Determining Spatial and Temporal Patterns of Submergence in Rice with MODIS Satellite Data

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Abstract

Rice submergence is the condition by which the water level rises above the rice crop canopy. In general, rice plant response to submergence is to elongate its shoots above the rising water level. This costs in energy and eventually has a direct impact in terms of reducing yields. A specific gene, called Sub1, when introgressed into popular rice varieties by Marker Assisted Back-crossing, nearly stops the natural elongation process and permits a given local rice variety to sustain submerged conditions for a generally recognized period of about 2 weeks. Plant breeders now look for well-identified and location-accurate submergence areas in order to disseminate such improved local rice varieties. Remote sensing is proposed to provide surface water maps at high temporal resolution, determining a percentage of occurrences of surface water for a given pixel. Occurrence is defined as the count of days of identified surface water within a given period, returned in a percentage on that period. Rice area maps and knowledge of crop calendars are proposed to add to the assessment of submergence prone areas in two study areas, the Northeastern Thailand and Nueva Ecija in North Central Philippines.

1. Introduction

Rice is often grown in the lowest parts of the landscape because these areas are relatively flat, fertile, and humid, and facilitate the creation of bunded fields that are flooded with water from rainfall and lateral water flow, and in many places from additional irrigation. Being in the lowest part of the landscape makes rice vulnerable to periods of excess water which can lead to flooding of the fields and submergence of the rice crop. Submergence occurs when the water level rises above the crop canopy. Most rice varieties can survive only a few days under water and respond to submergence by increased elongation, which may allow the plants to emerge above the water. This is a necessary response for rice plants growing in an environment where the water level steadily increases throughout the first part of the growing season. A clear example of this are the "deep-water rice" varieties that have a capacity for extreme elongation and can grow in fields that get as much as 5 m of standing water. For most varieties, the elongation response is effective if it allows the plants to emerge within a week or so. However, if they cannot grow out of the water within that period the plants die (Adkins et al., 1990). This is a widespread problem; submergence stress is considered the third most important abiotic stress (after drought and salinity) in rice production in India that frequently affects over 15 million ha (Widawsky and O'Toole, 1990). A few varieties have a different adaptation to submergence (Xu and Mackill, 1996, Xu et al., 2006 and Siangliw et al., 2003). They hardly elongate when submerged, and in that way they save energy to recover after the water recedes. It has been shown as a good strategy to flash-flood like submergence events that are characterized by high water levels during a relatively short period (up to 17 days; Singh et al., 2009). This "submergence-tolerance" trait has recently been introgressed into widely used rice varieties (Septiningsih et al., 2009). Estimating the potential benefits of these varieties and designing effective dissemination programs is not trivial. Among other things, it requires information about the spatial and temporal distribution of submergence events in rice fields, and their duration. It is particularly important to distinguish flash flood prone areas from areas with steadily increasing water levels. Here we explore the use of satellite remote sensing to detect and quantify the extent of flash flooding in rice fields. Remote sensing has been used to monitor major flood events (e.g., Smith, 1997 and Brakenridge et al., 2003), but not much work has been done on more localized flooding of rice fields. Moreover, the preferred way to detect water is active remote sensing using radar, because the emitted radiation measured by passive

ISSN 1686-6576 / © Geoinformatics International

approaches is obscured by the cloud cover (and submergence and high cloud cover often co-occur). An operational system based on Radarsat-2 imagery (GISTDA, 2012) is operated by GISTDA in Thailand, with a temporal resolution of 15 days. However, radar remote sensing products are not generally available for all locations and time periods. Here we evaluate the use MODIS satellite data, because it has a global coverage, high temporal resolution (daily) and reasonable spatial resolution (250 m). We used 8-day composite images to estimate the spatial and temporal extent of flooding in rice fields in two study areas (Northeast Thailand, and Nueva Ecija province, Philippines). For each pixel (grid cell) we determine the occurrence of surface water, this information is then combined with rice crop areas and known cropping calendars to provide an estimate of the area possibly affected by submergence. Multiple year coverage of flood extents should be investigated to determine the occurrence of surface water for each pixel.

This permits to discover hazardous events that come as a "surprise" to the farmers. Indeed, if it happens every year, farmers either do not grow rice, or do but in another season, or use permanently rice with longer straw varieties. Occurrence is defined as the count of days of identified surface water within a given period, returned as a percentage for that period. This information is then combined with rice crop areas and known cropping calendars to provide an estimate of the area affected by submergence. This work should form a basis for identifying priority areas for submergence-tolerant variety testing and dissemination across rice-growing areas.

2. Study Areas

We chose two study areas: northeast Thailand and Nueva Ecija province, Philippines (Figure 1). Both of these locations suffer regularly from the destructive effects of flooding on their rice production systems. Northeast Thailand covers about 524,000 km^2. There is about 8.8 million ha of rice (about 57% of the rice area in Thailand), producing about 45% of the national total (OAE, 2008). Most rice is grown on rainfed, typically flooded fields, with only about 10% of the area receiving irrigation water. The average annual rainfall is about 1300 mm. The rainy season normally starts beginning of May and ends by mid-October (TMD, 2007). In this season, there is a bi-modal rainfall pattern, with dry spells common in June and early July. Most rice is transplanted and seedbed preparation starts at the first or second rains, in May or June, transplanting being one month later (Sawano et al., 2008). Since the dominant rice varieties are photoperiod-sensitive, flowering is largely independent of the planting date, occurring by the end of September, and harvesting takes place in November. Submergence and drought are major constraints to rice production in Thailand, but submergence is more important. For example, in Thailand, the rice area that was lost due to flooding between 1989 and 2010 was 1.1 million ha (Figure 2). In the worst year, 2001, flooding resulted in the loss of about 4 million ha of rice (DDPM, 2008; NESDB, 2012). Nueva Ecija province is located in the central plain of Luzon island, about 96 km northeast of Manila (Figure 1).

Figure 1: Study areas: North-East Thailand and Nueva-Ecija in The Pihilippines

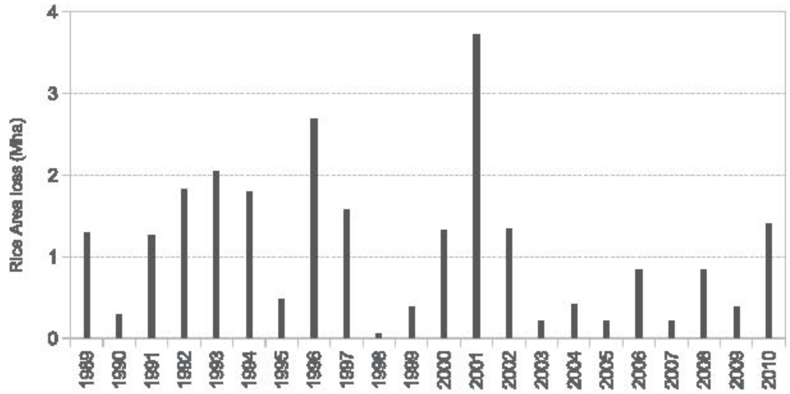

Figure 2: Rice area losses due to flooding in Thailand (1989-2010) Source: NESDB (2012)

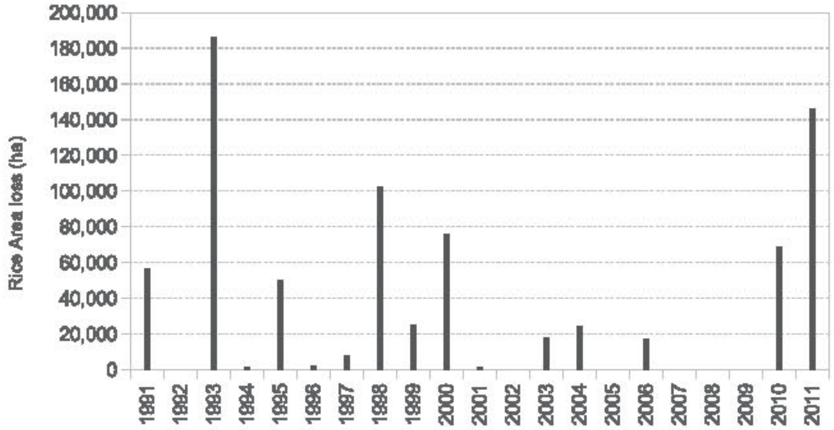

Figure 3: Rice area losses in the Philippines due to flood (BAS, 2012a; no data in 2007-09)

It is generally known as the rice granary of the Philippines. Average rice production for the 2002-2006 period was 1.11 million tons (PhilRice, 2006). The terrain consists of a mostly level to nearly level alluvial landscape in the western and southwestern side which represents the best agricultural areas. Rolling uplands can be found in the northeastern part of the province. In 2007, the harvested rice area was 274,850 hectares of which 236,150 ha were irrigated and 38,700 ha rainfed (PhilRice, 2007). Nueva Ecija province has distinct dry and wet seasons with rainfall peaking from July to August. The agricultural land areas in the province are dominated by paddy fields. In general, two rice crops are planted in the irrigated rice areas, and one rice crop in the rainfed areas followed by fallow or other crops than rice. For most of the irrigated areas, the first crop or wet season is sown in June, planted in late June or July, and harvested in late September to October. The second or dry season crop is usually sown or planted in late December to early January and harvested in April.

Most of the rice farmers practice direct-seeding rice during the dry season, and transplanting in the wet season (Casiwan et al., 2005). For Nueva Ecija, flooding causes more damage to rice crops than drought or pests (Table 1a-1c). Seasonal light to severe flooding occurs in the southwestern portion of the province (Figure 3) which is attributed to the impeded drainage and absence of natural drainage outlets (BSWM, 2004). Pantastico and Cardenas (1980) identified four major hazards to rice production in the Philippines; these are typhoons and floods, drought and pests. Figure 3 shows the impact of flooding to rice production in Nueva Ecija. Floods in 1993 and 1998 greatly affected rice production in the province. The damage amounted to about 9.11 million and 1 billion Philippine Pesos respectively which affected about 186,000 ha in 1993 and 102,000 hectares of rice areas in 1998. In 2010, the rice area damaged by typhoon affected 68,500 ha of rice, while in 2011 146,080 hectares of rice and corn was affected (BAS, 2012a).

Table 1a: Estimated production losses, value, area affected and damaged caused by typhoons and floods for Nueva Ecija

YEAR	Area Affected (ha)	Totally damaged	Production Losses (Mt)	Value of production (P'000)	Harvested Area (ha)	% Area affected
1991	56,292	-	39,375	196,877	241,740	23.29
1992					224,900	-
1993	186,260	-	151,983	911,898	238,600	78.06
1994	1,644	490	2,870	18,681	257,300	0.64
1995	49,875	1,080	42,737	341,895	263,083	18.96
1996	2,126	530	2,653	23,907	253,591	0.84
1997	8,000	-	2,780	22,240	249,579	3.21
1998	102,300	2,460	130,006	1,040,049	203,460	50.28
1999	24,742	4,957	26,445	277,662	240,643	10.28
2000	75,831	2,944	76,899	617,718	243,525	31.14
2001	1,350	235	1,985	15,880	245,763	0.55
2002					239,127	-
2003	18,250	3,150	16,335	147,015	243,499	7.49
2004	24,571	2,295	24,088	305,498	244,450	10.05
2005					245,223	-

Table 1b: Estimated production losses, value, area affected and damaged caused by drought for Nueva Ecija

YEAR	Area Affected (ha)	Totally Damaged	Production Losses (Mt)	Value of Production (P'000)	Harvested Area (ha)	% Area affected
1991					241,740	-
1992					224,900	-
1993					238,600	-
1994					257,300	-
1995	50	-	46	322	263,083	0.02
1996					253,591	-
1997					249,579	-
1998	10,210	1,325	12,664	102,715	203,460	5.02
1999					240,643	-
2000					243,525	-
2001					245,763	-
2002	300	80	644	5,792	239,127	0.13
2003					243,499	-
2004					244,450	-
2005					245,223	-

Table 1c: Estimated production losses, value, area affected and damaged caused by pests and diseases for Nueva Ecija

YEAR	Area Affected (Ha)	Totally damaged	production Losses (Mt)	Value of production (P'000)	Harvested Area (ha)	% Area affected
1991	-	-	-	-	241,740	-
1992	-	-	-	-	224,900	-
1993	-	-	-	-	238,600	-
1994	840	-	1,159	8,113	257,300	0.33
1995	1,060	52	1,535	10,745	263,083	0.40
1996	4,000	-	6,209	49,676	253,591	1.58
1997	16,035	-	2,678	21,692	249,579	6.42
1998	2,050	-	1,420	11,360	203,460	1.01
1999	-	-	-	-	240,643	-
2000	7,765	-	7,673	76,732	243,525	3.19
2001	-	-	-	-	245,763	-
2002	3,100	-	128	966	239,127	1.30
2003	-	-	-	-	243,499	-
2004	-	-	-	-	244,450	-
2005	-	-	-	-	245,223	-

2.1 Materials and Methods

The processing of this large dataset was made into a High-Performance Computing framework adapted from those found in Akhter et al., (2006, 2007, 2008) and Chemin (2012). The distributed framework is a Linux system based on GDAL library (2012) and C programming, enhanced with a distributed language called OpenMP (2012), used essentially for data distribution as in Chemin (2011). We used a 48 threads machine (2 cpus with hexa-cores having 4 threads each), Figure 4 shows a simplified example of the programming framework with only 4 cores. Consider A and B two RS image bands data streams, for iteration i=0, four data blocks (blocks no. *0-3*) from A and B are sent to process and the stored result sent to an output image stream C. This repeats at each iteration until the end of the data is reached (blocks no. *n*). The more working element (cores, threads, etc) are available to process the data for each iteration, the less iterations will be needed to process all the data. Large datasets can then be processed in a "more human" amount of time (i.e. few hours or minutes) than if processed in a single working element. A general perspective is to gain one order of magnitude in processing speed (months become days, days become hours, or hours become minutes). The Moderate Resolution Imaging Spectroradiometer (MODIS) is a sensor aboard the TERRA and AQUA satellites. These satellites cover each part of the earth every one to two days, acquiring data in 36 spectral bands with wavelength ranging from 0.4 µm to 14.4 µm. The spatial resolution varies from 250m to 1000m. Over 100 MODIS products can be accessed for free through the NASA websites (NASA, 2008). For this study (Figure 5), we used MODIS surface reflectance products, i.e., MOD09Q1 and MOD09A1 from 2000 to 2008. MOD09Q1 provides surface reflectance of the composites of the 8-day data for band 1 (red, 620-670nm), band 2 (NIR, 841-876nm) and quality control flags at 250m. It gives the amount of light reflected by the surface of the earth. We used the quality control flags to provide information on data correction, about data quality, errors or problems in the data and clouds state (MLSR-SCF, 2008) and removed unusable pixels from processing. MOD09A1 is a composite of the best observations during an 8-day period. The data includes surface reflectance for seven wavelengths, from 459nm (blue) to 2155nm ($SWIR_2$) and a state quality control flag for identifying the cloudy pixels, which we used to remove pixel values. We used band 7 (2155 nm) to detect water. The pixel values for both surface reflectance products ranges from -100 to 16000. We applied the standard scaling factor of 0.0001 to derive surface reflectance values with a normal range of 0 to 1.0 (MLSR-SCF, 2008) (values below 0 and above 1 were truncated). Rice area distribution data for the Philippines had a scale of 1:250,000 (Casiwan et al., 2005). Paddy rice area (i.e. excluding "upland rice") for NE Thailand was derived from a land use database for 2003 (LDD, 2003) by selecting all polygons for which rice was the principal land use. For the northeast Thailand, we used 360 8-days composite water images during the period of 2000-2008 (MODIS tiles h27v07/h28v07).

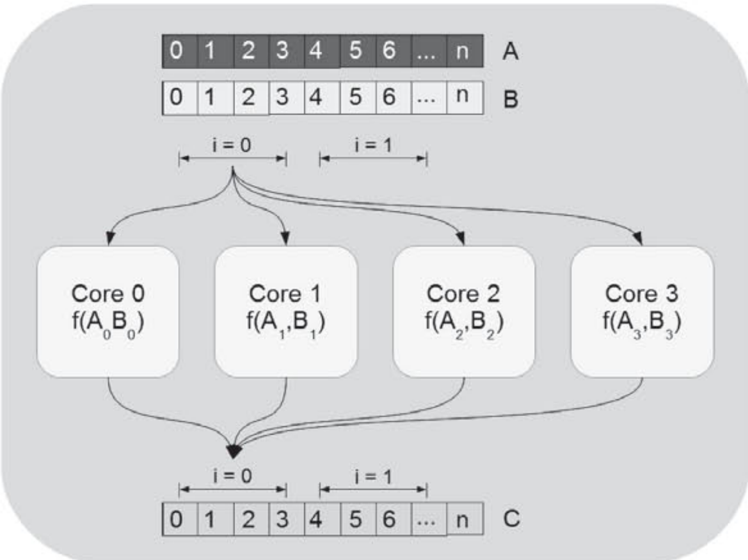

Figure 4: Distributed processing concept

For Nueva Ecija, MODIS tile h29v07, we had 380 images for this time period. We used the surface water detection methods by Xiao et al., (2006) and Roy et al., (2005). It is a MODIS based threshold system, where if NDVI < 0.1 and surface reflectance in Band 7 is less than 0.04, then the pixel is given a value of 1. Non-water pixels are set to 0. Faulty pixels (failed to process because of cloud, low sun angle, etc) were removed from further calculations. We computed averages over time for the binary (0/1) water occurrence values for each pixel. Initial mapping took an overview standpoint (Figures 5 and 6), using all available information and averaging the binary values over time. We refer to this [0-1] range as the relative frequency of detectable surface water occurrence. "Detectable water" refers to water that is above the crop canopy, unlike the desired situation in flooded rice fields, where there is surface water below the top of the canopy.

We also computed values for the few flooding prone months in the cropping season. Local cropping calendars (Table 2 for North-East Thailand, Table 3 for Nueva Ecija in The Philippines) were used to separate cropping seasons prior to process the occurrence of surface water, this provides convenient basis for seasonal events. For Northeastern Thailand, we identified August-September-October as the recurrent surface water season by combining information derived from Table 2 and monthly statistics from the remote sensing processing (Figure 7). For Nueva Ecija (Table 3 and Figure 8), it is less clear as the scale and the widespread irrigation control are mixing the signals. Flooding for transplanting in dry season starts in December, while in wet season flooding for transplanting in rice areas start in June (Casiwan et al., 2005). We combined the surface water maps with rice area maps to provide location targeting for submergence-tolerant rice variety dissemination.

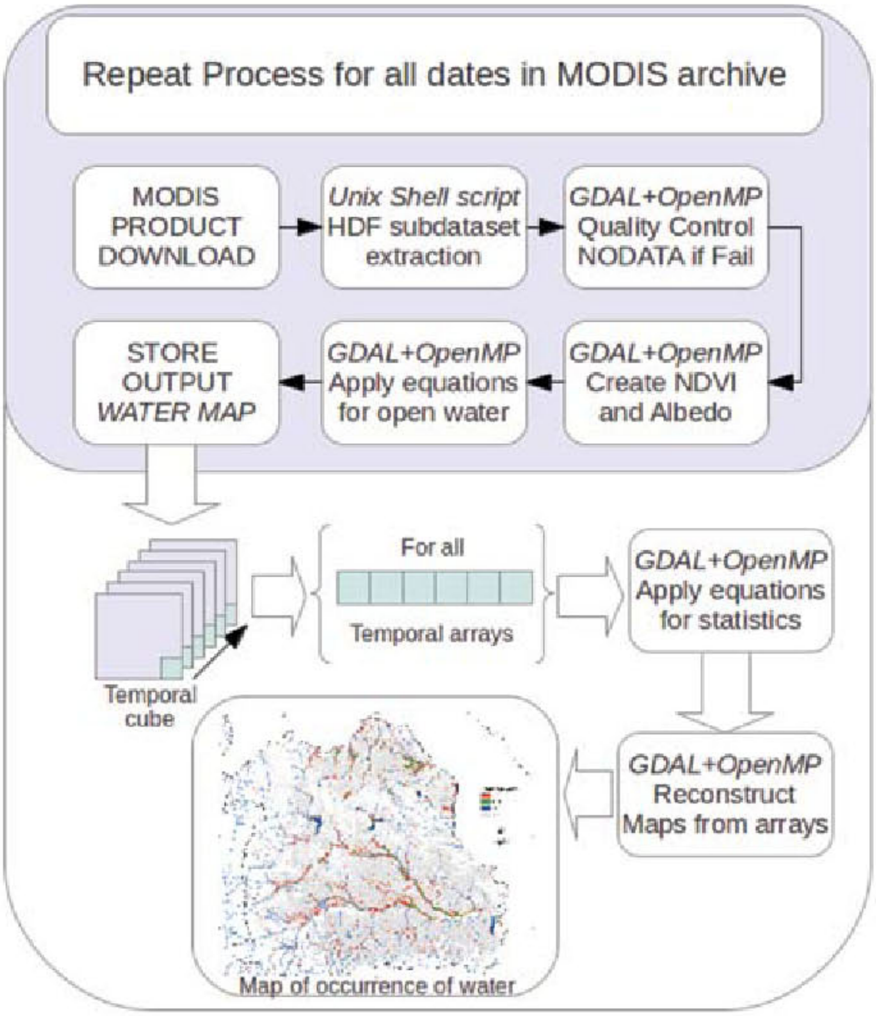

Figure 5: Chain processing of MODIS products, temporal cubes of water maps, statistical output maps

Table 2: North-East Thailand cropping calendar after Jornpradit (2007)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfed rice												
Irrigated dry season rice												

Table 3: Nueva Ecija rice cropping calendar after DoA (2012), PhilRice (2010) and RTDP (2000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dry season												
Wet season												

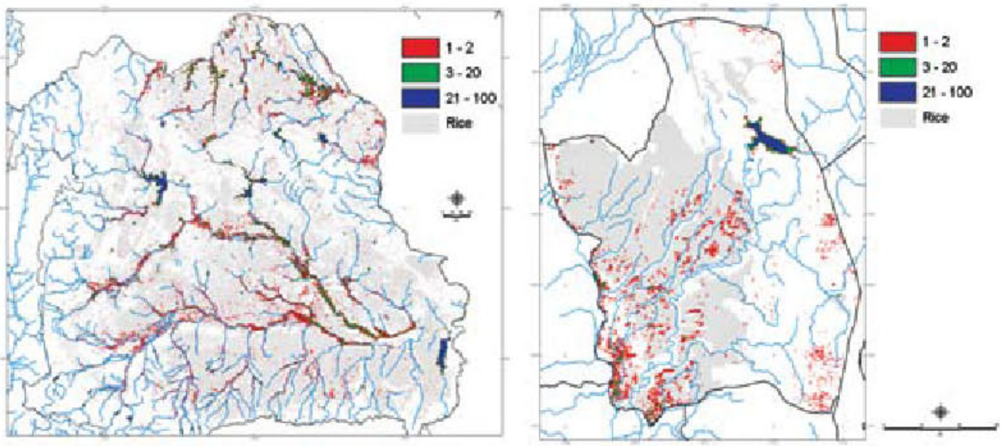

Figure 6: Relative frequency of detectable surface water occurrence (2000-08)
Left: Thailand, right: Philippines

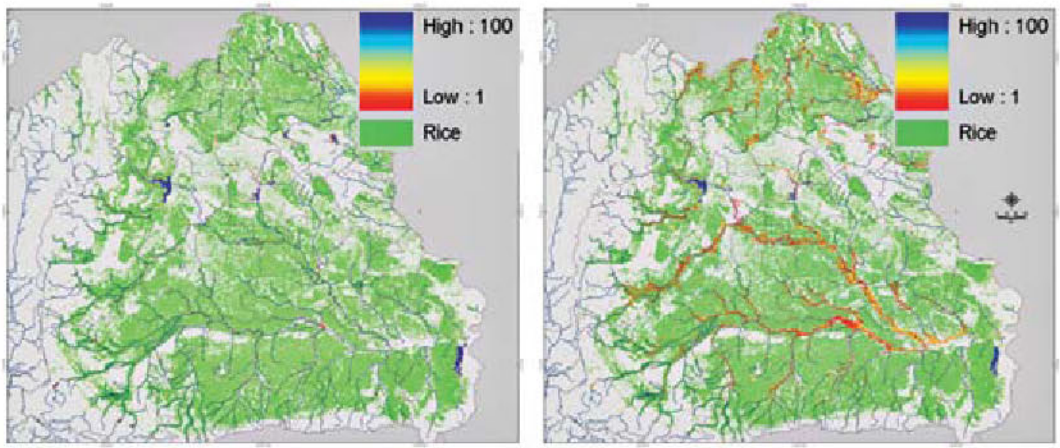

Figure 7: Average occurrence (2000-2008) of detectable surface water in
Northern Thailand in two months Left: January, right: September

3. Results

Figure 6 shows the percentage of surface water occurrence (2000-08) resulting in an end-to-end occurrence of surface water. The red color in figure 6 above is a surface water occurrence of 1-10% for all images analyzed.

In Northeastern Thailand, if only the 3 months rainfall peak is taken (August-October, not shown) the occurrence on the same areas expands to a range of about 5-30%. This can be stronger (Figure 7 right side, below) on a single month period of September occurrences ranging 10-75%.

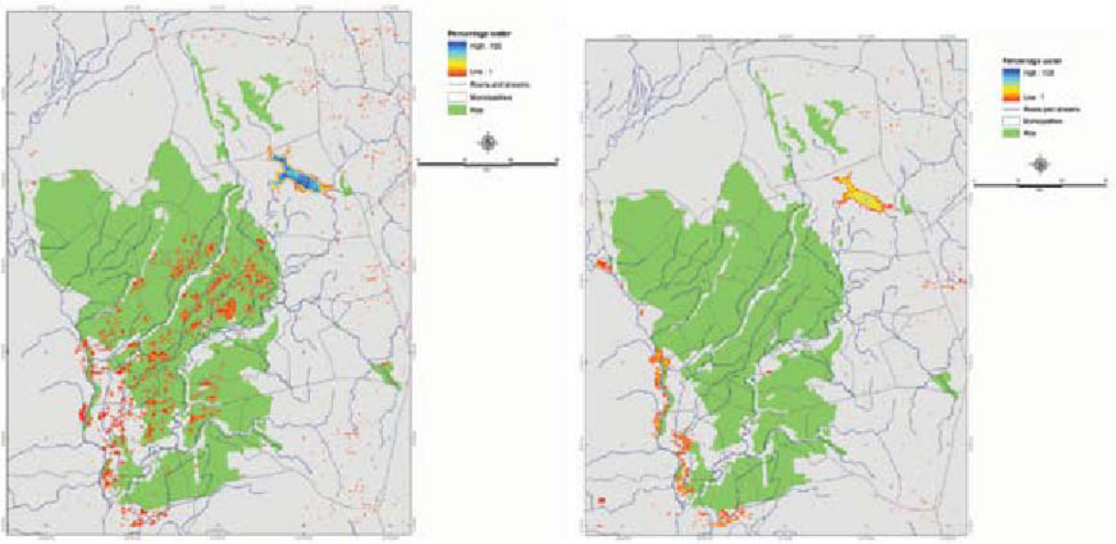

Figure 8: Monthly occurrence of surface water in Nueva Ecija
Left: January, right: September

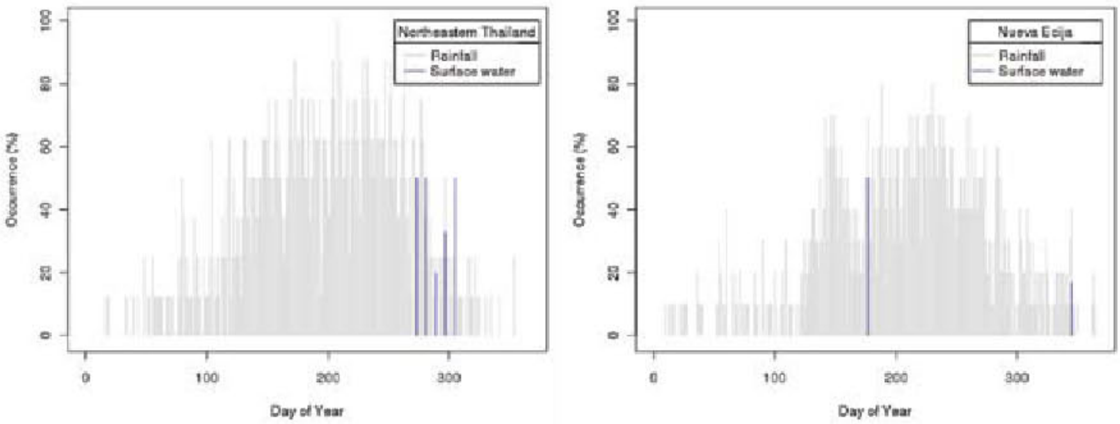

Figure 9: 8-daily occurrence, random pixel, Left: Northeast Thailand, right: Nueva Ecija

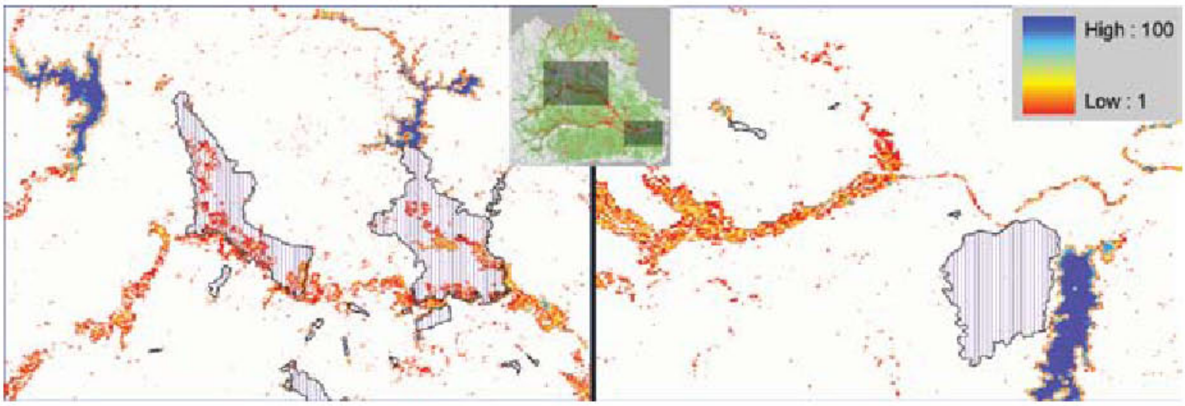

Figure 10: Submergence occurrence (%) in August-October with irrigated areas, NE Thailand

In Nueva Ecija (Figure 8), the monthly occurrence maps for January and September shows a different pattern altogether. January bringing widespread but infrequent, occurrence of surface water that is attributed to controlled flooding of rice paddies for the dry season cropping. Surface water detected in September, mostly around the Western side of the area, could be due to late controlled flooding for the wet season cropping or early season controlled flooding for the dry season rice crop. January is the time of flooding/transplanting and September is the time of reproductive-maturity stage for rice crop in Nueva Ecija. The southwestern part of the system area is prone to submergence and that it has standing water almost all throughout the rice wet cropping season. No rice is grown here during the rainy season due to flooding caused by impeded drainage and absence of natural drainage outlets. The graphs in Figure 9 expand a given pixel temporal occurrence of surface water every 8-days composite period of MODIS.

As can be seen in this figure's right side, the central location of Nueva Ecija, has detectable water in 50% of the years at day of the tear (DOY) =169 and 17% at DOY=345. In the case of Northeastern Thailand, one main season is found from October to November with a range of 20-50%, averaging at 41% occurrence of surface water over a period of 5*8=40 representative days. For this pixel, failed quality flags were found at all 8-days composites for all years at DOY=[121, 161, 177, 201, 209, 217, 225], the latest range being a contiguous period corresponding to the month of July. Parts of the irrigated areas of Northeastern Thailand (mostly grown with rice and sugarcane) are indeed under threat of submergence (Figure 10, left-side), and others are not (Figure 10, right-side). The right hand side map does not have surface water occurrence, because the irrigated area is located in a relatively high and undulated topography, taking water from the Sirindorn Dam (down right side of the map).

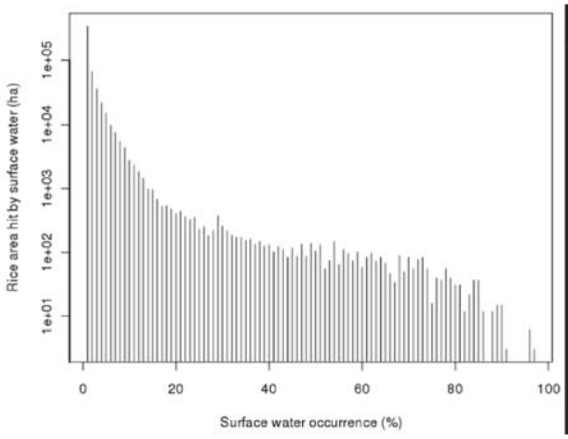

Figure 11: Distribution rice area affected by detectable surface water occurrence in NE Thailand. (note the logarithmic y-axis)

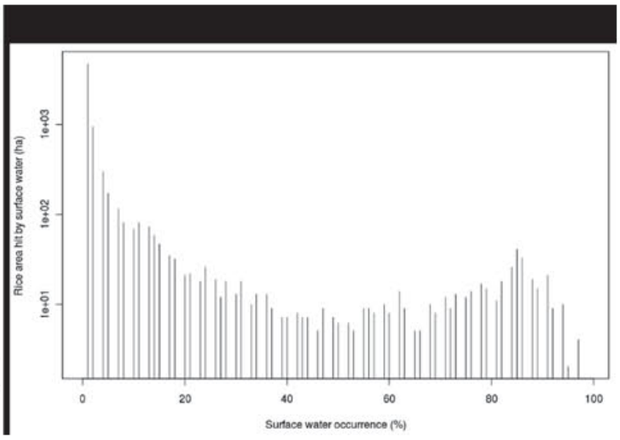

Figure 12: Distribution rice area affected by detectable surface water occurrence in Nueva-Ecija. (note the logarithmic y-axis)

Table 4: Rice area loss in Northeastern Thailand (MoA, 2012)

	Rice area loss (ha)
2005	82,286
2006	267,289
2007	252,972
2008	438,531
2009	97,968
2010	471,070
2011	593,630

On the other hand, the Left-side map of figure 10 is showing Ubon Rat Dam (top left) and Lam Pao Dam (top right), which are having downstream command areas under various threat (10-50% occurrence of surface water in August-October period). We found that in Northeastern Thailand, 6% of the rice areas had between 1 to 100% occurrence of surface water for the period of 2000 to 2008. The distribution of the rice area covered with surface water is shown in Figure 11 below. Figure 11 shows that most of the surface water in rice land is having an occurrence less than 10-20% of the time. Over the 9 years of this study, that means 300-400 days estimated of surface water.

While this is useful for the sensitivity of the rice land system in North East Thailand, Figure 11 only shows the spatial distribution, not the temporal distribution of surface water occurrence. When the detectable water occurrence is getting closer to 100%, nobody will grow rice at that location. The average area of rice that was found to be hit by some submergence at some point into the 9 years studied (i.e. probability of occurrence of submergence not null) is of 530,005 ha. When compared with information found in Figure 2, this is 50% of the total flood affected area of Thailand (1,013,670 ha) for the same period. When comparing with information from Table 4, which is from a different period, the average of Table 4 is 315,000 ha, lower than what was estimated for the period 2000-2008 with this study. When considering Figure 12, the first striking element is the near-similarity with Figure 11. Of course the scale is different, and there are averaging rules for North-East Thailand that will not apply to Nueva-Ecija. Likewise, Figure 12 shows that most of the rice area has a detectable surface water occurrence of 10-20%. The rice area affected is found to be of 37,807 ha, representing 13.75% of the rice harvested area on the basis of 2007 records. This compares well with Table 1a average of 19.5% and median of 10.2%.

4. Conclusion

Estimating the occurrence of open water provides information that can be related to known rice cropping areas in order to determine potential threat of submergence. However, we cannot ascertain the timing or the duration of surface water at this stage. To remedy to that, another and last geographic modeling is necessary, that is the combination of the cropping calendar and the temporal succession of surface water appearance using daily MODIS images that may provide a welcome support to enhance the quality of detection. Some of the limitations found when attending to the processing of the statistics of occurrence of surface water are that the identification models are simple relationships (which is also an advantage) and that we did not perform any temporal cloud filling procedure (i.e. interpolating binary information of presence or absence of surface water). This will change statistics, though the large number of pixels analyzed is helping in terms of statistical meaning. This research work gives ground to target location-based dissemination of Sub1 introgressed varieties of rice, to alleviate yield loss in case of submergence of rice by uncontrolled ponding water beyond the height of the plant. Some further work is required to find ways to interpolate binary information of the presence/absence of surface water in a given pixel along the temporal axis. Within another perspective, occurrence of open water could be potentially resourceful for the identification of temporary water storage in natural areas and large area on-farm water storage in agricultural areas as it is common in the Murray-Darling Basin as found in Chemin and Rabbani (2011) or rural tanks commonly found across Sri Lanka.

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