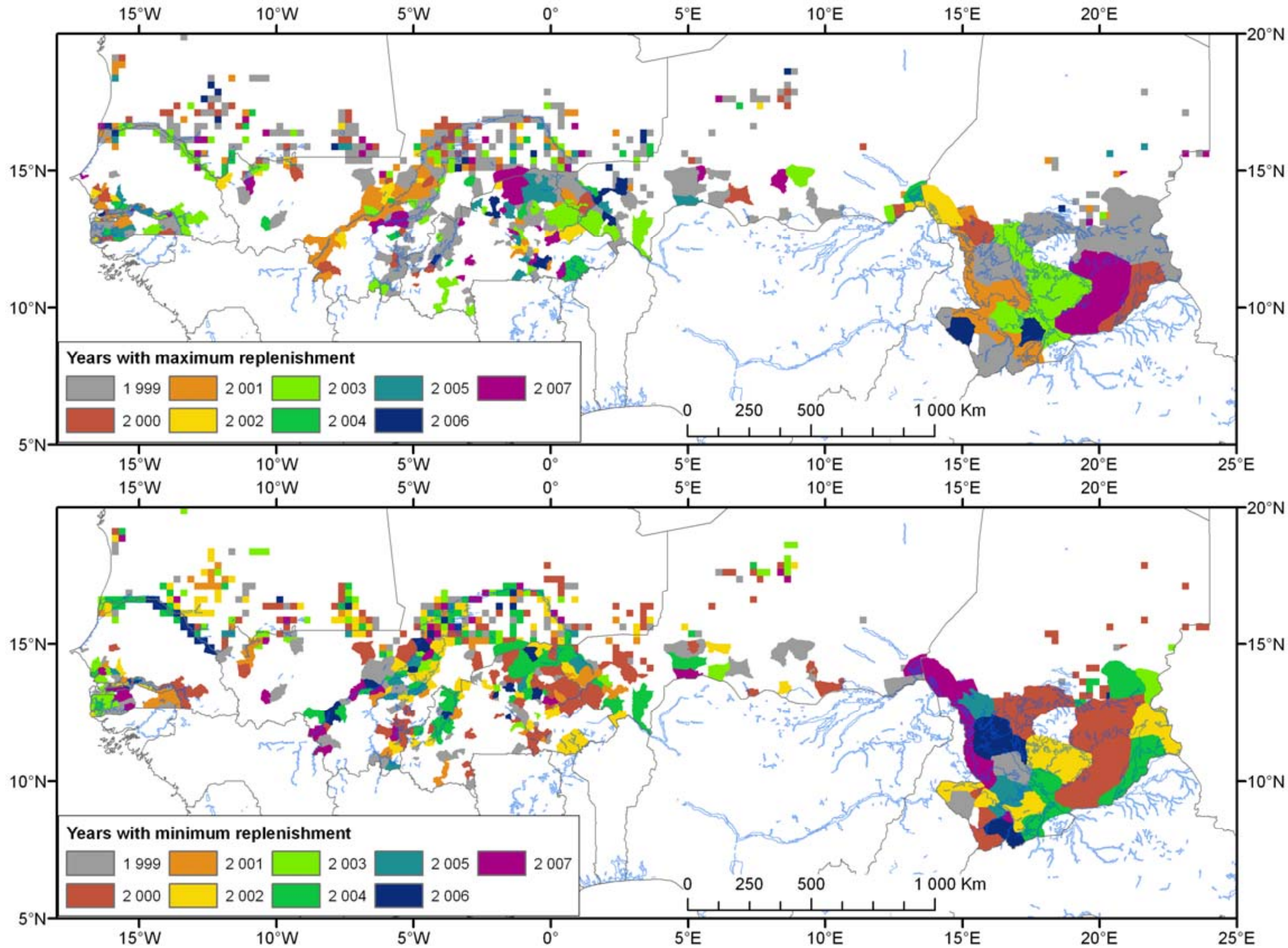

Figure 26. Best and worse years for small water bodies replenishment

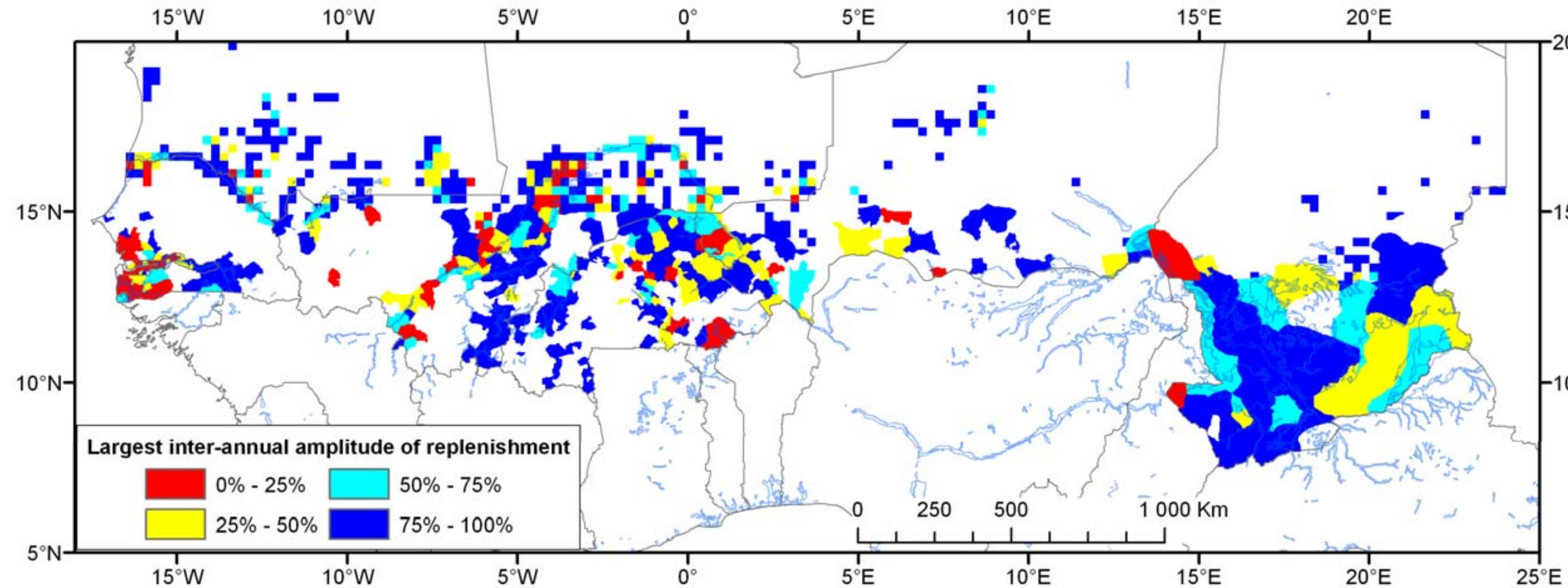

Figure 27. Largest inter-annual amplitude in term of percentage of the maximal replenishment.

5.2 Date and duration of availability of surface water

The detection of SWB is made every 10-day with the same geo-location for each pixel, allowing defining a time series of detection for each pixel, from which the date of re-plenishment and date of drainage can be assessed.

The date of start of replenishment (WBS, Water Body Start) and date of drainage (WBE, Water Body End) are estimated every 10-day (Bartholomé and Combal, 2006). At the end of the rainy season, WBS product show when each water body was found to replenish (Figure 28) in the season. The seasonality properties depend on each feature: the small water bodies replenish with the progression of the Inter-tropical convergence zone (ITCZ) to the north during the rainy season, from May to Aug. In the inner delta, most of water bodies are replenished by the river stream, water being brought around October or November.

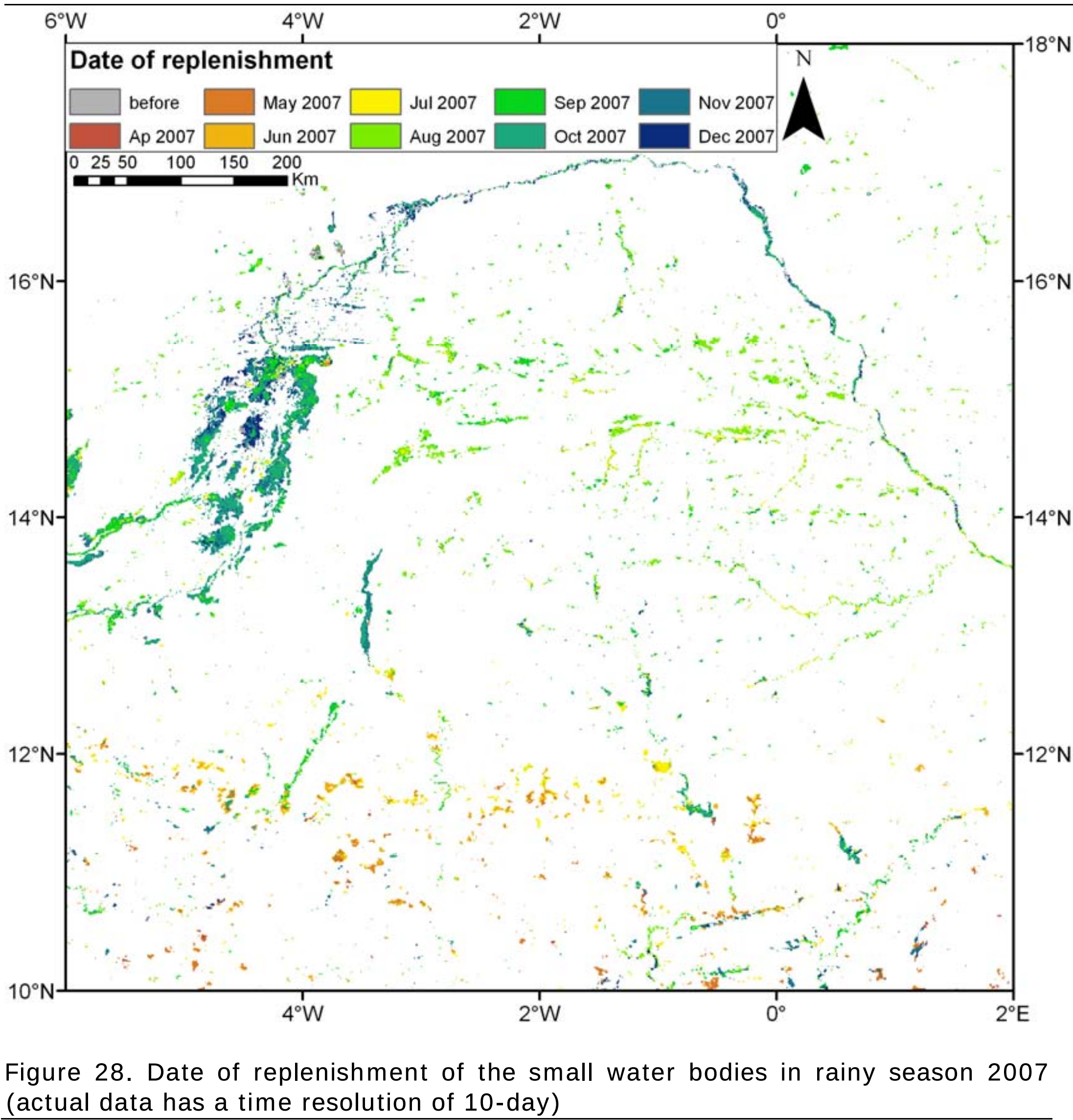

Figure 28. Date of replenishment of the small water bodies in rainy season 2007 (actual data has a time resolution of 10-day)

For environmental applications, one of the most critical information is the date and amount of replenishment during the rainy season, between April and late October.
For this purpose, the first occurrence of replenishment between those dates is assessed. This means that if a water body replenish, then dry and replenish again in the same season, the synthesis reports for the first date of replenishment. Such a situation can occur in the Southern regions where rainfall is abundant.

The first date of replenishment of water bodies in a season is assessed for each administrative unit. The synthesis of first date of replenishment in 1999 (Figure 30) shows consistent spatial pattern that are linked to local regime: the rain-fed water bodies are replenished with the first rain fall, while other structures will be filled later by the river stream.

Year 1999 is known to have exceptional rainfall. In some places there was no clear discontinuity with the preceding year, 1998, as depicted on Figure 29 for Mare d'Oursi (14°N, 0°29'60''E, North Burkina Faso). Water bodies that were already filled at the beginning of May 1999 are not considered, and the assessment of start can be delayed to the apparition of later water bodies.

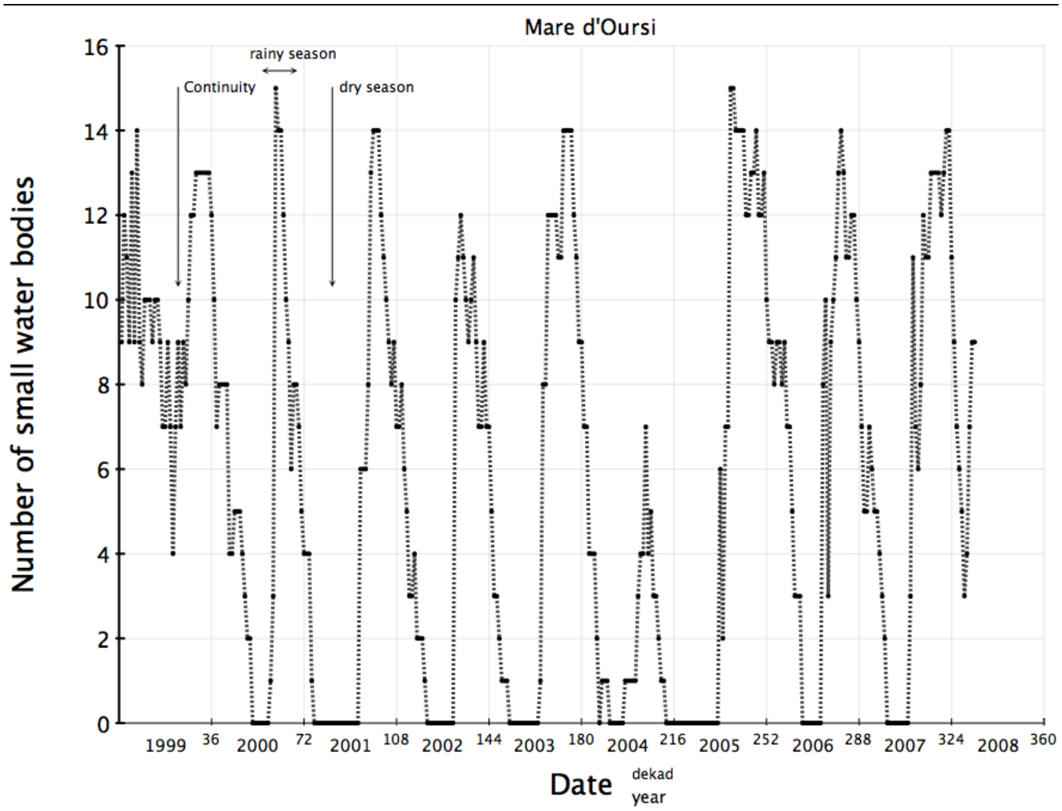

Figure 29. Count of small water bodies detection in Mare d'Oursi catchment.

The first date of start per administrative unit is computed for the following years (Figure 31 to Figure 38) with the difference to the former year.
The year 2002 shows more classical patterns of start of season: start around May or June in Burkina-Faso, start later in August in the upper part of the Niger River. In gen-

eral, south of Chad show the earliest replenishment. The river basin in Brakna and Assaba department in Mauritania fill the latest around October.
The first date of replenishment varies from one year to another. Year 2004 is well representative of the classical situation when the water bodies fill with the ITCZ progression to the north, first replenishment occurring in the southern regions, latest in the northern. Of course, the replenishment is not only contributed by the rainfall, since some can be filled later by water streams. In the Niger River Inner Delta most of the water bodies will be filled by the river itself, thus later than the start of the rainy season.
The difference in the first date of replenishment can be computed from one year to another, showing possible delay or advance. In general, the replenishment occurred mostly at the same date in 2000 than in 1999, some administrative units showing a sooner start (negative delay).

Year 2000 shows replenishment in advance compared to 1999 or at similar date.
In 2001, this date of replenishment occurs later than in 2000, except between 2.5°W and 0°W were the starts occurred a bit in advance.
In 2003 most of the start occurred before 2002.
In 2004 the situation is a bit more contrasted with some delays in Eastern Burkina Faso, while most of the other administrative units were found to have replenishments in advance.
The year 2006 shows that most units were provided with water later than in 2005.
Year 2007 shows adanced replenishment compared to 2006.

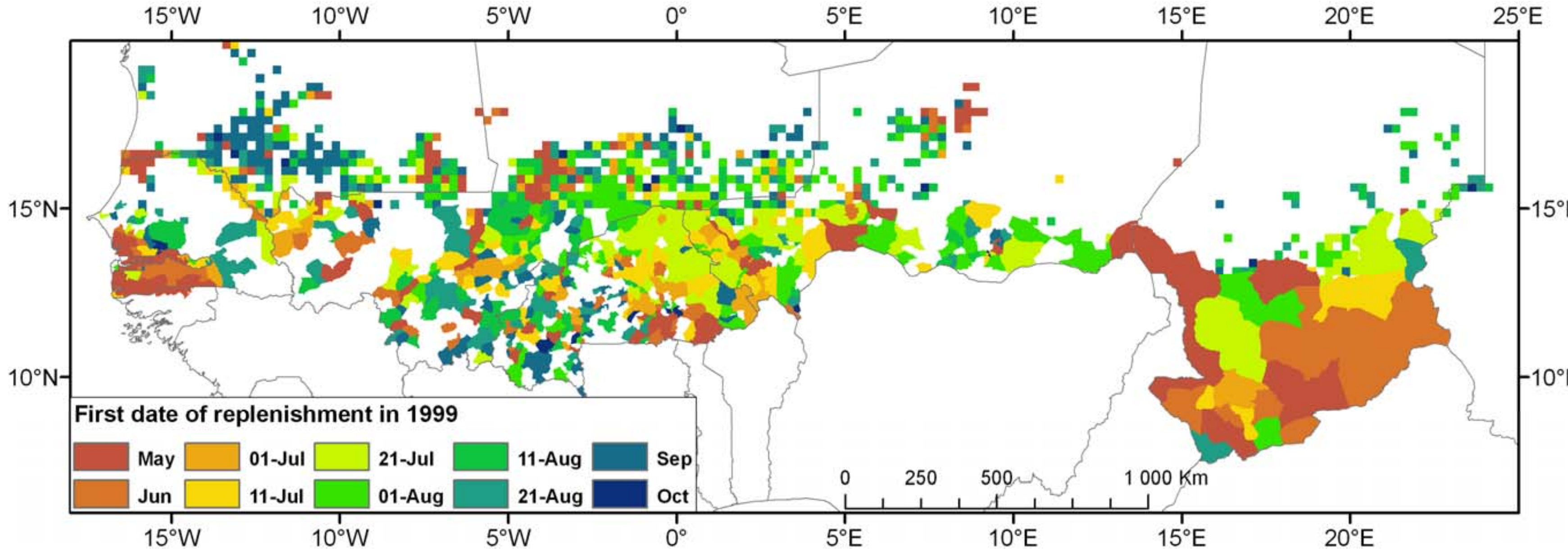

Figure 30. Date of replenishment in 1999

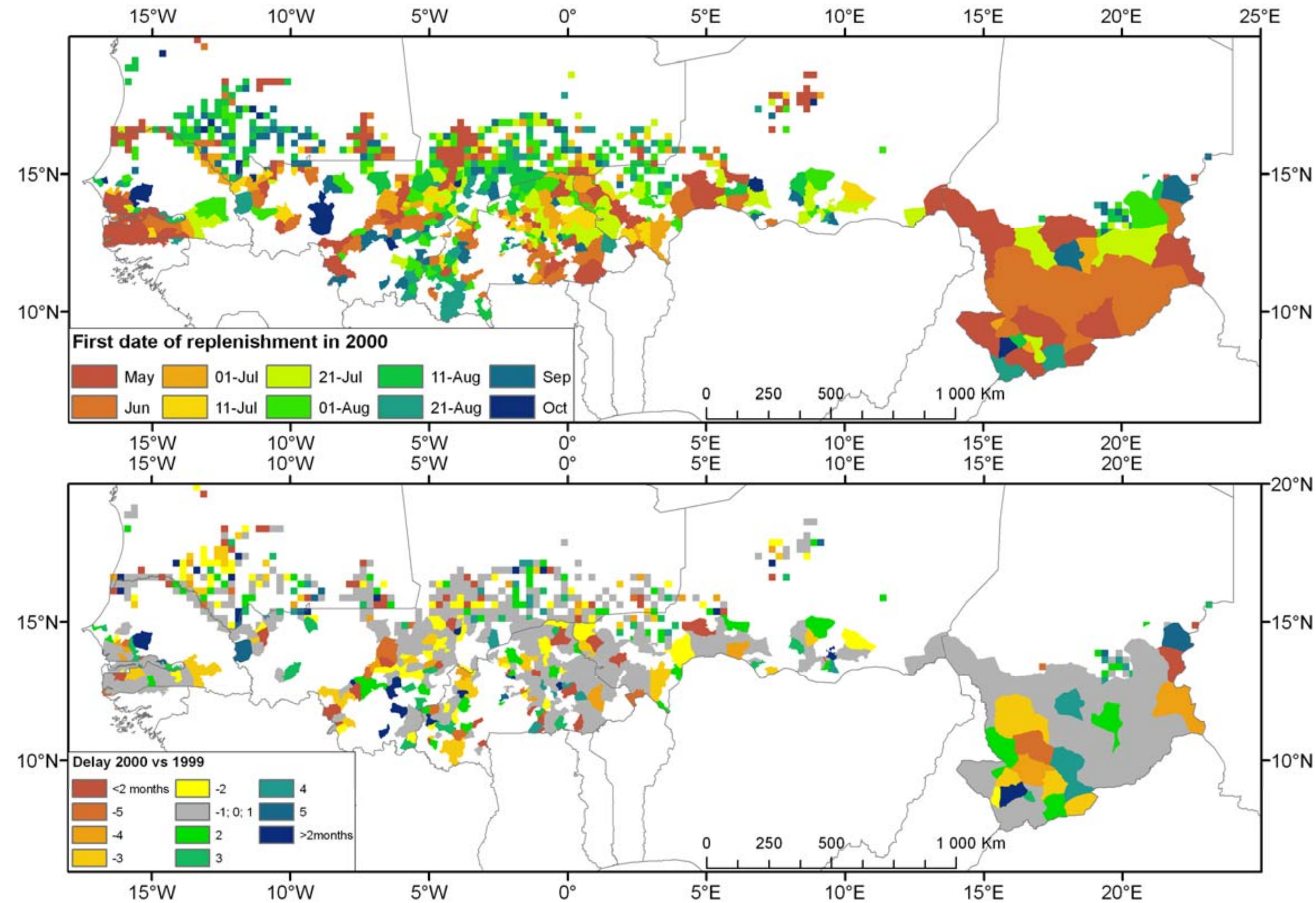

Figure 31. Date of replenishment in 2000 and delay compared to 1999

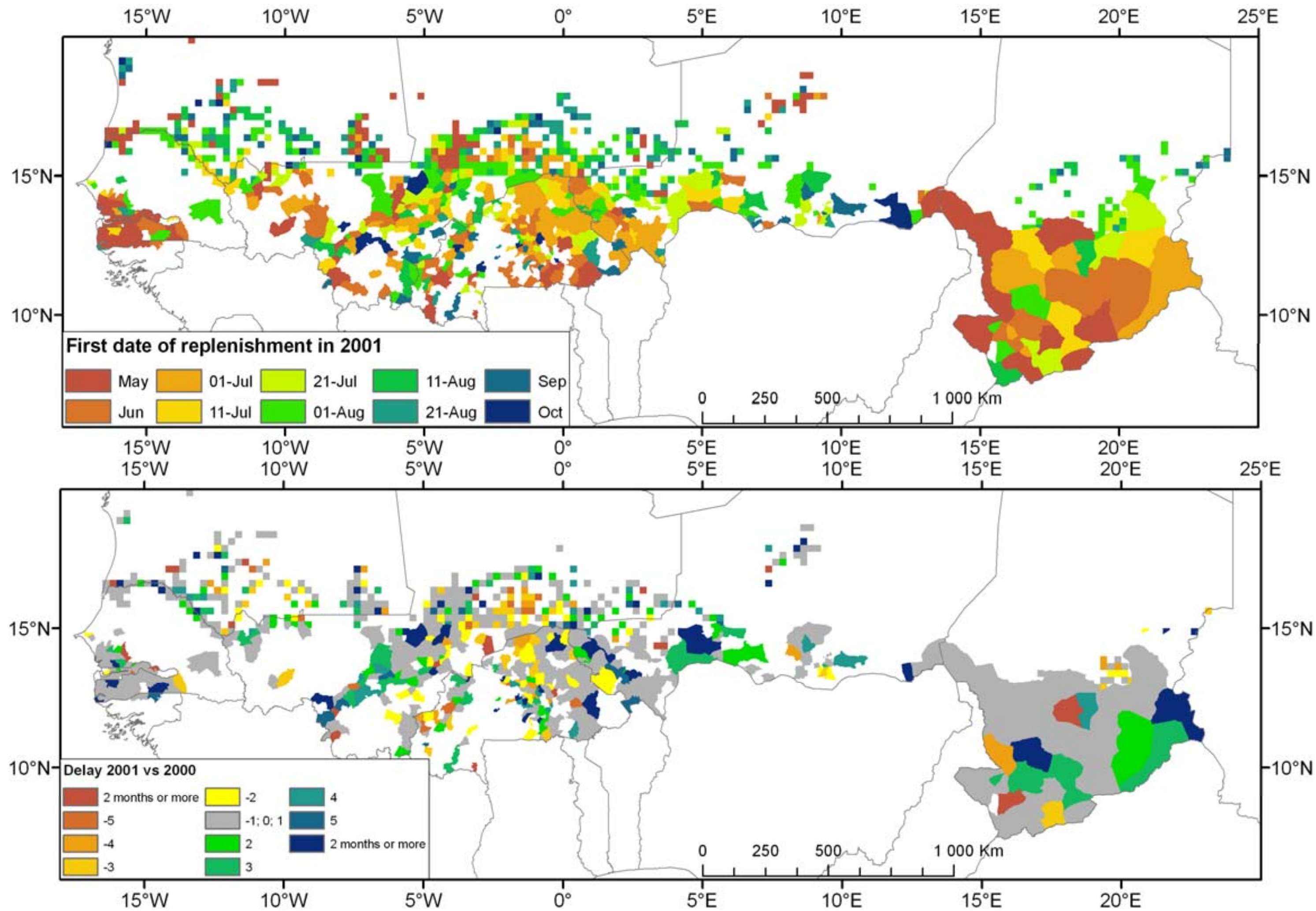

Figure 32. Date of replenishment in 2001 and delay compared to 2000

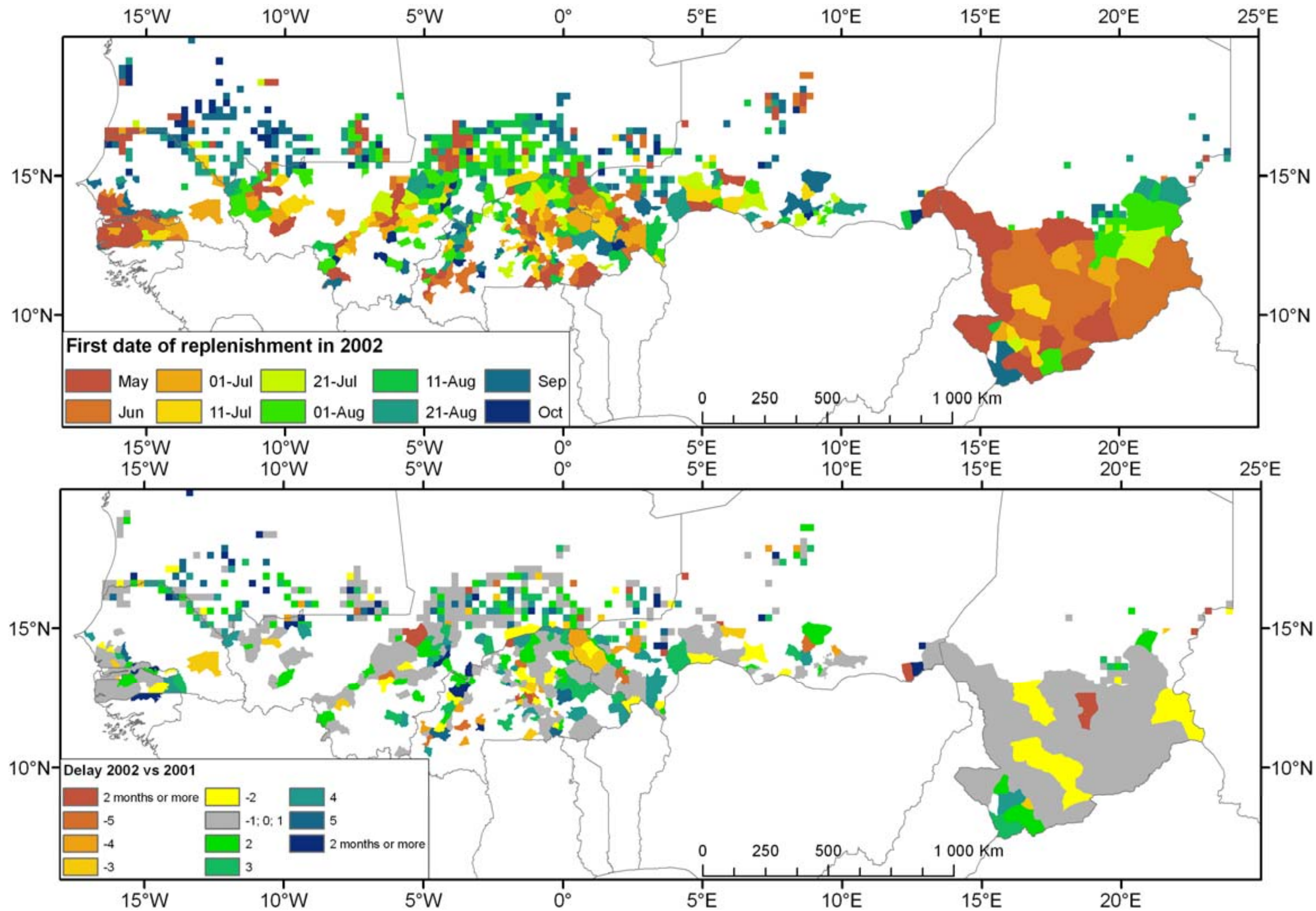

Figure 33. Date of replenishment in 2002 and delay compared to 2001

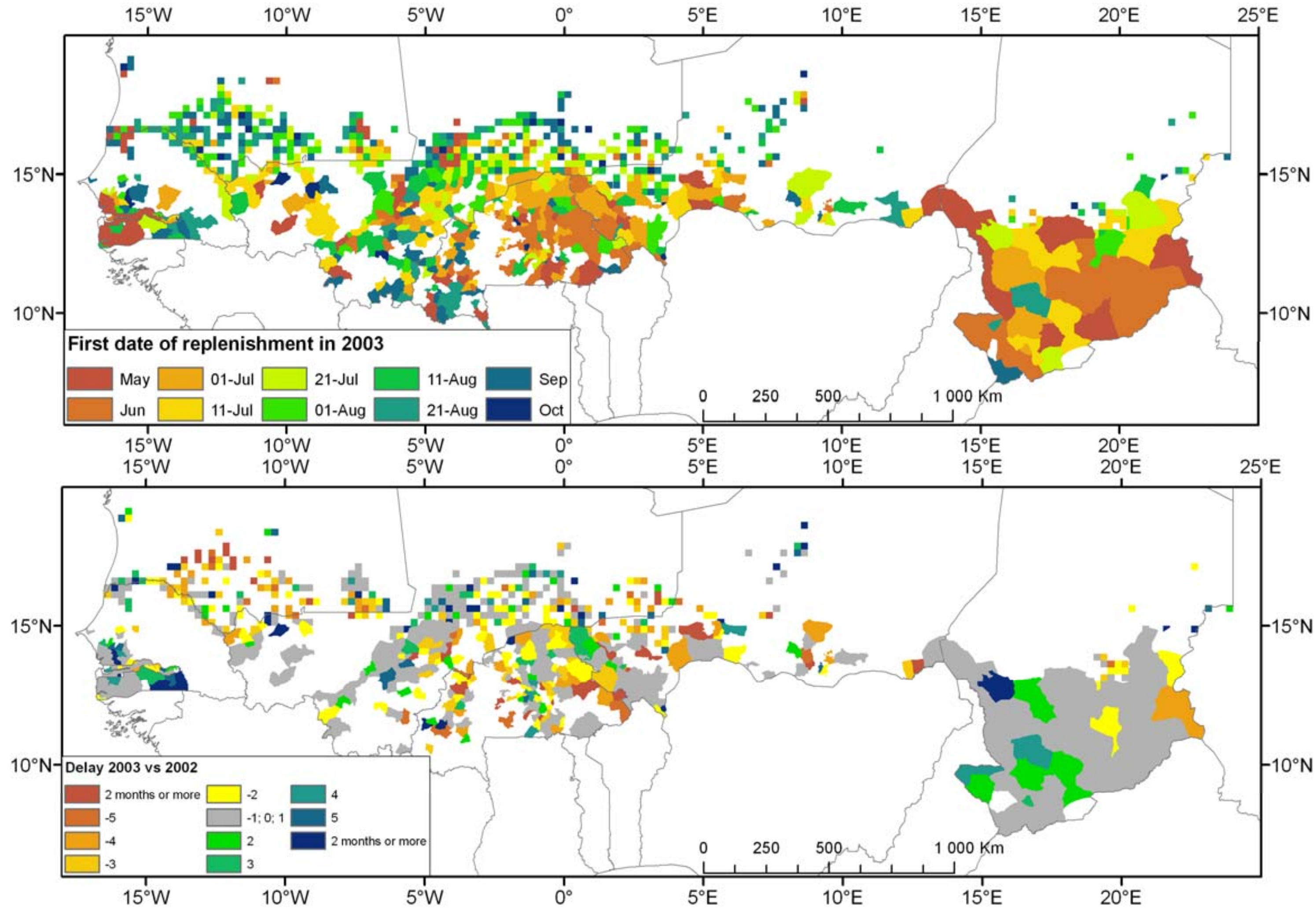

Figure 34. Date of replenishment in 2003 and delay compared to 2002

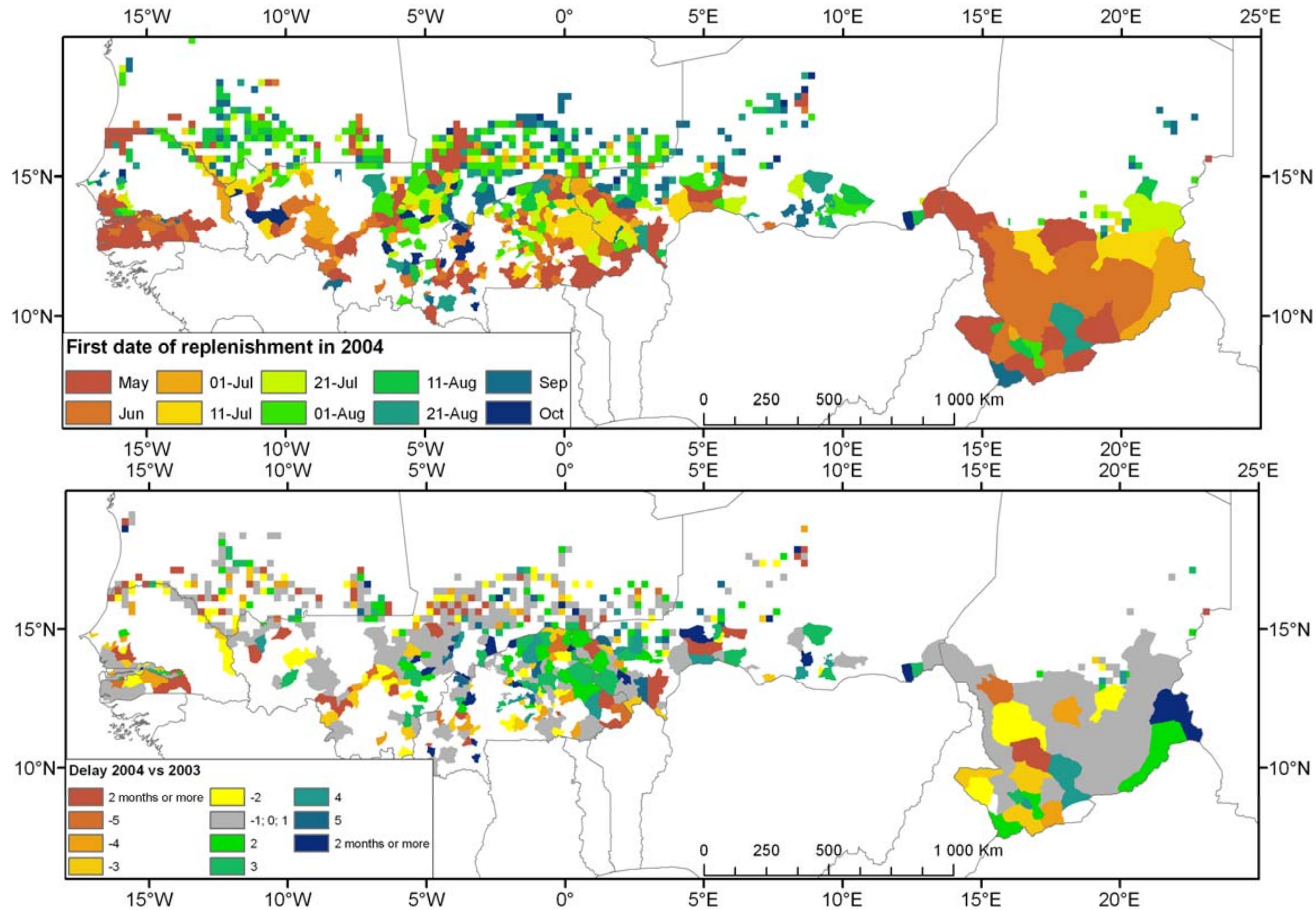

Figure 35. Date of replenishment in 2004 and delay compared to 2003

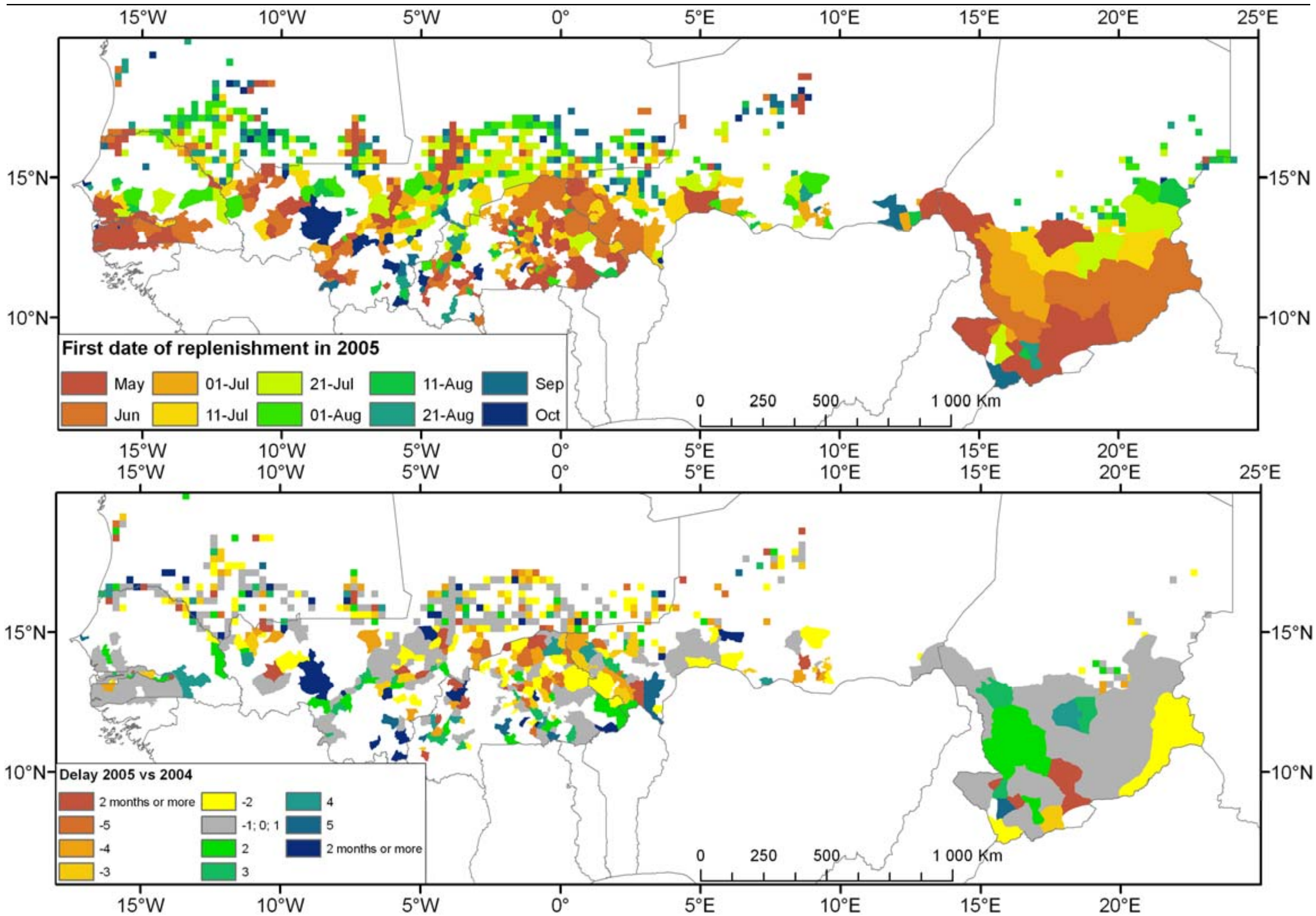

Figure 36. Date of replenishment in 2005 and delay compared to 2004.

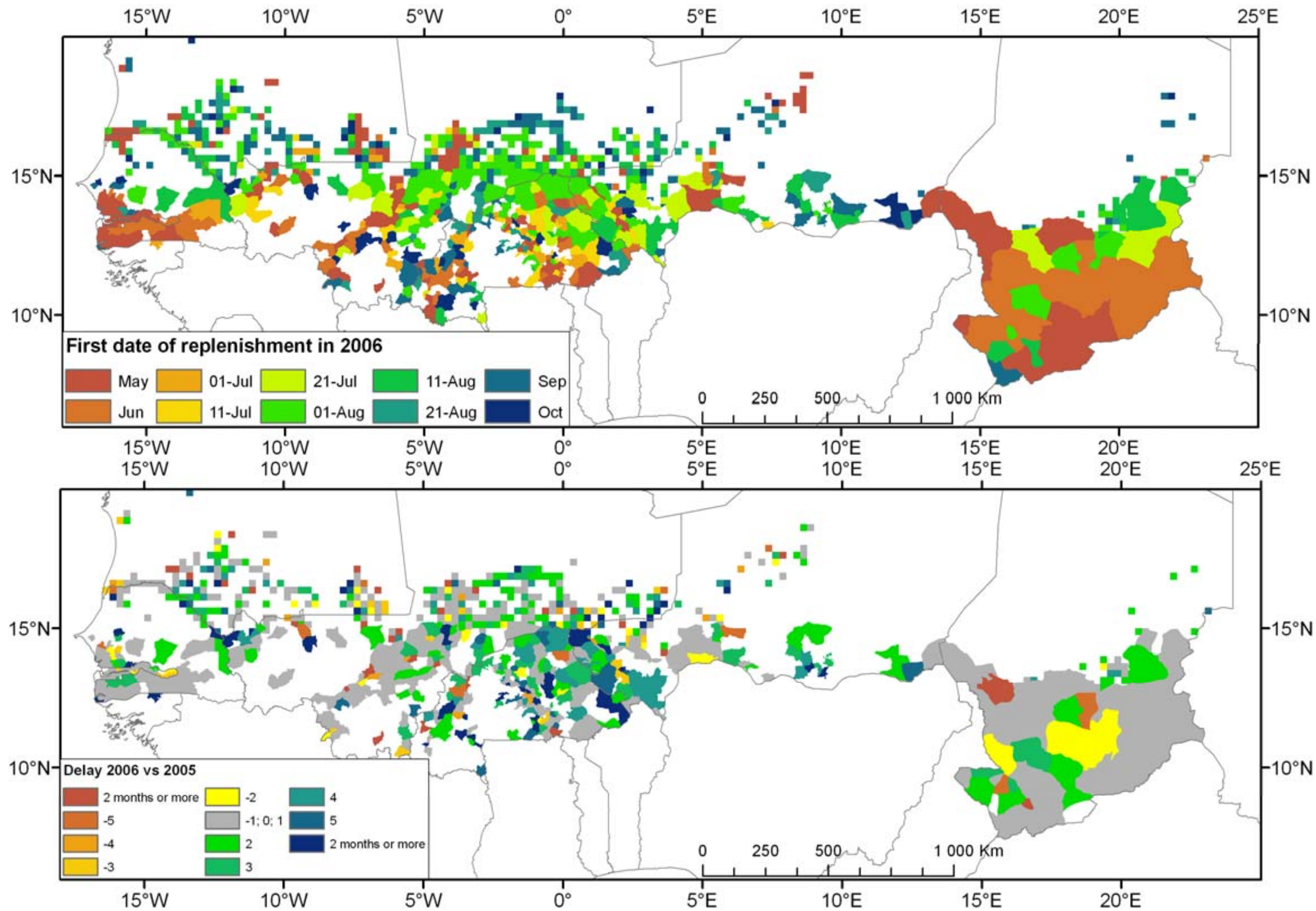

Figure 37. Date of replenishment in 2006 and delay compared to 2005.

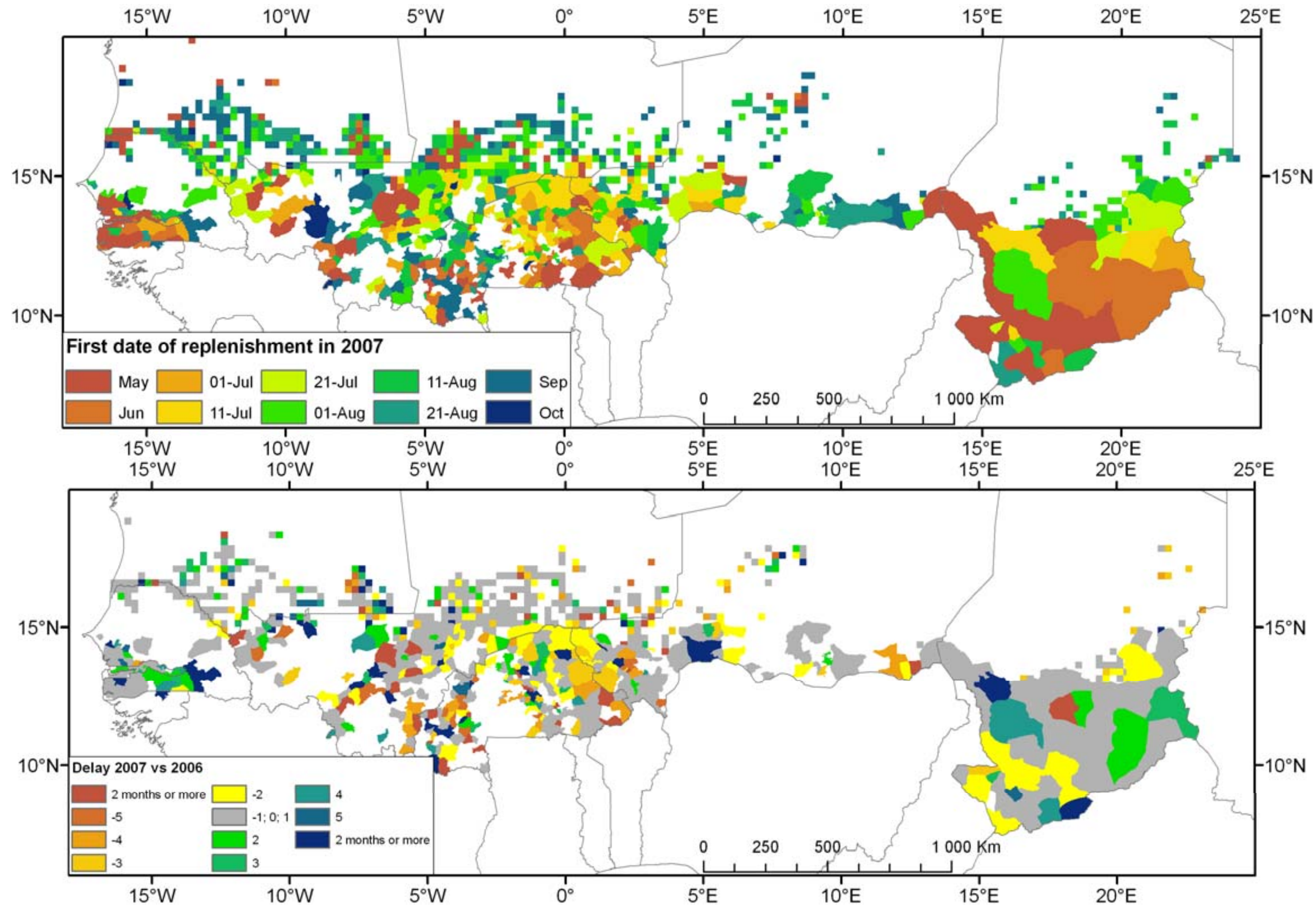

Figure 38. Date of replenishment in 2007 and delay compared to 2006

The average duration of surface water is computed as well as the difference of duration compared to the former year.

The year 1999 shows rather long duration (Figure 39): around 8 months in Eastern Burkina Faso, and up to 10 and 11 months in Niger River inner delta.

In general, the surface water lasted for shorter duration in 2000 (Figure 40) than in 1999 and in some places by more than 2 months. In Niger River inner delta, along the Senegal River or in South Chad, the water availability remained almost the same.

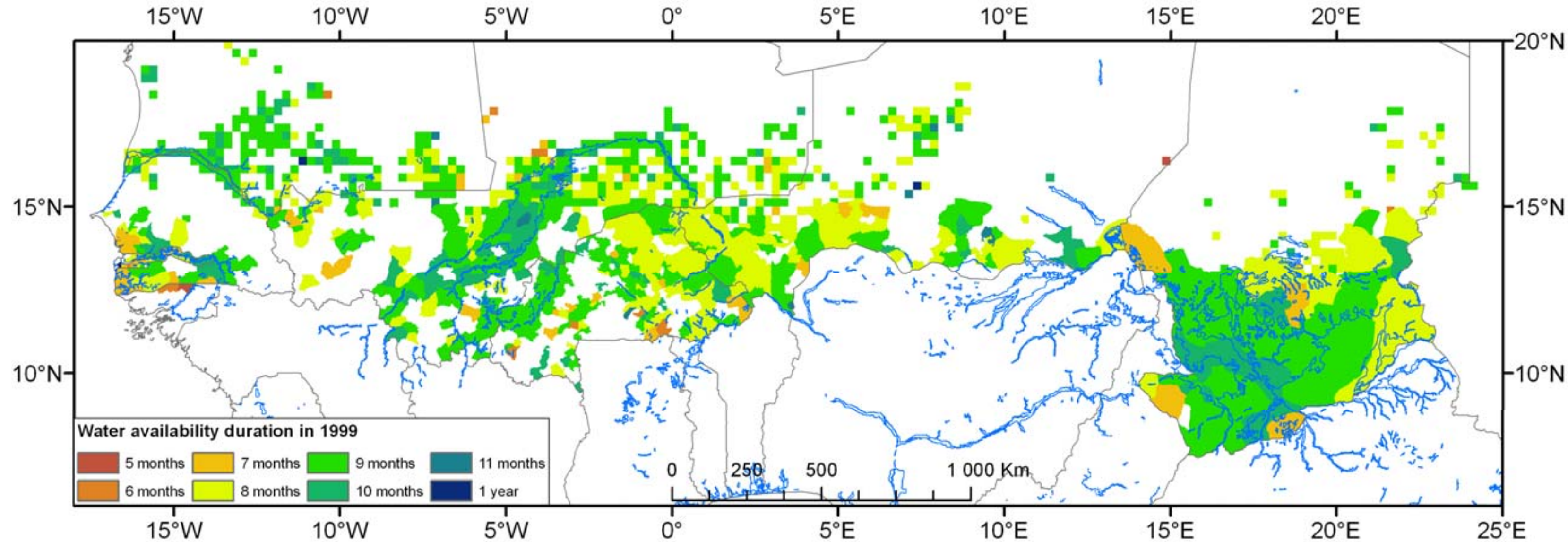

Figure 39. Averaged duration of the detected small water bodies in 1999

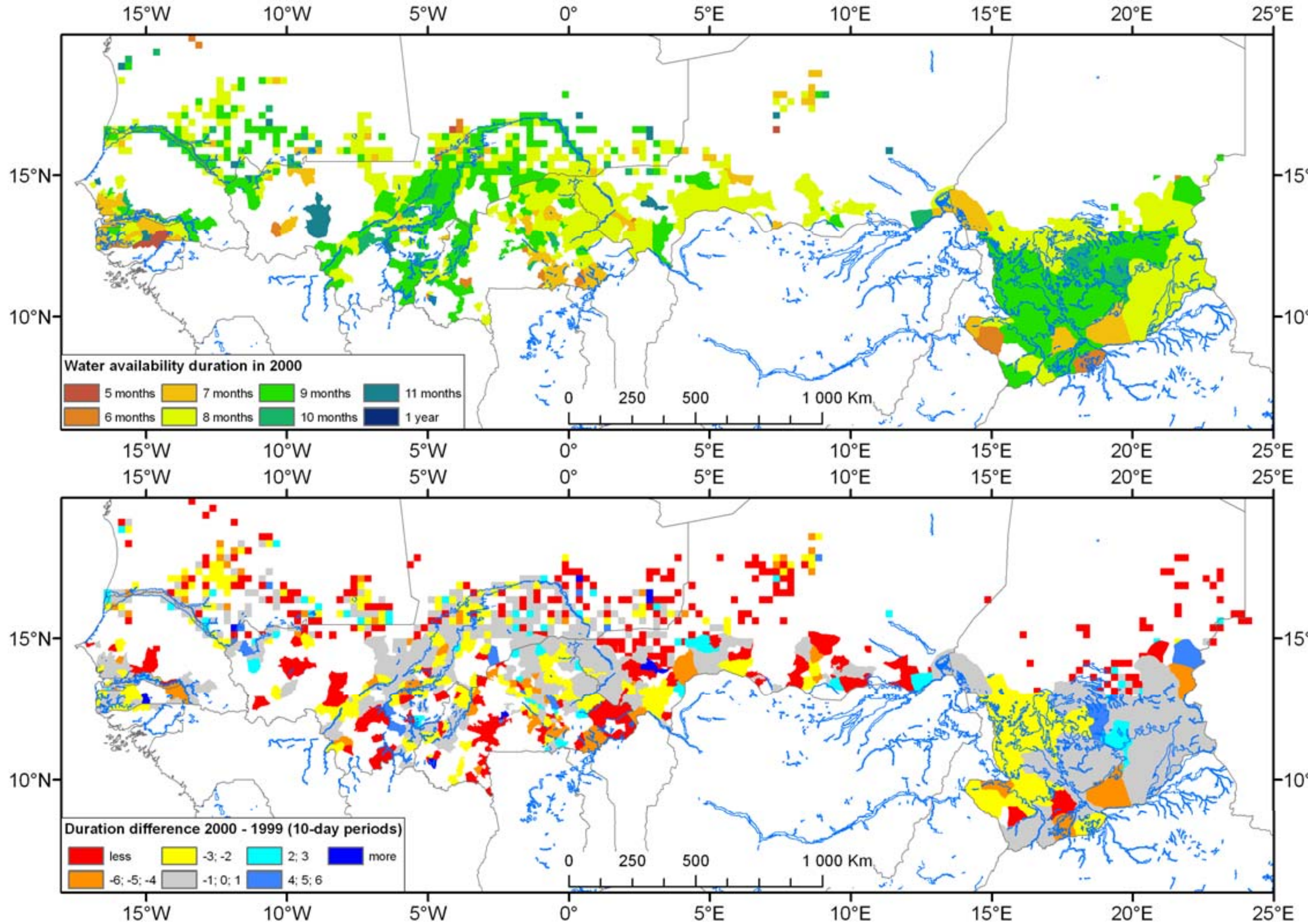

Figure 40. Averaged duration of the detected small water bodies in 2000 and difference to 1999

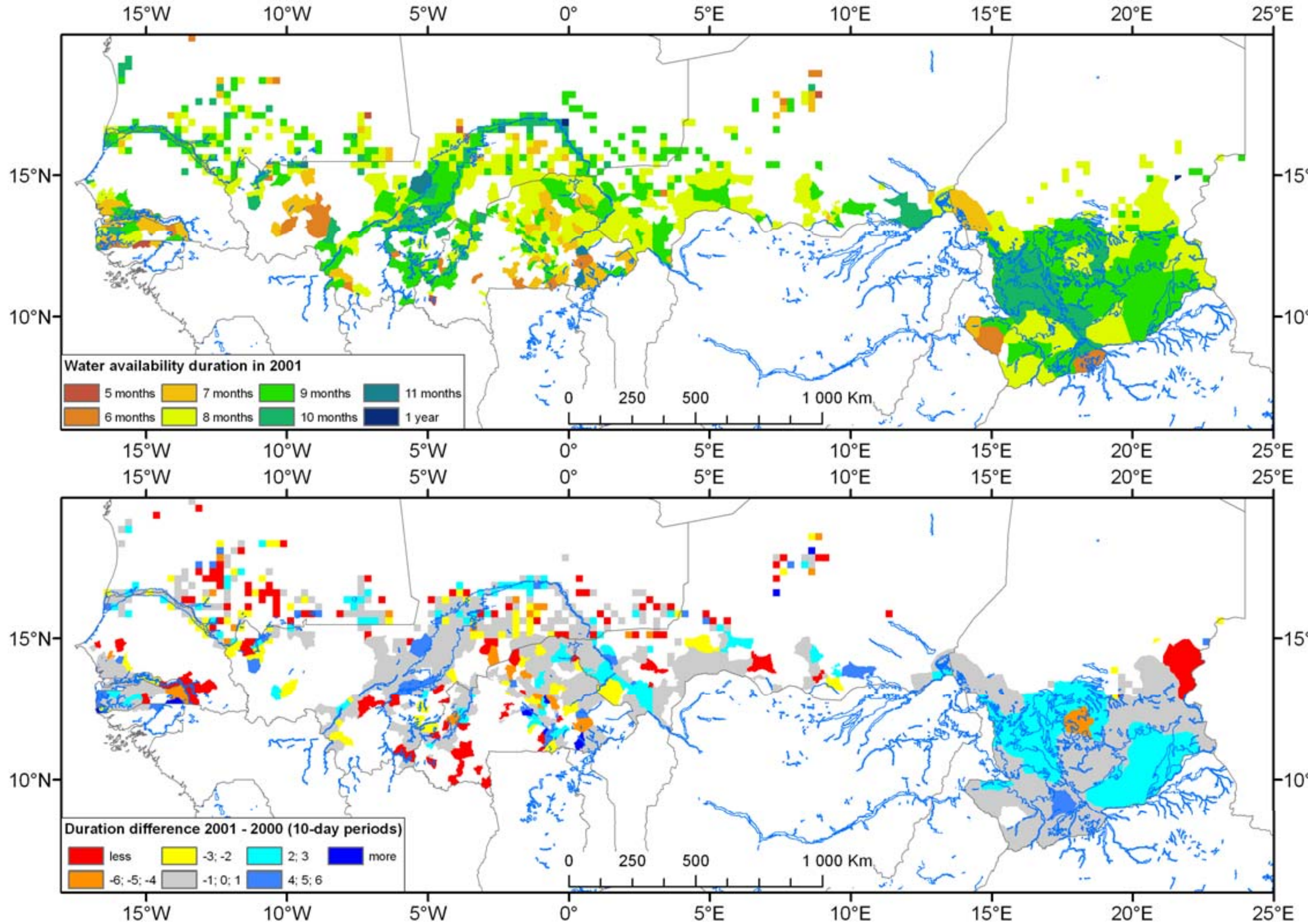

Figure 41. Averaged duration of the detected small water bodies in 2001 and difference to 2000

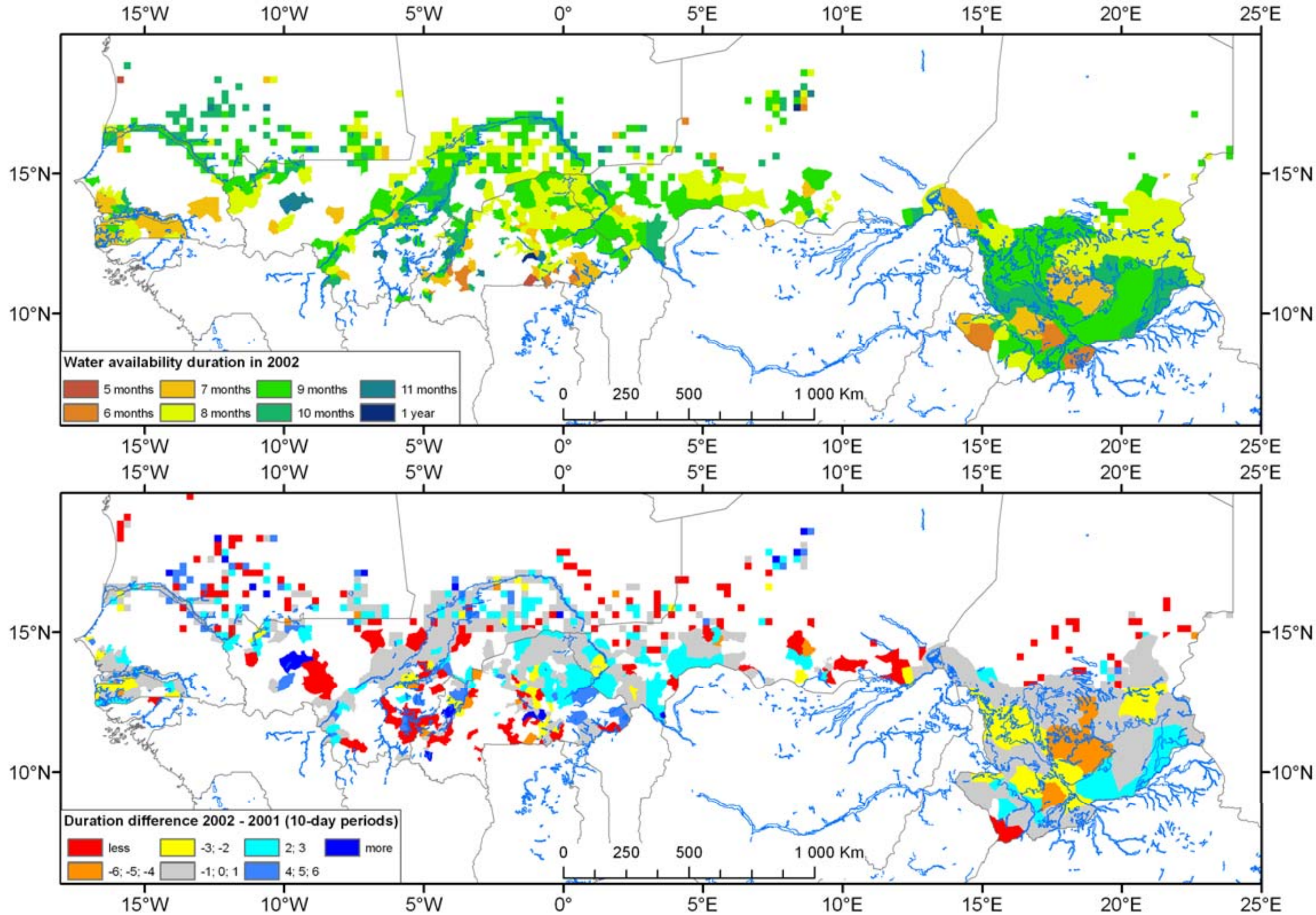

Figure 42. Averaged duration of the detected small water bodies in 2002 and difference to 2001

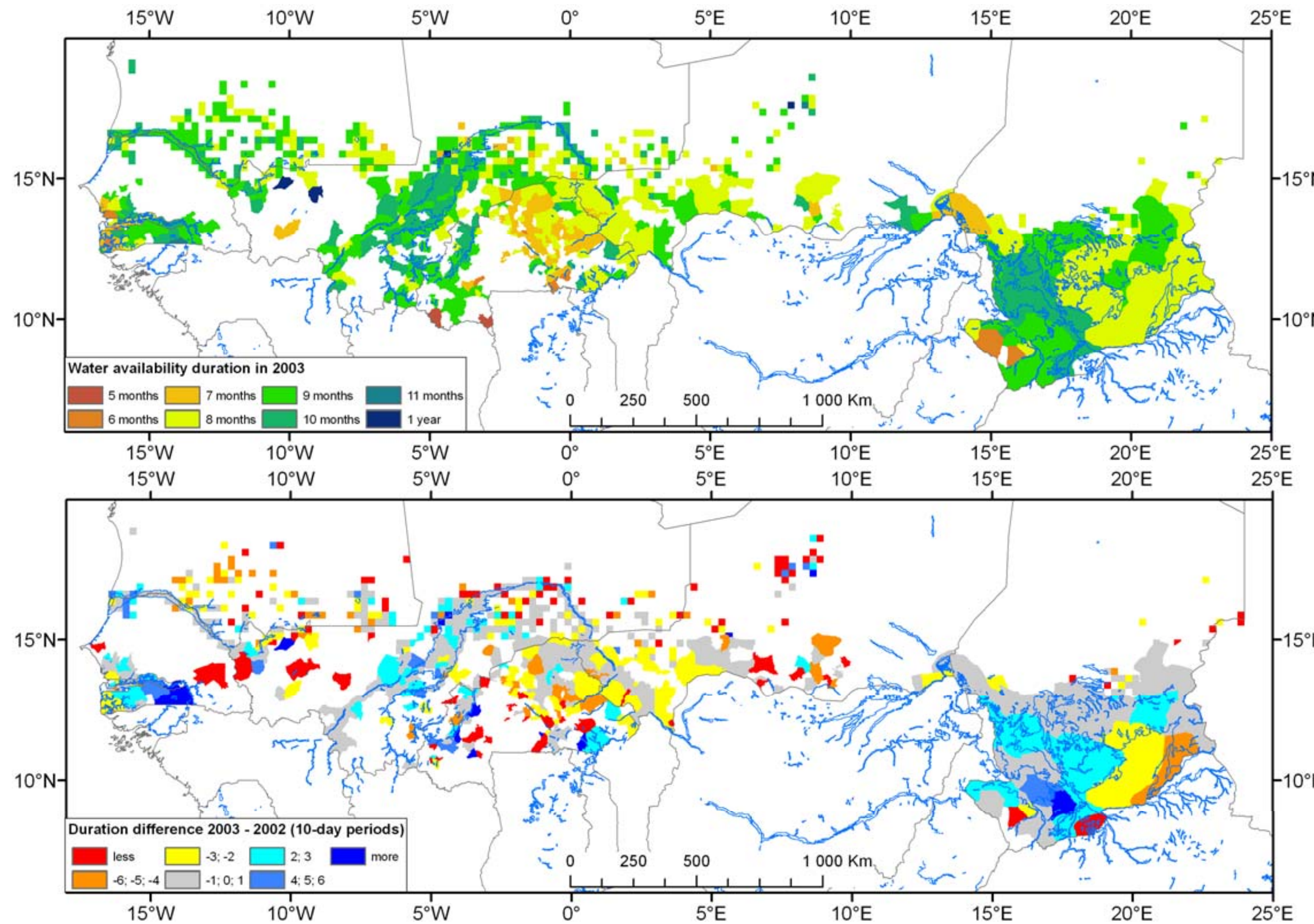

Figure 43. Averaged duration of the detected small water bodies in 2003 and difference to 2002

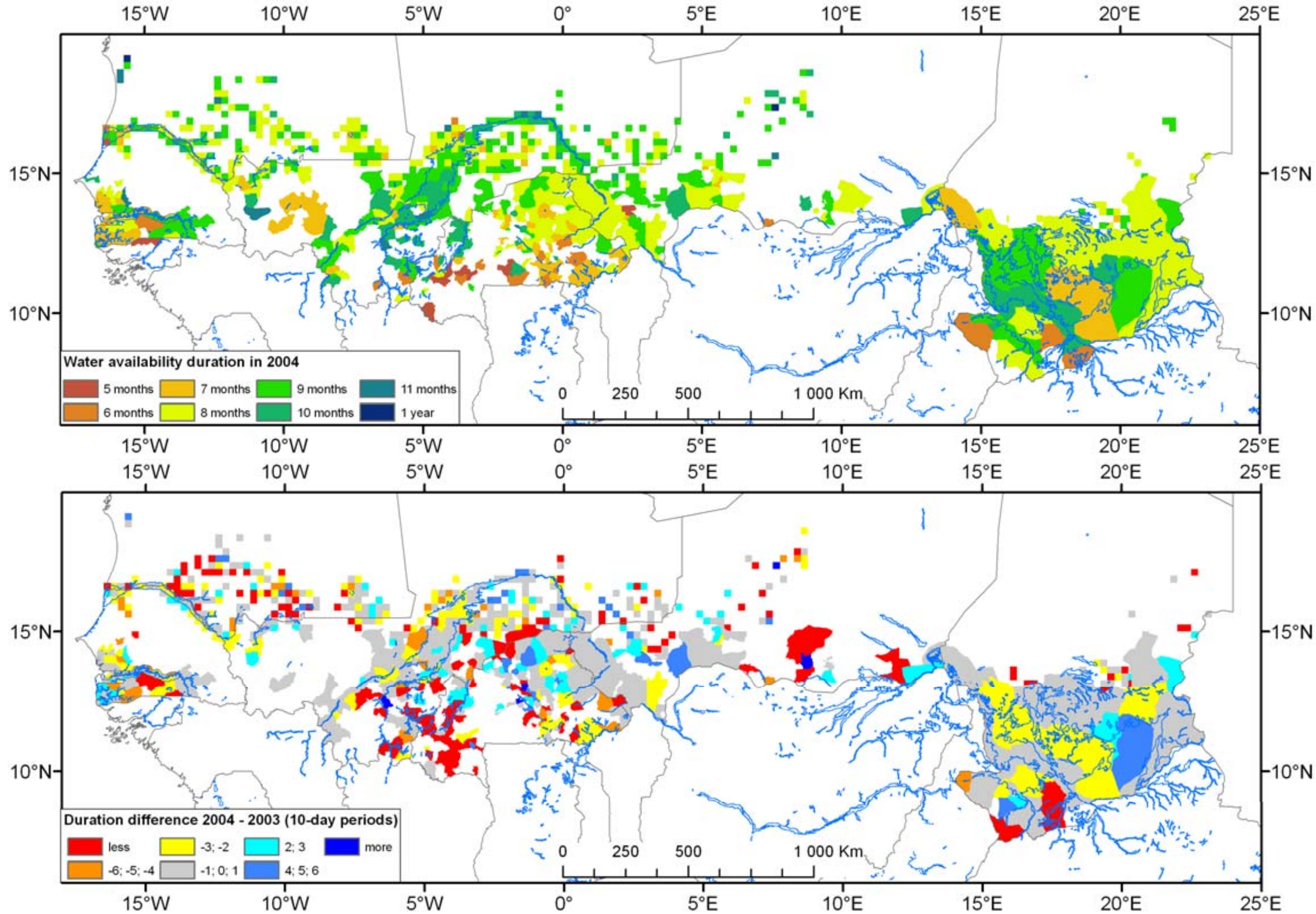

Figure 44. Averaged duration of the detected small water bodies in 2004 and difference to 2003

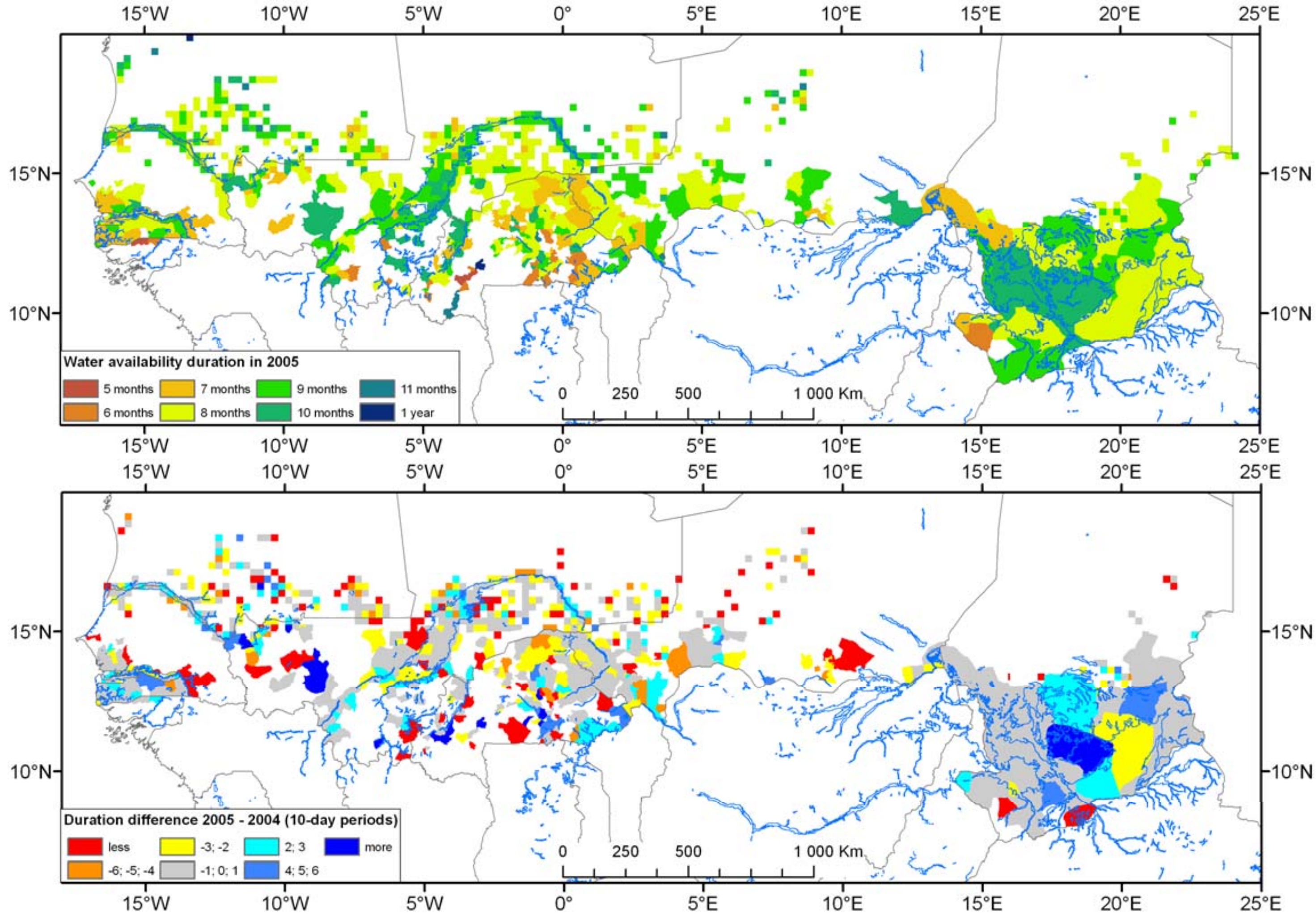

Figure 45. Averaged duration of the detected small water bodies in 2005

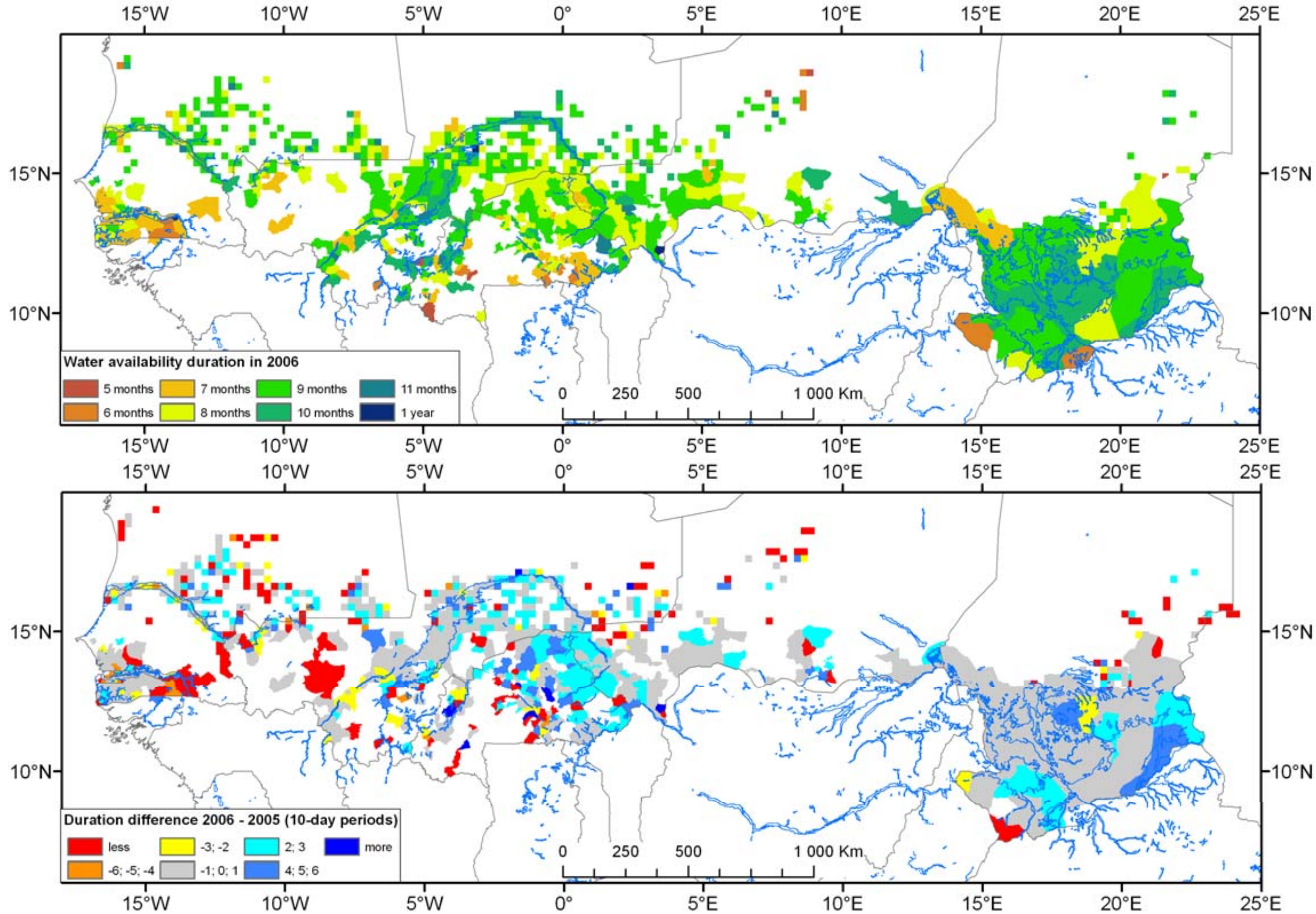

Figure 46. Averaged duration of the detected small water bodies in 2006

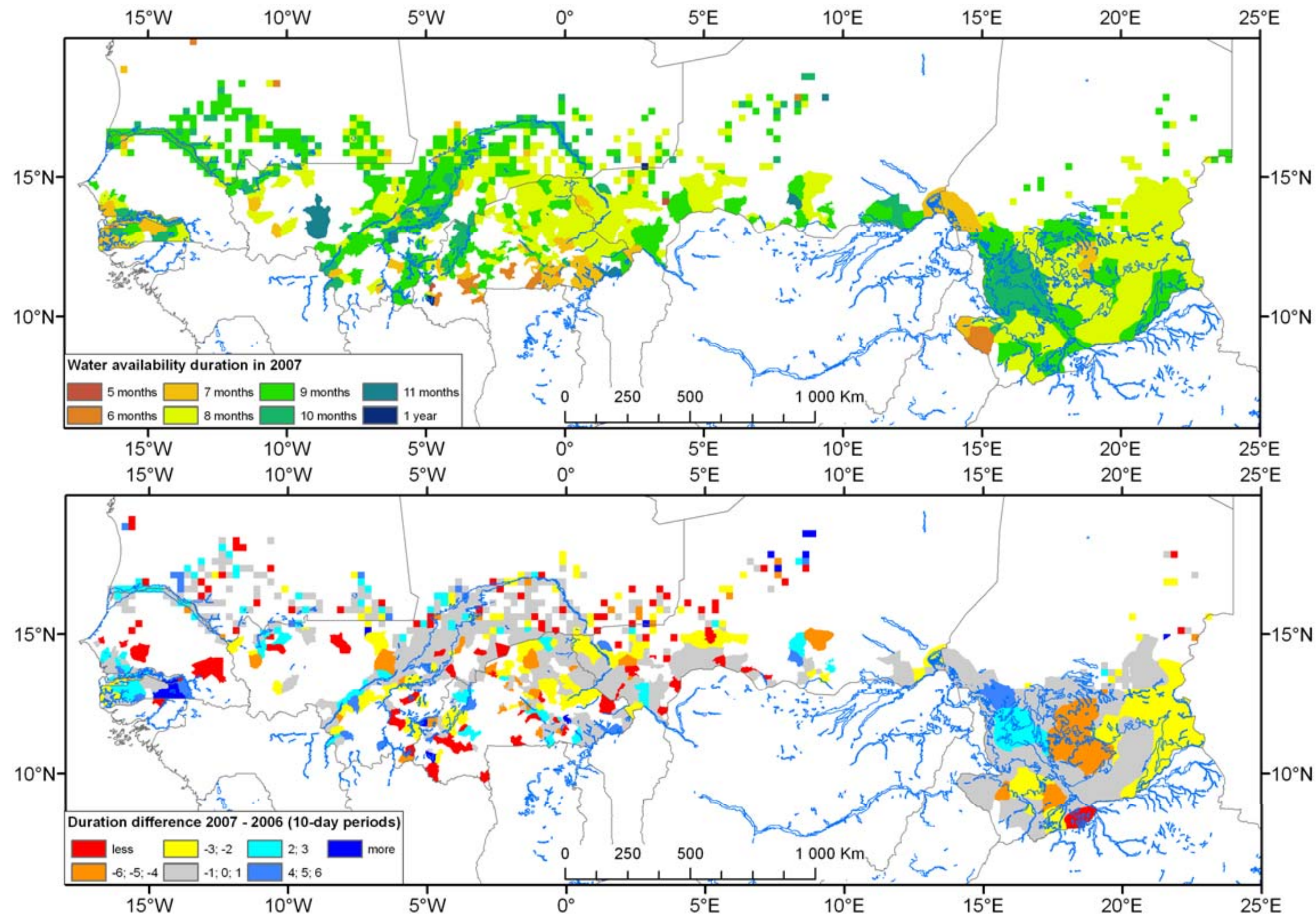

Figure 47. Averaged duration of the detected small water bodies in 2007

6 Conclusions

The surface water detection product generated by the VGT4Africa project and broadcasted by the EumetCAST system allows monitoring the characteristics of rainy seasons in Western Africa.

In this document, some characteristics of the rainy season in CILSS countries administrative units are shown for years from 1999 to 2007. Each pixel has a time series of detection of small water bodies, allowing deriving some general properties such as a class of highly probable correct detections or its probability of occurrence in a rainy season. A series of indicators was generated for characterizing the administrative units in term of water availability. The monitoring indicators shown in this document are the amount of replenishment, the date of start and the duration. Each value is compared to the preceding year.

The overall system is now in implementation in an automated monitoring system, developed by the MONDE action (EC/JRC/IES). The objective of such a system will be to provide the basis for writing a regular time step bulletin reporting on environmental conditions.

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Abstract
The detection of surface water with Spot/VEGETATION, at 1km resolution, is done every 10-days. The quality of the detection in arid and semi-arid regions in western Africa, and the regular time step of the observations, allow monitoring the surface water availability. The seasonal surface water can be mapped and its date of availability is known. From this information, some indicators were generated for assessing the relative amount of replenishment and delays in availability between two years.
The overall information, detections and dates assessments based on Spot/VEGETATION is broadcasted every 10-days to African users thanks to the EumetCAST system. The processing of the water availability indicators, such as those demonstrated in this document, can thus be implemented at the user level.

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