Hydrology and Earth System Sciences Discussions

Monitoring temporary ponds dynamics in arid areas with remote sensing and spatial modelling

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Abstract

A hydrologic pond model was developed that simulates daily spatial and temporal variations (area, volume and height) of temporary ponds around Barkedji, a village located in the Ferlo Region in Senegal. The model was tested with rainfall input data from a meteorological station and from Tropical Rainfall Measuring Mission (TRMM) satellites. During calibration phase, we used climatic, hydrologic and topographic field data of Barkedji pond collected daily during the 2002 rainy season. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Digital Elevation Model (DEM) and a QuickBird satellite image acquired in August 2005 (2.5 m pixel size) were used to apply the hydrologic model to all ponds (98 ponds) of the study area. With input rainfall data from the meteorological station, simulated water heights values for years 2001 and 2002 were significantly correlated with observed water heights for Furdu, Mous 2 and Mous 3 ponds, respectively with 0.81, 0.67 and 0.88 Nash coefficients. With rainfall data from TRMM satellite as model input, correlations were lower, particularly for year 2001. For year 2002, the results were acceptable with 0.61, 0.65 and 0.57 Nash coefficients for Barkedji, Furdu and Mous 3 ponds, respectively. To assess the accuracy of our model for simulating water areas, we used a pond map derived from Quickbird imagery (August 2007). The validation showed that modelled water areas were significantly correlated with observed pond surfaces (r^2=0.90). Overall, our results demonstrate the possibility of using a simple hydrologic model with remote sensing data (Quickbird, ASTER DEM, TRMM) to assess pond water heights and water areas of a homogeneous arid area.

1 Introduction

Ponds and lakes are essential for life in the semi-arid Sahel region of Africa. Besides hosting a considerable biodiversity, these water bodies can be filled during the rainy season, and often remain the primary water supply for human and animal consump-

tion (Diop et al., 2004, 1968). While being crucial for increasing aquifer recharge, these fragile aquatic ecosystems are subject to various natural (recurrent drought) or anthropogenic (overexploitation, dams, pollution, drainage) threats. Another major concern is that in such ecosystems, water bodies are at the same time favorable breeding sites
5 for mosquitoes (Linthicum et al., 1985) and focal points where humans and livestock accede to water (Diop et al., 2004). Water bodies in these regions therefore need to be closely monitored. However, it is considered particularly challenging to inventory and survey water bodies located in these arid areas, as it is difficult to obtain good quality data records of temporary and episodic floods in time and space (Lange et al., 1999).
10 Numerous studies for monitoring water bodies have been conducted on large water areas using remote sensing, particularly in flood monitoring (Barton and Bathols, 1989; Montanari et al., 2009; Sandholt et al., 2003) or water storage in large lakes (Dingzhi et al., 2005). In arid areas, the potential of time series from coarse-scale satellites images like AVHRR (Verdin, 1996), SPOT-Vegetation (Haas et al., 2006) or MODIS
15 (Moderate Resolution Imaging Spectroradiometer) (Soti et al., 2009) to survey large ponds and lakes at a broad scale with regularity was demonstrated. Nevertheless, the spatial resolution of those sensors is inappropriate for identifying water bodies with a surface area less than $170\,000\,\text{m}^2$ (Soti et al., 2009), which is the case for most of the ponds in the Sahel region.
20 Recently, it was shown that the new generation of high and very high spatial resolution remote sensing data (SPOT5 and Quickbird images) was suitable for the detailed mapping of temporary ponds at a local scale (Lacaux et al., 2007; Soti et al., 2009). Thus, an efficient and simple method to study the spatial dynamics of temporary ponds would consist in mapping the ponds from satellite images acquired at different dates,
25 and to survey their distribution and dynamics through the year (Lacaux et al., 2007; Tourre et al., 2008). However, with this method the temporal information obtained may be limited by the number of satellite images available, which can be constrained by cloud cover or others factors. For example, the follow-up of small ponds derived from SPOT-5 imagery was only possible with five images/year in 2003 (Lacaux et al., 2007).

Thus, a daily follow-up is not possible by this approach.

In order to access additional temporal information on pond dynamics, hydrologic models have been developed at the pond scale. The objectives of these studies (Desconnets, 1994; Desconnets et al., 1997; Martin-Rosales and Leduc, 2003) were to better understand the physical mechanisms involved in the pond dynamics (filling and emptying phases, infiltration, evaporation....) and to accurately simulate daily water level variations. These studies mainly uses meteorological data (rainfall) and also soil properties to evaluate water losses (Porphyre et al., 2005). Volume-Depth-Area hydrologic mathematical relations are used to simultaneously estimate depth, area and volume of the water body (Bengtsson and Malm, 1997; FAO, 1996; Gates and Diessendorf, 1977; Hayashi and Van der Kamp, 2000; O'Connor, 1989). Nevertheless, few hydrologic pond models take into account the topographic parameters likely to play a role in the filling and emptying phases (shape of the pond, drainage area). The difficulty to generalize the physical mechanisms observed at a pond scale over a large area could partly explain the lack of studies integrating the spatial dimension. However, Puech (1994) and Puech et al. (1998) showed that SPOT4 satellite images could be used to estimate the volume of water bodies using Volume-Depth-Area relations at a local scale, and this suggests that hydrological modeling could be coupled with remotely sensed information to improve pond monitoring in arid areas.

In this study, we further explore this possibility, on the region of Barkedji, Ferlo, Senegal, by developing a method using hydrological modeling with three different sources of remote sensing data: (1) high resolution optical satellite images to access pond location and surface area at given dates, (2) ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Digital Elevation Model (DEM) data to estimate pond catchment area and (3) TRMM (Tropical Rainfall Measuring Mission) data for rainfall estimates. First, a relatively simple hydrological model was developed for Sahelian temporary ponds. It requires a small number of parameters, some of which are estimated from remote sensing data, and simulates daily water level variations (emptying and filling phases) of ponds assuming that the latter are not connected. Only usual

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events causing direct rainfall and runoff are considered and not extensive flood events. Input rainfall data are either measured or estimated from TRMM data. Second, the model was calibrated on one pond and validated on three others, using ground measurements. The model was then applied on the 98 ponds of the study area allowing the simulation of daily water area/volume/level of each pond. Finally, simulations obtained using measured or TRMM-derived input rainfall data were compared and discussed.

2 Study area and data

2.1 Study area

The study area is located in the Ferlo Valley, North Senegal, between 15.14° and 15.20° N and 14.47° and 14.54° W (Fig. 1). The relief is composed of a lateritic cuirass partially covered by flattened dunes, stabilised by vegetation (Le Houerou, 1988; Pin-Diop et al., 2007). This plateau was eroded by a former affluent of the Senegal River, the Ferlo. This region is characterized by low altitude (25 m average) and has a semi-arid climate that receives low annual rainfall (~500 mm from July to December), with rainfall events which can be extremely variable in time and space (Wheater et al., 2007).

The study area covers an area of 11·10 km around the village of Barkedji and is characterized by a complex and dense network of ponds that are filled during the rainy season (from July to mid-October). Generally, the limits of these ponds are delineated by a belt of trees which corresponds to the maximum water pond extension. Most of the ponds in the study area are small (33% of ponds with an area less than 1000 m^2 and 64% with less than 2600 m^2), with the smallest one covering only 74 m^2 and the largest being the Barkedji pond with ~347 400 m^2 (Soti et al., 2009). The larger ponds are located in the main stream of the Ferlo valley and the smaller ones generally outside. During the rainy season, the temporary ponds are quickly filled in successive occasions, in the very few hours during and after the shower, whereas the emptying phase lasts longer, between a few days and several months after the last precipitation

(Martin-Rosales and Leduc, 2003).

2.2 Meteorological data

Two sets of rainfall data were used:

- Daily rainfall data collected from a meteorological station (Weather View Ltd) located in the village of Barkedji during the 2001 and 2002 (from July to October) rainy seasons.

- Daily TRMM rainfall with 0.25°×0.25° pixel resolution covering an area around 27 km by 27 km centred on the Barkedji village were downloaded from the NASA's Goddard Earth Sciences (GES) Data and Information Services Center (DISC) for the rainy seasons of 2001, 2002 and 2007.

  (http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42_daily.2.shtml)

2.3 Hydrological data

Water height data were collected daily from July to October in 2001 and 2002 from water level meters placed at the centre of four ponds, namely Barkedji, Furdu, Mous 2 and Mous 3 (Fig. 1). For the study, we used the Mous 2, Mous 3 and Furdu water height data collected during the two years 2001 and 2002 and the Barkedji water height data collected during the rainy season 2002 only.

2.4 Topographic data

We used elevation data from a detailed survey conducted in May 2003 with a total station for two ponds, one located in the main stream of the Ferlo valley (Niaka) and one outside of the Ferlo bed (Furdu) (Fig. 1). Survey points were spaced horizontally at 2 to 5 m intervals and then interpolated on a regular 2 m grid.

The ASTER DEM with 30·30 m pixel size covering the whole study area was downloaded from the ASTER Global DEM dataset of the NASA's Warehouse Inventory

Search Tool (WIST) website (https://wist.echo.nasa.gov/wist-bin/api/ims.cgi?mode=MAINSRCH&JS=1).

2.5   Pond maps

Two pond maps of the study area were extracted from two Quickbird satellite images. The first one was acquired on 4 August 2005 and used for extracting pond parameters (maximum surface area and estimation of the catchment area size for ponds outside of the main stream) used in the model. The second one covering a smaller area (8·8 km) was acquired on 20 August 2007 and used to assess the accuracy of the model to predict water surfaces. The data used in the study are summarized in Table 1.

3   Methods

3.1   The hydrologic model

We adapted a daily water balance model developed to predict surface, volume and height of temporary ponds which combined a pond filling model (rainfall/runoff model) and a pond emptying model (water losses model). The model considers only usual events, especially the hydrological pond dynamics related to (i) direct rainfall, (ii) runoff on the catchment area of each pond and (iii) the water losses through evaporation and infiltration (Fig. 2). A mathematical volume-area-depth relation is used to simultaneously calculate water volume, area and height of the pond (Fig. 2). Finally, the main input of the model is rainfall and the output is the simulation of daily water area/volume/level of the pond.

3.1.1 The daily water balance model description

The pond filling model

For the pond filling model, we used the hydrological model developed by Girard (1975) which gives predictions of the runoff value for one catchment area from daily rainfall time series. This model is particularly suited for studying small catchments of less than 100–150 km^2 located in the Sahel region (Dubreuil, 1986). In this study, we assumed that the rainfall is uniformly distributed over the study area. The runoff value at time t, noted ΔV_t, takes into account effective rainfall and runoff, and is expressed as follows:

$$\Delta V_t = P_t A_{t-1} + K r . \text{ER}_t . \text{CA} \tag{1}$$

In Eq. (1), the first term is the water contribution from the direct rainfall, expressed as the product between direct rainfall at time step $t (P_t)$ and the area of the water body in the pond at the time step $t - 1 (A_{t-1})$. The second term which is the runoff, is the product of a runoff coefficient (Kr), the effective rainfall at the time step t (ER_t) and the surface of the catchment area (CA). The soil capacity to runoff was supposed uniform over the study area and defined by a constant Kr coefficient. The effective rainfall (ER) corresponds to the part of the precipitation that produces runoff. ER is calculated as follows:

$$\text{ER}_t = \begin{cases} P_t - M_t & \text{if} \quad P_t - M_t \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

In Eq. (2), M_t is a time-dependent soil moisture variable which can be interpreted as a threshold value over which runoff can occur. M_t is defined by the difference between its initial value M_0 and an Antecedent Precipitation Index (API):

$$M_t = \begin{cases} M_0 - \text{API}_t & \text{if} \quad M_0 - \text{API}_t \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

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The tAPI Index (Kohler and Linsley, 1951) is a weighted summation of past daily precipitation amounts, used as an index of soil moisture and calculated as follows:

$$API_t = (API_{t-1} + P_{t-1}) \cdot k \tag{4}$$

where API_{t-1} is the API index at the time step $t-1$, k is a dimensionless coefficient between 0 and 1 expressing the soil moisture decrease in time, and P_{t-1} is the precipitation at time step $t-1$. The API_t has no regional meaning and, as such, cannot be compared between sites (Anctil et al., 2004). The k parameter generally ranges between 0.80 and 0.98 (Heggen, 2001) but takes lower value (around 0.7) for Sahelian regions (Girard, 1975).

The pond emptying model

The pond emptying model represents the outflows of the catchment. In our model, water losses (infiltration, evaporation) are simply summarized through L as a constant (Joannes et al., 1986). Thus, the water height in the pond, at time step t (h_t), is calculated as follows (Puech et al., 1993):

$$h_t = h_{t-1} - L \tag{5}$$

Generally, water losses ranged from 1 to 20 mm per day in arid areas (Puech, 1994). All parameters and variables of the model are summarized in Table 2.

3.1.2 The volume-area-depth model

We used two simple volume-depth ($V - h$) and area-depth ($A - h$) equations to assess the volume-area-depth relations of the ponds of the study area. Such mathematical relations have been used with efficiency for temporary ponds (Puech, 1994) and lakes modelling studies (Bengtsson and Malm, 1997; Gates and Diessendorf, 1977; O'Connor, 1989). Recently, Hayashi et al. (2000) tested these relations on 27 wetlands

and ephemeral ponds in the northern region of North America showing very good results. The rule of this approach is to estimate water volume V and area A from water depth h measurements for each time step t using $A - h$ (Eq. 6) and $V - h$ (Eq. 7) empirical relations:

$$A_t = S_0.h_t^{\alpha} \tag{6}$$

$$V_t = V_0 * h_t^{\alpha+1} \text{with } V_0 = S_0(\alpha + 1) \tag{7}$$

where

A_t is the pond area at time t,

h_t is the water height of the pond at time t,

S_0 is the area for 1 m water height in the pond (Table 2),

α is a shape parameter (Table 2),

V_t is the volume of the pond at time t,

V_0 is the volume for 1 m water height in the pond.

3.2 Estimation of pond variables

In our study area, we considered two sets of ponds: those located in the main stream of the Ferlo Valley (set 1) whose hydrological dynamics are due essentially to runoff, and the ponds located outside (set 2), which are smaller (Fig. 1), whose filling mechanisms are mainly due to direct rainfall. Only usual rainfall events were considered, and we assumed that there is no hydrological connexion between ponds and between their respective catchment areas.

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3.2.1 S_0 and α values

S_0 and α are parameters of the power function used to model the geometric relationship between water areas (A) and water heights (h) data for one pond full of water. α is related to the curve of the relation between A and h. Grésillon (1976) showed that pond shapes are relatively stable because of the low relief characterizing the Sahel region. In the literature, α has been estimated around 1.25 for Burkina Faso (D'At de Saint Foulc et al., 1986). In general, low values of α occur in depressions having smooth slopes from the centre to the margin, and high values occur in depressions having a flat bottom. The S_0 parameters relates to the size of the depression (Hayashi and Van der Kamp, 2000).

S_0, and α parameters were estimated for each of the two sets of ponds defined previously (inside/outside Ferlo Valley main stream) using the detailed bathymetry from Niaka and Furdu ponds. Thus, we assumed that these two ponds are representative of the two sets.

Geographic Information System (GIS) functionalities were used to calculate the water area and the water volume for several depths from the detailed DEMs (Nilsson, 2009) of Niaka and Furdu ponds (Area and Volume tool, ArcGIS 3D Analyst extension). S_0 and α parameters were then estimated by fitting with the observed data. As error function to be minimized, we used the root-mean-squared error (RMSE) A_{err} defined as:

$$A_{err} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(A_{DEM} - A_{PF})^2} \tag{8}$$

where A_{DEM} is the area calculated from DEM, and A_{PF} is the area given by the power function, and m is the number of data points.

3.2.2 Catchment area (CA)

The quality of the catchment area delineation is very important for the model because it determines the quantity of water that will reach a pond through runoff. For each pond of the main stream (set 1), where runoff is important, we calculated a corresponding catchment area using GIS functionalities on ASTER DEM (ArcGIS Arc Hydro Tools).

For other ponds located outside of the main stream (set 2), for which direct rainfall is more important, we arbitrarily fixed the runoff surface as three times the maximum radius of the pond. The latter was calculated from the pond map of 4 August 2005 that coincided with the peak of the rainy season (Soti et al., 2009).

3.3 Model calibration

The model was calibrated on Barkedji pond using rainfall and water height data of the 2002 rainy season. The calibration criteria is based on the coefficient of efficiency (Nash and Sutcliffe, 1970) which is expressed as follows:

$$C_{eff} = \frac{\sum_1^n (Vobs - Vcal)^2}{\sum_1^n (Vobs - \bar{V}obs)^2} \tag{9}$$

where Vobs is the observed data; Vcal is the calculated one and $\bar{V}$obs is the average of the observed data. Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. The closer the model efficiency is to 1, the more accurate the model is. For the calibration phase, parameters values were explored within a realistic range based on scientific knowledge (see Table 2). Kr, M_0, k and L parameters were chosen as the values leading to the model with the highest Nash coefficient. These parameters were then applied to all the ponds of the study area to simulate their spatial and temporal dynamics. Then, the results were fed back into the GIS by calculating an approximation to the daily radius

of each pond as follows:

$$R_t = \sqrt{\frac{A_t}{\pi}} \tag{10}$$

Polygons for each pond at each time step were generated using a buffer function inside the maximum pond extension derived from the pond map (4 August 2005). The maximum water area extension radius was noted R_{max}, and the negative buffer radius value used was $R_t - R_{max}$.

3.4 Model validation

The model was run for the 2001 and 2002 rainy seasons both with rainfall data collected on the field and from TRMM estimates. For the year 2007, because of the lack of field data, only TRMM rainfall data were used. To evaluate the quality of the simulations, we used the Nash coefficient (9) for water height and the RMSE (8) for surface area.

Water height simulations were evaluated for the 2001 and 2002 rainy seasons for three ponds (Furdu, Mous 2 and Mous 3 – see Fig. 1) where daily water height records were available (Table 1).

Water surface area simulations using 2007 TRMM rainfall data were evaluated against surfaces estimated using the pond map derived from the 20 August 2007 QuickBird image.

4 Results

4.1 Estimation of pond variables

4.1.1 S_0 and α variables

The power functions that approximate the $A - h$ relations of the two depressions (Furdu and Niaka) are shown in Fig. 3. Niaka and Furdu have relatively small sizes, which are

reflected in the range of the scaling constant S_0. The values of α are close to 2 (2.87 for Furdu and 2.08 for Niaka) which indicates that the depressions have a reasonably smooth and near-parabolic shape.

4.1.2 Catchment areas (CA)

The delineation of the catchment areas (see Fig. 4) was possible for the largest ponds of the study area because of the spatial resolution of the ASTER DEM. With such low slopes characterizing the Ferlo Valley, it is very delicate to precisely delineate the catchment areas, even for the largest ponds of the study area. In total, 6 larger catchments have been extracted, with sizes ranging from 30 to 1107 ha. All catchments are located in the northern side of the valley where slopes are higher, around 5–8%, than in the southern part where slopes are around 0–1% and the small ponds are numerous.

4.2 The model calibration result

The Kr, M_0, k and L parameter values were estimated from model calibration. An optimal Nash-Sutcliffe coefficient of 0.82 was obtained with the following parameters (Fig. 5a) which are close to hydrological values noted in scientific studies for such arid areas (see references in Table 2):

- Kr=0.21

- M_0=15 mm

- k=0.4

- L=15 mm

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4.3 Validation

4.3.1 Pond water height estimations

With rainfall field data as model input, water height simulations compared well with field measurements (Fig. 5b,c,d and Table 3), with the highest Nash-Sutcliffe coefficients of 0.81 and 0.76 obtained for Furdu and Mous 3 ponds, respectively. A lower correlation was observed for the smallest pond (Mous 2, Nash-Sutcliffe coefficient=0.69).

With TRMM rainfall estimates as model input, water height was not well simulated for year 2001 (Table 3). However, for year 2002, the results were acceptable with Nash-Sutcliffe coefficients of 0.61, 0.65 and 0.53 for Barkedji, Furdu and Mous 3 ponds, respectively. Again, the correlation was not significant for the smallest pond (Mous 2, Nash-Sutcliffe coefficient = 0.37). A temporal shift of about 2 weeks was observed between water heights simulated with rainfall from meteorological station and those with TRMM rainfall estimates (Fig. 6) for Barkedji pond in 2002.

4.3.2 Pond water area estimations

Pond area simulated for 20 August 2007 was compared with 71 pond areas from the QuickBird image acquired on the same day and showed significant correlations with a coefficient of determination (r^2) equal to 0.90 (Fig. 7a). A better fit was observed for the larger ponds of the study area (Fig. 7b). On the graph, we could also observe that the model underestimates surface areas for the smaller ponds and overestimates for the larger ones.

5 Discussion

In this paper, a simple hydrological model was used to simulate daily water level variations. With the use of remote sensing data (Quickbird imagery), the ASTER DEM, and the rainfall data from the TRMM satellite, the application of the model to the ponds (98)

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of the study area showed relatively good results both for water height and water area predictions but some limits could be underlined.

For the years 2001–2002, water height simulations showed good results for Furdu (Nash=0.81) and Mous 3 (Nash=0.76) ponds which are similar by their size and for Barkedji (Nash=0.82) the largest one. For Mous 2 which is the smallest pond ($501\,\mathrm{m}^2$) of the dataset, the result is not so significant with Nash=0.69. This difference of results between large and small ponds could probably be explained by the uncertainty in watershed delineation. In particular for the set of small ponds like Mous 2, catchment areas were empirically estimated as the equivalent of three times the maximum radius of the pond. In the same manner, the 2007 water area simulations showed unexpectedly good results for large ponds and not as good ones for small ponds. That could also partially be explained by the uncertainty in the watershed delineation from Aster DEM. For the study, the use of Aster DEM data (pixel size $30{\cdot}30\,\mathrm{m}$) has significantly improved the simulations in comparison with those obtained previously with the SRTM Digital Elevation Model ($90{\cdot}90\,\mathrm{m}$) not shown. For such areas characterized by low elevation, it was almost impossible with the SRTM DEM to extract the catchment area of each pond. The use of the Aster DEM allowed delineating the catchment area only for the largest ponds located in the main stream, and not for the smaller ones. The lack of catchment area information has direct consequences on simulation results for small ponds. This can be seen in Fig. 5 where the peaks and the slopes of the curve are correct in shape but not in amplitude, suggesting a lack of water reaching the ponds.

In opposition to the correct water height simulations, we also noted that water area simulation results were poor for the set of small ponds. That could be explained by the S_0 and α parameter estimation method that we used considering that bathymetric data was available for only three ponds. This led us to choose one set of parameters for large ponds and another for small ponds. A more accurate definition of S_0 and α parameters should be useful for improving the methodology. Indeed, there are methods requiring more field data to accurately define S_0 and α parameters. From a detailed elevation model over a large area, the determination of the $A-h$ and $V-h$ relations

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is relatively straightforward; A and h can be extracted from the DEM and S_0 and α determined for several ponds. Shjeflo (1968), Lakshman (1971) and Hayashi (2000) applied that method on 10, 15 and 27 wetlands, respectively. Otherwise, the estimation of water area (A) could be done from remote sensing imagery, from airborne or satellite sensors (Puech et al., 1993) or from a detail elevation model (bathymetry measured locally), knowing that the latter would be costly and time consuming.

This study also allowed assessing the contribution of rainfall from the TRMM satellite as input in the hydrologic model. The simulations showed mixed results especially for water heights simulations between the rainy season 2001 and 2002 with clearly better results for year 2002. The reason of this difference is probably due to rainfall events recorded by the satellite close to rainfall events located on the Barkedji village. The results of year 2002 showed that TRMM data could be very interesting for some studies, but at a local scale they should be used with caution. Indeed, as we can see for 2001, large differences could be observed between the field events and the TRMM records and conversely year 2002 showed relatively fewer differences between the TRMM and village rainfall data, although a few days shift in the output values was observed (Fig. 6). However, the use of TRMM data could be a good compromise for spatial studies at a scale equal or coarser than the 25·25 km TRMM data minimum pixel size.

Globally, these first unexpectedly good results of the hydrologic model allow considering the application of the model to all the ponds of the Ferlo Valley of which our study area is representative. The methodology that we developed is relatively simple, and could be implemented in another area. It requires the acquisition of one satellite image at the peak of the rainy season to locate and evaluate the maximum area of the ponds, and water heights and rainfall field data collected daily at least during two rainy seasons. For a better estimation of the pond shape parameters, a bathymetric map for more ponds (at least 10) should be necessary in order to significantly improve the results.

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6   Conclusions

In this paper, we developed a hydrologic pond model that we applied to all ponds of the study area located in the Ferlo Valley, North Senegal. The ASTER DEM was used to delineate the watershed of the larger ponds. The high resolution of the Quickbird satellite image was useful for locating and estimating ponds maximum surface area. Results showed the possibility to assess pond water heights and water areas of a homogeneous area with a hydrologic model coupled with very high resolution satellite image data. The results of simulations with TRMM rainfall data also showed good results for year 2002, suggesting that it is possible to assess hydrological pond dynamics over large areas. These first results are very promising for many disciplines interested in the assessment of water resource dynamics in relation with their specific questions. In epidemiology for example, the model presented here will be used to monitor daily water ring variations around the ponds, knowing that these are favourable breeding sites for mosquitoes such as *Aedes* species (Linthicum et al., 1984). In ecology, it may be interesting to use the model to better understand fauna spatial distribution and mobility in areas with temporary ponds (Redfern et al., 2003) or even to support water resources management.

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Table 1. Data.

Data	Acquisition date	Complementary information	Sources
Rainfall data from a meteorological station	2001, 2002	Daily data collected from a station located in the Barkedji village centre	IRD,CIRAD (ACI project)
Rainfall data from the TRMM satellite Water height data	2001, 2002, 2007 2001 2002	Daily data, 25·25 km pixel size – Furdu Mous 2 and Mous 3 ponds – Barkedji, Furdu Mous 2 and Mous 3 ponds	NASA IRD,CIRAD (ACI project)
Pond map	04/08/2005 20/08/2007	Extracted from a Quickbird Imagery sensor (2.47·2.47 m pixel size), Bands: B,G,R,NIR[a]	CIRAD (EDEN Project) IRD (API AMA)
DEM (ASTER)	2009	30·30 m pixel size	METI (Japan), NASA (USA)
Detailed DEM	2003	Furdu and Niaka ponds (2·2 m pixel size)	IRD, ACI project

[a] B: blue; G: green; R: red; NIR: near infrared.

Table 2. Parameters and variables of the hydrologic pond model.

Abbreviation	Parameters and variables	Value/Range of values /equation	Unit	Reference
Input variables				
P	Rainfall	$0 < P < 0.045$	mm	Field survey
State variables				
ΔV	Runoff value	Eq. (1)	m^3	
ER	Effective rainfall	Eq. (2)	m	
M	Soil moisture value	Eq. (3)	m	
API	Antecedent Precipitation Index	Eq. (4)	m	
h	Pond water height	Eq. (5)	m	
A	Pond water area	Eq. (6)	m^2	
V	Pond volume	Eq. (7)	m^3	
Parameters				
CA	Catchment area	$0 < CA < 150\,km^2$		(Dubreuil, 1986)
Kr	Runoff coefficient	$15 < Kr < 40$		(Girard, 1975) (FAO, 1996;
α	Water body shape factor	$1 < \alpha < 3$		Puech and Ousmane, 1998)
S_0	Water body scale factor	Depending of the water bodies		(D'At de Saint Foulc et al., 1986)
M_0	Initial value of soil moisture variable required to start runoff phenomena	$10 < M_0 < 20\,mm$		(FAO, 1996)
L	Water losses per day	$5 < L < 20\,mm$		(Piaton and Puech, 1992)
k	Dimensionless coefficient expressing the soil moisture decrease in time	$0 < k < 1\,mm$		(Heggen, 2001)

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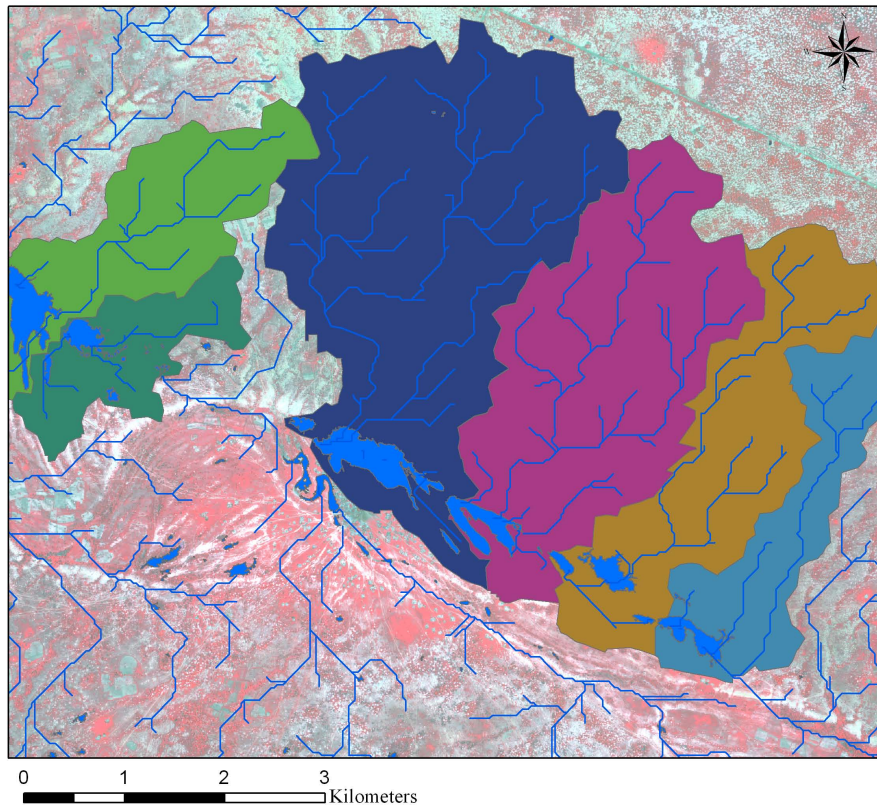Tables | Figures

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Table 3. Nash coefficients for water height simulations.

Pond name	Area (m^2)	Rainfall data from field station			Rainfall data from TRMM		
		2001–2002	2001	2002	2001–2002	2001	2002
Barkedji	336 211	–	–	0.82			0.61
Furdu	10 005	0.81	0.85	0.73	0.52	0.23	0.65
Mous 2	501	0.69	0.77	0.60	0.24	0.02	0.37
Mous 3	3341	0.76	0.79	0.69	0.27	0.02	0.53
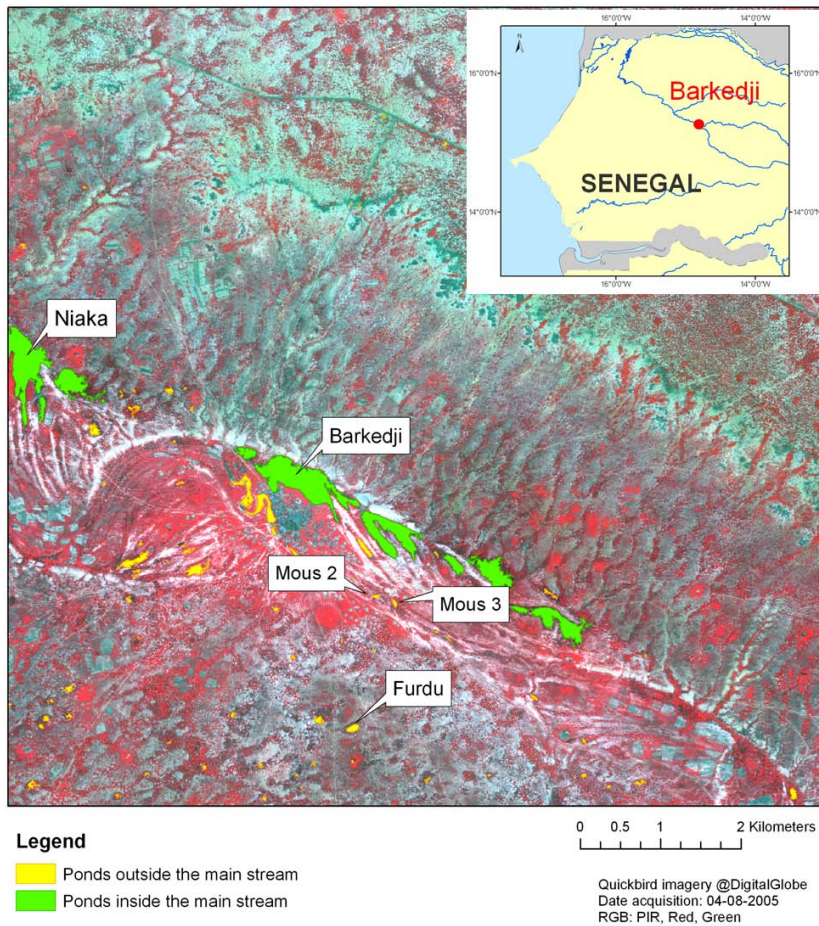
Fig. 1. Location of study area ponds, Barkedji village, Ferlo Region, Senegal.
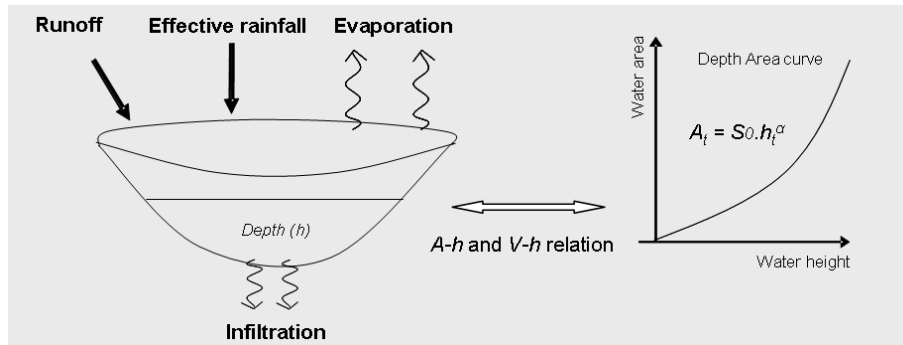
Fig. 2. General model description.
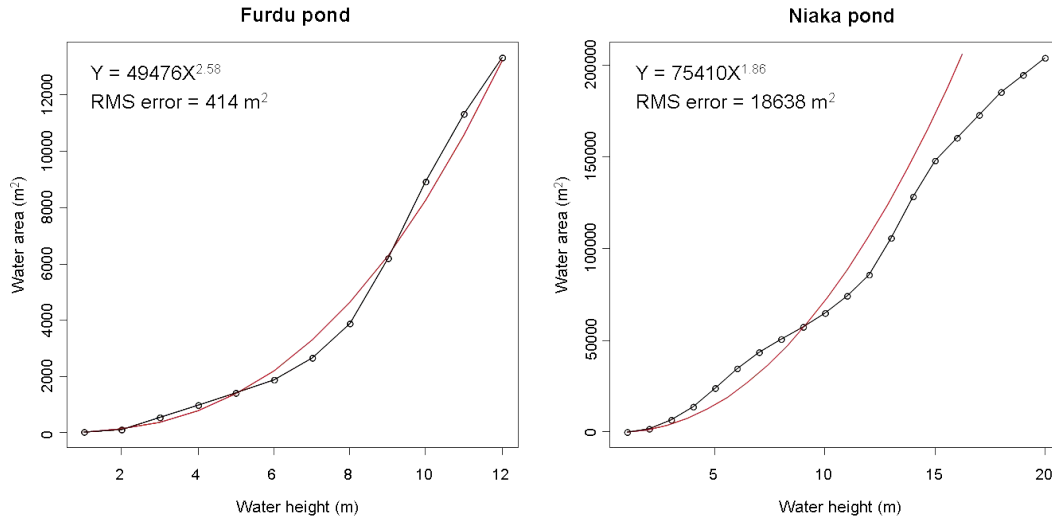
Fig. 3. Water area and water height relations for Furdu and Niaka ponds, Barkedji area, Ferlo region, Senegal.

Fig. 4. Catchment area delineation using ASTER DEM. Ferlo valley, Senegal.
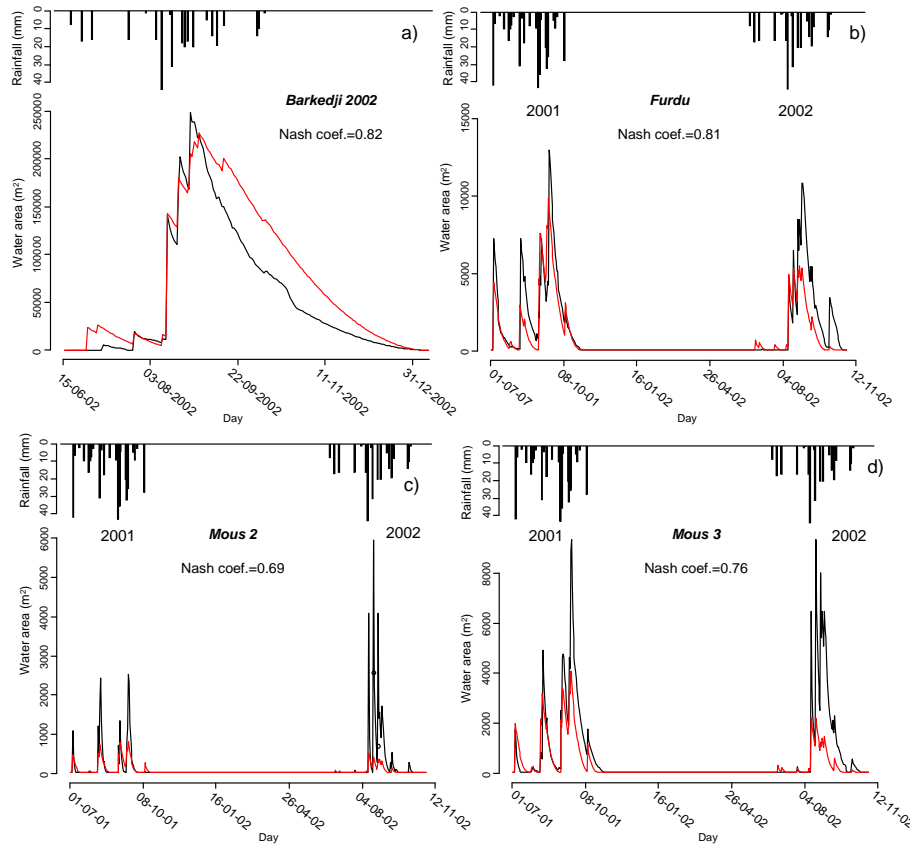
Fig. 5. Comparison of water heights field data (black) and water heights simulated data (red).
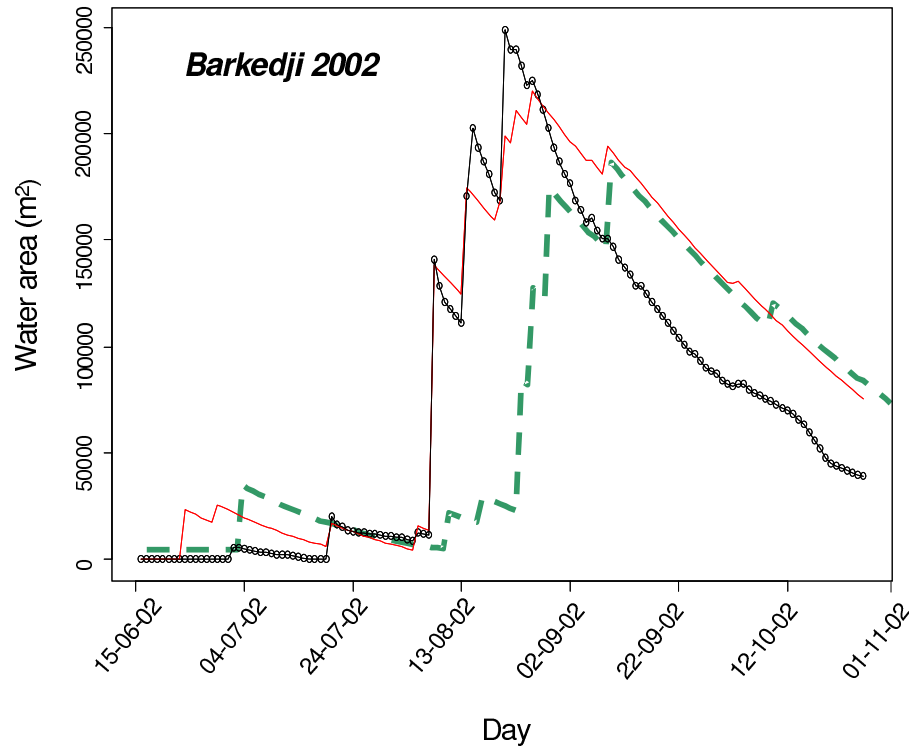
Fig. 6. Comparison of water area simulated data from rainfall from meteorological station (red) and rainfall from TRMM Satellite (green) on Barkedji pond in 2002.

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a)

b)
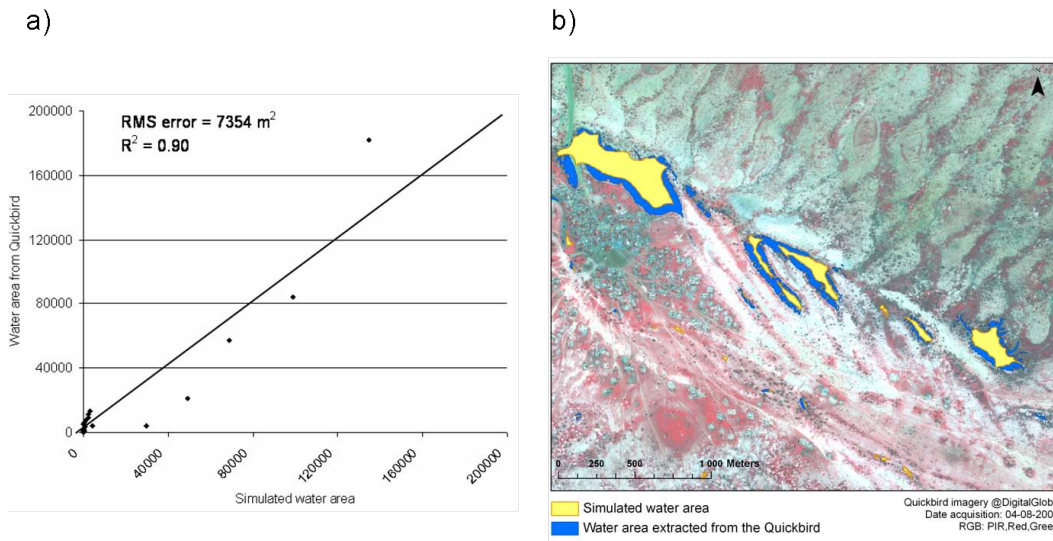
Fig. 7. Comparison of observed (Quickbird imagery, 20 August 2007) and modelled water areas simulated with TRMM rainfall data as input.