Modelling the flood cycle, aquaculture development potential and risk using MODIS data: A case study for the floodplain of the Rio Paraná, Argentina

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1. Introduction

Floodplains of the world’s large rivers are highly suitable areas for development of aquaculture, having good combinations of factors including water availability, slope, soil type and accessibility. On the other hand there may be vulnerability to flood events which need to be taken into consideration in siting aquaculture developments. There is increasing evidence that the world climate is changing with significant changes in rainfall, temperature and sea level already recorded (IPCC, 2007). Global climate models show that these changes will persist throughout this century and, although this effect will vary significantly with location, floodplains as receivers of water discharge from increased precipitation and extreme events may be particularly vulnerable.

Although aquaculture in Argentina is still considered as a marginal activity it has grown quickly in recent years. The Paraná River and its floodplain potentially provide access to considerable water resources and culture sites but this environment is highly influenced by flooding episodes which not only defines it but also represents an issue for the establishment of fish farms in the area. Suitability and risk for aquaculture development were assessed using an 11 year time series consisting of 8-day composites from the Moderate Resolution Imaging Spectroradiometer (MODIS). The data was used in association with established algorithms to indicate areas of surface water, the percentage of the time series where surface water flooding occurred and the relative exposure to flood risk in the lower Rio Paraná. 78% of the study area is unaffected by flooding, and 7% is permanent water bodies. The remainder is exposed to varying levels of risk, although very low risk areas may be enabled for aquaculture through engineering solutions. The tools described in this study can inform the site selection process in order to avoid or minimise the risk from flooding to potential aquaculture developments.

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increased by 10 to 30% in the last 40 years, probably affected by global warming and the ENSO, and heavy rainfall is becoming more frequent (Barros, 2006; Depetritis et al., 2000). These changes are contributing to an increase in the river level and in the number of flooding events, their duration and impact.

Remote sensing is a very useful tool for understanding and developing flood management strategies. Satellite imagery can provide synoptic data covering large areas and in combination with Geographic Information Systems (GIS) can give timely and cost efficient analysis of flood events. There have been several studies to identify and analyse flooding processes and water related activities in different parts of the world. Brivio et al. (2010) used RADAR systems combined with ancillary data to construct maps of recent flooding events and Karszenbaum et al. (2000) used RADAR technology to describe the Paraná Delta and its flood conditions. Both showed that one of the main advantages over optical imagery is its cloud penetration which allows it to be used during cloud covered episodes, but the difficulties in classifying the acquired signal make it less advantageous. Instead of RADAR technology, Xiao et al. (2005, 2006) used the Moderate Resolution Imaging Spectroradiometer (MODIS) from the Aqua and Terra satellites to map and monitor the development and use of paddy rice agriculture in Asia through the identification of their flooding periods. Westra and De Wulf (2006) used Vegetation Indexes obtained from MODIS to monitor the dynamics of the Sahel floodplain and Zheng et al. (2008) also used those indexes to study the effects of flooding on populations. The free access to data, a spatial resolution of 250 m or 500 m and the short-time interval of data acquisition make MODIS data very suitable for the study of flooding processes on a regional or continental scale.

Sakamoto et al. (2007) describe a methodology for using MODIS time series data for detecting changes in the timing and extent of annual flooding in the Mekong delta. The methodology has also been applied and verified in Bangladesh, another flood prone area (Islam et al., 2010). As site selection will be of key importance in the successful establishment of new aquaculture ventures in flood prone areas, this technique is used in the current study to model water coverage and the flooding cycle of the Lower Paraná. The flood data from the MODIS models is then used to develop specific risk indicators for aquaculture developments and to identify which sites show more potential for aquaculture in this section of river.

2. Study area

The La Plata Basin (Fig. 1) is the fifth biggest river basin in the world and only the second in South America after the Amazon Basin. This massive basin passes through five different countries and has a surface area of 3.5 million km² (Coronel and Menéndez, 2006). It is a very important resource for all the riparian countries because of the suitability of the area for agriculture. It also provides hydroelectric power through the construction of dams as well as substantial natural channels of communication as many of the rivers of the Basin are navigable. The Rio Paraná is one of the La Plata rivers and its basin covers a surface of 1.51 million km² with annual mean flow volume of 17,700 m³ s⁻¹.
and an average water velocity of 1 m·s\(^{-1}\) (Iriondo, 2007).

The area chosen in this study is the Lower Paraná which starts in the confluence of the Paraná and Paraguay rivers, near Corrientes city, and continues to the sea and is located between the latitude 27.5 and 34.2 S, and longitude 61.5 and 56 W (Fig. 1). This comprises a number of Argentinean provinces as well as parts of Paraguay, Brazil and Uruguay. It has a braided form with the river frequently divided between the main channel and secondary channels producing unstable islands throughout its route. The lower section is divided into two sections; the Middle Paraná which extends from Corrientes to Rosario having a length of approximately 600 km and is surrounded by a floodplain resulting from frequent flooding and the Lower Paraná which extends from Rosario to the sea and is strongly influenced by extraordinary lateral discharges that produce flooding due to the low height of its river banks, as well as tides in the delta.

In common with other riverine floodplains, the Paraná floodplain is important economically and ecologically, having a very productive landscape and high biodiversity. Tockner and Stanford (2002) assigned an economic value to such areas of US$ 19,580 ha \(\text{yr}^{-1}\) and high biodiversity. Tockner and Stanford (2002) assigned important economically and ecologically, having a very productive height of its river banks, as well as tides in the delta.

3. Database and model development

3.1. Satellite data

The current study makes use of the MODIS/Terra Surface Reflectance 8-day L3 Global data set which is represented on a sinusoidal grid with approximately 500 m resolution. The 8-day composites provide the best possible image collected over an 8 day period resulting in the minimum possible atmospheric water vapour interference.

The time series analysed extends from the launch of MODIS in March 2000 until May 2011 resulting in 501 images in total although some images from the sequence were unavailable. The Middle and Lower Paraná study area was represented in 4 tiles, h12v11, h12v12, h13v11 and h13v12, which were mosaiced into a single image (Fig. 1).

3.2. Water cover detection

MODIS data was processed in order to detect surface water following a modified version of the method described by Sakamoto et al. (2007). The two minor differences between the current methodology and that used by Sakamoto et al. (2007) are: no application of the wavelet transform to smooth the data, and no use of any interpolation of the cloud gaps. The reason behind these changes is to highlight areas that are flooded for short intervals and which may not be revealed if an excessively smoothed data series are used in the process.

A schematic representation of the algorithm used for identifying areas of surface water is provided in Fig. 2. The method makes use of threshold values for the Enhanced Vegetation Index (EVI) (Eq. (1)), Land Surface Water Index (LSWI) (Eq. (2)), and the Difference Value between EVI and LSWI (DVEL) (Eq. (3)). Pixels are initially classed as ‘water’ or ‘non flood’ areas with those that have been designated as water being further separated into 3 potential classes; flood, long-term water bodies (where water is present for 250 days or more per year), and mixture where it is estimated that the pixel contains both land and water areas.

\[
\text{EVI} = \frac{\text{NIR}-\text{RED}}{\text{NIR} + 6 \times \text{RED}} - (7.5 \times \text{BLUE}) + 1 \quad (1)
\]

\[
\text{LSWI} = \frac{\text{NIR}-\text{SWIR}}{\text{NIR} + \text{SWIR}} \quad (2)
\]

\[
\text{DVEL} = \text{EVI} - \text{LSWI} \quad (3)
\]

where: NIR = near infrared, RED = red band, BLUE = blue band, and SWIR = short wave infrared band.

As MODIS data is based on surface reflection, cloud cover has a significant influence and will likely result in land surface classification errors. The algorithm used in the current study excludes cloud areas based on a MODIS blue band (459–479 nm) surface reflectance value of 0.2 or greater. The end result for each time step within the data series is an output with all areas classified either as non-flood, flood, mixture, long-term water bodies, or cloud.

3.3. Animations

An animation was produced compiled from the entire MODIS time series with a frame rate of 0.2 s using GIS software. The animation shows the areas of permanent water, flooding, cloud cover and mixed pixels.

3.4. Flood frequency

In order to indicate the likelihood that a given area will be inundated by surface water the image series was used to calculate the percentage of time that a pixel was covered by water over the entire time series. The percentage was calculated for each pixel by comparing the number of images where water is indicated with the total number of available cloud free images where cloud was excluded based on MODIS band 3 (459–479 nm) values greater than 0.2. It is worth noting that the proportion of images which were cloud free over the areas of interest was high (Fig. 3).

4. Results

Figs. 4 and 5 provide examples of extreme situations within the area; a very dry condition with very few Flood pixels detected (Fig. 4) and a major flooding episode (Fig. 5). The reclassified images show 5 categories of identified pixel; Clouds, Flood, Land, Long Term Water Bodies (LTWB) which indicates the presence of lakes, rivers and other permanent water bodies, and finally Mixture pixels, which are those pixels that have a presence of both land and water. These pixels can be areas where the water is mixed with vegetation or land. Examination of the distribution of these pixels shows that they are principally located.
in the margins of other Water-related pixels like Flood or LTWB and only occur in low numbers.

In Fig. 4, it can be seen that very few Flood pixels are detected around the river or isolated far from water bodies. The river shows an expected braided shape and at some points the course appears intermittent due to the lack of pixels in that area. The detailed image insets show the presence of islands that divide the course of the Paraná and small lakes or ponds around the main channel.

By contrast, Fig. 5 represents a major flooding event and the quantity of Flood pixels along almost all the river course and adjacent areas is very significant. Some of the Flood pixels follow watercourses that are not otherwise revealed. Fig. 5 also shows the extent of the flooded areas, which are mostly towards the right bank of the river as far south as Rosario, where it changes to the left bank.

The presence of clouds in the images can be a limitation to a surface analysis. Some flood events can be covered by them and it is probable that clouds and flooding are simultaneous events.

The animation (available at: http://www.aqua.stir.ac.uk/GISAP/gis-group/daniel) clearly show the expansion and contraction of the floods from the most stable course of the river revealing how the inundation expands from the north towards the south. It can also be seen that normally there are smaller local flooding events, but during the period studied events appear that comprise the whole course of the river and produce extensive flooding at approximately 3 year intervals. Although the period of 11 years and 4 months used to produce the final dataset is considered relatively short in terms of climatology and flooding cycles, the animations are nevertheless extremely informative for illustration of trends and identifying locations for more detailed attention.

Fig. 6 shows the percentage of time that a pixel is covered by water during the time series used in the study. The main river channel and long term water bodies can be seen clearly as those areas where water is present for more than 75% of the time series and Table 1 shows the area affected in each category.

5. Discussion

This study used MODIS data along with an established algorithm to indicate the presence of surface water at 8 day intervals over a time series spanning March 2000 until May 2011. An animation was created from the series that allows visualisation of the flooding cycle and, despite the brevity of the time series, it allows identification of some trends. Identifying areas of permanent water plays an important role in siting aquaculture operations in terms of potential water supply for pond or tank culture, or as possible cage culture sites. An image was created showing the percentage of the time series where flooding was present. This would be useful in the site selection stage of setting up
aquaculture systems, allowing managers and regulators to identify which areas will be more suitable for these activities and which will represent less risk to the facilities and the investment.

The use of Geographic Information Systems (GIS) has an important role in informing decision makers about site selection and zoning and GIS-based models can allow for data such as that produced during this

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**Fig. 4.** Surface water in the dry season of 31 December, 2005. Detailed image shows the area around Rosario.

**Fig. 5.** Surface water in the flooding event of 26 February, 2007. Detailed image shows the area around Rosario.
study to be combined with a wide range of other data sources (e.g. topographical, infrastructure, and markets) in a structured way to highlight potentially suitable areas. This study has clearly demonstrated the value of remote sensing and GIS in determining flood potential and the consequences for aquaculture development. The percentage of time that a pixel is covered by water is considered as an indication of the probability that the water may cover it again considering that future flooding is likely to follow a similar spatial pattern. Examining flood frequency and focusing on areas that are inundated for a lower percentage of the total time series gives a good indication of areas that are likely to flood on a seasonal basis. Areas that are only inundated a few times during the entire time series (e.g. 0.5 to 1% of total) can be viewed as areas that may only flood on an occasional basis and for which engineering solutions (bunds, dykes) may be effective. Such information is of value in terms of site selection for aquaculture facilities or other activities as it may reveal a flood risk over potentially desirable land areas that may not be obvious during a typical year. Although the consequences of flooding for inland aquaculture in ponds is clear, ponds are not the only culture system suitable for all the candidate species in the region, and some, such as *surubi*, *pacú* and *rhamdia*, are suitable for cage aquaculture. Flood models are also relevant for optimisation of cage aquaculture as they give an indication of changing water levels and the associated risks.

Aquaculture in the Lower Paraná has a good potential to grow and develop into a profitable and mature activity. The use of the river and lakes as water sources and locations in the floodplain of the Paraná is an issue that requires careful site selection and risk assessment using tools such as those developed in this study. Establishing an aquaculture system in the floodplain of the Paraná also faces the issue that flooding could interrupt transportation and access to a site. Roads in the region have been designed following predictions from the first half of the century and some new roads are still built using those designs and are consequently unable to support the increase of the water level and the magnitude of the flooding events, especially taking climate change into account (Neiff et al., 2000). The designs of new roads and other systems, including aquaculture systems, should be made on the basis of hydrological risk that is associated with the recurrence of flooding as illustrated in Fig. 6 and in agreement with Depetris et al. (2000).

The presence of reservoirs and protected areas also limits site selection in the Lower Paraná, and a good example of this is the Esteros del Iberá area located in the Corrientes province. This protected area covers 12,000 km² but the adjacent wetlands are bigger than the protected area. Although it is a promising area in which to establish aquaculture systems, its protected status means that it should not be used for such developments, although one alternative could be the establishment of facilities for the recovery of endangered aquatic species.

### Table 1

<table>
<thead>
<tr>
<th>Percentage of time series where surface water is indicated</th>
<th>Area affected (km²)</th>
<th>Percentage of study area affected</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.5</td>
<td>1019081.5</td>
<td>78.23</td>
</tr>
<tr>
<td>0.5-1</td>
<td>71644.5</td>
<td>5.35</td>
</tr>
<tr>
<td>1-2</td>
<td>37170.9</td>
<td>2.80</td>
</tr>
<tr>
<td>2-5</td>
<td>34820.0</td>
<td>2.62</td>
</tr>
<tr>
<td>5-10</td>
<td>20371.8</td>
<td>1.53</td>
</tr>
<tr>
<td>10-25</td>
<td>18290.4</td>
<td>1.38</td>
</tr>
<tr>
<td>25-50</td>
<td>8691.1</td>
<td>0.65</td>
</tr>
<tr>
<td>50-75</td>
<td>4824.7</td>
<td>0.36</td>
</tr>
<tr>
<td>&gt;75</td>
<td>93995.8</td>
<td>7.08</td>
</tr>
</tbody>
</table>

Fig. 6. Percentage of time series where surface water flooding is present derived from the cloud free images.
In floodplain environments the planning of production systems and communication links with urban centres and markets should be based on the maximum extent of flood events modelled over an appropriate time period. Updated flood prediction models are key decision support tools and are clearly desirable, especially when considered alongside the trend for flood magnitudes to increase. The models and outcomes from the present study can contribute to the decision-making process for the development of a more sustainable and low-risk aquaculture industry in the floodplains of the world and have already been employed in the study area to designate locations for farm and hatchery construction.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.aquaculture.2013.10.043.

References


